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Hydrogen Pathways: Cost, Well-to-Wheels Energy Use, and Emissions for the Current Technology Status of Seven Hydrogen Production, Delivery, and Distribution Scenarios

Mark Ruth National Renewable Energy Laboratory

Melissa Laffen and Thomas A. Timbario *Alliance Technical Services, Inc.*  Technical Report NREL/TP-6A1-46612 September 2009



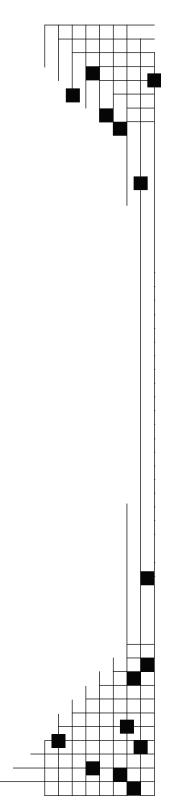
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Prepared under Task No. HS07.1002

*Technical Report* NREL/TP-6A1-46612 September 2009



National Renewable Energy Laboratory 1617 Cole Boulevard, Golden, Colorado 80401-3393 303-275-3000 • www.nrel.gov

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Contract No. DE-AC36-08-GO28308

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# Acknowledgements

The authors would like to acknowledge the following people for their assistance and support during this analysis.

The FreedomCar and Fuel Partnership's Fuel Pathway Integration Technical Team (FPITT) identified the need to examine concurrently the cost and well-to-wheels energy use and emissions of various hydrogen production and delivery pathways and to carefully document the key parameters of the analysis. They reviewed the results of the study both for content and for presentation and provided many helpful pointers. In addition, they performed the gap analysis that identified issues reported in Section 11. Current and past members of the team include Don Gardner and Matt Watkins (Exxon Mobil Corporation); Graham Moore, Bhaskar Balasubramanian, and Jonathan Weinert (Chevron Corporation); Jim Uihlein and Maria Curry-Nkansah (BP America Inc.); Ed Casey (Conoco-Phillips Company); Henk Mooiweer, Karel Kapoun and CJ Guo (Shell Hydrogen, LLC); Johanna Levene, Todd Ramsden, and Darlene Steward [National Renewable Energy Laboratory (NREL)]; and Fred Joseck [Department of Energy (DOE)].

Model developers assisted in the use of their models and understanding of underlying assumptions. Macro-System Model (MSM) developers include Victor Diakov (NREL) and Tim Sa, Mike Goldsby, Andy Lutz, and Keith Vanderveen [Sandia National Laboratories (SNL)]. H2A developers who assisted include Maggie Mann, Johanna Levene, Todd Ramsden, and Darlene Steward (NREL) and Brian James (Directed Technologies, Inc.). The Hydrogen Delivery Scenario Analysis Model (HDSAM) developers who assisted include Amgad Elgowainy [Argonne National Laboratory (ANL)] and Matt Ringer (NREL). The Greenhouse Gas, Regulated Emission, and Energy for Transportation (GREET) model developers who assisted include Amgad Elgowainy, Ye Wu, and Michael Wang (ANL). James Beetham (University of Colorado) assisted with MSM runs and data collection. Tien Nguyen (DOE) and Genevieve Saur (NREL) provided assistance in finding sources.

Fred Joseck (DOE) provided leadership, guidance, and funding for which we are grateful, and this analysis would not have been possible without him.

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# **1.0 Executive Summary**

The United States (U.S.) Department of Energy's (DOE) Fuel Cell Technologies Program (the Program) has identified a need to understand the cost, energy use, and emissions tradeoffs of various hydrogen production, delivery, and distribution options under consideration for fuel cell vehicles. The Program has been researching and developing hydrogen and fuel cell technologies because they have the potential to reduce U.S. dependence on foreign crude oil, diversify energy sources, decrease greenhouse gas (GHG) emissions, and provide domestic economic growth.

This document reports the levelized cost in 2005 U.S. dollars, energy use, and GHG emission benefits of the seven hydrogen production, delivery, and distribution pathways reported in Table 1.0.1. Current technology status is reported for each pathway and refers to technology that has been demonstrated at the bench scale at a minimum. All the technology options have potential for research and development (R&D) improvements.

	Feedstock	Central or Distributed Production	Carbon Capture and Sequestration	Delivery Method	Hydrogen Distribution
1	Natural Gas	Distributed	No	Not applicable	350 bar compressed gas
2	Electricity	Distributed	No	Not applicable	350 bar compressed gas
3	Biomass	Central	No	Liquid H <sub>2</sub> in trucks	350 bar compressed gas
4	Biomass	Central	No	Gaseous H <sub>2</sub> in pipelines	350 bar compressed gas
5	Natural Gas	Central	No	Gaseous H <sub>2</sub> in pipelines	350 bar compressed gas
6	Wind Electricity	Central	No	Gaseous H <sub>2</sub> in pipelines	350 bar compressed gas
7	Coal	Central	Yes	Gaseous H <sub>2</sub> in pipelines	350 bar compressed gas

Table 1.0.1. Seven Hydrogen Production, Delivery, and Distribution Pathways

Plausible production scenarios for mature hydrogen transportation-fuel markets combined with market penetration of hydrogen fuel cell vehicles were used in this analysis. They are not transition scenarios where equipment may not be fully utilized. The assumptions used in the analysis reflect current technology: technology that has been developed to the bench scale (at a minimum) but has not necessarily been demonstrated at commercial scales.

The pathways are described in detail, and system-level parameters are reported and referenced. Availability, cost, and characteristics of necessary resources are reported, as is the current status of supporting infrastructure. The sensitivities of each pathway's cost, pathway energy use, well-to-wheels energy use, and well-to-wheels emissions to many of the primary parameters are reported as an aid in understanding and assessing technology needs and progress, potential environmental impacts, and the energy-related economic benefits of various options. Some of the results are compared with those of current gasoline, diesel, and E85 vehicles including gasoline hybrid electric vehicles.

The Hydrogen Macro-System Model (MSM) was used to analyze the pathways by linking the H2A Production Model, the Hydrogen Delivery Scenario Analysis Model (HDSAM), and the Greenhouse Gas, Regulated Emission, and Energy for Transportation (GREET) Model. The MSM links those models so a single run utilizes the capabilities of each and ensures consistency among them. Also, the MSM is available to the public and enables users to analyze the pathways and complete sensitivity analyses that are not reported in this document.

The analysis has been reviewed by the FreedomCar and Fuel Partnership's Fuel Pathway Integration Technical Team (FPITT), which includes members from DOE, national laboratories, and energy companies (BP America Inc., Chevron Corporation, Conoco-Phillips Company, Exxon Mobil Corporation, and Shell Hydrogen, LLC).

This report compares fuel cost and well-to-wheel (WTW) emissions among multiple hydrogen fuel pathways and benchmarks those results against current gasoline and diesel fuel. Figure 1.0.1 illustrates six of the seven hydrogen pathways have GHG emissions that are lower than all the crude oil–based pathways and E85 generated from corn grain. All seven hydrogen pathways use less petroleum per mile traveled than the other pathways because of the increased efficiency fuel cells provide. Distributed electrolysis has high GHG emissions and high petroleum use when compared with the other hydrogen pathways because of the electricity grid mix. The coal pathway has low GHG emissions because 90% of the carbon dioxide generated in the hydrogen production facility is sequestered.

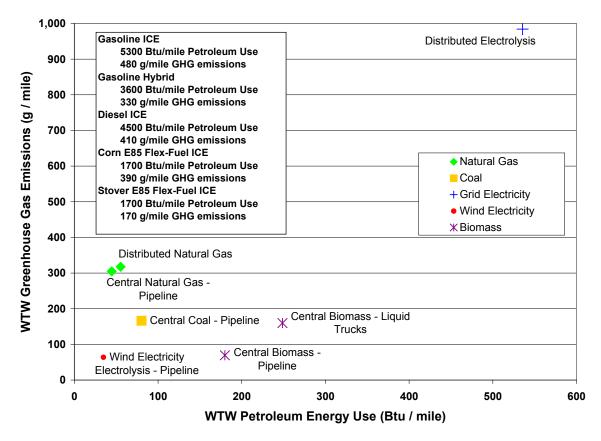


Figure 1.0.1. Comparison of pathways' petroleum use and greenhouse gas emissions

# 2.0 Introduction

## 2.1 Document's Intent

The U.S. DOE has identified a need to understand the lifecycle cost, energy use, and emissions tradeoffs of various hydrogen production and delivery pathways under consideration to enable a transition from a hydrocarbon-based economy to a hydrogen-and-electricity-based economy.

Feedstock, capital, capacity, and utility-sensitivity analyses on the cost of delivered hydrogen have been conducted for seven potential hydrogen production and delivery pathways using MSM. This analysis will aid in understanding and assessing technology needs and progress, potential environmental impacts, and the energy-related economic benefits of various hydrogen supply and demand pathways.

The objectives of this analysis were:

- Improved understanding of the primary parameters that affect the levelized cost, WTW fossil energy requirements, and WTW emissions of each of the seven pathways analyzed
- Referencing those parameters and performing an initial sensitivity analysis around them
- Giving industry (through FPITT) the opportunity to review those primary assumptions and provide feedback
- Completing a gap analysis around the parameters to identify possible production, delivery, and distribution issues.

This document reports a greater level of detail than analyses that show only the full pathway results (or maybe have a single break-point in the pathway), but it reports little information at the unit-operation level. Parameters that are expected to have major effects on the results are reported at the unit-operation level.

# 2.2 Market State and Technology Development Assumptions

The pathways analyzed are intended to be plausible production scenarios for mature technologies with full deployment of a regional hydrogen fueling network. They are not transition scenarios where equipment may not be utilized fully, nor are they technology validation activities where production, delivery, and vehicle costs are higher due to first-of-a-kind plants and low production levels of vehicles. Specifically, today's technical status is extrapolated to a scenario where 50% of the vehicles are fueled by hydrogen in a city with the area (553 mi<sup>2</sup>) and population (1,247,364) of Indianapolis, Indiana, and all equipment is fully utilized for its lifetime. Production facilities are not scaled to meet demand; instead, necessary demand from other nearby communities is assumed available so the facilities are kept at the H2A-defined natural scale.

Costs, energy use, and emissions estimates in this study are based on current technologies, and costs are reported in 2005 U.S. dollars. In this analysis, "current technology" refers to technology that is available currently at the bench scale—not necessarily technology that has been demonstrated at production scales. Thus, assumptions about larger-scale performance and equipment requirements and costs were necessary.

Designs and costs in this analysis do not include additional requirements of first-of-akind or one-of-a-kind technologies. In many cases, first-of-a-kind technologies require safety factors, instrumentation, and contingencies that are not necessary later in the development process. Those additional costs are not included in this analysis because they are difficult to account for and because they are not well understood. Instead, technology designs and costs are based on "n<sup>th</sup> plant" techniques (techniques which inherently assume that the technology is mature and do not include additional contingency, capital costs, and yield loss necessary for of first-of-a-kind plants cost estimation).

## 2.3 Analysis Boundaries

WTW energy use and emissions are assessed for each pathway using the GREET model. Included in the assessment are feedstock recovery, transportation, and storage; fuel production, transportation, storage, and distribution; and vehicle operation. The reported energy use includes both direct and indirect use of raw materials (natural gas, coal, and petroleum). For feedstock recovery, direct use of raw materials involves those used to recover and refine the feedstock, and indirect use of raw materials involves those needed to produce electricity and materials that are used directly.

Energy used and emissions generated to produce the vehicles, produce the equipment required to recover the feedstock, produce the fuel, etc., are not included. The GREET 2 series is capable of including energy and emissions for production, maintenance, and disposal of the vehicles, but it was not used in this analysis.

### 2.4 Pathways

The seven pathways included in this analysis are shown in Table 2.4.1.

	Feedstock	Central or Distributed Production	Carbon Capture and Sequestration	Delivery Method	Hydrogen Distribution
1	Natural Gas	Distributed	No	Not applicable	350 bar compressed gas
2	Electricity	Distributed	No	Not applicable	350 bar compressed gas
3	Biomass	Central	No	Liquid H <sub>2</sub> in trucks	350 bar compressed gas
4	Biomass	Central	No	Gaseous H <sub>2</sub> in pipelines	350 bar compressed gas
5	Natural Gas	Central	No	Gaseous H <sub>2</sub> in pipelines	350 bar compressed gas
6	Wind Electricity	Central	No	Gaseous H <sub>2</sub> in pipelines	350 bar compressed gas
7	Coal	Central	Yes	Gaseous H <sub>2</sub> in pipelines	350 bar compressed gas

 Table 2.4.1. Seven Hydrogen Production, Delivery, and Distribution Pathways

For convenience, the pathways are identified throughout this report using the feedstock and the delivery method; for example: Pathway 1 is referred to as the distributed natural gas pathway, Pathway 2 is referred to as the distributed electricity pathway, Pathway 3 is the central biomass with liquid delivery pathway, and Pathway 4 is the central biomass with pipeline delivery. The product from each of the pathways is the same: gaseous hydrogen with sufficient purity for dispensing to a hydrogen fuel-cell vehicle, compressed to 6,250 psi (430 bar) for on-board storage at 5,000 psi (350 bar).

Each pathway description below includes a flowchart showing the major subsystems of the hydrogen production and delivery pathway and the amount of energy required for each. Not included in these flowcharts are the energy requirements to supply the feedstock for hydrogen production; the energy use for feedstock production and delivery is included in the full WTW results presented in Section 9.0.

#### Pathway 1—Distributed Natural Gas

In the distributed natural gas pathway, hydrogen is produced from natural gas at the hydrogen refueling site using a 1,500 kg  $H_2$ /day steam methane reformer (SMR) with water-gas shift (WGS). Pressure swing adsorption (PSA) is used to obtain the required hydrogen purity. The hydrogen is then compressed to 6,250 psi (430 bar) and stored on-site prior to dispensing as a gaseous fuel to the 5,000-psi (350 bar) vehicle fuel tank. The flow diagram in Figure 2.4.1 shows the fuel production and delivery components of the distributed natural gas pathway and the energy balance for the major hydrogen-related subsystems, and the pathway is on a 1-gallon gasoline equivalent (gge) basis. The production technologies are detailed in Section 5.0, and the forecourt technologies are detailed in Section 6.0.

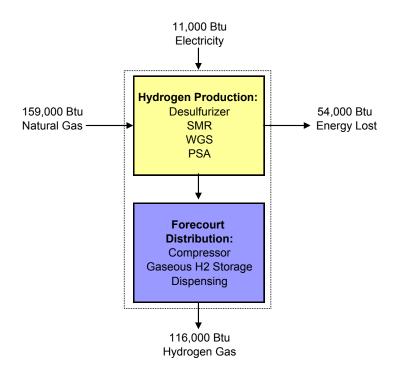


Figure 2.4.1. Flow diagram and energy balance of distributed natural gas pathway

Values may not sum to zero due to rounding.

This pathway is considered among the least costly in the near-term to establish early market refueling capability (Greene et al., 2008). In fact, several stations utilizing this pathway have already been installed throughout the world as seen in Table A.1., Appendix A (Fuel Cells 2000, 2009).

### Pathway 2—Distributed Electricity

In the distributed electricity pathway, hydrogen is produced from water at the hydrogen refueling site using a 1,500 kg  $H_2$ /day grid-powered electrolyzer. A scrubber is used to obtain the required hydrogen purity. The hydrogen is then compressed to 6,250 psi (430 bar) and stored on-site prior to dispensing as a gaseous fuel to the 5,000-psi (350 bar) vehicle fuel tank. The flow diagram in Figure 2.4.2 shows the fuel production and delivery components of the distributed electricity pathway and the energy balance for the major hydrogen-related subsystems, and the pathway is on a 1-gge basis. The production technologies are detailed in Section 5.0, and the forecourt technologies are detailed in Section 6.0.

This pathway offers an alternative to distributed natural gas, particularly in areas where clean, inexpensive electricity is available.

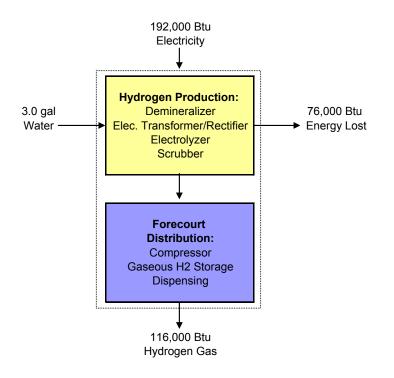


Figure 2.4.2. Flow diagram and energy balance of distributed electricity pathway

Values may not sum to zero due to rounding.

#### Pathway 3—Central Biomass–Liquid Truck Delivery

In the central biomass–liquid truck delivery pathway, woody biomass (poplar) within a 50-mile radius is transported via truck to a central hydrogen production facility with a design capacity of 2,000 bone dry metric ton/day biomass (~155,000 kg H<sub>2</sub>/day). An indirectly heated biomass gasifier converts the biomass to a biogas, which is then converted to hydrogen using a catalytic SMR with WGS. PSA is used to obtain the required hydrogen purity. The hydrogen is liquefied, stored as necessary, and delivered via tube trailer to a 1,500 kg/day forecourt hydrogen refueling station, where it is vaporized, compressed to 6,250 psi (430 bar), and dispensed as a gaseous fuel to the 5,000-psi (350 bar) vehicle fuel tank. The flow diagram in Figure 2.4.3 shows the fuel production and delivery components of the central biomass–liquid truck delivery pathway and the energy balance for the major hydrogen-related subsystems, and the pathway is on a 1-gge basis. The production technologies are detailed in Section 5.0, and the delivery technologies are detailed in Section 6.0.

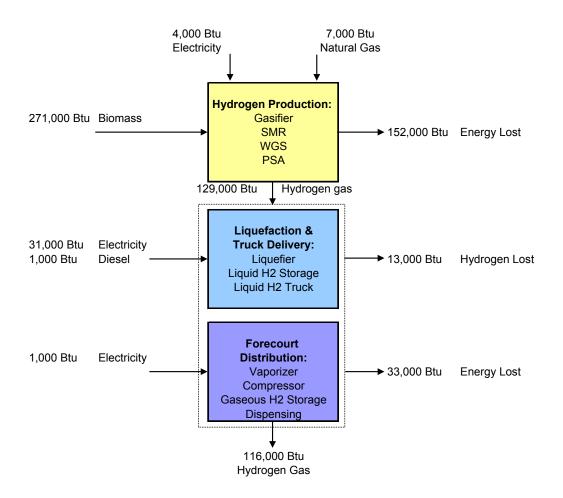
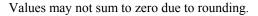


Figure 2.4.3. Flow diagram and energy balance of central biomass–liquid truck delivery pathway



The biomass pathways were selected for this study because of their potential to provide hydrogen with low- or zero-carbon dioxide  $(CO_2)$  emissions and because there are feedstock availability, delivery, and handling issues that are unique to biomass. These pathways are also more dependent on regional resource availability and costs than other pathways; while sensitivities to regionality are outside the scope of this study, they may be determined as more data become available.

This is the only pathway studied that utilizes liquid hydrogen delivery. Comparison with the central biomass-pipeline delivery pathway offers insights to the advantages, disadvantages, and issues associated with liquid hydrogen delivery. It also offers the opportunity to examine the sensitivity of both delivery options (liquid truck and gaseous pipeline) with parameters such as delivery distance and degree of hydrogen penetration in the vehicular fuel market.

#### Pathway 4—Central Biomass–Pipeline Delivery

In the central biomass–pipeline delivery pathway, woody biomass (poplar) within a 50mile radius is transported via truck to a central hydrogen production facility with a design capacity of 2,000 bone dry metric ton/day biomass (~155,000 kg H<sub>2</sub>/day). An indirectly heated biomass gasifier converts the biomass to a biogas, which is then converted to hydrogen using a catalytic SMR with WGS. PSA is used to obtain the required hydrogen purity. The hydrogen is compressed to 1,000 psi (69 bar) and injected into a pipeline, through which it is transported to a 1,500 kg/day forecourt hydrogen refueling station. There the hydrogen is compressed to 6,250 psi (430 bar) and dispensed as a gaseous fuel to the 5,000-psi (350 bar) vehicle fuel tank. The flow diagram in Figure 2.4.4 shows the fuel production and delivery components of the central biomass–pipeline delivery pathway and the energy balance for the major hydrogen-related subsystems. The production technologies are detailed in Section 5.0, and the delivery technologies are detailed in Section 6.0.

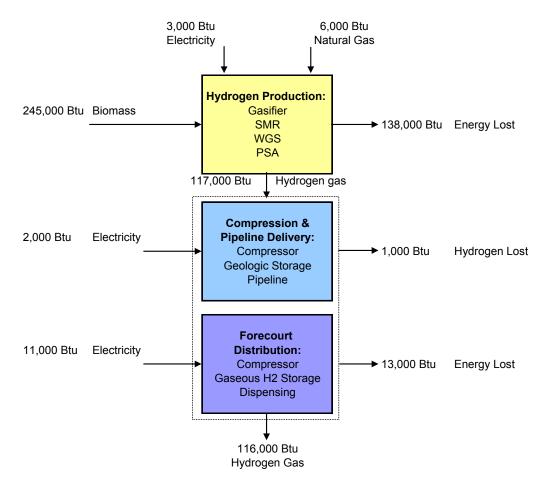
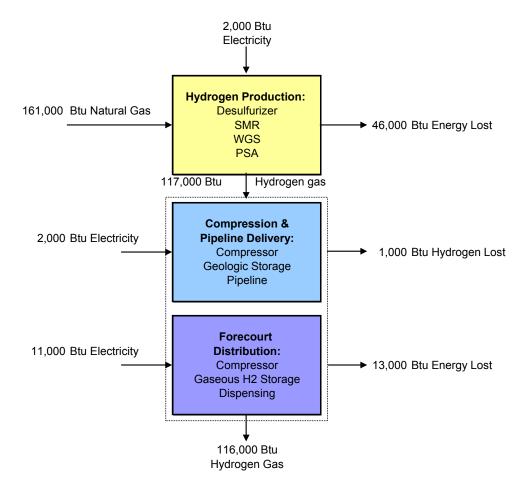


Figure 2.4.4. Flow diagram and energy balance of central biomass-pipeline delivery pathway

Values may not sum to zero due to rounding.

#### Pathway 5—Central Natural Gas–Pipeline Delivery

In the central natural gas–pipeline delivery pathway, natural gas is carried via pipeline to a central hydrogen production facility with a design capacity of ~379,000 kg H<sub>2</sub>/day where SMR with WGS is used to reform the natural gas to hydrogen. PSA is used to obtain the required hydrogen purity. The hydrogen is compressed to 1,000 psi (69 bar) and injected into a pipeline, through which it is transported to a 1,500 kg/day forecourt hydrogen refueling station. There the hydrogen is compressed to 6,250 psi (430 bar) and dispensed as a gaseous fuel to the 5,000-psi (350 bar) vehicle fuel tank. The flow diagram in Figure 2.4.5 shows the fuel production and delivery components of the central natural gas–pipeline delivery pathway and the energy balance for the major hydrogen-related subsystems. The production technologies are detailed in Section 5.0, and the delivery technologies are detailed in Section 6.0.



# Figure 2.4.5. Flow diagram and energy balance of central natural gas-pipeline delivery pathway

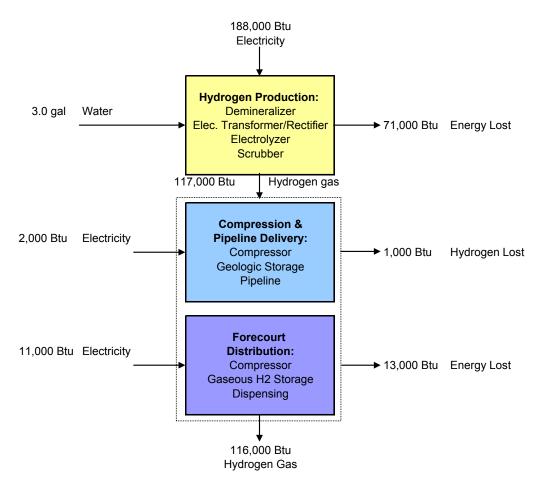
Values may not sum to zero due to rounding.

The central natural gas-pipeline delivery pathway was selected as a benchmark case for this study. Large-scale natural gas reforming is a mature process being used to produce

hydrogen for oil refining. It is expected to result in the lowest cost of hydrogen when pipeline delivery is employed.

#### Pathway 6—Central Wind Electricity–Pipeline Delivery

In the central wind electricity pathway, hydrogen is produced from water at a central production facility using a grid-powered electrolyzer with a design capacity of ~52,300 kg H<sub>2</sub>/day. It is assumed that the facility buys wind-power credits for all the electricity purchased. A scrubber is used to obtain the required hydrogen purity. The hydrogen is compressed to 1,000 psi (69 bar) and injected into a pipeline, through which it is transported to a 1,500 kg/day forecourt hydrogen refueling station. There the hydrogen is compressed to 6,250 psi (430 bar) and dispensed as a gaseous fuel to the 5,000 psi (350 bar) vehicle fuel tank. The flow diagram in Figure 2.4.6 shows the fuel production and delivery components of the central wind electricity pathway and the energy balance for the major hydrogen-related subsystems. The production technologies are detailed in Section 5.0, and the delivery technologies are detailed in Section 6.0.



# Figure 2.4.6. Flow diagram and energy balance of central wind electricity–pipeline delivery pathway

Values may not sum to zero due to rounding.

The central wind electricity–pipeline delivery pathway represents a low-carbon, renewable energy based option for providing hydrogen as a transportation fuel. Unlike the biomass pathways, which has potential geographic limitations, the wind electricity pathway can be implemented anywhere that wind-power credits are available for purchase.

#### Pathway 7—Central Coal with Carbon Capture and Sequestration (CCS)– Pipeline Delivery

In the central coal with carbon capture and sequestration (CCS)–pipeline delivery pathway, coal is delivered via rail to a central hydrogen production facility with a design capacity of ~308,000 kg H<sub>2</sub>/day where it is gasified. A shift converter is used to convert the syngas to a hydrogen-rich gas, which undergoes acid gas cleanup and sulfuric acid removal prior to entering a PSA unit, which is used to obtain the required hydrogen purity. Carbon dioxide is captured using a Selexol<sup>®</sup> process and is compressed to 2,200 psi (152 bar) for injection to a pipeline. It is transported via pipeline to a sequestration site. The hydrogen is compressed to 1,000 psi (69 bar) and injected into a pipeline, through which it is transported to a 1,500 kg/day forecourt hydrogen refueling station. There the hydrogen is compressed to 6,250 psi (430 bar) and dispensed as a gaseous fuel to the 5,000-psi (350 bar) vehicle fuel tank. The flow diagram in Figure 2.4.7 shows the fuel production and delivery components of the central coal with CCS–pipeline delivery pathway and the energy balance for the major hydrogen-related subsystems. The production technologies are detailed in Section 5.0, and the delivery technologies are detailed in Section 6.0.

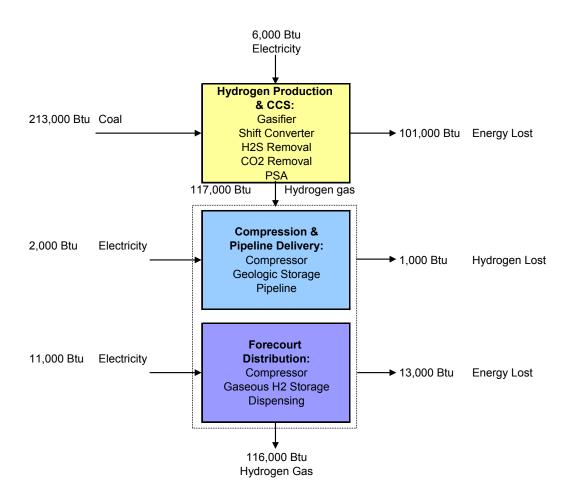
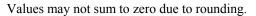


Figure 2.4.7. Flow diagram and energy balance of central coal with CCS–pipeline delivery pathway



Coal is the most abundant native fossil fuel in the U.S. and is available at lower cost than other fossil fuels. The central coal with CCS–pipeline delivery pathway was selected for this study to enable comparisons between coal and other fossil and renewable options for providing hydrogen transportation fuel. It is the only pathway studied that includes carbon capture and sequestration, thus offering opportunities for better understanding the effects of CCS on hydrogen costs, energy use, and emissions.

### 2.5 Models Used in the Pathway Analyses

The H2A Production Model Version 2.1 (Steward, Ramsden, and Zuboy, 2008) applies a standard discounted cash flow rate of return methodology to determine the minimum hydrogen selling price for central and forecourt hydrogen production technologies, including a specified after-tax internal rate of return. The H2A Production Model performs carbon sequestration calculations for centralized hydrogen production pathways and refueling station compression, storage, and dispensing calculations for distributed hydrogen production pathways.

The H2A Delivery Scenario Analysis Model (HDSAM) Version 2.0 (Mintz, Elgowainy, and Gillette, 2008) calculates the cost of hydrogen delivery using an engineering economics approach via a single or mixed mode for transmission and distribution (cryogenic tank truck, compressed gas truck, or pipeline) for a scenario defined by type and size of market, penetration rate, and refueling station capacity. Delivery in Version 2.0 includes all transport, storage, and conditioning activities from the outlets of a centralized hydrogen production facility to and including a fuel station that stores, in some cases further conditions, and dispenses the hydrogen to vehicles; this version does not model distributed production scenarios. Discounted cash flow is used to calculate the cost contribution of each component in the delivery chain.

The GREET model (Argonne National Laboratory, 2009) calculates the full fuel-cycle emissions and energy use associated with various transportation fuels for light-duty vehicles. Emissions included are the five criteria pollutants (volatile organic compounds, carbon monoxide, oxides of nitrogen, oxides of sulfur, and particulate matter) and three greenhouse gases (carbon dioxide, methane, and nitrous oxide). Additionally, total fuelcycle energy consumption, fossil fuel consumption and petroleum consumption are calculated. More than 100 fuel production pathways and more than 70 vehicle/fuel systems are available in the current version of GREET. For this hydrogen pathways report, a modified version of GREET 1.8b downloaded on September 5, 2008, was utilized. The GREET model was modified to make it consistent with previous versions by adjusting the "method for dealing with co-products of soybean-based fuel" from displacement to energy-based allocation.

MSM (Ruth et al., 2009) links the H2A Production Model, HDSAM, and GREET to perform WTW analysis of the energy use, emissions, and economics of hydrogen production and delivery pathways from feedstock extraction through end use of hydrogen in vehicles. The primary inputs to the MSM are technology year, city size and hydrogen fuel penetration, production and delivery technology, and vehicle fuel economy. H2A and HDSAM results are used as inputs for many of GREET's input parameters in each MSM run. Primary energy source requirements and emissions are analyzed. Outputs of the model include the amount and type of feedstock used to produce hydrogen, efficiencies of different technologies, energy use and emissions of various pathways, hydrogen production capacity to meet demand, and cost of hydrogen at the pump achievable under different scenarios.

The MSM provides a Web-based interface that allows users to perform hydrogen pathway analyses following their own interests. It also allows for extensive single-parameter and multi-parameter sensitivities. The MSM will be updated with future versions of the H2A Production Model, HDSAM, and GREET as they are made public. For access to the MSM, please contact Mark Ruth at <u>mark.ruth@nrel.gov</u>.

# 3.0 Resource Assumptions

The extent to which each of the pathways analyzed in this study can be deployed to supply hydrogen fuel for light-duty vehicles depends on the availability, cost, and quality of required feedstocks, energy sources, and supporting infrastructures. This section examines the availability, cost, and characteristics of each of the feedstocks and energy sources utilized by the seven pathways: natural gas, electricity (including wind electricity), biomass, and coal. The current status and potential of carbon sequestration in the U.S. are also briefly explored because carbon sequestration is an element of the central coal–pipeline delivery pathway assessed in this study.

Additional resources and supporting infrastructures required for producing hydrogen and/or FCVs include water, platinum, carbon fiber, steel, concrete, dispensing equipment, monitoring/safety equipment, testing equipment, land, and skilled labor. Assessment of these resources and infrastructures is outside the scope of this study; however, DOE and the Fuel Pathway Integration Tech Team are currently supporting separate analyses of water and carbon-fiber resources. A summary of platinum resources analyses conducted to date for the DOE Hydrogen Program is provided in Appendix H.

## 3.1 Natural Gas

Natural gas is an important potential-hydrogen feedstock and also a significant electricity-generation feedstock, accounting for more than 15% of current electricity generation in the U.S. Its availability and cost, therefore, impact the viability and cost of hydrogen for several of the pathways studied.

### Availability and Utilization

U.S. reserves of dry natural gas were estimated to be 237,726 billion cubic feet for 2007 (Energy Information Administration, 2009i). Data from EIA (Energy Information Administration, 2009c) show that the United States withdrew 26,032,337 million cubic feet of natural gas in 2008, which was up from 24,590,602 in 2007. For the same 2007–2008 time period, data (Energy Information Administration, 2009b) show the United States consumed 23,208,677 million cubic feet of natural gas in 2008 and 23,047,229 million cubic feet in 2007, increasing about 0.1%. Total consumption includes lease and plant fuel, pipeline and distribution use, and volumes delivered to consumers. The 2008 consumption was at near-record levels, second only to the amount consumed in 2000. One reason for the jump in consumption over 2007 levels was the 5.6% increase in heating degree days for 2008.

If the entire fleet of U.S. passenger vehicles were run on hydrogen produced from natural gas, 10 trillion normal cubic feet would be required annually to produce the necessary hydrogen (not including natural gas necessary for generation of the electricity used within the pathways). Ten trillion normal cubic feet is 43% of the total natural gas consumption in 2008. The demand calculation is based on a total vehicle miles traveled in passenger vehicles of 2.78 trillion (Bureau of Transportation Statistics, 2007), the vehicle fuel

economy used in this study (45 mpgge), and a yield of hydrogen from natural gas of 4.5  $Nm^3$  natural gas/kg H<sub>2</sub> (159 Nft<sup>3</sup> natural gas/kg H<sub>2</sub>, which is 71% efficiency on an LHV basis). This calculation and the natural gas supply scenarios for lower fuel cell vehicle penetration rates are shown in Section 9.1.

## Resource Cost

In cases where hydrogen is produced from natural gas, the natural gas price used for this analysis is \$0.24/Nm<sup>3</sup> (\$6.73/MMBtu), and in cases where natural gas is used for supplemental heat, the natural gas price used for this analysis is \$0.34/Nm<sup>3</sup> (\$9.52/MMBtu). These prices are different because industrial rates for natural gas were assumed for cases based on natural gas and because commercial rates were assumed for cases based on other feedstocks. Both rates are from EIA (2005) and are based on the High A Case. In 2007, the electric power price of natural gas was \$7.31 per thousand cubic feet (\$7.23/MMBtu). The cost jumped to \$9.35 per thousand cubic feet (\$9.24/MMBtu) in 2008 (Energy Information Administration, 2009d).

#### Characteristics

Natural gas consists of a high percentage of methane and varying amounts of ethane, propane, butane, and inert gases (nitrogen, carbon dioxide, and helium). Table 3.1.1 (Avallone and Baumeister, 1996) shows the composition and heating value of various natural gas samples from across the country. In this analysis, the natural gas has a higher heating value of 1089 Btu/ft<sup>3</sup> and a lower heating value of 983 Btu/ft<sup>3</sup>.

	Composition, mole %						
		Oil or C	Gas Well		Pipeline		
State of origin	LA	MS	NM	ΤX	СО	KS	OK
Methane	92.1	96.3	67.7	43.6	94.3	72.3	75.4
Ethane	3.8	0.1	5.6	18.3	2.1	5.9	6.4
Propane	1.0	0.0	3.1	14.2	0.4	2.7	3.6
Butane	0.3	0.0	1.5	8.6	0.2	0.3	1.0
Nitrogen	0.9	1.0	17.4	3.0	0.0	17.8	12.0
Carbon dioxide	1.1	2.3	0.1	0.5	2.8	0.1	0.1
Helium	trace	trace	1.4	trace	trace	0.4	0.4
Heating value <sup>*</sup>	1,062	978	1,044	1,899	1,010	934	1,044

Table 3.1.1. Composition and Heating Value of Natural Gas

<sup>\*</sup> Gross / higher heating value, Btu/ft<sup>3</sup>, dry at 60°F and 30 inches of Hg.

### 3.2 Electricity

Electricity is a primary feedstock for the hydrogen production pathways employing electrolysis and is an important energy source for all of the pathways studied, as it is used to run pumps, compressors, and other equipment and controls. Electricity prices vary due to many factors including the energy source used to generate electricity, purchase

volumes, time of day (peak vs. off-peak), and reliability requirements. The energy use and emissions attributable to electricity consumption also vary widely depending on how the electricity is produced. The grid mix and electricity prices used in this study are intended to represent a U.S. average; individual facilities may experience different mixes and prices.

#### Availability and Utilization

EIA data (Energy Information Administration, 2009e) for 2008 show that the United States generated 4,110,259 million kilowatt-hours of electricity, which was down from 4,156,745 million kilowatt-hours in 2007. For that same period, data (Energy Information Administration, 2009f) show that sales of electricity in the United States were 3,721,562 million kilowatt-hours and 3,764,561 million kilowatt-hours in 2008 and 2007, respectively.

If the entire fleet of U.S. passenger vehicles were run on hydrogen produced in distributed electrolysis plants, 3.5 trillion kilowatt-hours would be required annually to produce the necessary hydrogen. Three and a half trillion kilowatt-hours is 85% of the total electricity generated in 2008. The demand calculation is based on a total vehicle miles traveled in passenger vehicles of 2.78 trillion (Bureau of Transportation Statistics, 2007), the vehicle fuel economy used in this study (45 mpgge), and a yield of hydrogen from electricity of 55 kWh electricity/kg hydrogen (62% efficiency on a hydrogen LHV basis). This calculation and the electricity supply scenarios for lower fuel cell vehicle penetration rates are shown in Section 9.2.

The GREET U.S. mix was used in these pathway analyses and is shown in Table 3.2.1. It is based on the 2005 grid mix (Energy Information Administration, 2005). For comparison, Table 3.2.2 (Energy Information Administration, 2009e) displays the net generation by energy source for the years 2007 and 2008; they are similar to the 2005 mix.

	% of Total
Biomass	1.2
Coal	51.7
Natural Gas	15.7
Nuclear	20.3
Residual Oil	2.9
Others (Carbon Neutral)	8.2
Total	100.0

Table	3.2.1.	GREET	U.S. N	lix
		<b>U</b>		

	2007	2008	2007	2008
	thousand me	gawatt-hours	% 0	f total
Coal <sup>1</sup>	2,016,456	1,994,385	48.5	48.5
Petroleum liquids <sup>2</sup>	49,505	31,162	1.2	0.8
Petroleum coke	16,234	14,192	0.4	0.3
Natural gas	896,590	876,948	21.6	21.3
Other gases <sup>3</sup>	13,453	11,573	0.3	0.3
Nuclear	806,425	806,182	19.4	19.6
Hydroelectric conventional	247,510	248,085	6.0	6.0
Other renewables <sup>4</sup>	105,238	123,603	2.5	3.0
Hydroelectric pumped storage	-6,896	-6,238	-0.2	-0.2
Other <sup>5</sup>	12,231	10,367	0.3	0.3
Total	4,156,745	4,110,259	100.0	100.0

Table 3.2.2. Net Generation by Energy Source

<sup>1</sup> Anthracite, bituminous, subbituminous, lignite, waste coal, and coal synfuel.

<sup>2</sup> Distillate fuel oil, residual fuel oil, jet fuel, kerosene, and waste oil.

<sup>3</sup> Blast furnace gas, propane gas and other manufactured and waste gases derived from fossil fuels.

<sup>4</sup> Wood, black liquor, other wood waste, biogenic municipal solid waste, landfill gas, sludge waste, agriculture byproducts, other biomass, geothermal, solar thermal, photovoltaic, and wind.

<sup>5</sup> Non-biogenic municipal solid waste, batteries, chemicals, hydrogen, pitch, purchased steam, fire-derived fuel, and miscellaneous technologies.

### Feedstock Conversion Efficiency

Figure 3.2.1 shows various types of power plants for electricity generation and their thermodynamic efficiencies. Hydroelectric plants are by far the most efficient at over 90%. However, as shown previously, hydroelectric plants contribute just 6% of the electricity-generation mix. At over 48% of the source mix, coal is the largest source of power generation in the United States. A coal-fired steam turbine plant has an efficiency of just under 40%, whereas an integrated gasification combined cycle (IGCC) coal-fired plant can achieve approximately 45%. Typically, this type of plant uses syngas to fire a gas turbine whose waste heat is utilized by a steam turbine system.

### Resource Cost

Commercial electricity cost an average of \$0.0965 per kilowatt-hour in 2007. That cost jumped to \$0.1028 per kilowatt-hour in 2008. Industry paid \$0.0639 and \$0.0701 per kilowatt-hour in 2007 and 2008, respectively (Energy Information Administration, 2009a). The pathway analyses use the 2005 electricity prices from the Annual Energy Outlook 2005 High A Case (Energy Information Administration, 2005): \$0.08159 per kilowatt-hour (in 2005 dollars) for commercial electricity and \$0.05549 per kilowatt-hour (in 2005 dollars) for industrial electricity. The commercial electricity price is used for

the distributed natural gas pathway and for electricity used at the refueling station in the central production pathways. The industrial electricity price is used for the distributed electricity pathway and for electricity used in the centralized production of hydrogen.

#### Wind Electricity

Wind power contributed more than a third of all new electric-generating capacity in 2007, installing 5,332 MW of capacity and expanding the U.S.'s total wind power–generating capacity by 45% in a single year from 11,575 MW to 16,907 MW; as of April 2009, the installed capacity has grown to 28,365 MW as seen in Figure 3.2.2 (National Renewable Energy Laboratory, 2009). Figure 3.2.3 shows the U.S. wind resource map for different wind power classes [ranging from 3 (fair) to 7 (superb)].

DOE released a report (United States Department of Energy, 2008) concluding that the U.S. possessed sufficient wind resources that would enable it to obtain 20% of its electricity (1.16 billion MWh) from wind by the year 2030. In 2007, the U.S. wind power capacity totaled 11,575 MW (11.6 GW), with wind power installations across 35 states. In 2008, 52,025,898 thousand kilowatt-hours of wind electricity were generated in the U.S., up from 34,449,927 in 2007 (Energy Information Administration, 2009). Wind sources contributed approximately 1.4% of the electricity consumed.

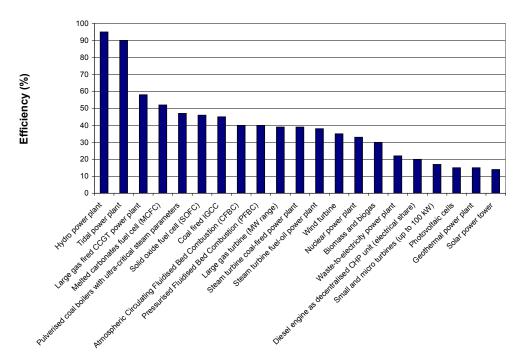


Figure 3.2.1. Efficiency in electricity generation from various sources (van Aart, 2004)

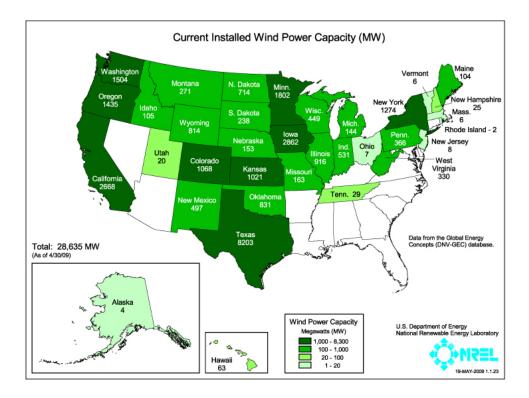


Figure 3.2.2. Installed wind capacity as of April 2009 (National Renewable Energy Laboratory, 2009)

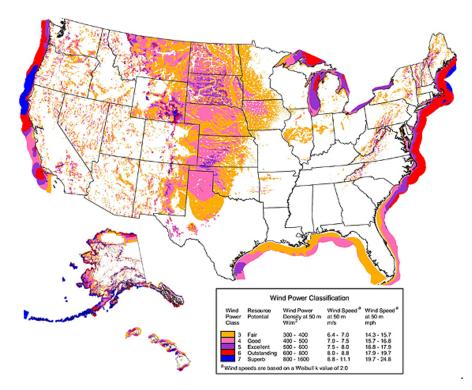


Figure 3.2.3. U.S. wind resource map (National Renewable Energy Laboratory, 2009)

Figure 3.2.4 shows the 2007 "bus-bar" energy cost for wind (wind plant costs only) by location (land-based or offshore) and by class of wind power. The U.S. has more than 8,000,000 MW (8,000 GW) of available land-based wind resources that can be captured economically.

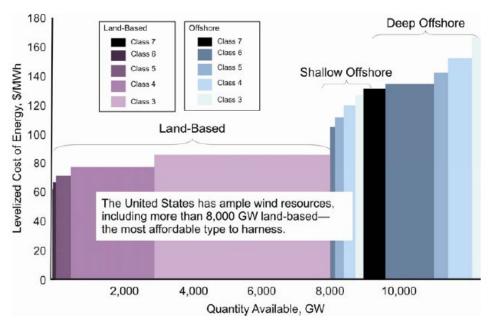


Figure 3.2.4. Wind energy supply curve (U.S. Department of Energy, 2008)

If the entire fleet of U.S. passenger vehicles were run on hydrogen produced from wind electricity, 3.4 trillion kilowatt-hours would be required annually to produce the necessary hydrogen, and 3.4 trillion kilowatt-hours is 6,500% of the total wind electricity consumption in 2008. The demand calculation is based on a total vehicle miles traveled in passenger vehicles of 2.78 trillion (Bureau of Transportation Statistics, 2007), the vehicle fuel economy used in this study (45 mpgge), and a yield of hydrogen from wind electricity of 53 kWh wind electricity/kg H<sub>2</sub>. This calculation and the wind electricity supply scenarios for lower fuel cell vehicle penetration rates are shown in Section 9.6.

# 3.3 Biomass (Wood)

Woody or herbaceous biomass may be a viable feedstock for hydrogen production in some areas of the U.S. and is already used in limited quantities in electricity generation. Biomass availability and cost vary widely and are location-specific.

### Availability and Utilization

The electric power sector, which is composed of electricity generation and combined heat and power (CHP) plants within North America and whose primary business is to sell electricity and/or heat to the public, generated a net of 10.9 billion kilowatt-hours in 2008 from wood and derived fuels, up from 10.7 billion kilowatt-hours in 2007; the industrial

sector generated a net of 27.9 billion kilowatt-hours in 2008, down from 28.3 billion kilowatt-hours in 2007 (Energy Information Administration, 2009j). This category included black liquor and wood/wood waste solids and liquids. The renewable energy sector contributed 9% of the 2008 electricity mix (Energy Information Administration, 2009k). Consumption of wood-derived fuels in 2008 was 2.041 quadrillion Btu (quads), accounting for approximately 52% of all biomass consumed for energy (3.884 quads, includes biofuels, waste, and wood-derived fuels) and 28% of all renewable energy consumed (7.301 quads).

In a joint study sponsored by the U.S. Department of Energy and the U.S. Department of Agriculture (Perlack et al., 2005), Oak Ridge National Laboratory sought to determine whether the land resources of the U.S. are capable of producing a sustainable supply of biomass sufficient to displace 30% or more of the U.S.'s present petroleum consumption. This goal would require approximately one billion dry tons of biomass feedstock per year. The researchers concluded that forestland and agriculture land, the two largest potential biomass sources, had the potential to provide 1.3 billion dry tons per year of biomass (see Figure 3.3.1) around the mid-21<sup>st</sup> century. This annual potential represents an increase in production of more than sevenfold from the amount of biomass consumed at the time of the report for bioenergy.

The report stated that forestlands in the contiguous U.S. could sustainably produce 368 million dry tons of biomass annually. That projection includes 52 million dry tons of fuelwood harvested from forests, 145 million dry tons of residues from wood-processing mills and pulp and paper mills, 47 million dry tons of urban wood residues including construction and demolition debris, 64 million dry tons of residues from logging and site-clearing operations, and 60 million dry tons of biomass from fuel-treatment operations to reduce fire hazards.

Concurrently, agricultural lands in the U.S. could produce one billion dry tons of biomass annually and still continue to meet food, feed, and export demands. This reported projection includes 428 million dry tons of annual crop residues, 377 million dry tons of perennial crops, 87 million dry tons of grains used for biofuels, and 106 million dry tons of animal manure, process residues, and other miscellaneous feedstocks.

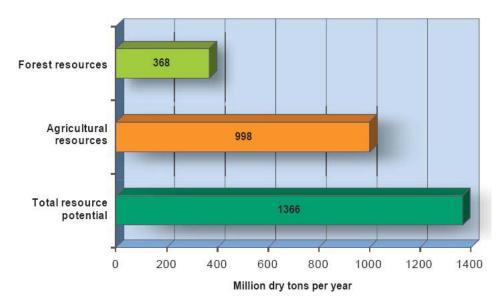


Figure 3.3.1. Annual biomass resource potential from forestland and agricultural land (Perlack et al., 2005)

If the entire fleet of U.S. passenger vehicles were run on hydrogen produced from biomass, 890 million dry tons of biomass would be required annually to produce the necessary hydrogen, and 890 million dry tons is 730% of the wood-derived fuels consumed in the U.S. in 2008. The demand calculation is based on a total vehicle miles traveled in passenger vehicles of 2.78 trillion (Bureau of Transportation Statistics, 2007), the vehicle fuel economy used in this study (45 mpgge), and a yield of hydrogen from biomass of 12.8 kg dry biomass/kg H<sub>2</sub>. This calculation and the biomass supply scenarios for lower fuel cell vehicle penetration rates are shown in Section 9.3.

#### Resource Cost

Table 3.3.1 summarizes the estimate of the main components that make up the non-feed and food crop biomass available in the U.S. in the near-term at approximately \$65 per ton delivered to the processing plant (Board on Energy and Environmental Systems, 2008). The table also includes other estimates for comparison.

	Biomass Amount (million tons per year)						
	NRC Near- Walsh et al. Milbrandt Perlack et al.						
	Term	(2000)	(2005)	(2005)	2030		
Crop residue	160	50	173	179	315		
Forest residues	55	44	62	136	55		
Mill wastes <sup>1</sup>	5	90	88	106			
Urban wood waste	30	37	34	37	30		
Energy crops	85	188	99	-	100		
Total	335	509	456	458	490		

 Table 3.3.1. Estimated Primary Solid Biomass Components Available in the United States in the Near Term and 2030 for Less than about \$65 per Ton (2007 dollars)

<sup>1</sup> NRC estimate includes only the fraction that is estimated as not already being used.

### Characteristics

Table 3.3.2 provides a typical analysis of dry wood (Avallone and Baumeister, 1996).

	Most Woods, range
Proximate analysis, %	
Volatile matter	74–82
Fixed carbon	17–23
Ash	0.5–2.2
Ultimate Analysis, %	
Carbon	49.6–53.1
Hydrogen	5.8-6.7
Oxygen	39.8–43.8
Heating value, Btu/lb	8,560–9,130

Table 3.3.2. Typical Analysis of Dry Wood

### 3.4 Coal

Because reserves of coal are abundant in the U.S., coal cannot be overlooked as a potential feedstock for hydrogen production. It is also the dominant feedstock for electricity production in the U.S. Coal availability and prices thus have both direct and indirect consequences for the costs of the hydrogen production pathways studied.

### Availability and Utilization

Data from EIA (Energy Information Administration, 2008d) show that the United States produced 1.15 billion short tons of coal in 2007 from 1,374 mines, but no data on coal production were reported for 2008. As of January 2008, the demonstrated U.S. reserve base was estimated to contain 489 billion short tons (Energy Information Administration, 2009l). Data (Energy Information Administration, 2009g) show the United States consumed 1.13 billion short tons of coal in 2007; data available for 2008 show the United States consumed 1.12 billion short tons of coal, down slightly from the previous year.

If the entire fleet of U.S. passenger vehicles were run on hydrogen produced from coal, 550 million short tons of coal would be required annually to produce the necessary hydrogen (not including coal necessary for generation of the electricity used within the pathways), and 550 million short tons is 49% of the total coal consumption in 2008. The demand calculation is based on a total vehicle miles traveled in passenger vehicles of 2.78 trillion (Bureau of Transportation Statistics, 2007), the vehicle fuel economy used in this study (45 mpgge), and a yield of hydrogen from coal of 7.85 kg coal/kg hydrogen (54% efficiency for Pittsburgh #8 coal on an LHV basis). This calculation and coal supply scenarios for lower fuel cell vehicle penetration rates are shown in Section 9.7.

#### Resource Cost

Electric utility plants paid an average of \$36.06 (2007 dollars) per short ton in 2007 (Energy Information Administration, 2008b). As was the case for coal production, no price data were available for 2008.

#### Characteristics

Approximate composition for the general ranks of coal (anthracite, bituminous, subbituminous, and lignite) used in electricity generation as well as their calorific values (Avallone and Baumeister, 1996) are shown in Table 3.4.1. The 2007 U.S. production volume (Energy Information Administration, 2008d) and 2007 U.S. average open-market sales price (Energy Information Administration, 2008a) for the coal ranks are shown in Table 3.4.2. Coal rank depends on the volatile matter, fixed carbon, inherent moisture, and oxygen. Typically, coal rank increases as the amount of fixed carbon increases and the amount of volatile matter and moisture decreases. For this analysis, Pittsburgh #8 coal is assumed.

		Calorific			
	Moisture	Value,			
		Matter	Carbon		Btu/lb
Anthracite	4.3	5.1	81.0	6.1	12,880
Bituminous <sup>1</sup>	8.4	36.1	46.9	14.4	12,177
Subbituminous <sup>2</sup>	21.4	32.8	40.9	32.1	9,607
Lignite	36.8	27.8	29.5	45.1	7,000

Table 3.4.1. Approximate Composition and Calorific Value of General Ranks of Coal

<sup>1</sup> Average of high-volatile bituminous A, B, and C coals.

<sup>2</sup> Average of subbituminous A, B, and C coals.

Table 3.4.2. U.S. Production Volume and Average Open-Market Sales Price for General
Ranks of Coal

	2007 U.S. Production, thousand short tons	2007 U.S. Average Open- Market Sales Price
Anthracite	1,568	\$52.24
Bituminous	542,758	\$40.80
Subbituminous	523,724	\$10.69
Lignite	78,585	\$14.89

## 3.5 Carbon Sequestration

Carbon sequestration entails the capturing and storing of  $CO_2$  that would otherwise be released into the atmosphere. It is of particular interest in commercial-scale plants using fossil energy because economies of scale are needed to make it practical and affordable. Carbon sequestration is assumed only for the central coal pathway in this report.

Two carbon dioxide capture methods—geological and terrestrial sequestration—are being explored by DOE (see Figure 3.5.1). Geological sequestration involves the separation and capture of  $CO_2$  at the point of emissions from stationary sources followed by storage in underground geological formations (i.e., deep salt formations or depleted oil and gas reservoirs). Terrestrial sequestration involves the net removal of  $CO_2$  from the atmosphere by plants during photosynthesis and its capture in vegetative biomass and in soils. Carbon dioxide uptake takes place in both land and in aquatic environments.

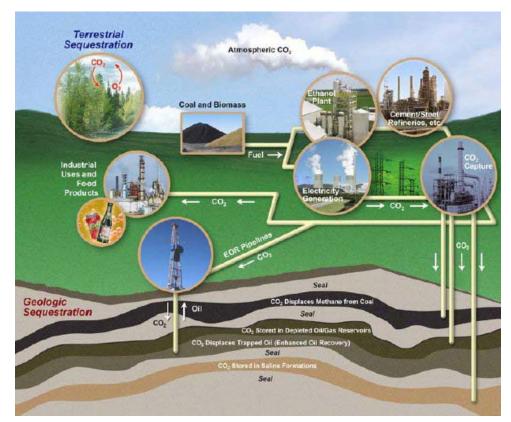


Figure 3.5.1. Geological and terrestrial sequestration (National Energy Technology Laboratory, 2008)

DOE formed Regional Carbon Sequestration Partnerships, public/private cooperative efforts to develop guidelines for the most suitable technologies, regulations and infrastructure needs for carbon capture, and storage for different regions of the U.S. and Canada. Seven partnerships exist and include: 1) Big Sky Carbon Sequestration Partnership (BSCSP); 2) Midwest Geological Sequestration Consortium (MGSC); 3) Midwest Regional Carbon Sequestration Partnership (MRCSP); 4) Plains CO<sub>2</sub> Reduction

(PCOR) Partnership; 5) Southeast Regional Carbon Sequestration Partnership (SECARB); 6) Southwest Regional Partnership (SWP); and 7) West Coast Regional Carbon Sequestration Partnership (WESTCARB). A map depicting the partnership locations can be seen in Figure 3.5.2.

The partnerships began in 2003 with a characterization phase to develop the framework to validate and deploy carbon capture and storage technologies. During this phase, the partnerships identified potential geological storage basins across North America. The conservative estimate of storage potential in North America can be found in Table 3.5.1 (National Energy Technology Laboratory, 2008).

Reservoir Type	Low	High
Deep saline formations	3,300	12,600
Unmineable coal seams	160	180
Oil and gas fields	140	140

Table 3.5.1. Conservative Geological Carbon Storage Potential in Gigatonnes

Currently, the partnerships are nearing the end of the validation phase, which as implied, validates the most promising regional carbon-sequestration opportunities. Eleven terrestrial sequestration projects were implemented during this phase on abandoned mine land, wetlands, agricultural fields, prairie lands, and forests. Figure 3.5.2 shows the validation-phase  $CO_2$  storage products being developed as well as their locations across the U.S. and Canada (National Energy Technology Laboratory, 2008). The development phase, estimated to extend to 2018, involves utilizing either geological or terrestrial sequestration of one million tons or more of  $CO_2$  by each partnership.



Figure 3.5.2. Regional carbon sequestration partnerships and their respective validation carbon storage projects (National Energy Technology Laboratory, 2008)

# 4.0 Status of Supporting Infrastructure

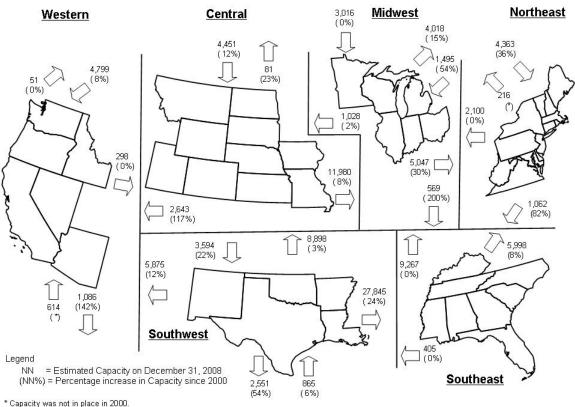
#### 4.1 Natural Gas Supply Infrastructure

The natural gas supply infrastructure in the U.S. consists of more than 210 natural gas pipeline systems, more than 1.400 compressor stations to maintain pressure on the natural gas pipeline network, more than 11,000 delivery points, 5,000 receipt points, 1,400 interconnection points, 24 hubs, 400 underground natural gas storage facilities, 49 import/export locations, 8 liquefied natural gas (LNG) import facilities, and 100 LNG peaking facilities (Energy Information Administration, 2008e). Table 4.1.1 estimates the natural gas pipeline mileage for the regions listed in Figure 4.1.1. As can be seen from the table, over 305,000 miles of pipeline exist in the United States; the Southwest region comprises over 109,000 miles of that total while the Western region has the least amount at fewer than 25,000 miles.

Region/	Pipeline	Region/	Pipeline	Region/	Pipeline	Region/	Pipeline	Region/	Pipeline	Region/	Pipeline
State	Mileage	State	Mileage	State	Mileage	State	Mileage	State	Mileage	State	Mileage
Central		Midwest		llortheast		Southeast		Southwest		Western	
Colorado	7,803	Illinois	11,911	Connecticut	628	Alabama	4,818	Arkansas	6,267	Arizona	5,989
lowa	5,421	Indiana	4,704	D elaware	280	Florida	4,971	Louisiana	18,900	California	11,770
Kansas	15,386	Michigan	9,722	Maine	609	Georgia	3,483	New Mexico	6,756	Idaho	1,567
Missouri	3,944	Minnesota	4,447	Maryland/D C	1,022	Kentucky	6,892	Oklahoma	18,539	Nevada	1,469
Montana	3,861	Ohio	7,670	Massachusetts	972	Mississippi	9,784	Texas	58,588	Oregon	1,823
Nebraska	5,697	Wisconsin	3,471	NewHampshire	291	North Carolina	2,484		109,050	Washington	2,072
North Dakota	1,873		41,925	New Jersey	1,520	South Carolina	2,265				24,690
South Dakota	1,242			New York	5,018	Tennessee	4,304				
Utah	3,175			Pennsylvania	8,680		39,001	Gulf Mexico <sup>1</sup>	9,458		
Wyoming	7,902			Rhode Island	100						
	56,304			Vermont	71						
				Virginia	2,577			Total US Pipeline Mileage Total Interstate <sup>1</sup> Total Non-interstate <sup>2</sup>			305,954
				West Virginia	3,758						217,306
					25,526					88,648	
In the Gulf of Mex	cico some	large-scale g	nthering sys	tems are FERC juri	sdictional a	nd are therefore co	unted as int	erstate.			

Includes intrastate transmission and non-FERC lunisdictional large diameter gathering systems or headers. Local distribution company (LDC) mileage excluded. Note: All mileage is approximate. Includes looped pipeline segments. Approximately 75 percent of Interstate pipeline systems are made up of pipeline diameters of 16 inches while only 34 percent of non-interstate pipeline systems are 16 inches or larger. Source: Energy Information Administration, Gas Transportation Information System, Pipeline Map Files and Pipeline Projects Database.

Ideally, natural gas pipelines would be utilized at or as close as possible to 100%. In reality, however, that rarely occurs. Several factors contribute to less-than-perfect utilization such as scheduled or unscheduled maintenance, decreases in demand, and weather disturbances. Figure 4.1.1 shows the interregional natural gas pipeline capacity levels with arrows indicating the direction of the interregional pipelines. Utilization rates below 100% do not necessarily mean that additional capacity is available for use. For instance, in the summer months, average utilization rates will be low compared to winter months. Additionally, rates can exceed 100% of the certified capacity (minimum level of service over an extended period of time) in periods of high demand. This rate can be accomplished by temporarily increasing compression within safety limits.



Source: Energy Information Administration, Gas Tran Gas Transportation Information System, Natural Gas Pipeline Capacity Database, December 31, 2008.

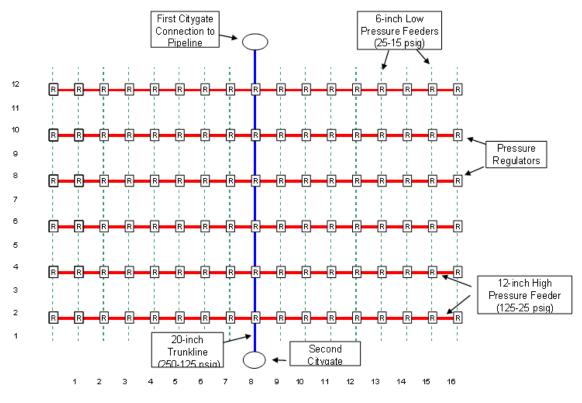
Figure 4.1.1. Interregional natural gas pipeline capacity levels (Energy Information Administration, 2008e)

Energy and Environmental Analysis (EEA), an ICF International Company, analyzed natural gas infrastructure requirements for hydrogen production for the U.S. Department of Energy (Vidas, 2007). The premise of the study was that hydrogen transportation fuel will be supplied to early adopters of hydrogen-fueled vehicles by distributed natural gasfueled steam methane reformers co-located with refueling stations. EEA sought to determine how much natural gas would be required for hydrogen production, how the natural gas demand would be distributed geographically, whether the existing or expected future natural gas transmission system could accommodate the anticipated demand, whether physical constraints would prevent local distribution companies (LDCs) from being able to supply natural gas to refueling stations, and how much needed natural gas infrastructure improvements would cost. It was assumed that 15% of light-duty vehicles in 27 largest U.S. cities (11.7 million vehicles) would be fueled by hydrogen, and that all of the hydrogen would be produced at 1,500 kg/day refueling stations using natural gas. At this penetration rate, almost 6,400 refueling stations (with a utilization factor of 75%) would be required in the 27 cities. Assuming that 170 cubic feet of natural gas is required to produce 1 kg of hydrogen, each station will require 255,000 cubic feet of natural gas per day. This volume of natural gas is considered a large load for an LDC, equivalent to the average load of 1,200 homes or two to three industrial plants.

EEA compared the natural gas needs for hydrogen against the total load for each city (all sectors) to determine the impact on transmission systems and estimated that hydrogen would increase total (all-sector) peak natural gas demand by an average of 1.7% (ranging from 0.6% to 5.8%) over projected demand in 2025 for the 27 cities. Only 3 of the 27 cities would experience a natural gas demand increase of more than 3% as a result of hydrogen production: Miami, Seattle, and Orlando.

The natural gas needs for hydrogen were also compared against residential and commercial loads to determine the impact on distribution systems. Hydrogen would increase residential/commercial peak natural gas demand by an average of 2.6% (ranging from 1.4% to over 45%) over projected demand in 2025 for the 27 cities. Four cities would experience a residential/commercial natural gas demand increase of more than 5% as a result of hydrogen production: Los Angeles, Miami, Phoenix, and Orlando.

Natural gas is delivered to city gates in interstate transmission pipelines that are 20–36 inches in diameter and flow at pressures between 1,000 and 750 psig. At the city gate, the pressure is stepped down to ~400 psig or lower. LDCs deliver the gas from the city gate to the end user through smaller-diameter trunk lines (>125 psig, ~20-inch diameter), high-pressure feeders (125–25 psig, ~12-inch diameter), low-pressure feeders (25–15 psig, ~6-inch diameter), and mains (15–5 psig, ~2-inch diameter). Figure 4.1.2 shows a hypothetical 12-mile by 16-mile city-wide gas distribution grid. Figure 4.1.3 shows hypothetical pressures in distribution mains serving a two-square mile area.



Note: Two-inch mains are not shown on this diagram.

Total square miles	192
Max flow per square mile (scf/hour)	164,386
Max flow for city (scf/hour)	31,562,042
Max flow per citygate (scf/hour)	15,781,021



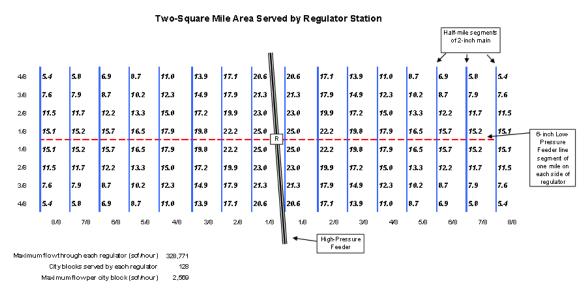


Figure 4.1.3. Hypothetical pressures (psig) in distribution mains at maximum design flows (Vidas, 2007)

EEA concluded that the changes to transmission pipeline capacities needed to accommodate the hydrogen production will depend on what LNG terminals, pipeline, and storage assets are built in the coming years to meet overall natural gas demand growth. Required hydrogen-related gas transmission expenditures were estimated to cost \$1 to \$1.5 billion, roughly 2% of the gas transmission expenditures expected in the next 20 years. Assuming gradual growth of hydrogen, EEA did not anticipate that gas transmission pipelines would represent a barrier to hydrogen production.

New service lines will have to be installed to accommodate refueling stations with natural gas loads of 255,000 cubic feet per day because a station of this size will require more gas than can be supplied through a typical 2-inch-diameter main. Initial stations may be sited on streets with feeder lines to minimize the cost to LDCs. Steward et al. (2009) asserted that 1,500 kg/day hydrogen stations with on-site hydrogen production from natural gas using SMR would need to tie into 4-inch or larger natural gas feeder lines.

One strategy under consideration for implementing early hydrogen fueling infrastructure is to establish networks of fueling stations in a limited number of urban centers, beginning with Southern California and the area surrounding New York City (Greene et al., 2008). Because existing gasoline stations are potential sites for future hydrogen fuel stations, the Fuel Pathway Integration Technical Team (Steward et al., 2009) assessed the proximity of existing gasoline fueling stations in Los Angeles to natural gas feeder lines. As shown in Figure 4.1.4, there are around 1,500 gasoline stations within a half mile of a feeder line in Los Angeles.

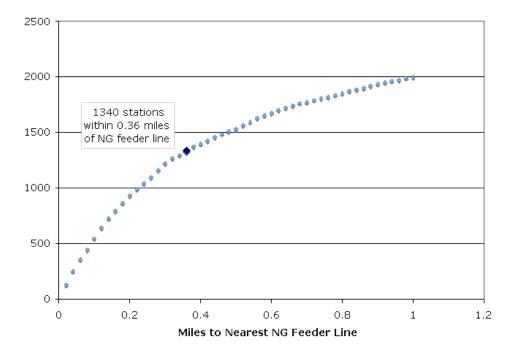


Figure 4.1.4 Number of refueling stations within one mile of natural gas feeder line in Los Angeles (Steward et al., 2009)

In HDSAM, the cost of installed pipelines with diameters less than 6 inches is estimated using the following equation:

\$/mile=5280\*(5.6822\*D^2-15.767\*D+66.212)

where D is the pipeline diameter in inches. Using this equation, a 4-inch feeder line will cost \$496,600 per mile (installed). The average distance of refueling stations in the Los Angeles metropolitan area to a feeder line is 0.73 miles, correlating to a cost of \$362,500 (installed) (Steward et al., 2009).

EEA (Vidas, 2007) estimated that required hydrogen-related gas distribution expenditures will cost \$1 to \$2.5 billion, about 1.5% of the gas distribution expenditures expected in the next 20 years. LDCs in warm locations with relatively low natural gas loads will be impacted most severely by the addition of natural gas–derived hydrogen.

## 4.2 Electricity Transmission Grid

The North American electricity transmission system is composed of three major interconnected power systems: the Eastern Interconnections, the Western Interconnections, and the Electric Reliability Council of Texas. Within each system, disturbances or reliability events are felt nearly instantaneously throughout the system. This transmission system was built over the past 100 years by vertically integrating utilities that produced electricity at large generation stations located close to fuel supplies. Over 150,000 miles of high-voltage transmission lines (both alternating current and direct current) link generators to load centers across the states and along the borders with Mexico and Canada. A 2002 U.S. Department of Energy report found that the U.S.'s transmission system was under stress (Abraham, 2002). Findings of that report attributed the stress to growth in electricity demand and new generation, lack of investment in new transmission facilities, and the incomplete transition to fully efficient and competitive wholesale markets. These factors allow for transmission bottlenecks, which lead to increased electricity costs to consumers as well as increased risk of blackouts.

Transmission bottlenecks occur when there is not enough transmission capability to accommodate all requests to ship power over existing lines and maintain adequate safety margins for reliability. Because electricity cannot be stored economically as of yet, transmission-system operators must deny requests for transmission service when they receive too many to prevent lines from becoming overloaded. Bottlenecking is managed through Transmission Loading Relief (TLR), also known as "calls," which determines which requests will be denied. The DOE report (Abraham, 2002) shows that the number of TLR calls increased between 1997 and 2001 (see Figure 4.2.1). More recent data are unavailable at this time. Frequent TLR calls increase consumer electricity costs by denying low-cost transactions in favor of high-cost transactions.

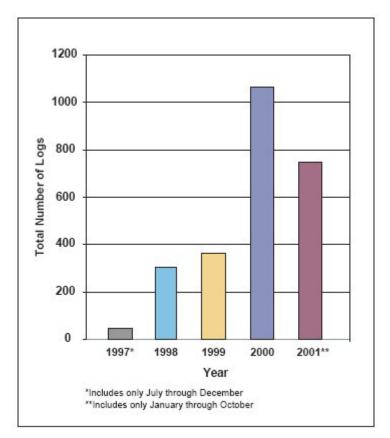


Figure 4.2.1. Transmission loading relief calls for 1997-2001 (Abraham, 2002)

Out of 186 transmission paths for the Eastern Interconnection, 50 were used to their maximum capacity at some point during the year, and 21 paths were congested more than 10% of the hours during the year studied in the 2002 DOE report. Figure 4.2.2 shows a map of the congestion for the Eastern Interconnection. The highest levels of congestion were found to be transmissions from Minnesota to Wisconsin, from the Midwest to the Mid-Atlantic, from the Mid-Atlantic to New York, and from the Southeast to Florida. Of the 106 transmission paths for the Western Interconnection, 37 were congested at some point during the year, half of these are congested less than 10% of the time, and no path is congested more than 60% of the hours during the year studied in the 2002 DOE report (see Figure 4.2.3). The Western Interconnection, which may account for the differences between the two.

Construction of new transmission facilities would alleviate the stress of bottlenecking. However, investment in new transmission facilities (see Figure 4.2.4) is lagging behind investment in new generation and growth in electricity demand. Construction of highvoltage transmission facilities is expected to increase by 6% (in line miles) by 2012 in contrast to the expected 20% increase in electricity demand and generation capacity (in MW). This projected growth, which does not include impacts of potential transportation technologies such as plug-in hybrid electric vehicles (PHEVs), was deemed inadequate to ensure grid reliability (Abraham, 2002). The North American Electric Reliability Corporation asserts that PHEVs have the potential to support grid reliability by supplementing electricity generation capacity during times of peak usage and drawing charging power from the grid during off-peak hours (North American Electric Reliability Corporation, 2009). FCVs may also have potential to support grid reliability; however, examination of grid effects of electric vehicles (PHEVs or FCVs) is beyond the scope of this study.

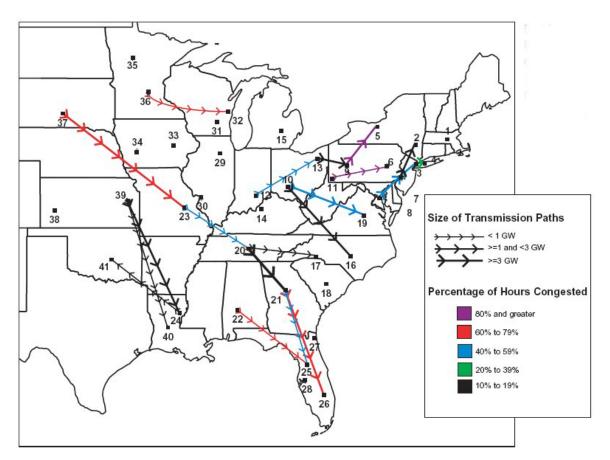


Figure 4.2.2. Map of Eastern Interconnection Congestion (Abraham, 2002)

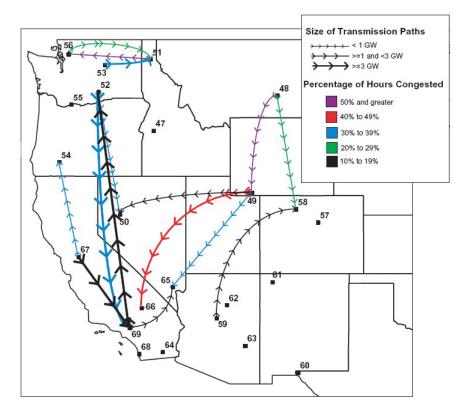


Figure 4.2.3. Map of Western Interconnection Congestion (Abraham, 2002)

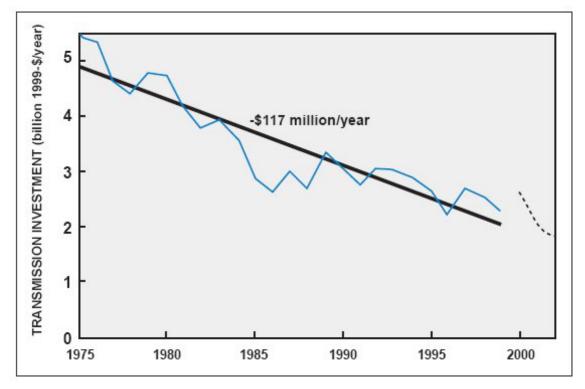


Figure 4.2.4. New transmission facility investment for the period 1975–2000 (Abraham, 2002)

## 4.3 Biomass Truck Transportation and Delivery

Delivery of biomass can be accomplished in multiple ways with rail or truck being the most common. The form of the truck is typically that of a tractor-trailer. Trailers can come in several varieties: log trailer, container trailer, or bulk van. Regardless of the tractor and trailer setup, an over-the-road truck of this combination is limited to a gross vehicle weight of 80,000 lbs. As an example and depending on the type of tractor (sleeper cab or non-sleeper), a bulk van will have a legal payload in the range of 42,000 to 52,000 lbs (20 to 25 tons), which translates to between 97 and 131 cubic yards of biomass (Hubbard, Biles, Mayfield, and Ashton, 2007). The capital cost of a tractor is approximately \$75,000; a trailer costs approximately \$35,000 (Harris et al., 2004).

Using the assumptions in this study, if the entire fleet of U.S. passenger vehicles were run on hydrogen produced from biomass, 890 million dry tons of biomass would be required annually to produce the necessary hydrogen (see Section 3.3). If all of this biomass were delivered by trucks with a payload of 20–25 tons, and each truck delivered three payloads per day on average, approximately 32,000–41,000 trucks would be needed.

The total number of Class 8 trucks (gross vehicle weight 33,001 lbs and more) in 2002 was estimated to be over 2.15 million. Annual retail sales of new Class 8 trucks ranged from 140,000 to 284,000 for the years 1998–2007 and averaged 200,000 over that 10-year timeframe (Davis et al., 2009). Truck availability is therefore not likely to limit implementation of biomass-gasification-based hydrogen production plants.

Perlack et al. (2005) estimated that 368 million dry tons of woody biomass is available from U.S. forest lands. Thus, to produce enough hydrogen to fuel all U.S. passenger vehicles, herbaceous biomass from agricultural lands would also be needed. Issues that impact biomass delivery distances and costs for woody and herbaceous biomass are described below.

#### Woody Biomass

In whatever form it takes (slash, small trees with limbs, or tree sections), woody biomass has an inherently low bulk density. Transportation costs are high due to this low bulk density because air is a major component of the transported biomass volume. Bulk density can be increased by processing (chipping, grinding, or shredding), which allows for the biomass to be compacted (see Figure 4.3.1). Processing, however, decreases biomass storage durability and longevity (Hubbard, Biles, Mayfield, and Ashton, 2007).

Additionally, woody biomass has a low energy density when compared to other fossil fuels (coal). For example, wood chips have approximately three times the bulk per unit energy than coal does and as a result need three times the storage space (Harris et al., 2004). Therefore, when compared to fossil fuels, biomass has a high transportation cost.

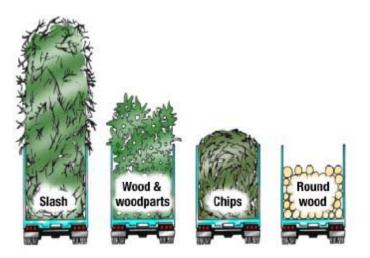


Figure 4.3.1. Bulk volume of woody biomass in different processed forms with the same weight (Hubbard, Biles, Mayfield, and Ashton, 2007)

A tradeoff between feedstock transportation and plant efficiency has resulted in an optimum electricity-generating power plant size of about 40–50 MW (1,750 tons woody biomass per day). This sized plant operating at full capacity would typically receive 70 truckloads per business day, requiring 140 daily truck trips (Timmons, Damery, Allen, and Petraglia, 2007). Processed (chipped) woody biomass can be accomplished at a cost of approximately \$12 per ton in-woods cost. Assuming a freight cost of \$2 per mile, a 25 ton payload of chipped biomass and a 50-mile delivery distance to the plant, the biomass can be transported at the cost of approximately \$16 per ton (Harris et al., 2004) for a feedstock cost of \$28 per wet ton or \$37.33 per dry ton. The 2012 industry initiation/low demand cost target, which was used in the analysis, is \$35 per dry ton in 2002 dollars or \$37.96 per dry ton in 2005 dollars (Hess, Denney, Wright, Radtke, and Perlack, 2007).

#### Herbaceous Biomass

The National Renewable Energy Laboratory conducted a tradeoff analysis (Aden et al., 2002) to determine the effect of ethanol production plant size on the required radius of corn stover collection. A maximum corn stover yield of 2 metric tons (MT) was assumed. It was also assumed that the ethanol plant would be located in the middle of the farmland from which the corn stover would be collected and that 75% of the total surrounding land area is farm land that can be planted. In Figure 4.3.2, 100% access represents a scenario in which all farmers are growing corn continuously and are willing to sell their stover, a highly unlikely scenario. A 50% access represents a scenario in which farmers split their land between soybean and corn. It was found that this scenario is also unlikely because a soybean/corn rotation would not likely produce 2 MT per acre. A 10% access is a more realistic scenario. Aden et al. assumed that plants would not collect corn stover outside a 50-mile radius around the ethanol plant. The plant size from Figure 4.3.2 corresponding to 10% access, and a 50-mile radius is 2,000 MT stover per day (1,823 tons stover per day). This sized ethanol plant is comparable to the 1,750-ton-per-day power plant discussed in the woody biomass section.

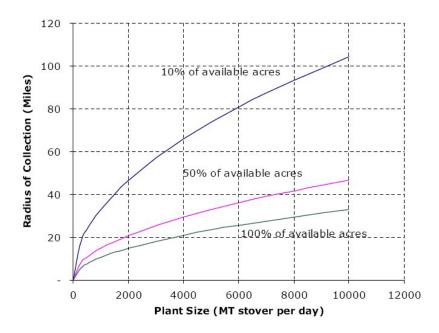


Figure 4.3.2. Effect of plant size on collection distance (Aden et al., 2002)

Figure 4.3.3 shows the relative contribution of the sources of costs for stover collection and delivery based on analyses done by Oak Ridge National Laboratory. The figure shows that 23% of the total delivered stover cost (\$62 per dry MT/\$56 per dry ton) is transportation cost. This \$13-per-ton stover transport cost agrees favorably with the \$16-per-ton woody biomass transport cost, both of which assume a 50-mile delivery distance.

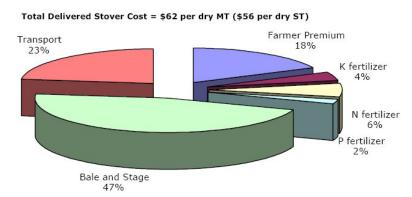


Figure 4.3.3. Breakdown of corn stover costs (Aden et al., 2002)

## 4.4 Coal Moved by Railway

For 2007, EIA reported that 1,138,529 thousand short tons of coal were moved via railroad from 18 states for electric-generation purposes (Energy Information Administration, 2008c). In November 2007, the U.S. Department of Transportation conducted research to determine future rail capacity to deliver increasing amounts of coal and the amount of investment that might be needed to fulfill that capacity (McCollum,

Ogden, and Chernicoff, 2007). The study looked at several different scenarios (see Table 4.4.1) for coal demand growth (see Figure 4.4.1) and considered the tradeoff between pulverized coal (PC) or IGCC power plants, as well as an additional amount of coal to produce hydrogen for fuel cell vehicles.

Scenario	Description
BAU1	Baseline scenario using EIA projection for coal power demand and
	assuming that all new coal plants will be PC
BAU2	BAU2a and BAU2b: A similar scenario to BAU1 but assuming that all
	new coal plants will be IGCC. BAU2b only: In addition to building
	new IGCC plants, all old PC plants are gradually retrofitted to IGCC.
BAU2+LowH2	A similar scenario to BAU2b except that in addition to IGCC plants
	being built, extra coal is used to supply a fleet of hydrogen fuel cell
	vehicles that obtain a 50% share of the total vehicle market by the year
	2050
BAU2+HighH2	A similar scenario to BAU2b except that in addition to IGCC plants
	being built, extra coal is used to supply a fleet of hydrogen fuel cell
	vehicles that obtain a 100% share of the total vehicle market by the
	year 2050

Table 4.4.1. Various Scenarios for Coal Demand Growth

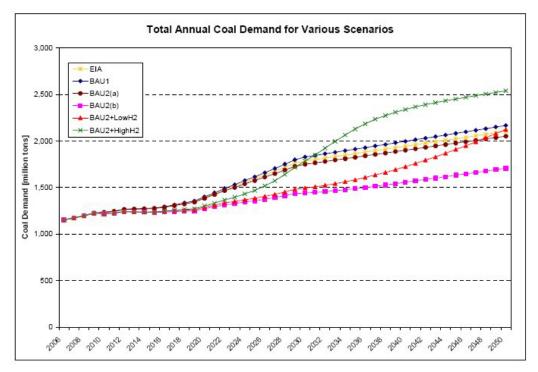


Figure 4.4.1. Total annual coal demand for various scenarios (McCollum, Ogden, and Chernicoff, 2007)

Coal traffic on each rail line was modeled using a confidential set of data known as the Carload Waybill Sample. Waybill sample data from 2004 (see Figure 4.4.2) were used in conjunction with the projections of the Freight Analysis Framework 2 (FAF2) program, which provides estimates of freight commodity flows. Projections were divided into coal (modified for the various scenarios) and non-coal (taken directly from FAF2) categories. Hypothetical waybill for future years for the various scenarios was then routed onto the rail network. Forty-two routes were identified that will likely carry the bulk of the coal demand in the future (see Figure 4.4.3). These routes represent approximately 5% of all route mileage in the North American rail network but are responsible for transporting more than 80% of the coal shipped by rail.

Four different capacity enhancement strategies were analyzed: 1) upgrading the signaling system to centralized traffic control; 2) upgrading the signaling system to positive train control; 3) adding new mainline track; and 4) upgrading the quality of mainline track, allowing heavier-capacity rail cars to be transported over them. It was determined that the incremental capital costs of adding capacity to all 42 routes is on the order of \$0.5–\$5.5 billion (in discounted terms, over the timeframe 2004–2050). The report also concluded that it did not seem likely that the incremental costs of adding new capacity will markedly increase coal transportation rates or the delivered price of coal, even under aggressive scenarios of coal demand growth.

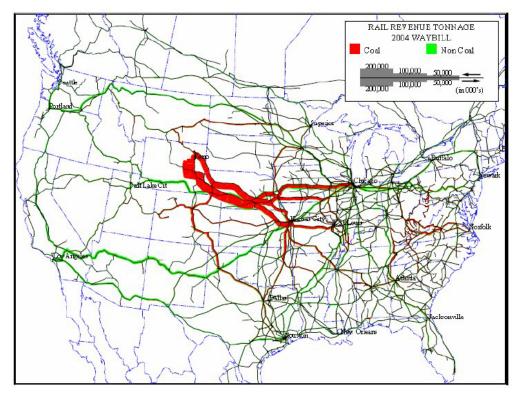


Figure 4.4.2. Rail traffic on the rail network for 2004 waybill sample data (McCollum, Ogden, and Chernicoff, 2007)

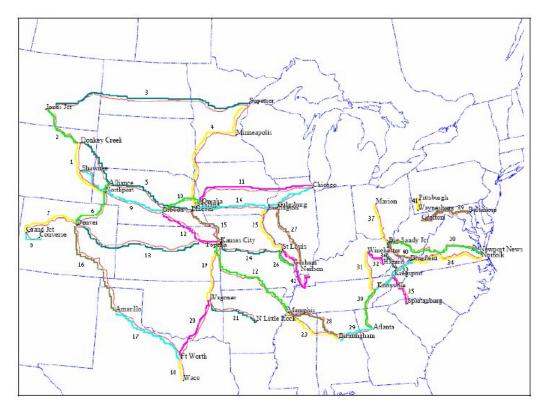


Figure 4.4.3. Coal rail routes (McCollum, Ogden, and Chernicoff, 2007)

# **5.0 Production Technology Description and Assumptions**

The hydrogen production technologies used in each of the seven pathways examined in this study are described below. Note that this study assumes that energy used in the production facility for lighting, control systems, etc. is small relative to the energy used directly in the production process; these items are therefore not included in the cost, energy use, and emissions calculations.

## 5.1 Distributed Natural Gas Reforming

The H2A distributed natural gas model (James, 2008) determines a baseline delivered cost of hydrogen for the forecourt production of hydrogen from natural gas steam reforming. The natural gas reforming process is based on an ASPEN simulation of a 20-atm conventional tube-in-shell SMR with hydro-desulfurization pre-treatment and PSA gas cleanup. The PSA is based on a four-bed Batta cycle achieving 75% hydrogen recovery (single pass). Multiple passes are used to increase recovery. The unit is assumed to be factory built (as opposed to on-site construction) and skid-mounted for easy and rapid installation.

Reforming (CnHm + nH<sub>2</sub>O  $\rightarrow$  (n+m/2)H<sub>2</sub> + nCO) and water-gas shift (CO + H<sub>2</sub>O  $\rightarrow$  CO<sub>2</sub> + H<sub>2</sub>) are the main reactions in the steam-reforming process. The reformer heat is supplied by the PSA offgas; a small amount of natural gas is added for burner control. The amount of natural gas added is equal to 10% of the heating value of the PSA offgas. The high-temperature-shift and low-temperature-shift reactors convert the majority of the CO into CO<sub>2</sub> and H<sub>2</sub> through the water-gas shift reaction.

A PSA unit is used to separate the hydrogen from the other components in the shifted gas stream, mainly  $CO_2$  and unreacted CO,  $CH_4$ , and other hydrocarbons. The hydrogen purity achieved from a PSA unit can be greater than 99.99%. For this analysis, the concentration of hydrogen in the shifted stream prior to the PSA is between 60 and 65 mol%. Therefore, part of the PSA hydrogen product stream is recycled back into the PSA feed to increase the hydrogen concentration to 70 mol%. For a 70-mol% hydrogen PSA feed, an overall hydrogen recovery rate of 85% is typical with a product purity of 99.9 vol%.

A single 1,500 kg/day unit is assumed (as opposed to the previous H2A assumption of parallel 750 kg/day units). The system is assumed to be air cooled (and thus requires no cooling water flow). The product hydrogen exits the PSA at 300 psi and is compressed for storage in metal cylinder storage tanks (2,500 psi max pressures). The hydrogen is next compressed to 6,250 psi (maximum) for transfer into a four-bed, high-pressure cascade system to allow rapid filling of 5,000-psi onboard hydrogen vehicular tanks. A process flow diagram is shown in Figure 5.1.1.

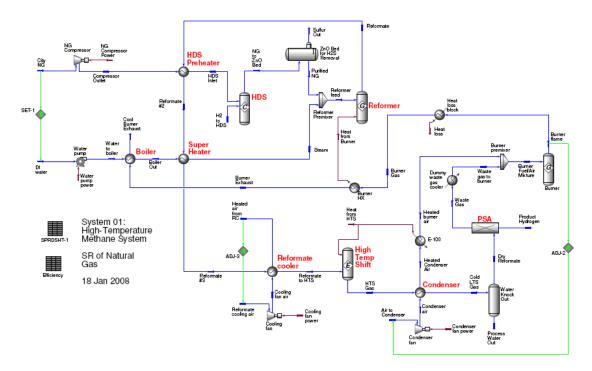


Figure 5.1.1. Distributed natural gas reforming process flow diagram (James, 2008)

## 5.2 Distributed Electrolysis

The system modeled in the H2A distributed electrolysis model (Ramsden, 2008b) is a standalone, grid-powered electrolyzer system with a total hydrogen production capacity of 1,500 kg/day. The system is based on the hydro bi-polar alkaline electrolyzer system [Atmospheric Type No.5040–5150 amp direct current (DC)]. The electrolyzer system modeled is a skid-mounted unit, including the electrolyzer system and necessary auxiliary subsystems. The electrolyzer units use process water for electrolysis and cooling water. KOH is the electrolyte in the system. The system includes the following equipment: transformer, thyristor, electrolyzer unit, lye tank, feed water demineralizer, hydrogen scrubber, gas holder, two compressor units to 30 bar (435 psig), deoxidizer, and twin tower dryer. A process flow chart and a mass balance diagram are shown in Figure 5.2.1 and Figure 5.2.2, respectively.

The electrolyzer system receives alternating current (AC) grid electricity, which is converted via transformer and rectifier sub-systems into DC electricity for use by the electrolyzer stack. The transformer subsystem is an oil-immersed, ambient air-cooled unit, manufactured to IEC-76. The rectifier sub-system converts the AC voltage to DC voltage using thyristors. Cooling is generally accomplished via forced air cooling achieved by fan(s) on the bottom of the rectifier cabinet but can also be accomplished with cooling water. The electrolyzer system uses 4.8 kWh of electricity per Nm<sup>3</sup> of hydrogen produced (53.4 kWh per kilogram of hydrogen produced) with the electrolyzer stack requiring 4.3 kWh and the remainder used by the balance of plant.

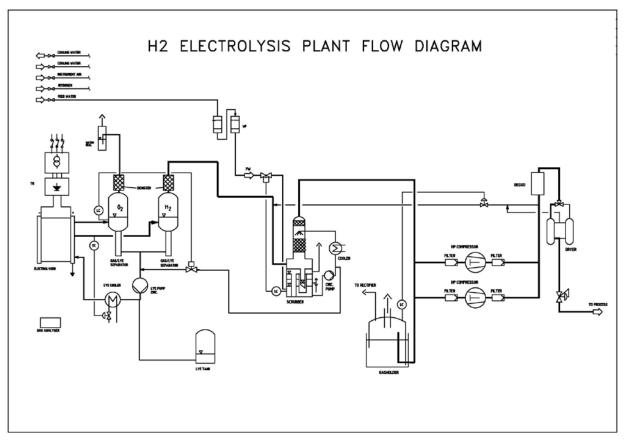


Figure 5.2.1. Distributed electrolysis process flow diagram (Ramsden, 2008b)

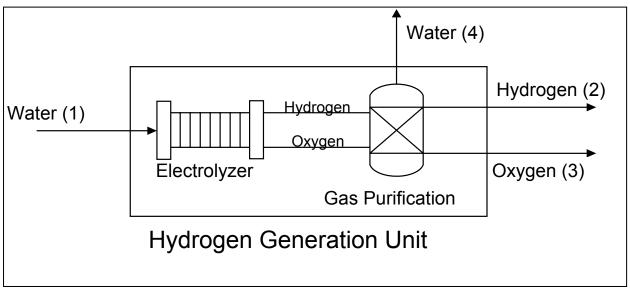


Figure 5.2.2. Distributed electrolysis mass balance diagram (Ramsden, 2008b)

The electrolyzer system requires high-purity water to avoid deterioration of electrolyzer performance. Process water is demineralized and softened to a specific resistance of 1 to 2 megaohm/cm in the demineralizer unit. The system requires 1 L of process water per Nm<sup>3</sup> of hydrogen produced (2.939 gal/kg H<sub>2</sub>).

The system requires 100 L of cooling water per Nm<sup>3</sup> of hydrogen produced (293.9 gal/kg H<sub>2</sub> produced). It is assumed that the cooling water system is a closed water loop (see Figure 5.2.3), which is maintained at approximately 30°C via a water evaporative spray cooler. The spray cooler requires approximately 611 kg/day of water (0.41 L/kg H<sub>2</sub> – 0.11 gal/kg H<sub>2</sub>).

The electrolyzer system produces hydrogen and oxygen from the electrolysis of feed water. The gas from each cell in the electrolyzer stack is collected in the hydrogen and oxygen flow channels and is fed into the gas/lye (KOH) separators. The lye, separated from the produced gas, is recycled through the lye pump, through the lye cooler, and back into the lye tank. Excess heat in the electrolyzer is removed by the lye cooler. Oxygen is removed from the lye in the oxygen/lye separator. The system modeled does not capture the oxygen gas, but capture of the high-purity oxygen gas is a possibility. Saturated hydrogen gas from the hydrogen. The hydrogen gas is held in a small gas holder unit and then is compressed to 435 psig (30 bar). Following compression, residual oxygen is removed from the hydrogen gas by the deoxidizer unit, and the hydrogen gas is then dried in the twin-tower dryer. The purity of the hydrogen gas coming off the electrolyzer stack is 99.9 %. Following the gas purifier, deoxidizer, and dryer stages, the purity of hydrogen increases to 99.9998% (2 ppm impurities).

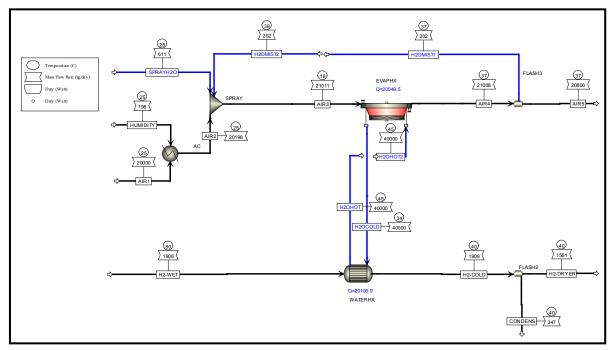


Figure 5.2.3. Distributed electrolysis process flow diagram cooling water detail (Ramsden, 2008b)

#### 5.3 Central Biomass Gasification

The systems examined in the H2A central biomass gasification model (Mann and Steward, 2008) are based on the Battelle/FERCO indirectly heated biomass gasifier, conventional catalytic steam reforming, WGS, and PSA purification. The indirectly heated biomass gasifier uses hot sand circulating between the char combustor and the gasifier to provide the heat necessary for gasification. Steam is used as the fluidizing gas; no oxygen (as pure oxygen or air) is fed to the gasifier. The biomass feedstock is assumed to be a woody biomass, represented as hybrid poplar. A process flow chart is shown in Figure 5.3.1. The as-received wood is dried from 50 wt% moisture to 12% employing a rotary dryer. The dryer uses gas from the char combustor as the drying medium. Conveyors and hoppers are used to feed the wood to the low-pressure, indirectly heated entrained flow gasifier. Heat for the endothermic gasification reactions is supplied by circulating hot synthetic olivine, which is calcined magnesium silicate [primarily enstatite (MgSiO<sub>3</sub>), forsterite (Mg2SiO<sub>3</sub>), and hematite (Fe<sub>2</sub>O<sub>3</sub>)] used as a sand for applications between the gasifier and a char combustor vessel. A small amount of MgO is added to the fresh olivine to keep it from forming glass-like bed agglomerations that would result from biomass potassium interacting with the silicate compounds. The gasification medium is steam. The char that is formed in the gasifier is burned in the combustor to reheat the olivine. Particulate removal is performed through cyclone separators. Ash and any sand particles are landfilled.

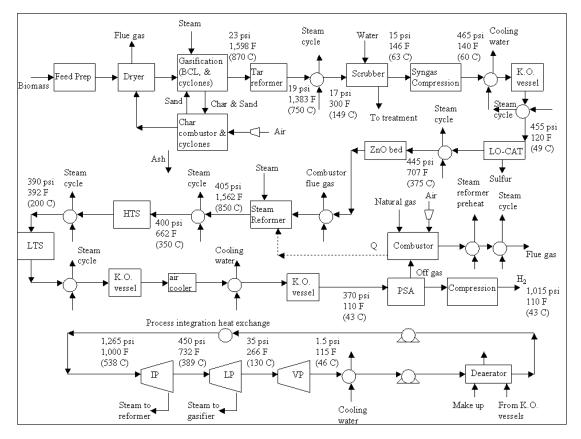


Figure 5.3.1. Central biomass gasification flow diagram (Mann and Steward, 2008)

Reforming (CnHm + nH<sub>2</sub>O  $\rightarrow$  (n+m/2)H<sub>2</sub> + nCO) and water-gas shift (CO + H<sub>2</sub>O  $\rightarrow$  CO<sub>2</sub> + H<sub>2</sub>) are the main reactions in the steam-reforming process. The reformer heat is supplied by PSA offgas; a small amount of natural gas is added for burner control. The amount of natural gas added is equal to 10% of the heating value of the PSA offgas. The high-temperature-shift and low-temperature-shift reactors convert the majority of the CO into CO<sub>2</sub> and H<sub>2</sub> through the water-gas shift reaction.

A PSA unit is used to separate the hydrogen from the other components in the shifted gas stream, mainly  $CO_2$  and unreacted CO,  $CH_4$ , and other hydrocarbons. The hydrogen purity achieved from a PSA unit can be greater than 99.99%. For this analysis, the concentration of hydrogen in the shifted stream prior to the PSA is between 60 and 65 mol%. Therefore, part of the PSA hydrogen product stream is recycled back into the PSA feed to increase the hydrogen concentration to 70 mol%. For a 70-mol% hydrogen PSA feed, an overall hydrogen recovery rate of 85% is typical with a product purity of 99.9 vol%.

The steam-cycle produces power in addition to providing steam for the gasifier and reformer operations. The steam cycle is integrated with the biomass-to-hydrogen production process. There is an extraction steam turbine/generator, and steam is supplied to the reformer and gasifer from the intermediate and low pressure turbine sections, respectively. Superheated steam enters the intermediate pressure turbine at 1,000°F and 1,265 psia and is expanded to a pressure of 450 psia. The steam then enters a low-pressure turbine and is expanded to a pressure of 35 psia. Finally, the steam enters a condensing turbine and is expanded to a pressure of 1.5 psia. Preheaters, steam generators, and superheaters are integrated within the process design. The condensate from the syngas compressor and the condensate from the cooled shifted-gas stream prior to the PSA are sent to the steam cycle, de-gassed, and combined with the make-up water. A pinch analysis was performed to determine the heat integration of the system.

A cooling water system is also included in the Aspen Plus<sup>®</sup> model to determine the requirements of each cooling-water heat exchanger within the hydrogen production system as well as the requirements of the cooling tower. The cooling water supply temperature is 90°F, and the return temperature is 110°F.

#### 5.4 Central Natural Gas Reforming

Steam reforming of hydrocarbons continues to be the most efficient, economical, and widely used process for production of hydrogen and mixtures of hydrogen and carbon monoxide (CO). The H2A central natural gas reforming model (Steward, 2008) assesses the economic production of hydrogen by steam reforming of natural gas.

A process flow chart is shown in Figure 5.4.1, and the stream summaries are shown in Table 5.4.1. Natural gas is fed to the plant from the pipeline at a pressure of 450 psia. The gas is generally sulfur-free, but odorizers with mercaptans must be cleaned from the gas to prevent contamination of the reformer catalyst. The desulfurized natural gas

feedstock is mixed with process steam to be reacted over a nickel-based catalyst contained inside a system of high alloy steel tubes. The reforming reaction, which converts the methane to a mixture of CO and  $H_2$ , is strongly endothermic, and the metallurgy of the tubes usually limits the reaction temperature to 1,400°F–1,700°F.

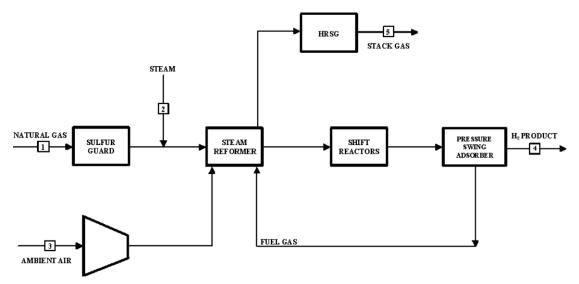


Figure 5.4.1. Central natural gas process flow diagram (Steward, 2008)

STREAM					
NUMBER	1	2	3	4	5
	Natural				Stack
	Gas	Steam	Air	Hydrogen	Gas
Mole Fraction					
Ar	0.0000	0.0000	0.0093	0.0000	0.0073
CH <sub>4</sub>	0.9000	0.0000	0.0000	0.0000	0.0000
$C_2H_6$	0.0500	0.0000	0.0000	0.0000	0.0000
CO <sub>2</sub>	0.0000	0.0000	0.0004	0.0013	0.1677
H <sub>2</sub>	0.0000	0.0000	0.0000	0.9947	0.0000
H <sub>2</sub> O	0.0000	1.0000	0.0101	0.0000	0.1835
$N_2$	0.0500	0.0000	0.7724	0.0040	0.6115
O <sub>2</sub>	0.0000	0.0000	0.2078	0.0000	0.0301
NO <sub>x</sub>					20 ppm
Total Flow					
(lbmol/hr)	6,981	24,432	29,489	16,102	37,697
Total Flow (lb/hr)	121,060	440,145	851,008	35,008	1,095,760
Temperature (°F)	59	750	60	108	280
Pressure (psia)	450.0	450.0	14.7	346.0	14.7

Table 5/11	Contral Natural	Gas Stroam	Summary	(Stoward	20081
Table 5.4.1.	Central Natural	Gas Stream	Summary	(Siewaru,	2000)

Reforming (CnHm + nH<sub>2</sub>O  $\rightarrow$  (n+m/2)H<sub>2</sub> + nCO) and water-gas shift (CO + H<sub>2</sub>O  $\rightarrow$  CO<sub>2</sub> + H<sub>2</sub>) are the main reactions in the steam-reforming process. The reformer heat is supplied by the PSA offgas; a small amount of natural gas is added for burner control. The amount of natural gas added is equal to 10% of the heating value of the PSA offgas. The high-temperature-shift and low-temperature-shift reactors convert the majority of the CO into CO<sub>2</sub> and H<sub>2</sub> through the water-gas shift reaction.

A PSA unit is used to separate the hydrogen from the other components in the shifted gas stream, mainly  $CO_2$  and unreacted CO,  $CH_4$ , and other hydrocarbons. The hydrogen purity achieved from a PSA unit can be greater than 99.99%. For this analysis, the concentration of hydrogen in the shifted stream prior to the PSA is between 60 and 65 mol%. Therefore, part of the PSA hydrogen product stream is recycled back into the PSA feed to increase the hydrogen concentration to 70 mol%. For a 70-mol% hydrogen PSA feed, an overall hydrogen recovery rate of 85% is typical with a product purity of 99.9 vol%.

The flue gas path of the fired reformer is integrated with additional boiler surfaces to produce about 700,000 lb/hour steam. Of this, about 450,000 lb/hour is superheated to 450 psia and 750°F to be added to the incoming natural gas. Additional steam from the boiler is sent off-site; however, revenue from the steam is not factored into the economic assessment. After the reformer, the process gas mixture of CO and H<sub>2</sub> passes through a heat recovery step and is fed into a water-gas shift reactor to produce additional H<sub>2</sub>.

## 5.5 Central Electrolysis

The system modeled in the H2A central electrolysis model (Ramsden, 2008a) is a standalone grid-powered electrolyzer system with a total hydrogen production capacity of 52,300 kg/day. The technology is identical to that used for distributed electrolysis even though it is 35 times larger, which provides economies-of-scale for the auxiliary components. As such, the process description for distributed electrolysis in Section 5.2 describes this production process as well.

The H2A central electrolysis model is not based on wind-power, so this analysis assumed that a single facility is buying electricity from the grid and wind-power credits for all the electricity purchased. Because the facility is using grid power, the operating capacity factor is 97%. If the facility were co-sited with the wind turbines, it is likely to have a lower operating capacity because the turbines will not be generating electricity much of the time. The optimal location and the capacity factor were not included in this analysis.

## 5.6 Central Coal with Carbon Capture and Sequestration

The H2A central coal with carbon capture and sequestration model (Rutkowski, 2008a) uses capital and operating cost data to be used to arrive at a plant gate cost for hydrogen produced from coal gasification. Hydrogen cost was determined by first preparing a plant design for hydrogen production based on currently available process technology

and then meeting current permitting regulations for environmental compliance. This baseline plant captures CO<sub>2</sub>.

To arrive at a cost estimate for hydrogen, the design includes commercially available process technology obtained from verifiable sources. The plant utilizes a Wabash River-scale ConocoPhillips (EGas<sup>TM</sup>) gasifier, conventional gas cooling, commercial shift conversion and acid gas cleanup, commercial sulfuric acid technology, and commercial PSA. A steam turbine supplies the electricity needed for the process except that required to compress the CO<sub>2</sub>. Two-stage Selexol<sup>®</sup> is used to remove CO<sub>2</sub>. Carbon dioxide is compressed to 2,200 psi for sequestration using electricity purchased from the grid (U.S. grid mix). The EGas<sup>TM</sup> gasifier is the gasifier of choice for this study because it has been operated on both bituminous and subbituminous coals. Simulations of hydrogen from coal in central plants are based on the use of Pittsburgh No. 8 bituminous coal while GREET simulations are based on generic coal. Table 5.6.1 presents the properties of Pittsburgh No. 8 coal used in the H2A analysis. A process flow chart is shown in Figure 5.6.1, and the energy efficiencies are shown in Table 5.6.2.

Component	Air Dry, %	Dry, %	As Received, %
Carbon	71.88%	73.79%	69.36%
Hydrogen	4.97%	4.81%	5.18%
Nitrogen	1.26%	1.29%	1.22%
Sulfur	2.99%	3.07%	2.89%
Ash	10.30%	10.57%	9.94%
Oxygen	8.60%	6.47%	11.41%
Total	100.00%	100.00%	100.00%
Moisture			6.00%
Volatile matter		38.20%	35.91%
Fixed carbon		51.23%	48.15%
Total (including ash)		100.00%	100.00%
Heating Values, standard units			

Dry, Btu/English

26,488,000

ton

As Received.

**Btu/English ton** 

24,900,000

#### Table 5.6.1. Pittsburgh No. 8 Coal Properties (Rutkowski, 2008a)

High heating value free of moisture and ash Low heating value	29,620,000	23,806,000
Heating Values, SI units		As Received,
Value	Dry, MJ/kg	MJ/kg
High heating value	30.804	28.957
High heating value free of moisture and ash	34.446	
Low heating value		27.685

Value

High heating value

Ash Constituents of Coal: Dry Coal-Based	
Component	Dry, %
Silica, SiO <sub>2</sub>	48.10%
Aluminum oxide, Al <sub>2</sub> O <sub>3</sub>	22.00%
Iron oxide, Fe <sub>2</sub> O <sub>3</sub>	24.00%
Titanium dioxide, TiO <sub>2</sub>	1.30%
Calcium oxide, CaO	1.30%
Magnesium oxide, MgO	0.60%
Sodium oxide, Na <sub>2</sub> O	0.30%
Potassium oxide, K <sub>2</sub> O	1.50%
Sulfur trioxide, SO <sub>3</sub>	0.80%
Phosphorous pentoxide, P <sub>2</sub> O <sub>5</sub>	0.10%
Total	100.00%

#### Ash Fusion Temperature, degrees F

Item	Reducing Atmosphere	Oxidizing Atmosphere
Initial deformation	2,015	2,570
Spherical	2,135	2,614
Hemispheric	2,225	2,628
Fluid	2,450	2,685

#### Ash Fusion Temperature, degrees C

Item	Reducing Atmosphere	Oxidizing Atmosphere
Initial deformation	1,087	1,396
Spherical	1,154	1,420
Hemispheric	1,204	1,428
Fluid	1,329	1,460

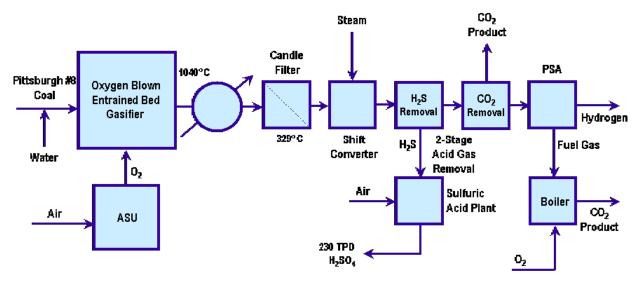


Figure 5.6.1. Central coal with carbon capture process flow diagram (Rutkowski, 2008a)

# Table 5.6.2. Energy Efficiencies of Process Components of the Central Coal with Carbon Capture and Sequestration Pathway (Rutkowski, 2008a)

Energy efficiencies for individual process steps (add rows as appropriate)	Value	Basis	Reference
Gasifier Cold Gas Effieiency	72%	LHV efficiency of energy in gasifier product gas coming out of gasifier divided by energy in coal fed to gasifier.	Aspen Plus Model
Carbon Conversion	99%	Percent of carbon in coal converted to gaseous product	ConocoPhillips gasifier spec.
Shift Reactor Conversion	90%	Molar percent of CO converted	Haldor Topsoe commercial catalyst spec.
PSA Hydrogen Separation	80%	Percent hydrogen rercovered from PSA feed gas	UOP commercial PSA design spec.

# 6.0 Delivery Technology Description and Assumptions

The hydrogen delivery and distribution technologies used in each of the seven pathways examined in this study are described below. Note that this study assumes that energy used in the hydrogen refueling station for lighting, cryogenic pumping, security cameras, etc. is small relative to the total delivery and distribution energy use; these items are therefore not included in the cost, energy use, and emissions calculations.

## 6.1 Liquid Hydrogen Delivery

The components for the liquid hydrogen pathway include: central production  $\rightarrow$  liquefier  $\rightarrow$  liquid hydrogen (including liquid storage for plant outages)  $\rightarrow$  liquid hydrogen truck transmission and distribution  $\rightarrow$  and liquid hydrogen fuel station. For liquid hydrogen truck transmission and distribution, HDSAM calculates the number and cost of the trucks and trailers required to deliver the fuel to fuel stations as well as distances traveled. The capital and operating costs of the delivery trucks, including the amount of diesel fuel required, are computed. Additionally, the cost of appropriately sized liquefiers, terminal storage, liquid pumps, vaporizers, etc. are calculated.

Peak demand is used to determine the design capacity of the terminal or depot where hydrogen is stored and loaded onto trailers for delivery to stations. Cryogenic storage tanks are used to mitigate production outages and demand surges and are assumed to be sited immediately adjacent to the production facility. The terminal's storage requirement is determined by the following factors: peak daily demand, days of summer peak demand, and expected days per year that the production plant is off-line. The amount of required storage determines the number of truck-filling bays required at the terminal, the capacities of storage tanks, and the resulting capital and operating costs associated with the terminal. Liquefier design is also linked to peak demand.

## 6.1.1 Liquid Hydrogen Truck

A typical liquid hydrogen trailer can carry up to 3,900 kg of hydrogen. HDSAM calculates the amount of hydrogen that is loaded on a trailer when it leaves the terminal. The equation is as follows:

$$H2(kg) = V_{\tan k} \rho_{LH2} A_{LH2truck}$$

Where:

 $V_{tank}$  = water volume of the trailer (m<sup>3</sup>)  $\rho_{LH2}$  = density of liquid hydrogen (g/L)  $A_{LH2Truck}$  = availability of the liquid truck

The amount of hydrogen loaded on the trailer is then used to calculate the amount of boiloff losses during delivery to a station, using the following equation:

$$H_{2,boil-off} = H_{2,prev}B_rT$$

Where:  $H_{2,prev}$  = hydrogen in trailer from previous station  $B_r$  = boil-off rate (fraction of a day) T = travel time (days)

HDSAM assumes there are only combinations of one tractor and one trailer. Additionally, it is assumed that the stations are the same distance from the terminal and that the same amount of hydrogen is delivered to each station.

Total fuel cost is determined by multiplying the HDSAM fuel cost value by the fuel consumption by trip, which is calculated based on truck fuel economy and distance traveled. Total capital (truck and trailer), labor and other operational and maintenance costs are added together so a cost for hydrogen can be determined.

### 6.1.2 Liquefier

For the pathways analysis, HDSAM is able to cost a single liquefier unit based on an idealized liquefier power equation and an energy requirement based on literature data. The actual power requirement is calculated using the curve in Figure 6.1.1. Figure 6.1.1 shows how the energy requirement of a liquefier decreases as the design capacity or hydrogen flow rate drops below 5 tonnes/day.

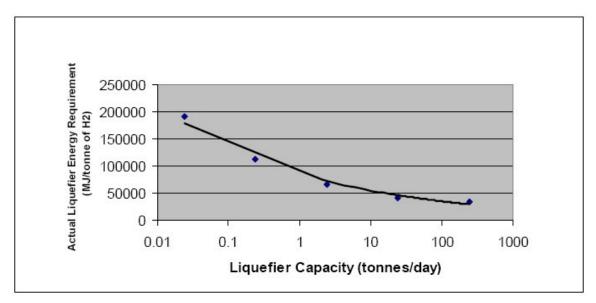


Figure 6.1.1. Liquefier energy requirement versus hydrogen flow rate (National Renewable Energy Laboratory, 2006)

The formula for the actual power requirement is as follows:

$$P_{liq} = P_{req} \frac{F_{avg}}{1 - loss}$$

Where:

 $P_{req}$  = curve fit from Figure 6.1.1  $F_{avg}$  = average hydrogen flow rate out *loss* = hydrogen loss during liquefaction

The thermodynamically ideal system for liquefaction assumes reversible isothermal compression and a reversible isentropic expansion. The theoretical power requirement is calculated using the following formula:

$$-\frac{\dot{W}_{net}}{\dot{m}} = T_1 (s_{in} - s_{out}) - (h_{in} - h_{out})$$

Where:

 $W_{net}$  = idealized net work required by the liquefier [kWh / (kg/day)] m = design capacity of the liquefier (kg/day)  $T_1$  = inlet temperature to the liquefier (K)  $s_m$  = hydrogen entropy at the inlet temperature [kWh / K(kg/day)]  $s_{out}$  = hydrogen entropy at the outlet temperature [kWh / K(kg/day)]  $h_{in}$  = hydrogen enthalpy at the inlet temperature [kWh / (kg/day)]

 $h_{out}$  = hydrogen enthalpy at the outlet temperature [kWh / (kg/day)]

The liquefier efficiency is then just the theoretical power divided by the actual power requirement.

It is assumed that the inlet and outlet pressures for the liquefier are both 1 atm and that the feed to the system is pure hydrogen.

A cost curve has been developed based on several literature sources that estimate the capital cost of a liquefier. Figure 6.1.2 displays the costs for a liquefier only and does not include other direct and indirect costs such as installation, contingencies, property taxes and engineering. The costs in Figure 6.1.2 were determined from reports published from 1986 to 2002 and were scaled to 2005 dollars using the GDP Deflator Price Index found in EIA's Short Term Energy Outlook.

It is assumed that a 30 tonne/day liquefier will require approximately  $25,000 \text{ m}^2$  of land. The land required for other sizes of liquefiers is calculated by taking the ratio of the design capacity to 30 tonnes/day; the result is then raised to the 0.6 power. That result is multiplied by 25,000 to give the amount of land required.

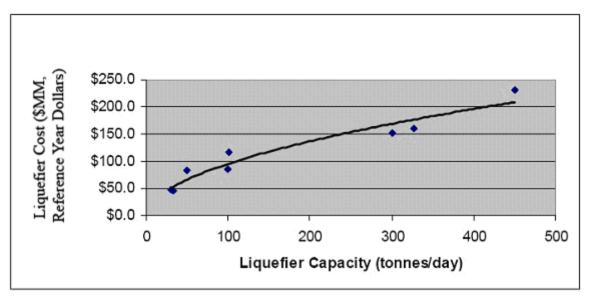


Figure 6.1.2. Liquefier cost versus design capacity (National Renewable Energy Laboratory, 2006)

The annual energy requirement is calculated using the following formula:

$$E_{ann} = 8760 P_{lig}$$

Where:  $E_{ann}$  = annual energy requirement  $P_{liq}$  = actual power requirement

The total utility cost is then determined by multiplying the H2A fuel/utility cost by the annual energy requirement. Total capital, labor, and other operational and maintenance costs (not inclusive to what is presented here) are added together so a cost for hydrogen can be determined.

#### 6.2 Gaseous Hydrogen Delivery

The components for gaseous hydrogen pathways include: central production  $\rightarrow$  compressor  $\rightarrow$  geologic storage for plant outages  $\rightarrow$  transmission and distribution pipeline  $\rightarrow$  and gaseous hydrogen fuel station. The largest diameter pipe of those in each scenario is the transmission pipeline. It extends from the production facility to the city gate. The diameter of the transmission pipeline is a function of its length, peak hydrogen demand, and the pressure differential between the pipeline inlet at the production end and the pipeline outlet at the city gate. An intermediate diameter pipe (trunk line) creates one or more rings within an area and is used to carry hydrogen from the transmission line to the individual service pipelines that connect to each individual hydrogen fuel station. HDSAM finds the least-cost combination of trunk and service lines and in doing so determines the number of trunk lines, their location, lengths, and diameters.

The pipeline system requires a compressor to increase hydrogen pressure from its production level to the pressure at the terminus of the transmission line. Design requirements for the pipeline central compressor can be calculated as a function of change in pressure and the peak hydrogen throughput (after accounting for losses in the pathway).

## 6.2.1 Pipeline

Pipeline diameter is calculated using the Panhandle B pipeline equation and is used to simulate compressible flow. The equation is as follows:

$$q_{sc} = 737 \left(\frac{T_{sc}}{P_{sc}}\right)^{1.02} \left(\frac{(P_1^2 - P_2^2)d^{4.961}}{\gamma^{0.961}LT_m Z_m}\right)^{0.51} E$$

Where:

 $q_{sc}$  = gas rate at standard conditions (scf / day)  $T_{sc}$  = temperature at standard conditions (°R)  $P_{sc}$  = pressure at standard conditions (psia)  $P_1$  = inlet pressure (psia)  $P_2$  = outlet pressure (psia) d = inside pipe diameter (in)  $\gamma$  = mean gas relative density (air = 1) L = pipeline length (mile)  $T_m$  = mean temperature of pipeline (°R)  $Z_m$  = mean compressibility factor

E = pipeline efficiency

 $T_{sc}$ ,  $P_{sc}$ , and E are assumed to be 530 R, 14.7 psia, and 0.92, respectively. It is assumed that no energy is required by the pipeline.

The H2A Delivery Components model uses a cost curve to estimate the capital cost of a hydrogen pipeline system. Data from the curve are based on a University of California, Davis study and is broken down into four parts: pipeline material cost, labor cost, miscellaneous cost and right-of-way cost. It is assumed that the cost of hydrogen pipeline will be 10% higher than that of natural gas pipeline given that materials and weld-types may be different. Total capital, labor, and other operational and maintenance costs for each part of the pipeline (transmission, trunk, and service) are added together so a cost for hydrogen can be determined (National Renewable Energy Laboratory, 2006).

## 6.2.2 Compressor

A compressor is required to raise the pressure of the hydrogen produced at a central facility to the pressure in a pipeline. These compressors are integral parts of the pipeline delivery network. HDSAM is designed to cost a centralized compressor that can raise the

pressure of a defined flow rate from one pressure to another. Spare compressor units are included in the model to ensure a high level of operational availability.

It is assumed that there are no pressure drops in the after-cooler or interstage coolers. Also, an electrical-powered compressor is assumed.

A cost curve has been developed to estimate the capital cost of a compressor. Data for the cost curve were acquired from an article published in the *Oil and Gas Journal* in the year 2000. Costs include the purchase costs for natural gas compressors, the cost of an aftercooler, and other direct and indirect capital costs (installation, contingencies, property taxes, and engineering). The data were adapted to that of a hydrogen compressor (1.3 times the cost of a natural gas compressor) and inflated to 2005 dollars using the GDP Implicit Deflator Price Index in EIA's Short Term Energy Outlook. Figure 6.2.1 shows the cost of a compressor versus power draw.

The capital cost of the compressor needs to be based on a unit that is capable of processing the peak hydrogen flow rate. During a typical operating year, however, the feed flow rate will fluctuate. Therefore, an average hydrogen flow rate is used as a basis to calculate the annual energy requirement. The equation is as follows:

$$E_{anm} = 8760 \frac{F_{avg}}{\eta_{isentrop}} ZRT_1 N_{st} \left(\frac{k}{k-1}\right) \left[\left(\frac{p_2}{p_1}\right)^{\frac{k-1}{kN_{st}}} - 1\right]$$

Where:

 $\eta_{isentrop}$  = isentropic compressor efficiency  $F_{avg}$  = average hydrogen flow rate R = gas constant  $T_{I}$  = inlet gas temperature  $N_{st}$  = number of compression stages k = ratio of specific heats  $p_{2}$  = outlet pressure  $p_{I}$  = inlet pressure

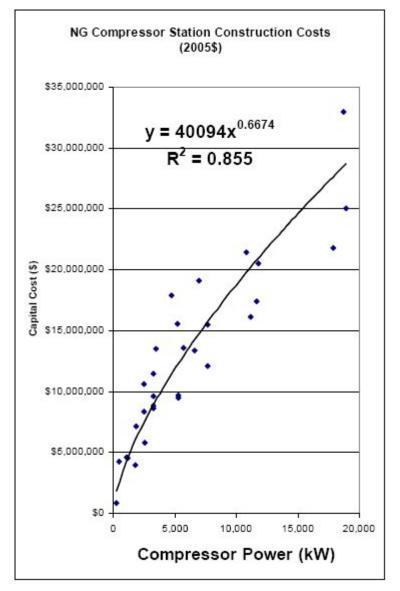


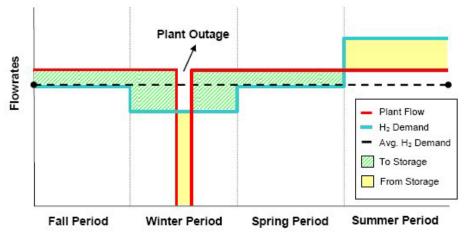
Figure 6.2.1. Compressor cost as a function of power draw (National Renewable Energy Laboratory, 2006)

The total utility cost is determined by multiplying the HDSAM fuel/utility cost by the annual energy requirement. Total capital, labor, and other operational and maintenance costs (not inclusive to what is presented here) are added together so a cost for hydrogen can be determined.

#### 6.3 Compression, Storage, and Dispensing

Hydrogen distribution requires compression, storage, and dispensing at the fueling station to transfer hydrogen at 6250 psi to vehicles in the required fill-up time.

Much like gasoline stations, hydrogen stations will experience seasonal demand. Summer demand is assumed in HDSAM to be approximately 10% higher than the average demand whereas winter demand is 10% lower. During early infrastructure development especially, a long-term storage system will be needed to store the 10% production excess in production during the winter for release to supplement production in the summer months (Nexant 2008). Figure 6.3.1 shows the annual schedule of production and demand used in the H2A models.



Time of Year

Figure 6.3.1. Hydrogen demand and required annual storage (Nexant 2008)

H2A appropriately sizes the storage capacity to handle the maximum of the two green shaded areas in Figure 6.3.1 and to handle any losses that may occur during the storage period. The daily design flow rate for the production plant is determined by calculating the annual hydrogen demand (area under the black or blue lines in Figure 6.3.1), adding all of the annual losses, and dividing by 365 days minus scheduled production outage days. Storage capacity is based on: 1) plant-outage period; 2) 10% increase in summer demand; 3) length of the summer period; and 4) length of the winter period. H2A assumes a plant-outage period of 10 days.

In addition to seasonal demand, demand variation occurs daily during the week as well as hourly during the day. Peak demand occurs on Fridays between 4:00 and 6:00 p.m. (Nexant, 2008). Figure 6.3.2 shows the hourly Friday demand profile at a refueling station over 24 hours. The area under the curve above the daily average hourly demand represents the minimum storage requirement to satisfy the station demand during peak hours (approximately 30% of daily demand).

The refueling site is the best location to handle daily and hourly fluctuations in demand and takes the form of low-pressure storage (2,500 psi). This eliminates the need for scaling upstream components to handle daily and hourly demand variations. For distributed hydrogen production facilities and stations supplied by pipeline, the lowpressure storage at the refueling station is sized at 30% of the total daily demand (472 kg  $H_2$  for distributed facilities and 470 kg  $H_2$  for pipeline-supplied facilities). For liquid trucks, the liquid storage tank (6,920 kg  $H_2$ ) would satisfy the increase in additional storage. Because truck deliveries do not exceed two deliveries per day, the truck would carry half the daily demand plus the 30% excess.

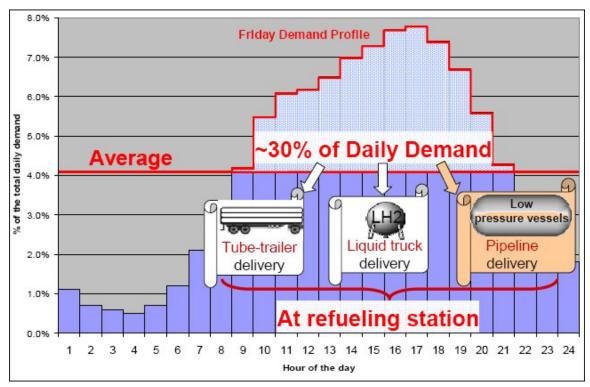


Figure 6.3.2. Hydrogen daily average demand (Nexant, 2008)

Refueling stations also include a cascade charging system with at least one bank of three pressure vessels operating under different pressures (6,000, 4,350, and 2,000 psi) to satisfy vehicle refueling requirements. Each vessel holds 21.3 kg hydrogen at a maximum pressure of 6,250 psi. For distributed hydrogen production facilities, the refueling station modeled includes cascade storage for 325 kg H<sub>2</sub>. For stations receiving liquid hydrogen, the cascade storage volume is 453 kg H<sub>2</sub>, and for stations supplied by pipeline, the cascade storage is sized for 582 kg H<sub>2</sub>.

The number of dispensers is determined by the metric utilized in gasoline stations known as hose-occupied fraction (HOF). The HOF is the average fraction of time that each hose is occupied during the peak hour of the day. By determining the HOF of a gasoline station, the number of dispensers at a hydrogen station can be selected such that the HOF is approximately equal to that of a gasoline station. Figure 6.3.3 shows the number of dispensers for a range of refueling station daily demands in kg/day (Nexant, 2008).

An equation, based on Figure 6.3.3, can also be used to determine the number of dispensers given a daily capacity (kg/day):

# of Dispensers = Daily Capacity/ $(305.85*Daily Capacity^{0.0763})$ 

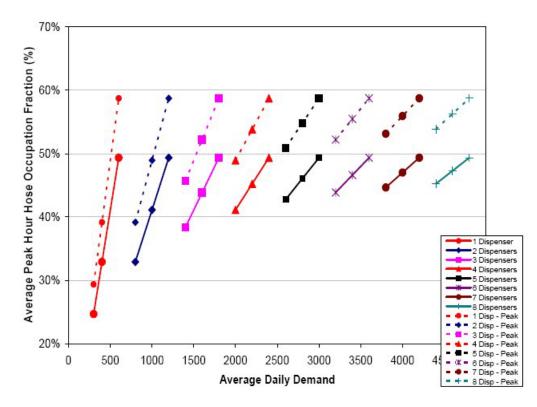


Figure 6.3.3. Recommended number of refueling station dispensers (Nexant 2008)

Once the number of dispensers is known, the maximum flow rate can be determined. This flow rate is integral in determining the required size of the refueling station compressor and cascade charging system.

The dispensing pressure is assumed to be 6,250 psi. A conservative assumption and worst-case scenario of occupying all the dispensing hoses during the first three minutes of each hour simultaneously is made to ensure adequate sizing of the refueling station components (see Section 2.3.2, Nexant, 2008). In addition, a small amount of 2,500-psi storage (1 day) is provided for in H2A at the liquid terminal to ensure smooth loading of liquid hydrogen trucks.

Dispensers are unlikely to use a significant amount of energy for operation, so there are no costs associated to fuel or utilities related to the dispenser. Capital, labor, and other operational and maintenance costs for compressed hydrogen storage are pooled together so the total hydrogen cost can be determined.

# 7.0 Vehicle Assumptions

Vehicle assumptions are engineering estimates based on both simulation and performance of the current generation of vehicles being tested under the Program's technology validation function.

## 7.1 Vehicle Fuel Economy

Vehicle fuel economy is a primary parameter for these analyses because it has an inversely proportional effect on cost per mile as well as energy use and emissions per mile. For this study, the estimated fuel economy is 45 miles per gallon gasoline equivalent (mpgge)

The fuel economy of 45 mpgge was estimated by running simulations using the Powertrain Simulation Analysis Toolkit (PSAT) V6.2 SP1, which was developed by Argonne National Laboratory. Simulations were run for both mid-size passenger cars and light trucks. The on-road adjusted fuel economies of the mid-size passenger car and light truck were estimated to be 53.6 mpgge and 37.8 mpgge, respectively. For a light-duty vehicle that is the composite of a car and a light truck, the two fuel economies were averaged using a weighting factor that reflects the ratio of new light truck sales to new car sales. Using the EIA-estimated light truck sales share of 46.4% for 2008, the on-road fuel economy of a new light-duty vehicle was estimated to be 45 mpgge (Singh and Nguyen, 2009).

In PSAT simulations, vehicle weight is specified because it is a crucial factor in determining a vehicle's fuel economy. Additional vehicle glider assumptions used in this analysis are listed in Table 7.1.1 (Rousseau and Wallner, 2008), and light truck parameters can be found in Delorme, Pagerit, Sharer, and Rousseau (2009). A wide variety of data sources were used to characterize the PSAT mid-size passenger car and fuel cell propulsion system. These sources include vehicle tear-down data, various automotive models, personal communications, and literature reviews.

		1
Parameter	Unit	Value
Glider mass	kg	990
Frontal area	m <sup>2</sup>	2.1
Drag coefficient		0.29
Wheel radius	m	0.137
Rolling resistance		0.008
0–60 mph	S	9 ± 0.1
0–30 mph	S	3
Grade at 60 mph	%	6
Maximum speed	mph	>100 <sup>1</sup>

Table 7.1.1. PSAT Mid-Size Passenger Car Assumption	tions
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<sup>1</sup> Two-gear transmission used for series

Table 7.1.2 shows the PSAT fuel cell system assumptions while Figure 7.1.1 shows the fuel cell power versus system efficiency used for PSAT simulations (Rousseau and Wallner, 2008).

Parameter	Unit	Current Status	FreedomCAR Goal
Specific power	W/kg	500	650
Peak efficiency	%	55	60

 Table 7.1.2. PSAT Fuel Cell System Assumptions

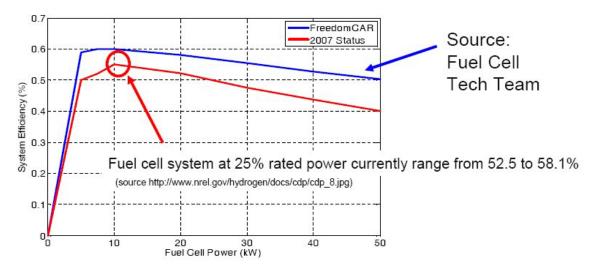


Figure 7.1.1. Fuel cell power versus system efficiency (Rousseau and Wallner, 2008)

Other studies on fuel economy have taken place. In another study that was based on the assumptions above, PSAT estimated that the overall [2008 Environmental Protection Agency (EPA) adjusted] vehicle fuel economy for fuel cell hybrid electric vehicles (HEVs) is 50.7 mpgge with an error bar of 7.5 mpgge (Rousseau and Wallner, 2008). The mid-size vehicle fuel economy used in this study (53.6 mpgge) is within that range.

Another simulated analysis was conducted in 2005 by the National Renewable Energy Laboratory (NREL) (National Renewable Energy Laboratory, 2005). Its fuel economy versus fuel cell size results are shown in Figure 7.1.2. The fuel cell HEV fuel economy shown in Figure 7.1.2 (52.5 mpgge) reflects EPA-combined fuel economy. Forty-five mpgge is equivalent to discounting the 52.5 mpgge by 15%, which is an approximation of EPA's pre-2008 reduction factor used to calculate on-road fuel economy from dynamometer test results. (The EPA reduction factor was equivalent to adjusting the city-driving test result downward by 10% and the highway-driving test result downward by 22%.)

NREL also collects fuel economy data under the Hydrogen Fleet and Infrastructure Demonstration and Validation Project (Wipke, Sprik, Kurtz, and Ramsden, 2009). Results from 2009 for that project are shown in Figure 7.1.3, and the upper range of those results includes 45 mpgge, which is the fuel economy used for this analysis.

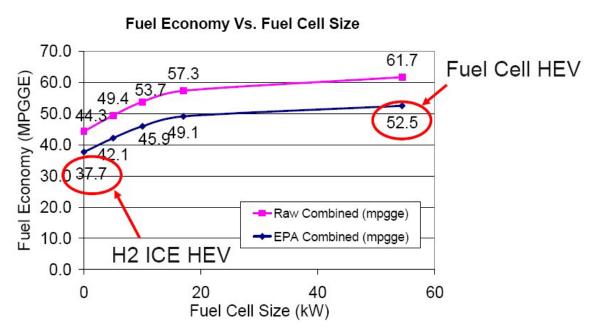


Figure 7.1.2. Fuel economy versus fuel cell size (Rousseau and Wallner, 2008)

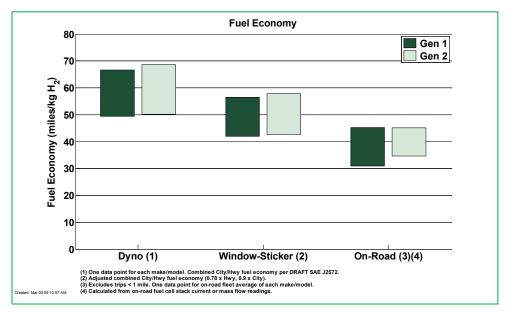


Figure 7.1.3. NREL hydrogen fleet and infrastructure demonstration and validation project fuel economy (Wipke, Sprik, Kurtz, and Ramsden, 2009)

### 7.2 Vehicle Criteria Pollutant Emissions

Table 7.2.1 presents the default values of emission change rates used in the GREET model for a hydrogen fuel cell vehicle as compared to the modeled gasoline vehicle. Those values were used for this study.

Hydrogen FCVs run on hydrogen instead of combustible carbon compounds, so there are no volatile organic carbon compounds (VOC) to either evaporate or be exhausted due to incomplete emissions. Likewise, there are no CO or methane (CH<sub>4</sub>) emissions. Because these vehicles run on fuel cells instead of combustion engines, combustion-caused pollutants are also avoided; therefore, there are no  $PM_{10}$ , NOx, or  $N_2O$  emissions.

Vehicles within the same class (mid-size passenger car), whether powered by a gasoline internal combustion engine or a hydrogen fuel cell, are assumed to have similar tire- and brake-wear (TBW) particulate matter (PM) emissions (Wang, 1999).

Vehicle		Evap.	СО	NOx	Exhaust	CH <sub>4</sub>	N <sub>2</sub> O	TBW
	VOC	VOC			PM			PM
H <sub>2</sub> FCV	-100%	-100%	-100%	-100%	-100%	-100%	-100%	0%

Table 7.2.1. Change in Exhaust as Compared to a Gasoline Vehicle

### 8.0 Financial Assumptions

The H2A model uses a common set of economic assumptions to allow for consistent and comparable results across technology options. Table 8.0.1 provides a set of key economic parameters selected by H2A analysts and discussed with industry collaborators who participated in the H2A effort.

Parameter	Value
Reference year	2005 dollars
Percentage equity financing	100%
After-tax internal rate of return	10% real
Inflation rate	1.9%
Effective corporate income tax rate	38.9%
Depreciation schedule	Modified Accelerated Cost Recovery System
Economic analysis period	
Central plant production	40 years
Forecourt production	20 years

Table 8.0.1. H2A Key Economic Parameters

In cases where the capital cost component is a large fraction of the levelized cost of producing hydrogen, the assumed after-tax internal rate of return (IRR) strongly affects the results calculated by H2A. As seen in Table 8.0.1, H2A uses an IRR of 10% real. The 10% real value was derived from return on equity statistics (adjusted for inflation) for large company stocks over the period from 1926–2002. Because returns already account for corporate taxes, this value is an after-tax return. The use of a 10% real IRR is intended to reflect a steady-state situation in the future in which hydrogen is a familiar and publicly accepted fuel and in which a significant demand for hydrogen for transportation exists (Pacific Northwest National Laboratory, 2004).

This 10% after-tax IRR is linked to the H2A assumption of 100% equity financing. Actual projects would probably be financed with a combination of debt and equity, but H2A analysts have been told that firms typically assume 100% equity financing for paper studies and analyses. When debt financing is used, a higher after-tax IRR can be achieved with the same levelized cost. The increase is dependent upon the fraction of debt financing and the interest rate on that debt. Figure 8.0.1 shows the after-tax IRR for multiple combinations of equity to debt financing at three different interest rates for production of hydrogen from coal in central facilities (see section 9.7 for details); delivery costs were not included in the data shown. Technologies with different ratios of capital to operating cost will result in slightly different curves.

Figure 8.0.1 also shows the before-tax IRR for the same equity to debt ratios. Corporate income tax can be considered a reduction in profits, so a pre-tax IRR is always greater than an after-tax IRR. Pre-tax IRRs are shown in Figure 8.0.1 because they are often easier to compare to performance of stocks or bonds, which are reported on a pre-tax basis.

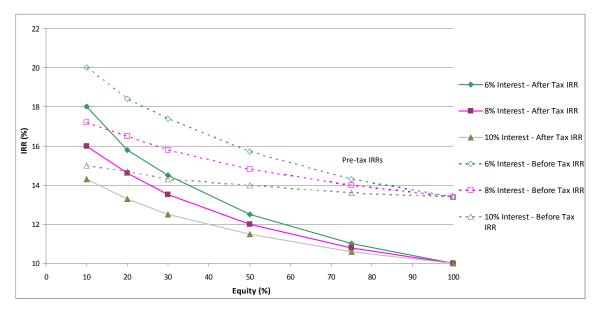


Figure 8.0.1. Post-tax and pre-tax IRRs that result in the same levelized cost for multiple equity to debt ratios (Central Production of Hydrogen from Coal with CCS)

## 9.0 Pathway Results

This study assessed the WTW cost, energy use, and GHG emissions of each of the seven pathways listed in Table 9.0.1 (see detailed descriptions of each pathway in Section 2.4).

	Central or Distributed Production	Feedstock	Delivery Method	Carbon Capture and Sequestration	Hydrogen Distribution for Fueling
1	Distributed	Natural Gas	Not applicable	No	350 bar compressed gas
2	Distributed	Electricity	Not applicable	No	350 bar compressed gas
3	Central	Biomass	Liquid H <sub>2</sub> in trucks	No	350 bar compressed gas
4	Central	Biomass	Gaseous H <sub>2</sub> in pipelines	No	350 bar compressed gas
5	Central	Natural Gas	Gaseous H <sub>2</sub> in pipelines	No	350 bar compressed gas
6	Central	Wind Electricity	Gaseous H <sub>2</sub> in pipelines	No	350 bar compressed gas
7	Central	Coal	Gaseous H <sub>2</sub> in pipelines	Yes	350 bar compressed gas

Table 9.0.1. Seven Hydrogen Production, Delivery, and Distribution Pathways

The hydrogen production technologies are described in Section 5.0, and the delivery technologies are detailed in Section 6.0. This section presents the results of the WTW cost, energy use, and GHG emissions analysis for each pathway.

#### 9.1 Distributed Natural Gas

Figure 9.1.1 shows the major inputs, assumptions, and outputs for each of the subsystems considered in the well-to-tank analysis, including feedstock supply and hydrogen dispensing. The complete set of assumptions is detailed in Appendix A.

The well-to-pump and well-to-wheels cost of hydrogen, energy use, and emissions for the distributed natural gas pathway are summarized in Table 9.1.1.

### 9.1.1 Cost Breakdown

Figure 9.1.2 shows the feedstock and energy price inputs and the resulting hydrogen production, delivery, and distribution costs for the distributed natural gas pathway. The financial assumptions used in this analysis are detailed in Section 8.0.

Figure 9.1.3 shows the contributions of hydrogen production, distribution (compression, storage, and dispensing—CSD), and losses to the levelized cost of hydrogen shown in Figure 9.1.2.

Figure 9.1.4 and Table 9.1.2 show the breakdown of levelized costs for the distributed natural gas pathway.

	Inputs	Graphic Depiction & Assumptions	C	Dutputs
		NG Recovery, Processing, & Transport NG Recovery Efficiency 97.2%		Average of gas companies Average of gas companies
Coal Input from "Weil" Natural Gas Input from "Weil" Petroleum Input from "Weil"	322 Btu / 116000Btu to Pump 124,113 Btu / 116000Btu to Pump 497 Btu / 116000Btu to Pump	NG emitted & combusted during recovery       0.35%         NG processing energy efficiency       97.2%         NG emitted & combusted during processin       0.15%         NG emitted & combusted during transport       0.14 g / MMBtu         NG transport distance       500 miles         Compression Reqs (stages & eff) average of gas companies	NG Cost NG Cost WTG CO2 Emissions WTG CH4 Emissions WTG N2O Emissions WTG GHG Emissions	\$0.243 2005 \$ / Nm <sup>4</sup> 3 \$0.907 2005\$ / kg H2 distributed 5,485 g / 116000Btu to Pump 239 g / 116000Btu to Pump 0 g / 116000Btu to Pump 11,475 g CO2 eq./ 116000 Btu
Natural Gas consumption Electricity consumption Process Water Consumption	4.5 N m^3/kg H2 produced 1.11 kWh / kg H2 5.77 L / kg H2	Hydrogen Production	Hydrogen Output Pressure Hydrogen Outlet Quality	300 psi 1
Electricity price	\$0.0816 2005 \$/kWh \$1,138,995 2005\$	Design Capacity     1,500 kg/day       Capacity factor     85%       Process energy efficiency     71.3%       Electricity Mix     US Mix       After-tax IRR     10%       Assumed Plant Life     20 years	Total capital investment Electricity cost Other operating costs Levelized Cost of Prod (excl feedst	2005\$ / annual kg H2 \$2.44 (effective capacity) \$0.09 2005\$ / kg H2 produced \$0.36 2005\$ / kg H2 produced \$0.71 2005\$ / kg H2 distributed
Coal Input from "Well" Natural Gas Input from "Well" Petroleum Input from "Well"	6,572 Btu / 116000Btu to Pump 47,754 Btu / 116000Btu to Pump 664 Btu / 116000Btu to Pump		SMR CO2 Emissions SMR CH4 Emissions SMR N2O Emissions SMR GHG Emissions	10,523 g / 116000Btu to Pump 11 g / 116000Btu to Pump 0 g / 116000Btu to Pump 10,815 g CO2 eq./ 116000 Btu
Electricity consumption	1.96 kWh / kg H2		Hydrogen outlet pressure	6,250 psi
		Compression, Storage, & Dispensing	Basis Hydrogen Quantity	Btu (116,000 Btu/gal non- oxygenated conventional 116,000 unleaded gasoline)
Total Capital Investment	\$3,993,763 2005\$	Number of Distribution Stations270Energy efficiency94%Number of Compression Stages6Isentropic Efficiency65%	Total capital investment Electricity cost Levelized Cost of Distribution	2005\$ / annual kg H2 \$8.56 (effective capacity) \$0.16 2005\$ / kg H2 \$1.88 2005\$ / kg H2 distributed
Coal Input from "Well" Natural Gas Input from "Well" Petroleum Input from "Well"	11,382 Btu / 116000Btu to Pump 3,269 Btu / 116000Btu to Pump 848 Btu / 116000Btu to Pump	Site storage 62% capacity	CSD CO2 Emissions CSD CH4 Emissions CSD N2O Emissions CSD GHG Emissions	1,502 g / 116000Btu to Pump 2 g / 116000Btu to Pump 0 g / 116000Btu to Pump 1,558 g CO2 eq./ 116000 Btu

#### Figure 9.1.1. Summary of distributed natural gas pathway major inputs, assumptions, and outputs by subsystem

Coal, natural gas, and petroleum inputs from "well" include those used directly in the hydrogen production and delivery pathway as feedstocks and fuels; those used to produce electricity and other materials used in the pathway; and those used upstream of the pathway to recover, refine, and deliver the feedstock.

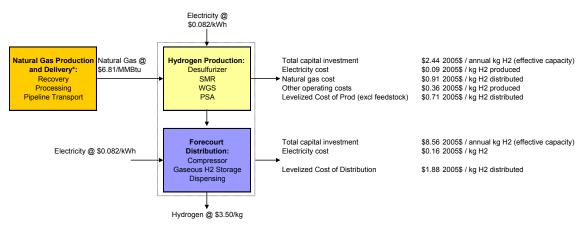
		Well-to-Pump	Well-to	-Wheels
Coal Input from "Well"*	18,300	Btu / 116,000 Btu	410	Btu / mi
Natural Gas Input from "Well"*	175,100	Btu / 116,000 Btu	3,900	Btu / mi
Petroleum Input from "Well"*	2,000	Btu / 116,000 Btu	45	Btu / mi
Fossil Energy Input from "Well"*	195,400	Btu / 116,000 Btu	4,350	Btu / mi
WTP CO <sub>2</sub> Emissions***	12,700	g / 116,000 Btu	280	g / mi
WTP CH <sub>4</sub> Emissions	41	g / 116,000 Btu	1	g / mi
WTP N <sub>2</sub> O Emissions	0	g / 116,000 Btu	0	g / mi
WTP GHG Emissions*	13,700	g CO <sub>2</sub> eq. / 116,000 Btu	310	g / mi
Levelized Cost of Hydrogen (\$/kg)	\$3.50	2005 \$/kg	\$0.0777	2005 \$/mi

Table 9.1.1. Well-to-Pump and Well-to-Wheels Results for Distributed Natural Gas Pathway

\* Well-to-pump results are rounded to the nearest hundred; well-to-wheels results are rounded to the nearest ten.

\*\* Includes the carbon content of CO, CH<sub>4</sub>, and volatile organic compound emissions that decompose in the atmosphere to CO<sub>2</sub>

Coal, natural gas, and petroleum inputs from "well" include those used directly in the hydrogen production and delivery pathway as feedstocks and fuels; those used to produce electricity and other materials used in the pathway; and those used upstream of the pathway to recover, refine, and deliver the feedstock.



\* This box represents the natural gas that is converted to hydrogen or otherwise consumed/lost as a process feedstock.

It does not include natural gas used as a heating fuel or to produce electricity.

## Figure 9.1.2. Cost analysis inputs and high-level results for distributed natural gas pathway

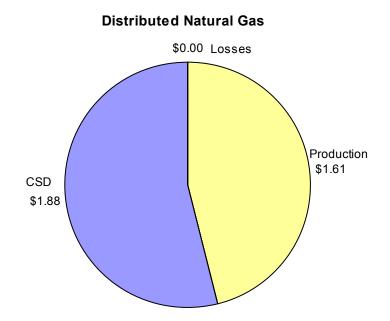


Figure 9.1.3. Contribution of hydrogen production, CSD, and losses to the levelized cost of hydrogen for distributed natural gas pathway

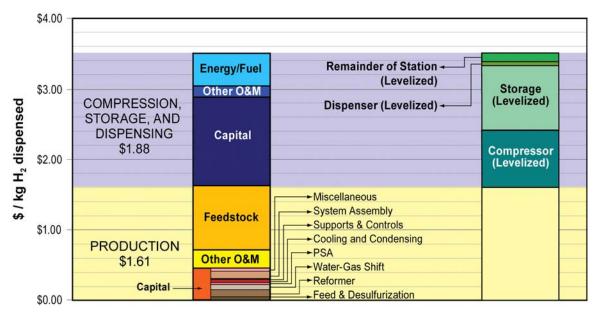


Figure 9.1.4. Breakdown of levelized costs for distributed natural gas pathway

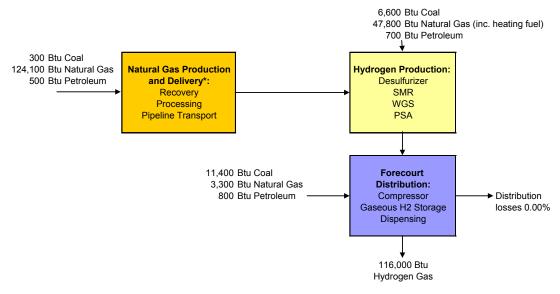
Cost Component	Capital	Other O&M	Feedstock	Energy/ Fuel	Total
Production	\$0.45	\$0.26	\$0.91		\$1.61
Feed & Desulfurization	\$0.05				
Reformer	\$0.09				
Water-Gas Shift	\$0.08				
PSA	\$0.03				
Cooling & Condensing	\$0.03				
Supports & Controls	\$0.03				
System Assembly	\$0.10				
Miscellaneous	\$0.04				
Compression, Storage, & Dispensing	\$1.26	\$0.16		\$0.46	\$1.88
Compressor (Levelized)					\$0.80
Storage (Levelized)					\$0.94
Dispenser (Levelized)					\$0.03
Remainder of Station (Levelized)					\$0.11
Losses					\$0.00
Total	\$1.71	\$0.42	\$0.91	\$0.46	\$3.50

 Table 9.1.2. Contribution of Production and CSD Processes to Levelized Hydrogen Cost

 for Distributed Natural Gas Pathway

#### 9.1.2 Energy Use and Emissions Breakdown

Figures 9.1.5 and 9.1.6 show the WTW energy inputs and losses for the distributed natural gas pathway. The WTW energy inputs to natural gas production and delivery include those necessary to produce 116,000 Btu of natural gas for reforming. Additional WTW energy inputs for natural gas needed for heating and lost in reforming are reported as inputs to hydrogen production.



\* This box represents the natural gas that is converted to hydrogen or otherwise consumed/lost as a process feedstock. It does not include natural gas used as a heating fuel or to produce electricity.



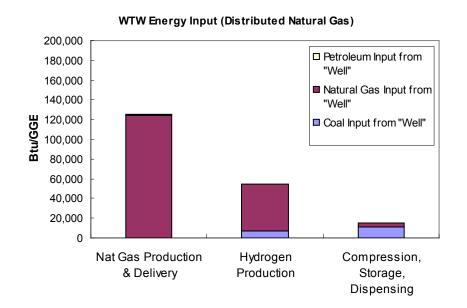
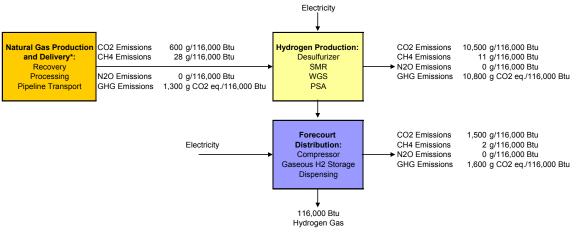
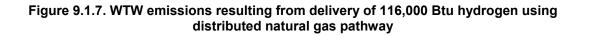


Figure 9.1.6. WTW petroleum, natural gas, and coal inputs to deliver 116,000 Btu hydrogen using distributed natural gas pathway

Figures 9.1.7 and 9.1.8 show the WTW emissions resulting from the delivery of 116,000 Btu hydrogen to a vehicle fuel tank using the distributed natural gas pathway.



\* This box represents the natural gas that is converted to hydrogen or otherwise consumed/lost as a process feedstock. It does not include natural gas used as a heating fuel or to produce electricity.



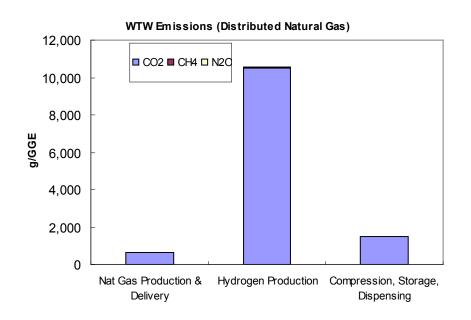


Figure 9.1.8. WTW CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O emissions resulting from delivery of 116,000 Btu hydrogen to a vehicle using distributed natural gas pathway

#### 9.1.3 Natural Gas Supply Scenarios

Assuming a total vehicle miles traveled in passenger vehicles of 2.78 trillion (Bureau of Transportation Statistics, 2007), the vehicle fuel economy used in this study (45 mpgge),

and a yield of hydrogen from natural gas of 4.5  $\text{Nm}^3$  natural gas/kg H<sub>2</sub> (159  $\text{Nft}^3$  natural gas/kg H<sub>2</sub>), the amount of natural gas required to supply 100%, 75%, 50%, or 25% of light-duty vehicles with natural gas–derived hydrogen fuel was calculated and compared to the U.S. natural gas reserves and consumption estimates shown in Section 3.1 (Table 9.1.3).

 Table 9.1.3. Natural Gas Supply Scenarios for Distributed Natural Gas Pathway

	100%	75%	50%	25%
	Penetration	Penetration	Penetration	Penetration
	Curr hydrog	ent Technolog gen production	y – 45 mpgge yield 4.5 Nm <sup>3</sup>	FCV, /kg H₂ <sup>1</sup>
Natural Gas Required (trillion ft <sup>3</sup> /yr)	10.0	7.5	5.0	2.5
Percent of Estimated U.S. Reserves (237.7 trillion ft <sup>3</sup> , dry) <sup>2</sup>	4%	3%	2%	1%
Percent of Annual U.S. Consumption (23.2 trillion ft <sup>3</sup> /yr) <sup>3</sup>	43%	32%	22%	11%

<sup>1</sup> Calculation does not include energy or hydrogen losses.

<sup>2</sup> Energy Information Administration (2009i)

<sup>3</sup> Energy Information Administration (2009b)

No sample scenarios for domestic hydrogen production from natural gas are included in the Hydrogen Posture Plan (United States Department of Energy, 2006).

### 9.1.4 Sensitivities

### Production Sensitivities

The parameters used for this analysis are not known absolutely, so sensitivity analyses were performed to better understand the potential effects of that lack of knowledge on the final results. Several sensitivities were run on this pathway. They focused primarily on cost factors; however, several sensitivities also affect energy use and emissions. Figure 9.1.9 shows the effects of several production parameters on the pathway's levelized cost, and Table 9.1.4 shows the effect of production energy efficiency on WTW energy use and emissions.

The assumed electrical grid mix also affects the energy use and emissions. Table 9.1.5 shows the differences in energy use and GHG emissions between the U.S. average grid mix (which was used for all other sensitivities) and a hypothetical green grid mix that is 100% renewable energy (solar and wind).

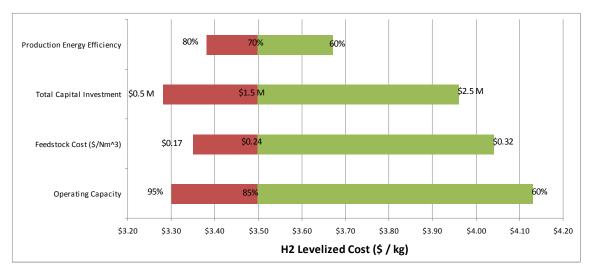


Figure 9.1.9. Production sensitivities for distributed natural gas pathway

Table 9.1.4. The Effects of Production Energy Efficiency on Primary Energy and Emissions
from Distributed Natural Gas Pathway (current technology)

	60%	70%	80%
	Efficiency	Efficiency	Efficiency
WTW GHG Emissions (g/mile)	350	310	270
WTW Fossil Energy (Btu/mile)	5,030	4,350	3,850
WTW Petroleum Energy (Btu/mile)	47	45	43
WTW Total Energy (Btu/mile)	5,120	4,430	3,930

Table 9.1.5. The Effects of Grid Mix on Use of Primary Energy and Emissions from
Distributed Natural Gas Pathway (current technology)

	U.S. Average	"Green"
	Grid Mix	Grid Mix
WTW GHG Emissions (g/mile)	310	250
WTW Fossil Energy (Btu/mile)	4,350	3,790
WTW Petroleum Energy (Btu/mile)	45	14
WTW Total Energy (Btu/mile)	4,430	4,060

### 9.1.5 Advanced Conversion and Delivery/Distribution Technology

For advanced technology analysis, parameters were changed to future projections. The "Future" H2A production case was used, and HDSAM was modified to include achievement of delivery targets as defined in the Hydrogen, Fuel Cells and Infrastructure Technologies (HFCIT) Multi-Year Program Plan (MYPP). The vehicle fuel economy was increased to 65 mpgge. In addition, the electricity grid mix was updated to match EIA's projection for technology success in 2020 (51.1% coal, 19.2% natural gas, 18.5% nuclear, 1.9% residual oil, 1.0% biomass, and 8.3% zero-carbon). WTW results from

cases with those modifications are shown in Table 9.1.6. The results match those in Hydrogen Program Record 9002 (2009).

Coal Input from "Well"	370	Btu / mi
Natural Gas Input from "Well"	2440	Btu / mi
Petroleum Input from "Well"	29	Btu / mi
Fossil Energy Input from "Well"	2840	Btu / mi
WTW CO <sub>2</sub> Emissions	190	g / mi
WTW CH <sub>4</sub> Emissions	0.58	g / mi
WTW N <sub>2</sub> O Emissions	0.001	g / mi
WTW GHG Emissions	200	g / mi
Levelized Cost of Hydrogen (\$ / kg)	\$3.23	2005 \$ / kg
Levelized Cost of Hydrogen (\$ / mi)	\$0.0496	2005 \$ / mi

Table 9.1.6. Well-to-Wheels Results for Distributed Natural Gas Pathway with AdvancedTechnology

Several sensitivities were run on this pathway. They focused primarily on cost factors; however, several sensitivities also affect energy use and emissions. Figure 9.1.10 shows the effects of several production parameters on the pathway's levelized cost, and Table 9.1.7 shows the effect of varying production energy efficiency on WTW energy use and emissions.

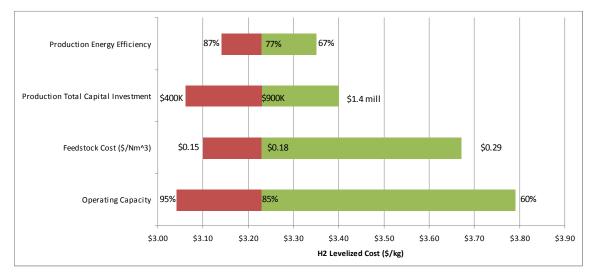


Figure 9.1.10. Production sensitivities for distributed natural gas pathway with advanced technology

	67%	77%	87%
	Efficiency	Efficiency	Efficiency
WTW GHG Emissions (g/mile)	230	200	190
WTW Fossil Energy (Btu/mile)	3,230	2,840	2,550
WTW Petroleum Energy (Btu/mile)	31	29	28
WTW Total Energy (Btu/mile)	3,300	2,910	2,630

Table 9.1.7. The Effects of Production Energy Efficiency on Primary Energy and Emissions from Distributed Natural Gas Pathway (advanced technology)

The assumed electrical grid mix also affects the energy use and emissions. Table 9.1.8 shows the differences in energy use and GHG emissions between the U.S. average grid mix (which was used for all other sensitivities) and a hypothetical green grid mix that is 100% renewable energy (solar and wind).

Table 9.1.8. The Effects of Grid Mix on Use of Primary Energy and Emissions from Distributed Natural Gas Pathway (advanced technology)

	<b>Projected U.S.</b>	"Green"
	Average Grid	Grid Mix
	Mix	
WTW GHG Emissions (g/mile)	200	150
WTW Fossil Energy (Btu/mile)	2,840	2,330
WTW Petroleum Energy (Btu/mile)	29	9
WTW Total Energy (Btu/mile)	2,910	2,580

Assuming a total vehicle miles traveled in passenger vehicles of 2.78 trillion (Bureau of Transportation Statistics, 2007), the vehicle fuel economy for advanced FCVs used in this study (65 mpgge), and a yield of hydrogen from natural gas of 4.0  $\text{Nm}^3$  natural gas/kg H<sub>2</sub> (140 Nft<sup>3</sup> natural gas/kg H<sub>2</sub>), the amount of natural gas required to supply 100%, 75%. 50%, or 25% of light-duty vehicles with natural gas-derived hydrogen fuel was calculated and compared to the U.S. natural gas reserves and consumption estimates shown in Section 3.1 (Table 9.1.9).

	100%	75%	50%	25%		
	Penetration	Penetration Penetration Penetration				
	Advar	nced Technolo	gy – 65 mpgg	e FCV,		
	hydrogen production yield 4.0 Nm <sup>3</sup> /kg H <sub>2</sub> <sup>1</sup>					
Natural Gas Required (trillion ft <sup>3</sup> /yr)	6.1	4.6	3.1	1.5		
Percent of Estimated U.S. Reserves (237.7 trillion ft <sup>3</sup> , dry) <sup>2</sup>	3% 2% 1% 0.					
Percent of Annual U.S. Consumption (23.2 trillion ft <sup>3</sup> /yr) <sup>3</sup>	26%	20%	13%	7%		

<sup>1</sup> Calculation does not include energy or hydrogen losses.

<sup>2</sup> Energy Information Administration (2009i)
 <sup>3</sup> Energy Information Administration (2009b)

### 9.2 Distributed Electricity

Figure 9.2.1 shows the major inputs, assumptions, and outputs for each of the subsystems considered in the well-to-tank analysis, including feedstock supply and hydrogen dispensing. The complete set of assumptions is detailed in Appendix B.

The well-to-pump and well-to-wheels cost of hydrogen, energy use, and emissions for the distributed electricity pathway are summarized in Table 9.2.1.

### 9.2.1 Cost Breakdown

Figure 9.2.2 shows the feedstock and energy price inputs and the resulting hydrogen production, delivery, and distribution costs for the distributed electricity pathway. The financial assumptions used in this analysis are detailed in Section 8.0.

Figure 9.2.3 shows the contributions of hydrogen production, distribution (CSD), and losses to the levelized cost of hydrogen shown in Figure 9.2.2.

Figure 9.2.4 and Table 9.2.2 show the breakdown of levelized costs for the distributed electricity pathway.

	Inputs	Graphic Depiction &	Assumptions	Outputs	
Coal Input from "Well" Natural Gas Input from "Well" Petroleum Input from "Well"	310,710 Btu / 116000Btu to Pump 89,250 Btu / 116000Btu to Pump 23,152 Btu / 116000Btu to Pump	Electrolysis Electricity Generation & Transport Includes Resource Recovery, Processing, & Transport         Grid Mix         Biomass Fraction       1.20%         Coal Fraction       51.70%         Natural Gas Fraction       15.70%         Nuclear Fraction       20.30%         Residual Oil Fraction       2.90%         Others (Carbon Neutral)       8.20%		Electricity Cost Electricity Cost WTG CO2 Emissions WTG CH4 Emissions WTG N2O Emissions WTG GHG Emissions	\$0.055 2005 \$ / kWh \$2.804 2005\$ / kg H2 distributed 353,525 g / 116000Btu to Pump 464 g / 116000Btu to Pump 5 g / 116000Btu to Pump 366,556 g CO2 eq./ 116000 Btu
Natural Gas consumption Electricity consumption Process Water Consumption	0.0 N m^3/kg H2 produced 53.48 kWh / kg H2 0.00 L / kg H2	Hydrogen Prod	uction	Hydrogen Output Pressure Hydrogen Outlet Quality	435 psi 1
Total Capital Investment	\$2,738,292 2005\$	Design Capacity Capacity factor Process energy efficiency After-tax IRR Assumed Plant Life	1,500 kg/day 85% 62.3% 10% 20	Total capital investment Other operating costs Levelized Cost of Prod (excl feedstock)	2005\$ / annual kg H2 \$5.87 (effective capacity) \$0.60 2005\$ / kg H2 produced \$1.42 2005\$ / kg H2 distributed
Coal Input from "Well" Natural Gas Input from "Well" Petroleum Input from "Well"	0 Btu / 116000Btu to Pump 0 Btu / 116000Btu to Pump 0 Btu / 116000Btu to Pump			SMR CO2 Emissions SMR CH4 Emissions SMR N2O Emissions SMR GHG Emissions	0 g / 116000Btu to Pump 0 g / 116000Btu to Pump 0 g / 116000Btu to Pump 0 g CO2 eg / 116000 Btu
Electricity consumption	1.73 kWh / kg H2			Hydrogen outlet pressure	6,250 psi
	1.0 KM17 kg H2	Compression, Storage,	& Dispensing	Basis Hydrogen Quantity	Btu (116,000 Btu/gal non- oxygenated conventional 116,000 unleaded gasoline)
Total Capital Investment Coal Input from "Well" Natural Gas Input from "Well" Petroleum Input from "Well"	\$3,989,011 2005\$ 12,477 Btu / 116000Btu to Pump 3,584 Btu / 116000Btu to Pump 930 Btu / 116000Btu to Pump	Number of Distribution Stations Energy efficiency Number of Compression Stages Isentropic Efficiency Site storage	270 95% 5 65% 62% capacity	Total capital investment Electricity cost Levelized Cost of Distribution CSD CO2 Emissions CSD CH4 Emissions CSD N2O Emissions CSD GHG Emissions	2005\$ / annual kg H2 \$8.55 (effective capacity) \$0.10 2005\$ / kg H2 \$1.82 2005\$ / kg H2 distributed 1,647 g / 116000Btu to Pump 2 g / 116000Btu to Pump 0 g / 116000Btu to Pump 1,707 g CO2 eg / 116000 Btu

#### Figure 9.2.1. Distributed electricity pathway summary of major inputs, assumptions, and outputs by subsystem

Coal, natural gas, and petroleum inputs from "well" include those used directly in the hydrogen production and delivery pathway as feedstocks and fuels; those used to produce electricity and other materials used in the pathway; and those used upstream of the pathway to recover, refine, and deliver the feedstock.

	Well-to-Pump		Well-to-Wheels	
Coal Input from "Well"*	323,200	Btu / 116,000 Btu	7,190	Btu / mi
Natural Gas Input from "Well"*	92,800	Btu / 116,000 Btu	2,070	Btu / mi
Petroleum Input from "Well"*	24,100	Btu / 116,000 Btu	540	Btu / mi
Fossil Energy Input from "Well"*	440,100	Btu / 116,000 Btu	9,790	Btu / mi
WTP CO <sub>2</sub> Emissions***	42,700	g / 116,000 Btu	950	g / mi
WTP CH <sub>4</sub> Emissions	56	g / 116,000 Btu	1	g / mi
WTP N <sub>2</sub> O Emissions	1	g / 116,000 Btu	0	g / mi
WTP GHG Emissions*	44,300	g CO <sub>2</sub> eq./ 116,000 Btu	980	g / mi
Levelized Cost of Hydrogen (\$/kg)	\$6.05	2005 \$/kg	\$0.1344	2005 \$/mi

Table 9.2.1. Well-to-Pump and Well-to-Wheels Results for Distributed Electricity Pathway

\* Well-to-pump results are rounded to the nearest hundred; well-to-wheels results are rounded to the nearest ten.

\*\* Includes the carbon content of CO,  $CH_4$ , and volatile organic compound emissions that decompose in the atmosphere to  $CO_2$ 

Coal, natural gas, and petroleum inputs from "well" include those used directly in the hydrogen production and delivery pathway as feedstocks and fuels; those used to produce electricity and other materials used in the pathway; and those used upstream of the pathway to recover, refine, and deliver the feedstock.

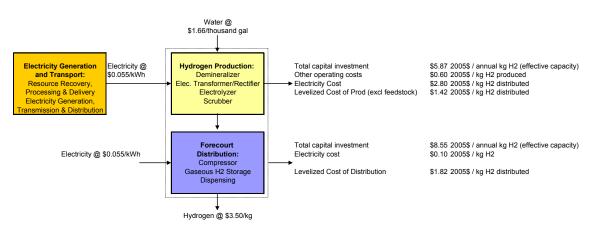


Figure 9.2.2. Cost analysis inputs and high-level results for distributed electricity pathway

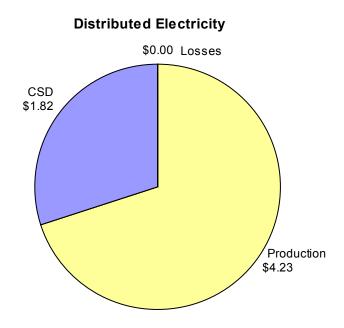


Figure 9.2.3. Contribution of hydrogen production, CSD, and losses to the levelized cost of hydrogen for distributed electricity pathway

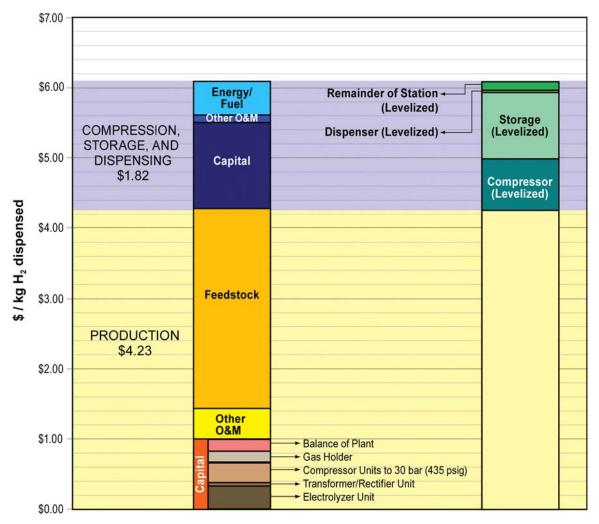


Figure 9.2.4. Breakdown of levelized costs for distributed electricity pathway

Table 9.2.2. Contribution of Production and CSD Processes to Levelized Hydrogen Cost
for Distributed Electricity Pathway

		Other		Energy/	
Cost Component	Capital	O&M	Feedstock	Fuel	Total
Production	\$0.98	\$0.45	\$2.80		\$4.23
Electrolyzer Unit	\$0.31				
Transformer/Rectifier Unit	\$0.06				
Compressor Units to 30 bar (435 psig)	\$0.28				
Gas Holder	\$0.15				
Balance of Plant	\$0.18				
Compression, Storage, & Dispensing	\$1.26	\$0.10		\$0.46	\$1.82
Compressor (Levelized)					\$0.73
Storage (Levelized)					\$0.94
Dispenser (Levelized)					\$0.03
Remainder of Station (Levelized)					\$0.11
Losses					\$0.00
Total	\$2.24	\$0.55	\$2.80	\$0.46	\$6.05

#### 9.2.2 Energy Use and Emissions Breakdown

Figures 9.2.5 and 9.2.6 show the WTW energy inputs and losses for the distributed electricity pathway.

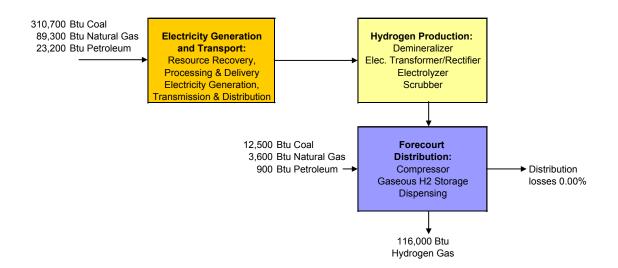
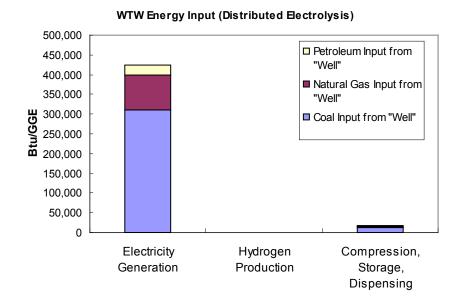
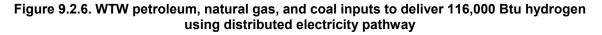


Figure 9.2.5. WTW energy inputs to deliver 116,000 Btu hydrogen to a vehicle using distributed electricity pathway





Figures 9.2.7 and 9.2.8 show the WTW emissions resulting from the delivery of 116,000 Btu hydrogen to a vehicle fuel tank using the distributed electricity pathway.

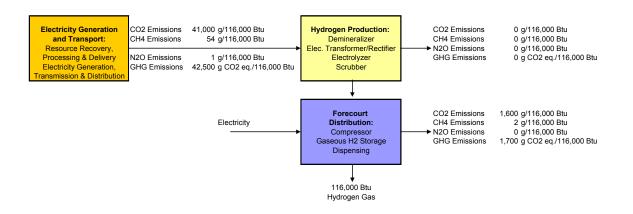


Figure 9.2.7. WTW emissions resulting from delivery of 116,000 Btu hydrogen using distributed electricity pathway

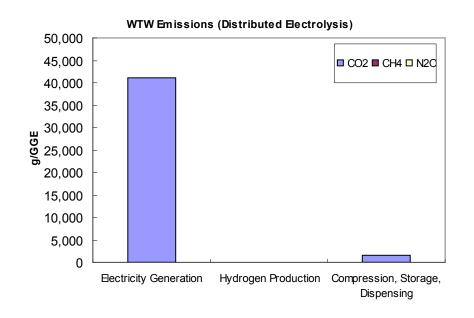


Figure 9.2.8. WTW CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O emissions resulting from delivery of 116,000 Btu hydrogen to a vehicle using distributed electricity pathway

### 9.2.3 Electricity Supply Scenarios

Assuming a total vehicle miles traveled in passenger vehicles of 2.78 trillion (Bureau of Transportation Statistics, 2007), the vehicle fuel economy used in this study (45 mpgge),

and a yield of hydrogen from electricity of 55 kWh electricity/kg  $H_2$ , the amount of electricity required to supply 100%, 75%, 50%, or 25% of light-duty vehicles with electrolysis-derived hydrogen fuel was calculated and compared to the projected 2030 U.S. electricity demand (United States Department of Energy, 2009), the 2008 U.S. electricity generation, and the 2008 U.S. electricity consumption estimates shown in Section 3.2 (Table 9.2.3).

	100%	75%	50%	25%	
	Penetration	Penetration	Penetration	Penetration	
	Current Technology - 45 mpgge FCV, hydrogen production yield 55 kWh/kg $H_2^{1}$				
Electricity Required (trillion kWh/yr)	3.5	2.6	1.7	0.9	
Percent of Projected 2030 U.S. Electricity Demand (5.8 trillion kWh) <sup>2</sup>	60%	45%	30%	15%	
Percent of 2008 U.S. Net Electricity Generation (4.1 trillion kWh) <sup>3</sup>	85%	64%	42%	21%	
Percent of Annual U.S. Consumption (3.7 trillion kWh) <sup>4</sup>	94%	70%	47%	23%	

<sup>1</sup>Calculation does not include energy or hydrogen losses.

<sup>2</sup> United States Department of Energy (2008)

<sup>3</sup> Energy Information Administration (2009e)

<sup>4</sup> Energy Information Administration (2009f)

No sample scenarios for domestic hydrogen production from grid electricity are included in the Hydrogen Posture Plan (United States Department of Energy, 2006).

### 9.2.4 Sensitivities

#### **Production Sensitivities**

The parameters used for this analysis are not known absolutely, so sensitivity analyses were performed to better understand the potential effects of that lack of knowledge on the final results. Several sensitivities were run on this pathway. They focused primarily on cost factors; however, several sensitivities also affect energy use and emissions. Figure 9.2.9 shows the effects of several production parameters on the pathway's levelized cost, and Table 9.2.4 shows the effect of production energy efficiency on WTW energy use and emissions.

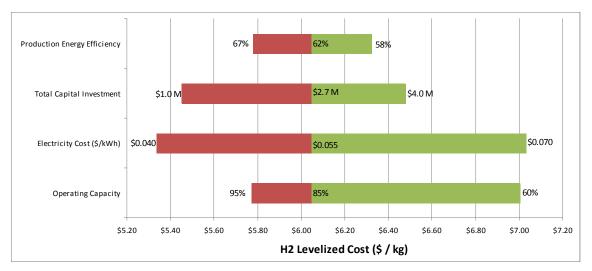


Figure 9.2.9. Production sensitivities for distributed electrolysis pathway

Table 9.2.4. The Effects of Production Energy Efficiency on Primary Energy and Emissions
from Distributed Natural Gas Pathway (current technology)

	58%	62%	67%
	Efficiency	Efficiency	Efficiency
WTW GHG Emissions (g/mile)	1,050	980	920
WTW Fossil Energy (Btu/mile)	10,400	9,800	9,200
WTW Petroleum Energy (Btu/mile)	570	540	500
WTW Total Energy (Btu/mile)	12,000	11,300	10,600

The assumed electrical grid mix also affects the energy use and emissions. If a hypothetical green grid mix that is 100% renewable energy (solar and wind) is used instead of the average grid mix (which was used for all other sensitivities), no fossil energy is used, nor are there any GHG emissions.

### 9.2.5 Advanced Conversion and Delivery/Distribution Technology

For advanced technology analysis, parameters were changed to future projections. The "Future" H2A production case was used, and HDSAM was modified to include achievement of delivery targets as defined in the Hydrogen, Fuel Cells and Infrastructure Technologies (HFCIT) Multi-Year Program Plan (MYPP). The vehicle fuel economy was increased to 65 mpgge. In addition, the electricity grid mix was updated to match EIA's projection for technology success in 2020 (51.1% coal, 19.2% natural gas, 18.5% nuclear, 1.9% residual oil, and 1.0% biomass, and 8.3% zero-carbon).

WTW results from cases with those modifications are shown in Table 9.2.5. The results do not match those in Hydrogen Program Record 9002 (2009) because the production yield and cost of electrolyzers were modified in the Program Record case.

	1	
Coal Input from "Well"	4050	Btu / mi
Natural Gas Input from "Well"	1330	Btu / mi
Petroleum Input from "Well"	220	Btu / mi
Fossil Energy Input from "Well"	5600	Btu / mi
WTW CO <sub>2</sub> Emissions	540	g / mi
WTW CH <sub>4</sub> Emissions	0.72	g / mi
WTW N <sub>2</sub> O Emissions	0.008	g / mi
WTW GHG Emissions	560	g / mi
Levelized Cost of Hydrogen (\$/kg)	\$4.93	2005 \$/kg
Levelized Cost of Hydrogen (\$/mi)	\$0.0759	2005 \$/mi

# Table 9.2.5. Well-to-Wheels Results for Distributed Electrolysis Pathway with Advanced Technology

Assuming a total vehicle miles traveled in passenger vehicles of 2.78 trillion (Bureau of Transportation Statistics, 2007), the vehicle fuel economy for advanced FCVs used in this study (65 mpgge), and a yield of hydrogen from electricity of 45 kWh electricity/kg H<sub>2</sub>, the amount of electricity required to supply 100%, 75%, 50%, or 25% of light-duty vehicles with electrolysis-derived hydrogen fuel was calculated and compared to the projected 2030 U.S. electricity demand (United States Department of Energy, 2009), the 2008 U.S. electricity generation, and the 2008 U.S. electricity consumption estimates shown in Section 3.2 (Table 9.2.6).

	100%	75%	50%	25%
	Penetration	Penetration	Penetration	Penetration
	Advan hydrog	ced Technologien production	gy – 65 mpgge yield 45 kWh	e FCV, /kg H₂ <sup>1</sup>
Electricity Required (trillion kWh/yr)	2.0	1.5	1.0	0.5
Percent of Projected 2030 U.S. Electricity Demand (5.8 trillion kWh) <sup>2</sup>	34%	25%	17%	8%
Percent of 2008 U.S. Net Electricity Generation (4.1 trillion kWh) <sup>3</sup>	48%	36%	24%	12%
Percent of Annual U.S. Consumption (3.7 trillion kWh) <sup>4</sup>	52%	39%	26%	13%

<sup>1</sup> Calculation does not include energy or hydrogen losses.

<sup>2</sup> United States Department of Energy (2008)

<sup>3</sup> Energy Information Administration (2009e)

<sup>4</sup> Energy Information Administration (2009f)

### 9.3 Central Biomass – Liquid Delivery

Figure 9.3.1 shows the major inputs, assumptions, and outputs for each of the subsystems considered in the well-to-tank analysis, including feedstock supply and hydrogen dispensing. The complete set of assumptions is detailed in Appendix C.

The well-to-pump and well-to-wheels cost of hydrogen, energy use, and emissions for the central biomass–liquid truck delivery pathway are summarized in Table 9.3.1.

The GHG emissions include carbon dioxide uptake of 112,500 g  $CO_2$  / dry ton biomass due to direct land use change. That uptake is in addition to carbon dioxide that is converted into plant matter and subsequently released during gasification and reforming. If the land use change had a neutral effect on GHG emissions, the WTP GHG emissions would increase by 1,700 CO<sub>2</sub> eq. / 116,000 Btu H<sub>2</sub>, and the WTW GHG emissions would increase by 38 CO<sub>2</sub> eq. / mile.

### 9.3.1 Cost Breakdown

Figure 9.3.2 shows the feedstock and energy price inputs and the resulting hydrogen production, delivery, and distribution costs for the central biomass–liquid truck delivery pathway. The financial assumptions used in this analysis are detailed in Section 8.0.

	Inputs	Graphic Depiction & A	ssumptions		Outputs
		Biomass Production &	Delivery	Biomass moisture content Woody biomass LHV	25% 16,811,019 Btu / dry ton
Coal Input from "Well" Natural Gas Input from "Well" Petroleum Input from "Well"	269 Btu / 116000Btu to Pump 427 Btu / 116000Btu to Pump 2,832 Btu / 116000Btu to Pump	Fraction of Woody Biomass (Remaining is H Grams of Nitrogen / dry ton biomass Grams of P2O5 / dry ton biomass Grams of K2O / dry ton biomass Herbicide use Insecticide use Average dist from farm to H2 production	erbaceous) 100% 709 189 331 24 g / dry ton 2 g / dry ton 40 miles	Biomass price at H2 production Levelized Cost of Biomass WTG CO2 Emissions WTG CH4 Emissions WTG N2O Emissions WTG GHG Emissions	\$37.96 2005 \$ / dry ton \$0.61 2005\$ / kg H2 distributed -26,911 g / 116000Btu to Pump 0 g / 116000Btu to Pump 0 g / 116000Btu to Pump -26,867 g CO2 eq./ 116000 Btu
Biomass consumption	12.8 kg (dry) / kg H2 produced			Hydrogen Output Pressure	300 psi
Natural gas consumption Electricity consumption	0.17 N m^3/kg H2 produced 0.98 kWh / kg H2	Hydrogen Produc	tion	Hydrogen Outlet Quality	98 minimum
Process Water Consumption	5.00 L / kg H2	Central plant design capacity	155,236 kg/day	Total capital investment	\$3.03 2005\$ / annual kg H2 (effective capacity)
Natural gas price Electricity price	\$0.340 2005\$ / N m^3 \$0.0555 2005 \$/kWh	Capacity factor Process energy efficiency	90% 46.0%	Levelized Electricity cost Levelized Natural Gas Cost	\$0.05 2005\$ / kg H2 produced \$0.06 2005\$ / kg H2 produced
Total Capital Investment	\$154,644,297 2005\$		S Mix	Levelized Other operating costs	\$0.32 2005\$ / kg H2 produced
		After-tax IRR	0	Levelized Cost of Prod (excl feedstock)	\$1.18 2005\$ / kg H2 distributed
		Assumed Plant Life	40	SMR CO2 Emissions	26,979 g / 116000Btu to Pump
Coal Input from "Well"	6,356 Btu / 116000Btu to Pump			SMR CH4 Emissions	3 g / 116000Btu to Pump
Natural Gas Input from "Well"	9,009 Btu / 116000Btu to Pump			SMR N2O Emissions	0 g / 116000Btu to Pump
Petroleum Input from "Well"	3,570 Btu / 116000Btu to Pump			SMR GHG Emissions	27,091 g CO2 eq./ 116000 Btu
Liquefaction electricity consumption	8.2 kWh / kg H2			Total capital investment	\$6.37 2005\$/annual kg delivered
Diesel consumption	7.3 gal / 1000 kg H2	Liquefaction and Truck	-Delivery	Levelized Electricity cost	\$0.49 2005\$ / kg H2 delivered
				Levelized Diesel cost	\$0.01 2005\$ / kg H2 delivered
		City Population Hydrogen Vehicle Penetration	1,247,364 people 50%	Levelized Labor cost Levelized Other operating costs	\$0.13 2005\$ / kg H2 delivered \$0.28 2005\$ / kg H2 delivered
Total Capital Investment	\$800,063,746	City hydrogen use	125,810,766 kg / yr	Ecvenzed outer operating costs	40.20 20004 / Kg H2 delivered
		Liquefaction efficiency	80.3%		
		Terminal Design Capacity Number of truck-trips required	3,532,139 kg H2 31,009 per year	Levelized Cost of Distribution	\$2.04 2005\$ / kg H2 distributed
		Truck hydrogen capacity	4,372 kg / truckload		
		One-way distance for delivery	49 miles	Delivery CO2 Emissions	6,708 g / 116000Btu to Pump
Coal Input from "Well" Natural Gas Input from "Well"	50,184 Btu / 116000Btu to Pump 14,462 Btu / 116000Btu to Pump	Hydrogen losses	10.1%	Delivery CH4 Emissions Delivery N2O Emissions	9 g / 116000Btu to Pump 0 g / 116000Btu to Pump
Petroleum Input from "Well"	4,778 Btu / 116000Btu to Pump			Delivery GHG Emissions	6,955 g CO2 eq./ 116000 Btu
		-			
Electricity consumption	3.04 kWh / kg H2			Hydrogen outlet pressure	6,250 psi
		Forecourt Distribu	tion		Btu (116,000 Btu/gal non-oxygenated
Electricity price	\$0.082 2005\$ / kWh			Basis Hydrogen Quantity	116,000 conventional unleaded gasoline)
				Total capital investment	\$5.85 2005\$/annual kg
		Number of Distribution Stations	270	Levelized Electricity cost	\$0.25 2005\$ / kg H2
		Energy efficiency Number of Compression Steps	92% 4	Levelized Cost of Distribution	\$1.05 2005\$ / kg H2 distributed
		Isentropic Efficiency	4 65%	Levenzed Cost of Distribution	φ1.00 2000φ7 kg Hz uistributeu
		Site storage	52% capacity	CSD CO2 Emissions	0 g / 116000Btu to Pump
Coal Input from "Well"	0 Btu / 116000Btu to Pump	Hydrogen losses	0.50%	CSD CH4 Emissions	0 g / 116000Btu to Pump
Natural Gas Input from "Well" Petroleum Input from "Well"	0 Btu / 116000Btu to Pump 0 Btu / 116000Btu to Pump	Hydrogen loss factor	1.005	CSD N2O Emissions CSD GHG Emissions	0 g / 116000Btu to Pump 0 g CO2 eg./ 116000 Btu

#### Figure 9.3.1. Central biomass-liquid truck delivery pathway summary of major inputs, assumptions, and outputs by subsystem

Coal, natural gas, and petroleum inputs from "well" include those used directly in the hydrogen production and delivery pathway as feedstocks and fuels; those used to produce electricity and other materials used in the pathway; and those used upstream of the pathway to recover, refine, and deliver the feedstock.

		Well-to-Pump	Well-to	o-Wheels
Coal Input from "Well"*	56,800	Btu / 116,000 Btu	100	Btu / mi
Natural Gas Input from "Well"*	23,900	Btu / 116,000 Btu	3,910	Btu / mi
Petroleum Input from "Well"*	11,200	Btu / 116,000 Btu	250	Btu / mi
Fossil Energy Input from "Well"*	91,900	Btu / 116,000 Btu	2,040	Btu / mi
WTP CO <sub>2</sub> Emissions <sup>*,**</sup>	6,800	g / 116,000 Btu	150	g / mi
WTP CH <sub>4</sub> Emissions*	12	g / 116,000 Btu	0	g / mi
WTP N <sub>2</sub> O Emissions	0	g / 116,000 Btu	0	g / mi
WTP GHG Emissions*	7,200	g CO <sub>2</sub> eq. / 116,000 Btu	160	g / mi
Levelized Cost of Hydrogen (\$/kg)	\$4.88	2005 \$/kg	\$0.1086	2005 \$/mi

 Table 9.3.1. Well-to-Pump and Well-to-Wheels Results for Central Biomass–Liquid Truck

 Delivery Pathway

\* Well-to-pump results are rounded to the nearest hundred; well-to-wheels results are rounded to the nearest ten.

<sup>\*\*</sup> Includes the carbon content of CO,  $CH_4$ , and volatile organic compound emissions that decompose in the atmosphere to  $CO_2$ 

Coal, natural gas, and petroleum inputs from "well" include those used directly in the hydrogen production and delivery pathway as feedstocks and fuels; those used to produce electricity and other materials used in the pathway; and those used upstream of the pathway to recover, refine, and deliver the feedstock.

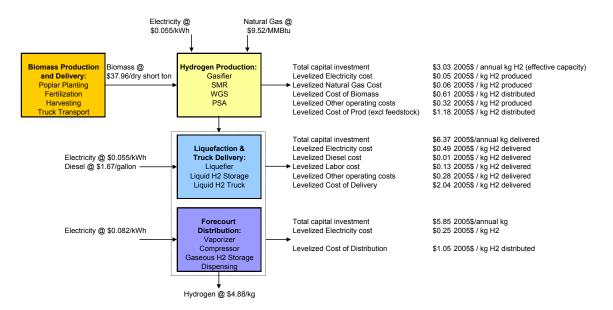
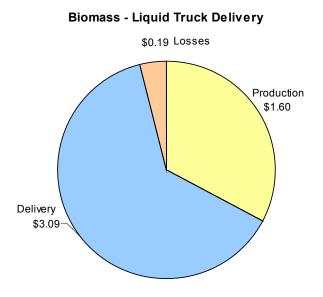


Figure 9.3.2. Cost analysis inputs and high-level results for central biomass–liquid truck delivery pathway

Figure 9.3.3 shows the contributions of hydrogen production, delivery, and losses to the levelized cost of hydrogen shown in Figure 9.3.2.



# Figure 9.3.3. Contribution of hydrogen production, delivery, and losses to the levelized cost of hydrogen for central biomass–liquid truck delivery pathway

Figure 9.3.4 and Table 9.3.2 show the breakdown of levelized costs for the central biomass–liquid truck delivery pathway.

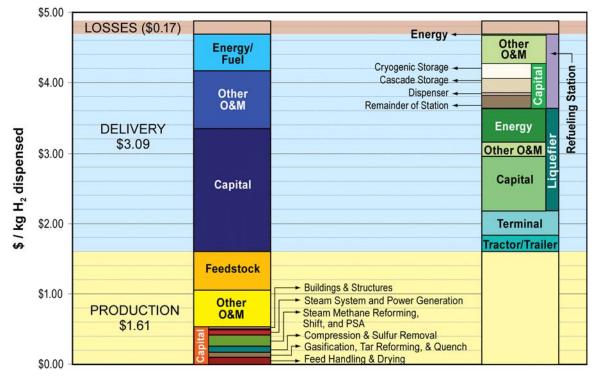


Figure 9.3.4. Breakdown of levelized costs for central biomass–liquid truck delivery pathway

		Other		Energy/	
Cost Component	Capital	O&M	Feedstock	Fuel	Total
Production	\$0.53	\$0.52	\$0.55		\$1.61
Feed Handling & Drying	\$0.10				
Gasification, Tar Reforming, & Quench	\$0.09				
Compression & Sulfur Removal	\$0.08				
SMR, WGS, and PSA	\$0.15				
Steam System and Power Generation	\$0.07				
Cooling Water and Other Utilities	\$0.02				
Buildings & Structures	\$0.03				
Delivery	\$1.76	\$0.82		\$0.52	\$3.09
Tractor/Trailer					\$0.24
Terminal					\$0.34
Liquefier	\$0.79	\$0.19		\$0.50	\$1.46
Gaseous Refueling Station	\$0.64	\$0.40		\$0.02	\$1.05
Cryogenic Storage	\$0.22				
Cascade Storage	\$0.20				
Dispenser	\$0.04				
Remainder of Station	\$0.18				
Losses					\$0.19
Total	\$2.29	\$1.34	\$0.55	\$0.52	\$4.88

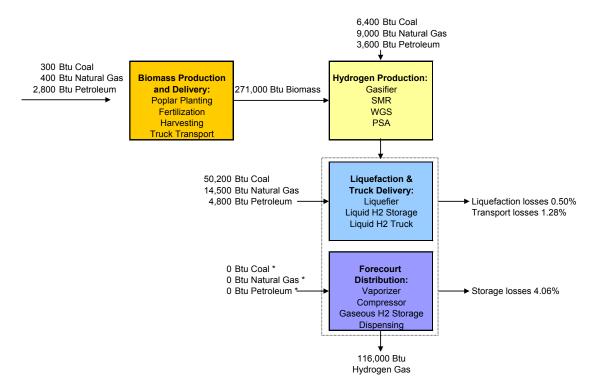
 Table 9.3.2. Contribution of Production and Delivery Processes to Levelized Hydrogen

 Cost for Central Biomass–Liquid Truck Delivery Pathway

### 9.3.2 Energy Use and Emissions Breakdown

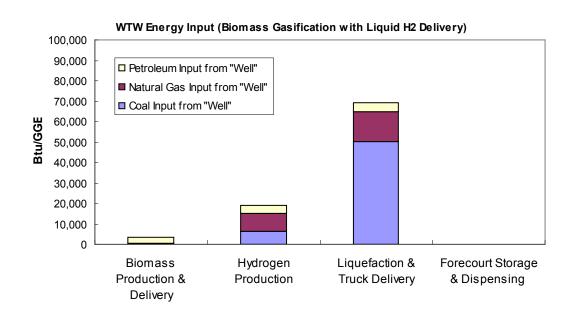
Figures 9.3.5 and 9.3.6 show the WTW energy inputs and losses for the central biomass–liquid truck delivery pathway.

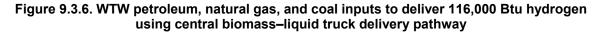
Figures 9.3.7 and 9.3.8 show the WTW emissions resulting from the delivery of 116,000 Btu hydrogen to a vehicle fuel tank using the central biomass–liquid truck delivery pathway. As noted above, carbon dioxide uptake within the plant matter and due to direct land use change is included in the biomass production section of the GHG calculations. If the land use change had a neutral effect on GHG emissions, the WTP GHG emissions would increase by 1,700 CO<sub>2</sub> eq. / 116,000 Btu H<sub>2</sub>, and the WTW GHG emissions would increase by 38 CO<sub>2</sub> eq. / mile.



\* Electricity (1,000 Btu) is used in the distribution of hydrogen to the pump. However, GREET does not model this electricity usage for the case of liquid hydrogen delivery to the station; thus, the coal, natural gas, and petroleum used in the production of the electricity are not shown here.

# Figure 9.3.5. WTW energy inputs to deliver 116,000 Btu hydrogen to a vehicle using central biomass–liquid truck delivery pathway





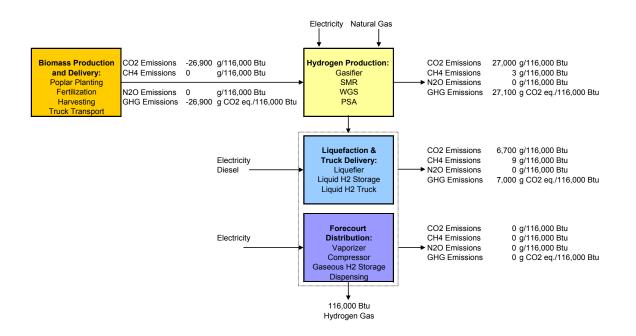
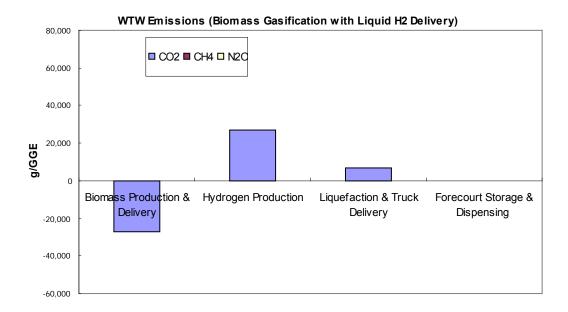
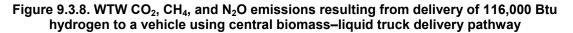


Figure 9.3.7. WTW emissions resulting from delivery of 116,000 Btu hydrogen using central biomass–liquid truck delivery pathway





#### 9.3.3 Biomass Supply Scenarios

Assuming a total vehicle miles traveled in passenger vehicles of 2.78 trillion (Bureau of Transportation Statistics, 2007), the vehicle fuel economy used in this study (45 mpgge), and a yield of hydrogen from biomass of 13 kg biomass (dry)/kg H<sub>2</sub>, the amount of biomass required to supply 100%, 75%, 50%, or 25% of light-duty vehicles with biomass-derived hydrogen fuel was calculated and compared to the projected U.S. biomass potential and the 2008 U.S. biomass consumption estimates shown in Section 3.3 (Table 9.3.3).

Table 9.3.3. Biomass Supply Scenarios for the Central Biomass–Liquid Truck Delivery
Pathway

	100%	75%	50%	25%	
	Penetration	Penetration	Penetration	Penetration	
	Current Technology – 45 mpgge FCV, hydrogen production yield 13 kg dry biomass/kg H <sub>2</sub> <sup>1</sup>				
Biomass Required (billion dry tons/yr)	0.89	0.67	0.45	0.22	
Percent of U.S. Biomass Potential (1.4 billion dry tons) <sup>2</sup>	65%	49%	33%	16%	
Percent of 2008 U.S. Wood Derived Fuels Consumption (0.12 billion dry					
tons) <sup>3</sup>	730%	550%	370%	180%	

<sup>1</sup> Calculation does not include energy or hydrogen losses.

<sup>2</sup> Perlack et al. (2005)

<sup>3</sup> Calculated from values in Energy Information Administration (2009k)

Table 9.3.4 compares a sample scenario for hydrogen production from biomass from DOE's Hydrogen Posture Plan (United States Department of Energy, 2006) to a 20% FCV penetration scenario using the assumptions in this study, as described above.

	DOE Hydrogen Posture Plan (2006)	Hydrogen Pathways Report (2009)*
Total Hydrogen Demand	64 million metric tons/yr	63.1 million metric tons/yr
Amount of Demand to Be Supplied by Resource	13 million metric tons/yr (20%)	12.6 million metric tons/yr (20%)
Biomass Needed for H <sub>2</sub>	140-280 million metric tons/yr	162 million metric tons/yr
Biomass Availability	512-1,300 million dry short tons/yr	1,368 million dry short tons/yr
Biomass Consumption (current)	190 million metric tons/yr	110 million metric tons/yr (using 16.8 million Btu/dry short ton LHV for biomass)
Increase in Biomass Consumption with H <sub>2</sub> Production	1.7-2.5 X	2.5 X

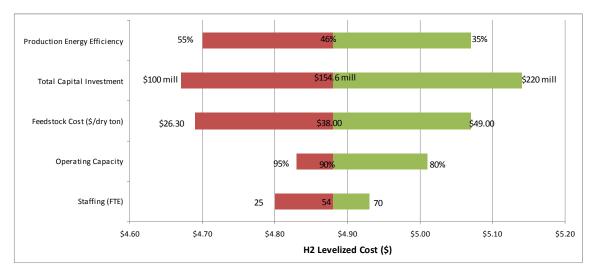
Table 9.3.4. Comparison of Biomass Supply Scenarios to Hydrogen Posture Plan

\* Calculated using the assumptions in Table 9.3.3 with 20% penetration of FCVs in light-duty vehicle market

### 9.3.4 Sensitivities

#### **Production Sensitivities**

Several sensitivities were run on the production portion of the central biomass–liquid truck delivery pathway. These sensitivities focused primarily on cost factors; however, several sensitivities also affect energy use and emissions. Figure 9.3.9 shows the effects of several production parameters on the pathway's levelized cost, and Table 9.3.5 shows the effects of varying production energy efficiency on WTW energy use and emissions.





	38%	48%	58%
	Efficiency	Efficiency	Efficiency
WTW GHG Emissions (g/mile)	150	160	170
WTW Fossil Energy (Btu/mile)	2,090	2,040	2,010
WTW Petroleum Energy (Btu/mile)	290	250	220
WTW Total Energy (Btu/mile)	9,930	8,170	6,980

 
 Table 9.3.5. The Effects of Production Energy Efficiency on Primary Energy and Emissions from Central Biomass–Liquid Truck Delivery Pathway

The assumed electrical grid mix also affects the energy use and emissions. Table 9.3.6 shows the differences in energy use and GHG emissions between the U.S. average grid mix (which was used for all other sensitivities) and a hypothetical green grid mix that is 100% renewable energy (solar and wind).

Table 9.3.6. The Effects of Grid Mix on Use of Primary Energy and Emissions from Central
Biomass–Liquid Truck Delivery Pathway

	U.S. Average Grid Mix	"Green" Grid Mix
WTW GHG Emissions (g/mile)	160	-13
WTW Fossil Energy (Btu/mile)	2,040	330
WTW Petroleum Energy (Btu/mile)	250	160
WTW Total Energy (Btu/mile)	8,170	7,010

#### **Delivery Sensitivities**

Delivery cost, energy use, and emissions are strongly dependent upon daily consumption of hydrogen within a city and delivery distance from the central facility to the city gate. Sensitivities were run to show some of those effects. Daily consumption was varied by keeping the city size constant and adjusting the penetration of hydrogen vehicles from the base case of 50%. Resulting consumption is shown in Figure 9.3.10.

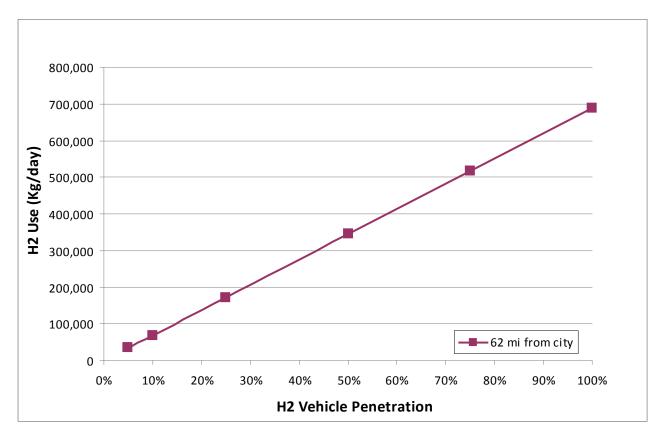


Figure 9.3.10. Daily hydrogen consumption versus hydrogen vehicle penetration for the central biomass–liquid truck delivery pathway

As expected there are economies of scale for higher penetration/hydrogen consumption, and the levelized cost of delivery decreases as the distance from the production plant to the city gate is shortened. Figures 9.3.11 and 9.3.12 show those economic effects (The figures show identical data but are organized differently.).

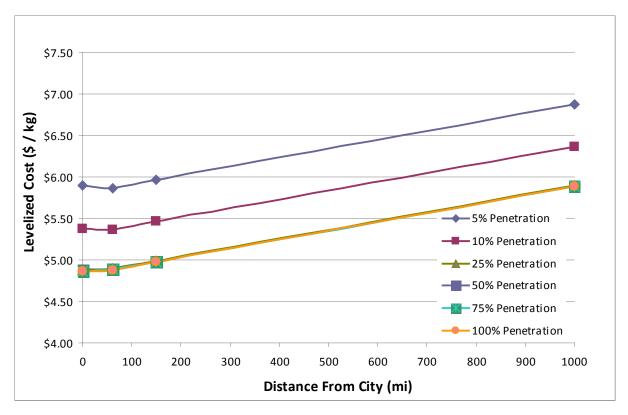
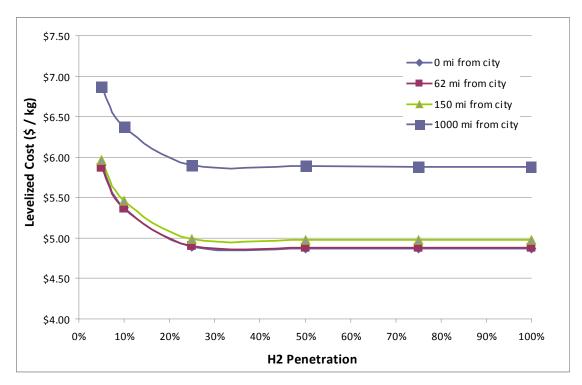


Figure 9.3.11. Levelized cost versus hydrogen vehicle penetration and distance between production facility and city gate for the central biomass–liquid truck delivery pathway





As Figure 9.3.12 shows, there is a \$0.20 increase in levelized cost when the production facility is assumed to be 150 miles from the city gate as compared to being at the city gate. There is a much larger levelized-cost increase when the distance is assumed to be 1,000 miles because the levelized cost of trucking increases with added distance due to additional driver time, additional fuel requirements, and an increased number of trucks and trailers required. Figure 9.3.13 shows the liquid truck portion of the levelized cost; note that the base case distance is 62 miles and that the truck's levelized cost is \$0.235 for all penetration levels at that distance. Because the city size is constant and the assumed station size is sufficient to utilize a full truckload at each station, each delivery has the same travel distance and takes the same amount of time within the city regardless of penetration level; therefore, the levelized cost within the city gate is constant for all penetration levels.

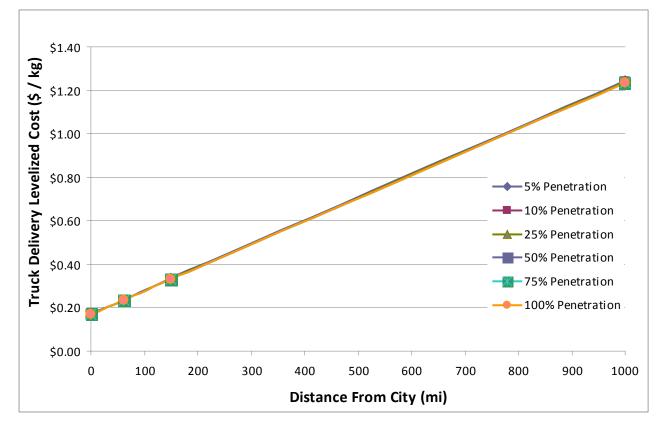


Figure 9.3.13. Truck levelized cost versus distance between production facility and city gate for the central biomass–liquid truck delivery pathway

The most notable feature in Figure 9.3.13 is the reduction in levelized cost as penetration increases to 25%. That levelized cost decrease is due to reduced cost of liquefaction, which is shown in Figure 9.3.14 (Liquefier cost is constant for all distances from the city.).

The majority of the liquefaction system's cost driver is capital (Table 9.3.2 shows that the capital accounts for  $0.79/kg H_2$  of the  $1.47/kg H_2$  total liquefaction cost.). As shown in Figure 9.3.15 capital-cost reduction drives the cost decrease as penetration increases.

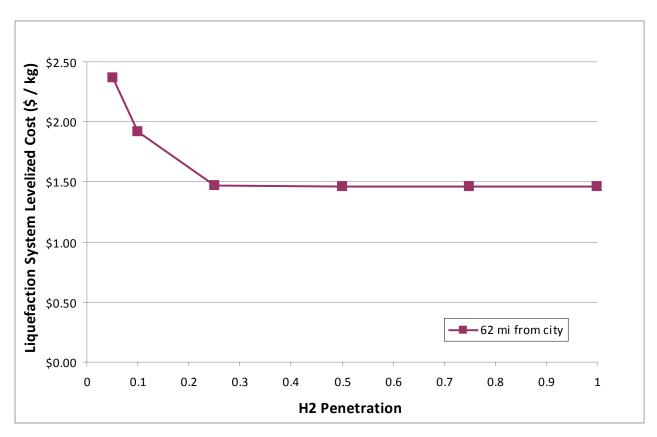


Figure 9.3.14. Liquefaction system levelized cost versus penetration for the central biomass–liquid truck delivery pathway

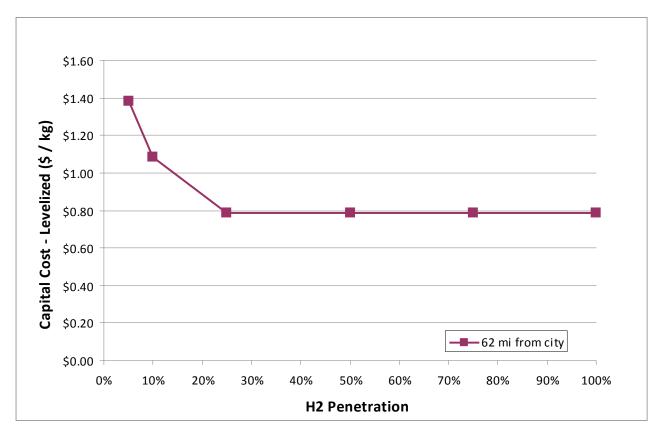


Figure 9.3.15. Liquefaction system capital cost (levelized) versus penetration for the central biomass–liquid truck delivery pathway

The additional cost variable for the liquefaction system levelized cost is the system efficiency because increased efficiency reduces the energy required for liquefaction. Figure 9.3.16 shows the effect of penetration (directly affecting liquefier size) on efficiency.

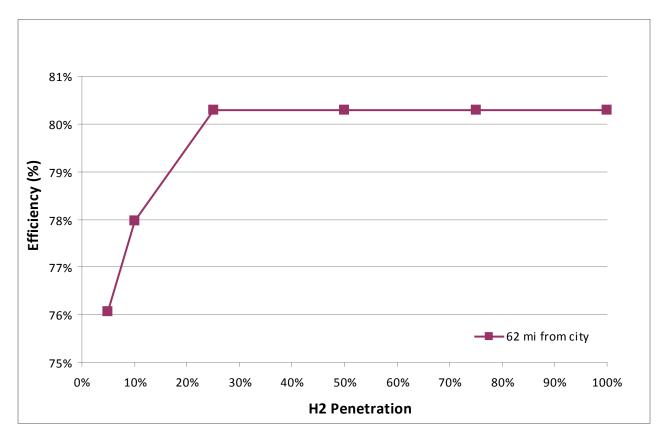


Figure 9.3.16. Liquefaction system efficiency versus penetration for the central biomass– liquid truck delivery pathway

The effects of penetration and distance between production facility and city-gate on WTW greenhouse gas emissions, WTW petroleum use, and WTW fossil energy use are shown in Figures 9.3.17, 9.3.18, and 9.3.19, respectively. In each case, the energy use and emissions decrease as liquefier efficiency increases with penetration and then plateaus as discussed above. Energy use and emissions are also reduced when the production facility is closer to the city gate because of reduced diesel use for trucking.

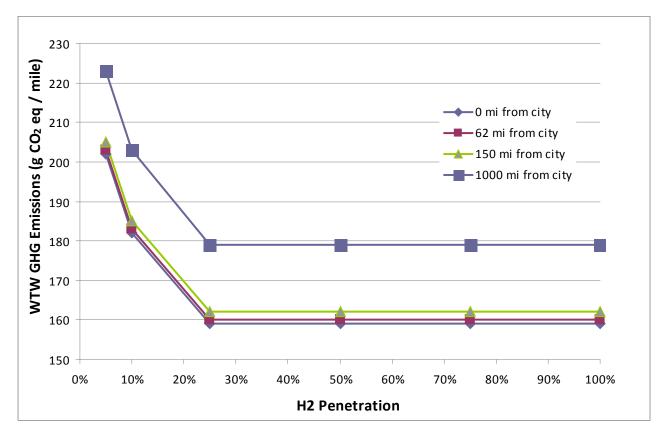


Figure 9.3.17. WTW greenhouse gas emissions versus penetration for the central biomass–liquid truck delivery pathway

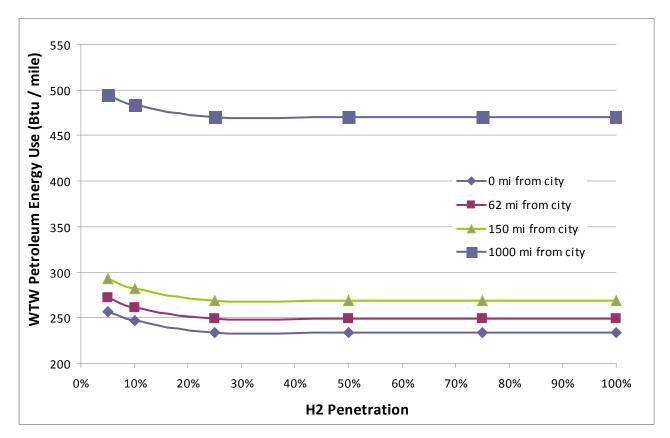


Figure 9.3.18. WTW petroleum use versus penetration for the central biomass–liquid truck delivery pathway

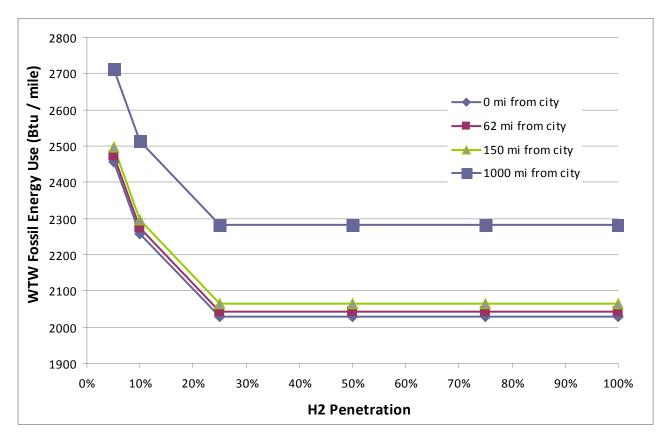


Figure 9.3.19. WTW fossil energy use versus penetration for the central biomass–liquid truck delivery pathway

### 9.4 Central Biomass – Pipeline Delivery

Figure 9.4.1 shows the major inputs, assumptions, and outputs for each of the subsystems considered in the well-to-tank analysis, including feedstock supply and hydrogen dispensing. The complete set of assumptions is detailed in Appendix D.

The well-to-pump and well-to-wheels cost of hydrogen, energy use, and emissions for the central biomass–pipeline delivery pathway are summarized in Table 9.4.1.

The GHG emissions include carbon dioxide uptake of 112,500 g  $CO_2$  / dry ton biomass due to direct land use change. That uptake is in addition to carbon dioxide that is converted into plant matter and subsequently released during gasification and reforming. If the land use change had a neutral effect on GHG emissions, the WTP GHG emissions would increase by 1,700 CO<sub>2</sub> eq. / 116,000 Btu H<sub>2</sub>, and the WTW GHG emissions would increase by 36 CO<sub>2</sub> eq. / mile.

#### 9.4.1 Cost Breakdown

Figure 9.4.2 shows the feedstock and energy price inputs and the resulting hydrogen production, delivery, and distribution costs for the central biomass–pipeline delivery pathway. The financial assumptions used in this analysis are detailed in Section 8.0.

Figure 9.4.3 shows the contributions of hydrogen production, delivery, and losses to the levelized cost of hydrogen shown in Figure 9.4.2.

Figure 9.4.4 and Table 9.4.2 show the breakdown of levelized costs for the central biomass–pipeline delivery pathway.

Inputs		Graphic Depiction & Assumptions	Outputs	
			Biomass moisture content	25%
		Biomass Production & Delivery	Woody biomass LHV	16,811,019 Btu / dry ton
		Fraction of Woody Biomass (Remaining is Herbaceous)     100%       Grams of Nitrogen / dry ton biomass     709       Grams of P205 / dry ton biomass     189       Grams of K20 / dry ton biomass     331	Biomass price at H2 production Levelized Cost of Biomass	\$37.96 2005 \$ / dry ton \$0.56 2005\$ / kg H2 distributed
		Herbicide use 24 g / dry ton	Levenzed Cost of Biomass	40.50 2005¢7 kg H2 distributed
Coal Input from "Well" Natural Gas Input from "Well"	261 Btu / 116000Btu to Pump 418 Btu / 116000Btu to Pump	Insecticide use 2 g / dry ton Average dist from farm to H2 production 40 miles	WTG CO2 Emissions WTG CH4 Emissions WTG N2O Emissions	-25,632 g / 116000Btu to Pump 0 g / 116000Btu to Pump 0 g / 116000Btu to Pump
Petroleum Input from "Well"	2,900 Btu / 116000Btu to Pump		WTG GHG Emissions	-25,590 g CO2 eq./ 116000 Btu
Biomass consumption Natural gas consumption Electricity consumption	12.8 kg (dry) / kg H2 produced 0.17 N m^3/kg H2 produced 0.98 kWh / kg H2	Hydrogen Production	Hydrogen Output Pressure Hydrogen Outlet Quality	300 psi 1
Process Water Consumption	5.00 L / kg H2	Central plant design capacity 155,236 kg/day	Total capital investment	2005\$ / annual kg H2 \$3.03 (effective capacity)
Natural gas price Electricity price	\$0.340 2005\$ / N m^3 \$0.055 2005 \$/kWh	Capacity factor 90% Process energy efficiency 46.0%	Electricity cost Natural Gas Cost	\$0.05 2005\$ / kg H2 produced \$0.06 2005\$ / kg H2 produced
Total Capital Investment	\$154,644,297 2005\$	Electricity Mix US Mix After-tax IRR 0 Assumed Plant Life 40	Other operating costs Levelized Cost of Prod (excl feedst	\$0.38 2005\$ / kg H2 produced \$1.07 2005\$ / kg H2 distributed
Coal Input from "Well"	6,063 Btu / 116000Btu to Pump		CO2 Emissions CH4 Emissions	25,733 g / 116000Btu to Pump 3 g / 116000Btu to Pump
Natural Gas Input from "Well" Petroleum Input from "Well"	8,598 Btu / 116000Btu to Pump 3,623 Btu / 116000Btu to Pump		N2O Emissions GHG Emissions	0 g / 116000Btu to Pump
	3,023 Bld / 110000Bld to Pump		GHG EINISSIONS	25,839 g CO2 eq./ 116000 Btu
Electricity consumption for compressor	0.56 kWh / kg H2		Total capital investment	\$3.51 2005\$/annual kg distributed
Electricity consumption for geo storage Total electricity consumption	0.01 kWh / kg H2 0.57 kWh / kg H2	Pipelines for Delivery	Electricity cost	\$0.03 2005\$ / kg H2
Electricity price for compressor Electricity price for geologic storage	\$0.056 2005\$ / kWh \$0.052 2005\$ / kWh	City Population 1,247,364 people Hydrogen Vehicle Penetration 50%	Levelized Cost of Delivery	\$0.92 2005\$ / kg H2 distributed
Electricity price for geologic storage	\$0.052 2005\$ / KWII	City hydrogen use 125,810,766 kg / yr	Levenzed Cost of Derivery	\$0.92 2005\$ / kg H2 distributed
		Distance from City to Production Facility 62 miles		
		Geologic storage capacity 3,762,787 kg H2 Trunk #1-line length 17 miles		
		Trunk #2-line length 40 miles		
Coal Input from "Well"	3,306 Btu / 116000Btu to Pump	Service-line length 1.1 miles / line Number of service lines 270	Delivery CO2 Emissions Delivery CH4 Emissions	436 g / 116000Btu to Pump 1 g / 116000Btu to Pump
Natural Gas Input from "Well"	950 Btu / 116000Btu to Pump	Hydrogen losses 1.12%	Delivery N2O Emissions	0 g / 116000Btu to Pump
Petroleum Input from "Well"	246 Btu / 116000Btu to Pump	Hydrogen loss factor 1.011	Delivery GHG Emissions	452 g CO2 eq./ 116000 Btu
Electricity consumption	3.04 kWh / kg H2		Hydrogen outlet pressure	6,250 psi
		Forecourt Distribution		Btu (116,000 Btu/gal non-
Electricity price	\$0.082 2005\$ / kWh		Basis Hydrogen Quantity	oxygenated conventional 116,000 unleaded gasoline)
		Number of Distribution Stations 270	Total capital investment Electricity cost	\$6.69 2005\$/annual kg \$0.25 2005\$ / kg H2
		Energy efficiency 92% Number of Compression Steps 4 Isentropic Efficiency 65%	Levelized Cost of Distribution	\$1.69 2005\$ / kg H2 distributed
		Site storage 69% capacity	CSD CO2 Emissions	2,333 g / 116000Btu to Pump
Coal Input from "Well" Natural Gas Input from "Well"	17,677 Btu / 116000Btu to Pump 5,078 Btu / 116000Btu to Pump	Hydrogen losses 0.50% Hydrogen loss factor 1.005	CSD CH4 Emissions CSD N2O Emissions	3 g / 116000Btu to Pump 0 g / 116000Btu to Pump
Petroleum Input from "Well"	1,317 Btu / 116000Btu to Pump	1.000 I.000	CSD GHG Emissions	2,419 g CO2 eq./ 116000 Btu

#### Figure 9.4.1. Central biomass-pipeline delivery pathway summary of major inputs, assumptions, and outputs by subsystem

Coal, natural gas, and petroleum inputs from "well" include those used directly in the hydrogen production and delivery pathway as feedstocks and fuels; those used to produce electricity and other materials used in the pathway; and those used upstream of the pathway to recover, refine, and deliver the feedstock.

	Well-to-Pump		Well-to-Wheels	
Coal Input from "Well"*	27,300	Btu / 116,000 Btu	610	Btu / mi
Natural Gas Input from "Well"*	15,000	Btu / 116,000 Btu	340	Btu / mi
Petroleum Input from "Well"*	8,100	Btu / 116,000 Btu	180	Btu / mi
Fossil Energy Input from "Well"*	50,400	Btu / 116,000 Btu	1,120	Btu / mi
WTP CO <sub>2</sub> Emissions***	2,900	g / 116,000 Btu	60	g / mi
WTP CH <sub>4</sub> Emissions	7	g / 116,000 Btu	0	g / mi
WTP N <sub>2</sub> O Emissions	0	g / 116,000 Btu	0	g / mi
WTP GHG Emissions*	3,100	g CO2 eq. / 116000 Btu	70	g / mi
Levelized Cost of Hydrogen (\$/kg)	\$4.23	2005 \$/kg	\$0.0941	2005 \$/mi

# Table 9.4.1. Well-to-Pump and Well-to-Wheels Results for Central Biomass–Pipeline Delivery Pathway

\* Well-to-pump results are rounded to the nearest hundred; well-to-wheels results are rounded to the nearest ten.

\*\* Includes the carbon content of CO,  $CH_4$ , and volatile organic compound emissions that decompose in the atmosphere to  $CO_2$ 

Coal, natural gas, and petroleum inputs from "well" include those used directly in the hydrogen production and delivery pathway as feedstocks and fuels; those used to produce electricity and other materials used in the pathway; and those used upstream of the pathway to recover, refine, and deliver the feedstock.

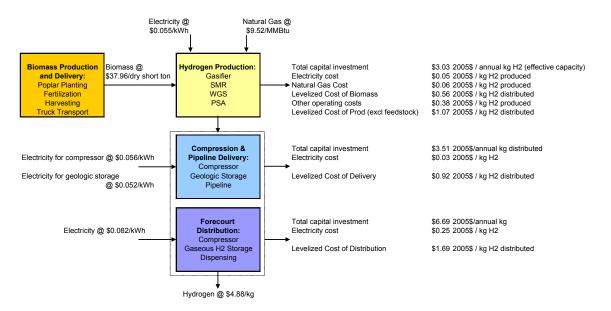


Figure 9.4.2. Cost analysis inputs and high-level results for central biomass–pipeline delivery pathway

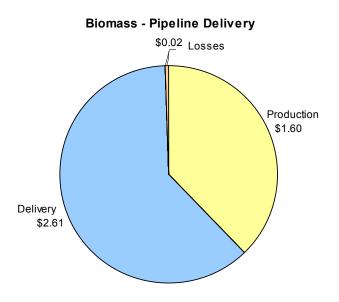


Figure 9.4.3. Contribution of hydrogen production, delivery, and losses to the levelized cost of hydrogen for central biomass–pipeline delivery pathway

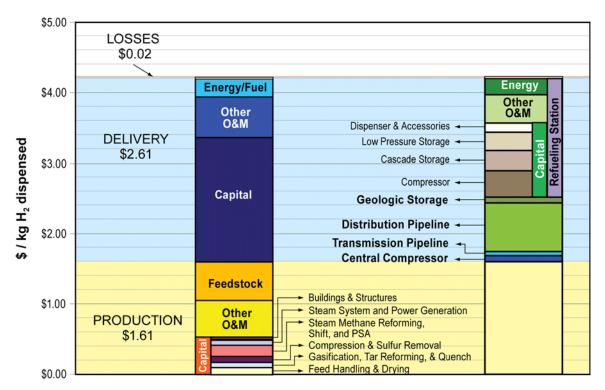


Figure 9.4.4. Breakdown of levelized costs for central biomass-pipeline delivery pathway

		Other		Energy/	
Cost Component	Capital	O&M	Feedstock	Fuel	Total
Production	\$0.53	\$0.52	\$0.55		\$1.61
Feed Handling & Drying	\$0.10				
Gasification, Tar Reforming, & Quench	\$0.09				
Compression & Sulfur Removal	\$0.08				
SMR, WGS, and PSA	\$0.15				
Steam System and Power Generation	\$0.07				
Cooling Water and Other Utilities	\$0.02				
Buildings & Structures	\$0.03				
Delivery	\$1.77	\$0.58		\$0.26	\$2.61
Central Compressor					\$0.08
Transmission Pipeline					\$0.07
Distribution Pipeline					\$0.70
Geologic Storage					\$0.08
Gaseous Refueling Station	\$1.06	\$0.41		\$0.23	\$1.69
Compressor	\$0.39				
Cascade Storage	\$0.29				
Low Pressure Storage	\$0.26				
Dispenser & Accessories	\$0.12				
Losses					\$0.02
Total	\$2.30	\$1.10	\$0.55	\$0.26	\$4.23

# Table 9.4.2. Contribution of Production and Delivery Processes to Levelized Hydrogen Cost for Central Biomass–Pipeline Delivery Pathway

### 9.4.2 Energy Use and Emissions Breakdown

Figures 9.4.5 and 9.4.6 show the WTW energy inputs and losses for the central biomass–pipeline delivery pathway.

Figures 9.4.7 and 9.4.8 show the WTW emissions resulting from the delivery of 116,000 Btu hydrogen to a vehicle fuel tank using the central biomass–pipeline delivery pathway.

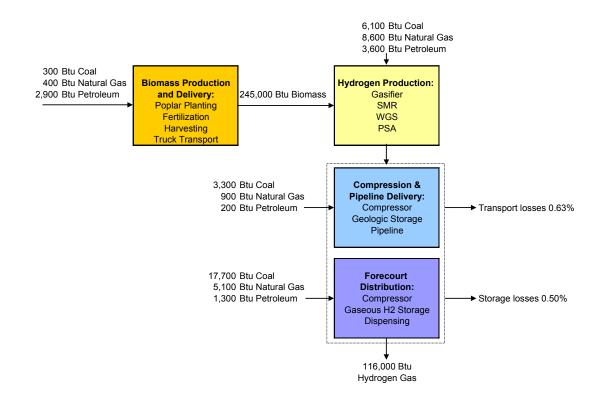


Figure 9.4.5. WTW energy inputs to deliver 116,000 Btu hydrogen to a vehicle using central biomass–pipeline delivery pathway

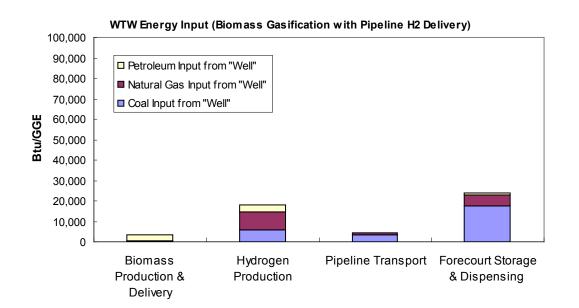


Figure 9.4.6. WTW petroleum, natural gas, and coal inputs to deliver 116,000 Btu hydrogen using central biomass-pipeline delivery pathway

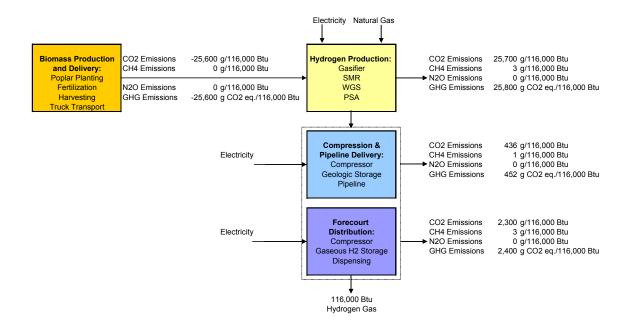


Figure 9.4.7. WTW emissions resulting from delivery of 116,000 Btu hydrogen using central biomass-pipeline delivery pathway

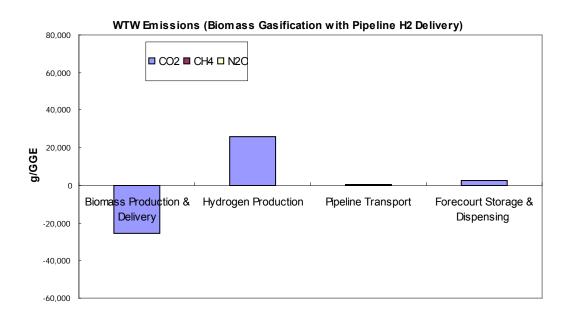


Figure 9.4.8. WTW CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O emissions resulting from delivery of 116,000 Btu hydrogen to a vehicle using central biomass–pipeline delivery pathway

### 9.4.3 Biomass Supply Scenarios

Because the feedstock, calculated yield, and assumed fuel economy for this pathway are the same as those for the central biomass–liquid truck delivery pathway, the supply scenarios are the same as those shown in Section 9.3.3.

### 9.4.4 Sensitivities

### Production Sensitivities

Several sensitivities were run on the production portion of the central biomass–pipeline delivery pathway. These sensitivities focused primarily on cost factors; however, several sensitivities also affect energy use and emissions. Figure 9.4.9 shows the effects of several production parameters on the pathway's levelized cost, and Table 9.4.3 shows the effects of varying production energy efficiency on WTW energy use and emissions.

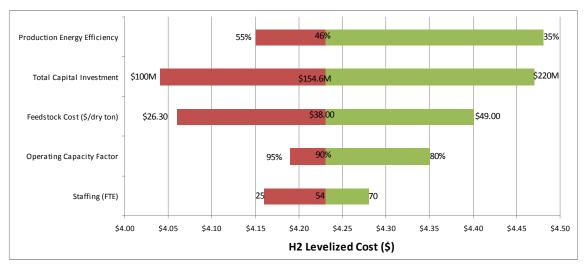


Figure 9.4.9. Production sensitivities for central biomass-pipeline delivery pathway

Table 9.4.3. The Effects of Production Energy Efficiency on Primary Energy and Emissions
from Central Biomass–Pipeline Delivery Pathway (current technology)

	35%	46%	55%
	Efficiency	Efficiency	Efficiency
WTW GHG Emissions (g/mile)	60	62	73
WTW Fossil Energy (Btu/mile)	1,190	1,040	1,100
WTW Petroleum Energy (Btu/mile)	240	170	160
WTW Total Energy (Btu/mile)	9,100	6,410	5,840

The assumed electrical grid mix also affects the energy use and emissions. Table 9.4.4 shows the differences in energy use and GHG emissions between the U.S. average grid mix (which was used for all other sensitivities) and a hypothetical green grid mix that is 100% renewable energy (solar and wind).

	U.S. Average	"Green"
	Grid Mix	Grid Mix
WTW GHG Emissions (g/mile)	62	-17
WTW Fossil Energy (Btu/mile)	1,040	220
WTW Petroleum Energy (Btu/mile)	170	130
WTW Total Energy (Btu/mile)	6,410	5,870

# Table 9.4.4. The Effects of Grid Mix on Use of Primary Energy and Emissions from Central Biomass–Pipeline Delivery Pathway

### Delivery Sensitivities

Delivery cost, energy use, and emissions are strongly dependent upon daily consumption of hydrogen within a city and delivery distance from the central facility to the city gate. Sensitivities were run to show some of those effects. Daily consumption was varied by keeping the city size constant and adjusting the penetration of hydrogen vehicles from the base case of 50%. Resulting consumption is shown in Figure 9.4.10.

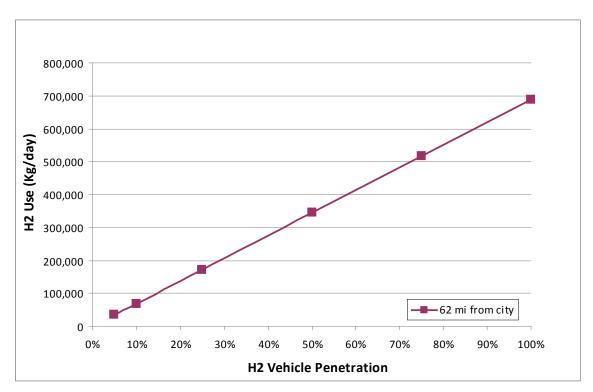
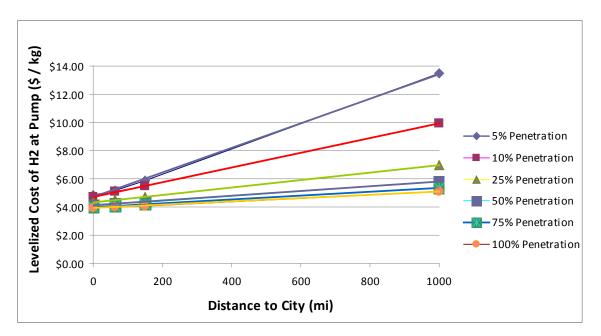


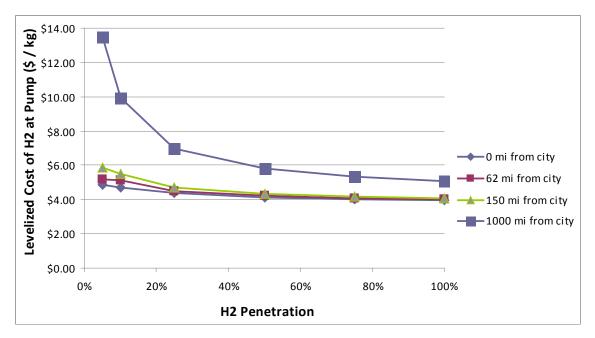
Figure 9.4.10. Daily hydrogen consumption versus hydrogen vehicle penetration for central biomass-pipeline delivery pathway

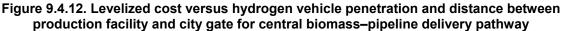
As expected there are economies of scale for higher penetration/hydrogen consumption, and the levelized cost of delivery decreases as the distance from the production plant to the city gate is shortened. Figures 9.4.11 and 9.4.12 show those economic effects (The figures show identical data but are organized differently.).



As Figure 9.4.12 shows, the cost increase due to distance from the city is more gradual with higher penetration because the cost of the transmission pipeline is shared more fully with increased demand.

Figure 9.4.11. Levelized cost versus hydrogen vehicle penetration and distance between production facility and city gate for central biomass-pipeline delivery pathway





The effects of penetration and distance between production facility and city gate on WTW greenhouse gas emissions, WTW petroleum use, and WTW fossil energy use are shown in Figures 9.4.13, 9.4.14, and 9.4.15. The overall emissions change little with penetration because the additional energy required for distance is minimal. That additional electricity requirement is for compression over the distance. The total energy required for compression varies little with increased penetration because the total electricity required to compress each kilogram of hydrogen is nearly constant for all penetrations. That is the case because only a small portion of the total energy is needed for compression for the pipelines (see Figure 9.4.1), and much of the pressure drop is in the service pipelines instead of the transmission or trunk pipelines.

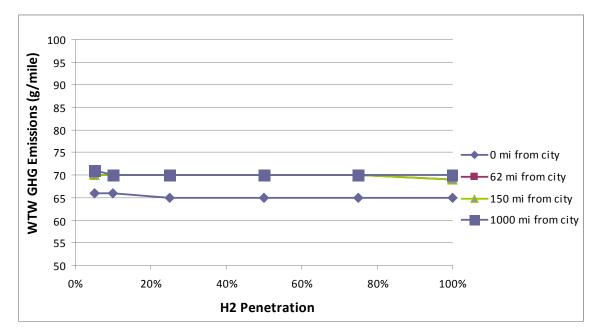


Figure 9.4.13. WTW greenhouse gas emissions versus penetration for central biomass– pipeline delivery pathway

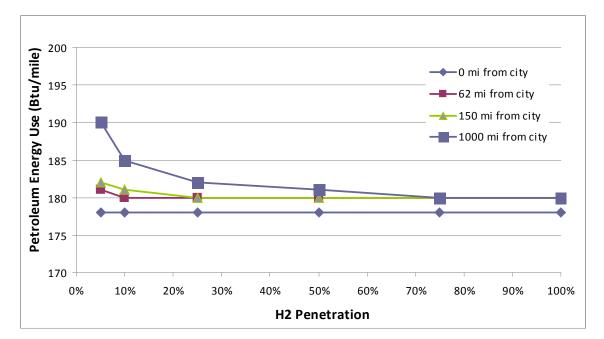


Figure 9.4.14. WTW petroleum use versus penetration for central biomass-pipeline delivery pathway

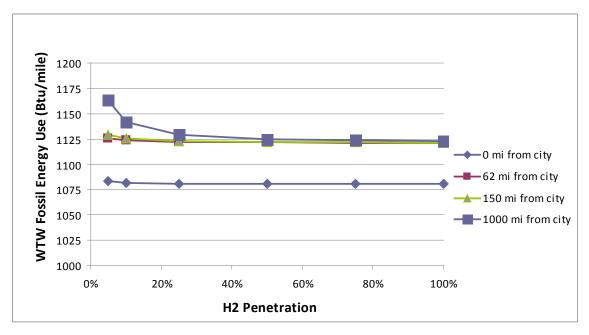


Figure 9.4.15. WTW fossil energy use versus penetration for central biomass–pipeline delivery pathway

#### 9.4.5 Advanced Conversion and Delivery / Distribution Technology

For advanced technology analysis, parameters were changed to future projections. The "Future" H2A production case was used, and HDSAM was modified to include achievement of delivery targets as defined in the HFCIT MYPP. The vehicle fuel economy was increased to 65 mpgge. In addition, the electricity grid mix was updated to match EIA's projection for technology success in 2020 (51.1% coal, 19.2% natural gas, 18.5% nuclear, 1.9% residual oil, 1.0% biomass, and 8.3% zero-carbon). Well-to-wheels results from cases with those modifications are shown in Table 9.4.5. The results match those in Hydrogen Program Record 9002 (2009).

# Table 9.4.5. Well-to-Wheels Results for Central Biomass–Pipeline Delivery Pathway with Advanced Technology

Coal Input from "Well" Natural Gas Input from "Well" Petroleum Input from "Well" Fossil Energy Input from "Well" WTW CO <sub>2</sub> Emissions WTW CH <sub>4</sub> Emissions WTW N <sub>2</sub> O Emissions	450 210 100 750 49 0.096 0.004	Btu / mi Btu / mi Btu / mi g / mi g / mi g / mi
WTW GHG Emissions	53	g / mi
Levelized Cost of Hydrogen (\$/kg) Levelized Cost of Hydrogen (\$/mi)	\$3.26 \$0.0501	2005 \$/kg 2005 \$/mi

Several sensitivities were run on the production portion of the central biomass-pipeline pathway. These sensitivities focused primarily on cost factors; however, several sensitivities also affect energy use and emissions. Figure 9.4.16 shows the effects of several production parameters on the pathway's levelized cost, and Table 9.4.6 shows the effects of varying production energy efficiency on WTW energy use and emissions.

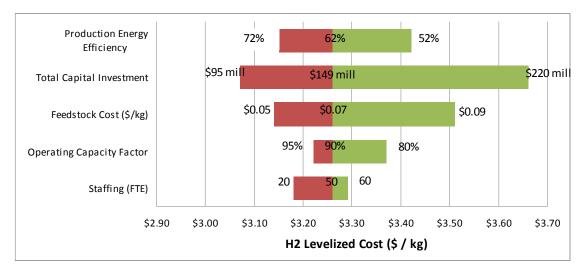


Figure 9.4.16. Production sensitivities for central biomass–pipeline delivery pathway with advanced technology

Table 9.4.6. The Effects of Production Energy Efficiency on Primary Energy and Emissions
from Central Biomass–Pipeline Delivery Pathway (advanced technology)

	52% Efficiency	62% Efficiency	72% Efficiency
WTW GHG Emissions (g/mile)	50	53	55
WTW Fossil Energy (Btu/mile)	770	750	730
WTW Petroleum Energy (Btu/mile)	112	96	84
WTW Total Energy (Btu/mile)	4,360	3,710	3,230

The assumed electrical grid mix also affects the energy use and emissions. Table 9.4.7 shows the differences in energy use and GHG emissions between the U.S. average grid mix (which was used for all other sensitivities) and a hypothetical green grid mix that is 100% renewable energy (solar and wind). The advanced conversion pathway has a higher conversion efficiency than the current technology, so less biomass is used; therefore, less carbon is removed from the atmosphere for each kilogram of hydrogen produced, and the "green" grid mix has GHG emissions less negative than that for the current technology.

	Projected U.S. Average Grid Mix	"Green" Grid Mix
WTW GHG Emissions (g/mile)	53	-9
WTW Fossil Energy (Btu/mile)	750	130
WTW Petroleum Energy (Btu/mile)	96	72
WTW Total Energy (Btu/mile)	3,710	3,300

 Table 9.4.7. The Effects of Grid Mix on Use of Primary Energy and Emissions from Central Biomass–Pipeline Delivery Pathway (advanced technology)

Assuming a total vehicle miles traveled in passenger vehicles of 2.78 trillion (Bureau of Transportation Statistics, 2007), the vehicle fuel economy for advanced FCVs used in this study (65 mpgge), and a yield of hydrogen from biomass of 9.8 kg biomass (dry)/kg H<sub>2</sub>, the amount of biomass required to supply 100%, 75%, 50%, or 25% of light-duty vehicles with biomass-derived hydrogen fuel was calculated and compared to the projected U.S. biomass potential and the 2008 U.S. biomass consumption estimates shown in Section 3.3 (Table 9.4.8).

Table 9.4.8. Biomass Supply Scenarios for the Advanced Central Biomass–Liquid Truck
Delivery Pathway

	100%	75%	50%	25%
	Penetration	Penetration	Penetration	Penetration
	Advanced Technology – 65 mpgge FCV, hydroge production yield 9.8 kg dry biomass/kg H <sub>2</sub> <sup>1</sup>			
Biomass Required (billion dry tons/yr)	0.47	0.35	0.24	0.12
Percent of U.S. Biomass Potential (1.4 billion dry tons) <sup>2</sup>	34%	26%	17%	9%
Percent of 2008 U.S. Wood Derived Fuels Consumption (0.12 billion dry				
tons) <sup>3</sup>	390%	290%	190%	100%

<sup>1</sup>Calculation does not include energy or hydrogen losses.

<sup>2</sup> Perlack et al. (2005)

<sup>3</sup> Calculated from values in Energy Information Administration (2009k)

Table 9.4.9 compares a sample scenario for hydrogen production from biomass from DOE's Hydrogen Posture Plan (United States Department of Energy, 2006) to a 20% FCV penetration scenario using the advanced technology assumptions in this section, as described above.

	DOE Hydrogen Posture Plan (2006)	Hydrogen Pathways Report (2009)*
Total Hydrogen Demand	64 million metric tons/yr	63.1 million metric tons/yr
Amount of Demand to Be Supplied by Resource	13 million metric tons/yr (20%)	12.6 million metric tons/yr (20%)
Biomass Needed for $H_2$	140-280 million metric tons/yr	64 million metric tons/yr
Biomass Availability	512-1,300 million dry short tons/yr	1,368 million dry short tons/yr
Biomass Consumption (current)	190 million metric tons/yr	110 million metric tons/yr (using 16.8 million Btu/dry short ton LHV for biomass)
Increase in Biomass Consumption with H <sub>2</sub> Production	1.7-2.5 X	1.6 X

# Table 9.4.9. Comparison of Biomass Supply Scenarios to Hydrogen Posture Plan forAdvanced Hydrogen Technology

\* Calculated using the assumptions in Table 9.4.8 with 20% penetration of FCVs in light-duty vehicle market

### 9.5 Central Natural Gas – Pipeline Delivery

Figure 9.5.1 shows the major inputs, assumptions, and outputs for each of the subsystems considered in the well-to-tank analysis, including feedstock supply and hydrogen dispensing. The complete set of assumptions is detailed in Appendix E.

The well-to-pump and well-to-wheels cost of hydrogen, energy use, and emissions for the central natural gas-pipeline delivery pathway are summarized in Table 9.5.1.

### 9.5.1 Cost Breakdown

Figure 9.5.2 shows the feedstock and energy price inputs and the resulting hydrogen production, delivery, and distribution costs for the central natural gas—pipeline delivery pathway. The financial assumptions used in this analysis are detailed in Section 8.0.

Figure 9.5.3 shows the contributions of hydrogen production, delivery, and losses to the levelized cost of hydrogen shown in Figure 9.5.2.

Figure 9.5.4 and Table 9.5.2 show the breakdown of levelized costs for the central natural gas–pipeline delivery pathway.

Inp	outs	Graphic Depiction & A	ssumptions	O	ıtguts
		NG Recovery, Processing, NG Recovery Efficiency NG emitted & combusted during recovery NG processing energy efficiency	97.2% 0.35% 97.2%	NG Quality at Delivery Av	verage of gas companies verage of gas companies \$0.243 2005 \$ / Nm^3
Coal Input from "Well" Natural Gas Input from "Well" Petroleum Input from "Well"	252 Btu / 116000Btu to Pump 122,927 Btu / 116000Btu to Pump 492 Btu / 116000Btu to Pump	NG emitted & combusted during processin NG emitted & combusted during transport NG transport distance Compression Reqs (stages & eff) average of	0.15% 0.14 g / MMBtu 500 miles f gas companies	NG Cost WTG CO2 Emissions WTG CH4 Emissions WTG N20 Emissions WTG GHG Emissions	\$0.958 2005\$ / kg H2 distributed 5,079 g / 116000Btu to Pump 139 g / 116000Btu to Pump 0 g / 116000Btu to Pump 8,571 g CO2 eq./ 116000 Btu
Natural gas consumption Electricity consumption Process (De-lonized) Water Consumption	4.50 N m^3/kg H2 produced 0.57 kWh / kg H2 12.70 L / kg H2	Hydrogen Product	ion	Hydrogen Output Pressure Hydrogen Outlet Quality 98	300 psi minimum
Cooling Water Consumption Electricity price Total Capital Investment	5.66 L / kg H2 \$0.0555 2005 \$/kWh \$180,543,901 2005\$	Central plant design capacity Capacity factor Process energy efficiency Electricity Mix After-tax IRR Assumed Plant Life	379,387 kg/day 90% 71.9% US Mix 10% 40 years	Total capital investment Electricity cost Other operating costs Levelized Cost of Prod (excl feedst	2005\$ / annual kg H2 \$1.45 (effective capacity) \$0.03 2005\$ / kg H2 produced \$0.08 2005\$ / kg H2 produced \$0.38 2005\$ / kg H2 distributed
Coal Input from "Well" Natural Gas Input from "Well" Petroleum Input from "Well"	3,440 Btu / 116000Btu to Pump 47,416 Btu / 116000Btu to Pump 433 Btu / 116000Btu to Pump			SMR CO2 Emissions SMR CH4 Emissions SMR N2O Emissions SMR GHG Emissions	10,233 g / 116000Btu to Pump 7 g / 116000Btu to Pump 0 g / 116000Btu to Pump 10,410 g CO2 eq./ 116000 Btu
Electricity consumption for compressor Electricity consumption for geo storage Total electricity consumption	0.56 kWh / kg H2 0.01 kWh / kg H2 0.57 kWh / kg H2	Pipelines for Deliv	ery	Total capital investment Electricity cost	\$3.51 2005\$/annual kg distributed \$0.03 2005\$ / kg H2
Electricity price for compressor Electricity price for geologic storage	\$0.056 2005\$ / WVh \$0.052 2005\$ / kWh	City Population Hydrogen Vehicle Penetration City hydrogen use Distance from City to Production Facility Geologic storage capacity Trunk #1-line length Trunk #2-line length	1,247,364 people 50% 125,810,766 kg / yr 62 miles 3,762,787 kg H2 17 miles 40 miles	Levelized Cost of Delivery	\$0.92 2005\$ / kg H2 distributed
Coal Input from "Well" Natural Gas Input from "Well" Petroleum Input from "Well"	3,306 Btu / 116000Btu to Pump 950 Btu / 116000Btu to Pump 246 Btu / 116000Btu to Pump	Service-line length Number of service lines Hydrogen losses	1.1 miles / line 270 1.12%	Delivery CO2 Emissions Delivery CH4 Emissions Delivery N2O Emissions Delivery GHG Emissions	436 g / 116000Btu to Pump 1 g / 116000Btu to Pump 0 g / 116000Btu to Pump 452 g CO2 eq./ 116000 Btu
Electricity consumption	3.04 kWh / kg H2			Hydrogen outlet pressure	6,250 psi
Electricity price	\$0.082 2005\$ / kWh	Forecourt Distribut	tion	Basis Hydrogen Quantity	Btu (116,000 Btu/gal non- oxygenated conventional 116,000 unleaded gasoline)
		Number of Distribution Stations Energy efficiency Number of Compression Steps Isentropic Efficiency	270 92% 4 65%	Total capital investment Electricity cost Levelized Cost of Distribution	\$6.69 2005\$/annual kg \$0.25 2005\$ / kg H2 \$1.69 2005\$ / kg H2 distributed
Coal Input from "Well" Natural Gas Input from "Well" Petroleum Input from "Well"	17,677 Btu / 116000Btu to Pump 5,078 Btu / 116000Btu to Pump 1,317 Btu / 116000Btu to Pump	Site storage Hydrogen losses	69% capacity 0.50%	CSD CO2 Emissions CSD CH4 Emissions CSD N2O Emissions CSD GHG Emissions	2,333 g / 116000Btu to Pump 3 g / 116000Btu to Pump 0 g / 116000Btu to Pump 2,419 g CO2 eq./ 116000 Btu

#### Figure 9.5.1. Central natural gas-pipeline delivery pathway summary of major inputs, assumptions, and outputs by subsystem

Coal, natural gas, and petroleum inputs from "well" include those used directly in the hydrogen production and delivery pathway as feedstocks and fuels; those used to produce electricity and other materials used in the pathway; and those used upstream of the pathway to recover, refine, and deliver the feedstock.

	Well-to-Pump		Well-te	o-Wheels
Coal Input from "Well"*	24,700	Btu / 116,000 Btu	550	Btu / mi
Natural Gas Input from "Well"*	176,400	Btu / 116,000 Btu	3,920	Btu / mi
Petroleum Input from "Well"*	2,500	Btu / 116,000 Btu	55	Btu / mi
Fossil Energy Input from "Well"*	203,500	Btu / 116,000 Btu	4,530	Btu / mi
WTP CO <sub>2</sub> Emissions <sup>*,**</sup>	13,600	g / 116,000 Btu	300	g / mi
WTP CH <sub>4</sub> Emissions	26	g / 116,000 Btu	1	g / mi
WTP N <sub>2</sub> O Emissions	0	g / 116,000 Btu	0	g / mi
WTP GHG Emissions*	14,300	g CO2 eq. / 116000 Btu	320	g / mi
Levelized Cost of Hydrogen (\$/kg)	\$3.95	2005 \$/kg	\$0.0878	2005 \$/mi

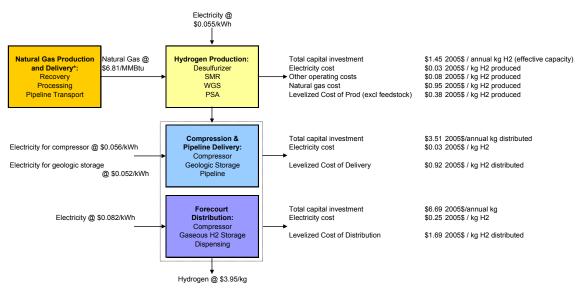
# Table 9.5.1. Well-to-Pump and Well-to-Wheels Results for Central Natural Gas–Pipeline Delivery Pathway

\* Well-to-pump results are rounded to the nearest hundred; well-to-wheels results are rounded to

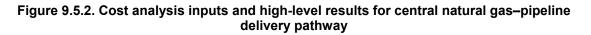
the nearest ten.

\*\* Includes the carbon content of CO,  $CH_4$ , and volatile organic compound emissions that decompose in the atmosphere to  $CO_2$ 

Coal, natural gas, and petroleum inputs from "well" include those used directly in the hydrogen production and delivery pathway as feedstocks and fuels; those used to produce electricity and other materials used in the pathway; and those used upstream of the pathway to recover, refine, and deliver the feedstock.



\* This box represents the natural gas that is converted to hydrogen or otherwise consumed/lost as a process feedstock. It does not include natural gas used as a heating fuel or to produce electricity.



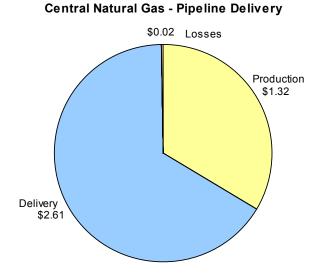


Figure 9.5.3. Contribution of hydrogen production, delivery, and losses to the levelized cost of hydrogen from central natural gas-pipeline delivery pathway

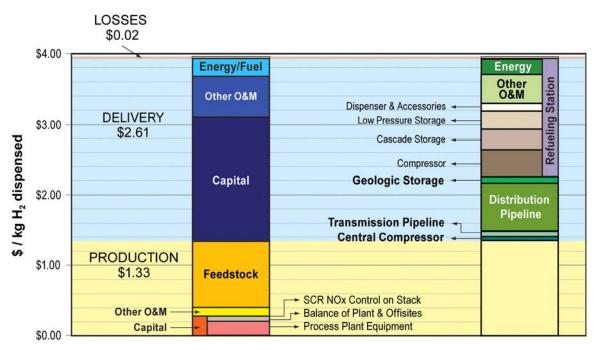


Figure 9.5.4. Breakdown of levelized costs for central natural gas-pipeline delivery pathway

		Other		Energy/	
Cost Component	Capital	O&M	Feedstock	Fuel	Total
Production	\$0.26	\$0.12	\$0.95		\$1.33
Process Plant Equipment	\$0.18				
Balance of Plant and Offsites	\$0.07				
SCR NOx Control on Stack	\$0.00				
Delivery	\$1.77	\$0.58		\$0.26	\$2.61
Central Compressor					\$0.08
Transmission Pipeline					\$0.07
Distribution Pipeline					\$0.70
Geologic Storage					\$0.08
Gaseous Refueling Station	\$1.06	\$0.41		\$0.23	\$1.69
Compressor	\$0.39				
Cascade Storage	\$0.29				
Low Pressure Storage	\$0.26				
Dispenser & Accessories	\$0.12				
Losses					\$0.02
Total	\$2.03	\$0.70	\$0.95	\$0.26	\$3.95

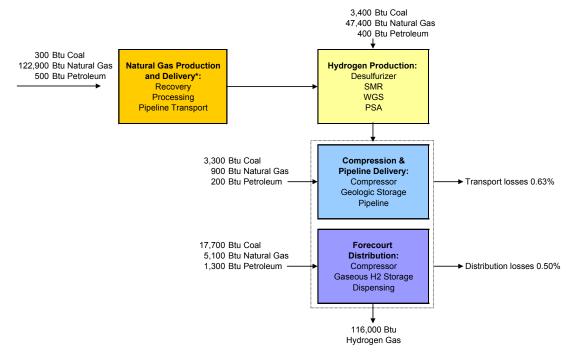
 Table 9.5.2. Contribution of Production and Delivery Processes to Levelized Hydrogen

 Cost for Central Natural Gas–Pipeline Delivery Pathway

### 9.5.2 Energy Use and Emissions Breakdown

Figures 9.5.5 and 9.5.6 show the WTW energy inputs and losses for the central natural gas–pipeline delivery pathway.

Figures 9.5.7 and 9.5.8 show the WTW emissions resulting from the delivery of 116,000 Btu hydrogen to a vehicle fuel tank using the central natural gas—pipeline delivery pathway. The WTW energy inputs to natural gas production and delivery include those necessary to produce 116,000 Btu of natural gas for reforming. Additional WTW energy inputs for natural gas needed for heating and lost in reforming are reported as inputs to hydrogen production.



\* This box represents the natural gas that is converted to hydrogen or otherwise consumed/lost as a process feedstock. It does not include natural gas used as a heating fuel or to produce electricity.

Figure 9.5.5. WTW energy inputs to deliver 116,000 Btu hydrogen to a vehicle using central natural gas-pipeline delivery pathway

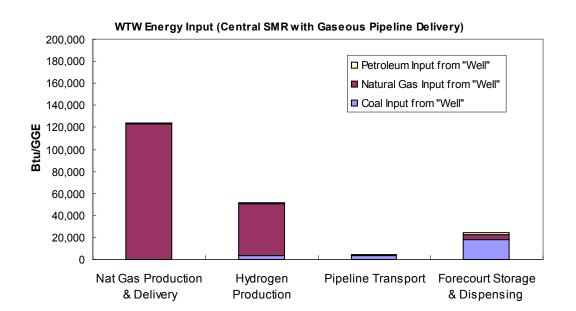
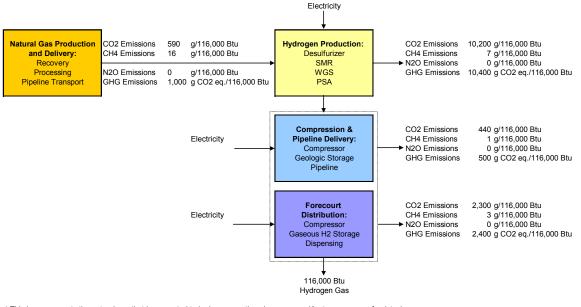
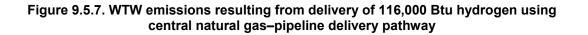


Figure 9.5.6. WTW petroleum, natural gas, and coal inputs to deliver 116,000 Btu hydrogen using central natural gas–pipeline delivery pathway



\* This box represents the natural gas that is converted to hydrogen or otherwise consumed/lost as a process feedstock. It does not include natural gas used as a heating fuel or to produce electricity.



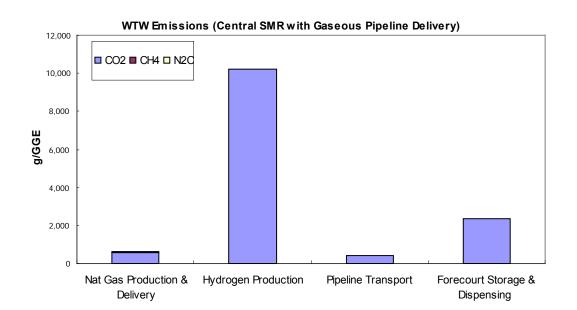


Figure 9.5.8. WTW CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O emissions resulting from delivery of 116,000 Btu hydrogen to a vehicle using central natural gas–pipeline delivery pathway

### 9.5.3 Natural Gas Supply Scenarios

Because the feedstock, calculated yield, and assumed fuel economy for this pathway are the same as those for the distributed natural gas pathway, the supply scenarios are the same as those shown in Section 9.1.3.

### 9.5.4 Sensitivities

### Production Sensitivities

Several sensitivities were run on the production portion of the central biomass-pipeline delivery pathway. These sensitivities focused primarily on cost factors; however, several sensitivities also affect energy use and emissions. Figure 9.5.9 shows the effects of several production parameters on the pathway's levelized cost, and Table 9.5.3 shows the effects of varying production energy efficiency on WTW energy use and emissions.

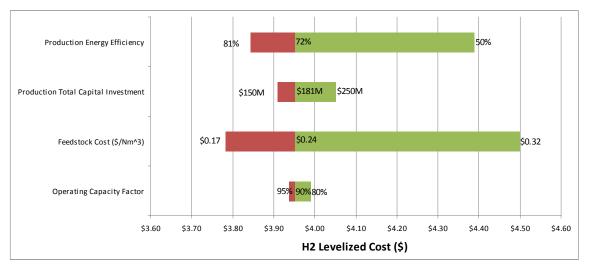


Figure 9.5.9. Production sensitivities for central natural gas-pipeline delivery pathway

Table 9.5.3. The Effects of Production Energy Efficiency on Primary Energy and Emissions
from Central Natural Gas–Pipeline Delivery Pathway (current technology)

	50%	72%	81%
	Efficiency	Efficiency	Efficiency
WTW GHG Emissions (g/mile)	430	320	290
WTW Fossil Energy (Btu/mile)	6,200	4,500	4,100
WTW Petroleum Energy (Btu/mile)	62	55	54
WTW Total Energy (Btu/mile)	6,400	4,700	4,200

The assumed electrical grid mix also affects the energy use and emissions. Table 9.5.4 shows the differences in energy use and GHG emissions between the U.S. average grid mix (which was used for all other sensitivities) and a hypothetical green grid mix that is 100% renewable energy (solar and wind).

	U.S. Average	"Green"
	Grid Mix	Grid Mix
WTW GHG Emissions (g/mile)	320	240
WTW Fossil Energy (Btu/mile)	4,500	3,800
WTW Petroleum Energy (Btu/mile)	55	14
WTW Total Energy (Btu/mile)	4,700	4,200

## Table 9.5.4. The Effects of Grid Mix on Use of Primary Energy and Emissions from Central Natural Gas–Pipeline Delivery Pathway

### Delivery Sensitivities

Pipeline delivery sensitivities are reported for the biomass production scenario in Section 9.4.4. The effects of the sensitivities will be the same for all pipeline delivery scenarios.

### 9.5.5 Advanced Conversion and Delivery/Distribution Technology

For advanced technology analysis, parameters were changed to future projections. The "Future" H2A production case was used, and HDSAM was modified to include achievement of delivery targets as defined in the Hydrogen, Fuel Cells and Infrastructure Technologies (HFCIT) Multi-Year Program Plan (MYPP). The vehicle fuel economy was increased to 65 mpgge. In addition, the electricity grid mix was updated to match EIA's projection for technology success in 2020 (51.1% coal, 19.2% natural gas, 18.5% nuclear, 1.9% residual oil, and 1.0% biomass, and 8.3% zero-carbon).

WTW results from cases with those modifications are shown in Table 9.5.5. Corresponding results were not published in Hydrogen Program Record 9002 (2009).

Coal Input from "Well"	340	Btu / mi
Natural Gas Input from "Well"	2760	Btu / mi
Petroleum Input from "Well"	40	Btu / mi
Fossil Energy Input from "Well"	3140	Btu / mi
WTW CO <sub>2</sub> Emissions	208	g / mi
WTW CH <sub>4</sub> Emissions	0.41	g / mi
WTW N <sub>2</sub> O Emissions	0.001	g / mi
WTW GHG Emissions	220	g / mi
Levelized Cost of Hydrogen (\$/kg)	\$2.96	2005 \$/kg
Levelized Cost of Hydrogen (\$/mi)	\$0.0456	2005 \$/mi

Table 9.5.5. Well-to-Wheels Results for central natural gas-pipeline pathway with advanced technology

### 9.6 Central Wind Electricity – Pipeline Delivery

Figure 9.6.1 shows the major inputs, assumptions, and outputs for each of the subsystems considered in the well-to-tank analysis, including feedstock supply and hydrogen dispensing. The complete set of assumptions is detailed in Appendix F.

The well-to-pump and well-to-wheels cost of hydrogen, energy use, and emissions for the central wind electricity-pipeline delivery pathway are summarized in Table 9.6.1.

### 9.6.1 Cost Breakdown

Figure 9.6.2 shows the feedstock and energy price inputs and the resulting hydrogen production, delivery, and distribution costs for the central wind electricity–pipeline delivery pathway. The financial assumptions used in this analysis are detailed in Section 8.0.

Figure 9.6.3 shows the contributions of hydrogen production, delivery, and losses to the levelized cost of hydrogen shown in Figure 9.6.2.

Figure 9.6.4 and Table 9.6.2 show the breakdown of levelized costs for the central wind electricity–pipeline delivery pathway.

Inputs		Graphic Depiction & Assum	otions	Ou	tputs
		Wind Electricity Wind-generated electricity on the grid is assumed. The electrolyzers are not necessarily co-located with t	he wind farm.		•
				Electricity price at H2 production Levelized Cost of Wind Electricity WTG CO2 Emissions	\$0.055 2005 \$ / short ton \$2.99 2005\$ / kg H2 distributed 0 g / 116000Btu to Pump
Coal Input from "Well" Natural Gas Input from "Well" Petroleum Input from "Well"	0 Btu / 116000Btu to Pump 0 Btu / 116000Btu to Pump 0 Btu / 116000Btu to Pump			WTG CH4 Emissions WTG N2O Emissions WTG GHG Emissions	0 g / 116000Btu to Pump 0 g / 116000Btu to Pump 0 g CO2 eq./ 116000 Btu
Electricity consumption	53.48 kWh / kg H2			Hydrogen Output Pressure	300 psi
		Hydrogen Production			2005# ( 22222 1/2 1/2
Process Water Consumption Cooling Water Consumption	11.1 L / kg H2 1112 L / kg H2 675 \$ / kW	Capacity factor Process energy efficiency Electricity Mix Wind Elec		Total capital investment Electricity cost Other operating costs Levelized Cost of Prod (excl feedst	2005\$ / annual kg H2 \$5.96 (effective capacity) \$2.96 2005\$ / kg H2 produced \$0.38 2005\$ / kg H2 produced \$1.56 2005\$ / kg H2 distributed
Total Capital Investment	\$110,432,050 2005\$	After-tax IRR Assumed Plant Life	10% 40		
Coal Input from "Well" Natural Gas Input from "Well" Petroleum Input from "Well"	0 Btu / 116000Btu to Pump 0 Btu / 116000Btu to Pump 0 Btu / 116000Btu to Pump			H2 Prod CO2 Emissions H2 Prod CH4 Emissions H2 Prod N2O Emissions H2 Prod GHG Emissions	0 g / 116000Btu to Pump 0 g / 116000Btu to Pump 0 g / 116000Btu to Pump 0 g CO2 eq./ 116000 Btu
Electricity consumption for compressor	0.56 kWh / kg H2			Total capital investment	\$3.51 2005\$/annual kg distributed
Electricity consumption for geo storage Total electricity consumption Electricity price for compressor Electricity price for geologic storage	0.01 kWh / kg H2 0.57 kWh / kg H2 \$0.056 2005\$ / kWh \$0.052 2005\$ / kWh	Hydrogen Vehicle Penetration City hydrogen use 125,81 Distance from City to Production Facility	47,364 people 50% 10,766 kg / yr 62 miles 27.27 L kp	Electricity cost	\$0.03 2005\$ / kg H2 \$0.92 2005\$ / kg H2 distributed
Coal Input from "Well" Natural Gas Input from "Well"	3,307 Btu / 116000Btu to Pump 949 Btu / 116000Btu to Pump	Trunk #1-line length Trunk #2-line length Service-line length Number of service lines	52,787 kg H2 17 miles 40 miles 1.1 miles / line 270 1.12%	Delivery CO2 Emissions Delivery CH4 Emissions Delivery N2O Emissions	436 g / 116000Btu to Pump 1 g / 116000Btu to Pump 0 g / 116000Btu to Pump
Petroleum Input from "Well"	246 Btu / 116000Btu to Pump		1.011	Delivery GHG Emissions	453 g CO2 eq./ 116000 Btu
Electricity consumption	3.04 kWh / kg H2			Hydrogen outlet pressure	6,250 psi
Electricity price	\$0.082 2005\$ / kWh	Forecourt Distribution		Basis Hydrogen Quantity	Btu (116,000 Btu/gal non- oxygenated conventional 116,000 unleaded gasoline)
		Number of Distribution Stations Energy efficiency	270 92%	Total capital investment Electricity cost	\$6.69 2005\$/annual kg \$0.25 2005\$ / kg H2
		Number of Compression Steps Isentropic Efficiency Site storage	4 65% 69% capacity	Levelized Cost of Distribution CSD CO2 Emissions	\$1.69 2005\$ / kg H2 distributed 2,333 g / 116000Btu to Pump
Coal Input from "Well" Natural Gas Input from "Well" Petroleum Input from "Well"	17,681 Btu / 116000Btu to Pump 5,076 Btu / 116000Btu to Pump 1,317 Btu / 116000Btu to Pump	Hydrogen losses	0.50% 1.005	CSD CH4 Emissions CSD N2O Emissions CSD GHG Emissions	3 g / 116000Btu to Pump 0 g / 116000Btu to Pump 2,419 g CO2 eq./ 116000 Btu

#### Figure 9.6.1. Central wind electricity-pipeline delivery pathway summary of major inputs, assumptions, and outputs by subsystem

Coal, natural gas, and petroleum inputs from "well" include those used directly in the hydrogen production and delivery pathway as feedstocks and fuels; those used to produce electricity and other materials used in the pathway; and those used upstream of the pathway to recover, refine, and deliver the feedstock.

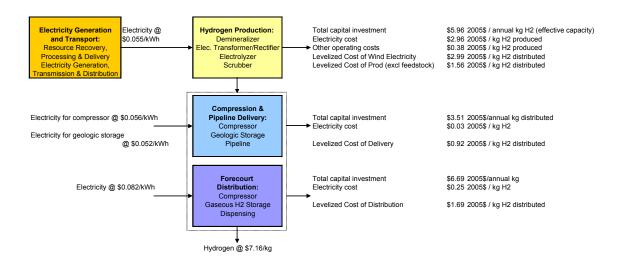
	Well-to-Pump		Well-to-Pump Well-to-			
Coal Input from "Well"*	21,000	Btu / 116,000 Btu	470	Btu / mi		
Natural Gas Input from "Well"*	6,000	Btu / 116,000 Btu	130	Btu / mi		
Petroleum Input from "Well"*	1,600	Btu / 116,000 Btu	35	Btu / mi		
Fossil Energy Input from "Well"*	28,600	Btu / 116,000 Btu	640	Btu / mi		
WTP CO <sub>2</sub> Emissions <sup>*,**</sup>	2,800	g / 116,000 Btu	62	g / mi		
WTP CH <sub>4</sub> Emissions	4	g / 116,000 Btu	0	g / mi		
WTP N <sub>2</sub> O Emissions	0	g / 116,000 Btu	0	g / mi		
WTP GHG Emissions*	2,900	g CO2 eq. / 116000 Btu	64	g / mi		
Levelized Cost of Hydrogen (\$/kg)	\$7.16	2005 \$/kg	\$0.1591	2005 \$/mi		

## Table 9.6.1. Well-to-Pump and Well-to-Wheels Results for Central Wind Electricity–Pipeline Delivery Pathway

\* Well-to-pump results are rounded to the nearest hundred; well-to-wheels results are rounded to the nearest ten.

\*\* Includes the carbon content of CO,  $CH_4$ , and volatile organic compound emissions that decompose in the atmosphere to  $CO_2$ 

Coal, natural gas, and petroleum inputs from "well" include those used directly in the hydrogen production and delivery pathway as feedstocks and fuels; those used to produce electricity and other materials used in the pathway; and those used upstream of the pathway to recover, refine, and deliver the feedstock.





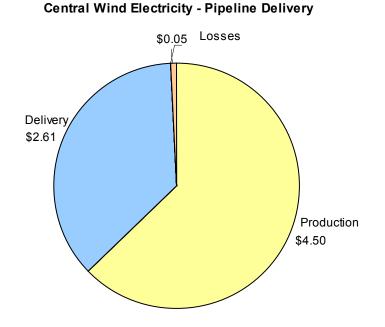


Figure 9.6.3. Contribution of hydrogen production, delivery, and losses to the levelized cost of hydrogen from central wind electricity–pipeline delivery pathway

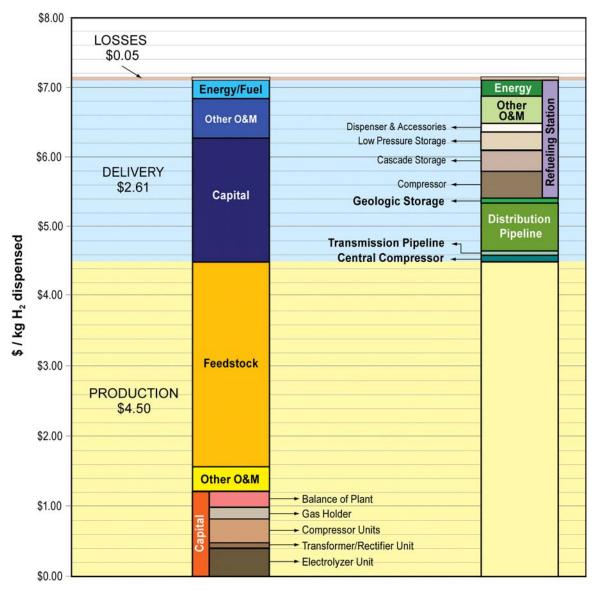


Figure 9.6.4. Breakdown of levelized costs for central wind electricity–pipeline delivery pathway

## Table 9.6.2. Contribution of Production and Delivery Processes to Levelized Hydrogen Cost from Central Wind Electricity–Pipeline Delivery Pathway

		Other		Energy/	
Cost Component	Capital	O&M	Feedstock	Fuel	Total
Production	\$1.16	\$0.38	\$2.96		\$4.50
Electrolyzer Units	\$0.37				
Transformer/Rectifier Units	\$0.07				
Compressor Units	\$0.34				
Gas Holders	\$0.17				
Balance of Plant	\$0.21				
Delivery	\$1.77	\$0.58		\$0.26	\$2.61
Central Compressor					\$0.08

Transmission Pipeline					\$0.07
Distribution Pipeline					\$0.70
Geologic Storage					\$0.08
Gaseous Refueling Station	\$1.06	\$0.41		\$0.23	\$1.69
Compressor	\$0.39				
Cascade Storage	\$0.29				
Low Pressure Storage	\$0.26				
Dispenser & Accessories	\$0.12				
Losses					\$0.05
Total	\$2.93	\$0.96	\$2.96	\$0.26	\$7.16

#### 9.6.2 Energy Use and Emissions Breakdown

Figures 9.6.5 and 9.6.6 show the WTW energy inputs and losses for the central wind electricity–pipeline delivery pathway.

Figures 9.6.7 and 9.6.8 show the WTW emissions resulting from the delivery of 116,000 Btu hydrogen to a vehicle fuel tank using the central wind electricity–pipeline delivery pathway.

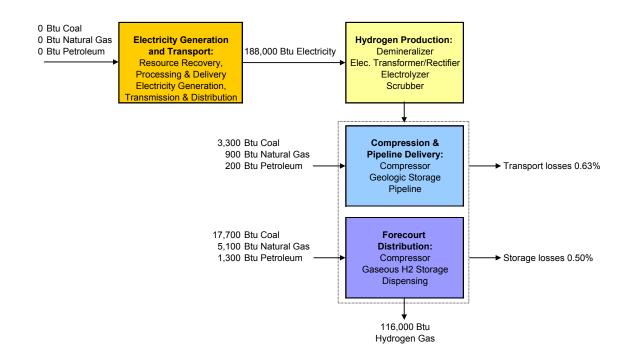


Figure 9.6.5. WTW energy inputs to deliver 116,000 Btu hydrogen to a vehicle using central wind electricity-pipeline delivery pathway

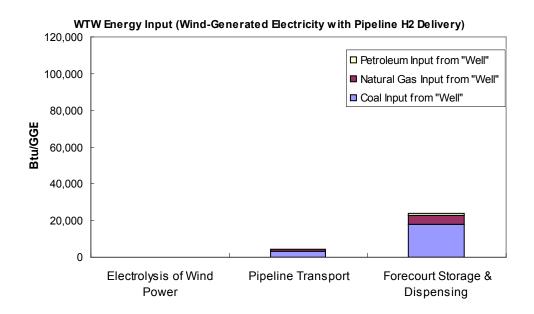


Figure 9.6.6. WTW petroleum, natural gas, and coal inputs to deliver 116,000 Btu hydrogen using central wind electricity–pipeline delivery pathway

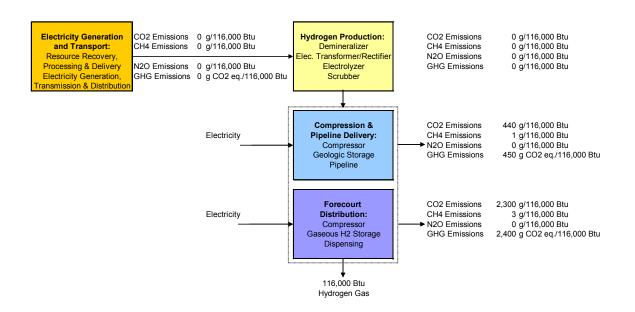
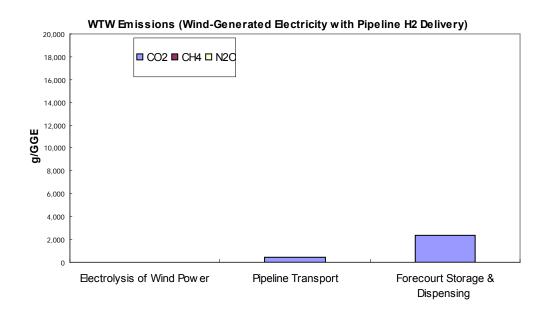


Figure 9.6.7. WTW emissions resulting from delivery of 116,000 Btu hydrogen using central wind electricity–pipeline delivery pathway



## Figure 9.6.8. WTW CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O emissions resulting from delivery of 116,000 Btu hydrogen to a vehicle using central wind electricity–pipeline delivery pathway

#### 9.6.3 Wind Electricity Supply Scenarios

Assuming a total vehicle miles traveled in passenger vehicles of 2.78 trillion (Bureau of Transportation Statistics, 2007), the vehicle fuel economy used in this study (45 mpgge), and a yield of hydrogen from wind electricity of 53 kWh wind electricity/kg H<sub>2</sub>, the amount of wind electricity required to supply 100%, 75%, 50%, or 25% of light-duty vehicles with wind electricity-derived hydrogen fuel was calculated and compared to the potential 2030 U.S. wind electricity generation capacity and the 2008 U.S. wind electricity consumption estimates shown in Section 3.2 (Table 9.6.3).

 Table 9.6.3. Wind Electricity Supply Scenarios for the Central Wind Electricity–Pipeline

 Delivery Pathway

	100%	75%	50%	25%	
	Penetration	Penetration	Penetration	Penetration	
	Current Technology – 45 mpgge FCV, hydroger production yield 53 kWh/kg H <sub>2</sub> <sup>1</sup>				
Wind Electricity Required (trillion kWh/yr)	3.4	2.5	1.7	0.84	
Percent of Potential U.S. Capacity in 2030 (1.16 trillion kWh) <sup>2</sup>	290%	220%	150%	70%	
Percent of 2008 U.S. Consumption (0.052 trillion kWh) <sup>3</sup>	6,500%	4,900%	3,200%	1,600%	

<sup>1</sup> Calculation does not include energy or hydrogen losses.

<sup>2</sup> United States Department of Energy (2008)

<sup>3</sup> Energy Information Administration (2009j)

Table 9.6.4 compares a sample scenario for hydrogen production from wind electricity from DOE's Hydrogen Posture Plan (United States Department of Energy, 2006) to a 20% FCV penetration scenario using the assumptions in this study, as described above.

	DOE Hydrogen Posture Plan (2006)	Hydrogen Pathways Report (2009)*
Total Hydrogen Demand	64 million metric tons/yr	63.1 million metric tons/yr
Amount of Demand to Be Supplied by Resource	13 million metric tons/yr (20%)	12.6 million metric tons/yr (20%)
Wind Electricity Needed for $H_2$	200 GWe	675 billion kWh/yr
Wind Electricity Availability	2,300 GWe nameplate capacity	1,160 billion kWh/yr in 2030
Wind Electricity Consumption (current)	10 GWe installed nameplate capacity	52 billion kWh/yr in 2008
Increase in Wind Electricity Consumption with H <sub>2</sub> Production	28 X	14 X

\* Calculated using the assumptions in Table 9.6.3 with 20% penetration of FCVs in light-duty vehicle market

#### 9.6.4 Sensitivities

#### Production Sensitivities

Several sensitivities were run on the production portion of the central electrolysis of wind-generated electricity-pipeline delivery pathway. These sensitivities focused primarily on cost factors. Figure 9.6.9 shows the effects of several production parameters on the pathway's levelized cost.

Note that the electricity cost is the sensitivity with the greatest potential effect on the levelized cost. The baseline electricity cost is the industrial electricity price estimated in the Annual Energy Outlook 2005 High Case (Energy Information Administration, 2005) and may be too low for wind electricity.

Effects of the sensitivities on WTW energy use and emissions are not shown because, due to the assumption that the electricity feedstock is wind-generated, the production fossil energy use and emissions are zero at all efficiencies.



Figure 9.6.9. Production sensitivities for central wind electrolysis–pipeline delivery pathway

#### Delivery Sensitivities

Pipeline delivery sensitivities are reported for the biomass production scenario in Section 9.4.4. The effects of the sensitivities will be the same for all pipeline delivery scenarios.

#### 9.6.5 Advanced Conversion and Delivery/Distribution Technology

For advanced technology analysis, parameters were changed to future projections. The "Future" H2A production case was used, and HDSAM was modified to include achievement of delivery targets as defined in the Hydrogen, Fuel Cells and Infrastructure Technologies (HFCIT) Multi-Year Program Plan (MYPP). The vehicle fuel economy was increased to 65 mpgge. In addition, the electricity grid mix was updated to match EIA's projection for technology success in 2020 (51.1% coal, 19.2% natural gas, 18.5% nuclear, 1.9% residual oil, and 1.0% biomass, and 8.3% zero-carbon).

WTW results from cases with those modifications are shown in Table 9.6.5. The results do not match those in Hydrogen Program Record 9002 (2009) because the production yield and cost of electrolyzers were modified in the Program Record case.

 Table 9.6.5. Well-to-Wheels Results for central wind-pipeline pathway with advanced technology

Coal Input from "Well"	290	Btu / mi
Natural Gas Input from "Well"	130	Btu / mi
Petroleum Input from "Well"	20	Btu / mi
Fossil Energy Input from "Well"	440	Btu / mi
WTW CO <sub>2</sub> Emissions	41	g / mi
WTW CH <sub>4</sub> Emissions	0.06	g / mi
WTW N <sub>2</sub> O Emissions	0.0006	g / mi
WTW GHG Emissions	43	g / mi

Levelized Cost of Hydrogen (\$/kg)	\$4.88	2005 \$/kg
Levelized Cost of Hydrogen (\$/mi)	\$0.0752	2005 \$/mi

Assuming a total vehicle miles traveled in passenger vehicles of 2.78 trillion (Bureau of Transportation Statistics, 2007), the vehicle fuel economy for advanced FCVs used in this study (65 mpgge), and a yield of hydrogen from wind electricity of 45 kWh wind electricity/kg H<sub>2</sub>, the amount of wind electricity required to supply 100%, 75%, 50%, or 25% of light-duty vehicles with wind electricity-derived hydrogen fuel was calculated and compared to the potential 2030 U.S. wind electricity generation capacity and the 2008 U.S. wind electricity consumption estimates shown in Section 3.2 (Table 9.6.6).

Table 9.6.6. Wind Electricity Supply Scenarios for the Central Wind Electricity-Pipeline **Delivery Pathway** 

	100%	75%	50%	25%	
	Penetration	Penetration	Penetration	Penetration	
	Advanced Technology – 65 mpgge FCV, hydro				
	р	roduction yield	d 45 kWh/kg H	2	
Wind Electricity Required (trillion kWh/yr)	2.0	1.5	1.0	0.5	
Percent of Potential U.S. Capacity in 2030 (1.16 trillion kWh) <sup>2</sup>	170%	130%	80%	40%	
Percent of 2008 U.S. Consumption (0.052 trillion kWh) <sup>3</sup>	3,800%	2,800%	1,900%	900%	

<sup>1</sup> Calculation does not include energy or hydrogen losses. <sup>2</sup> United States Department of Energy (2008)

<sup>3</sup> Energy Information Administration (2009j)

Table 9.6.7 compares a sample scenario for hydrogen production from wind electricity from DOE's Hydrogen Posture Plan (United States Department of Energy, 2006) to a 20% FCV penetration scenario using the advanced technology assumptions in this section, as described above.

#### Table 9.6.7. Comparison of Wind Electricity Supply Scenarios to Hydrogen Posture Plan for Advanced Hydrogen Technology

	DOE Hydrogen Posture Plan (2006)	Hydrogen Pathways Report (2009)*
Total Hydrogen Demand	64 million metric tons/yr	63.1 million metric tons/yr
Amount of Demand to Be Supplied by Resource	13 million metric tons/yr (20%)	12.6 million metric tons/yr (20%)
Wind Electricity Needed for H <sub>2</sub>	200 GWe	390 billion kWh/yr
Wind Electricity Availability	2,300 GWe nameplate capacity	1,160 billion kWh/yr in 2030
Wind Electricity Consumption (current)	10 GWe installed nameplate capacity	52 billion kWh/yr in 2008
Increase in Wind Electricity Consumption with $H_2$ Production	28 X	8.5 X

\* Calculated using the assumptions in Table 9.6.6 with 20% penetration of FCVs in light-duty vehicle market

# 9.7 Central Coal with Carbon Capture and Sequestration (CCS) – Pipeline Delivery

Figure 9.7.1 shows the major inputs, assumptions, and outputs for each of the subsystems considered in the well-to-tank analysis, including feedstock supply and hydrogen dispensing. The complete set of assumptions is detailed in Appendix G.

The well-to-pump and well-to-wheels cost of hydrogen, energy use, and emissions for the central coal with CCS–pipeline delivery pathway are summarized in Table 9.7.1.

#### 9.7.1 Cost Breakdown

Figure 9.7.2 shows the feedstock and energy price inputs and the resulting hydrogen production, delivery, and distribution costs for the central coal with CCS–pipeline delivery pathway. The financial assumptions used in this analysis are detailed in Section 8.0.

Figure 9.7.3 shows the contributions of hydrogen production, delivery, and losses to the levelized cost of hydrogen shown in Figure 9.7.2.

Figure 9.7.4 and Table 9.7.2 show the breakdown of levelized costs for the central coal with CCS–pipeline delivery pathway.

In	puts	Graphic Depiction & A	ssumptions	(	Dutputs
		Coal Mining & Deliv	very		•
		Energy Recovery Energy Used	99.3% 7049 Btu / MMBtu Coal Delivered		
		Diesel Used	3948 Btu / MMBtu Coal Delivered 1692 Btu / MMBtu Coal	Coal price at H2 production	\$33.98 2005 \$ / short ton
		Electricity Used	<sup>1692</sup> Delivered	Levelized Cost of Coal	\$0.31 2005\$ / kg H2 distributed
Coal Input from "Well" Natural Gas Input from "Well" Petroleum Input from "Well"	116,427 Btu / 116000Btu to Pump 145 Btu / 116000Btu to Pump 712 Btu / 116000Btu to Pump			WTG CO2 Emissions WTG CH4 Emissions WTG N2O Emissions WTG GHG Emissions	114 g / 116000Btu to Pump 14 g / 116000Btu to Pump 0 g / 116000Btu to Pump 462 g CO2 eq./ 116000 Btu
Coal consumption Natural gas consumption Electricity consumption	7.8 kg / kg H2 produced 0.00 N m^3/kg H2 produced 1.72 kWh / kg H2	Hydrogen Production	& CCS	Hydrogen Output Pressure	300 psi
Process Water Consumption Electricity price Total Capital Investment	11.02 L / kg H2 \$0.0555 2005 \$/kWh \$691,377,851 2005\$	Central plant design capacity Capacity factor Process energy efficiency Electricity Mix After-tax IRR Assumed Plant Life	307,673 kg/day 90% 53,6% US Mix 10% 40	Total capital investment Electricity cost Natural Gas Cost Other operating costs Levelized Cost of Prod (excl feedstock)	\$6.84 2005\$ / annual kg H2 (effective capacity) \$0.10 20055 / kg H2 produced \$0.00 20055 / kg H2 produced \$0.38 2005\$ / kg H2 produced \$1.76 2005\$ / kg H2 distributed
Coal Input from "Well" Vatural Gas Input from "Well" Petroleum Input from "Well"	105,782 Btu / 116000Btu to Pump 3,022 Btu / 116000Btu to Pump 1,332 Btu / 116000Btu to Pump	CO2 Captured for sequestration CO2 Pipeline Length Number of injection wells Injection well depth	90% 100 miles 1 1524 m	H2 Prod CO2 Emissions H2 Prod CH4 Emissions H2 Prod N2O Emissions H2 Prod GHG Emissions	3,803 g / 116000Btu to Pump 13 g / 116000Btu to Pump 0 g / 116000Btu to Pump 4,136 g CO2 eq./ 116000 Btu
Electricity consumption for compressor Electricity consumption for geo storage Total electricity consumption	0.56 kWh / kg H2 0.01 kWh / kg H2 0.57 kWh / kg H2	Pipelines for Deliv		Total capital investment Electricity cost	\$3.51 2005\$/annual kg distribute \$0.03 2005\$ / kg H2
Electricity price for compressor Electricity price for geologic storage	\$0.056 2005\$ / kWh \$0.052 2005\$ / kWh	City Population Hydrogen Vehicle Penetration City hydrogen use Distance from City to Production Facility Geologic storage capacity Trunk #1-line length Trunk #2-line length	1,247,364 people 50% 125,810,766 kg / yr 62 miles 3,762,787 kg H2 17 miles 40 miles	Levelized Cost of Delivery	\$0.92 2005\$ / kg H2 distributed
Coal Input from "Well" Natural Gas Input from "Well" Petroleum Input from "Well"	3,306 Btu / 116000Btu to Pump 950 Btu / 116000Btu to Pump 246 Btu / 116000Btu to Pump	Service-line length Number of service lines Hydrogen losses Hydrogen loss factor	1.1 miles / line 270 1.12% 1.011	Delivery CO2 Emissions Delivery CH4 Emissions Delivery N2O Emissions Delivery GHG Emissions	436 g / 116000Btu to Pump 1 g / 116000Btu to Pump 0 g / 116000Btu to Pump 452 g CO2 eq./ 116000 Btu
Electricity consumption	3.04 kWh / kg H2	Forecourt Distribu	tion	Hydrogen outlet pressure Basis Hydrogen Quantity	6,250 psi <b>116,000</b> Btu (116,000 Btu/gal non- oxygenated conventional unleaded gasoline)
Electricity price	\$0.082 2005\$ / kWh 17,677 Btu / 116000Btu to Pump	Number of Distribution Stations Energy efficiency Number of Compression Steps Isentropic Efficiency Site storage Hydrogen losses	270 92% 4 65% 69% capacity 0.50%	Total capital investment Electricity cost Levelized Cost of Distribution CSD CO2 Emissions CSD CH4 Emissions	\$6.69 2005\$/annual kg \$0.25 2005\$ / kg H2 \$1.69 2005\$ / kg H2 distributed 2,333 g / 116000Btu to Pump 3 g / 116000Btu to Pump
Coal Input from "Well" Natural Gas Input from "Well" Petroleum Input from "Well"	5,078 Btu / 116000Btu to Pump 5,078 Btu / 116000Btu to Pump 1,317 Btu / 116000Btu to Pump	Hydrogen losses Hydrogen loss factor	0.50% 1.005	CSD CH4 Emissions CSD N2O Emissions CSD GHG Emissions	3 g / 116000Btu to Pump 0 g / 116000Btu to Pump 2,419 g CO2 eq./ 116000 Btu

#### Figure 9.7.1. Central coal with CCS-pipeline delivery pathway summary of major inputs, assumptions, and outputs by subsystem

Coal, natural gas, and petroleum inputs from "well" include those used directly in the hydrogen production and delivery pathway as feedstocks and fuels; those used to produce electricity and other materials used in the pathway; and those used upstream of the pathway to recover, refine, and deliver the feedstock.

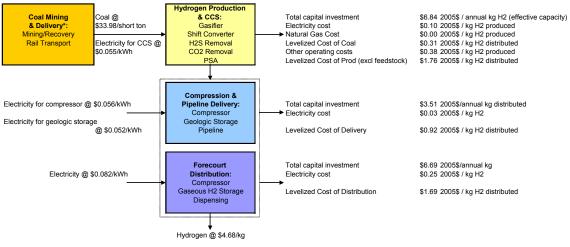
		Well-to-Pump	Well-to	-Wheels
Coal Input from "Well"*	243,200	Btu / 116,000 Btu	5,410	Btu / mi
Natural Gas Input from "Well"*	9,200	Btu / 116,000 Btu	200	Btu / mi
Petroleum Input from "Well"*	3,600	Btu / 116,000 Btu	80	Btu / mi
Fossil Energy Input from "Well"*	256,000	Btu / 116,000 Btu	5,690	Btu / mi
WTP CO <sub>2</sub> Emissions***	6,700	g / 116,000 Btu	150	g / mi
WTP CH <sub>4</sub> Emissions	31	g / 116,000 Btu	1	g / mi
WTP N <sub>2</sub> O Emissions	0	g / 116,000 Btu	0	g / mi
WTP GHG Emissions*	7,500	g CO2 eq. / 116000 Btu	170	g / mi
Levelized Cost of Hydrogen (\$/kg)	\$4.68	2005 \$/kg	\$0.1040	2005 \$/mi

## Table 9.7.1. Well-to-Pump and Well-to-Wheels Results for Central Coal with CCS–Pipeline Delivery Pathway

\* Well-to-pump results are rounded to the nearest hundred; well-to-wheels results are rounded to the nearest ten.

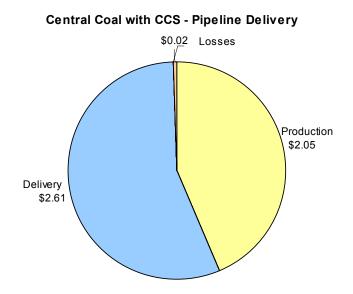
\*\* Includes the carbon content of CO,  $CH_4$ , and volatile organic compound emissions that decompose in the atmosphere to  $CO_2$ 

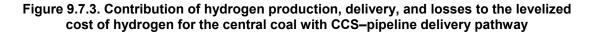
Coal, natural gas, and petroleum inputs from "well" include those used directly in the hydrogen production and delivery pathway as feedstocks and fuels; those used to produce electricity and other materials used in the pathway; and those used upstream of the pathway to recover, refine, and deliver the feedstock.

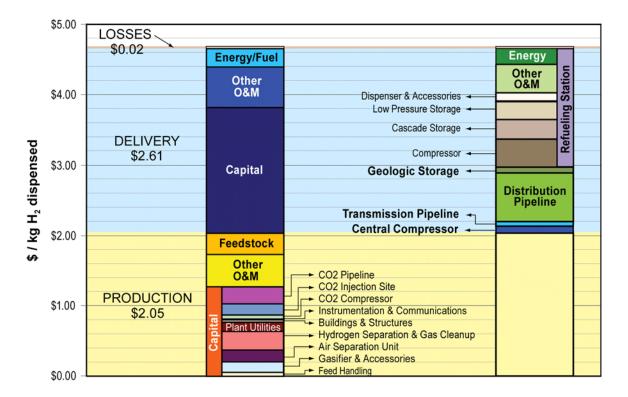


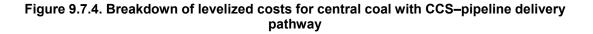
\* This box represents the coal that is converted to hydrogen or otherwise consumed/lost as a process feedstock. It does not include coal used as a heating fuel or to produce electricity.

### Figure 9.7.2. Cost analysis inputs and high-level results for central coal with CCS-pipeline delivery pathway









		Other		Energy/	
Cost Component	Capital	O&M	Feedstock	Fuel	Total
Production	\$1.27	\$0.47	\$0.31		\$2.05
Feed Handling	\$0.06				
Gasifier & Accessories	\$0.15				
Air Separation Unit	\$0.16				
Hydrogen Separation & Gas Cleanup	\$0.27				
Plant Utilities	\$0.13				
Buildings & Structures	\$0.01				
Instrumentation & Communications	\$0.02				
CO <sub>2</sub> Compressor	\$0.07				
CO <sub>2</sub> Injection Site	\$0.16				
CO <sub>2</sub> Pipeline	\$0.24				
Delivery	\$1.77	\$0.58		\$0.26	\$2.61
Central Compressor					\$0.08
Transmission Pipeline					\$0.07
Distribution Pipeline					\$0.70
Geologic Storage					\$0.08
Gaseous Refueling Station	\$1.06	\$0.41		\$0.23	\$1.69
Compressor	\$0.39				
Cascade Storage	\$0.29				
Low Pressure Storage	\$0.26				
Dispenser & Accessories	\$0.12				
Losses					\$0.02
Total	\$3.04	\$1.05	\$0.31	\$0.26	\$4.68

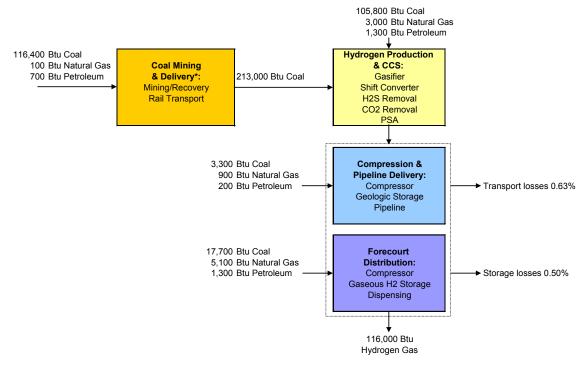
 Table 9.7.2. Contribution of Production and Delivery Processes to Levelized Hydrogen

 Cost from Central Coal with CCS-pipeline Delivery Pathway

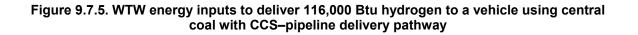
#### 9.7.2 Energy Use and Emissions Breakdown

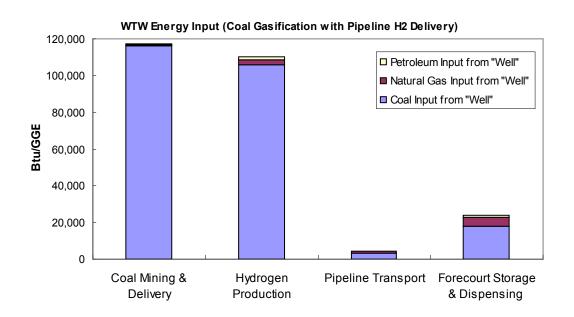
Figures 9.7.5 and 9.7.6 show the WTW energy inputs and losses for the central coal with CCS–pipeline delivery pathway. The WTW energy inputs to coal mining and delivery include those necessary to produce 116,000 Btu of coal for gasifying. Additional WTW energy inputs for coal needed for heating, electricity, and process-inefficiency are reported as inputs to hydrogen production.

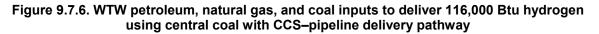
Figures 9.7.7 and 9.7.8 show the WTW emissions resulting from the delivery of 116,000 Btu hydrogen to a vehicle fuel tank using the central coal with CCS–pipeline delivery pathway.

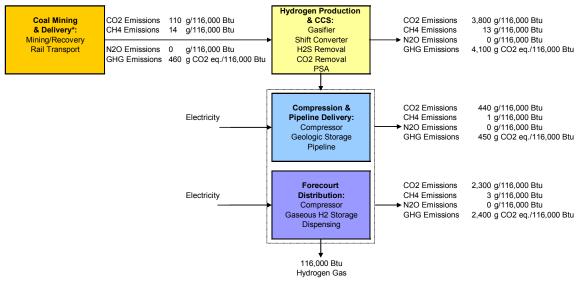


\* This box represents the coal that is converted to hydrogen or otherwise consumed/lost as a process feedstock. It does not include coal used as a heating fuel or to produce electricity.

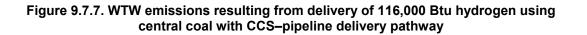


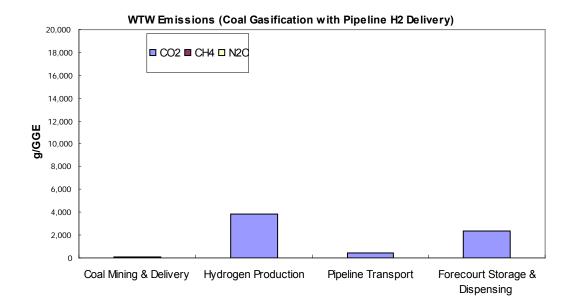


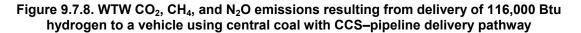




\* This box represents the coal that is converted to hydrogen or otherwise consumed/lost as a process feedstock. It does not include coal used as a heating fuel or to produce electricity.







#### 9.7.3 Coal Supply Scenarios

Assuming a total vehicle miles traveled in passenger vehicles of 2.78 trillion (Bureau of Transportation Statistics, 2007), the vehicle fuel economy used in this study (45 mpgge), and a yield of hydrogen from coal of 7.9 kg coal/kg H<sub>2</sub>, the amount of coal required to supply 100%, 75%, 50%, or 25% of light-duty vehicles with coal-derived hydrogen fuel was calculated and compared to the U.S. coal reserves, 2007 U.S. coal production, and 2008 U.S. coal consumption estimates shown in Section 3.4 (Table 9.7.3).

		-		
	100%	75%	50%	25%
	Penetration	Penetration	Penetration	Penetration
	Curre hydroger	ent Technolog	y – 45 mpgge eld 7.85 kg co	FCV, al/kg H <sub>2</sub> <sup>1</sup>
Coal Required (million short tons)	550	410	270	140
Percent of U.S. Reserves (489,000 million short tons) <sup>2</sup>	0.11%	0.08%	0.06%	0.03%
Percent of 2007 U.S. Production (1,171 million short tons) <sup>3</sup>	47%	35%	23%	12%
Percent of 2008 U.S. Consumption $(1,122 \text{ million short tons})^4$	49%	37%	24%	12%

Table 9.7.3. Coal Supply Scenarios for the Central Coal with CCS–Pipeline Delivery Pathway

<sup>1</sup> Calculation does not include energy or hydrogen losses. <sup>2</sup> United States Department of Energy (2008)

<sup>3</sup> Energy Information Administration (2008d)

<sup>4</sup> Energy Information Administration (2009j)

Table 9.7.4 compares a sample scenario for hydrogen production from biomass from DOE's Hydrogen Posture Plan (United States Department of Energy, 2006) to a 20% FCV penetration scenario using the assumptions in this study, as described above.

	DOE Hydrogen Posture Plan (2006)	Hydrogen Pathways Report (2009)*
Total Hydrogen Demand	64 million metric tons/yr	63.1 million metric tons/yr
Amount of Demand to Be Supplied by Resource	13 million metric tons/yr (20%)	12.6 million metric tons/yr (20%)
Coal Needed for H <sub>2</sub>	110 million metric tons/yr	99 million metric tons/yr
Coal Availability	268 billion tons estimated recoverable reserves, 493 billion tons demonstrated coal base	489 billion short tons
Coal Consumption (current)	1,100 million metric tons/yr (all grades)	1,017 million metric tons/yr
Increase in Coal Consumption with $H_2$ Production	1.1 X	1.1 X

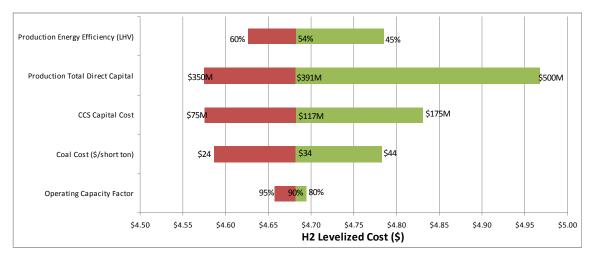
Table 9.7.4. Comparison of Coal Supply Scenarios to Hydrogen Posture Plan

\* Calculated using the assumptions in Table 9.7.3 with 20% penetration of FCVs in light-duty vehicle market

#### 9.7.4 Sensitivities

#### **Production Sensitivities**

Several sensitivities were run on the production portion of the central coal with CCS – pipeline delivery pathway. These sensitivities focused primarily on cost factors; however, several sensitivities also affect energy use and emissions. Figure 9.7.9 shows the effects of several production parameters on the pathway's levelized cost, and Table 9.7.5 shows the effect of varying production efficiency on the WTW results.





	45%	54%	60%
	Efficiency	Efficiency	Efficiency
WTW GHG Emissions (g/mile)	190	170	160
WTW Fossil Energy (Btu/mile)	6,700	5,700	5,200
WTW Petroleum Energy (Btu/mile)	89	80	76
WTW Total Energy (Btu/mile)	6,900	5,900	5,300

 
 Table 9.7.5. The Effects of Production Energy Efficiency on Primary Energy and Emissions from Central Coal with CCS–Pipeline Delivery Pathway (current technology)

The assumed electrical grid mix also affects the energy use and emissions because grid electricity is needed for delivery and distribution. Electricity for the production facility is generated internally and can be considered a parasitic loss. Table 9.7.6 shows the differences in energy use and GHG emissions between the U.S. average grid mix (which was used for all other sensitivities) and a hypothetical green grid mix that is 100% renewable energy (solar and wind).

Table 9.7.6. The Effects of Grid Mix on Use of Primary Energy and Emissions from Central
Coal with CCS-pipeline Delivery Pathway

	U.S. Average	"Green"
	Grid Mix	Grid Mix
WTW GHG Emissions (g/mile)	170	70
WTW Fossil Energy (Btu/mile)	5,700	4,700
WTW Petroleum Energy (Btu/mile)	80	28
WTW Total Energy (Btu/mile)	5,900	5,200

#### **Delivery Sensitivities**

Pipeline delivery sensitivities are reported for the biomass production scenario in Section 9.4.4. The effects of the sensitivities will be the same for all pipeline delivery scenarios.

#### 9.7.5 Advanced Conversion and Delivery/Distribution Technology

For advanced technology analysis, parameters were changed to future projections. The "Future" H2A production case was used, and HDSAM was modified to include achievement of delivery targets as defined in the Hydrogen, Fuel Cells and Infrastructure Technologies (HFCIT) Multi-Year Program Plan (MYPP). The vehicle fuel economy was increased to 65 mpgge. In addition, the electricity grid mix was updated to match EIA's projection for technology success in 2020 (51.1% coal, 19.2% natural gas, 18.5% nuclear, 1.9% residual oil, and 1.0% biomass, and 8.3% zero-carbon).

WTW results from cases with those modifications are shown in Table 9.7.7. The results do not match those in Hydrogen Program Record 9002 (2009) because the H2A case with advanced technology has a larger electricity byproduct than the case used for the Program

Record. Carbon dioxide and GHG emissions are negative because 50,400 Btu (14.8 kWh) electricity is produced for every GGE hydrogen distributed, and that electricity displaces grid electricity with higher GHG emissions. Electricity displacement is also the reason why WTW natural gas and petroleum use are negative.

Table 9.7.7. Well-to-Wheels Results for central coal with CCS-pipeline pathway with
advanced technology

Coal Input from "Well"	2330	Btu / mi
Natural Gas Input from "Well"	-360	Btu / mi
Petroleum Input from "Well"	-40	Btu / mi
Fossil Energy Input from "Well"	1900	Btu / mi
WTW CO <sub>2</sub> Emissions	-79	g / mi
WTW CH <sub>4</sub> Emissions	0.21	g / mi
WTW N <sub>2</sub> O Emissions	-0.002	g / mi
WTW GHG Emissions	-74	g / mi
Levelized Cost of Hydrogen (\$/kg)	\$3.53	2005 \$/kg
Levelized Cost of Hydrogen (\$/mi)	\$0.0543	2005 \$/mi

### **10.0 Pathway Results Comparison**

In this section, results from the individual pathways are compared. Each pathway's current estimated levelized cost, WTW petroleum use, and WTW GHG emissions are shown for comparison to the other pathways, several crude oil-based transportation options, and ethanol as E85. The crude oil-based options are gasoline in a standard spark-ignition ICE; gasoline in a spark-ignition HEV; and diesel in a compression-ignition direct-injection ICE.

Fuel economies used for each option are shown in Table 10.0.1. GREET-default fuel economies and upstream parameters were used for the crude oil–based transportation options and E85 from corn grain. The gasoline ICE fuel economy is based on data presented by the Environmental Protection Agency (2005). The fuel economies for other, non-hydrogen vehicles are based on PSAT results (Elgowainy, 2009). The GREET yield for corn stover–based E85 was modified to 72.6 gal / dry ton to match the 2008 status in Table B-5 of the Biomass Program Plan (Office of the Biomass Program, 2009). Other key parameters are shown in Table 10.0.2.

Vehicle Type	Fuel Economy
Hydrogen FCV	45 mpgge
Gasoline ICE	23.2 mpg
Gasoline HEV	34.3 mpg
Diesel ICE	27.8 mpgge (equivalent to 30.8 mpg diesel)
E85 Flex-Fuel FCV	23.2 mpgge (equivalent to 16.4 mpg E85)

#### Table 10.0.1. Fuel Economies for Vehicle Options

Parameter	Value and Section with Description
Technology status	Current technology (Section 2.2). Technology is described
	in Sections 6.0 and 7.0, and parameters are shown in the
	appendices.
City size	553 mi <sup>2</sup> and 1,247,364 people (equivalent to Indianapolis,
	IN) (Section 2.2)
Market penetration	50% of hydrogen vehicles (Section 2.2)
Analysis boundaries	Includes feedstock recovery, transportation, and storage;
	fuel production, transportation, storage, and distribution;
	and vehicle operation (Section 2.3)
Monetary value	2005 dollars (Section 8.0)
Equity financing	100% (Section 8.0)
After tax internal rate of	10% (Section 8.0)
return	
Effective total tax rate	38.9%
Carbon capture efficiency	90% (Section 9.7)
in coal with CCS case	

#### Table 10.0.2. Key Analysis Parameters

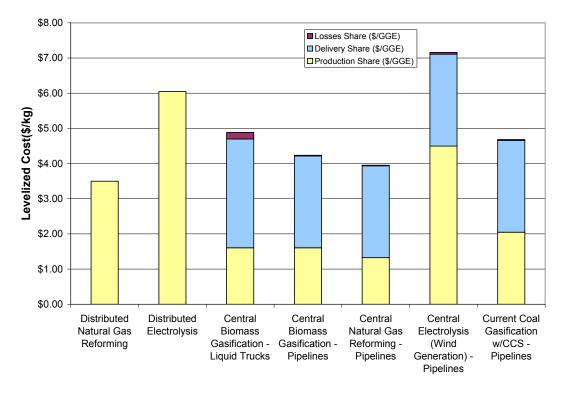


Figure 10.0.1. Levelized cost of hydrogen for seven pathways

Figure 10.0.1 shows the levelized cost of hydrogen for all seven hydrogen pathways with the parameters described in Section 9 and referenced in Appendices A–G. Some of the most important parameters are shown in Table 10.0.2, and additional parameters are in sections 2–8. Sensitivities on parameters in each hydrogen pathway are reported in Section 9.

The levelized cost of hydrogen is calculated directly in the H2A model for the distributed hydrogen production cases because the H2A distributed hydrogen production model includes the forecourt station capital and operating costs. For central production cases, the levelized cost of hydrogen is the sum of levelized production cost, levelized delivery cost, and the cost of excess production due to losses in delivery.

The Program has set a hydrogen levelized cost target of \$2.00–\$3.00/gge delivered at the pump (Hydrogen, Fuel Cells and Infrastructure Technology Program, 2007), and the comparison in Figure 10.0.1 shows that the target has not been met. Niche opportunities with low-cost feed or capital costs, different financing options, or higher capacities may meet the target. Otherwise, additional research is necessary to meet them. Other analysts have used different parameters and reached slightly different levelized costs of hydrogen in their studies. One example of an analysis that showed that the \$2.00–\$3.00/gge levelized cost has been met for the distributed natural gas reforming pathway is Fletcher

and Callaghan (2007). The primary difference between their analysis and this one is a lower cost for CSD (They estimated \$0.88/kg, and the estimate in this study is \$1.88/kg.).

Figure 10.0.2 shows a comparison hydrogen pathway energy use. Pathway energy includes only the energy used directly by the pathway. It differs from the WTW energy in that WTW energy includes upstream energy requirements. For example, while electricity is reported as a pathway energy source, the primary energy sources used to generate the electricity (coal, natural gas, etc.) are included in the WTW calculations. As expected, the dominant pathway energy source is the one named in the title of each pathway.

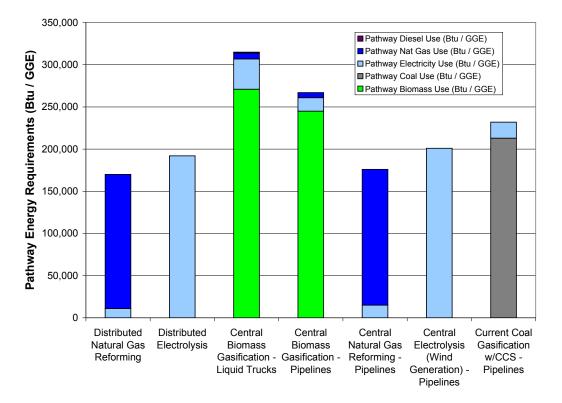


Figure 10.0.2. Pathway energy use for seven pathways

The pathway efficiency can be considered the inverse of the energy use; Figure 10.0.3 shows those efficiencies. The yellow bars show the production efficiencies that are calculated as the LHV of the hydrogen produced divided by the LHV of all the production inputs reported in Section 9. The blue bars show the pathway efficiencies that are calculated as the LHV of the hydrogen delivered divided by the LHV of all the pathway inputs, which are shown in Figure 10.0.2. The red bars show the WTP efficiencies that are calculated as the LHV of the hydrogen delivered divided by the LHV of all the pathway inputs, which are shown in Figure 10.0.2. The red bars show the WTP efficiencies that are calculated as the LHV of the hydrogen delivered divided by the LHV of all the primary energy inputs (coal, natural gas, crude oil, and biomass) that are used directly or indirectly by the pathway.

As an example, Figure 10.0.3 shows that the production efficiency of the distributed natural gas reforming pathway is 71% (i.e., 71% of all of the energy delivered to the hydrogen production plant is contained in the hydrogen product). Because the pathway includes both the production plant and CSD, the pathway efficiency must account for hydrogen lost and energy required for compression; thus, the pathway efficiency is somewhat lower at 68% for the distributed natural gas reforming pathway. Some additional energy is required to produce and delivery the natural gas and electricity to the facility, so the WTP efficiency is lower yet at 58% for the distributed natural gas reforming pathway.

The pathways with the highest efficiency are the natural gas pathways followed by electrolysis and coal, and those with the lowest efficiency are the biomass pathways.

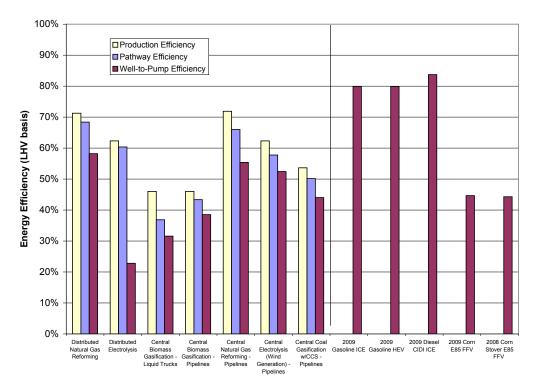


Figure 10.0.3. WTW, pathway, and production efficiencies for seven hydrogen pathways, three crude oil-based fuel options, and two E85 options

Figure 10.0.4 shows the WTW petroleum use for the seven hydrogen pathways, the three crude oil–based pathways, and two E85 pathways. Because the petroleum use is so high for the crude oil pathway, Figure 10.0.5 shows the WTW petroleum use for the seven hydrogen pathways alone. Most of the petroleum use is for electricity generation for the pathways' grid electricity requirements (2.9% of the grid mix is electricity generated from residual oil.). The largest grid-electricity user is distributed electrolysis (requiring 55 kWh/kg H<sub>2</sub> produced), and if the grid mix did not include residual oil, its WTW petroleum use would be reduced by 410 Btu/mile.

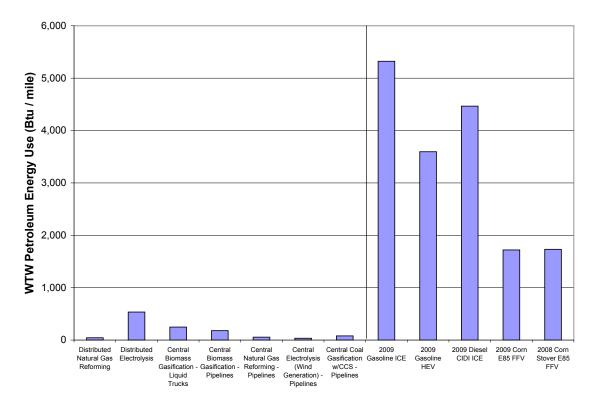


Figure 10.0.4. WTW petroleum energy use for seven hydrogen pathways, three crude oilbased fuel options, and two E85 options

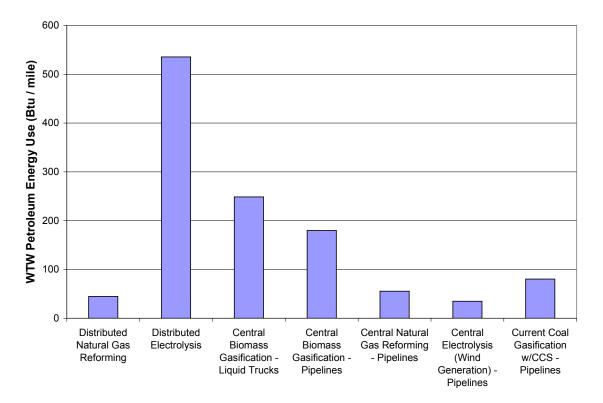


Figure 10.0.5. WTW petroleum energy use for seven hydrogen pathways

Figure 10.0.6 shows the comparative WTW GHG emissions for the seven pathways, the crude oil-based pathways, and two E85 pathways. Well-to-pump (WTP) emissions are colored green, and pump-to-wheels (i.e., tailpipe) emissions are colored blue. Hydrogen FCVs have no tailpipe GHG emissions because reacting hydrogen forms water. The corn stover E85 FFV pathway has negative WTP emissions because more carbon dioxide is removed from the atmosphere while the plants are growing than is released in growing the plants, harvesting and transporting the biomass, producing ethanol, and delivering ethanol.

All the hydrogen pathways except distributed electrolysis have estimated GHG emissions lower than the crude oil options. The primary source (89%) of GHG emissions for the distributed natural gas reforming pathway is generation of hydrogen with some additional GHGs generated to produce electricity for CSD and in natural gas recovery and delivery. Distributed electrolysis requires 55 kWh electricity per kg H<sub>2</sub> produced, and the current grid mix produces 800 g CO<sub>2</sub> eq./kWh, so electricity generation is the primary emitter of its 980 g CO<sub>2</sub> eq./mile traveled. In the biomass / liquid pathway, the GHGs removed from the atmosphere to grow biomass are essentially equivalent to the GHGs generated in producing hydrogen (see Section 9.3 for details). In that pathway, most of the net GHGs emitted (97%) are from liquefaction and transport of the liquid hydrogen. Likewise, in the biomass pipeline pathway, most of the net GHGs emitted (92%) are from electricity generation for CSD of the hydrogen. Central natural gas reforming generates GHGs in both hydrogen production and in CSD. All the GHGs emitted from the central electrolysis of wind electricity are from electricity generation for CSD, which is assumed to be purchased from the grid without wind energy credits. Fifty-five percent of the GHGs emitted from the central coal with CCS and pipeline delivery pathway are GHGs that were not sequestered in the hydrogen production process with the remainder emitted during coal mining, transport and hydrogen CSD.

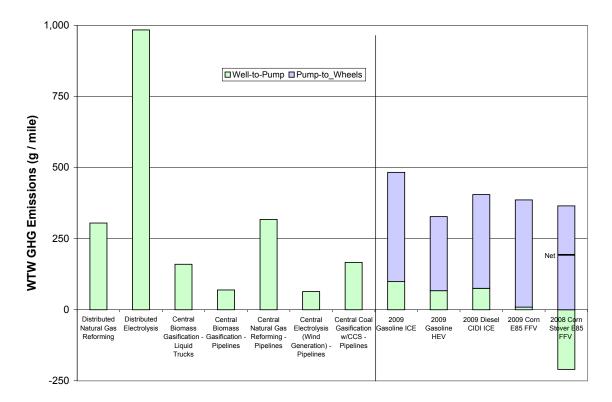


Figure 10.0.6. WTW GHG emissions for seven hydrogen pathways, three crude oil-based fuel options, and two E85 options

As seen in Figure 10.0.6, all the pathways except distributed electrolysis result in lower GHG emissions (on a g/mile basis) than a comparable ICE vehicle fueled by gasoline because of the increased efficiency fuel cells provide. Distributed electrolysis has both high GHG emissions and high petroleum use when compared to the other hydrogen pathways because of the electricity grid mix. The pathways that use natural gas as a feedstock use little petroleum but have high GHG emissions compared to most of the other pathways due to the GHGs released in producing hydrogen from natural gas. The coal pathway has a slightly higher petroleum use than the natural gas pathways because petroleum-fueled rail is used to deliver coal to the hydrogen production facility and has lower GHG emissions because of the efficient sequestration system that is assumed. The biomass cases have higher petroleum use than all but the distributed electrolysis pathway because the biomass is delivered using trucks.

Because using hydrogen as a transportation fuel has an effect on both WTW GHG emissions and WTW petroleum use and because that effect varies depending upon the hydrogen production/delivery pathway, Figure 10.0.7 shows both.

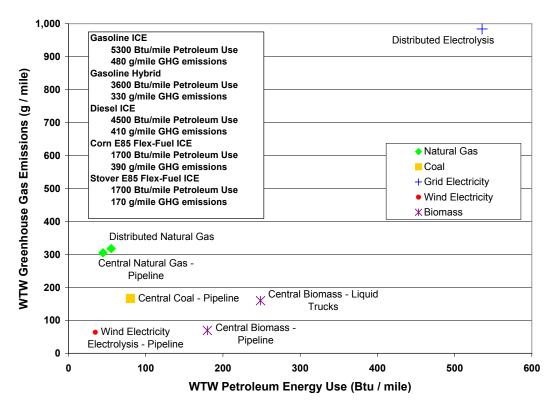


Figure 10.0.7. Comparison of pathways' petroleum use and GHG emissions

Figure 10.0.8 shows the levelized fuel cost per mile and the WTW GHG emissions. For comparison, it also shows the market price per mile and GHG emissions for gasoline and diesel vehicles. The levelized fuel cost was put onto a per-mile basis to simplify the comparison with other fuel/vehicle combinations that have different vehicle fuel economies. Ideally, the vehicle's purchase, maintenance, and insurance costs would also be put onto a per-mile basis, and the totals would be summed; however, those values are outside the scope of this analysis.

Gasoline, diesel, and corn-based E85 prices are based on projected market prices unlike the reported costs for hydrogen- and stover-based E85, which are based on calculated levelized costs. Projected market prices are used because they are available for technologies that are mature and commercialized. Levelized costs are not available for most of those technologies because capital and operating costs are separated for longterm commercial products with multiple improvements. For gasoline, the projected market price used in this analysis is \$2.535/gal based on the 2009 high-energy case in the 2007 Annual Energy Outlook (Energy Information Administration, 2007). The estimated taxes are \$0.391/gal (Federal Highway Administration, 2009), so a tax-free price of \$2.14/gal is used. For diesel, the reported market price is \$2.536/gal (Energy Information Administration, 2007) with taxes of \$0.452/gal (Federal Highway Administration, 2009), resulting in a tax-free price of \$2.08/gal. The diesel price was converted to \$1.88/gge using the lower heating values reported in GREET (Wang, 1999) because the vehicles' fuel economy is on a gge basis. The corresponding projected crude oil prices that match the gasoline and diesel prices are \$67.70/bbl for imported low-sulfur light crude oil and \$60.71/bbl for imported crude oil (Energy Information Administration, 2007). The crude oil prices include delivery to refineries. Corn grain–based E85 is also based on the 2009 high-energy case in the 2007 Annual Energy Outlook (Energy Information Administration, 2007). It is \$2.505/gal ethanol and is reported to have 74% ethanol. Reduction by the gasoline tax of \$0.391/gal and conversion to the common basis bring the price to \$2.83/gge.

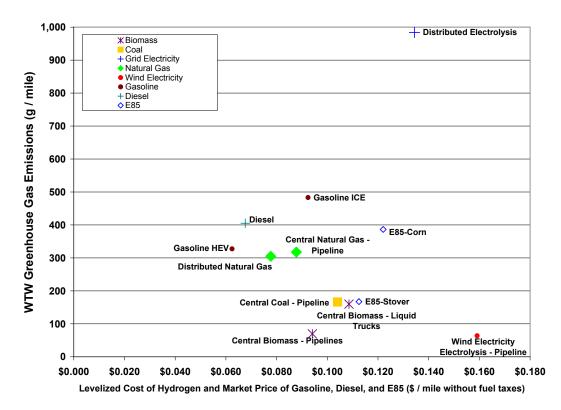


Figure 10.0.8. Comparison of pathways' levelized costs/market and GHG emissions

Figure 10.0.9 shows the levelized cost of hydrogen and the gasoline and diesel market prices on a per-mile-traveled basis with two possible levels of carbon taxation. The tops of the red bars indicate the wholesale, levelized costs including a \$50/ton CO<sub>2</sub>-equivalent tax, and the tops of the yellow bars indicate the wholesale, levelized costs including a \$100/ton CO<sub>2</sub>-equivalent tax. The tax calculation is based on WTW GHG emissions, so it includes increased costs due to upstream emissions as well as those generated while producing the hydrogen. A \$100/ton CO<sub>2</sub> equivalent tax increases the per-mile levelized cost of hydrogen from electrolysis by 81%, the central and distributed natural gas cases by 40% and 43%, respectively, and all the other cases by less than 20%.

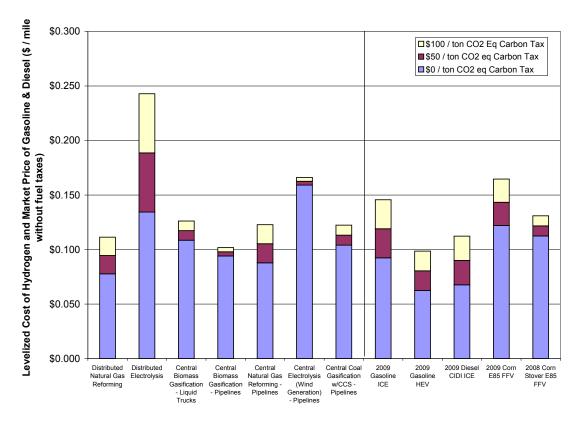


Figure 10.0.9. Levelized costs/market prices with possible carbon taxes for seven hydrogen pathways, three crude oil-based fuel options, and two E85 options

### 11.0 Analysis Gaps

FPITT of the FreedomCAR and Fuel Partnership is composed of representatives of four energy companies (ConocoPhillips, ExxonMobil, Chevron, and Shell), NREL, and the Hydrogen Systems Analyst of the U.S. Department of Energy. The energy company representatives on this team have conducted peer reviews of the hydrogen pathway analyses with the intention of identifying gaps in the analysis and opportunities for additional analysis. Some of the gaps that were identified have been addressed in analyses performed to date, and the results are incorporated in this report. Some gaps, however, have not yet been addressed or are beyond the scope of this effort; these gaps are noted below.

#### All Pathways

- One gap that was identified was the lack of consensus on the amount of hydrogen storage required at the forecourt site. Since identification of this gap, considerable effort has been directed toward understanding the on-site hydrogen storage needs for forecourt hydrogen stations. The amount of on-site storage assumed in this study for the distributed hydrogen production cases is 797 kg H<sub>2</sub> (62% of the design distribution capacity of the station). For the central hydrogen production pathways with gaseous hydrogen delivery via pipeline, on-site storage is assumed to be 1,052 kg H<sub>2</sub> (69% of the design distribution capacity of the station). For the station). For the central biomass–liquid truck delivery pathway, on-site storage is assumed to be 6,920 kg liquid H<sub>2</sub> plus 453 kg gaseous H<sub>2</sub> (486% of the design distribution capacity of the station).
- Additional analysis is needed to determine the ideal size and siting of hydrogen distribution stations.
- The on-board storage pressure for all the analyses in this report is 5,000 psi, which requires a pressure at distribution of 6,250 psi. Some organizations are considering on-board storage of compressed hydrogen at 10,000 psi and are interested in the effect of higher pressure on pathway cost, energy use, and emissions.
- The tradeoffs between hydrogen quality and fuel cell performance (i.e., durability, reliability, and efficiency) are not well understood.

#### Distributed Natural Gas and Distributed Electrolysis Pathways

- The hydrogen storage in the distributed electrolysis pathway is not optimized for peak power requirements. To optimize the pathway, the tradeoffs between the effects of full-time operation on the grid (transmission and distribution congestion and peaking power dispatch) and the costs of running the electrolyzers at less-than-full-time need to be understood, and a study over 8,760 hours/year is needed.
- The cascade storage volumes may need to be different for distributed production than for central production cases. The necessary volumes need more investigation.

#### All Centralized Production Pathways

- Hydrogen losses during both pipeline and liquid hydrogen delivery as estimated by HDSAM appear to be higher than those for natural gas delivery and may be higher than actual losses. Additional analysis is necessary to determine if the loss estimates are appropriate.
- Caverns may not be available in most locations for hydrogen storage; thus, alternative options for storing volumes of hydrogen necessary for seasonal variations, including storage as a liquid, need to be identified and characterized. The potential storage capacity for hydrogen should be compared to that for the current natural gas infrastructure.
- The need for hydrogen gas clean-up after the hydrogen is extracted from caverns or other geologic storage is not well understood and requires study. Gas clean-up requirements and costs are a gap in the analysis for all of the pathways employing hydrogen delivery by pipeline.
- The contribution of hydrogen distribution (service) pipelines to the cost of hydrogen is uncertain. The sensitivity of the hydrogen cost to the length of the distribution pipelines should be examined.
- Geologic storage is modeled currently with variable pressure; however, constant pressure is required in salt caverns. The pressure requirements for non-salt geologic structures are not well understood and require study.

#### Central Biomass Pathways

- Only woody biomass has been included in the analysis. The H2A production models do not currently include data to model herbaceous biomass feedstocks. The theoretical yields of hydrogen from herbaceous biomass should be compared with woody biomass. Empirical kinetic models on biomass gasification exist and may be used.
- The accuracy of the GREET default value for CO<sub>2</sub> emissions from gasification of woody biomass needs to be determined.
- There does not appear to be consensus in the scientific community on the best way to determine and communicate CO<sub>2</sub> emissions/absorption resulting from biomass production. Thus, this analysis does not include representation of the emissions from biomass production.
- The low-pressure gasifier currently used in the analysis may not be the optimal technology for hydrogen production. The results may be significantly different if a high-pressure gasifier is used because a high-pressure gasifier may increase conversion efficiency enough to overcome additional capital costs. A better understanding of the optimal gasifier technology for hydrogen production from biomass is needed.
- The effects of land use changes are not captured in this analysis.
- The land area required to support a specific size of gasifier needs to be calculated to determine if biomass transportation distance is a constraint to hydrogen production plant size. Road capacity is a potential constraint as well. While corn can be barged to some ethanol plants sited on rivers, not all crops and/or geographies will be

amenable to large-scale import of biomass feedstock. A statistical analysis is needed to evaluate the sensitivity of the hydrogen cost to transport distance.

- Using trucks to deliver biomass requires more petroleum than other potential options. Investigations of smaller conversion facilities, distributed gasification facilities with centralized hydrogen production and purification, and other conversion technologies (e.g., cold pyrolysis) are warranted.
- The sensitivity of the biomass/pipeline and biomass/truck pathway costs to power purchase prices should be examined. Producing power on-site using biomass feedstock would reduce the requirement for natural gas and electricity, as well as GHG emissions, to the extent that sufficient biomass is available at a viable cost. It may be worthwhile to configure the model to represent power production from biomass for internal gasification plant use (including liquefaction).

#### Central Natural Gas Pathway

• Natural gas costs may be different for central natural gas reforming facilities than for distributed reforming facilities. These costs should be compared. The cost of natural gas for the central natural gas pathway should also be compared to the price that utilities pay for natural gas at power plants.

#### Central Electrolysis Using Wind-Generated Electricity

- The actual price of wind-generated electricity is time-dependent and different than a grid-electricity price. This analysis used a single price of electricity that matched the grid price. Using the time-dependent price is a gap in this analysis.
- This analysis was based on a central electrolysis facility with an operating capacity factor of 97%. A facility may be co-sited with the wind turbines and have a lower operating capacity factor. The optimal location and capacity factor were not included in this analysis.

#### Central Coal with CCS Pathway

• The availability of carbon sequestration sites and the cost of monitoring at and upkeep of those sites were not included in this analysis. A single cost for sequestration was included.

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# Appendix A — Distributed Natural Gas Supporting Tables and Figures

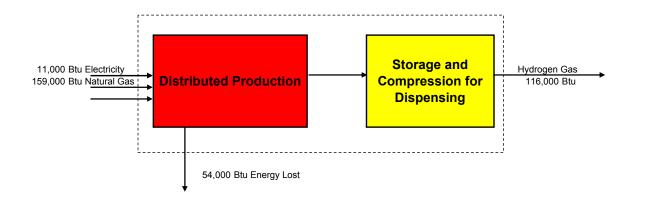
#### Location **Date Opened** Name Auburn, CA PG&E Service Center and Division Office 2004 Kia-Hyundai America Technical Center 2006 Chino, CA Oakland, CA AC Transit Oakland 2005 Torrance, CA Honda Home Energy 2003 Orlando International Airport Orlando, FL 2006 Selfridge Air National Guard Base (Chevron) Selfridge, MI 2007 Las Vegas, NV Las Vegas Energy Station 2002 Latham, NY Home Energy Station 2004 East Penn Manufacturing Distribution Center Topton, PA 2007 Austin, TX University of Texas 2007 Sustainable Transport Energy for Perth Perth, Australia 2004 Berlin, Germany Second Clean Energy Partnership Project 2006 Stuttgart, Germany **CUTE Bus Demonstration** 2003 Mantova, Italy AGIP MultiEnergy Public Service Station 2007 Milan, Italy Milan-Bicocca Project 2004 Nagoya, Japan Central Japan International Airport 2006 WE-NET Hydrogen Refueling Station Osaka, Japan 2002 Senju, Japan Senju Hydrogen Station 2002 Takamatsu, Japan WE-NET Hydrogen Refueling Station 2002 Tokai, Japan Toho Gas Research Laboratory 2002 Stavanger, Norway HyNor Stavangar Hydrogen Station 2006 Porto, Portugal **CUTE Bus Demonstration** 2003 Daejeon, S. Korea Korean Gas Technology Corporation 2006 **CUTE Bus Demonstration**

2003

Madrid, Spain

### Table A.1. Worldwide Distributed SMR Hydrogen Fueling Stations

### **Distributed Hydrogen Production**



Well-to-Wheels Total Energy Use (Btu/mile)	4,432
Well-to-Wheels Petroleum Energy Use (Btu/mile)	45
Well-to-Wheels Greenhouse Gas Emissions (g/mile)	305
Levelized Cost of H2 at Pump (\$/kg)	3.50

Production Process Energy Efficiency     71%       Pathway Efficiency     68%       WTP Efficiency     58%       WTP Emissions (lb CO2 Equivalent / GGE fuel available):     30		
WTP Efficiency     58%       WTP Emissions (lb     000000000000000000000000000000000000		71%
WTP Emissions (lb CO2 Equivalent / 30	Pathway Efficiency	68%
CO2 Equivalent / 30	WTP Efficiency	58%
	CO2 Equivalent /	30

### Case Definition

Year: 2005 Hydrogen as Gas Forecourt Production Natural Gas Feedstock Sequestration: No Transport for Delivery: None Vehicle Efficiency: 45.0 mile / GGE City Hydrogen Use: 344451 kg/day

Inputs		Graphic Depiction &	Assumptions	(	Outputs
		NG Recovery, Processir     NG Recovery Efficiency     NG emitted & combusted during recover,     NG processing energy efficiency     NG emitted & combusted during process     NG emitted & combusted during transpo	97.2% y 0.35% 97.2% in 0.15%	NG Delivery Pressure NG Quality at Delivery NG Cost NG Cost	Average of gas companies Average of gas companies \$0.243.2005 \$ / Nm^3 \$0.907.2005\$ / kg H2 distributed
Coal Input from "Well" Natural Gas Input from "Well" Petroleum Input from "Well"	322 Btu / 116000Btu to Pump 124,113 Btu / 116000Btu to Pump 497 Btu / 116000Btu to Pump	NG transport distance Compression Reqs (stages & eff) averag	500 miles	WTG CO2 Emissions WTG CH4 Emissions WTG N2O Emissions WTG GHG Emissions	636 g / 116000Btu to Pump 28 g / 116000Btu to Pump 0 g / 116000Btu to Pump 1,331 g CO2 eq./ 116000 Btu
Natural Gas consumption Electricity consumption Process Water Consumption Electricity price	4.5 N m^3/kg H2 produced 1.11 kWh / kg H2 5.77 L / kg H2 \$0.0816 2005 \$/kWh	Hydrogen Prod Design Capacity Capacity factor	uction 1,500 kg/day 85%	Hydrogen Output Pressure Hydrogen Outlet Quality Total capital investment Electricity cost	300 psi 1 \$2.44 2005\$ / annual kg H2 (effective \$0.09 2005\$ / kg H2 produced
Total Capital Investment	\$1,138,995 2005\$	Process energy efficiency Electricity Mix After-tax IRR Assumed Plant Life	71.3% US Mix 10% 20 years	Other operating costs Levelized Cost of Prod (excl feeds	\$0.36 2005\$ / kg H2 produced t \$0.71 2005\$ / kg H2 distributed
Coal Input from "Well" Natural Gas Input from "Well" Petroleum Input from "Well"	6,572 Btu / 116000Btu to Pump 47,754 Btu / 116000Btu to Pump 664 Btu / 116000Btu to Pump			SMR CO2 Emissions SMR CH4 Emissions SMR N2O Emissions SMR GHG Emissions	10,523 g / 116000Btu to Pump 11 g / 116000Btu to Pump 0 g / 116000Btu to Pump 10,815 g CO2 eq./ 116000 Btu
Electricity consumption	1.96 kWh / kg H2	Compression, Storage,	& Dispensing	Hydrogen outlet pressure Basis Hydrogen Quantity	6,250 psi 116,000 Btu (116,000 Btu/gal non-oxyg
Total Capital Investment	\$3,993,763 2005\$	Number of Distribution Stations Energy efficiency Number of Compression Stages Isentropic Efficiency Site storage	270 94% 6 65% 62% capacity	Total capital investment Electricity cost Levelized Cost of Distribution CSD CO2 Emissions	\$8.56 2005\$ / annual kg H2 (effective \$0.16 2005\$ / kg H2 \$1.88 2005\$ / kg H2 distributed 1.502 g / 116000Btu to Pump
Coal Input from "Well" Natural Gas Input from "Well" Petroleum Input from "Well"	11,382 Btu / 116000Btu to Pump 3,269 Btu / 116000Btu to Pump 848 Btu / 116000Btu to Pump			CSD CH4 Emissions CSD N2O Emissions CSD GHG Emissions	2 g / 116000Btu to Pump 0 g / 116000Btu to Pump 1,558 g CO2 eq./ 116000 Btu
		Well-to-Pump Results Coal Input from "Well" Petroleum Input from "Well" Fossil Energy Input from "Well" WTP CO2 Emissions WTP CH4 Emissions WTP CH4 Emissions WTP GHG Emissions	18,276 Btu / 116000 Btu 175,136 Btu / 116000 Btu 2,009 Btu / 116000 Btu 195,421 Btu / 116000 Btu 12,667 g / 116000 Btu 41 g / 116000 Btu 0 g / 116000 Btu 13,710 116000 Btu		

Levelized Cost of Hydrogen (\$/kg)

Vehicle Fuel Economy Ratio of FCV VOCs (exaissions) to GVs fueled with CG & RFG Ratio of FCV VOCs (exaporative) to GVs fueled with CG & RFG Ratio of FCV CO emissions to GVs fueled with CG & RFG Ratio of FCV NOx emissions to GVs fueled with CG & RFG

Ratio of FCV Exhaust PM10 emissions to GVs fueled with CG & RFG

Ratio of FCV Brake & Tire Wear PM10 emissions to GVs fueled with CG & RFG

Ratio of FCV Exhaust PM2.5 emissions to GVs fueled with CG & RFG

Ratio of FCV Brake & Tire Wear PM2.5 emissions to GVs fueled with CG & RFG Ratio of FCV CH4 emissions to GVs fueled with CG & RFG Ratio of FCV N2O emissions to GVs fueled with CG & RFG

Well-to-Wheel Results Coal Input from "Well" Natural Gas Input from "Well" Petroleum Input from "Well" Fossil Energy Input from "Well" WTW CO2 Emissions WTW CH4 Emissions WTW QHG Emissions

Levelized Cost of Hydrogen (\$/mi)

Vehicle

\$3.50 2005 \$/ kg

45.0 mi / GGE 0% 0% 0% 0%

0%

100%

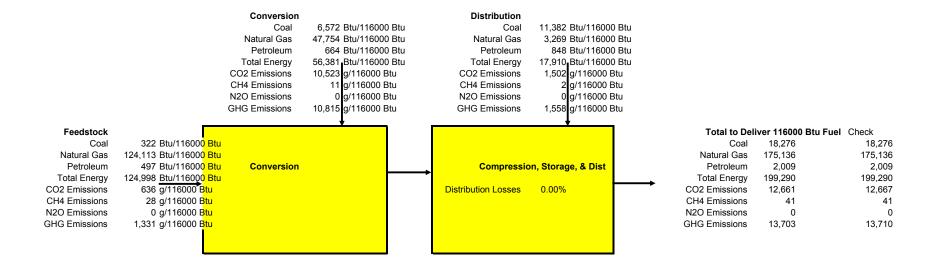
0%

100% 0% 0%

406 Btu / mi 3,895 Btu / mi 45 Btu / mi 4,346 Btu / mi 282 g / mi 1 g / mi 0 g / mi 305 g / mi

\$0.0777 2005 \$/mi

Dist-SMR Pathway Details R090219C 090817 v09.xls 178



Paran	neter		Value	Units	Reference	Comments
ase C	Definition	1				
	Base Yea	ar	2005		None	Default for Dist-SMR Pathway study
		n Technology	Woody Biomass		None	Default for Dist-SMR Pathway study
	Form of H Delivery M		Liquid Liquid Truck		None	Default for Dist-SMR Pathway study Default for Dist-SMR Pathway study
					James, B.D. (2008, May 23).Current (2005) Steam Methan Reformer (SMR) at Forecourt	
		t Station Size		kg/day	1500kg/day. Arlington, VA: Directed Technologies Inc.	Current forecourt H2A production from natural gas basis version 2.0.1; Input_Sheet_Template tab; Plant Output, cell
	Vehicle T	уре	passenger cars		None	Default for Dist-SMR Pathway study
	Vehicles'	Fuel Economy	45.0	mile / gge	Rousseau, A. & Wallner, T. (2008, October 7) Prospects on Fuel Efficiency Improvements for Hydrogen Powered Vehicles. Argonne National Laboroatory presentation, Chicago, IL. Retreive from http://www.transportation.ani.gov/pdfs/HV/530.pdf	Calculated from data in the presentation. The fuel economy for today's average mid-size vehicle was estimated by th Powertrain Simulation Analysis Tookit V 6.2 SP1, Summer 2008 (PSAT - Mitp://www.transportation.ani.gov/modeling_simulation/PSAT/index.html). 45 mile/gge is the estimated on-road fuel economy which was determined by multiplying the projected EPA lab-rated fuel economy of 52.5 mile/gge by 0.85.
arket	t Definitio	on				
	City Popu	ulation	1,247,364	people	Elgowainy, A., Mintz, M. & Gillette, J. (2006) Hydrogen Delivery Scenario Analysis Model (HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	HDSAM City Selection; Scenario tab; Indianapolis, IN, cell B9
			500/		U.S. Department of Energy & U.S. Department of Transportation. (2006, DecemberHydrogen	
	Market pe	enetration	50%	(% vehicles in city)	Posture Plan An Inegrated Research, Development and Demonstration Pla.	Basis for posture plan
		of H2 vehicles in city		H2 vehicles / city	Elgowainy, A., Mintz, M. & Gillette, J. (2006) Hydrogen Delivery Scenario Analysis Model	Demand calculation by HDSAM version 2.02; Scenario tab; Number of H2 vehicles in city, cell F17
	Miles driv	ven per vehicle		mile / vehicle year	Elgowainy, A., Mintz, M. & Gillette, J. (2006) Hydrogen Delivery Scenario Analysis Model	Key delivery input in HDSAM version 2.02; Scenario tab; Miles driven per year/ vehicle, cell C19
_	City hydro	pgen use	344,451		Elgowainy, A., Mintz, M. & Gillette, J. (2006) Hydrogen Delivery Scenario Analysis Model	Demand calculation by HDSAM version 2.02; Scenario tab; City H2 daily use, cell F18
				kg/u	(HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	
	Number o	of H2 refueling stations in city	270		Elgowainy, A., Mintz, M. & Gillette, J. (2006) Hydrogen Delivery Scenario Analysis Model (HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	Demand calculation by HDSAM version 2.02; Scenario tab; Number of H2 fueling stations in city, cell F19
	Number o	of H2 stations/Number of gasoline stations	41%		Elgowainy, A., Mintz, M. & Gillette, J. (2006) Hydrogen Delivery Scenario Analysis Model (HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	Demand calculation by HDSAM version 2.02; Scenario tab; Number of H2 stations/Number of gasoline stations, cell
	Average of	distance between stations (mi)	1.46	miles	Elgowainy, A., Mintz, M. & Gillette, J. (2006) <i>Hydrogen Delivery Scenario Analysis Model</i> (HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	Demand calculation by HDSAM version 2.02; Scenario tab; Average distance between stations, cell F22
eedst	tock Rec	overy, Processing, & Transport				
omas	s					
	Percentag	ge of Woody Biomass (Remainder is Herbaceous)	100%		Mann, M & Steward, D.M. (2008, May 28).Current (2005) Hydrogen from Biomass via Gasification and Catalytic Steam Reforming Golden, CO: National Renewable Energy	Current central H2A production via biomass gasification version 2.1.2 basis
	Biomass	Moisture Content	25%		Laboratory Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1:	Page 66
					Methodology, development, Use and Results. Argonne, IL: Argonne National Laboratory.	
	Grams of	Nitrogen / short ton biomass	709	g / dry ton	M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walsh 1998).	Equivalent to 75 lb N / ac in the maintenance year Year 3 or 4) which is reported by De La Torre Ugarte, 2003, App assuming 6 dry tons biomass per acre, and harvesting once every 8 years. App 3.1 is for planting on cropland that w used for traditional crops.
		Nitrogen / short ton biomass P2O5 / short ton biomass		g / dry ton g / dry ton	M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walsh 1999). M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walsh 1998).	Equivalent to 75 lb N / ac in the maintenance year Year 3 or 4) which is reported by De La Torre Ugarte, 2003, App 2 hassuming 6 dry tons biomass per acre, and harvesting once very 8 years. App 3.1 is for planting on cropland that w used for traditional crops. Equivalent to 20 lb P / ac in the maintenance year (Year 3) which is in the range of 15-50 lb P / ac reported by De La Ugarte, 2003, App 3.1, assuming 6 dry tons biomass per ace and harvesting once event 8 years
	Grams of	•	709		M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walsh 1999). M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walsh 1998).	Equivalent to 75 lb N / ac in the maintenance year Year 3 or 4) which is reported by De La Torre Ugarte, 2003, App 5 assuming 6 dry tons biomass per acre, and harvesting once very 8 years. App 3.1 is for planting on cropland that used for fraditional crops. Equivalent to 20 lb P / ac in the maintenance year (Year 3) which is in the range of 15-50 lb P / ac reported by De La Ugarte. 2003, App 3.1, assuming 6 dry tons biomass per acre and harvesting once every 8 years Equivalent to 35 lb K / ac in the maintenance year (Year 3) which is in the range of 15-50 lb K / ac reported by De La Equivalent to 35 lb K / ac in the maintenance year (Year 3) which is in the range of 15-50 lb K / ac reported by De La Ugarte. 2003, App 3.1, assuming 6 dry tons biomass per acre and harvesting once every 8 years)
	Grams of Grams of	P2O5 / short ton biomass	709 189	g / dry ton	M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst 1998). M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst 1998). M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst 1998). M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst 1998).	Equivalent to 75 lb N / ac in the maintenance year Year 3 or 4) which is reported by De La Torre Ugarte, 2003, App assuming 6 dry tons biomass per acre, and harvesting once very 8 years. App 3.1 is for planting on cropland that w used for fraditional crops. Equivalent to 20 lb P / ac in the maintenance year (Year 3) which is in the range of 15-50 lb P / ac reported by De La Ugarte, 2003, App 3.1, assuming 6 dry tons biomass per acre and harvesting once every 8 years Equivalent to 35 lb K / ac in the maintenance year (Year 3) which is in the range of 15-50 lb K / ac reported by De La Ugarte, 2003, App 3.1, assuming 6 dry tons biomass per acre and harvesting once every 8 years Equivalent to 35 lb K / ac in the maintenance year (Year 3) which is in the range of 15-50 lb K / ac reported by De La Equivalent to 2.0 lb herbicide / ac in the planting year which similar to the 2.0 lb hybricaste / ac reported by De La T Ugarte, 2003, App 3.2, assuming 6 dry tons biomass per acre and harvesting once every 8 years). Equivalent to 2.0 lb herbicide / a dry tons biomass per acre and harvesting once every 8 years.
	Grams of Grams of Grams of	P2O5 / short ton biomass K2O / short ton biomass	709 189	g / dry ton g / dry ton g / dry ton	M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst 1998). M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst 1998). M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst 1998). M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst 1998).	Equivalent to 75 lb N / ac in the maintenance year Year 3 or 4) which is reported by De La Torre Ugarte, 2003, App. assuming 6 dry tons biomass per acre, and harvesting once very 6 years. App 3.1 is for planting on cropland that we used for traditional crops. Equivalent to 20 lb P / ac in the maintenance year (Year 3) which is in the range of 15-50 lb P / ac reported by De La Ugarte, 2003, App 3.1, assuming 6 dry tons biomass per acre and harvesting once every 8 years. Equivalent to 35 lb K / ac in the maintenance year (Year 3) which is in the range of 15-50 lb K / ac reported by De La Ugarte, 2003, App 3.1, assuming 6 dry tons biomass per acre and harvesting once every 8 years. Equivalent to 35 lb K / ac in the maintenance year (Year 3) which is in the range of 15-50 lb K / ac reported by De La Ugarte, 2003, App 3.1, assuming 6 dry tons biomass per acre and harvesting once every 8 years. Equivalent to 2.0 lb hetricide / ac in the planting year which similar to the 2.0 lb glyphosate / ac reported by De La Tiflugarte, 2003, App 3.2, assuming 6 dry tons biomass per acre and harvesting once every 8 years. Bugarte, 2004, App 3.2, assuming 6 dry tons biomass per acre and harvesting once every 8 years. Bugarte, 2004, App 3.2, assuming 6 dry tons biomass per acre and harvesting once every 8 years. Bodto reported Tifluralin (5 Lha) and Metribuzin (395 gha), App 3.2 ls for planting on currently idled cropland or cropland that was used for pasture. As a check, looked at Chastagner: Up to 5% of acreage annually spraved with Dimethoate (Digon 400, 2.3 pints per acre, up to 5% of acreage annually spraved with Parenthrin 2.B. (Ambush, 6.4 ounces per acre); Up to 12% of acreage annually spraved with Dimethoate (Digon 400, 2.3 pints per acre); up to 5% of acreage annually spraved with Dimethoate (Digon 400, 1.2% pints per sub to 12% of acreage annually spraved with Dimethoate (Digon 400, 1.2% pints per acre ) which are an ender sub sprayed with Parenthrin 2.B. (Ambush, 6.4 ounces per acre); Up to 12% of acre
	Grams of Grams of Grams of Grams of	P2O5 / short ton biomass (K2O / short ton biomass I herbicide / short ton biomass	709 189 331 24 2	g / dry ton g / dry ton	M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walsh 1998).     M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walsh 1998).     M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walsh 1998).     M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walsh 1998).     M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walsh 1998).     M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walsh 1998).     M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walsh 1998).	Equivalent to 75 lb N as in the maintenance year Year 3 or 4) which is reported by De La Torre Ugarte, 2003. App assuming 6 dy yone biomass per acce, and harvesting once every 8 years. App 3.1 is for planting on cropland that v used for traditional crops. Equivalent to 20 lb P / ac in the maintenance year (Year 3) which is in the range of 15.50 lb P / ac reported by De Li Ugarte, 2003. App 3.1 assuming 6 dry tons biomass per acre and harvesting once every 8 years. Equivalent to 20 lb P / ac in the maintenance year (Year 3) which is in the range of 15.50 lb F / ac reported by De Li Ugarte, 2003. App 3.1 assuming 6 dry tons biomass per acre and harvesting once every 8 years). Equivalent to 20 lb horbicide / ac in the planting year which similar to the 2.0 b glynobael / ac reported by De Li Ugarte, 2000. App 3.2 assuming 6 dry tons biomass per acre and harvesting once every 8 years). Equivalent to 2.0 lb horbicide / ac in the planting year which similar to the 2.0 b glynobael / ac reported by De Li Ugarte, 2000. App 3.2 assuming 6 dry tons biomass per acre and harvesting once every 8 years. Booth reported Triffrain (6 Lha) and Metribuzin (986 gha). App 3.2 is for planting on currently tilded cropland or cropland that was used for pasture. As a check, looked at Chastagener: Up to 56% of acreage annually sprayed with Dimethoate (Digon 400. 2-3 pints pr acre); up to 56% of acreage annually sprayed with Permethin 2.1 6, Annush, 4.4 ounces per acre); Up to 12% of a annually sprayed with Endosulting 3.5 (Cz 40. WA 200025, 2 tg ts per acre).
	Grams of Grams of Grams of Grams of Grams of	P2O5 / short ton biomass K2O / short ton biomass *herbicide / short ton biomass insecticide / short ton biomass CO2 removed from atmosphere per dry ton woody biomass produced	709 189 331 24 2	g / dry ton g / dry ton g / dry ton g / dry ton g / dry ton	M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst 1999).     M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst 1999).     M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst 1999).     M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst 1999).     M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst 1999).     M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst 1999).     M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst 1999).     Wang, M. O. (1999, August). <i>GREET 1.5 - Transportation Fuel-Cycle Model Volume 1</i> :	Equivalent to 75 lb N as in the maintenance year Year 3 or 4) which is reported by De La Torre Ugarte, 2003, App assuming 6 dry tons biomass per acre, and harvesting once every 8 years. App 3.1 is for planting on cropland that used for traditional crops. In the maintenance year (Year 3) which is in the range of 15-50 lb P ac reported by De Li Equivalent to 30 lb r/s and the maintenance year (Year 3) which is in the range of 15-50 lb P / ac reported by De Li Ugarte, 2003, App 3.1 assuming 6 dry tons biomass per acre and harvesting once every 8 years. Equivalent to 30 lb r/s is in the maintenance year (Year 3) which is in the range of 15-50 lb P / ac reported by De Li Ugarte, 2003, App 3.1 assuming 6 dry tons biomass per acre and harvesting once every 8 years. Equivalent to 20 lb herbiode / ac in the planting year which aimlar to the 2.0 by bythostae / ac reported by De La Ugarte, 2003, App 3.1 assuming 6 dry tons biomass per acre and harvesting once every 8 years. Bolt Equivalent to 2.0 lb herbiode / ac in the planting year which aimlar to the 2.0 bythostae / ac reported by De La Triffuralin (5 Lha) and Methuzun (395 gha). App 3.2 ls for planting on currently lided cropland or cropland that was used for pasture. As a check, kooked at Chastagner: Up to 55% of acreage annually syrayed with Dimethoate (Digon 400, 2-3 pints p annually syrayed with doubland BEC (24 W-4990022, 24 gb er acre). (BreET model default based on ANL personal communications
	Grams of Grams of Grams of Grams of Average of	P2O5 / short ton biomass (K2O / short ton biomass I herbicide / short ton biomass	709 189 331 24 2	g / dry ton g / dry ton g / dry ton	M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst 1999).     M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst 1999).     M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst 1999).     M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst 1999).     M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst 1999).     M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst 1999).     M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst 1999).	Equivalent to 75 lb N as in the maintenance year Year 3 or 4) which is reported by De La Torne Ugarte. 2003. App assuming 6 dy yone biomass per acce, and harvesting once every 8 years. App 3.1 is for planting on cropland that used for traditional crops. Equivalent to 2016 P / ac in the maintenance year (Year 3) which is in the range of 15.50 lb P / ac reported by De L Ugarte. 2003. App 3.1 assuming 6 dry tors biomass per acre and harvesting once every 8 years Equivalent to 20 lb r / ac in the maintenance year (Year 3) which is in the range of 15.50 lb K / ac reported by De L Ugarte. 2003. App 3.1 assuming 6 dry tors biomass per acre and harvesting once every 8 years Equivalent to 20 lb r horticide / a cin the planting year which similar to the 2.0 b glynoset / ac reported by De La Tiguriarte. 2000. App 3.2 assuming 6 dry tons biomass per acre and harvesting once every 8 years. Equivalent to 2.0 lb horticide / ac in the planting year which similar to the 2.0 b glynoset / ac reported by De La Tiguriarte. 10 a lb horticide / ac in the planting year which similar to the 2.0 b glynoset / ac reported by De La S a check, looked at Chastagener. Up to 56% of acreage annually sprayed with Dimethoate (Digon 400. 2-3 pints p face); up to 56% of acreage annually sprayed with Permethin 2.16 (Ambush, 64 ounces per acre); Up to 12% of a annually sprayed with Endocultar 3.50 (24 cM x x 2005. 2 (st per acre).
atural	Grams of Grams of Grams of Grams of Average of Gas	P2O5 / short ton biomass K2O / short ton biomass insticide / short ton biomass insecticide / short ton biomass iCO2 removed from atmosphere per dry ton woody biomass produced distance from farm to hydrogen production facility	709 189 331 24 2 -112,500 40	g / dry ton g / dry ton g / dry ton g / dry ton g / dry ton	M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst 1999).     M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst 1999).     M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst 1999).     M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst 1999).     M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst 1999).     M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst 1999).     Walsh (personal communication via telephone and meeting between M. Wang and M. Walst 1999).     Wang, M. O. (1999, August). <i>GREET 1.5 - Transportation Fuel-Cycle Model Volume 1:</i> Methodology, development, Use and Result: Argonne, IL: Argonne National Laboratory.	Equivalent to 75 lb N / ac in the maintenance year Year 3 or 4) which is reported by De La Torre Ugarte, 2003, App assuming 6 dry tons biomass per acre, and harvesting once very 8 years. App 3.1 is for planting on cropland that veated for traditional crops. Equivalent to 20 lb P / ac in the maintenance year (Year 3) which is in the range of 15:50 lb P / ac reported by De L [Equivalent to 20 lb P / ac in the maintenance year (Year 3) which is in the range of 15:50 lb K / ac reported by De L [Equivalent to 35 lb K / ac in the maintenance year (Year 3) which is in the range of 15:50 lb K / ac reported by De L [Equivalent to 35 lb K / ac in the maintenance year (Year 3) which is in the range of 15:50 lb K / ac reported by De L [Equivalent to 35 lb K / ac in the maintenance year (Year 3) which is in the range of 15:50 lb K / ac reported by De L [Equivalent to 2.0 lb hetricide / ac in the planting year which similar to the 2.0 lb hyphosate / ac reported by De L [Equivalent to 2.0 lb hetricide / ac in the planting year which similar to the 2.0 lb hyphosate / ac reported by De L [Equivalent to 2.0 lb hetricide / ac in the planting year which similar to the 2.0 lb hyphosate / ac reported by De L [Equivalent to 4.0 lb hetricide / ac in the planting year which similar to the 2.0 lb hyphosate / ac reported by De L [Equivalent 5.0 lb hetricide / ac in the planting year which which were similar to the 2.0 lb hyphosate / ac reported by De L [Equivalent 5.0 lb hetricide / ac in the planting yeary which which were similar to a complant that was used for pastive. [Equivalent 6.0 hoted at Chastagner: Up to 56% of acreage annually sprayed with Dimethoate (Digon 400, 2-3 pints p annually spraved with Endosultina 3 EC (24c WA-990025, 2 dts per acre). [GREET model default based on ANL personal communications [GREET model default based on ANL p
ntural	Grams of Grams of Grams of Grams of Average of Gas	P2O5 / short ton biomass K2O / short ton biomass *herbicide / short ton biomass insecticide / short ton biomass CO2 removed from atmosphere per dry ton woody biomass produced	709 189 331 24 2	g / dry ton g / dry ton g / dry ton g / dry ton g / dry ton	M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walsh 1998).     M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walsh 1998).     M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walsh 1998).     M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walsh 1998).     M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walsh 1998).     M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walsh 1998).     M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walsh 1998).     Wangh (Quersonal communication via telephone and meeting between M. Wang and M. Walsh 1998).     Wangh (Quersonal communication via telephone and meeting between M. Wang and M. Walsh 1998).     Wangh (Quersonal communication via telephone and meeting between M. Wang and M. Walsh 1998).     Wangh (Quersonal communication via telephone and meeting between M. Wang and M. Walsh 1998).     Wangh (Quersonal communication via telephone and meeting between M. Wang and M. Walsh 1998).     Wangh (Quersonal communication via telephone and meeting between M. Wang and M. Walsh 1998).     Wangh (Quersonal communication via telephone and meeting between M. Wang and M. Walsh 1998).     Wangh (Quersonal communication via telephone and meeting between M. Wang and M. Walsh 1998).     Wangh (Quersonal communication via telephone and meeting between M. Wang and M. Walsh 1998).     Wangh (Quersonal communication via telephone and meeting between M. Wangh (Quersonal communication via telephone and meeting between M. Wangh (Quersonal communication via telephone and meeting between M. Wangh (Quersonal communication via telephone and meeting between telephone and telephone and telephone an	Equivalent to 75 lb N as in the maintenance year Year 3 or 4) which is reported by De La Torre Ugarte, 2003, App assuming 6 dry tons biomass per acre, and harvesting once every 8 years. App 3.1 is for jlanting on criptiand har used for traditional cross. In the maintenance year (Year 3) which is in the range of 15-50 lb 7 as reported by De Li Equivalent to 30 lb r/s and the maintenance year (Year 3) which is in the range of 15-50 lb 7 as reported by De Li Ugarte, 2003, App 3.1 assuming 6 dry tons biomass per acre and harvesting once every 8 years. Equivalent to 35 lb r/s are the maintenance year (Year 3) which is in the range of 15-50 lb 7/ as reported by De Li Ugarte, 2003, App 3.1 assuming 6 dry tons biomass per acre and harvesting once every 8 years. Equivalent to 25 lb r/s as the maintenance year (Year 3) which is in the range of 15-50 lb 7/ as reported by De Li Ugarte, 2003, App 3.1 assuming 6 dry tons biomass per acre and harvesting once every 8 years. Equivalent to 2.0 lb hetribide / ac in the planting year which similar to the 2.0 b physicsale / as reported by De Li Tifluzarie, (51 hb) and Metribuzin (38 gr hb). App 3.2 ls for planting on currently lided cropland or cropland that was used for pasture. As a check, kooked at Chastagner: Up to 55% of acreage annually sprayed with Permethrin 2.18 (Anbush, 6.4 ounces per acre), Up to 12% of a amually sprayed which dividual to bace (24 W-M-990022, 24 gp era acre). (GREET model which tablead to ANL personal communications
atural	Grams of Grams of Grams of Grams of Average of Gasson NG recov	P2O5 / short ton biomass K2O / short ton biomass insticide / short ton biomass CO2 removed from atmosphere per dry ton woody biomass produced distance from farm to hydrogen production facility ery efficiency	709 189 331 24 2 2 -112,500 40 97.2%	g / dry ton g / dry ton g / dry ton g / dry ton g / dry ton	M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walsh 1998).     M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walsh 1998).     M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walsh 1998).     M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walsh 1998).     M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walsh 1998).     M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walsh 1998).     M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walsh 1998).     Wangh (QL) (1999, August). <i>GREET 1.5 - Transportation Fuel-Cycle Model Volume 1:</i> Methodology, development, Use and Result. Argonne, IL: Argonne National Laboratory.     Wang, M.O. (1999, August). <i>GREET 1.5 - Transportation Fuel-Cycle Model Volume 1:</i> Methodology, development, Use and Result. Argonne, IL: Argonne National Laboratory.     Wang, M.O. (1999, August). <i>GREET 1.5 - Transportation Fuel-Cycle Model Volume 1:</i> Methodology. development, Use and Result. Argonne, IL: Argonne National Laboratory.	Equivalent to 75 lb N / ac in the maintenance year Year 3 or 4) which is reported by De La Torre Ugarte, 2003, App assuming 6 dry tons biomass per acre, and harvesting once very 8 years. App 3.1 is for planting on cropland that v used for traditional crops. Equivalent to 20 lb P / ac in the maintenance year (Year 3) which is in the range of 15-50 lb P / ac reported by De L Equivalent to 20 lb P / ac in the maintenance year (Year 3) which is in the range of 15-50 lb F / ac reported by De L Equivalent to 35 lb K / ac in the maintenance year (Year 3) which is in the range of 15-50 lb K / ac reported by De L Equivalent to 35 lb K / ac in the maintenance year (Year 3) which is in the range of 15-50 lb K / ac reported by De L Equivalent to 20 lb P / ac suming dery tons biomass per acre and harvesting once every 8 years. Equivalent to 2.1 b herbicide / ac in the planting year which similar to the 2.0 lb gryphosate / ac reported by De La Tugarte, 2003, App 3.2, assuming d dry tons biomass per acre and harvesting once every 8 years. Bed of planting of a dry tons biomass per acre and harvesting once every 8 years. Bed of planting of dry tons biomass per acre and harvesting once every 8 years. Bed of planting (5 Lha) and Metribuzin (395 gha). App 3.2 ls for planting on currently lided cropland cor cropland that was used for pasture. As a check, looked at Chastagner: Up to 56% of acreage annually sprayed with Dimethoate (Digon 400, 2-3 pints p acre; up to 56% of acreage annually sprayed with Permethin/ 2.18 (Annush, 6 4 ounces per acre); Up to 512% of acreage annually sprayed with Endealut based on ALL personal Communications GREET model featult based on ALL personal Communications GREET uses 97% which is comparable to several other models (Table 4.11)
atural	Grams of Grams of Grams of Grams of Average of Gasson NG recov	P2O5 / short ton biomass K2O / short ton biomass insticide / short ton biomass insecticide / short ton biomass iCO2 removed from atmosphere per dry ton woody biomass produced distance from farm to hydrogen production facility	709 189 331 24 2 -112,500 40	g / dry ton g / dry ton g / dry ton g / dry ton g / dry ton	M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst 1999). M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst 1999). M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst 1998). M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst 1998). M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst 1998). M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst 1998). M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst 1998). M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst 1998). Wang, M. O. (1999, August). <i>GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology, development, Use and Result, Argonne, IL: Argonne National Laboratory.</i> Wang, M. O. (1999, August). <i>GREET 1.5 - Transportation Fuel-Cycle Model Volume 7: Methodology, development, use and Result, Surgonne, Li L'Argonne</i> National Laboratory. Wang, M. O. (1999, August). <i>GREET 1.5 - Transportation Fuel-Cycle Model Volume 7: Methodology, development, Use and Result, Argonne, IL: Argonne</i> National Laboratory. Wang, M. O. (1999, August). <i>GREET 1.5 - Transportation Fuel-Cycle Model Volume 7: Methodology, development, Use and Result, Argonne, IL: Argonne</i> National Laboratory. Wang, M. O. (1999, August). <i>GREET 1.5 - Transportation Fuel-Cycle Model Volume 7: Methodology, development, Use and Result, Argonne</i> , IL: Argonne National Laboratory. Wang, M. O. (1999, August). <i>GREET 1.5 - Transportation Fuel-Cycle Model Volume 7:</i> Methodology. <i>Beetopment</i> See and Result, Argonne, IL: Argonne National Laboratory. Wang, M. O. (1999, August). <i>GREET 1.5 - Transportation Fuel-Cycle Model Volume 7:</i> Methodology. <i>Beetopment</i> See and Result, Argonne, IL: Argonne National Laboratory. Wang, M. O. (1999, August). <i>GREET 1.5 - Transportation Fuel-Cycle Model Volume 7:</i>	Equivalent to 75 lb N / ac in the maintenance year Year 3 or 4) which is reported by De La Torre Ugarte, 2003, App assuming 6 dry tons biomass per acre, and harvesting once every 8 years. App 3.1 is for planting on cropland that valued for traditional crops. Equivalent to 20 lb P / ac in the maintenance year (Year 3) which is in the range of 15-50 lb P / ac reported by De L Equivalent to 20 lb P / ac in the maintenance year (Year 3) which is in the range of 15-50 lb K / ac reported by De L (Jugarte, 2003, App 3.1, assuming 6 dry tons biomass per acre and harvesting once every 8 years Equivalent to 35 lb K / ac in the maintenance year (Year 3) which is in the range of 15-50 lb K / ac reported by De L L (Jugarte, 2003, App 3.1, assuming 6 dry tons biomass per acre and harvesting once every 8 years) Equivalent to 2.0 lb hetricide / ac in the planting year which similar to the 2.0 lb hyphosate / ac reported by De L La Tidgarte, 2003, App 3.2, assuming 6 dry tons biomass per acre and harvesting once every 8 years). Equivalent to 2.0 lb hetricide / ac in the planting year which similar to the 2.0 lb hyphosate / ac reported by De L La Tidgarte, 2004, App 3.2, assuming 6 dry tons biomass per acre and harvesting once every 8 years). Booth reported Trifluralin (5 Lha) and Metribuzin (395 gha). App 3.2 is for planting on currently idled cropland or cropland that was used for pasture. As a check, looked at Chastagner: Up to 56% of acreage annually sprayed with Dimethoate (Digon 400, 2-3 pints p aonually spraved with Endocultina 3 EC (24c WA-990025, 2 dts per acre). GREET model default based on ANL personal communications GREET model default based on ANL personal communications GREET model default based on ANL personal communications
atural	Grams of Grams of Grams of Grams of Average of Gas NG recov NG used	P2O5 / short ton biomass K2O / short ton biomass herbicide / short ton biomass insecticide / short ton biomass iCO2 removed from atmosphere per dry ton woody biomass produced distance from farm to hydrogen production facility ery efficiency & tost during recovery	709 189 331 24 2 2 -112,500 40 97.2% 0.35%	g / dry ton g / dry ton g / dry ton g / dry ton g / dry ton	M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walsh 1999). M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walsh 1999). M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walsh 1999). M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walsh 1998). M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walsh 1998). M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walsh 1998). M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walsh 1998). M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walsh 1998). Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology, development, Use and Result. Argonne, IL: Argonne National Laboratory. Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology, development, Use and Result. Argonne, National Laboratory. Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology, development, Use and Result. Argonne, IL: Argonne National Laboratory. Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology, development, Use and Result. Argonne, IL: Argonne National Laboratory. Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology, development, Use and Result. Argonne, IL: Argonne National Laboratory. Wang, M.G. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology, development, Use and Result. Argonne, IL: Argonne National Laboratory. Wang, M.G. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology, development, Use and Result. Argonne, IL: Argonne National Laboratory.	Equivalent to 75 lb N / ac in the maintenance year Year 3 or 4) which is reported by De La Torre Ugarte, 2003, App assuming 6 dry tons biomass per acre, and harvesting once very 8 years. App 3.1 is for planting on cropland that v used for traditional crops. Equivalent to 20 lb P / ac in the maintenance year (Year 3) which is in the range of 15-50 lb P / ac reported by De L Equivalent to 20 lb P / ac in the maintenance year (Year 3) which is in the range of 15-50 lb F / ac reported by De L Equivalent to 35 lb K / ac in the maintenance year (Year 3) which is in the range of 15-50 lb K / ac reported by De L Equivalent to 35 lb K / a cin the maintenance year (Year 3) which is in the range of 15-50 lb K / ac reported by De L Equivalent to 35 lb K / a cin the maintenance year (Year 3) which is in the range of 15-50 lb K / ac reported by De L Equivalent to 2.0 lb hetricide / ac in the planting year which similar to the 2.0 lb glyphosate / ac reported by De L Thugarte. 2003. App 3.2, assuming d ry tons biomass per acre and harvesting once every 8 years. Bug of planting (5 Lha) and Metribuzin (395 gha). App 3.2 ls for planting on currently lidled cropland or cropland that was used for pasture. As a check, looked at Chastagner: Up to 56% of acreage annually sprayed with Dimethoate (Digon 400, 2-3 pints p acre; up to 56% of acreage annually sprayed with Dimethoate (Digon 400, 2-3 pints p CREET model default based on ANL personal communications GREET tasis: distance could be limited by transport costs? GREET tasis: distance comparable to several other models (Table 4.11) GREET tasis
atural	Grams of Grams of Grams of Grams of Grams of Average of Average of NG recov NG used NG proce	P2O5 / short ton biomass K2O / short ton biomass 'herbicide / short ton biomass 'insecticide / short ton biomass CO2 removed from atmosphere per dry ton woody biomass produced distance from farm to hydrogen production facility ery efficiency & lost during recovery ussing energy efficiency	709 189 331 24 -112,500 40 97.2% 0.35% 97.2%	g / dry ton g / dry ton g / dry ton g / dry ton g / dry ton	M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst 1998).     M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst 1998).     M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst 1998).     M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst 1998).     M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst 1998).     M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst 1998).     M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst 1998).     Wang, M.O. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology, development, Use and Result. Argonne, IL: Argonne National Laboratory. Wang, M.O. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology, development, Use and Result. Argonne, IL: Argonne National Laboratory. Wang, M.O. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology, development, Use and Result. Argonne, IL: Argonne National Laboratory. Wang, M.O. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology, development, Use and Result. Argonne, IL: Argonne National Laboratory. Wang, M.O. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology, development, Use and Result. Argonne, National Laboratory. Wang, M.O. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology, development, Use and Result. Argonne, National Laboratory. Wang, M.O. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology, development, Use and Result. Argonne, National Laboratory. Wang, M.O. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology. development, Cycle and Result. Argonne, National Labo	Equivalent to 75 lb N / ac in the maintenance year Year 3 or 4) which is reported by De La Torre Ugarte, 2003, App assuming 6 dry tons biomass per acre, and harvesting once very 8 years. App 3.1 is for planting on cropland that v used for traditional crops. Equivalent to 20 lb P / ac in the maintenance year (Year 3) which is in the range of 15-50 lb P / ac reported by De L Equivalent to 20 lb P / ac in the maintenance year (Year 3) which is in the range of 15-50 lb F / ac reported by De L Equivalent to 35 lb K / ac in the maintenance year (Year 3) which is in the range of 15-50 lb K / ac reported by De L Equivalent to 35 lb K / ac in the maintenance year (Year 3) which is in the range of 15-50 lb K / ac reported by De L Equivalent to 20 lb P / ac suming dery tons biomass per acre and harvesting once every 8 years. Equivalent to 2.1 b herbicide / ac in the planting year which similar to the 2.0 lb gryphosate / ac reported by De La Tugarte, 2003, App 3.2, assuming d dry tons biomass per acre and harvesting once every 8 years. Bed of planting of a dry tons biomass per acre and harvesting once every 8 years. Bed of planting of dry tons biomass per acre and harvesting once every 8 years. Bed of planting (5 Lha) and Metribuzin (395 gha). App 3.2 ls for planting on currently lided cropland cor cropland that was used for pasture. As a check, looked at Chastagner: Up to 56% of acreage annually sprayed with Dimethoate (Digon 400, 2-3 pints p acre; up to 56% of acreage annually sprayed with Permethin/ 2.18 (Annush, 6 4 ounces per acre); Up to 512% of acreage annually sprayed with Endealut based on ALL personal Communications GREET model featult based on ALL personal Communications GREET uses 97% which is comparable to several other models (Table 4.11)
atural	Grams of Grams of Grams of Grams of Grams of Average of Average of NG recov NG used NG proce	P2O5 / short ton biomass K2O / short ton biomass herbicide / short ton biomass insecticide / short ton biomass iCO2 removed from atmosphere per dry ton woody biomass produced distance from farm to hydrogen production facility ery efficiency & tost during recovery	709 189 331 24 2 2 -112,500 40 97.2% 0.35%	g / dry ton g / dry ton g / dry ton g / dry ton g / dry ton	M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst 1989).     M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst 1998).     M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst 1998).     M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst 1998).     M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst 1998).     M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst 1998).     M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst 1998).     M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst 1998).     Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology. development, Use and Result. Argonne. L. Argonne National Laboratory. Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology. development, Use and Result. Argonne. L. Argonne National Laboratory. Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology. development, Use and Results. Argonne. L. Argonne National Laboratory. Wang, M.G. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology. development, Use and Results. Argonne. L. Argonne National Laboratory. Wang, M.G. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology. development, Use and Results. Argonne. L. Argonne National Laboratory. Wang, M.G. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology. development, Use and Results. Argonne, L. Argonne National Laboratory. Methodology. development, Use and Results. Argonne, L. Argonne National Laboratory. Methodology. development, Use and Results. Argonne, National Laboratory. Methodology. development,	Equivalent to 75 lb N is on the maintenance year Year 3 or 4) which is reported by De La Torre Ugarte, 2003, App assuming 6 dry tons biocnass per acre, and harvesting once every 8 years. App 3.1 is for jainting on cropland that used for traditional crops. Equivalent to 20 lb 14, assuming 6 dry tons biomass per acre and harvesting once every 8 years. Equivalent to 35 lb K / as reported by De L Ugarte, 2003, App 3.1, assuming 6 dry tons biomass per acre and harvesting once every 8 years. Equivalent to 35 lb K / as reported by De L Ugarte, 2003, App 3.1, assuming 6 dry tons biomass per acre and harvesting once every 8 years. Equivalent to 35 lb K / as reported by De L Ugarte, 2003, App 3.1, assuming 6 dry tons biomass per acre and harvesting once every 8 years. Equivalent to 25 lb K / As reported by De L Ugarte, 2003, App 3.1, assuming 6 dry tons biomass per acre and harvesting once every 8 years. Bequivalent to 2.0 lb hetribode / ac in the planting year which aimilar to the 2.0 b Byphosate / ac reported by De L 1 Ugarte, 2004, App 3.2, assuming 6 dry tons biomass per acre and harvesting once every 8 years. Bequivalent to 2.0 lb hetribode / ac in the planting year which bianting year which harvesting once every 8 years. See of the status of dry tons biomasys per acre and harvesting once every 8 years. See of the status and Chastagner: Up to 56% of acreage annually sprayed with Demotel (Digon 400, 2.3 pints p annually sprayed with Aresoulian 3 EC (24e WA-990025, 2 gts per acre). GREET model default based on ANL personal communications GREET uses 97% which is comparable to several other models (Table 4.11) GREET sees 97.5% which is comparable to several other models (Table 4.11) Volume lost from EPA/GRI paper and DOE/EIA-0573; future marginal increase is assumed to be less than current average.
atural	Grams of Grams of Grams of Grams of Grams of Average of Average of Average of NG recov NG used NG proce	P2O5 / short ton biomass K2O / short ton biomass 'herbicide / short ton biomass 'insecticide / short ton biomass CO2 removed from atmosphere per dry ton woody biomass produced distance from farm to hydrogen production facility ery efficiency & lost during recovery ussing energy efficiency	709 189 331 24 -112,500 40 97.2% 0.35% 97.2%	g / dry ton g / dry ton g / dry ton g / dry ton g / dry ton	<ul> <li>M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst (1999).</li> <li>M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst (1999).</li> <li>M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst (1999).</li> <li>M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst (1998).</li> <li>M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst (1998).</li> <li>M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst (1998).</li> <li>M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst (1998).</li> <li>M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst (1998).</li> <li>Wang, M. O. (1999, August). <i>GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology, development, Use and Result, Argonne, Li: Argonne National Laboratory.</i></li> <li>Wang, M. O. (1999, August). <i>GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology, development, Use and Result, Argonne, Li: Argonne National Laboratory.</i></li> <li>Wang, M. O. (1999, August). <i>GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology, development, Use and Result, Argonne, Li: Argonne National Laboratory.</i></li> <li>Wang, M. O. (1999, August). <i>GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology, development, Use and Result, Argonne, Li: Argonne National Laboratory.</i></li> <li>Wang, M. O. (1999, August). <i>GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology, development, Use and Result, Argonne, Li: Argonne National Laboratory.</i></li> <li>Wang, M. O. (1999, August). <i>GREET 1.5 - Transportation Fuel-Cycle Model Volume 7: Methodology, development, Use and Result, Argonne, Li: Argonne National Laboratory.</i></li> <li>Kirchgessner, D. A., Lott, R. A., Cowgill, R. M., Harrison, M. R. &amp; Shires,</li></ul>	Equivalent to 75 lb N /a cin the maintenance year Year 3 or 4) which is reported by De La Torne Ugarte. 2003. App assuming 6 dry tone biomass per acre, and harvesting once every 8 years. App 3.1 is for planting on cropland that v used for traditional crops. Equivalent to 20 b P / ac in the maintenance year (Year 3) which is in the range of 15.50 lb P / ac reported by De L Ugarte. 2003. App 3.1. assuming 6 dry tons biomass per acre and harvesting once every 8 years. Equivalent to 20 lb P / ac in the maintenance year (Year 3) which is in the range of 15.50 lb F / ac reported by De L Ugarte. 2003. App 3.1. assuming 6 dry tons biomass per acre and harvesting once every 8 years. Equivalent to 20 lb horbicide / a cin the planting year which similar to the 2.0 b glyhocaler (a ac reported by De La Ugarte. 2003. App 3.1. assuming 6 dry tons biomass per acre and harvesting once every 8 years. Equivalent to 20 lb horbicide / ac in the planting year which similar to the 2.0 b glyhocaler (a ac reported by De La Tiffuralin (5 Lha) and Metribuzin (36 gfha). App 3.2 is for planting on currently tilled cropland or cropland that was used for pasture. As a check, looked at Chastagner: Up to 56% of acreage annually sprayed with Endexillar 5 CC (24 cWA90025. 2 qt per acre). GREET model default based on ANL personal communications GREET model default based on ANL personal communications GREET model default based on ANL personal communications GREET uses 97% which is comparable to several other models (Table 4.11) GREET tasis GREET tasis GREET uses 97.5% which is comparable to several other models (Table 4.11)
ıtural	Grams of Grams of Grams of Grams of Grams of Average of Average of NG used NG proce NG used	P2O5 / short ton biomass K2O / short ton biomass K2O / short ton biomass insecticide / short ton biomass CO2 removed from atmosphere per dry ton woody biomass produced distance from farm to hydrogen production facility ery efficiency & tost during recovery sissing energy efficiency & tost during processing & tost during transport	709 189 331 24 2 -112,500 40 97.2% 97.2% 0.35% 0.15%	g / dry ton g / dry ton g / dry ton g / dry ton g / dry ton miles g / (MM Btu mil)	M. Waish (personal communication via telephone and meeting between M. Wang and M. Waist 1989).     M. Waish (personal communication via telephone and meeting between M. Wang and M. Waist 1999).     M. Waish (personal communication via telephone and meeting between M. Wang and M. Waist 1999).     M. Waish (personal communication via telephone and meeting between M. Wang and M. Waist 1999).     M. Waish (personal communication via telephone and meeting between M. Wang and M. Waist 1999).     M. Waish (personal communication via telephone and meeting between M. Wang and M. Waist 1999).     M. Waish (personal communication via telephone and meeting between M. Wang and M. Waist 1999).     Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology. development. Use and Result. Argonne. L. Argonne National Laboratory. Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology. development. Use and Result. Argonne. L. Argonne National Laboratory. Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology. development. Use and Result. Argonne. National Laboratory. Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology. development. Use and Result. Argonne. National Laboratory. Wang, M.G. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology. development. Use and Result. Argonne. National Laboratory. Wang, M.G. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology. development. Use and Result. Argonne. National Laboratory. Wang, M.G. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology. development. Use and Result. Argonne. National Laboratory. Wang, M.G. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology. development. Use and Result. Argonne. National Laboratory. Wang, M.G. (199	Equivalent to 75 lb N / ac in the maintenance year Year 3 or 4) which is reported by De La Torre Ugarte, 2003, App assuming 6 dry tons biomass per acre, and harvesting once very 8 years. App 3.1 is for planting on cropland that V used for traditional crops. Equivalent to 20 lb P / ac in the maintenance year (Year 3) which is in the range of 15-50 lb F / ac reported by De La Equivalent to 20 lb P / ac in the maintenance year (Year 3) which is in the range of 15-50 lb F / ac reported by De La Equivalent to 35 lb K / ac in the maintenance year (Year 3) which is in the range of 15-50 lb K / ac reported by De La Equivalent to 35 lb K / ac in the maintenance year (Year 3) which is in the range of 15-50 lb K / ac reported by De La Equivalent to 2.0 lb herbicide / ac in the planting year which similar to the 2.0 lb gryphosate / ac reported by De La Equivalent to 2.0 lb herbicide / ac in the planting year which similar to the 2.0 lb gryphosate / ac reported by De La Tifluralin (5 Lha) and Metribuzin (356 grha). App 3.2 ls for planting on currently lided cropland or cropland that was aced for pasture. As a check, looked at Chastagner: Up to 56% of acreage annually sprayed with Dimethoate (Digon 400, 2-3 pints pi As a check, looked at Chastagner: Up to 56% of acreage annually sprayed with Dimethoate (Digon 400, 2-3 pints pi As a Check Tooked at Chastagner. Up to 56% of acreage annually sprayed with Dimethoate (Digon 400, 2-3 pints pi As a Check Tooked at Chastagner. Up to 56% of acreage annually sprayed with Dimethoate (Digon 400, 2-3 pints pi As a check looked at Chastagner. Up to 56% of acreage annually sprayed with Dimethoate (Digon 400, 2-3 pints pi As a check looked at Chastagner. Up to 56% of acreage annually sprayed with Dimethoate (Digon 400, 2-3 pints pi As a check looked at Chastagner. Up to 56% of acreage annually sprayed with Dimethoate (Digon 400, 2-3 pints pi As a check looked at Chastagner. Up to 56% of acreage annually sprayed with Dimethoate (Digon 400, 2-3 pints pi As annualty sprayed
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tural	Grams of Grams of Grams of Grams of Grams of Average of NG recov NG used NG used NG used NG used NG used	P2O5 / short ton biomass K2O / short ton biomass K2O / short ton biomass insecticide / short ton biomass C02 removed from atmosphere per dry ton woody biomass produced distance from farm to hydrogen production facility ery efficiency & tost during recovery ssing energy efficiency & tost during processing & tost during transport port distance	709 189 331 24 2 3112,500 40 97,2% 0,35% 97,2% 0,15% 0,14 500	g / dry ton g / dry ton g / dry ton g / dry ton g / dry ton miles g / (MM Btu mil)	<ul> <li>M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst 1989).</li> <li>M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst 1989).</li> <li>M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst 1989).</li> <li>M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst 1998).</li> <li>M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst 1998).</li> <li>M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst 1998).</li> <li>M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst 1998).</li> <li>M. Walsh (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology. development. Use and Result: Argonne, IL: Argonne National Laboratory.</li> <li>Wang, M.O. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology. development. Use and Result: Argonne, IL: Argonne National Laboratory.</li> <li>Wang, M.O. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology. development. Use and Result: Argonne, IL: Argonne National Laboratory.</li> <li>Wang, M.O. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology. development. Use and Result: Argonne, IL: Argonne National Laboratory.</li> <li>Wang, M.O. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology. development. Use and Result: Argonne, IL: Argonne National Laboratory.</li> <li>Kirchgessner, D. A., Lut, R.A., Cowgill, R. M., Harrison, M. R. &amp; Shires, T. M. (1996)Estimate of Methane Emissions from the U.S. Natural Gas. Industry, EPAGas Research Institute paper.</li> <li>Retrieved from http://www.epa.gov/thich/Hafag42Ch14/related/methane.p.</li> <li>Kirchgessner, D. A., Lut, R.A., Cowgill, R. M., Harrison, M. R. &amp; Shires, T. M. (1996)Estimate of Methane</li></ul>	Equivalent to 75 lb N / ac in the maintenance year Year 3 or 4) which is reported by De La Torre Ugarte, 2003, App assuming 6 dry tons biomass per acre, and harvesting once very 6 years. App 3.1 is for planting on cropland that we used for traditional crops. Equivalent to 20 lb P / ac in the maintenance year (Year 3) which is in the range of 15-50 lb P / ac reported by De La Equivalent to 20 lb P / ac in the maintenance year (Year 3) which is in the range of 15-50 lb P / ac reported by De La Equivalent to 20 lb P / ac in the maintenance year (Year 3) which is in the range of 15-50 lb P / ac reported by De La Equivalent to 35 lb K / ac in the maintenance year (Year 3) which is in the range of 15-50 lb K / ac reported by De La Equivalent to 20 lb P / ac suming 6 dry tons biomass per acre and harvesting once very 8 years. Equivalent to 2.0 lb herbicide / ac in the planting year which similar to the 2.0 lb glyphoate/ / ac reported by De La Tiflugarie. 2003. App 2, assuming 6 dry tons biomass per acre and harvesting once very 8 years. Bed for pastice def for pastice of dry tons biomass per acre and harvesting once very 8 years. Bed collection (5 Lb herbicide / ac in the planting year which similar to the 2.0 lb glyphoate/ / ac reported by De La Tiflugarie. 2004. App 2, assuming 6 dry tons biomass per acre and harvesting once very 8 years. Bed collection (5 Lb herbicide / ac in the planting years which sinter the 2.0 lb glyphoate/ / ac reported by De La Tiflugarie. 2004. App 2, assuming 6 dry tons biomass per acre 2. GREET model fault based on ANL personal communications GREET model fault based on ANL personal communications GREET to sets 97% which is comparable to several other models (Table 4.11) Volume lost from EPA/GRI paper and DOE/EIA-0573; future marginal increase is assumed to be less than current average. GREET basis GREET basis
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tural	Grams of Grams of Grams of Grams of Grams of Average of NG recov NG used NG used NG used NG used NG used	P2O5 / short ton biomass K2O / short ton biomass K2O / short ton biomass insecticide / short ton biomass C2O removed from atmosphere per dry ton woody biomass produced distance from farm to hydrogen production facility ery efficiency & tost during recovery ssing energy efficiency & tost during processing & tost during transport port distance	709 189 331 24 2 3112,500 40 97,2% 0,35% 97,2% 0,15% 0,14 500	g / dry ton g / dry ton g / dry ton g / dry ton g / dry ton miles g / (MM Btu mil)	<ul> <li>M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst 1989).</li> <li>M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst 1989).</li> <li>M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst 1989).</li> <li>M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst 1998).</li> <li>M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst 1998).</li> <li>M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst 1998).</li> <li>M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst 1998).</li> <li>M. Walsh (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology. development. Use and Result: Argonne, IL: Argonne National Laboratory.</li> <li>Wang, M.O. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology. development. Use and Result: Argonne, IL: Argonne National Laboratory.</li> <li>Wang, M.O. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology. development. Use and Result: Argonne, IL: Argonne National Laboratory.</li> <li>Wang, M.O. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology. development. Use and Result: Argonne, IL: Argonne National Laboratory.</li> <li>Wang, M.O. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology. development. Use and Result: Argonne, IL: Argonne National Laboratory.</li> <li>Kirchgessner, D. A., Lut, R.A., Cowgill, R. M., Harrison, M. R. &amp; Shires, T. M. (1996)Estimate of Methane Emissions from the U.S. Natural Gas. Industry, EPAGas Research Institute paper.</li> <li>Retrieved from http://www.epa.gov/thich/Hafag42Ch14/related/methane.p.</li> <li>Kirchgessner, D. A., Lut, R.A., Cowgill, R. M., Harrison, M. R. &amp; Shires, T. M. (1996)Estimate of Methane</li></ul>	Equivalent to 75 lb N /a cin the maintenance year Year 3 or 4) which is reported by De La Torne Ugarte. 2003. App Saswing 6 dry tone biomass per acre, and harvesting once every 8 years. App 3.1 is for planting on cropland that to used for traditional crops. Equivalent to 20 lb 7 /a cin the maintenance year Year 3) which is in the range of 15.50 lb 7 / ac reported by De L Ugarte. 2003. App 3.1 assuming 6 dry tons biomass per acre and harvesting once every 8 years. Equivalent to 20 lb 7 /a cin the maintenance year (Year 3) which is in the range of 15.50 lb 7 / ac reported by De L Ugarte. 2003. App 3.1 assuming 6 dry tons biomass per acre and harvesting once every 8 years. Equivalent to 20 lb horbicide / a cin the planting year which similar to the 2.0 lb g/horbasel / ac reported by De La Ugarte. 2003. App 3.1 assuming 6 dry tons biomass per acre and harvesting once every 8 years. Equivalent to 30 lb horbicide / a cin the planting year which similar to the 2.0 lb g/horbasel / ac reported by De La Ugarte. 2000. App 3.2 assuming 6 dry tons biomass per acre and harvesting once every 8 years. Boto 1 bhorbicide / a cin the planting year which similar to the 2.0 lb g/horbasel / ac reported by De La Tiffurain (6 Lha) and Metribuzin (365 g/ha). App 3.2 is for planting on currently tilled cropland or cropland that was used for pasture. As a check, looked at Chastagener: Up to 56% of acreage annually sprayed with Dimethoate (Digon 400. 2-3 pints p face); up to 56% of acreage annually sprayed with Permethin's 2.16 (Ambush, 6 4 ounces per acre); Up to 12% of ac annually sprayed with Endosultins 5 CC 42c WA90025. 2 qt pser acre). GREET model default Based on ANL personal communications GREET basis: distance could be limited by transport costs? GREET tasis: GREET uses 97.5% which is comparable to several other models (Table 4.11) Volume lost from EPA/GRI paper and DOE/EIA-0573; future marginal increase is assumed to be less than current average.
atural	Grams of Grams of Grams of Grams of Average of Gas NG recov NG used NG used NG used NG used NG used	P2O5 / short ton biomass K2O / short ton biomass K2O / short ton biomass insecticide / short ton biomass CC2 removed from atmosphere per dry ton woody biomass produced distance from farm to hydrogen production facility Cery efficiency & tost during recovery sissing energy efficiency & tost during processing & tost during transport port distance for production	709 189 331 24 2 3112,500 40 97,2% 0,35% 97,2% 0,15% 0,14 500	g / dry ton g / dry ton g / dry ton g / dry ton g / dry ton miles g / (MM Btu mil)	<ul> <li>M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst (1989).</li> <li>M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst (1989).</li> <li>M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst (1989).</li> <li>M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst (1989).</li> <li>M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst (1989).</li> <li>M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst (1989).</li> <li>M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst (1989).</li> <li>Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology. development. Use and Results. Argonne. L. Argonne National Laboratory.</li> <li>Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology. development. Use and Results. Argonne. L. Argonne National Laboratory.</li> <li>Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology. development. Use and Results. Argonne. L. Argonne National Laboratory.</li> <li>Wang, M.G. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology. development. Use and Results. Argonne. L. Argonne National Laboratory.</li> <li>Wang, M.G. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology. development. Use and Results. Argonne. L. Argonne National Laboratory.</li> <li>Wang, M.G. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology. development. US. and Results. Angonne. National Laboratory.</li> <li>Wang, M.G. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology. development. US. Natural Gas. Industry: F2AGas. Research. Institule paper. Retrieved from http://www.epa.aov/linc/islaf</li></ul>	Equivalent to 75 lb N as in the maintenance year Year 3 or 4) which is reported by De La Torre Ugarte, 2003, App assuming 6 dry tons bornass per acre, and harvesting once every 8 years. App 3.1 is for planting on cropland that year Ugarte, 2003, App 3.1, assuming 6 dry tons bornass per acre and harvesting once every 8 years. App 3.0 lb K / as it mentioners are acre and harvesting once every 8 years. App 3.0 lb K / as it mentioners by the La Equivalent 2016 P / as the summing 6 dry tons bornass per acre and harvesting once every 8 years. Equivalent 2016 D / D habridoic / acre of the bornass per acre and harvesting once every 8 years. Equivalent 2016 D habridoic / acre in the planting year which similar to the 2.0 b g/habridoste / acreported by De La Equivalent 2016 D habridoic / acre in the planting year which similar to the 2.0 b g/habridoste / acreported by De La Ugarte, 2003, App 3.2, assuming 6 dry tons blomass per acre and harvesting once every 8 years. Booth reported High and Nethousing 5 dry tons blomass per acre and harvesting once every 8 years. Booth reported 14 yearte, 2000, App 3.2, assuming 6 dry tons blomass per acre and harvesting once every 8 years. Booth reported 14 yearte, 2000, App 3.2, assuming 5 dry acre acre and harvesting once every 8 years. Booth reported 14 yearte, 2000, App 3.2, assuming 5 dry acre acre and harvesting once every 8 years. Booth reported 14 yearte, 2000, App 3.2, assuming 5 dry acre acre and harvesting once every 8 years. Booth reported 14 yearte, 2000, App 3.2, assuming 5 dry acre acre acre and harvesting once every 8 years. Booth reported 14 yearte, 2000, App 3.2, assuming 5 dry acre acre acre and harvesting once every 8 years. Booth reported 14 yearte, 2005, App 3.1, assuming 5 dry acre acre acre and harvesting once every 8 years. Booth reported 14 yearte, 2000, App 3.2, assuming 5 dry acre acre acre acre acre acre acre acre
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atural	Grams of Grams of Grams of Grams of Average of Gas NG recov NG used NG used NG used NG used NG used	P2O5 / short ton biomass (K2O / short ton biomass (K2O / short ton biomass ) Insecticide / short ton biomass CC02 removed from atmosphere per dry ton woody biomass produced distance from farm to hydrogen production facility ery efficiency & lost during recovery essing energy efficiency & lost during processing & lost during transport port distance for production Biomass Fraction	709 189 331 24 2 112,500 40 97.2% 0.35% 97.2% 0.15% 0.15% 0.15% 0.15% 0.15% 0.14 500 US Mix	g / dry ton g / dry ton g / dry ton g / dry ton g / dry ton miles g / (MM Btu mil)	<ul> <li>M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst (1989).</li> <li>M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst (1999).</li> <li>M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst (1999).</li> <li>M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst (1999).</li> <li>M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst (1998).</li> <li>M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst (1998).</li> <li>M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst (1999).</li> <li>M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst (1999).</li> <li>Wang, M. O. (1999, August). <i>GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology, development, Use and Result, Argonne, Li: Argonne National Laboratory.</i></li> <li>Wang, M. O. (1999, August). <i>GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology, development, Use and Result, Argonne, Li: Argonne National Laboratory.</i></li> <li>Wang, M. O. (1999, August). <i>GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology, development, Use and Result, Argonne, Li: Argonne National Laboratory.</i></li> <li>Wang, M. O. (1999, August). <i>GREET 1.5 - Transportation Fuel-Cycle Model Volume 7: Methodology, development, Use and Result, Argonne, Li: Argonne National Laboratory.</i></li> <li>Wang, M. O. (1999, August). <i>GREET 1.5 - Transportation Fuel-Cycle Model Volume 7: Methodology, development, U.S. Naturul Gas Industry, FLAGRA Research Institute paper.</i></li> <li>Retrieved from http://www.epa.ao/Unic/lifa/g2/c114/related/methane.pn</li> <li>Kirchgessner, D. A., Lott, R. A., Cowgill, R. M., Harrison, M. R. &amp; Shires, T. M. (1999)/Estimate of Methane Emissions from the U.S. Naturul Gas. Industry, FLAGRA Research</li></ul>	Equivalent to 75 lb N as in the maintenance year Year 3 or 4) which is reported by De La Torre Ugarte, 2003, App assuming 6 dry tons bornass per acre, and harvesting once every 8 years. App 3.1 is for planting on cropland that y Buyunalent 2010 to 100
atural	Grams of Grams of Grams of Grams of Average of Gas NG recov NG used NG used NG used NG used NG used	P2O5 / short ton biomass K2O / short ton biomass K2O / short ton biomass herbicide / short ton biomass CO2 removed from atmosphere per dry ton woody biomass produced distance from farm to hydrogen production facility ery efficiency & lost during recovery sseing energy efficiency & lost during transport port distance for production Biomass Fraction Coal Fraction	709 189 331 24 2 3112,500 40 97,2% 0,35% 97,2% 0,15% 0,14 500	g / dry ton g / dry ton g / dry ton g / dry ton g / dry ton miles g / (MM Btu mil)	<ul> <li>M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst (1998).</li> <li>M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst (1998).</li> <li>M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst (1998).</li> <li>M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst (1998).</li> <li>M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst (1998).</li> <li>M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst (1998).</li> <li>M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst (1998).</li> <li>M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst (1998).</li> <li>Wang, M. O. (1999, August). <i>GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology, development, Use and Result, Argonne, Li: Argonne National Laboratory.</i></li> <li>Wang, M. O. (1999, August). <i>GREET 1.5 - Transportation Fuel-Cycle Model Volume 7: Methodology, development, Use and Result, Argonne, Li: Argonne National Laboratory.</i></li> <li>Wang, M. O. (1999, August). <i>GREET 1.5 - Transportation Fuel-Cycle Model Volume 7: Methodology, development, Use and Result, Argonne, Li: Argonne National Laboratory.</i></li> <li>Wang, M. O. (1999, August). <i>GREET 1.5 - Transportation Fuel-Cycle Model Volume 7: Methodology, development, Use and Result, Strugone, Li: Argonne National Laboratory.</i></li> <li>Wang, M. O. (1999, August). <i>GREET 1.5 - Transportation Fuel-Cycle Model Volume 7: Methodology, development, U.S. Naturul Gas Industry, FEA/Gas Research Institute paper.</i> Retrieved from http://www.epa.aoy/thci/lefap42/ch14/related/methane.pn</li> <li>Kirchgessner, D. A., Lutt, R. A., Cowajil, R. M., Harrison, M. R. &amp; Shires, T. M. (1998)/Estimate of Methane Emissions from the U.S. Naturul Gas Industry, FEA/Gas Research Institute</li></ul>	Equivalent to 75 Ib N / as in the maintenance year Year 3 or 4) which is reported by De La Torre Ugarte. 2003. App Saswing 6 dry tone biomass per acre, and harvesting once every 8 years. App 3.1 is for planting on cropiand that to staged for traditional crops. Equivalent to 20 Ib 7 / as in the maintenance year Year 3) which is in the range of 15.50 Ib 7 / as cropted by De L Ugarte. 2003. App 3.1 assuming 6 dry tons biomass per acre and harvesting once every 8 years. Equivalent to 20 Ib 7 / as in the maintenance year (Year 3) which is in the range of 15.50 Ib 7 / as cropted by De L Ugarte. 2003. App 3.1 assuming 6 dry tons biomass per acre and harvesting once every 8 years. Equivalent to 20 Ib horbicide / as in the planting year which similar to the 2.0 Ib glyhoself / as reported by De La Ugarte. 2003. App 3.1 assuming 6 dry tons biomass per acre and harvesting once every 8 years. Equivalent to 2.0 Ib horbicide / as in the planting year which similar to the 2.0 Ib glyhoself / as reported by De La Ugarte. 2000. App 3.2 assuming 6 dry tons biomass per acre and harvesting once every 8 years. Boto 1 b horbicide / as 10 herbicide / as 10 b glyhoself / as reported by De La Tiffrain (6 Linha) and Metribuzin (366 gha). App 3.2 is for planting on currently idled cropland or cropland that was used for pasture. As a check, looked at Chastagener: Up to 56% of acreage annually sprayed with Dimethoate (Digon 400. 2-3 pints pi Care): Up to 56% of acreage annually sprayed with Permethin 2.1B (Ambush, 6 a onces per acre): Up to 12% of as annually sprayed with Endosultan 5 EC (24: WA90025. 2 qt spe acre). GREET model default based on ANL personal communications GREET uses 97% which is comparable to several other models (Table 4.11) Volume lost from EPA/GRI paper and DOE/EIA-0573; future marginal increase is assumed to be less than current average. GREET basis Default. US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages call from total generation v
ectric	Grams of Grams of Grams of Grams of Average of Gas NG recov NG used NG used NG used NG used NG used	P2O5 / short ton biomass (K2O / short ton biomass (K2O / short ton biomass (insecticide / short ton biomass CO2 removed from atmosphere per dry ton woody biomass produced distance from farm to hydrogen production facility a lost during processing a lost during transport port distance for production Biomass Fraction Coal Fraction Natural Gas Fraction	709 189 331 24 2 112,500 40 97.2% 0.35% 97.2% 0.15% 0.15% 0.15% 0.15% 0.15% 0.14 500 US Mix	g / dry ton g / dry ton g / dry ton g / dry ton g / dry ton miles g / (MM Btu mil)	M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst 1989).     M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst 1999).     M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst 1999).     M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst 1999).     M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst 1999).     M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst 1999).     M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walst 1999).     Wang, M.O. (1999, August). <i>GREET 1.5 - Transportation Fuel-Cycle Model Volume 1:</i> <i>Methodology, development, Use and Result, Argonne, Li Argonne National Laboratory.</i> <i>Windthodology, development, Use and Result, Argonne, Li Argonne National Laboratory.</i> <i>Wang, M.O.</i> (1999, August). <i>GREET 1.5 - Transportation Fuel-Cycle Model Volume 1:</i> <i>Methodology, development, Use and Result, Argonne, Li Argonne National Laboratory.</i> <i>Wang, M.O.</i> (1999, August). <i>GREET 1.5 - Transportation Fuel-Cycle Model Volume 7:</i> <i>Methodology, development, Use and Result, Argonne, Li Argonne National Laboratory.</i> <i>Wang, M.O.</i> (1999, August). <i>GREET 1.5 - Transportation Fuel-Cycle Model Volume 7:</i> <i>Methodology, development, Use and Result, Argonne, Li Argonne, National Laboratory.</i> <i>Kirchgessner, D. A., Lott, R.A., Cowyill, R. M., Harrison, M. R. &amp; Shires, T. M.</i> (1999): <i>Estimate of Methane Emissions from the U.S. Natural Gas. Industry, EPA/Gas Research Institute paper.</i> <i>Retireved from http://www.epa.gov/thich/eligat/2/ch14/related/methane.pu</i> <i>Kirchgessner, D. A., Lott, R. A., Cowyill, R. M., Harrison, M. R. &amp; Shires, T. M.</i> (1999): <i>Estimate of Methane Emissions from the U.S. Natural Gas. Industry, EPA/Gas Research Institute paper.</i> <i>Retireved from http://www.epa.gov/thich/eligat/2/ch14/related/methane.pu</i> <i>Kirchgessner, D. A., Lott, R. A., Cowyill, R</i>	Equivalent to 75 lb N as in the maintenance year Year 3 or 4) which is reported by De La Torre Ugarte, 2003, App assuming 6 dry tons biomas per acre, and harvesting once every 8 years. App 3.1 is for jainting on cropland that year to the intervention of the period of the term of the transport 155 lb P / ac reported by De L Ugarte, 2003, App 3.1 is summing 6 dry tons biomass per acre and harvesting once every 8 years. The Equivalent 2003 to X as in the maintenance year Year 3) which is the range of 155 lb P / ac reported by De L Ugarte, 2003, App 3.1 is summing 6 dry tons biomass per acre and harvesting once every 8 years. So lb K / ac in the maintenance year (rear 4) which is the range of 155 lb K / ac reported by De L Ugarte, 2003, App 3.1 assuming 6 dry tons biomass per acre and harvesting once every 8 years. Booth reported Equivalent 10 35 lb horbickie / ac in the planningwer which similar to ac 2 db by/phrote / ace ported by De La Ugarte, 2000, App 3.2 assuming 6 dry tons biomass per acre and harvesting once every 8 years. Booth reported Highran (5 Lh) and Metribuzin (396 gha). App 3.2 is for planting on currently tied cropland or corpland that was a chock, looked at Chastspaner Up to 55% of acreage annually sprayed with Dimension (D) (D) 2.2 jn tisp ac city up 56% of acreage annually sprayed with Permethin 216 (Ambush, 6.4 ounces per acre); Up to 12% of ac annually sprayed with Endosultina 5 EC (24 VM-90025, 2 dts per acre). GREET basis: distance could be limited by transport costs? GREET tasis: distance could be limited by transport costs? GREET basis: distance could be limited by transport costs? GREET tasis: distance could be limited by transport costs?

Parame	eter		Value	Units	Reference	Comments
			Fuide	0		US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages calcul
	c	Others (Carbon Neutral)			Annual Energy Outlook 2007 www.eia.doe.gov/oiaf/archive/aeo07/index.html	from total generation values reported with all renewables except biomass aggregated into the "Others (Carbon Neutral
0	Grid mix fo	or liquefaction with biomass production	US Mix		None	category Default for Bio-Liquid Pathway study
		or liquefaction with coal production	US Mix		None	Default for Bio-Liquid Pathway study
		or liquefaction with central natural gas production	NGCC		None	Default for Bio-Liquid Pathway study
			Nuclear Power		None	Default for Bio-Liquid Pathway study
0	Grid mix fo	or pipeline compressors	US Mix		None	Default for Bio-Liquid Pathway study
0	Grid mix fo	or compression at distribution	US Mix		None	Default for Bio-Liquid Pathway study
2 Prod	uction					
FIU	uction					
C	CO2 Captu	ured for Sequestration	0%			Not available in this case study
					Spath, P., Aden, A., Eggeman, T., Ringer, M., Wallace, B. & Jechura, J. (2005, MayBiomass to	
F	Production	n Facility Average Output	139,712	kg / facility d (after capacity factor is included)	Indirectly-Heated Gasifier. Section 3.0. NREL/1P-510-37408. Golden, CO: National Renewable Energy Laboratory	besign feed rate for current design plant of 2000 bone dry metric tonne biomass per day (see Section 3.0)
	c	Corresponding capacity factor	90%		Mann, M., & Steward, D.M. (2008, May 28) <i>Current (2005) Hydrogen from Biomass via</i> Gasification and Catalytic Steam Reforming Golden, CO: National Renewable Energy Laboratory	Current central H2A production from biomass basis version 2.1.2; Input_Sheet_Template tab; Operating Capacity Fa cell C21
					Spath, P., Aden, A., Eggeman, T., Ringer, M., Wallace, B. & Jechura, J. (2005, MayBiomass to	
т	Total Capit	tal Investment	\$154,644,29	72005 \$		protal installed capital cost of \$102M (\$2002) (see Table 10, Current Design) was escalated to \$2005 dollars. Capital for additional compression was removed to maintain consistency with H2A central model assumptions.
					Spath, P., Aden, A., Eggeman, T., Ringer, M., Wallace, B. & Jechura, J. (2005, MayBiomass to	Biomass usage calculated from plant efficiency of 45.6%. The LHV for woody biomass is taken from HyARC, and is h
E	Biomass fe	eedstock consumption	12.8	kg (dry) / kg H2	Hydrogen Production Detailed Design and Economics Utilizing the Battelle Columbus Laborator Indirectly-Heated Gasifier. Appendex A. NREL/TP-510-37408. Golden, CO: National Renewable Energy Laboratory	(geonass usage calculated inon plant enclency of 90.0%. The Erv for woody domass is taken inon rysky, and is in (8406 Btulb x 8606 Btulb) than used in Spath. Appendix A - Design Report: Current Case; Hydrogen Yield = 70.4 i dry US ton feedstock
E	Biomass fe	eedstock cost	\$37.96	3 2005\$ / dry short ton	Hess, R., Denney, K., Wright, C., Radtke, C., Perlack, W. (2007, April 18-19) <i>Cellulosic</i> Biomass Feedstocks for Renewable Bioenergy. EERE presentation to the National Academy of Sciences Commettee on Resource Needs for Fuel Cell and Hydrogen, Washington, D.C.	Feedslock price is taken from the Biomass Program 2012 Target price of \$35/ton (\$2002) escalated to \$2005
N	Natural gas	is feedstock consumption	0.00	) normal m^3 / kg H2 produced	Mann, M., & Steward, D.M. (2008, May 28) Current (2005) Hydrogen from Biomass via Gasification and Catalytic Steam Reforming Golden, CO: National Renewable Energy Laboratory	Current central H2A production from biomass basis version 2.1.2; Results tab; Energy Data
N	Natural Ga	as feedstock cost	N/A			N/A
N	Natural Ga	as LHV	34,714	Btu / normal m^3.	Hydrogen Analysis Resource Center. (2008, September 5% ower and Higher Heating Values of Hydrogen and Fuels. Retrieved from http://hydrogen.pnl.gov/cocoon/morf/hydrogen/article/401	LHV of Natural Gas; 983 Btu/ft3
٢	Natural gas	s utility consumption	0.17	normal m^3 / kg H2 produced	Spath, P., Aden, A., Eggeman, T., Ringer, M., Wallace, B. & Jechura, J. (2005, May&iomass to Hydrogen Production Detailed Design and Economics Utilizing the Battelle Columbus Laboraton Indirectly-Heated Gasifier: Appendex A. NREL/TP-510-37408. Golden, CO: National Renewable Energy Laboratory	Natural gas usage from overall energy balance: Appendix C, A401: stream 427 = 1669 lb/hr; Appendix C, A501: strea 424 = 14260 lb/hr; conversion vields 0.15 (not 0.17)
•	Natural gas	is utility price	\$0.340	2005\$ / Nm^3	Energy Information Administation. (2005, February)Annual Energy Outlook 2005 With Projections to 2025. DOE/EIA-0383(2005). Washington, D.C.: U.S. Department of Energy.	AEO 2005 High A Case - Commercial price; Escalated from 2003 dollars to 2005 dollars. File downloaded from http://www.eia.doe.gov/oiaf/aeo/index.html (file name aeo_hw-3.xls)
N	Natural gas	is utility pressure	N/A	kPa	None	Not in H2A or GREET
			#VALUE!	psi	Conversion calculation	conversion calculation
E	Electricity f	feedstock consumption	0.00	kWh / kg H2	Mann, M., & Steward, D. M. (2008, May 28), Current (2005) Hydrogen from Biomass via Gasification and Catalytic Steam Reforming Golden, CO: National Renewable Energy Laboratoty	Current central H2A production from biomass basis version 2.1.2; Results tab; Energy Data
E	Electricity (	utility consumption (both production and compression)	0.98	3 kWh / kg H2	Indirectly-Heated Gasifier. NREL/TP-510-37408. Golden, CO: National Renewable Energy Laboratory	Electricity usage from overall energy balance with energy usage for hydrogen compression (3899 kW) removed. App A, Total Plant Electricity = 5.54 kWh/kg H2 -
E	Electricity (	utility consumption (production only)	0.98	3 kWh / kg H2	Spath, P., Aden, A., Eggeman, T., Ringer, M., Wallace, B. & Jechura, J. (2005, May&iomass to Hydrogen Production Detailed Design and Economics Utilizing the Battelle Columbus Laboraton Indirectly-Heated Gasifier. NREL/TP-510-37408. Golden, CO: National Renewable Energy Laboratory	Electricity usage from overall energy balance with energy usage for hydrogen compression (3899 kW) removed. App A, Total Plant Electricity = 5.54 kWh/kg H2. Electricity consumption reduced in H2A because Spath has hydrogen pr at 360 psi and H2A's standard is 300 psi.
E	Electricity I	Utility Price	0.0555	2005 \$/kWh	Energy Information Administation. (2005, February)Annual Energy Outlook 2005 With Projections to 2025. DOE/EIA-0383(2005). Washington, D.C.: U.S. Department of Energy.	AEO 2005 High A Case - Industrial price; Escalated from 2003 dollars to 2005 dollars. File downloaded from http://www.eia.doe.gov/oiaf/aeo/index.html (file name aeo_hw-3.xis)
F	Process W	Vater Consumption	1.32	gal / kg H2	Indirectly-Heated Gasifier. NREL/TP-510-37408. Golden, CO: National Renewable Energy Laboratory	Appendix C, A202: stream 218 = 738 lb/hr; Appendix C, A601: stream 620 = 102749 lb/hr; Appendix C, A701: stream = 131921 lb/hr
	Nator Cr-	isumption for Cooling	0.00008	gal / kg H2	Spath, P., Aden, A., Eggeman, T., Ringer, M., Wallace, B. & Jechura, J. (2005, May@iomass to Hydrogen Production Detailed Design and Economics Utilizing the Battelle Columbus Laboraton Indirectly-Heated Gasifier. NREL/TP-510-37408. Golden, CO: National Renewable Energy Laboratory	Assume all make-up water is process water
		co-product production	0.00	kWh / kg H2		All electricity co-product used internally
6	Oxygen co	p-product production	0.0	kg / kg H2	None	N/A
		product production		kg / kg H2	None	N/A
т	Total Annu	ual Fixed Operating Costs	\$10,391,486	3 2005\$ / yr	Spath, P., Aden, A., Eggeman, T., Ringer, M., Wallace, B. & Jechura, J. (2005, MayBiomass to Hydrogen Production Detailed Design and Economics Utilizing the Battelle Columbus Laboraton Indirectly-Heated Gasifier. Section 9.2. NREL/TP-510-37408. Golden, CO: National Renewable Energy Laboratory	Section 9.2 Fixed Operating Costs. Costs were escalated from \$2002 to \$2005 dollars.
т	Total Annu	ual Variable Operating Costs	\$43,162,900		Spath, P., Aden, A., Eggeman, T., Ringer, M., Wallace, B. & Jechura, J. (2005, May&iomass to Hydrogen Production Detailed Design and Economics Utilizing the Battelle Columbus Laboraton Indirectly-Heated Gasifier. Table 13. NREL/TP-510-37408. Golden, CO: National Renewable Energy Laboratory	
т	Total Annu	ual Operating Costs	\$53,554,386		None	Addtion of Annual Total Fixed Operating Costs and Total Annual Variable Operating Costs
F	Production	n energy efficiency (does not include electricity for forecourt compress	46.0%		Calculated from H2A values	Calculated from H2A values
S	Share of pr	rocess fuel - biomass	93.1%		Calculated from H2A values	Calculated from H2A values
		rocess fuel - coal	0.0%		Calculated from H2A values	Calculated from H2A values
		rocess fuel - natural gas rocess fuel - ethanol	2.5%		Calculated from H2A values Calculated from H2A values	Calculated from H2A values Calculated from H2A values
	Share of m			4	Concentration in the Challenge	

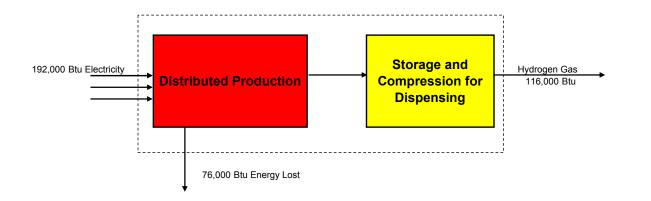
Param	antor.	Value	Units	Reference	Comments
raram		value	Units	Spath, P., Aden, A., Eggeman, T., Ringer, M., Wallace. B. & Jechura. J. (2005. MavRiomass to	Comments
	Hydrogen outlet pressure (before CSD)	300	psi	Laboratory	Final compression step modeled in the analysis was removed for the H2A case study to maintain consistency with H2A default value. Spath's compression was to 360 psi and H2A standard is 300 psi. Reducing the compression reduced th electricity use.
	Hydrogen quality before transport	98 minimum	% H2	Spath, P., Aden, A., Eggeman, T., Ringer, M., Wallace, B. & Jechura, J. (2005, May@iomass to Hydrogen Production Detailed Design and Economics Utilizing the Battelle Columbus Laborato Indirectly-Heated Gasifier. NREL/TP-510-37408. Golden, CO: National Renewable Energy Laboratory	Fage 5, product purity of 99.9 vol%
Financial	Parameters		70112		
	After-tax Real IRR	10%		Mann, M., & Steward, D.M. (2008, May 28).Current (2005) Hydrogen from Biomass via Gasification and Catalytic Steam Reforming Golden, CO: National Renewable Energy Laboratoly	Current central H2A production from biomass basis version 2.1.2; Input_Sheet_Template tab; After-tax Real IRR, cell C
	Plant Life	40	years	Mann, M., & Steward, D.M. (2008, May 28).Current (2005) Hydrogen from Biomass via Gasification and Catalytic Steam Reforming Golden, CO: National Renewable Energy Laboratoty Mann, M., & Steward, D.M. (2008, May 28).Current (2005) Hydrogen from Biomass via	Current central H2A production from biomass basis version 2.1.2; Input_Sheet_Template tab; Plant life, cell C34
	Federal Tax Rate	35.0%		mainti, mi, su diserval, Joshin (2000), Weig zby Zahng, Joboy Tryburgghi nom blandasi vie Gastification and Catalytic Steam Reforming Golden, CC: National Renewable Energy Laboratoty Mann, M., & Steward, D.M. (2008, May 28), Current (2005) Hydrogen from Biomass via	Current central H2A production from biomass basis version 2.1.2; Input_Sheet_Template tab; Federal taxes, cell C49
	State Tax Rate	6.0%		mainti, wi, a steward, U.W. (2000; Weg 20). United (2000) Hydrogen num blumass wa Gasification and Catalytic Steam Reforming Golden, CC: National Renewable Energy Laboratoty Mann, M., & Steward, D.M. (2008, May 28). Current (2005) Hydrogen from Biomass via	Current central H2A production from biomass basis version 2.1.2; Input_Sheet_Template tab; State taxes, cell C48
	Total Tax Rate	38.9%		meant, m., a steward, D.W. (2006, Way 20). Unren (2000) Hydrogen num burnass via Gasification and Catalytic Steam Reforming Golden, CC: National Renewable Energy Laboratoty Mann, M., & Steward, D.M. (2008, May 28). Current (2005) Hydrogen from Biomass via	Current central H2A production from biomass basis version 2.1.2; Input_Sheet_Template tab; Total tax Rate, cell C50
	Frection Equity	100%		Maini, m., a Steward, D.M. (2006, May 20)Current (2000) rydrogen rom bounass via Gasification and Catalytic Steam Reforming Golden, CO: National Renewable Energy Laboratoty	Current central H2A production from biomass basis version 2.1.2; Input_Sheet_Template tab; Equity Financing, cell C3
Transpo	ort, Delivery, and Storage Energy Requirements				
Liquid Tr	uck Delivery				
	Hydrogen entering liquefaction	382,396	kg / day	Elgowainy, A., Mintz, M. & Gillette, J. (2006) <i>Hydrogen Delivery Scenario Analysis Model</i> ( <i>HDSAM</i> ) V2.0. Argonne, IL: Argonne National Laboratory Nexant, Inc. et al. (2008, May) <i>H2A Hydrogen Delivery Infrastructure Analysis Models and</i>	HDSAM version 2.02 calculation based on input parameters: city selection, market penetration, dispensing rate
	Liquefaction electricity requirement		kW hr / yr	Conventional Pathway Options Analysis Results. Interim Report Sections 2.2.7.3 and 2.2.7.5. DE-FG36-05GO15032.	Discussions with Linde Kryotechnic AG, Switzerland (Nexant Report - Sections 2.2.7.3 and 2.2.7.5)
	Liquefaction electricity requirement	8.2	kW hr / kg H2	None Nexant, Inc. et al. (2008, May)H2A Hydrogen Delivery Infrastructure Analysis Models and	Calculation
	Hydrogen lost in liquefier	0.5%		Conventional Pathway Options Analysis Results. Interim Report Section 2.2.7.2. DE-FG36- 05G015032.	Discussions with Linde Kryotechnic AG, Switzerland (Nexant Report - Section 2.2.7.2)
	Liquefaction efficiency	80.3%		Nexant, Inc. et al. (2008, May)H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results Interim Report Section 2.2.7.2. DE-FG36- 05GO15032. INexant, Inc. et al. (2008, May)H2A Hydrogen Delivery Infrastructure Analysis Models and	Discussions with Linde Kryotechnic AG, Switzerland and Praxair (Nexant Report-Section 2.2.7.2)
	Liquefaction System total capital investment	\$559,414,686	2005\$	Conventional Pathway Options Analysis Results. Interim Report Section 2.2.7.4. DE-FG36- 05GO15032.	Discussions with Linde Kryotechnic AG, Switzerland and Praxair (Nexant Report - Section 2.2.7.4)
	Liquefaction System electricity cost	\$60,690,228	2005\$ / yr	Nexant, Inc. et al. (2008, May)H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results Interim Report Section 2.2.7.4. DE-FG36- 05GO15032. INexant, Inc. et al. (2008, May)H2A Hydrogen Delivery Infrastructure Analysis Models and	Discussions with Linde Kryotechnic AG, Switzerland and Praxair (Nexant Report - Section 2.2.7.4)
	Liquefaction System labor cost	\$592,895	2005\$ / yr	Conventional Pathway Options Analysis Results. Interim Report Section 2.2.1.3. DE-FG36- 05GO15032.	Bureau of Labor and Statistics (Nexant Report - Section 2.2.1.3)
	Liquefaction System total operating cost	\$83,647,930	2005\$ / yr	Elgowainy, A., Mintz, M. & Gillette, J. (2006) Hydrogen Delivery Scenario Analysis Model (HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	HDSAM version 2.02 calculation, H2 Liquifer tab, cell B135: sum of total labor cost, total electricity cost and total other fixed costs
	Terminal Storage Design Capacity	3,532,139	kg H2	Elgowainy, A., Mintz, M. & Gillette, J. (2006) Hydrogen Delivery Scenario Analysis Model (HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	HDSAM version 2.02 calculation, Liquid H2 Terminal tab, cell B73: based on liquid storage capacity, terminal average fl
	Hydrogen lost in terminal	2.8%		Nexant, Inc. et al. (2008, May)H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results Interim Report Section 2.2.14. DE-FG36- 05GO15032.	HDSAM parameter, recommendations from Nexant in conjuction with Air Liquide, GTI, Chevron, TIAX, ANL, PNNL and NREL (Nexant Report-Section 2.2.14)
	Terminal total capital investment	\$191,649,060	2005\$	Nexant, Inc. et al. (2008, May)H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.2.11.1. DE-FG36- 05G015032.	CB&I (Nexant Report - Section 2.2.11.1)
	Terminal electricity cost	\$565,492	2005\$ / yr	Elgowainy, A., Mintz, M. & Gillette, J. (2006) Hydrogen Delivery Scenario Analysis Model (HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	HDSAM version 2.02 calculation, Liquid H2 Terminal tab, cell B187: electricity prices are from EIA AEO 2005 and 2007
	Terminal labor cost	\$588,708	2005\$ / yr	Nexant, Inc. et al. (2008, May)/H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.2.1.3. DE-FG36- 05GO15032.	Bureau of Labor and Statistics (Nexant Report - Section 2.2.1.3)
	Terminal total operating cost	\$8,842,213	2005\$ / yr	Elgowainy, A., Mintz, M. & Gillette, J. (2006) Hydrogen Delivery Scenario Analysis Model (HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	HDSAM version 2.02 calculation, Liquid H2 Terminal tab, cell B201: sum of total labor cost, total electricity cost and tota other fixed costs
	Truck Payload leaving terminal	4,372	kg / truckload	Nexant, Inc. et al. (2008, May)H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results Interim Report Section 2.1.8. DE-FG36- JGGO15032.	HDSAM calculation; default value (Nexant Report- Section 2.1.8)
	Truck Trips	31,009	per year	Elgowainy, A., Mintz, M. & Gillette, J. (2006) Hydrogen Delivery Scenario Analysis Model (HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	HDSAM version 2.02 calculation, Truck - LH2 Delivery tab, cell B66: city yearly use(kg)*ref.station.mass efficiency(H2out/H2 in) / H2 delivered per trip (kg)
	One-way distance per trip	49	miles / trip (one way)	Elgowainy, A., Mintz, M. & Gillette, J. (2006) Hydrogen Delivery Scenario Analysis Model (HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	HDSAM version 2.02 calculation, Truck - LH2 Delivery tab, cell B39: distance to the city gate + 1.5 * sqrt(city area)
	Diesel for Truck Trips	3,837	m^3 / yr	Nexant, Inc. et al. (2008, May)H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.1.8. DE-FG36- 05GO15032.	HDSAM calculation, fuel consumption data from Nexant in conjuction with Air Liquide, GTI, Chevron, TIAX, ANL, PNNL and NREL (Nexant Report - Section 2.1.8)
	Hydrogen Losses during loading / transport / unloading	6.1%		Nexant, Inc. et al. (2008, May)H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.2.14. DE-FG36- 05GO15032.	HDSAM parameter, recommendations from Nexant in conjuction with Air Liquide, GTI, Chevron, TIAX, ANL, PNNL and NREL (Nexant Report- Section 2.2.14)
	Hydrogen Losses during liquefaction/loading / transport / unloading	10.08%		Nexant, Inc. et al. (2008, May)H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results Interim Report Section 2.2.14. DE-FG36- 05GO15032.	HDSAM parameter, recommendations from Nexant in conjuction with Air Liquide, GTI, Chevron, TIAX, ANL, PNNL and NREL (Nexant Report- Section 2.2.14)
	Truck/trailer total capital investment	\$49,000,000	2005\$	Nexant, Inc. et al. (2008, May) H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results Interim Report. DE-FG36-05G015032.	\$625,000 per each tank trailer and \$75,00 per each truck cab; recommendations from Nexant in conjuction with Air Liquide, GTI, Chevron, TIAX, ANL, PNNL and NREL
				Elgowainy, A., Mintz, M. & Gillette, J. (2006) Hydrogen Delivery Scenario Analysis Model	

Parameter	Value	Units	Reference	Comments
Truck/trailer Diesel cost	\$1,692,270		Elgowainy, A., Mintz, M. & Gillette, J. (2006) Hydrogen Delivery Scenario Analysis Model	HDSAM version 2.02 calculation, Truck - LH2 Delivery tab, cell B116: default milage - 6 mpg; diesel cost data are from i
		2005\$ / yr	(HDSAM) V2.0. Argonne, IL: Argonne National Laboratory Nexant, Inc. et al. (2008, May)H2A Hydrogen Delivery Infrastructure Analysis Models and	AEO 2005 and 2007
Truck/trailer labor cost	\$15,193,193	2005\$ / yr	Conventional Pathway Options Analysis Results. Interim Report Section 2.2.1.3. DE-FG36- 05GO15032.	Bureau of Labor and Statistics (Nexant Report - Section 2.2.1.3)
Truck/trailer total operating cost	\$21,691,089	2005\$ / yr	Elgowainy, A., Mintz, M. & Gillette, J. (2006) <i>Hydrogen Delivery Scenario Analysis Model</i> ( <i>HDSAM</i> ) V2.0. Argonne, IL: Argonne National Laboratory	HDSAM version 2.02 calculation, Truck - LH2 Delivery tab, cell B137: sum of total labor cost, total fuel cost and total othe fixed costs
Distribution Station				
Liquid Receiving/Distributing Stations				
Hydrogen Dispensed at Forecourt Station	465,647	ko / station vear	Elgowainy, A., Mintz, M. & Gillette, J. (2006) Hydrogen Delivery Scenario Analysis Model (HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	HDSAM version 2.02 calculation based on input: dispensing rate
Electricity Required by Forecourt Station	116,673	kWh / station year	Elgowainy, A., Mintz, M. & Gillette, J. (2006) Hydrogen Delivery Scenario Analysis Model (HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	HDSAM version 2.02 calculation based on pump power requirement (see equation in Design Data tab)
Design Capacity	1,516	kg H2 / day	Nexant, Inc. et al. (2008, May) H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.1.4. DE-FG36- 05GO15032.	HDSAM calculation based on Chevron fueling profiles (Nexant Report-Section 2.1.4): = adjusted disp. Rate*(1+summer surge)*(1+Friday surge)
Operating Capacity	1,278		James, B.D. (2008, May 23).Current (2005) Steam Methan Reformer (SMR) at Forecourt 1500kg/day. Arlington, VA: Directed Technologies Inc.	Current forecourt H2A production from natural gas basis version 2.0.1; Input_Sheet_Template tab; Plant Output, cell C23
Capacity Factor	84%	kg nz / uay	None	Calculation
Site storage (liquid)	6,920	kg H2	Nexant, Inc. et al. (2008, May)H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results Interim Report Section 2.2.11.2. DE-FG36- 056G015632	HDSAM calculation based on number of deliveries per day (Nexant Report-Section 2.2.11.2)
Site storage (gaseous)	453		Nexant, Inc. et al. (2008, May)H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results Interim Report Section 2.3.2.4. DE-FG36-	HDSAM calculation (Nexant Report - Section 2.3.2.4)
Site storage	486%	kg H2 % of design H2 distribution	05GO15032. None	Calculation
Dispensing Pressure	6,250	psi	Nexant, Inc. et al. (2008, May)H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.3.2. DE-FG36- 05GO15032.	HDSAM default (see Nexant Report-Section 2.3.2)
Hydrogen Losses due to leaks	1.34%	5	Nexant, Inc. et al. (2006, May)H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.2.14. DE-FG36- 05GG15032.	HDSAM parameter, recommendations from Nexant in conjuction with Air Liquide, GTI, Chevron, TIAX, ANL, PNNL and NREL (Nexant Report - Section 2.2.14)
Distribution System total capital investment	\$2,073,185	2005\$ / station	Nexant, Inc. et al. (2008, May) H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2:2.4.2. DE-FG36- 05GG15032.	Data from CP Industries, McMaster-Carr, Bechtel, Nexant manufacturer survey, Nexant recommendations (Nexant Rep Section 2.2.4.2)
Distribution System electricity cost	\$9,512	2005\$ / station yr	Nexant, Inc. et al. (2008, May)H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.2.4.2. DE-FG36- 05GG15032	Data from CP Industries, McMaster-Carr, Bechtel, Nexant manufacturer survey, Nexant recommendations (Nexant Rep Section 2.2.4.2)
Distribution Labor Required	3,951	hr / station vr	Decordsus: Nexari, Inc. et al. (2008, May)H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.2.1.3. DE-FG36- 05GO15032.	HDSAM calculation (Nexant Report -Section 2.2.1.3)
Distribution System labor cost	\$39,513	2005\$ / station vr	Deport buse. Nexarit, Inc. et al. (2008, May)H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.2.1.3. DE-FG36- 05GO15032.	Bureau of Labor and Statistics (Nexant Report - Section 2.2.1.3)
Distribution System total O&M cost	\$189,192	2005\$ / station yr	DISOL 1902. INEXARI, IC. et al. (2008, May)H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.2.1.2. DE-FG36-06GO15032.	HDSAM calculations (Nexant Report - Section 2.2.1.2)
Other Assumptions for WTW Calculations				
Share of RFG in Total Gasoline Use	100%		U.S. Department of Energy & U.S. Department of Transportation. (2006, December/Hydrogen Posture Plan An Inegrated Research, Development and Demonstration Pla.	Basis for posture plan
Type of Oxygenate in RFG	None		U.S. Department of Energy & U.S. Department of Transportation. (2006, December)Hydrogen Posture Plan An Inegrated Research, Development and Demonstration Pla.	Basis for posture plan
02 Content in RFG	0%	wt %	U.S. Department of Energy & U.S. Department of Transportation. (2006, December/Hydrogen	Basis for posture plan
O2 Content in RFG Ratio of FCV VOCs (emissions) to GVs fueled with CG & RFG	0%		Posture Plan An Inegrated Research, Development and Demonstration Pla . Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1:	GREET default, Table 4.45 FCV: H2
Ratio of FCV VOCs (evaporative) to GVs fueled with CG & RFG	0%		Methodology, development, Use and Results. Argonne, IL: Argonne National Laboratory. Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1:	GREET default, Table 4.45 FCV: H2
			Methodology, development, Use and Results. Argonne, IL: Argonne National Laboratory. Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1:	
Ratio of FCV CO emissions to GVs fueled with CG & RFG	0%		Methodology, development, Use and Results. Argonne, IL: Argonne National Laboratory.	GREET default, Table 4.45 FCV: H2
Ratio of FCV NOx emissions to GVs fueled with CG & RFG	0%		Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology, development, Use and Results. Argonne, IL: Argonne National Laboratory.	GREET default, Table 4.45 FCV: H2
Ratio of FCV Exhaust PM10 emissions to GVs fueled with CG & RFG	0%		Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology, development, Use and Results. Argonne, IL: Argonne National Laboratory.	GREET default, Table 4.45 FCV: H2
Ratio of FCV Brake & Tire Wear PM10 emissions to GVs fueled with CG & RFG	100%	5	Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology, development, Use and Results. Argonne, IL: Argonne National Laboratory.	GREET default, page 197: vehicles within the same weight class have similar tire and brake wear emissions
Ratio of FCV Exhaust PM2.5 emissions to GVs fueled with CG & RFG	0%		Wang, M.O. (2008, September 5). The Greenhouse Gases. Regulited Emissions, and Energy Use in Transportation (GREET) Model, Version 1.8b. Argonne, IL: Argonne National Laboratory	GREET default.well-known fuel cell emissions (no PM2.5)
Ratio of FCV Brake & Tire Wear PM2.5 emissions to GVs fueled with CG & RFG	100%		Wang, M.Q. (2008, September 5). The Greenhouse Gases, Regualted Emissions, and Energy Use in Transportation (GREET) Model, Version 1.8b. Argonne, IL: Argonne National Laboratory	GREET default:reasonable to assume FCV has same driving pattern as GV
Ratio of FCV CH4 emissions to GVs fueled with CG & RFG	0%		Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1:	GREET default, Table 4.45 FCV: H2
Ratio of FCV N2O emissions to GVs fueled with CG & RFG	0%		Methodology, development, Use and Results. Argonne, IL: Argonne National Laboratory. Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1:	GREET default, Table 4.45 FCV: H2
Marginal Electricity Generation Mix for Transportation Use	US Mix		Methodology, development, Use and Results. Argonne, IL: Argonne National Laboratory. U.S. Department of Energy & U.S. Department of Transportation. (2006, December#/drogen Posture Plan An Inegrated Research, Development and Demonstration Pla.	Basis for posture plan
Results				
Levelized Cost	\$4.88	\$ / kg	Ruth, M. et al. (2009, March). Hydrogen Macro System Model User Guide. NREL/TP-6A1-4479 Golden, CO: National Renewable Energy Laboratory.	9 MSM Results
WTW Coal Input	100		Ruth, M. et al. (2009, March). Hydrogen Macro System Model User Guide. NREL/TP-6A1-4479 Golden, CO: National Renewable Energy Laboratory.	MSM Results

Parameter	Value	Units	Reference	Comments
WTW Natural Gas Input	3,911	Btu / mile		MSM Results
WTW Petroleum Input	249	Btu / mile		MSM Results
WTW Fossil Energy Input	2,044	Btu / mile	Ruth, M. et al. (2009, March). Hydrogen Macro System Model User Guide. NREL/TP-6A1-4479 Golden, CO: National Renewable Energy Laboratory.	MSM Results
WTW Total Energy Input	8,170	Btu / mile	Ruth, M. et al. (2009, March). Hydrogen Macro System Model User Guide. NREL/TP-6A1-4479 Golden, CO: National Renewable Energy Laboratory.	MSM Results
WTW CO2 Emissions	151	g / mile	Ruth, M. et al. (2009, March). Hydrogen Macro System Model User Guide. NREL/TP-6A1-4479 Golden, CO: National Renewable Energy Laboratory.	MSM Results
WTW CH4 Emissions	0	g / mile		MSM Results
WTW N2O Emissions	0	g / mile		MSM Results
WTW GHG Emissions	160		Ruth, M. et al. (2009, March). Hydrogen Macro System Model User Guide. NREL/TP-6A1-4479 Golden, CO: National Renewable Energy Laboratory.	MSM Results

Appendix B — Distributed Electrolysis Supporting Tables and Figures

## **Distributed Hydrogen Production**



Well-to-Wheels Total Energy Use (Btu/mile)	11,310
Well-to-Wheels Petroleum Energy Use (Btu/mile)	536
Well-to-Wheels Greenhouse Gas Emissions (g/mile)	984
Levelized Cost of H2 at Pump (\$/kg)	6.05

Production Process Energy Efficiency     62%       Pathway Efficiency     60%       WTP Efficiency     23%       WTP Emissions (Ib CO2 Equivalent /     98	
WTP Efficiency 239 WTP Emissions (Ib CO2 Equivalent / 98	6
WTP Emissions (lb CO2 Equivalent / 98	6
CO2 Equivalent / 98	6
GGE fuel available):	

### Case Definition

Year: 2005 Hydrogen as Gas Forecourt Production Electrolysis Feedstock Sequestration: No Transport for Delivery: None Vehicle Efficiency: 45.0 mile / GGE City Hydrogen Use: 344451 kg/day

	Inputs	Graphic Depiction	& Assumptions	Ou	itputs
Coal input from "Weil" Natural Gas input from "Weil" Petroleum input from "Weil"	310,710 Btu / 116000Btu to Pump 89,250 Btu / 116000Btu to Pump 23,152 Btu / 116000Btu to Pump	Electrolysis Electricity Ge Includes Resource Recovery, Grid Mix Biomass Fraction Caal Fraction Natural Gas Fraction Nuclear Fraction Residual Oil Fraction Others (Carbon Neutral)		Electricity Cost Electricity Cost WTG CO2 Emissions WTG CH4 Emissions WTG N20 Emissions WTG GHG Emissions	\$0.055 2005 \$ / kWh \$2.804 2005\$ / kg H2 distributed 41,009 g / 116000Btu to Pump 54 g / 116000Btu to Pump 1 g / 116000Btu to Pump 42,520 g CO2 eq / 116000 Btu
Natural Gas consumption Electricity consumption Process Water Consumption	0.0 N m^3/kg H2 produced 53.48 kWh / kg H2 2.94 L / kg H2 \$2,738,292 2005\$	Hydrogen Pr Design Capacity Capacity factor Process energy efficiency Atter-tax IRR Assumed Plant Life	oduction 1.500 kg/day 85% 62.3% 10% 20	Hydrogen Output Pressure Hydrogen Outlet Quality Total capital investment Other operating costs Levelized Cost of Prod (excl feedst	435 psi 1 \$5.87 2005\$ / annual kg H2 (effective \$0.60 2005\$ / kg H2 produced \$1.42 2005\$ / kg H2 distributed
Coal Input from "Weil" Natural Gas Input from "Weil" Petroleum Input from "Weil"	0 Btu / 116000Btu to Pump 0 Btu / 116000Btu to Pump 0 Btu / 116000Btu to Pump			SMR CO2 Emissions SMR CH4 Emissions SMR N2O Emissions SMR GHG Emissions	0 g / 116000Btu to Pump 0 g / 116000Btu to Pump 0 g / 116000Btu to Pump 0 g CO2 eq./ 116000 Btu
Electricity consumption	1.73 kWh / kg H2	Compression, Storaç	je, & Dispensing	Hydrogen outlet pressure Basis Hydrogen Quantity	6,250 psi 116,000 Btu (116,000 Btu/gal non-oxyg
Total Capital Investment	\$3,989,011 2005\$	Number of Distribution Stations Energy efficiency Number of Compression Stages Isentropic Efficiency	270 95% 5 65%	Total capital investment Electricity cost Levelized Cost of Distribution	\$8.55 2005\$ / annual kg H2 (effective \$0.10 2005\$ / kg H2 \$1.82 2005\$ / kg H2 distributed
Coal Input from "Well" Natural Gas Input from "Well" Petroleum Input from "Well"	12,477 Btu / 116000Btu to Pump 3,584 Btu / 116000Btu to Pump 930 Btu / 116000Btu to Pump	Site storage	62% capacity	CSD CO2 Emissions CSD CH4 Emissions CSD N2O Emissions CSD GHG Emissions	1,647 g / 116000Btu to Pump 2 g / 116000Btu to Pump 0 g / 116000Btu to Pump 1,707 g CO2 eq./ 116000 Btu

323,186 Btu / 116000 Btu

323,186 Btu / 116000 Btu 92,834 Btu / 116000 Btu 24,082 Btu / 116000 Btu 440,102 Btu / 116000 Btu 440,102 Btu / 116000 Btu 56 g / 116000 Btu 1 g / 116000 Btu 44,256 116000 Btu

\$6.05 2005 \$/ kg

45.0 mi / GGE 0% 0% 0% 0%

0%

100%

0%

100% 0%

0%

7,187 Btu / mi

7,187 Btu / mi 2,065 Btu / mi 536 Btu / mi 9,788 Btu / mi 949 g / mi 1 g / mi 0 g / mi 984 g / mi

\$0.1344 2005 \$/mi

Well-to-Pump Results Coal Input from "Well" Natural Gas Input from "Well" Petroleum Input from "Well" Fossil Energy Input from "Well" WTP CO2 Emissions WTP N20 Emissions WTP N20 Emissions

Levelized Cost of Hydrogen (\$/kg)

Vehicle Fuel Economy Ratio of FCV VOCs (emissions) to GVs fueled with CG & RFG Ratio of FCV VOCs (evaporative) to GVs fueled with CG & RFG Ratio of FCV VOC emissions to GVs fueled with CG & RFG Ratio of FCV NOX emissions to GVs fueled with CG & RFG

Ratio of FCV Exhaust PM10 emissions to GVs fueled with CG & RFG

Ratio of FCV Brake & Tire Wear PM10 emissions to GVs fueled with CG & RFG

Ratio of FCV Exhaust PM2.5 emissions to GVs fueled with CG & RFG

Ratio of FCV Brake & Tire Wear PM2.5 emissions to GVs fueled with CG & RFG Ratio of FCV CH4 emissions to GVs fueled with CG & RFG

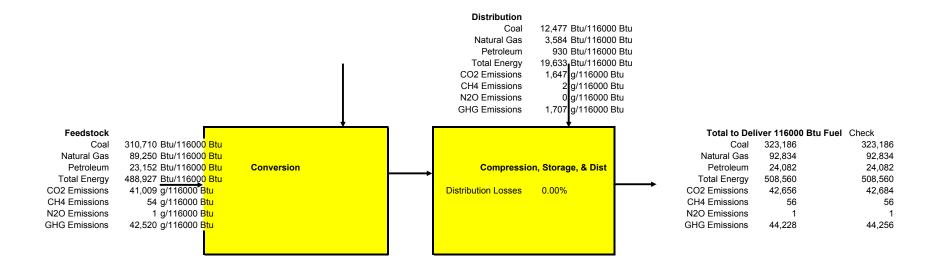
Ratio of FCV N2O emissions to GVs fueled with CG & RFG

Well-to-Wheel Results Coal Input from "Well" Natural Gas Input from "Well" Petroleum Input from "Well" Fossil Energy Input from "Well" WTW CO2 Emissions WTW CH4 Emissions

WTW N2O Emissions WTW GHG Emissions Levelized Cost of Hydrogen (\$/mi)

WTP GHG Emissions

Dist-Elec Pathway Details R090304D 090827 v10.xls 187



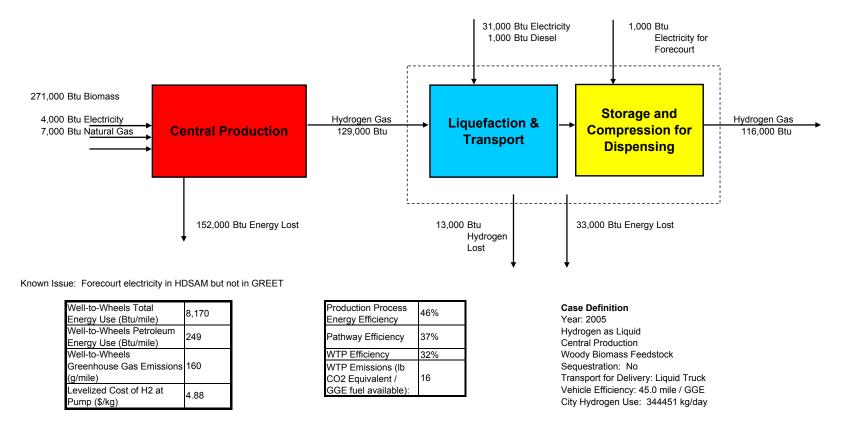
			Referenced		
Parameter	Value	Units	Value	Reference	Comments
Case Definition					
Base Year	2005		2006	None	Default for Dist-Elec Pathway study
Production Technology	Electrolysis		Woody Biomass		Default for Dist-Elec Pathway study
Form of H2 During Delivery	Gas			None	Default for Dist-Elec Pathway study
	None		Pipeline	None Ramsden, T. (2008, July 2). Current (2005) Hydrogen Production from Distributed Grid	Default for Dist-Elec Pathway study Current forecourt H2A production from grid electrolysis basis version 2.1.2; Input Sheet Template tab; Plant Output, ce
Forecourt Station Size		kg/day	1278	Electrolysis . Golden, CO: National Renewable Energy Laboratory	C23
Vehicle Type	passenger cars		passenger cars	None	Default for Dist-Elec Pathway study
				Rousseau, A. & Wallner, T. (2008, October 7). Prospects on Fuel Efficiency Improvements for	Calculated from data in the presentation. The fuel economy for today's average mid-size vehicle was estimated by the Powertrain Simulation Analysis Toolkit V 6.2 SP1, Summer 2008 (PSAT -
Vehicles' Fuel Economy	45.0	mile / gge	45.0	Hydrogen Powered Vehicles. Argonne National Laboroatory presentation, Chicago, IL. Retreive from http://www.transportation.anl.gov/pdfs/HV/530.pdf	http://www.transportation.anl.gov/modeling_simulation/PSAT/index.html). 45 mile/gge is the estimated on road fuel
				inon napowww.uanaportation.anit.gov/pular 19330.pul	economy which was determined by multiplying the projected EPA lab-rated fuel economy of 52.5 mile/gge by 0.85.
Market Definition					
				Figure 1. Material A. O'lletter 1. (2020). (Automore Defines Described and the def	
City Population	1,247,364	people	1,247,364	Elgowainy, A., Mintz, M. & Gillette, J. (2006). Hydrogen Delivery Scenario Analysis Model (HDSAM) V2.0. Argonne, IL: Argonne National Laborator	HDSAM City Selection; Scenario tab; Indianapolis, IN, cell B9
Market penetration	50%	(% vehicles in city)	50%	U.S. Department of Energy & U.S. Department of Transportation. (2006, December)Hydrogen	Basis for posture plan
Number of H2 vehicles in city	460 770	H2 vehicles / city	462.772	Posture Plan An Inegrated Research, Development and Demonstration Plan. Elgowainy, A., Mintz, M. & Gillette, J. (2006). Hydrogen Delivery Scenario Analysis Model	Demand calculation by HDSAM version 2.02; Scenario tab; Number of H2 vehicles in city, cell F17
Number of H2 vehicles in city	462,772	H2 Vehicles / city	462,772	(HDSAM) V2.0. Argonne, IL: Argonne National Laborator	Demand calculation by HDSAM version 2.02; Scenario tab; Number of H2 venicles in city, cell F17
Miles driven per vehicle	12,000	mile / vehicle year	12,000	Elgowainy, A., Mintz, M. & Gillette, J. (2006). Hydrogen Delivery Scenario Analysis Model (HDSAM) V2.0. Argonne, IL: Argonne National Laborator	Key delivery input in HDSAM version 2.02; Scenario tab; Miles driven per year/ vehicle, cell C19
City hydrogen use	344,451	ka / d	344,451	Elgowainy, A., Mintz, M. & Gillette, J. (2006). Hydrogen Delivery Scenario Analysis Model	Demand calculation by HDSAM version 2.02; Scenario tab; City H2 daily use, cell F18
	070	kg/u		(HDSAM) V2.0. Argonne, IL: Argonne National Laborator Elgowainy, A., Mintz, M. & Gillette, J. (2006). Hydrogen Delivery Scenario Analysis Model	
Number of H2 refueling stations in city	270		270	(HDSAM) V2.0. Argonne, IL: Argonne National Laborator	Demand calculation by HDSAM version 2.02; Scenario tab; Number of H2 fueling stations in city, cell F19
Number of H2 stations/Number of gasoline stations	41%		41%	Elgowainy, A., Mintz, M. & Gillette, J. (2006). Hydrogen Delivery Scenario Analysis Model (HDSAM) V2.0. Argonne, IL: Argonne National Laborator	Demand calculation by HDSAM version 2.02; Scenario tab; Number of H2 stations/Number of gasoline stations, cell F21
Average distance between stations (mi)	1.46	miles	1.46	Elgowainy, A., Mintz, M. & Gillette, J. (2006). Hydrogen Delivery Scenario Analysis Model (HDSAM) V2.0. Argonne, IL: Argonne National Laborator	Demand calculation by HDSAM version 2.02; Scenario tab; Average distance between stations, cell F22
		mies		(HDSAM) V2.0. Argonne, iL: Argonne National Laborator	
Feedstock Recovery, Processing, & Transport					
Electricity					
Grid mix for production	US Mix		US Mix	None	Default for Dist-Elec Pathway study US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages
Biomass Fraction				Energy Information Administration. (2007, February). Annual Energy Outlook 2007 with Projections to 2030. DOE/EIA-0383(2007). Washington, D.C. Retreived from	calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbon
	1.2%		1.2%	www.eia.doe.gov/oiaf/archive/aeo07/index.htm	Neutral)" category
Coal Fraction				Energy Information Administration. (2007, February). Annual Energy Outlook 2007 with Projections to 2030. DOE/EIA-0383(2007). Washington, D.C. Retreived from	US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbon
	51.7%		51.7%	www.eia.doe.gov/oiaf/archive/aeo07/index.htm	Neutral)" category
Natural Gas Fraction				Energy Information Administration. (2007, February). Annual Energy Outlook 2007 with Projections to 2030. DOE/EIA-0383(2007). Washington, D.C. Retreived from	US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbo
Natara Gas Fraction	15.7%		15.7%	www.eia.doe.gov/oiaf/archive/aeo07/index.htm	Neutral)" category
Nucleor Freedon				Energy Information Administration. (2007, February). Annual Energy Outlook 2007 with	US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages
Nuclear Fraction	20.3%		20.3%	Projections to 2030. DOE/EIA-0383(2007). Washington, D.C. Retreived from www.eia.doe.gov/oiaf/archive/aeo07/index.htm	calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbon Neutral)" category
	20.3%		20.3%	Projections to 2030. DOE/EIA-0383(2007). Washington, D.C. Retreived from www.eia.doe.gov/oiat/archive/aeo07/index.htm Energy Information Administration. (2007. February).Annual Energy Outlook 2007 with	calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbon Neutral)" category US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages
Nuclear Fraction Residual Oil Fraction	20.3%			Projections to 2030. DOE/EIA-0383(2007). Washington, D.C. Retreived from www.eia.doe.gov/oial/ach/we/aeo07/index.htm Energy Information Administration. (2007, February).Annual Energy Outlook 2007 with Projections to 2030. DOE/EIA-0383(2007). Washington, D.C. Retreived from	calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbo Neutral)" category US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbo Neutral)" category
Residual Oil Fraction				Projections to 2030. DOEELH-0383(2007). Washington, D.C. Retreived from www.eia.doe.gov/aid/arch/wieaeod/index.htm Energy Information Administration. (2007, February). <i>Annual Energy Outlook</i> 2007 with <i>Projections to</i> 2030. DOEELH-0382(2007). Washington, D.C. Retreived from www.eia.doe.gov/aid/arch/wieae07/index.htm Energy Information Administration. (2007. February). <i>Annual Energy Outlook</i> 2007 with Energy Information Administration. (2007. February). <i>Annual Energy Outlook</i> 2007 with	calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbo Neutral)" category US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbo Neutral)" category US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages
			2.9%	Projections to 2030. DOEEL-N0383(2007). Washington, D.C. Retreived from www.eia.doe.gov/ai/afarchive/aea/orn/Index.htm Energy Information Administration. (2007, February).Annual Energy Outlook 2007 with Projections to 2030. DOEEL-N0383(2007). Washington, D.C. Retreived from www.eia.doe.gov/aiaf/archive/aea07/index.htm Energy Information Administration. (2007, February).Annual Energy Outlook 2007 with Projections to 2030. DOEEL-N0383(2007). Washington, D.C. Retreived from	calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbo Neutral)" calcopory US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbo Neutral)" calcopation values reported with all renewables except biomass aggregated into the "Others (Carbo Neutral)" calcopation values reported with all renewables except biomass aggregated into the "Others (Carbo
Residual Oil Fraction           Others (Carbon Neutral)	2.9%		2.9%	Projections to 2030. DOEELH-0383(2007). Washington, D.C. Retreived from www.eia.doe.gov/aid/arch/wieaeod/index.htm Energy Information Administration. (2007, February). <i>Annual Energy Outlook</i> 2007 with <i>Projections to</i> 2030. DOEELH-0382(2007). Washington, D.C. Retreived from www.eia.doe.gov/aid/arch/wieae07/index.htm Energy Information Administration. (2007. February). <i>Annual Energy Outlook</i> 2007 with Energy Information Administration. (2007. February). <i>Annual Energy Outlook</i> 2007 with	calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbo Neutral)" category
Residual Oil Fraction	2.9%		2.9%	Projections to 2030. DDE/ELIA-0383(2007). Washington, D.C. Retreived from www.eia.doe.gov/ai/ar/chvie/aea07/index.htm Energy Information Administration. (2007, February).Annual Energy Outlook 2007 with Projectons to 2030. DDE/EL-0383(2007). Washington, D.C. Retreived from www.eia.doe.gov/ai/ai/ar/chvie/aea07/index.htm Energy Information Administration. (2007, February).Annual Energy Outlook 2007 with Projections to 2030. DDE/EL-0383(2007). Washington, D.C. Retreived from www.eia.doe.gov/ai/ai/ar/chvie/aea07/index.htm	calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbon Neutral) Calcopory US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbon Neutral)" calcopation electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbon Calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbon Neutral)" calcopated in the second second total generation values reported with all renewables except biomass aggregated into the "Others (Carbon Neutral)" calcopated into the "Others (Carbon Neutral)" calcopated into the
Residual Oil Fraction     Others (Carbon Neutral)      H2 Production	2.9%		2.9% 8.2%	Projections to 2030. DDEE/EIA-0383(2007). Washington, D.C. Retreived from www.eia.doe.gov/aid/arch/wieaeo07/index.htm Energy information Administration. (2007, February). <i>Annual Energy Outlook</i> 2007 with <i>Projections to</i> 2030. DDEE/EIA-0383(2007). Washington, D.C. Retreived from www.eia.doe.gov/aid/arch/wieaeo07/index.htm Energy information Administration. (2007, February). <i>Annual Energy Outlook</i> 2007 with <i>Projections to</i> 2030. DDEE/EIA-0383(2007). Washington, D.C. Retreived from www.eia.doe.gov/oiaf/arch/weiaeo07/index.htm Ramsden, T. (2008, July 2). <i>Current (2005) Hydrogen Production from Distributed Grid</i>	calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbon Neutral)" category US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbon Neutral)" category US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbon Neutral)" category US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbon Neutral)" category
Residual Oil Fraction     Others (Carbon Neutral)	2.9%	kg / facility d (after capacity factor is included)	2.9% 8.2%	Projections to 2030. DOEELH-0383(2007). Washington, D.C. Retreived from www.eia.doe.gov/aid/arch/veiaeoa/in/dex.htm Energy information Administration. (2007, February). <i>Annual Energy Outlook</i> 2007 with <i>Projections to</i> 2030. DOEELH-0383(2007). Washington, D.C. Retreived from www.eia.doe.gov/aid/arch/veiaeo07/index.htm Energy information Administration. (2007, February). <i>Annual Energy Outlook</i> 2007 with <i>Projections to</i> 2030. DOEELH-0383(2007). Washington, D.C. Retreived from www.eia.doe.gov/aid/arch/veiaeo07/index.htm Ramsden, T. (2008, July 2). <i>Current</i> (2005) <i>Hydrogen Production from Distributed Grid</i> Electrolysis. Golden, CO: National Renewable Energy Laboratory. And Nexant, Inc. et al. (2006) Way, H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Option	calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbon Neutral)" category Class grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbon Neutral)" category US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbon Neutral)" category US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbon Neutral)" category Current forecourt H2A production from grid electrolysis basis version 2.1.2; Input_Sheet_Template tab; Piant Output, cel
Residual Oil Fraction     Others (Carbon Neutral)      H2 Production	2.9% 8.2% 1,278	kg / facility d (after capacity factor is included)	2.9% 8.2% 1,278	Projections to 2030. DOEEL-03032(2007). Washington, D.C. Retreived from www.eia.doe.gov/oiaflarch/wieaeo07/index.htm Energy Information Administration. (2007, February). <i>Annual Energy Outlook</i> 2007 with <i>Projections to 2030</i> . DOEEL-03032(2007). Washington, D.C. Retreived from www.eia.doe.gov/oiaflarch/wieaeo07/index.htm <i>Projections to 2030</i> . DOEEL-03032(2007). Washington, D.C. Retreived from www.eia.doe.gov/oiaflarch/wieaeo07/index.htm Ramsden, T. (2008, July 2). <i>Current</i> (2005) <i>Hydrogen Production from Distributed Grid</i> <i>Ecchrolysis</i> . Golden, CO: National Renewable Energy Laboratory. An Nexant, Inc. et al. (2008 May); H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Option Analysis Results.Interim Report Section 21.6. DE-630-05001020	calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbo Neutral)" category US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbo Neutral)" category US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbo Neutral)" category US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbo Neutral)" category Current forecourt H2A production from grid electrolysis basis version 2.1.2; Input_Sheet_Template tab; Plant Output, cel C23. Calculated based on 1500kg/day and capacity factor; Nexant report only looks filling station, not production, but in Therecourt is linked, so daily production related to daily dispensing profile.
Residual Oil Fraction     Others (Carbon Neutral)      H2 Production	2.9%	kg / facility d (after capacity factor is included)	2.9% 8.2%	Projections to 2030. DOEEL-03032(2007). Washington, D.C. Retreived from www.sia.doe.gov/ai/ai/chv/ai/ae/ac/mdex.htm Energy Information Administration. (2007. February).Annual Energy Outlook 2007 with Projections to 2030. DOEEL-03032(2007). Washington, D.C. Retreived from www.sia.doe.gov/au/ai/ac/thv/ai/ao/2017/index.htm Thergections to 2020. DOEEL-0303(2007). Washington, D.C. Retreived from www.sia.doe.gov/au/ai/ac/thv/ai/ao/2017/index.htm Projections to 2020. DOEEL-0303(2007). Washington, D.C. Retreived from www.sia.doe.gov/au/ai/ac/thv/ai/ao/2017/index.htm Ramadan, T. (2008. July 2). Current (2005). Hydrogen Production from Distributed Grid Energivguir. Colden. CO. Nutrional Renergivable Energy Laboratory. And Nexant, Inc. et al. (2008 Analysia: Results. Interim Report Section 2.1.5. DE-FG38-0950150322 Ramastan, I. (2008. July 2). Current (2005). Hydrogen Production from Distributed Grid Analysia: Results. Interim Report Section 2.1.5. DE-FG38-095015032	calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbo Neutral)" category Carbo mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbo Neutral)" category calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbo Neutral)" category calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbo Neutral)" category calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbo Neutral)" category carbo model of the second seco
Image: Contraction Production       Image: Production Production       Production Facility Average Output       Image: Corresponding capacity factor	2.9% 8.2% 1,278 85%		2.9% 8.2% 1,278	Projections to 2030. DOEEL-No383(2007). Washington, D.C. Retreived from www.eia.doe.gov/ai/arch/wieaeo/Tindex.htm Energy Information Administration. (2007. February).Annual Energy Outlook 2007 with Projectors to 2030. DOEEL-No382(2007). Washington, D.C. Retreived from www.eia.doe.gov/ai/ai/arch/wieaeo/Tindex.htm Hergy Jonne 2030. DOEEL-No382(2007). Washington, D.C. Retreived from www.eia.doe.gov/ai/ai/arch/wieaeo/Tindex.htm www.eia.doe.gov/ai/arch/wieaeo/Tindex.htm Ramaden, T. (2008, July 2). Current (2005) Hydrogen Production from Distributed Grid Electrolysis. Golden, CO. National Renewable Energy Laboratory. And Nexant, Inc. et al. (2008 Ramaden, T. (2008, July 2). Current (2005) Hydrogen Production from Distributed Grid Electrolysis. Golden, CO. National Renewable Energy Laboratory. And Nexant, Inc. et al. (2008 Ramatien, T. (2008, July 2). Current (2005) Hydrogen Production from Distributed Grid Electrolysis. Golden, CO. National Renewable Energy Laboratory. And Nexant, Inc. et al. (2006 Ramatien, T. (2008, July 2). Current (2005) Hydrogen Production from Distributed Grid Electrolysis. Golden, CO. National Renewable Energy Laboratory. And Nexant, Inc. et al. (2007 Ramatien, T. (2008, July 2). Current (2005) Hydrogen Production from Distributed Grid Electrolysis. Golden, CO. National Renewable Energy Laboratory.	calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbo Neutral)" category US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbo Neutral)" category US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbo Neutral)" category US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbo Neutral)" category Current forecourt H2A production from grid electrolysis basis version 2.1.2; Input_Sheet_Template tab; Plant Output, cel C23. Calculated based on 1500kg/day and capacity factor; Nexant report only looks filling station, not production, but in Therecourt is linked, so daily production related to daily dispensing profile.
Image: Carbon Neutral       Residual Oil Fraction       Others (Carbon Neutral)       H2 Production       Production Facility Average Output       Corresponding capacity factor       Total Capital Investment (both production and CSD)	2.9% 2.9% 8.2% 1,278 85% \$6,727,303		2.9% 8.2% 1.276 85% \$6,727,303	Projections to 2030. DOEEL-03032(2007). Washington, D.C. Retreived from www.eia.doe.gov/oiaffarchvie/aeo07/index.htm Energy Information Administration. (2007, February).Annual Energy Outlook 2007 with Projectons to 2030. DOEEL-03032(2007). Washington, D.C. Retreived from www.eia.doe.gov/oiaffarchvie/aeo07/index.htm Energy Information Administration. (2007, February).Annual Energy Outlook 2007 with Projections to 2030. DOEEL-03032(2007). Washington, D.C. Retreived from www.eia.doe.gov/oiaffarchvie/aeo07/index.htm Ramsden, T. (2008, July 2). Current (2005) Hydrogen Production from Distributed Grid Electrohysis. Golden, CO: National Renewable Energy Laboratory. And Nexant, Inc. et al. (2008 May). H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Option Analysis Results.Interim Report Benevable Energy Laboratory. And Nexant, Inc. et al. (2008 Ramsden, T. (2008, July 2). Current (2005) Hydrogen Production from Distributed Grid Electrohysis. Golden, CO: National Renewable Energy Laboratory. Ramsden, T. (2008, July 2). Current (2005) Hydrogen Production from Distributed Grid Electrohysis. Golden, CO: National Renewable Energy Laboratory. And Nexant, Inc. et al. (2006 Ramsden, T. (2008, July 2). Current (2005) Hydrogen Production from Distributed Grid Electrohysis. Golden, CO: National Renewable Energy Laboratory. And Nexant, Inc. et al. (2006 Retrohysis. Golden, CO: National Renewable Energy Laboratory. Barbard Grid Electrohysis. Golden	calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbo Neutral)" category US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbo Neutral)" category US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbo Neutral)" category US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbo Neutral)" category Current forecourt H2A production from grid electrolysis basis version 2.1.2; Input_Sheet_Template tab; Plant Output, cel Current forecourt H2A production related to dati dispensing profile. Current forecourt H2A production from grid electrolysis basis version 2.1.2; Input_Sheet_Template tab; Plant Design Capacity, cell C21 Sum of row 63 and row 227
Residual Oil Fraction       Others (Carbon Neutral)       H2 Production       Production Facility Average Output       Corresponding capacity factor       Total Capital Investment (both production and CSD)       Total Capital Investment (production only)	2.9% 8.2% 1,278 85% \$6,727.303 \$2,738,292	2005\$	2.9% 8.2% 1.276 85% \$6,727,303 2,738,292	Projections to 2030. DOEELH-0383(2007). Washington, D.C. Retreived from www.eia.doe.gov/iolafarch/weiaeo07/index.htm Energy Information Administration. (2007, February).Annual Energy Outlook 2007 with Projections to 2030. DOEELH-0383(2007). Washington, D.C. Retreived from www.eia.doe.gov/iolafarch/weiaeo07/index.htm Energy Information Administration. (2007, February).Annual Energy Outlook 2007 with Projections to 2030. DOEELH-0383(2007). Washington, D.C. Retreived from www.eia.doe.gov/iolafarch/weiaeo07/index.htm Energy Information Administration. (2007, February).Annual Energy Outlook 2007 with Projections to 2030. DOEELH-0383(2007). Washington, D.C. Retreived from www.eia.doe.gov/iolafarch/weiaeo07/index.htm Energy Information: Renewable Energy Laboratory. And Nexant, Inc. et al. (2008 May). H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Option Analysis Results.Interim Report Section 2.1.5. DE-F30-950010320 Ramation, T. (2008, July 2). Current (2005) Hydrogen Production from Distributed Grid Electrolysis. Coden, CO. National Renewable Energy Laboratory. Ramation, T. (2008, July 2). Current (2005) Hydrogen Production from Distributed Grid Electrolysis. Coden, CO. National Renewable Energy Laboratory Ramation, T. (2008, July 2). Current (2005) Hydrogen Production from Distributed Grid Electrolysis. Coden, CO. National Renewable Energy Laboratory Ramation, T. (2008, July 2). Current (2005) Hydrogen Production from Distributed Grid Electrolysis. Coden, CO. National Renewable Energy Laboratory Ramation, T. (2008, July 2). Current (2005) Hydrogen Production from Distributed Grid Electrolysis. Coden, CO. National Renewable Energy Laboratory Ramation, T. (2008, July 2). Current (2005) Hydrogen Production from Distributed Grid Electrolysis. Coden, CO. National Renewable Energy Laboratory Ramation, T. (2008, July 2). Current (2005) Hydrogen Production from Distributed Grid Electrolysis. Coden, CO. National Renewable Energy Laboratory function from Distributed Gr	calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbo Neutral)" category US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbo Neutral)" category US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbo Neutral)" category US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbo Neutral)" category Current forecourt H2A production from grid electrolysis basis version 2.1.2; Input_Sheet_Template tab; Plant Output, cel Carcent forecourt H2A production from grid electrolysis basis version 2.1.2; Input_Sheet_Template tab; Plant Design Carpacity, cell C21 Sum of row 63 and row 227 Current forecourt H2A production from grid electrolysis basis version 2.1.2; Input_Sheet_Template tab; Plant Design Capacity, cell C21
Image: Contraction     Residual Oil Fraction       Others (Carbon Neutral)       H2 Production       Production Facility Average Output       Corresponding capacity factor       Total Capital Investment (both production and CSD)	2.9% 8.2% 1,278 85% \$6,727.303 \$2,738,292		2.9% 8.2% 1.276 85% \$6,727,303 2,738,292	Projections to 2030. DOEEL-03032(2007). Washington, D.C. Retreived from www.eia.doe.gov/ailar/chv/eiaed/7index.htm Energy Information Administration. (2007. February).Annual Energy Outlook 2007 with Projectors to 2030. DOEEL-03032(2007). Washington, D.C. Retreived from www.eia.doe.gov/ailar/chv/eiaed/7index.htm Projectors to 2030. DOEEL-03032(2007). Washington, D.C. Retreived from www.eia.doe.gov/ailar/chv/eiaed/7index.htm Ramaden, T. (2008, July 2). Current (2005) Hydrogen Production from Distributed Grid Electrolysis. Golden, CO. National Renewable Energy Laboratory. And Nexant, Inc. et al. (2006 Ramaden, T. (2008, July 2). Current (2005) Hydrogen Production from Distributed Grid Electrolysis. Golden, CO. National Renewable Energy Laboratory. And Nexant, Inc. et al. (2006 Ramaden, T. (2008, July 2). Current (2005) Hydrogen Production from Distributed Grid Electrolysis. Golden, CO. National Renewable Energy Laboratory. And Nexant, Inc. et al. (2006 Ramaden, T. (2008, July 2). Current (2005) Hydrogen Production from Distributed Grid Electrolysis. Golden, CO. National Renewable Energy Laboratory. Ramaden, T. (2008, July 2). Current (2005) Hydrogen Production from Distributed Grid Electrolysis. Golden, CO. National Renewable Energy Laboratory. Ramaden, T. (2008, July 2). Current (2005) Hydrogen Production from Distributed Grid Electrolysis. Golden, CO. National Renewable Energy Laboratory. Ramaden, T. (2008, July 2). Current (2005) Hydrogen Production from Distributed Grid Electrolysis. Golden, CO. National Renewable Energy Laboratory. Ramaden, T. (2008, July 2). Current (2005) Hydrogen Production from Distributed Grid Electrolysis. Golden, CO. National Renewable Energy Laboratory. Ramaden, T. (2008, July 2). Current (2005) Hydrogen Production from Distributed Grid Electrolysis. Golden, CO. National Renewable Energy Laboratory. None	calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbon Neutral)" category US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbon Neutral)" category US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages US grid mix. National electricity generation data from tables percent data from tables except biomass aggregated into the "Others (Carbon Neutral)" category Current forecourt H2A production from grid electrolysis basis version 2.1.2; Input_Sheet_Template tab; Plant Output, cell Cagan drive data data from grid electrolysis basis version 2.1.2; Input_Sheet_Template tab; Plant Design Capacity, cell C21 Sum of row 63 and row 227 Covers (Grecourt H2A production from grid electrolysis basis version 2.1.2; Input_Sheet_Template tab; Total Capital Covers, cell C71 Covers (Grecourt H2A production from grid electrolysis basis version 2.1.2; Input_Sheet_Template tab; Total Capital Covers, cell C71
Residual Oil Fraction       Others (Carbon Neutral)       H2 Production       Production Facility Average Output       Corresponding capacity factor       Total Capital Investment (both production and CSD)       Total Capital Investment (production only)	2.9% 8.2% 1.278 85% \$6,727,303 \$2,738,202 \$3,48 \$0,0555	2005 \$ KWh / kg H2	2.9% 8.2% 1.276 85% \$6,727,303 2,738,292	Projections to 2030. DOEEL-03033(2007). Washington, D.C. Retreived from www.eia.doe.gov/oiaffarchive/aea07/index.htm Energy Information Administration. (2007, February).Annual Energy Outlook 2007 with Projections to 2030. DOEEL-03032(2007). Washington, D.C. Retreived from www.eia.doe.gov/oiaffarchive/aea07/index.htm Energy Information Administration. (2007, February).Annual Energy Outlook 2007 with Projections to 2030. DOEEL-03032(2007). Washington, D.C. Retreived from www.eia.doe.gov/oiaffarchive/aea07/index.htm Energy Information Administration. (2007, February).Annual Energy Outlook 2007 with Projections to 2030. DOEEL-03032(2007). Washington, D.C. Retreived from www.eia.doe.gov/oiaffarchive/aea07/index.htm Enerdrysis. Coden, CO: National Renewable Energy Laboratory. And Nexant, Inc. et al. (2008 May). H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Option Analysis Results.Interim Report Section 2.1.5. DE-F30-630-63032 Ramsden, T. (2008, July 2). Current (2005) Hydrogen Production from Distributed Grid Electrohysis. Coden, CO: National Renewable Energy Laboratory. Ramsden, T. (2008, July 2). Current (2005) Hydrogen Production from Distributed Grid Electrohysis. Coden, CO: National Renewable Energy Laboratory Ramsden, T. (2008, July 2). Current (2005) Hydrogen Production from Distributed Grid Electrohysis. Coden, CO: National Renewable Energy Laboratory Ramsden, T. (2008, July 2). Current (2005) Hydrogen Production from Distributed Grid Electrohysis. Coden, CO: National Renewable Energy Laboratory Ramsden, T. (2008, July 2). Current (2005) Hydrogen Production from Distributed Grid Electrohysis. Coden, CO: National Renewable Energy Laboratory Ramsden, T. (2008, July 2). Current (2005) Hydrogen Production from Distributed Grid Electrohysis. Coden, CO: National Renewable Energy Laboratory None Energy Information Administation. (2005, February).Annual Energy Outlook 2005 With	calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbo Neutral)" category US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbo Neutral)" category US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbo Neutral)" category US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbo Neutral)" category Current forecourt H2A production from grid electrolysis basis version 2.1.2; Input_Sheet_Template tab; Plant Output, cel Cagacity, cell C21 Current forecourt H2A production from grid electrolysis basis version 2.1.2; Input_Sheet_Template tab; Plant Design Cagacity, cell C21 Sum of row 63 and row 227 Current forecourt H2A production from grid electrolysis basis version 2.1.2; Input_Sheet_Template tab; Total Capital Cates. ell C71 Carbos filencing on LHV basis from Norsk Hydro Quote
	2.9% 8.2% 1.278 85% \$6,727,303 \$2,738,202 \$3,48 \$0,0555	2005\$	2.9% 8.2% 1.276 85% \$6,727,300 2,738,290 53.48	Projections to 2030. DOEEL-03032(2007). Washington, D.C. Retreived from www.sia.doe.gov/ai/ai/chv/ai/ae/ac/mdex.htm Energy Information Administration. (2007. February).Annual Energy Outlook 2007 with Projections to 2030. DOEEL-03032(2007). Washington, D.C. Retreived from www.sia.doe.gov/ai/ai/chv/ai/ai/2007. Projections to 2030. DOEEL-03032(2007). Washington, D.C. Retreived from www.sia.doe.gov/ai/ai/ai/chv/ai/ai/2007). Washington, D.C. Retreived from www.sia.doe.gov/ai/ai/ai/chv/ai/ai/2003/ Projections to 2020. DOEEL-03032(2007). Retreived from Distributed Grid Energy/Outlock 2000. DOEEL-03032(2007). Retreived from Distributed Grid Energy/Outlock 2000. DOEEL-03032(2007). Retreived from Distributed Grid Energy/Outlock 2000. July 20. Current (2005). Hydrogen Production from Distributed Grid Energy/Outlock 2000. July 20. Current (2005). Hydrogen Production from Distributed Grid Energy/Outlock 2000. July 20. Current (2005). Hydrogen Production from Distributed Grid Electrolysis. Golden, CO.O. National Renewable Energy Laboration. Ramaden, T. (2008, July 20. Current (2005). Hydrogen Production from Distributed Grid Electrolysis. Golden, CO. National Renewable Energy Laboration. Ramaden, T. (2008, July 20. Current (2005). Hydrogen Production from Distributed Grid Electrolysis. Golden, CO. National Renewable Energy Laboraton. Ramaden, T. (2008, July 20. Current (2005). Hydrogen Production from Distributed Grid Electrolysis. Golden, CO. National Renewable Energy Laboraton. Ramaden, T. (2005). Sebanay J. Annuel Energy Outlook 2005 With Projections to 2005. DEEEL-03032(2005). Washington, D.C. U.S. Department of Energy. Energy Information Administation. (2005). February J. Annuel Energy Outlook 2005 With Projections to 2005. DEEEL-03032(2005). Washington, D.C. U.S. Department of Energy.	calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbo Neutral)" category US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbo Neutral)" category US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages US grid mix. National electricity generation data from tables ported with all renewables except biomass aggregated into the "Others (Carbo Neutral)" category Current forecourt H2A production from grid electrolysis basis version 2.1.2; input_Sheet_Template tab; Plant Output, cell Carlent forecourt H2A production regrid electrolysis basis version 2.1.2; input_Sheet_Template tab; Plant Design Capacity, cell C21 Sum of row 63 and row 227 Covers (Grecourt H2A production from grid electrolysis basis version 2.1.2; input_Sheet_Template tab; Total Capital Coets, cell C71 EXEst Efficiency on LHV basis from Norsk Hydro Quote
Residual Oil Fraction           Others (Carbon Neutral)           H2 Production           Production Facility Average Output           Corresponding capacity factor           Total Capital Investment (both production and CSD)           Total Capital Investment (production only)           Electricity Feedstock Price (if Industrial Electricity is used)	2.9% 2.9% 8.2% 1,278 85% \$6,727,303 \$2,738,292 5.3.48 \$0.0555	2005 \$ KWh / kg H2	2.9% 8.2% 1.276 85% \$6.727.30 2.738.292 53.46 \$0.0555	Projections to 2030. DOEEL-No383(2007). Washington, D.C. Retreived from www.eia.doe.gov/oiaffarchvieaeo07/index.htm Energy Information Administration. (2007, February).Annual Energy Outlook 2007 with Projections to 2030. DOEEL-No383(2007). Washington, D.C. Retreived from www.eia.doe.gov/oiaffarchvieaeo07/index.htm Energy Information Administration. (2007, February).Annual Energy Outlook 2007 with Projections to 2030. DOEEL-No383(2007). Washington, D.C. Retreived from www.eia.doe.gov/oiaffarchvieaeo07/index.htm Energy Information Administration. (2007, February).Annual Energy Outlook 2007 with Projections to 2030. DOEEL-No383(2007). Washington, D.C. Retreived from www.eia.doe.gov/oiaffarchvieaeo07/index.htm Electrohysis. Golden, CO: National Renewable Energy Laboratory. And Nexant, Inc. et al. (2008 May). H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Option Analysis Results.Interim Report Benewable Energy Laboratory. Ramsden, T. (2008, July 2). Current (2005) Hydrogen Production from Distributed Grid Electrohysis. Golden, CO: National Renewable Energy Laboratory. Ramsden, T. (2008, July 2). Current (2005) Hydrogen Production from Distributed Grid Electrohysis. Golden, CO: National Renewable Energy Laboratory. Ramsden, T. (2008, July 2). Current (2005) Hydrogen Production from Distributed Grid Electrohysis. Golden, CO: National Renewable Energy Laboratory. Ramsden, T. (2008, July 2). Current (2005) Hydrogen Production from Distributed Grid Electrohysis. Golden, CO: National Renewable Energy Laboratory. None Energy Information Administation. (2005, February). Annual Energy Outlook 2005 With Projectora to 2025. DOEEL-No38(2005). Washington, D.C. U.S. Department of Energy. Projectora to 2025. DOEELE-No38(2005). Washington, D.C. U.S. Department of Energy.	calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbon Neutral)" category Class grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbon Neutral)" category US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbon Neutral)" category US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbon Neutral)" category Current foreocurt H2A production from grid electrolysis basis version 2.1.2. Input_Sheet_Template tab: Plant Output, eoi Carbon foreocurt H2A production related to daily dispensing profile. Current foreocurt H2A production from grid electrolysis basis version 2.1.2. Input_Sheet_Template tab; Plant Design Cagacity, edl C 200 227 Current foreocurt H2A production from grid electrolysis basis version 2.1.2. Input_Sheet_Template tab; Total Capital D2% Efficiency on LHV basis from Norsk Hydro Quote Industrial electricity price from AEO 2005 "High A" case for startup year (2005). Escalated from 2003 dollars to 2005 dollars. Tile downloaded from http://www.eia.doe.gov/oiaf/aeo/index.html (file name aeo_mv-3.4s)
	2.9% 2.9% 8.2% 1.278 85% \$6,727,303 \$2,738,292 53,48 \$0,0555 1.73	2005 \$ KWh / kg H2 2005 \$AKWh	2.9% 8.2% 1.276 85% \$6,727,300 2,738,290 53.48	Projections to 2030. DOEEL-No383(2007). Washington, D.C. Retreived from www.eia.doe.gov/oiaffarchvieaeo07/index.htm Energy Information Administration. (2007, February).Annual Energy Outlook 2007 with Projectons to 2030. DOEEL-No383(2007). Washington, D.C. Retreived from www.eia.doe.gov/oiaffarchvieaeo07/index.htm Energy Information Administration. (2007, February).Annual Energy Outlook 2007 with Projections to 2030. DOEEL-No383(2007). Washington, D.C. Retreived from www.eia.doe.gov/oiaffarchvieaeo07/index.htm Energy Information Administration. (2007, February).Annual Energy Outlook 2007 with Projections to 2030. DOEEL-No383(2007). Washington, D.C. Retreived from www.eia.doe.gov/oiaffarchvieaeo07/index.htm Electrohysis. Colden, CO: National Renewable Energy Laboratory. And Nexant, Inc. et al. (2006 May). H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Option Analysis Results.Interim Report Benevable Energy Laboratory. Ramsden, T. (2008, July 2). Current (2005) Hydrogen Production from Distributed Grid Electrohysis. Colden, CO: National Renewable Energy Laboratory. Ramsden, T. (2008, July 2). Current (2005) Hydrogen Production from Distributed Grid Electrohysis. Colden, CO: National Renewable Energy Laboratory. Ramsden, T. (2008, July 2). Current (2005) Hydrogen Production from Distributed Grid Electrohysis. Colden, CO: National Renewable Energy Laboratory. None Denergy Information Administation. (2005, February). Annual Energy Laboratory. None Distributed Grid Electrohysis. Colden, CO: National Renewable Energy Laboratory. National Distributed Grid Electrohysis. Colden, CO: National Renewable Energy Laboratory. None Distributed Grid Electrohysis. Colden, Deliver Infrastructure Analysis Models and Conventional Pathway Option National Distributed Grid Electrohysis. Colden, Deliver Infrastructure Ranking Models and Conventional Pathway Option National Distributed Grid Electrohysis. Colden, Deliver Infrastructure Ranking Models and Conventional Pathway Op	calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbo Neutral)" category US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbo Neutral)" category US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages Calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbo Neutral)" category Current forecourt H2A production from grid electrolysis basis version 2.1.2; Input_Sheet_Template tab; Plant Output, cel C22. Calculated based on 1500kg/day and capacity factor; Nexant report only looks filling station, not production, but in forecourt is linked, so daily production related to daily dispensing profile. Current forecourt H2A production from grid electrolysis basis version 2.1.2; Input_Sheet_Template tab; Plant Design Capacity, cell C21 Sum of row 63 and row 227 Corten Carbon V approduction from grid electrolysis basis version 2.1.2; Input_Sheet_Template tab; Total Capital Costs, cell C71 Corten Carbon V approduction from grid electrolysis basis version 2.1.2; Input_Sheet_Template tab; Total Capital Costs, cell C71 Costs, cell C71
Residual Oil Fraction       Residual Oil Fraction       Others (Carbon Neutral)       H2 Production       Production Facility Average Output       Corresponding capacity factor       Total Capital Investment (both production and CSD)       Total Capital Investment (production only)       Electricity feedstock consumption       Electricity efedstock Price (if Industrial Electricity is used)       Electricity utility consumption (both production and compression)	2.0% 2.0% 8.2% 1.278 85% 56,727,333 \$2,738,292 53,48 \$0,0655 1.73	2005 \$ KWh / kg H2 2005 \$/KWh KWh / kg H2	2.9% 8.2% 1.276 85% \$6,72,300 \$6,72,300 \$3.44 \$0.0556 1.73	Projections to 2030. DOEEL-A0383(2007). Washington, D.C. Retreived from www.sia.doe.gov/ai/ai/chv/ai/ae/ac/mdex.htm Energy Information Administration. (2007, February).Annual Energy Outlook 2007 with Projections to 2030. DOEEL-A038(2007). Washington, D.C. Retreived from www.sia.doe.gov/au/ai/ac/thv/ai/thv/ai/	calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbo Neutral)" category US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbo Neutral)" category US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbo Neutral)" category US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages CaSC acticulated based on t500kg/day and capacity factor; Nexant report only looks filing station, not production, but in Thorecourt II alk production from grid electrolysis basis version 2.1.2; Input_Sheet_Template tab; Plant Output, cel CaSC. Calculated based on t500kg/day and capacity factor; Nexant report only looks filing station, not production, but in Therecourt II alk production from grid electrolysis basis version 2.1.2; Input_Sheet_Template tab; Plant Design Capacity, cell C21 Sum of row 63 and row 227 Courrent forecourt H2A production from grid electrolysis basis version 2.1.2; Input_Sheet_Template tab; Total Capital Costs, cell C71 Sets: Efficiency on LHV basis from Norsk Hydro Quote Industrial electricity price from AEO 2005 "High A" case for statup year (2005). Escated from 2003 dollars to 2005 collars. File downloaded from http://www.eia.doe.gov/oiaf/aeOn/date.html (fle name aeo_hw-3.xis) Compression elec use based on H2A Delivery Components and H2A Delivery Scenario Analysis Model, using onsite H2 production, default compressor values are from Nexant, et al. (2008), section 2.2.5
Residual Oil Fraction           Others (Carbon Neutral)           H2 Production           Production Facility Average Output           Corresponding capacity factor           Total Capital Investment (both production and CSD)           Total Capital Investment (both production only)           Electricity Feeddstock Price (if Industrial Electricity is used)	2.0% 2.0% 8.2% 1.278 85% 56,727,333 \$2,738,292 53,48 \$0,0655 1.73	2005 \$ KWh / kg H2 2005 \$/KWh KWh / kg H2	2.9% 8.2% 1.276 85% \$6,72,300 \$6,72,300 \$3.44 \$0.0556 1.73	Projections to 2030. DOEEL-A0383(2007). Washington, D.C. Retreived from www.sia.doe.gov/ai/ai/chv/ai/ae/ac/mdex.htm Energy Information Administration. (2007, February).Annual Energy Outlook 2007 with Projections to 2030. DOEEL-A038(2007). Washington, D.C. Retreived from www.sia.doe.gov/au/ai/ac/thv/ai/thv/ai/	calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbo Neutral)" category US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbo Neutral)" category US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages Calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbo Neutral)" category Current forecourt H2A production from grid electrolysis basis version 2.1.2; Input_Sheet_Template tab; Plant Output, cel C22. Calculated based on 1500kg/day and capacity factor; Nexant report only looks filling station, not production, but in forecourt is linked, so daily production related to daily dispensing profile. Current forecourt H2A production from grid electrolysis basis version 2.1.2; Input_Sheet_Template tab; Plant Design Capacity, cell C21 Sum of row 63 and row 227 Corten Carbon V approduction from grid electrolysis basis version 2.1.2; Input_Sheet_Template tab; Total Capital Costs, cell C71 Corten Carbon V approduction from grid electrolysis basis version 2.1.2; Input_Sheet_Template tab; Total Capital Costs, cell C71 Costs, cell C71
Residual Oil Fraction     Residual Oil Fraction     Others (Carbon Neutral)  H2 Production     Production     Production Facility Average Output     Corresponding capacity factor     Total Capital Investment (both production and CSD)     Total Capital Investment (production only)     Electricity feedstock consumption     Electricity redistock Price (if Industrial Electricity is used)     Electricity utility consumption (both production and compression)	2.9% 8.2% 1.278 85% \$6,727,303 \$2,738,292 \$3,48 \$0,0555 1.73	2005 \$ KWh / kg H2 2005 \$AKWh	2.9% 8.2% 1,276 85% \$6,727,300 2,738,395 53.46 \$0.0556 1.75 1.75 0.00	Projections to 2030. DOEEL-Ro3032(2007). Washington, D.C. Retreived from www.eia.doe.gov/oia/archive/aeao/7index.htm Energy Information Administration. (2007, February). <i>Annual Energy Outlook</i> 2007 with Projectons to 2030. DOEEL-Ro3032(2007). Washington, D.C. Retreived from www.eia.doe.gov/oia/archive/aeao07/index.htm Energy Information Administration. (2007, February). <i>Annual Energy Outlook</i> 2007 with Projections to 2030. DOEEL-Ro3032(2007). Washington, D.C. Retreived from www.eia.doe.gov/oia/archive/aeao07/index.htm Energy Information Administration. (2007, February). <i>Annual Energy Outlook</i> 2007 with Projections to 2030. DOEEL-Ro3032(2007). Washington, D.C. Retreived from www.eia.doe.gov/oia/archive/aeao07/index.htm Energy Information. (2008, July 2). <i>Current</i> (2005) <i>Hydrogen Production from Distributed Grid</i> <i>Electrolysis</i> . Golden, CO: National Renewable Energy Laboratory. And Nexant, Inc. et al. (2008 May). H2A: Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Option Analysis Results. Interim Report Section 21.5. DE-F630-630(5) Electrolysis. Golden, CO: National Renewable Energy Laboratory. And Nexant, Inc. et al. (2008 Electrolysis. Golden, CO: National Renewable Energy Laboratory Energy Information Administration. (2005, February) Annual Energy Outlook 2005 With Projections to 2025. DOEEEL-A0332(2005). Washington, D.C. U.S. Department of Energy. Energy Information Administration. (2005, February) Annual Energy Outlook 2005 With Projections to 2025. DOEEEL-A0332(2005). Washington, D.C. U.S. Department of Energy. Energy Information Administration. (2005, February) Annual Energy Cutlook 2005 With Projections to 2025. DOEEEL-A0332(2005). Washington, D.C. U.S. Department of Energy. Energy Information Administration. (2005, February) Laboratory. And Nexant, Inc. et al. (2008 May). H2A: Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Option Analysis Results. Interim Report Section 2.2.5. DE-E-G38-050105022 Emerdonsis. Coldon, July 2).	calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbon Neutral)" category US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbon Neutral)" category US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbon Neutral)" category Current forecourt H2A production from grid electrolysis basis version 2.1.2. Input_Sheet_Template tab: Plant Output, col C22.3. Calculated based on 1500kg/day and capacity factor. Nexant report only looks filling station, not production, but in forecourt is linked, so daily production related to daily dispensing profile. Current forecourt H2A production from grid electrolysis basis version 2.1.2. Input_Sheet_Template tab: Plant Design Capacity, cell C 200 Sum of row 63 and row 227 Current forecourt H2A production from grid electrolysis basis version 2.1.2. Input_Sheet_Template tab: Total Capital Costs, cell C11 Z2% Efficiency on LHV basis from Norsk Hydro Quote Industrial electricity price from AEO 2005 "High A" case for startup year (2005). Escalated from 2003 dolars to 2005 dolars. Tel downloaded from http://www.eia.de.gov/oi/af/acoindex.thmf (file name ae_hw-3.4s) Compression elec use based on H2A Delivery Components and H2A Delivery Scenario Analysis Model, using onsite H2 groduction, default compressor values are from Nexant, et al. (2008), section 2.2.5. All electricity for production from grid electrolysis basis version 2.1.2. Input_Sheet_Template tab; Cell D134. Value
Residual Oil Fraction       Residual Oil Fraction       Others (Carbon Neutral)       H2 Production       Production Facility Average Output       Corresponding capacity factor       Total Capital Investment (both production and CSD)       Total Capital Investment (production only)       Electricity feedstock consumption       Electricity efedstock Price (if Industrial Electricity is used)       Electricity utility consumption (both production and compression)	2,9% 8,2% 1,278 86% \$6,727,303 \$2,78,392 \$53,44 \$0,0655 1,73 9,0005	2005 \$ KWh / kg H2 2005 \$/KWh KWh / kg H2	2.9% 8.2% 1.276 85% \$6,72,300 \$6,72,300 \$6,72,300 \$3,44 \$0,0556 \$1,73	Projections to 2030. DOEEL-A0383(2007). Washington, D.C. Retreived from www.eia.doe.gov/ailar/chv/aeaa/rok/mdex.htm Energy Information Administration. (2007, February).Annual Energy Outlook 2007 with Projections to 2030. DOEEL-A038(2007). Washington, D.C. Retreived from www.eia.doe.gov/aulinechv/aeao07/index.htm tamay Administration. (2007, February).Annual Energy Outlook 2007 with Projections to 2020. DOEEL-A038(2007). Washington, D.C. Retreived from www.eia.doe.gov/aulinechv/aeao07/index.htm Ramsdan, T. (2008, July 2). Current (2005). Hydrogen Production from Distributed Grid Energy/Outlook 2000 EEL-A038(2007). Washington, D.C. Retreived from www.eia.doe.gov/aulinechv/aeao07/index.htm Ramsdan, T. (2008, July 2). Current (2005). Hydrogen Production from Distributed Grid Energy/Outlook, July 2). Current (2005). Hydrogen Production from Distributed Grid Energy/Outlook, July 2). Current (2005). Hydrogen Production from Distributed Grid Electrolysis. Colden, CO. National Renewable Energy Laboraton, Ramsdan, T. (2008, July 2). Current (2005). Hydrogen Production from Distributed Grid Electrolysis. Colden, CO. National Renewable Energy Laboraton, Ramsdan, T. (2008, July 2). Current (2005). Hydrogen Production from Distributed Grid Electrolysis. Colden, CO. National Renewable Energy Laboraton, Ramsdan, T. (2008, July 2). Current (2005). Hydrogen Production from Distributed Grid Electrolysis. Colden, CO. National Renewable Energy Laboraton, Ramsdan, T. (2008, July 2). Current (2005). Hydrogen Production from Distributed Grid Electrolysis. Colden, CO. National Renewable Energy Laboraton, Ramsdan, T. (2008, July 2). Current (2005). Hydrogen Production from Distributed Grid Electrolysis. Golden, CO. National Renewable Energy Laboraton, Ramsdan, T. (2008, July 2). Current (2005). Hydrogen Production from Distributed Grid Electrolysis. Golden, CO. National Renewable Energy Laboraton, Ramsdan, T. (2008, July 2). Current (2005). Hydrogen Production from Distributed Grid Electrolysis. Golden, CO. N	calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbo Neutral") category Clis grid mix. National electricity generation data from tables D-7 & D-9 using the 2005 timeframe. Percentages calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbo Neutral") category Carbo no total generation values reported with all renewables except biomass aggregated into the "Others (Carbo Neutral") category Current forecourt H2A production from grid electrolysis basis version 2.1.2; Input_Sheet_Template tab; Plant Output, cet Carbo no total generation values reported with all renewables except biomass aggregated into the "Others (Carbo Neutral)" category Current forecourt H2A production from grid electrolysis basis version 2.1.2; Input_Sheet_Template tab; Plant Output, cet Carbo neutral is linked, so daily production related to daily dispensing profile. Carent forecourt H2A production from grid electrolysis basis version 2.1.2; Input_Sheet_Template tab; Plant Design Cagaedito, cetl C21 Sum of row 63 and row 227 Current forecourt H2A production from grid electrolysis basis version 2.1.2; Input_Sheet_Template tab; Total Capital Cables. File Generation and electrolysis basis version 2.1.2; Input_Sheet_Template tab; Total Capital Cables. File Generation and the cable daily dispensing profile. Carbo dailars. File downaded from trip/inweit al.dog ou/cableadindex.html (III ename age_hm-3.xis) Compression elec use based on H2A Delivery Components and H2A Delivery Scenario Analysis Model, using onsite H2 production, default compressor values are from Nexant, et al. (2006), section 2.2.5 All electricity for production from grid electrolysis basis version 2.1.2; Input_Sheet_Template tab; Total Capital Carbo Mixer Kables dailer. The downaded from trip/inversion downaded from trip/inversion deviced dailer. File downaded from trip/inversion values are from Nexant, et al. (2006), section 2.2.5 All electricity for produc
Image: Construction           Residual Oil Fraction           Others (Carbon Neutral)           H2 Production           Production Facility Average Output           Corresponding capacity factor           Total Capital Investment (both production and CSD)           Total Capital Investment (both production only)           Electricity rededstoc.commution           Electricity rededstoc.commution           Electricity utility consumption (both production and compression)           Electricity utility consumption (production only)           Process Water Consumption	2,9% 8,2% 1,278 86% \$6,727,303 \$2,78,392 \$53,44 \$0,0655 1,73 9,0005	2005 \$ KWh / kg H2 2005 \$ikWh kWh / kg H2 kWh / kg H2 gal / kg H2	2.9% 8.2% 1,276 85% \$6,727,300 2,738,395 53.46 \$0.0556 1.75 1.75 0.00	Projections to 2030. DOEEL-03032(2007). Washington, D.C. Retreived from www.aia.doe.gov/ailar/achvie/aea07/index.htm Energy Information Administration. (2007, February). <i>Annual Energy Outlook</i> 2007 with <i>Projectons to</i> 2030. DOEEL-03032(2007). Washington, D.C. Retreived from www.aia.doe.gov/ailar/achvie/aea07/index.htm Energy Information Administration. (2007, February). <i>Annual Energy Outlook</i> 2007 with <i>Projectons to</i> 2030. DOEEL-03032(2007). Washington, D.C. Retreived from www.aia.doe.gov/ailar/achvie/aea07/index.htm Energy Information Administration. (2007, February). Annual Energy Information Administration. (2007, February). Annual Energy Information Administration. Reterviews: Golden, C.O. National Renewable Energy Laboratory. And Nexant, Inc. et al. (2008 May). H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Option Analysis Results. Interim Report Section 21.5. DE-F630-805010302. Ramaden, T. (2008, July 2). Current (2005) Hydrogen Production from Distributed Grid Electrolysis. Golden, C.O. National Renewable Energy Laboratory. And Nexant, Inc. et al. (2008 Ramaden, T. (2008, July 2). Current (2005) Hydrogen Production from Distributed Grid Electrolysis. Golden, C.O. National Renewable Energy Laboratory. Ramaden, T. (2008, July 2). Current (2005) Hydrogen Production from Distributed Grid Electrolysis. Golden, C.O. National Renewable Energy Laboratory. Ramaden, T. (2008, July 2). Current (2005) Hydrogen Production from Distributed Grid Electrolysis. Golden, C.O. National Renewable Energy Laboratory. Ramaden, T. (2008, July 2). Current (2005) Hydrogen Production from Distributed Grid Electrolysis. Golden, C.O. National Renewable Energy Laboratory. Ramaden, T. (2008, July 2). Current (2005) Hydrogen Production from Distributed Grid Electrolysis. Golden, C.O. National Renewable Energy Laboratory. Ramaden, T. (2008, July 2). Current (2005) Hydrogen Production from Distributed Grid Electrolysis. Golden, C.O. National Renewable Energy Laboratory. Ramaden,	calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbon Neutral)" category
Residual Oil Fraction           Residual Oil Fraction           Others (Carbon Neutral)           H2 Production           Production Facility Average Output           Corresponding capacity factor           Total Capital Investment (both production and CSD)           Total Capital Investment (production only)           Electricity feedstock consumption           Electricity utility consumption (both production and compression)           Electricity utility consumption (production only)           Process Water Consumption           Water Consumption	2.9% 8.2% 1.278 85% 56.727,303 \$2.738,292 53.48 \$0.0555 1.73 0.000 2.94	2005 \$ KWh / kg H2 2005 \$A:Wh KWh / kg H2 KWh / kg H2 gal / kg H2 gal / kg H2	2.9% 8.2% 1.276 85% \$6,727,300 2.738,292 53.46 \$0.0556 1.73 0.00 2.94 0.01	Projections to 2030. DOEEL-0303(2007). Washington, D.C. Retreived from www.eia.doe.gov/oiaffarchvieaeo07/index.htm Energy Information Administration. (2007, February). <i>Annual Energy Outlook</i> 2007 with Projections to 2030. DOEEL-0303(2007). Washington, D.C. Retreived from www.eia.doe.gov/oiaffarchvieaeo07/index.htm Energy Information Administration. (2007, February). <i>Annual Energy Outlook</i> 2007 with Projections to 2030. DOEEL-0303(2007). Washington, D.C. Retreived from www.eia.doe.gov/oiaffarchvieaeo07/index.htm Energy Information Administration. (2007, February). <i>Annual Energy Outlook</i> 2007 with Projections to 2030. DOEEL-0303(2007). Washington, D.C. Retreived from www.eia.doe.gov/oiaffarchvieaeo07/index.htm Energy Information. Com Nationa Renewable Energy Laboratory. And Nexant, Inc. et al. (2008 May). H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Option Analysis Results. Interim Report Section 2.1.5. DE-Fa30-950015032 Ramsden, T. (2008, July 2). <i>Current</i> (2005) <i>Hydrogen Production from Distributed Grid</i> Electrohysis. Coluen, CO. National Renewable Energy Laboratory. Ramsden, T. (2008, July 2). <i>Current</i> (2005) <i>Hydrogen Production from Distributed Grid</i> Electrohysis. Coluen, CO. National Renewable Energy Laboratory. Ramsden, T. (2008, July 2). <i>Current</i> (2005) <i>Hydrogen Production from Distributed Grid</i> Electrohysis. Coluen, CO. National Renewable Energy Laboratory. Note Denergy Information Administation. (2005, February). <i>Annual Energy Outlook</i> 2005 With Projections to 2025. DOEELA-038(2005). Washington, D.C. U.S. Department of Energy. Parasden, T. (2008, July 2). <i>Current</i> (2005) <i>Hydrogen Production from Distributed Grid</i> Electrohysis. Coluen, CO. National Renewable Energy Laboratory. Ramsden, T. (2008, July 2). <i>Current</i> (2005) <i>Hydrogen Production from Distributed Grid</i> Electrohysis. Coluen, CO. National Renewable Energy Laboratory. Ramsden, T. (2008, July 2). <i>Current</i> (2005) <i>Hydrogen Production from Distributed Grid</i> Electrohysis. Coluen,	calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbo Neutral") category US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbo Neutral") category US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbo Neutral") category unrent foreocurt H2A production from grid electrolysis basis version 2.1.2; Input_Sheet_Template tab; Plant Output, cel 22.3 Calculated based on 1500kg/day and capacity factor; Neuranit report only bools filling station, not production, but in forecourt is fined, so daily production related to daily dispensing profile. Current foreocurt H2A production from grid electrolysis basis version 2.1.2; Input_Sheet_Template tab; Plant Desgn Capacity, cell C21 Sum of foreocurt H2A production from grid electrolysis basis version 2.1.2; Input_Sheet_Template tab; Total Capital Capacity, cell C21 Current foreocurt H2A production from grid electrolysis basis version 2.1.2; Input_Sheet_Template tab; Total Capital Casts, cell C71 Current foreocurt H2A production from grid electrolysis basis version 2.1.2; Input_Sheet_Template tab; Total Capital Cobas, cell C71 Current foreocurt H2A production from grid electrolysis basis version 2.1.2; Input_Sheet_Template tab; Total Capital Casts, cell C71 Current foreocurt H2A production from grid electrolysis basis version 2.1.2; Input_Sheet_Template tab; Total Capital Cobas, cell C71 Current foreocurt H2A production from grid electrolysis basis version 2.1.2; Input_Sheet_Template tab; Total Capital Cobas, cell C71 Current foreocurt H2A production from grid electrolysis basis version 2.1.2; Results tab, Energy Data Current foreocurt H2A production from grid electrolysis
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Residual Oil Fraction           Residual Oil Fraction           Others (Carbon Neutral)           H2 Production           Production Facility Average Output           Corresponding capacity factor           Total Capital Investment (both production and CSD)           Total Capital Investment (production only)           Electricity feedstock consumption           Electricity effects on the production and compression)           Electricity utility consumption (both production and compression)           Electricity utility consumption (production only)           Process Water Consumption           Water Consumption	2.9% 8.2% 1.278 85% 56.727,303 \$2.738,292 53.48 \$0.0555 1.73 0.000 2.94	2005 \$ KWh / kg H2 2005 \$A:Wh KWh / kg H2 KWh / kg H2 gal / kg H2 gal / kg H2 Mm <sup>4</sup> 3 / kg H2	2.9% 8.2% 1.276 85% \$6,727,300 2.738,292 53.46 \$0.0556 1.73 0.00 2.94 0.01	Projections to 2030. DOEEL-A0383(2007). Washington, D.C. 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(2008, July 2). <i>Current</i> (2005) <i>Hydrogen Production from Distributed Grid</i> <i>Electrolysis</i> . Colden, CO. National Renewable Energy Laboratory. Ramaden, T. (2008, July 2). <i>Current</i> (2005) <i>Hydrogen Production from Distributed Grid</i> <i>Electrolysis</i> . Colde, CO. National Renewable Energy Laboratory. Nathwa Energy Information Administration. (2005, February). <i>Annual Energy Outlook</i> 2005 With Projections to 2025, DDEEELA0383(2005). Washington, D.C. U.S. Department of Energy. Ramaden, T. (2008, July 2). Current (2005) Hydrogen Production from Distributed Grid <i>Electrolysis</i> . Colden, CO. National Renewable Energy Laboratory. Ramaden, T. (2008, July 2). Current (2005) Hydrogen Production from Distributed Grid <i>Electrolysis</i> . Colden, CO. National Renewable Energy Laboratory. Ramaden, T. (2008, July 2). Current (2005) Hydrogen Production from Distributed Grid <i>Electrolysis</i> . Colden, CO. National Renewable Energy Laboratory. Ramaden, T. 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Residual Oil Fraction           Residual Oil Fraction           Others (Carbon Neutral)           H2 Production           Production Facility Average Output           Corresponding capacity factor           Total Capital Investment (both production and CSD)           Total Capital Investment (both production only)           Electricity feedstock consumption           Electricity utility consumption (both production and compression)           Electricity utility consumption (both production and compression)           Electricity utility consumption (production only)           Process Water Consumption           Water Consumption for Cooling           Compressed Inert Gas           Total Annual Fixed Operating Costis	2.9% 8.2% 1.278 85% \$6,727,303 \$2,738,292 \$3,48 \$0,0555 1.73 0.000 2.94 0.10832 0.023 5183,640	2005 \$ KWh / kg H2 2005 \$k:Wh KWh / kg H2 KWh / kg H2 gal / kg H2 gal / kg H2 gal / kg H2 2005 / yr	2.9% 8.2% 1.276 85% \$6,727,302 53.46 \$0.0555 1.77 0.005 2.94 0.011 0.022 \$183,945	Projections to 2030. 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H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Option Analysis Results. Interim Report Section 21.5. DE-Fa30-930(51032) Ramsden, T. (2008, July 2). <i>Current</i> (2005) <i>Hydrogen Production from Distributed Grid</i> <i>Electrolysis</i> . Colden, CO: National Renewable Energy Laboratory. Ramsden, T. (2008, July 2). <i>Current</i> (2005) <i>Hydrogen Production from Distributed Grid</i> <i>Electrolysis</i> . Colden, CO: National Renewable Energy Laboratory. None Energy Information Administration. (2005, February). <i>Annual Energy Outlook</i> 2005 With Projections to 2025, DDEELH-0383(2005). Wydrogen Production from Distributed Grid <i>Electrolysis</i> . Colden, CO: National Renewable Energy Laboratory. Energy Information Administration. (2005, February). <i>Annual Energy Outlook</i> 2005 With Projections to 2025, DDEELH-0383(2005). Wydrogen Production from Distributed Grid <i>Electrolysis</i> . Colden, CO: National Renewable Energy Laboratory. 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Residual Oil Fraction           Qthers (Carbon Neutral)           H2 Production           Production Facility Average Output           Corresponding capacity factor           Total Capital Investment (both production and CSD)           Total Capital Investment (both production and CSD)           Electricity feedslock consumption           Electricity rededslock Price (if Industrial Electricity is used)           Electricity utility consumption (both production and compression)           Electricity utility consumption (production only)           Electricity utility consumption (production only)           Process Water Consumption           Water Consumption           Water Consumption for Cooling           Compressed Inert Gas           Total Annual Fixed Operating Costs	2,9% 8,2% 8,2% 56,727,303 56,727,303 56,727,303 56,727,303 56,727,303 56,727,303 56,727,303 56,727,303 51,204,888 51,404,888	2005 \$ KWh / kg H2 2005 \$JkWh KWh / kg H2 KWh / kg H2 gal / kg H2 gal / kg H2 S005 / yr 2005 / yr 2005 / yr	2.9% 8.2% 1.276 85% \$6,727,300 2.738,292 5.34 \$0,0555 1.73 0.000 2.94 0.11 0.022 \$183,945 \$1,404,888	Projections to 2030. DOEEL-No383(2007). Washington, D.C. Retreived from www.eia.doe.gov/oial/archive/aeao/Tridex.htm Energy Information Administration. (2007, February). <i>Annual Energy Outlook 2007 with</i> <i>Projections to 2030</i> . DOEEL-No382(2007). Washington, D.C. Retreived from www.eia.doe.gov/oial/archive/aeao/Tridex.htm Energy Information Administration. (2007, February). <i>Annual Energy Outlook 2007 with</i> <i>Projections to 2030</i> . DOEEL-No382(2007). Washington, D.C. Retreived from www.eia.doe.gov/oial/archive/aeao/Tridex.htm Energy Information Administration. (2007, February). <i>Annual Energy Outlook 2007 with</i> <i>Projections to 2030</i> . DOEEL-No382(2007). Washington, D.C. Retreived from www.eia.doe.gov/oial/archive/aeao/Tridex.htm Ramsden, T. (2008, July 2). <i>Current</i> (2005) <i>Hydrogen Production from Distributed Grid</i> <i>Electrolysis</i> . Golden, CO. National Renewable Energy Laboratory. And Nexant, Inc. et al. (2006 May). 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Calculated based on 1500/gdys and capacity factor: Nexant report only looks filing station, not production, but in forecourt H2A production from grid electrolysis basis version 2.1.2: Input_Sheet_Template tab; Plant Design Carrent forecourt H2A production from grid electrolysis basis version 2.1.2; Input_Sheet_Template tab; Plant Design Carrent forecourt H2A production from grid electrolysis basis version 2.1.2; Input_Sheet_Template tab; Plant Design Carrent forecourt H2A production from grid electrolysis basis version 2.1.2; Input_Sheet_Template tab; Total Capital Costs, cell C71 25% Efficiency on LHV basis from Norsk Hydro Quote Industrial electricity price from AEO 2005 High A* case for startup year (2005). Escalated from 2003 dollars to 2005 dollars. File downloaded from H1b; //www eia.doe govical/aeo/index.html (file name aeo, 1w-3.xis) Compression elec: use based on H2A Delivery Components and H2A Delivery Searario Analysis Model, using onsite H2 production, default compressor values are from Nexant, et al. (2008) section 2.2.5 All electrolysis basis version 2.1.2; Input_Sheet_Template tab; Cell D136; ASPEN modeling - see ProcessFlow sheet for details (Mike Penery) in Ramiden, 2008. Current forecourt H2A production from grid electrolysis basi
Residual Oil Fraction           Residual Oil Fraction           Others (Carbon Neutral)           H2 Production           Production Facility Average Output           Corresponding capacity factor           Total Capital Investment (both production and CSD)           Total Capital Investment (production only)           Electricity redistock consumption           Electricity utility consumption (both production and compression)           Electricity utility consumption (both production and compression)           Electricity utility consumption (production only)           Process Water Consumption           Water Consumption           Water Consumption for Cooling           Compressed Inert Gas           Total Annual Variable Operating Costs           Total Annual Variable Operating Costs	2.9% 8.2% 1.278 85% \$6,727,303 \$2,738,292 \$3,48 \$0,0555 1.73 0.000 2.94 0.10832 0.023 5183,640	2005 \$ KWh / kg H2 2005 \$JkWh KWh / kg H2 KWh / kg H2 gal / kg H2 gal / kg H2 S005 / yr 2005 / yr 2005 / yr	2.9% 8.2% 1,275 85% \$6,727,300 2,738,292 53.46 \$0.0555 1.73 0.000 2.94 0.011 0.022 \$183,945 \$1,404,888 \$1,1588,835	Projections to 2030. DOEEL-No383(2007). Washington, D.C. Retreived from www.eia.doe.gov/oial/archive/aeao/Tridex.htm Energy Information Administration. (2007, February). <i>Annual Energy Outlook 2007 with</i> <i>Projections to 2030</i> . DOEEL-No382(2007). Washington, D.C. Retreived from www.eia.doe.gov/oial/archive/aeao/Tridex.htm Energy Information Administration. (2007, February). <i>Annual Energy Outlook 2007 with</i> <i>Projections to 2030</i> . DOEEL-No382(2007). Washington, D.C. Retreived from www.eia.doe.gov/oial/archive/aeao/Tridex.htm Energy Information Administration. (2007, February). <i>Annual Energy Outlook 2007 with</i> <i>Projections to 2030</i> . DOEEL-No382(2007). Washington, D.C. Retreived from www.eia.doe.gov/oial/archive/aeao/Tridex.htm Ramsden, T. (2008, July 2). <i>Current</i> (2005) <i>Hydrogen Production from Distributed Grid</i> <i>Electrolysis</i> . Golden, CO. National Renewable Energy Laboratory. And Nexant, Inc. et al. (2006 May). HZA Hydrogen Delivery Infrastructure Analysis Models and Carvention from Distributed Grid <i>Electrolysis</i> . Golden, CO. National Renewable Energy Laboratory. And Nexant, Inc. et al. (2006 Ramsden, T. (2008, July 2). Current (2005) <i>Hydrogen Production from Distributed Grid</i> <i>Electrolysis</i> . Golden, CO. National Renewable Energy Laboratory. Ramsden, T. (2008, July 2). Current (2005) <i>Hydrogen Production from Distributed Grid</i> <i>Electrolysis</i> . Golden, CO. National Renewable Energy Laboratory. Ramsden, T. (2008, July 2). Current (2005) <i>Hydrogen Production from Distributed Grid</i> <i>Electrolysis</i> . Golden, CO. National Renewable Energy Laboratory. Ramsden, T. (2008, July 2). Current (2005) <i>Hydrogen Production from Distributed Grid</i> <i>Electrolysis</i> . Golden, CO. National Renewable Energy Laboratory. Ramsden, T. (2008, July 2). Current (2005) <i>Hydrogen Production from Distributed Grid</i> <i>Electrolysis</i> . Golden, CO. 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Residual Oil Fraction           Residual Oil Fraction           Others (Carbon Neutral)           H2 Production           Production Facility Average Output           Corresponding capacity factor           Total Capital Investment (both production and CSD)           Total Capital Investment (production only)           Electricity feedstock consumption           Electricity utility consumption (both production and compression)           Electricity utility consumption (both production and compression)           Electricity utility consumption (production only)           Process Water Consumption           Water Consumption for Cooling           Compressed Inert Gas           Total Annual Variable Operating Costs           Total Annual Variable Operating Costs           Total Annual Operating Costs           Total Annual Operating Costs           Total Annual Operating Costs	2,9% 8,2% 8,2% 8,2% 8,27,303 8,5%,727,303 8,2738,592 8,57,7,303 8,2738,592 9,374 9,0055 9,005 9,0	2005 \$ KWh / kg H2 2005 \$JkWh KWh / kg H2 KWh / kg H2 gal / kg H2 gal / kg H2 S005 / yr 2005 / yr 2005 / yr	2.9% 8.2% 1.276 85% \$6,72,300 53.44 \$0.0556 1.73 0.000 2.94 0.11 0.022 \$183,945 \$1.404,888 \$1.588,633 62.3% 0.0%	Projections to 2030. DOEEL-A0383(2007). Washington, D.C. Retreived from www.sia.doe.gov/alianchv/alexador/Index.htm Energy Information Administration. (2007, February).Annual Energy Outlook 2007 with Projections to 2030. DOEEL-A038(2007). Washington, D.C. Retreived from www.sia.doe.gov/alianchv/alexador/Index.htm www.sia.doe.gov/alianchv/alexador/Index.htm Energy Information Administration. (2007, February).Annual Energy Outlook 2007 with Projections to 2020. DOEEL-A038(2007). Washington, D.C. Retreived from www.sia.doe.gov/alianchv/alexador/Index.htm Ramsdan, T. (2008, July 2). Current (2005). Hydrogen Production from Distributed Grid Energy/Oylia. Colden. CO. National Renewable Energy Laboratory. Ann Nexant, Inc. et al. (2008 Analysis Results. Interim Report Section 2.1.5. DE-FG38-0950(19532) Ramsdan, T. (2008, July 2). Current (2005). Hydrogen Production from Distributed Grid Electrolysis. Colden. CO. National Renewable Energy Laboratory. Ramsdan, T. (2008, July 2). Current (2005). Hydrogen Production from Distributed Grid Electrolysis. Colden. CO. National Renewable Energy Laboratory. Ramsdan, T. (2008, July 2). Current (2005). Hydrogen Production from Distributed Grid Electrolysis. Colden. CO. National Renewable Energy Laboratory. Ramsdan, T. (2008, July 2). Current (2005). Hydrogen Production from Distributed Grid Electrolysis. Colden. CO. National Renewable Energy Laboratory. Ramsdan, T. (2008, July 2). Current (2005). Hydrogen Production from Distributed Grid Electrolysis. Colden. CO. National Renewable Energy Laboratory. Ramsdan, T. (2008, July 2). Current (2005). Hydrogen Production from Distributed Grid Electrolysis. Colden. CO. National Renewable Energy Laboratory. Ramsdan, T. (2008, July 2). Current (2005). Hydrogen Production from Distributed Grid Electrolysis. Golden. CO. National Renewable Energy Laboratory. Ramsdan, T. (2008, July 2). Current (2005). Hydrogen Production from Distributed Grid Electrolysis. Golden. CO. National Renewable Energy Laboratory. Ramsdan, T.	calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbo Neutral)" category calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbo Neutral)" category calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbo Neutral)" category Current fore total generation values reported with all renewables except biomass aggregated into the "Others (Carbo Neutral)" category Current fore total generation values reported with all renewables except biomass aggregated into the "Others (Carbo Neutral)" category Current forecourt H2A production from grid electrolysis basis version 2.1.2; Input_Sheet_Template tab; Plant Output, cell Carcent forecourt H2A production from grid electrolysis basis version 2.1.2; Input_Sheet_Template tab; Plant Design Capacity, cell C21 Sum of row 53 and row 227 Corrent forecourt H2A production from grid electrolysis basis version 2.1.2; Input_Sheet_Template tab; Plant Design Carrent forecourt H2A production from grid electrolysis basis version 2.1.2; Input_Sheet_Template tab; Plant Design Capacity, cell C21 Sum of row 53 and row 227 Corrent forecourt H2A production from grid electrolysis basis version 2.1.2; Input_Sheet_Template tab; Total Capital Costs. cell C71 Gene Carcel C71 Gene Carcel C71 Compression elec use based on H2A Delivery Components and H2A Delivery Scenario Analysis Model, using onsite H2 production, default compressor values are from Nexant, et al. (2006), seclar 2.2 for Mail electricity for for mark from grid electrolysis basis version 2.1.2; Input_Sheet_Template tab; Cell D134, Value mon Nork Hydro Joude (2002) I.1 per Nm3 H2A Alls (Mile Panne) in Analysis Model, using onsite H2 production, default compressor values are from Nexant, et al. (2006), seclar 2.2 5 All electricity for production from grid electrolysis basis version 2.1.2; Input_Sheet_Template tab; Cell D134, Value mon Nork Hydro Joude (200
Residual Oil Fraction           Others (Carbon Neutral)           H2 Production           Production Facility Average Output           Corresponding capacity factor           Total Capital Investment (both production and CSD)           Total Capital Investment (both production and CSD)           Electricity feedstock consumption           Electricity feedstock consumption           Electricity dility consumption (both production and compression)           Electricity utility consumption (both production and compression)           Electricity utility consumption (production only)           Process Water Consumption           Water Consumption for Cooling           Compressed Inert Cas           Total Annual Fixed Operating Costs           Total Annual Variable Operating Costs           Total Annual Variable Operating Costs           Total Annual Operating Costs           Total Annual Core (cost           Total Annual Core (cost	2,9% 2,9% 8,2% 5,727,303 5,727,303 5,727,303 5,85,727,303 5,85,727,303 5,85,727,303 5,85,727,303 5,95,828 0,005 5,1404,688 5,1404,688 5,1404,688	2005 \$ KWh / kg H2 2005 \$JkWh KWh / kg H2 KWh / kg H2 gal / kg H2 gal / kg H2 S005 / yr 2005 / yr 2005 / yr	2.9% 8.2% 1.276 85% \$6,727,300 2.738,282 5.344 \$0.0555 1.73 0.000 2.94 0.11 0.022 \$183,944 \$1,404,888 \$1,404,888 \$1,588,633 62,3% 0.0%	Projections to 2030. 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(2008, July 2). <i>Current (2005)</i> Hydrogen Production from Distributed Grid Electrolysis: G	calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbo Neutral)" category US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbo Neutral)" category US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbo Neutral)" category Neutral)" category Current forecourt H2A production from grid electrolysis basis version 2.1.2; Input_Sheet_Template tab; Plant Output, cell C23. Calculated based on 1500kg/day and capacity factor; Nexant report only looks filling station, not production, but in florecourt II approximation in grid electrolysis basis version 2.1.2; Input_Sheet_Template tab; Plant Design Capacity, cell C21 Sum of row 63 and row 227 Current forecourt H2A production from grid electrolysis basis version 2.1.2; Input_Sheet_Template tab; Plant Design Capacity, cell C21 Sum of row 63 and row 227 Costs, cell C71 Costs, cell C71 Costs, cell C71 Costs, cell C71 Compression ellec use based on H2A Dolivery Components and H2A Dolivery Scenario Analysis Model, using onsite H2 production, default compressor values are from Nexant, et al. (2006), section 2.2.5 All electricity for production from grid electrolysis basis version 2.1.2; Input_Sheet_Template tab; Cell D134, Value from Norsk Hydro Quote 1760 (2001) Tuper Nm3 H2.4 R8.9 g H2Nm3 and 3.786Lgal, this equals 2.939 galving Current forecourt H2A production from grid electrolysis basis version 2.1.2; Input_Sheet_Template tab; Cell D134, Value from Norsk Hydro Quote (2002) Tuper Nm3 H2.4 R8.9 g H2Nm3 and 3.786Lgal, this equals 2.939 galving Current forecourt H2A production from grid electrolysis basis version 2.1.2; Input_Sheet_Template tab; Cell D134, Current forecourt
Residual Oil Fraction           Others (Carbon Neutral)           H2 Production           Production Facility Average Output           Corresponding capacity factor           Total Capital Investment (both production and CSD)           Total Capital Investment (production and CSD)           Total Capital Investment (production and CSD)           Electricity feedstock consumption           Electricity redistock consumption           Electricity utility consumption (both production and compression)           Electricity utility consumption (both production and compression)           Electricity utility consumption (both production only)           Process Water Consumption           Water Consumption for Cooling           Compressed Inert Cas           Total Annual Fixed Operating Costs           Total Annual Variable Operating Costs           Total Annual Variable Operating Costs           Total Annual Trick of the one of the output of the order of process State- of process State- coal	2,9% 2,9% 8,2% 8,2% 9,6% 9,77,303 9,738,392 9,548 9,00555 1,733 9,00555 1,733 9,00555 1,733 9,00555 1,738,392 0,0055 5,1404,888 5,1508,538,538 5,1508,558,558,558,558,558,558,558,558,558,	2005 \$  KWh / kg H2 2005 \$/kWh  kWh / kg H2 kWh / kg H2 kWh / kg H2 gal / kg H2 gal / kg H2 2005s / yr 2005s / yr 2005s / yr	2.9% 8.2% 1.276 85% \$6,727,300 2.738,240 5.3.44 \$0.0555 1.73 0.000 2.94 0.11 0.022 \$183,945 \$1,404,888 \$1,404,888 \$1,588,339 2.3% 0.0% 0.0%	Projections to 2030. DOEEL-03032(2007). Washington, D.C. Retreived from www.aia.doe.gov/oial/archive/aeao/Tindex.htm Energy Information Administration. (2007, February). <i>Annual Energy Outlook 2007 with</i> <i>Projections to 2030. DOEEL-03032(2007).</i> Washington, D.C. Retreived from www.aia.doe.gov/oial/archive/aeao/Tindex.htm Energy Information Administration. (2007, February). <i>Annual Energy Outlook 2007 with</i> <i>Projections to 2030. DOEEL-03032(2007).</i> Washington, D.C. Retreived from www.aia.doe.gov/oial/archive/aeao/Tindex.htm Energy Information Administration. (2007, February). <i>Annual Energy Outlook 2007 with</i> <i>Projections to 2030. DOEEL-03032(2007).</i> Washington, D.C. Retreived from www.aia.doe.gov/oial/archive/aeao/Tindex.htm Ramsden, T. (2008, July 2). <i>Current (2005) Hydrogen Production from Distributed Grid</i> <i>Electrolysis.</i> Golden, C.O. National Renewable Energy Laboratory. And NexanI, Inc. et al. (2008 May). H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Option Analysis Results. Interim Report Section 21.5. DE-Fab.0405010302 Ramsden, T. (2008, July 2). <i>Current (2005) Hydrogen Production from Distributed Grid</i> <i>Electrolysis.</i> Golden, C.O. National Renewable Energy Laboratory. And NexanI, Inc. et al. (2008 Ramsden, T. (2008, July 2). <i>Current (2005) Hydrogen Production from Distributed Grid</i> <i>Electrolysis.</i> Golden, C.O. National Renewable Energy Laboratory. Ramsden, T. (2008, July 2). <i>Current (2005) Hydrogen Production from Distributed Grid</i> <i>Electrolysis.</i> Golden, C.O. National Renewable Energy Laboratory. Ramsden, T. (2008, July 2). <i>Current (2005) Hydrogen Production from Distributed Grid</i> <i>Electrolysis.</i> Golden, C.O. National Renewable Energy Laboratory. Ramsden, T. (2008, July 2). <i>Current (2005) Hydrogen Production from Distributed Grid</i> <i>Electrolysis.</i> Golden, C.O. National Renewable Energy Laboratory. Ramsden, T. (2008, July 2). <i>Current (2005) Hydrogen Production from Distributed Grid</i> <i>Electrolysis.</i> Golden, C.O. National Renewable Energy La	calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbo Neutral)" category US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbo Neutral)" category US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbo Neutral)" category US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbo Neutral)" category Current forecourt H2A production from grid electrolysis basis version 2.1.2; Input_Sheet_Template tab; Plant Output, cei Cas: Calculated based on 1500kg/day and capacity factor; Nexant report only looks filling station, not production, but in florecourt is linked, so daily production from grid electrolysis basis version 2.1.2; Input_Sheet_Template tab; Plant Design Carrent forecourt H2A production from grid electrolysis basis version 2.1.2; Input_Sheet_Template tab; Total Capital Costs, cell C71 Costs, cell C71 Compression elec use based on H2A Delivery Couptents and H2A Delivery Scenario Analysis Model, using onsite H2 production, default compressor values are from Nexant, et al. (2005), section 2.2.5 All electricity for production is considered "feedstock.* Current central H2A production from grid electrolysis basis version 2.1.2; Input_Sheet_Template tab; Cell D134, Value from Norsh Hydro David (Suc) 1, per Nm3 H2 Al 89 a 9 H2ANna and 3.786Lydal, this equate 2.399 galvag Current forecourt H2A production from grid electrolysis basis version 2.1.2; In

		1		Referenced		
Param	eter	Value	Units	Valuo	Reference	Comments
	Hydrogen outlet pressure (before CSD)	435	psi	435	Remember 2008, July 2). Current (2005) Hydrogen Production from Distributed Grid Electrolysis. Golden, CO: National Renewable Energy Laboratory	Final compression step modeled in the analysis was removed for the H2A case study to maintain consistency with H2J default value.
inancial	Hydrogen quality before transport	99.990%	% H2	99.990%	D. Steward (personal communication).	
- Than to la	After-tax Real IRR	10%		10%	Ramsden, T. (2008, May 28). Current (2005) Hydrogen Production from Distributed Grid	Current central H2A production from grid electrolysis basis version 2.1.2; Input_Sheet_Template tab; After-tax Real IR cell C47
	Plant I ife	20		40	Electrolysis . Golden, CO: National Renewable Energy Laboratoty Ramsden, T. (2008, May 28). Current (2005) Hydrogen Production from Distributed Grid	cell C47 Current central H2A production from grid electrolysis basis version 2.1.2; Input_Sheet_Template tab; Plant life, cell C3
	Federal Tax Rate	35.0%	years	35.0%	Electrolysis . Golden, CO: National Renewable Energy Laboratoty Ramsden, T. (2008, May 28). Current (2005) Hydrogen Production from Distributed Grid	Current central H2A production from grid electrolysis basis version 2.1.2; Input_Sheet_Template tab; Federal taxes, ce
					Electrolysis . Golden, CO: National Renewable Energy Laboratoty Ramsden, T. (2008, May 28). Current (2005) Hydrogen Production from Distributed Grid	C49 Current central H2A production from grid electrolysis basis version 2.1.2; Input Sheet Template tab; State taxes, cell
	State Tax Rate	6.0%		6.0%	Electrolysis . Golden, CO: National Renewable Energy Laboratoty	C48
	Total Tax Rate	38.9%		38.9%	Ramsden, T. (2008, May 28). Current (2005) Hydrogen Production from Distributed Grid Electrolysis . Golden, CO: National Renewable Energy Laboratoty	Current central H2A production from grid electrolysis basis version 2.1.2; Input_Sheet_Template tab; Total tax Rate, c C50
	Frection Equity	100%		100%	Ramsden, T. (2008, May 28). Current (2005) Hydrogen Production from Distributed Grid Electrolysis . Golden, CO: National Renewable Energy Laboratoty	Current central H2A production from grid electrolysis basis version 2.1.2; Input_Sheet_Template tab; Equity Financing cell C38
listrihi	tion Station					
	on Stations for Forecourt Production					
isuibut	Compressor Efficiency at Forecourt production stations	94.8%		94.8%	Ramsden, T. (2008, July 2). Current (2005) Hydrogen Production from Distributed Grid	Current central H2A production from grid electrolysis basis version 2.1.2; Refueling Station tab; cell B41 includes
	Electricity Required by Forecourt Station			808,030	Electrolysis . Golden, CO: National Renewable Energy Laboratory Ramsden, T. (2008, July 2). Current (2005) Hydrogen Production from Distributed Grid	hydrogen loss. This calculation only includes electricity Current central H2A production from grid electrolysis basis version 2.1.2; Refueling Station tab; cell B212
			kWh / station year		Electrolysis . Golden, CO: National Renewable Energy Laboratory Ramsden, T. (2008, July 2). Current (2005) Hydrogen Production from Distributed Grid	
	Electricity required for forecourt compressors	1.73	kWh / kg H2		Electrolysis . Golden, CO: National Renewable Energy Laboratory	Current central H2A production from grid electrolysis basis version 2.1.2; Refueling Station tab; cell B213 divided by B
	Number of Compressor Stages	5	Stages in compressor	4	Ramsden, T. (2008, July 2). Current (2005) Hydrogen Production from Distributed Grid Electrolysis . Golden, CO: National Renewable Energy Laboratory	Current central H2A production from grid electrolysis basis version 2.1.2; Refueling Station tab; Number of Stages, ce B205
	Compressor Isentropic Efficiency	65%		65%	Ramsden, T. (2008, July 2). Current (2005) Hydrogen Production from Distributed Grid	Current central H2A production from grid electrolysis basis version 2.1.2; Refueling Station tab; cell B88
	Site storage (Low Pressure - includes heel)	472			Electrolysis . Golden, CO: National Renewable Energy Laboraton, Nexant, Inc. et al. (2008, May), H2A Hydrogen Delivery Infrastructure Analysis Models and Competitional Delivery Online Academical Results. Introduced Sociale 2.2.2, DE EC26	HDSAM calculation, see description in Nexant Report - Section 2.2.3. Case study includes storage for supplying
	Sile Storage (Low Pressure - Includes neel)	4/2	kg H2	472	Conventional Pathway Options Analysis Results . Interim Report Section 2.2.3. DE-FG36- 05GO15032.	compressor suction side to meet hourly demand (including heel) + 14 hrs of storage based on daily demand for unplat outages.
	Site storage (Cascade)	325		325	Nexant, Inc. et al. (2008, May). H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results . Interim Report Section 2.3.2.4. DE-FG36-	HDSAM calculations, see description in Nexant Report - Section 2.3.2.4
	••••		kg H2 % of design H2 distribution per day		05G015032. Calculation	Calculation of total storage (LP + cascade) divided by design hydrogen distribution per da
	Site storage		% of design H2 distribution per day		Nexant, Inc. et al. (2008, May). H2A Hydrogen Delivery Infrastructure Analysis Models and	
	Dispensing Pressure	6,250	psi	6,250	Conventional Pathway Options Analysis Results . Interim Report Section 2.2.3. DE-FG36- 05GO15032.	HDSAM default, see Nexant Report - Section 2.3.2
	Hydrogen Losses due to leaks in forecourt production station	0.50%		0.00%	Ramsden, T. (2008, July 2). Current (2005) Hydrogen Production from Distributed Grid Electrolysis . Golden, CO: National Renewable Energy Laboratory	Current central H2A production from grid electrolysis basis version 2.1.2; Refueling Station tab; Hydrogen Lost During Compression. cell B90
	Distribution System total capital investment	\$3,989,011		\$3.993.763	Ramsden, T. (2008, July 2). Current (2005) Hydrogen Production from Distributed Grid	Current forecourt H2A production from grid electrolysis basis version 2.1.2; Refueling Station tab; Total Capital
			2005 \$ / station		Electrolysis . Golden, CO: National Renewable Energy Laboratory Ramsden, T. (2008, July 2). Current (2005) Hydrogen Production from Distributed Grid	Investment, cell B162 Current forecourt H2A production from grid electrolysis basis version 2.1.2; Refueling Station tab; Yearly energy cost,
	Distribution System electricity cost	\$44,770	2005\$ / station yr	\$74,512	Electrolysis . Golden, CO: National Renewable Energy Laboratory Ramsden, T. (2008, July 2). Current (2005) Hydrogen Production from Distributed Grid	F35
	Distribution Labor Required	3,958	hr / station yr	3,951	Ramsden, 1. (2008, July 2), Current (2009) Hydrogen Production from Distributed Gra Electrolysis: Golden, CC) National Renewable Energy Laboraton Nexant, Inc. et al. (2008, May).H2A Hydrogen Delivery Infrastructure Analysis Models and	Current forecourt H2A production from grid electrolysis basis version 2.1.2; Refueling Station tab; Labor Cost, cell B16
	Distribution System labor cost	\$39,583	8	\$39,513	Conventional Pathway Options Analysis Results . Interim Report Section 2.2.1.3. DE-FG36-	Bureau of Labor and Statistics, Nexant Report - Section 2.2.1.3
			2005\$ / station yr		05GO15032. Nexant, Inc. et al. (2008, May). H2A Hydrogen Delivery Infrastructure Analysis Models and	
	Distribution System total O&M cost	\$215,265	2005\$ / station vr	\$215,353	Conventional Pathway Options Analysis Results . Interim Report Section 2.2.1.2. DE-FG36- 05G015032.	HDSAM calculations, see recommendations in Nexant Report -Section 2.2.1.2
	ssumptions for WTW Calculations		200007044017		00010002.	
Juner A						
Share of I	RFG in Total Gasoline Use	100%	Þ	100%	U.S. Department of Energy & U.S. Department of Transportation. (2006, December)Hydrogen Posture Plan An Inegrated Research, Development and Demonstration Plan.	Basis for posture plan
Type of C	xygenate in RFG	None		None	U.S. Department of Energy & U.S. Department of Transportation. (2006, December)Hydrogen Posture Plan An Inegrated Research, Development and Demonstration Plan.	Basis for posture plan
D2 Conte		0%	wt %		U.S. Department of Energy & U.S. Department of Transportation. (2006, December)Hydrogen	Basis for posture plan
	nt in RFG CV VOCs (emissions) to GVs fueled with CG & RFG	0%		0%	Posture Plan An Inegrated Research, Development and Demonstration Plan. Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1:	GREET default. Table 4.45 FCV: H2
					Methodology, development, Use and Results. Argonne, IL: Argonne National Laboratory Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1:	
	CV VOCs (evaporative) to GVs fueled with CG & RFG	0%		0%	Methodology, development, Use and Results. Argonne, IL: Argonne National Laboratory	GREET default, Table 4.45 FCV: H2
Ratio of F	CV CO emissions to GVs fueled with CG & RFG	0%	8	0%	Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology, development, Use and Results. Argonne, IL: Argonne National Laboratory	GREET default, Table 4.45 FCV: H2
Ratio of F	CV NOx emissions to GVs fueled with CG & RFG	0%	5	0%	Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology, development, Use and Results. Argonne, IL: Argonne National Laboratory	GREET default, Table 4.45 FCV: H2
Ratio of F	CV Exhaust PM10 emissions to GVs fueled with CG & RFG	0%		0%	Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1:	GREET default, Table 4.45 FCV: H2
	CV Brake & Tire Wear PM10 emissions to GVs fueled with CG & RFG	100%		100%	Methodology, development, Use and Results. Argonne, IL: Argonne National Laboratory Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1:	GREET default, page 197: vehicles within the same weight class have similar tire and brake wear emissions
and UI F	ov slake a me wear i wro emissions to ovs tueled with Co a RFG	100%		100%	Methodology, development, Use and Results. Argonne, IL: Argonne National Laboratory	on see a sonowit, page 197. Vernices within the same weight Gidss fidde shiftidi the drid blake wear emissions
Ratio of F	CV Exhaust PM2.5 emissions to GVs fueled with CG & RFG	0%		0%	Wang, M.Q. (2008, September 5). The Greenhouse Gases, Regualted Emissions, and Energy Use in Transportation (GREET) Model, Version 1.8b. Argonne, IL: Argonne National Laboratory	GREET default:well-known fuel cell emissions (no PM2.5)
		+		1	Wang, M.Q. (2008, September 5). The Greenhouse Gases, Regualted Emissions, and Energy	
Ratio of F	CV Brake & Tire Wear PM2.5 emissions to GVs fueled with CG & RFG	100%	1	100%	Use in Transportation (GREET) Model, Version 1.8b. Argonne, IL: Argonne National Laboratory	GREET default:reasonable to assume FCV has same driving pattern as GV
Ratio of F	CV CH4 emissions to GVs fueled with CG & RFG	0%		0%	Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1:	GREET default, Table 4.45 FCV: H2
Ratio of E	CV N2O emissions to GVs fueled with CG & REG	0%		0%	Methodology, development, Use and Results. Argonne, IL: Argonne National Laboratory Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1:	GREET default, Table 4.45 FCV: H2
					Methodology, development, Use and Results. Argonne, IL: Argonne National Laboratory U.S. Department of Energy & U.S. Department of Transportation. (2006, December)Hydrogen	
Marginal	Electricity Generation Mix for Transportation Use	US Mix		US Mix	Posture Plan An Inegrated Research, Development and Demonstration Plan.	Basis for posture plan
Results						
evelized	Cost	\$0.0E		\$0.0E	Ruth, M. et al. (2009, March). Hydrogen Macro System Model User Guide. NREL/TP-6A1	
-evenzed	0081		\$ / kg		Ruth, M. et al. (2009, March). Hydrogen Macro System Model User Guide. NREL/1P-6A1 44799. Golden, CO: National Renewable Energy Laboratory. Ruth, M. et al. (2009, March). Hydrogen Macro System Model User Guide. NREL/TP-6A1	MSM Results
WTW Coa	al Input	7,187	Btu / mile	7,107	44799. Golden, CO: National Renewable Energy Laboratory. Ruth, M. et al. (2009, March), Hydrogen Macro System Model User Guide. NREL/TP-6A1 44799. Golden, CO: National Renewable Energy Laboratory.	MSM Results

			Referenced		
Parameter	Value	Units	Value	Reference	Comments
	536		536	Ruth, M. et al. (2009, March). Hydrogen Macro System Model User Guide. NREL/TP-6A1	
WTW Petroleum Input	000	Btu / mile	000		MSM Results
	0.799		0.799	Ruth, M. et al. (2009, March). Hydrogen Macro System Model User Guide. NREL/TP-6A1	
WTW Fossil Energy Input	3,700	Btu / mile	3,700	Ruth, M. et al. (2009, March). Hydrogen Macro System Model User Guide. NREL/TP-6A1 44799. Golden. CO: National Renewable Energy Laboratory.	MSM Results
	11 210		44.040	Ruth, M. et al. (2009, March). Hydrogen Macro System Model Oser Guide. INREL/TF-0A1	
WTW Total Energy Input	11,310	Btu / mile		44799. Golden, CO: National Renewable Energy Laboratory.	MSM Results
	0.40		040	Ruth, M. et al. (2009, March). Hydrogen Macro System Model User Guide. NREL/TP-6A1	
WTW CO2 Emissions	949	g / mile			MSM Results
				Ruth, M. et al. (2009, March). Hydrogen Macro System Model User Guide. NREL/TP-6A1	
WTW CH4 Emissions		g / mile			MSM Results
	0		0	Ruth, M. et al. (2009, March). Hydrogen Macro System Model User Guide. NREL/TP-6A1	
WTW N2O Emissions	0	g / mile	U	44799. Golden, CO: National Renewable Energy Laboratory.	MSM Results
	084		084	Ruth, M. et al. (2009, March). Hydrogen Macro System Model User Guide. NREL/TP-6A1	
WTW GHG Emissions	904	g / mile	904	44799. Golden, CO: National Renewable Energy Laboratory.	MSM Results

Appendix C — Biomass–Liquid Truck Supporting Tables and Figures

### Hydrogen Produced In Central Plant and Transported as Liquid via Truck



	Inputs	Graphic Depiction & As	sumptions	C	utputs
		♥ Biomass Production & D	elivery	Biomass moisture content Woody biomass LHV	25% 16,811,019 Btu / dry ton
Coal Input from "Well" Natural Gas Input from "Well" Petroleum input from "Well"	269 Btu / 116000Btu to Pump 427 Btu / 116000Btu to Pump 2,832 Btu / 116000Btu to Pump	Fraction of Woody Biomass (Remaining is He Grams of Nitrogen / dry ton biomass Grams of P2O5 / dry ton biomass Herbicide use Insecticide use Average dist from farm to H2 production		Biomass price at H2 production Levelized Cost of Biomass WTG CO2 Emissions WTG CH4 Emissions WTG CH6 Emissions WTG GH6 Emissions	\$37.96 2005 \$ / dry ton \$0.61 2005\$ / kg H2 distributed -26,911 g / 116000Btu to Pump 0 g / 116000Btu to Pump 0 g / 116000Btu to Pump -26,867 g CO2 eq./ 116000 Btu
Biomass consumption Natural gas consumption Electricity consumption Process Water Consumption Natural gas price Electricity price Total Capital Investment Coal Input from "Well" Natural Gas Input from "Well"	12.8 kg (dry) / kg H2 produced 0.17 N m*3/kg H2 produced 0.98 kWh / kg H2 5.00 L / kg H2 \$0.340 20055 / N m*3 \$0.0555 2005 \$/kWh \$154,644,297 2005\$ 6,356 Btu / 116000Btu to Pump 9,009 Btu / 116000Btu to Pump 3,570 Btu / 116000Btu to Pump	Hydrogen Production Central plant design capacity Capacity factor Process energy efficiency Process energy efficiency Electricity Mix After-tax IRR Assumed Plant Life	n 155,236 kg/day 90% 46,0% Mix 0 40	Hydrogen Output Pressure Hydrogen Outbet Quality Total capital investment Leveilzed Electricity cost Leveilzed Alatural Gas Cost Leveilzed Other operating costs Leveilzed Cost of Prod (excl feedst SMR CO2 Emissions SMR CH4 Emissions SMR CH6 Emissions	300 psi 38 minimum \$3.03 2005\$ / kg H2 produced \$0.06 2005\$ / kg H2 produced \$0.32 2005\$ / kg H2 produced \$1.18 2005\$ / kg H2 distributed 26,979 g / 116000Btu to Pump 3 g / 116000Btu to Pump 0 g / 116000Btu to Pump 27,091 g CO2 eq./ 116000 Btu
Liquefaction electricity consumption Diesel consumption Total Capital Investment Coal Input from "Well" Natural Gas Input from "Well"	8.2 kWh / kg H2 7.3 gal / 1000 kg H2 \$800,063,746 50,184 Btu / 116000Btu to Pump 14,462 Btu / 116000Btu to Pump 4,778 Btu / 116000Btu to Pump	Liquefaction and Truck-D City Population Hydrogen Vehicle Penetration City hydrogen use Liquefaction efficiency Terminal Design Capacity Number of truck-trips required Truck hydrogen capacity One-way distance for delivery Hydrogen losses	elivery 1,247,364 people 50% 125,810,766 kg / yr 80.3% 3,532,139 kg H2 31,009 per year 4,372 kg / truckload 49 miles 10.1%	Total capital investment Levelized Electricity cost Levelized Diesel cost Levelized Labor cost Levelized Other operating costs Levelized Cost of Distribution Delivery CO2 Emissions Delivery N2O Emissions Delivery N2O Emissions Delivery GHG Emissions	\$6.37 2005\$/annual kg delivered \$0.49 2005\$ / kg H2 delivered \$0.01 2005\$ / kg H2 delivered \$0.13 2005\$ / kg H2 delivered \$0.28 2005\$ / kg H2 delivered \$2.04 2005\$ / kg H2 distributed 6,708 g / 116000Btu to Pump 9 g / 116000Btu to Pump 0 g / 116000Btu to Pump 6,955 g CO2 eg/ 116000 Btu
Electricity consumption Electricity price Coal Input from "Weil" Natural Gas Input from "Weil" Petroleum Input from "Weil"	3.04 kWh / kg H2 \$0.082 2005\$ / kWh 0 Btu / 116000Btu to Pump 0 Btu / 116000Btu to Pump 0 Btu / 116000Btu to Pump 0 Btu / 116000Btu to Pump	Forecourt Distribution Number of Distribution Stations Energy efficiency Number of Compression Steps Isentropic Efficiency Site storage Hydrogen Iosses Hydrogen Ioss factor	270 92% 4 65% 52% capacity 0.50% 1.005	Hydrogen outlet pressure Basis Hydrogen Quantity Total capital investment Levelized Electricity cost Levelized Cost of Distribution CSD CO2 Emissions CSD CH4 Emissions CSD Q4D Emissions CSD Q4D Emissions	6,250 psi <b>116,000</b> Btu (116,000 Btu/gal non-oxy \$5.85 2005\$/annual kg \$0.25 2005\$ / kg H2 \$1.05 2005\$ / kg H2 distributed 0 g / 116000Btu to Pump 0 g / 116000Btu to Pump 0 g / 116000Btu to Pump 0 g 0 202 eg / 116000 Btu
			56,809 Elu / 116000 Elu 23,898 Elu / 116000 Elu 11,180 Elu / 116000 Elu 13,87 Elu / 116000 Elu 3 g / 116000 Elu 3 g / 116000 Elu 61,93 116000 Elu 54.88 2005 \$/ kg 45.0 mi / GGE 0% 0% 0% 0% 100% 0% 100% 0%		
		Coal Input from "Well" Natural Gas Input from "Well" Petroleum Input from "Well" Fossil Energy Input from "Well" WTW CO2 Emissions WTW CH4 Emissions WTW VCH4 Emissions WTW GH6 Emissions	100 Btu / mi 3,911 Btu / mi 249 Btu / mi 2,044 Btu / mi 151 g / mi 0 g / mi 0 g / mi 160 g / mi		

Bio-Liquid Pathway Details R090219B 090818 v09.xls 194

\$0.1086 2005 \$/mi

Levelized Cost of Hydrogen (\$/mi)

		Gasification Coal Natural Gas Petroleum CO2 Emissions CH4 Emissions N20 Emissions GHG Emissions	6,356 Btu/mmBtu 9,009 Btu/mmBtu 3,570 Btu/mmBtu 26,979 g/mmBtu 3 g/mmBtu 0 g/mmBtu 27,091 g/mmBtu	Liquefaction Coal Natural Gas Petroleum CO2 Emissions CH4 Emissions N2O Emissions GHG Emissions	50,159 Btu/mmBtu 14,408 Btu/mmBtu 3,735 Btu/mmBtu 6,620 g/mmBtu 9 g/mmBtu 0 g/mmBtu 6,864 g/mmBtu	Transport Coal Natural Gas Petroleum CO2 Emissions CH4 Emissions N2O Emissions GHG Emissions	26 Btu/mmBtu 54 Btu/mmBtu 1,042 Btu/mmBtu 88 g/mmBtu 0 g/mmBtu 0 g/mmBtu 91 g/mmBtu	Storage Coal Natural Gas Petroleum CO2 Emissions CH4 Emissions N2O Emissions GHG Emissions	0 Btu/mmBtu 0 Btu/mmBtu 0 g/mmBtu 0 g/mmBtu 0 g/mmBtu 0 g/mmBtu 0 g/mmBtu		B	3asis	116000 Btu
Feedstock Coal Natural Gas Petroleum CO2 Emissions CH4 Emissions GHG Emissions	269 Btu/mmBtu 427 Btu/mmBtu 2.832 Btu/mmBtu -26,911 g/mmBtu 0 g/mmBtu 0 g/mmBtu 26,867 g/mmBtu	Gasification	Conversion	 Liquefaction Liquefaction Losses	0.50%	 Transport Transport Losses	1.28%	 Storage Storage Losses	4.06%	<b>→</b>	Total to Deli Coal Natural Gas Petroleum CO2 Emissions CH4 Emissions GHG Emissions	iver 116000 56,809 23,898 11,180 6,776 12 0 7,179	<b>B Btu Fuel</b> Check 56,809 23,898 11,180 6,785 12 0 7,188

Part with the second					Referenced		
Note Mathem         Other Mathem         Other Mathem         Other Mathem         Other Mathematical Mathamatical Mathematical	Paramet	er	Value	Units		Reference	Comments
Note         Note <t< td=""><td>Case Defi</td><td>nition</td><td></td><td></td><td></td><td></td><td></td></t<>	Case Defi	nition					
Image: market in the state is a state if a state is a			2005		2005	Nana	Defeult for Disk CMD Dellauren ehndu
Image and set of the							Default for Dist-SMR Pathway study
Image: state in the s	Fo	rm of H2 During Delivery			Gas	None	
Notice         Notice<		· · · · ·				Lawrence D. D. (2000) May 200) Connect (2000) Of the Marther Defense (2000) of Frances	
Image: Section         Image:				kg/day		1500kg/day. Arlington, VA: Directed Technologies Inc.	
$ \begin{array}{                                    $	VE	nicie Type	passenger cars		passenger cars	None	
$ \begin{array}{                                    $						Rousseau, A. & Wallner, T. (2008, October 7). Prospects on Fuel Efficiency Improvements for	Calculated from data in the presentation. The fuel economy for today's average mid-size vehicle was estimated by the Powertrain Simulation Analysis Toolkit V 6 2 SP1. Summer 2008 (PSAT -
Image: Section         Image:	Ve	hicles' Fuel Economy	45.0	mile / gge	45.0	Hydrogen Powered Vehicles. Argonne National Laboroatory presentation, Chicago, IL. Retreive from http://www.transportation.anl.com/orffc/LN//530.orff	http://www.transportation.anl.gov/modeling_simulation/PSAT/index.html). 45 mile/gge is the estimated on-road fuel
Image: Section						non napsiwww.uanaporation.ani.gov/palar 19356.pui	economy which was determined by multiplying the projected EPA lab-rated fuel economy of 52.5 mile/gge by 0.85.
Image: Section	Market De	finition					
Image: Process of the system of the						Electronica A Mintz M & Gillette I (2006) Mutrogen Delivery Scenario Analysis Model	
Image state         Control Logics         Control L	Ci	ty Population	1,247,364	people	1,247,364	(HDSAM) V2.0. Argonne, IL: Argonne National Laborator	HDSAM City Selection; Scenario tab; Indianapolis, IN, cell B9
Interview         Add by Table where $A$	Ma	arket penetration	50%	(% vehicles in city)	50%	U.S. Department of Energy & U.S. Department of Transportation. (2006, December)Hydrogen Posture Plan An Inegrated Research, Development and Demonstration Plan	
$ \begin{vmatrix}                                     $	Nu	umber of H2 vehicles in city			462,772	Elgowainy, A., Mintz, M. & Gillette, J. (2006). Hydrogen Delivery Scenario Analysis Model	Demand calculation by HDSAM version 2.02; Scenario tab; Number of H2 vehicles in city, cell F17
$ \begin{vmatrix}                                     $				mile / vehicle year	12,000	Elgowainy, A., Mintz, M. & Gillette, J. (2006). Hydrogen Delivery Scenario Analysis Model	Key delivery input in HDSAM version 2.02; Scenario tab; Miles driven per year/ vehicle, cell C19
Image data status data st	Ci	ty hydrogen use	344,451	kg / d	267,247		Demand calculation by HDSAM version 2.02; Scenario tab; City H2 daily use, cell F18
Image: 10 association data along         10 bit data along the provide status (m) bit data along the provide statu	N	umber of H2 refueling stations in city	270		210	Elgowainy, A., Mintz, M. & Gillette, J. (2006). Hydrogen Delivery Scenario Analysis Model	Demand calculation by HDSAM version 2.02; Scenario tab; Number of H2 fueling stations in city, cell F19
Image: database index (iii)         Image: database index (iiii)         Image: database index (iii)         <			440/		200/	Elgowainy, A., Mintz, M. & Gillette, J. (2006). Hydrogen Delivery Scenario Analysis Model	
		•				(HDSAM) V2.0. Argonne, IL: Argonne National Laborator	
Image: Interfact inter	A	rerage distance between stations (mi)	1.46	miles	1.65	(HDSAM) V2.0. Argonne, IL: Argonne National Laborator	Demand calculation by HDSAM version 2.02; Scenario tab; Average distance between stations, cell F22
instance	Feedstoc	k Recovery Processing & Transport					
Percent of Work borns the ended of Work borns the	Biomaga	,					
Percent of Work borns the ended of Work borns the	Biomass					Mann, M & Steward, D.M. (2008, May 28), Current (2005) Hydrogen from Biomass via	
Image Mature Context         Pars         Pars<	Pe	ercentage of Woody Biomass (Remainder is Herbaceous)	100%		100%	Gasification and Catalytic Steam Reforming. Golden, CO: National Renewable Energy	Current central H2A production via biomass gasification version 2.1.2 basis
InterfactorControl </td <td></td> <td>Notes Order</td> <td>050</td> <td></td> <td>05%</td> <td>Mana M.O. (1999, August), CREET 15, Transportation Fuel Cuele Medal Valume 1</td> <td>Dec. 00</td>		Notes Order	050		05%	Mana M.O. (1999, August), CREET 15, Transportation Fuel Cuele Medal Valume 1	Dec. 00
Desc         Program         P	в	omass Moisture Content	25%		25%	Methodology, development, Use and Results. Argonne, IL: Argonne National Laboratory	-
Construction         Construction<	Gi	ams of Nitrogen / short ton biomass	709		709	M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walsh	assuming 6 dry tons biomass per acre, and harvesting once every 8 years. App 3.1 is for planting on cropland that was
Image: Construct in the				g / dry ton		M Welek (serees) communication via telephone and meeting behavior M Weng and M Welek	just used for traditional crops.
Description         Description         The subject 200 mm         The subject 200 mm </td <td>Gi</td> <td>rams of P2O5 / short ton biomass</td> <td>189</td> <td>g / dry ton</td> <td>189</td> <td>1998).</td> <td>Torre Ugarte, 2003, App 3.1, assuming 6 dry tons biomass per acre and harvesting once every 8 years</td>	Gi	rams of P2O5 / short ton biomass	189	g / dry ton	189	1998).	Torre Ugarte, 2003, App 3.1, assuming 6 dry tons biomass per acre and harvesting once every 8 years
$ \begin{vmatrix} c \\ c$	Gi	rams of K2O / short ton biomass	331	a / dov top	331		Equivalent to 35 lb K / ac in the maintenance year (Year 3) which is in the range of 15-50 lb K / ac reported by De La
Betwork     Part of Marcels Are Jost tab binmas     Part of Marcels Are Jost tab binmas <th< td=""><td></td><td></td><td></td><td>gr diy ton</td><td></td><td></td><td></td></th<>				gr diy ton			
Image: Control       Image: Contro       Image: Control       Image	Gi	ams of herbicide / short ton biomass	24		24	M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walsh	Ugarte, 2000, App 3.2, assuming 6 dry tons biomass per acre and harvesting once every 8 years. Booth reported
Construction         Construction<				g / dry ton			used for pasture.
Image: Constraint of Code retricted from analysing erged with Endowalds and code with an by dynamic straint on by dynamic straint o	G	ame of insecticida / short ton biomase	2			w. waish (personal communication via telephone and meeting between w. wang and w. waish	As a check, looked at Chastagner: Up to 56% of acreage annually sprayed with Dimethoate (Digon 400, 2-3 pints per
Marge distance from furm to hydrogen production facility         And mine         Warge distance from furm (Lee and Result, Ulgen CL. Augern L. Augern L. Augern L. Margen (L. Bargen Result, Ulgen CL. Bargen L. Barge			-	g / dry ton	2	1998).	annually sprayed with Endosulfan 3 EC (24c WA-990025, 2 qts per acre).
Writege         Building         Bits         All         <			-112,500	g / dry ton	-112,500	Wang M.O. (1999, August), GREET 1.5 - Transportation Fuel Cycle Model Volume 1:	
In Obcody Bindlardy     Intel Medicing, development, Lis and Fascith, Angones, E., Agrones, R. Lagrones, N. L	Av	rerage distance from farm to hydrogen production facility	40	miles	40		GREET basis: distance could be limited by transport costs?
In Notoniy Waldardy     Int A     Methodology, development, Lie and Fasult, Angores, L. Agores National Laboratory     ORE: To also 1% minute utile introduction (Intoles (1-4))       No Used 8 to during scoreshing     0.35%     Wing, M.G. (1999), Anguit, GREET 15. Transportes FacU-Cyck Model Volums 1: Methodology, development, Lie and Fasult, Angores, L. Agores National Laboratory     GREET to also 1% minute utile introduction (Intoles (1-4))       No used 8 to during scoreshing     0.35%     Wing, M.G. (1999), Anguit, GREET 15. Transportes FacU-Cyck Model Volums 1: Methodology, development, Lie and Fasult, Angores, L. Agores National Laboratory     GREET to also 1% minute utile introduction (Intoles (1-4))       No used 8 to during scoreshing     0.35%     Control Methodology, development, Lie and Fasult, Angores, L. Agores National Laboratory     GREET to also 1% minute utile introduction (Intoles (1-4))       No used 8 to during scoreshing     0.35%     Control Methodology, development, Lie Agores National Laboratory     GREET to also 1% minute utile introduction (Intoles (1-4))       No used 8 to during scoreshing     0.31%     Control Methodology, development, Lie Agores National Laboratory     GREET to also 1       No used 8 to during scoreshing with a scoregarable for PADCEI poper and DDEEI AGD73, future marginal increase is assumed to be less and the margin (Intoless 17)     GREET to also 1     Colar (Intoless 17)       No used 8 to during scoreshing with a congenitable for PADCEI poper and DDEEI AGD73, future marginal increase is assumed to be less and use to poper addition to also poper additincrease assumed to be less and use to poper additincrease assumed	Natural Gas	i				Mana M.O. (1000, August), CREET 1.5. Transportation Fuel Cuele Madel Valume 1:	
No uset & lost during recovery     0.055     Image: Statuting recovery     0.055     CREET Takes     CREET Takes     CREET Takes       No rouss in genery efficiency     0.724     CREET Takes     CREET Takes     CREET Takes     CREET Takes       No rouss in genery efficiency     0.724     CREET Takes     CREET Takes     CREET Takes     CREET Takes       No rouss in genery efficiency     0.724     CREET Takes     CREET Takes     CREET Takes       No rouss in genery efficiency     0.724     CREET Takes     CREET Takes     CREET Takes       No rouss in genery efficiency     0.724     CREET Takes     CREET Takes     CREET Takes       No rouss in genery efficiency     0.724     CREET Takes     CREET Takes     CREET Takes       No rouss in genery efficiency     0.724     CREET Takes     CREET Takes     CREET Takes       No rouss in genery efficiency     0.724     CREET Takes     CREET Takes     CREET Takes       No rouss in genery efficiency     0.724     CREET Takes     CREET Takes     CREET Takes       No rouss in genery efficiency     0.724     CREET Takes     CREET Takes     CREET Takes       No rouss in genery efficiency     0.724     CREET Takes     CREET Takes     CREET Takes       No rouss in genery efficiency     0.724     CREET Takes     CREET Ta	N	3 recovery efficiency	97.2%			Methodology, development, Use and Results. Argonne, IL: Argonne National Laboratory	GREET uses 97% which is comparable to several other models (Table 4.11)
NG processing energy efficiency         97.2%         Weing MA (1999, August) GREET 1:5 Transportation Fuel/Cycle Model Volume 1: Methodology, development, La grant Ratur, Ragon, La Jonne Ratur, Dycola, La Jonne Ratur, Dycola, La Jonne Ratur, Buyd, Bayer, and DOE/EIA-0573, future marginal increase is assumed to be less derage.           NG steed & lost during processing         0.15%         Call France Mark B. Shires, T. M. (1996, Ediment derage and DOE/EIA-0573, future marginal increase is assumed to be less derage.         Call France Mark B. Shires, T. M. (1996, Ediment derage and DOE/EIA-0573, future marginal increase is assumed to be less derage.           NG steed & lost during transport         0.14         Skirzbage and DOE/EIA-0573, future marginal increase is assumed to be less derage.           NG steed & lost during transport         0.14         Skirzbage and DOE/EIA-0573, future marginal increase is assumed to be less derage.           NG transport distance         500         Methodology, development, Las and Restir, Agones I. M. (1996, Agant).           Statistical deriver distance         500         Weing MA (1999, Agant).         Call Statistical deriver distance           Statistical deriver distance         500         Weing MA (1996, Agant).         Call Statistical deriver distance         Default           GREET Lass 37.5%         1000 Mites         Methodology, development, Lass and Restin. Agones I. A	N	G used & lost during recovery	0.35%			Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1:	CREET have
No. Land & Lott outring processing         D.15%         Interface Status / Location & Location / Loca	NZ	Parassasing anarry affeires	07.2%			Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1:	
NG used & lost during processing     0.15%     of Membra Emissions from Hu JS. Natural Gas Industry. EPAGs Research Institute pager Retrieved from Hulling Pack Analysis Tabulation Links Pack Analysis Tabulation Li	INC	5 processing energy eniciency	91.276			Methodology, development, Use and Results. Argonne, IL: Argonne National Laboratory	GREET uses 97.5% which is comparable to several other models (Table 4.11)
Image: Construct of the product of the prod	N	3 used & lost during processing	0.15%			of Methane Emissions from the U.S. Natural Gas Industry, EPA/Gas Research Institute paper,	Volume lost from EPA/GRI paper and DOE/EIA-0573; future marginal increase is assumed to be less than current
NG used & lost during transport         0.14         of Methane Emissions from the U.S. Natural Gas industry, EPA/Gas Research Institute pare Retrieved from thg/Jowaw agaput/bitel/specific/dot/institute/pare and Jowawa Retrieved from thg/Jowawa agaput/bitel/specific/dot/institute/pare adapticle/dot/institute/pare adaptic/dot/institute/pare adaptic/dot/instinstinstitute/pare adaptic/dot/institute/pare adaptic/dot						Retrieved from http://www.epa.gov/ttn/chief/ap42/ch14/related/methane.pdf	average.
Image: Control distance       G / (MM Blu mi)       Retrieved from http://www.ga.go//tht/ic/leiged/2ch14/religed/methane.pdf       Parage: Control distance       Parage: Contron distance       Parage: Contron d	N	3 used & lost during transport	0.14			of Methane Emissions from the U.S. Natural Gas Industry, EPA/Gas Research Institute paper.	Volume lost from EPA/GRI paper and DOE/EIA-0573; future marginal increase is assumed to be less than current
Or Destriction         Other Section         Other S		-		g / (MM Btu mil)	l	Retrieved from http://www.epa.gov/ttn/chief/ap42/ch14/related/methane.pdf	average.
Electricity         Image: Control of the for production         US Mix         US Mix         US Mix         Default           Gid mix for production         US Mix         US Mix         US Mix         US gid mix for production         US gid mix form tables D-7 & D-8 using the 2005 timeframe. Per calculated from tables except biomass aggregated into the starting? calculated from tables except biomass aggregated into the starting? calculated from tables except biomass aggregated into the starting? calculated from tables except biomass aggregated into the starting? calculated from table generation values reported with all renewables except biomass aggregated into the starting? calculated from table generation values reported with all renewables except biomass aggregated into the starting? calculated from table generation values reported with all renewables except biomass aggregated into the starting? calculated from table generation values reported with all renewables except biomass aggregated into the starting? calculated from table generation values reported with all renewables except biomass aggregated into the starting? calculated from table generation values reported with all renewables except biomass aggregated into the values reported with all renewables except biomass aggregated into the starting?           Matural Gas Fraction         15.7%         Annual Energy Outlook 2007 - www.eia.doe.gov/cial/archive/aeo7/index.html         calculated from tables periation data from tables D-7 & D-8 using the 2005 interfame. Pe calculated from table generation values reported with all renewables except biomass aggregated into the tables dent form tables D-	N	3 transport distance	500	miles		Wethodology, development, Use and Results. Argonne, IL: Argonne National Laboratory	GREET basis
Image: Standard S	Electricity	tid mix for production	LIS Mix		LIS Mix		
Biomass Fraction         Annual Energy Outlook 2007 – www.eia.doe.gov/oiaf/archive/aeo07/index.html         Calculated motal generation values reported with all enervables except biomass aggregated into 1.2%           Marcel Energy Outlook 2007 – www.eia.doe.gov/oiaf/archive/aeo07/index.html         Calculated motal generation values reported with all enervables except biomass aggregated into 1.2%         US gid mix. National electricity generation data from tables 0-7 & D-8 using the 2005 timeframe. Per calculated motal generation values reported with all renervables except biomass aggregated into 1.8%           Marcel Energy Outlook 2007 – www.eia.doe.gov/oiaf/archive/aeo07/index.html         US gid mix. National electricity generation data from tables 0-7 & D-8 using the 2005 timeframe. Per calculated motal generation values reported with all renervables except biomass aggregated into 1.8%           Marcel Fraction         12.5%         Annual Energy Outlook 2007 – www.eia.doe.gov/oiaf/archive/aeo07/index.html         US gid mix. National electricity generation data from tables 0-7 & D-8 using the 2005 timeframe. Pe calculated from tables encept biomass aggregated into 1.8%           Musclear Fraction         20.3%         Annual Energy Outlook 2007 – www.eia.doe.gov/oiaf/archive/aeo07/index.html         US gid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Pe calculated from tables encept biomass aggregated into 1.8%           Musclear Fraction         20.3%         Annual Energy Outlook 2007 – www.eia.doe.gov/oiaf/archive/aeo07/index.html         US gid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Pe calculater for tables D-7 & D-8 using the 2005	G		US INIX		SS INIA		US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages
Cal Fraction         US grid mix Automal electricity generation data from tables D-7 & D-8 using the 2006 timeframe. Per calculated from table generation data from tables D-7 & D-8 using the 2006 timeframe. Per calculated from table generation data from tables D-7 & D-8 using the 2006 timeframe. Per calculated from table generation data from tables D-7 & D-8 using the 2006 timeframe. Per calculated from table generation data from tables D-7 & D-8 using the 2006 timeframe. Per calculated from table generation data from tables D-7 & D-8 using the 2005 timeframe. Per calculated from table generation data from tables D-7 & D-8 using the 2005 timeframe. Per calculated from table generation data from tables D-7 & D-8 using the 2005 timeframe. Per calculated from table generation data from tables D-7 & D-8 using the 2005 timeframe. Per calculated from table generation data from tables D-7 & D-8 using the 2005 timeframe. Per calculated from table generation data from tables D-7 & D-8 using the 2005 timeframe. Per calculated from table generation data from tables D-7 & D-8 using the 2005 timeframe. Per calculated from table generation data from tables D-7 & D-8 using the 2005 timeframe. Per calculated from table generation data from tables D-7 & D-8 using the 2005 timeframe. Per calculated from table generation data from tables P-7 & D-8 using the 2005 timeframe. Per calculated from table generation data from tables D-7 & D-8 using the 2005 timeframe. Per calculated from table generation data from tables P-7 & D-8 using the 2005 timeframe. Per calculated from table generation data from tables D-7 & D-8 using the 2005 timeframe. Per calculated from table generation data from tables D-7 & D-8 using the 2005 timeframe. Per calculated from table generation values reported with all renewables except biomass aggregated into table from table generation values reported with all renewables except biomass aggregated into table from table generation values reported with all renewables except biomass		Biomass Fraction	4.000		4 00/	Annual Energy Outlook 2007 www.eia.doe.gov/oiaf/archive/aeo07/index.html	calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carb
Cal Fraction       Annual Energy Outlook 2007 - www.eia.doe.gov/oiaf/archive/aeo07/index.html       calculated (not ball generation values reported with all renewables except biomass aggregated into 1         Natural Gas Fraction       15.7%       Annual Energy Outlook 2007 - www.eia.doe.gov/oiaf/archive/aeo07/index.html       calculated (not ball generation values reported with all renewables except biomass aggregated into 1         Version       Natural Gas Fraction       US grid mix. National electricity generation values reported with all renewables except biomass aggregated into 1         Version       Natural Gas Fraction       US grid mix. National electricity generation values reported with all renewables except biomass aggregated into 1         Version       Nuclear Fraction       15.7%       Annual Energy Outlook 2007 - www.eia.doe.gov/oiaf/archive/aeo07/index.html       Calculated from total generation values reported with all renewables except biomass aggregated into 1         Version       20.8%       Annual Energy Outlook 2007 - www.eia.doe.gov/oiaf/archive/aeo07/index.html       Version       Version       Dis grid mix. National electricity generation values reported with all renewables except biomass aggregated into 1         Version       20.9%       Annual Energy Outlook 2007 - www.eia.doe.gov/oiaf/archive/aeo07/index.html       Version       Version       Scientification         Version       20.9%       Annual Energy Outlook 2007 - www.eia.doe.gov/oiaf/archive/aeo07/index.html       Version       Version       Version       Ve			1.2%		1.2%		US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages
Natural Gas Fraction         US grid mix.         Natural Gas Fraction         US grid mix.         Statistical electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Per calculated from tail generation values reported with all renewables except biomass aggregated into 1 15.7%           Nuclear Fraction         15.7%         15.7%         Nuclear Strational electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Per calculated from tail generation values reported with all renewables except biomass aggregated into 1 Nuclear Strating and electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Per calculated from table generation values reported with all renewables except biomass aggregated into 1 Nuclear Strating and electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Per calculated from table generation values reported with all renewables except biomass aggregated into 1 Nuclear Strating and electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Per calculated from tables except biomass aggregated into 1 Nuclear Strating and electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Per calculated from tables except biomass aggregated into 1 Nuclear Strating and electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Per calculated from tables except biomass aggregated into 1 Nuclear Strating and electricity generation values reported with all renewables except biomass aggregated into 1 Nuclear Strating and electricity generation values reported with all renewables except biomass aggregated into 1 Nuclear Strating and electricity generation values reported with all renewables except biomass aggregated into 1 Nuclear Strating and electricity generation values reported with all renewables except biomass aggregated into 1 Nuclear Strating as production <td></td> <td>Coal Fraction</td> <td>51 7%</td> <td></td> <td>51 70/</td> <td>Annual Energy Outlook 2007 www.eia.doe.gov/oiaf/archive/aeo07/index.html</td> <td>calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carb</td>		Coal Fraction	51 7%		51 70/	Annual Energy Outlook 2007 www.eia.doe.gov/oiaf/archive/aeo07/index.html	calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carb
Image: Second			51.7%		51.770		US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages
Nuclear Fraction         US grid mix. Mational electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Per 2005 ti		Natural Gas Fraction	15 70/		15 70/	Annual Energy Outlook 2007 www.eia.doe.gov/oiaf/archive/aeo07/index.html	calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carb
Image: Control of the section of t			13.7%		13.770		US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages
Residual Oli Fraction         US grid mix.         Matchnal electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Pe           2.9%         2.9%         2.9%         cline in the integration of the second integratintegration of the second integratintegrating integra		Nuclear Fraction	20.3%		20.2%	Annual Energy Outlook 2007 www.eia.doe.gov/oiaf/archive/aeo07/index.html	calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbo Neutral)" category
Image: Control Neutral)         2.9%         2.9%         Neutral 2007           Others (Carbon Neutral)         8.2%         Annual Energy Outlook 2007 – www.eia.doe.gov/oia/farchive/aeo07/index.html         US grid mixe. Data generation data from tables D-7 & D-8 using the 2005 limeFrame. Per calculated from tables Ported with all renewables except biomass aggregated into 1           Others (Carbon Neutral)         8.2%         Annual Energy Outlook 2007 – www.eia.doe.gov/oia/farchive/aeo07/index.html         Neutral/2005 limeFrame. Per calculated from tables D-7 & D-8 using the 2005 limeFrame. Per calculated from tables Ported with all renewables except biomass aggregated into 1           Orid mix for inguefaction with biomass production         US Mix         US Mix         None         Default for Del-Liquid Pathway study           Grid mix for inguefaction with nechaltry modules         NGCC         None         Default for Del-Liquid Pathway study           Grid mix for inguefaction with nechaltry modules         NGCC         None         Default for Del-Liquid Pathway study           Grid mix for inguefaction with nechaltry modules         NGCR         None         Default for Del-Liquid Pathway study			20.3%		20.370		US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages
Others (Carbon Neutral)         8.2%         Annual Energy Outlook 2007 - www.eia.doe.gov/oiaf/archive/aeo07/index.html         citizational electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Pe           Others (Carbon Neutral)         8.2%         8.2%         8.2%         None         Neutral)         citizations           Grid mix for liguefaction with bomass production         US Mix         US Mix         None         Default for Bio-Liquid Pathway study           Grid mix for liguefaction with cell production         US Mix         US Mix         None         Default for Bio-Liquid Pathway study           Grid mix for liguefaction with cell production         NGCC         None         Default for Bio-Liquid Pathway study           Grid mix for liguefaction with nuclear production         NGCC         None         Default for Bio-Liquid Pathway study		Residual Oil Fraction	2.0%		2 00/	Annual Energy Outlook 2007 www.eia.doe.gov/oiaf/archive/aeo07/index.html	calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carb
Bit Min for Iguefaction with biomass production         US Mix         0.82%         Neutral? elegacyn         0.01%           Grid mix for Iguefaction with const production         US Mix         US Mix         None         Default for Bio-Liquid Pathway study           Grid mix for Iguefaction with const production         US Mix         US Mix         None         Default for Bio-Liquid Pathway study           Grid mix for Iguefaction with centar production         US Mix         US Mix         None         Default for Bio-Liquid Pathway study           Grid mix for Iguefaction with nuclear production         NGCC         None         Default for Bio-Liquid Pathway study			2.9%		2.970		US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages
Orid mix for inguestion with biomass production         US Mix         US Mix         None         Default for Bio-Liquid Pathway study           Grid mix for inguestication with coaltraptocition         US Mix         US Mix         None         Default for Bio-Liquid Pathway study           Grid mix for inguestication with central natural gas production         NS Mix         US Mix         None         Default for Bio-Liquid Pathway study           Grid mix for inguestication with central natural gas production         NGCC         None         Default for Bio-Liquid Pathway study           Grid mix for inguestication with nuclear production         Nuclear Power         None         Default for Bio-Liquid Pathway study		Others (Carbon Neutral)	8 2%		8 D0/	Annual Energy Outlook 2007 www.eia.doe.gov/oiaf/archive/aeo07/index.html	calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carb Neutral)" category
Orid mix for liquefaction with coal production         US Mix         US Mix         None         Default for Biol-Liquid Pathway study           Orid mix for liquefaction with coal production         NGCC         None         Default for Biol-Liquid Pathway study           Grid mix for liquefaction with cuelar production         NGCC         None         Default for Biol-Liquid Pathway study           Grid mix for liquefaction with nuclear production         Nuclear Power         None         Default for Biol-Liquid Pathway study					US Mix		Default for Bio-Liquid Pathway study
Grid mix for liquefaction with nuclear production Nuclear Power Nuclear Power None Default for Bio-Liquid Pathway study	Gi	id mix for liquefaction with coal production					Default for Bio-Liquid Pathway study
	Gr	id mix for liquefaction with nuclear production	Nuclear Power		Nuclear Power	None	Default for Bio-Liquid Pathway study
	Gi	id mix for pipeline compressors	US Mix		US Mix	None	Default for Bio-Liquid Pathway study

Parame	otor	Value	Units	Referenced Value	Reference	Comments
	Grid mix for compression at distribution	US Mix	Units	US Mix	None	Default for Bio-Liquid Pathway study
2 Prod						
	CO2 Captured for Sequestration	0%		0%	Spath, P., Aden, A., Eggeman, T., Ringer, M., Wallace, B. & Jechura, J. (2005, May) Biomass	Not available in this case study
1	Production Facility Average Output	139,712	kg / facility d (after capacity factor is included)	139,712	Optimit, ", reden, A., Eggeninali, F., Naliger, M., Nealack, D. & Seconda, S. (2007, Mary) Damass to Hydrogen Production Detailed Design and Economics Utilizing the Battelife Columbus Laboratory Indirectly-Heated Gasifier, Section 3.0. NREL/TP-510-37408. Golden, CO: National Renewable Energy Laboratory	Design feed rate for current design plant of 2000 bone dry metric tonne biomass per day (see Section 3.0)
	Corresponding capacity factor	90%		90%	Mann, M., & Steward, D.M. (2008, May 28). Current (2005) Hydrogen from Biomass via Gasification and Catalytic Steam Reforming. Golden, CO: National Renewable Energy I aboratoty.	Current central H2A production from biomass basis version 2.1.2; Input_Sheet_Template tab; Operating Capacity Fa cell C21
	Total Capital Investment	\$154,644,297	2005 \$	\$154,644,297	Spath, P., Aden, A., Eggerman, T., Ringer, M., Wallace, B. & Jechura, J. (2005, May) Biomass to Hydrogen Production Detailed Design and Economics Utilizing the Battelle Columbus Laboratory Indirectly-Heated Gasifier. Table 10. NREL/TP-510-37408. Golden, CO: National Renewable Energy Laboratory	Total installed capital cost of \$102M (\$2002) (see Table 10, Current Design) was escalated to \$2005 dollars. Capital for additional compression was removed to maintain consistency with HZA central model assumptions.
1	Biomass feedstock consumption	12.8	kg (dry) / kg H2	12.8	Spath, P., Aden, A., Eggeman, T., Ringer, M., Wallace, B. & Jechura, J. (2005, May) Biomass to Hydrogen Production Detailed Design and Economics Utilizing the Battelle Columbus Laboratory Indirectly-Heated Gasifier Appendex A. NREL/TP-510-37408. Golden, CO: Nationa Renewable Energy Laboratory	Bonnase usage calculated from plant efficiency of 45.5%. The LHV for woody biomase is taken from HyARC, and is higher (#408 Bulb) w .8509 Bullb) than used in Spath. Appendix A - Design Report: Current Case; Hydrogen Yield 70.4 kg/ dry US for fleedstock
	Biomass feedstock cost	\$37.96	2005\$ / dry short ton		Sciences Commettee on Resource Needs for Fuel Cell and Hydrogen, Washington, D.C.	Feedstock price is taken from the Biomass Program 2012 Target price of \$35/ton (\$2002) escalated to \$2005
1	Natural gas feedstock consumption	0.00	normal m <sup>*</sup> 3 / kg H2 produced		Mann, M., & Steward, D. J.M. (2008, May 28), Current (2005) Hydrogen from Biomass via Gasification and Catalytic Steam Reforming. Golden, CO: National Renewable Energy Laboratoly.	Current central H2A production from biomass basis version 2.1.2; Results tab; Energy Data
	Natural Gas feedstock cost	N/A		N/A	None	IWA
ļ	Natural Gas LHV	34,714	Btu / normal m^3.	36,692	Hydrogen Analysis Resource Center. (2008, September 5)Lower and Higher Heating Values of Hydrogen and Fuels. Retrieved from http://hydrogen.pnl.gov/coccon/morf/hydrogen/article/401	LHV of Natural Gas; 983 Btu/ft3
1	Natural gas utility consumption	0.17	normal m^3 / kg H2 produced		Spath, P., Aden, A., Eggeman, T., Ringer, M., Wallace, B. & Jechura, J. (2006, May) Biomass to Hydrogen Production Detailed Design and Economics Ulilizing the Battelle Columbus Laboratory Indirectly-Heated Gasifier. Appendex A. NREL/TP-510-37408. Golden, CO: Nationa Renewable Encry Laboratory	Natural gas usage from overall energy balance; Appendix C, A401: stream 427 = 1669 lb/hr; Appendix C, A501: stre 424 = 14280 lb/hr; conversion vields 0.15 (not 0.17)
	Natural gas utility price		2005\$ / Nm^3	\$0.340	Energy Information Administation. (2005, February). Annual Energy Outlook 2005 With Projections to 2025. DOE/EIA-0383(2005). Washington, D.C.: U.S. Department of Energy.	AEO 2005 High A Case - Commercial price; Escalated from 2003 dollars to 2005 dollars. File downloaded from http://www.eia.doe.gov/oiaf/aeo/index.html (file name aeo_hw-3.xls)
[	Natural gas utility pressure	N/A #VALUE!	kPa nsi	N/A #VALUE!	None Conversion calculation	Not in H2A or GREET conversion calculation
1	Electricity feedstock consumption	0.00	kWh / kg H2		Mann, M., & Steward, D.M. (2008, May 28). Current (2005) Hydrogen from Biomass via Gasification and Catalytic Steam Reforming. Golden, CO: National Renewable Energy Laboratoty.	Current central H2A production from biomass basis version 2.1.2; Results tab; Energy Data
	Electricity utility consumption (both production and compression)	0.98	KWh / kg H2	0.98	Spath, P., Aden, A., Eggeman, T., Ringer, M., Wallace, B. & Jechura, J. (2005, May) Biomass to Hydrogen Production Detailed Design and Economics Utilizing the Battelle Columbus Laboratory Indirectly-Heated Gasifier. NREL/TP-510-37408. Golden, CO: National Renewable Energy Laboratory	Electricity usage from overall energy balance with energy usage for hydrogen compression (3899 kW) removed. Appendix A, Total Plant Electricity = 5.54 kWh/kg H2 -
ł	Electricity utility consumption (production only)	0.98	kWh / kg H2	0.96	Spath, P., Aden, A., Eggeman, T., Ringer, M., Wallace, B. & Jechura, J. (2005, May) Biomass to Hydrogen Production Detailed Design and Economics Utilizing the Battelle Columbus Laboratory Indirectly-Heated Gasifier. NREL/TP-510-37408. Golden, CO: National Renewable Energy Laboratory	Electricity usage from overall energy balance with energy usage for hydrogen compression (3899 kW) removed. Appendix A, Total Plant Electricity = 5.54 kWh/kg H2
1	Electricity Utility Price	0.0555	2005 \$/kWh	0.0555	Energy Information Administation. (2005, February). Annual Energy Outlook 2005 With Projections to 2025. DOE/EIA-0383(2005). Washington, D.C.: U.S. Department of Energy.	AEO 2005 High A Case - Industrial price; Escalated from 2003 dollars to 2005 dollars. File downloaded from http://www.eia.doe.gov/oiat/aeo/index.html (file name aeo_hw-3.xls)
	Process Water Consumption	1.32	gal / kg H2	1.32	Spath, P., Aden, A., Eggeman, T., Ringer, M., Wallace, B. & Jechura, J. (2005, May) Biomass to Hydrogen Production Detailed Design and Economics Utilizing the Battelle Columbus Laboratory Indirectly-Heated Gasifier. NREL/TP-510-37408. Golden, CO: National Renewable Energy Laboratory	Appendix C, A202: stream 218 = 738 lb/hr; Appendix C, A601: stream 620 = 102749 lb/hr; Appendix C, A701: stream 710 = 131921 lb/hr
		0.00008	gur ng ra	0.00	Lineity Laboratory Spath, P., Aden, A., Eggeman, T., Ringer, M., Wallace, B. & Jechura, J. (2005, May) Biomass to Hydrogen Production Detailed Design and Economics Utilizing the Battelle Columbus Laboratory Indirectiv-Heated Cashier, NRELUTP-510-37408, Golden, CO: National Renewable	Assume all make-up water is process water
	Water Consumption for Cooling		gal / kg H2		Energy Laboratory	All a la shife bu a sa sa sha ka sa shi fala sa shi
	Electricity co-product production Oxygen co-product production		kWh / kg H2 kg / kg H2		None	All electricity co-product used internally N/A
	Steam co-product production	0.0	kg / kg H2	0.0	None	N/A
	Total Annual Fixed Operating Costs	\$10,391,486	2005\$ / yr	\$10,391,486	Spath, P., Aden, A., Eggeman, T., Ringer, M., Wallace, B. & Jechura, J. (2005, May) Biomass to Hydrogen Production Detailed Design and Economics Utilizing the Battelle Columbus Laboratory Indirectly-Heated Gasifier. Section 9.2. NRELITP-510-37408. Golden, CO: National Renewable Energy Laboratory Spath, P., Aden, A., Eggeman, T., Ringer, M., Wallace, B. & Jechura, J. (2005, May) Biomass	Section 9.2 Fixed Operating Costs. Costs were escalated from \$2002 to \$2005 dollars.
-	Total Annual Variable Operating Costs	\$43,162,900		\$44,917,200	Spatin, F., Aden, A., Eggernan, I., Kniger, M., Walade, B. & Jecnura, J. (2005, May) Elomass to Hydrogen Production Detailed Design and Economics Utilizing the Battelle Columbus Laboratory Indirectly-Heated Gasifier. Table 13. NREL/TP-510-37408. Golden, CO: National Renewable Energy Laboratory	Table 13: Variable Operating Costs. Costs were escalated from \$2002 to \$2005 dollars.
	Total Annual Operating Costs	\$53,554,386	2005\$ / yr	\$55,308,686	None	Addition of Annual Total Fixed Operating Costs and Total Annual Variable Operating Costs
	Production energy efficiency (does not include electricity for forecourt compress Share of process fuel - biomass	46.0%		45.6%	Calculated from H2A values Calculated from H2A values	Calculated from H2A values Calculated from H2A values
;	Share of process fuel - coal	0.0%		0.0%	Calculated from H2A values	Calculated from H2A values
	Share of process fuel - natural gas	2.5%		4.0%	Calculated from H2A values Calculated from H2A values	Calculated from H2A values Calculated from H2A values
	Share of process fuel - ethanol Share of process fuel - electricity	0.0%			Calculated from H2A values	Calculated from H2A values Calculated from H2A values
	Hydrogen outlet pressure (before CSD)	300	psi		Spath, P., Aden, A., Eggeman, T., Ringer, M., Wallace, B. & Jechura, J. (2005, May) Biomass to Hydrogen Production Detailed Design and Economics Utilizing the Battelle Columbus Laboratory Indirectly-Heated Gasifier. NREL/TP-510-37408. Golden, CO: National Renewable Energy Laboratory	Final compression step modeled in the analysis was removed for the H2A case study to maintain consistency with H default value.
1	Hydrogen quality before transport	98 minimum	% H2	98 minimum	path, P., Aden, A., Eggeman, T., Ringer, M., Wallace, B. & Jechura, J. (2005, May) Biomass to Hydrogen Production Detailed Design and Economics Utilizing the Battelle Columbus Laboratory Indirectly-Heated Gasifier. NREL/TP-510-37408. Golden, CO: National Renewable Energy Laboratory	Page 5, product purity of 99.9 vol%
ancial F	Parameters					
	After-tax Real IRR	10%			Mann, M., & Steward, D. M. (2008, May 28). Current (2005) Hydrogen from Biomass via Gasification and Catalytic Steam Reforming. Golden, CO: National Renewable Energy Laboratoty.	Current central H2A production from biomass basis version 2.1.2; Input_Sheet_Template tab; After-tax Real IRR, cr C47
	Plant Life	40		40	Mann, M., & Steward, D.M. (2008, May 28). Current (2005) Hydrogen from Biomass via Gasification and Catalytic Steam Reforming. Golden, CO: National Renewable Energy	Current central H2A production from biomass basis version 2.1.2; Input Sheet Template tab; Plant life, cell C34

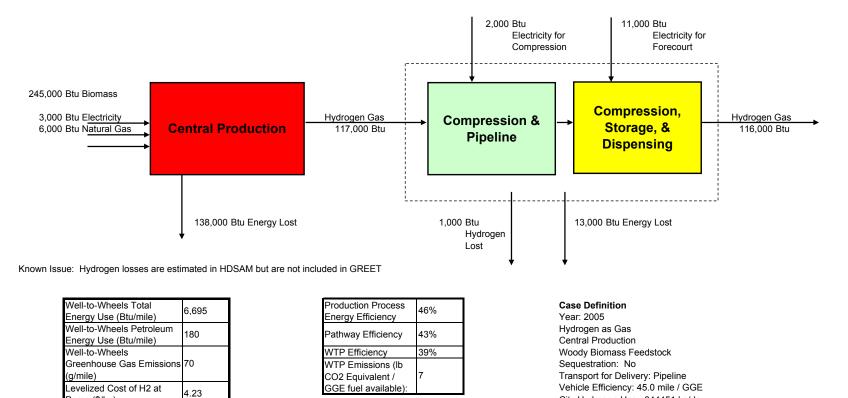
			Referenced		
Parameter	Value	Units	Value	Reference Mann, M., & Steward, D.M. (2008, May 28). Current (2005) Hydrogen from Biomass via	Comments
Federal Tax Rate	35.0%		35.0%	Gasification and Catalytic Steam Reforming. Golden, CO: National Renewable Energy Laboratoty.	Current central H2A production from biomass basis version 2.1.2; Input_Sheet_Template tab; Federal taxes, cell C49
State Tax Rate	6.0%		6.0%	Mann, M., & Steward, D.M. (2008, May 28). Current (2005) Hydrogen from Biomass via Gasification and Catalytic Steam Reforming. Golden, CO: National Renewable Energy Laboratory.	Current central H2A production from biomass basis version 2.1.2; Input_Sheet_Template tab; State taxes, cell C48
Total Tax Rate	38.9%		38.9%	Mann, M., & Steward, D.M. (2008, May 28). Current (2005) Hydrogen from Biomass via Gasification and Catalytic Stearn Reforming. Golden, CO: National Renewable Energy Laboratoty.	Current central H2A production from biomass basis version 2.1.2; Input_Sheet_Template tab; Total tax Rate, cell C50
Frection Equity	100%		100%	Mann, M., & Steward, D.M. (2008, May 28). Current (2005) Hydrogen from Biomass via Gasification and Catalytic Steam Reforming. Golden, CO: National Renewable Energy Laboratoty.	Current central H2A production from biomass basis version 2.1.2; Input_Sheet_Template tab; Equity Financing, cell C38
Transport, Delivery, and Storage Energy Requirements					
Liquid Truck Delivery				Elecusion A. Miste M. & Cillette J. (2008). Hudesee Delivery Secretic Archiel Medel	
Hydrogen entering liquefaction	382,396	kg / day	382,396	Elgowainy, A., Mintz, M. & Gillette, J. (2006). Hydrogen Delivery Scenario Analysis Model (HDSAM) V2.0. Argonne, IL: Argonne National Laborator	HDSAM version 2.02 calculation based on input parameters: city selection, market penetration, dispensing rate
Liquefaction electricity requirement	1,136,394,945	kW hr / yr		Nexant, Inc. et al. (2008, May). H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Sections 2.2.7.3 and 2.2.7.5. DE-FG38-050015032.	
Liquefaction electricity requirement		kW hr / kg H2	1,136,394,945	Nexant, Inc. et al. (2008, May). H2A Hydrogen Delivery Infrastructure Analysis Models and	Calculation
Hydrogen lost in liquefier	0.5%		0.5%	Conventional Pathway Options Analysis Results . Interim Report Section 2.2.7.2. DE-FG36- 05GO15032. Nexant, Inc. et al. (2008, May). H2A Hydrogen Delivery Infrastructure Analysis Models and	Discussions with Linde Kryotechnic AG, Switzerland (Nexant Report - Section 2.2.7.2)
Liquefaction efficiency	80.3%		80.3%	Conventional Pathway Options Analysis Results . Interim Report Section 2.2.7.2. DE-FG36- 05GO15032.	Discussions with Linde Kryotechnic AG, Switzerland and Praxair (Nexant Report-Section 2.2.7.2)
Liquefaction System total capital investment	\$559,414,686	2005\$	\$559,414,686	Nexant, Inc. et al. (2008, May). H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.2.7.4. DE-FG36- USGO15032.	Discussions with Linde Kryotechnic AG, Switzerland and Praxair (Nexant Report - Section 2.2.7.4)
Liquefaction System electricity cost	\$60,690,228	2005\$ / yr	\$60,690,228	Nexant, Inc. et al. (2008, May). H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.2.7.4. DE-FG36- 05GO15032.	Discussions with Linde Kryotechnic AG, Switzerland and Praxair (Nexant Report - Section 2.2.7.4)
Liquefaction System labor cost	\$592,895	2005\$ / yr	\$592,895	Nexant, Inc. et al. (2008, May). H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.2.1.3. DE-FG36- 05GO15032.	Bureau of Labor and Statistics (Nexant Report - Section 2.2.1.3)
Liquefaction System total operating cost	\$83,647,930	2005\$ / vr	\$83,647,930	Elgowainy, A., Mintz, M. & Gillette, J. (2006). Hydrogen Delivery Scenario Analysis Model	HDSAM version 2.02 calculation, H2 Liquifer tab, cell B135: sum of total labor cost, total electricity cost and total other fixed costs
Terminal Storage Design Capacity	3,532,139	kg H2	3,532,139	(HDSAM) V2.0. Argonne, IL: Argonne National Laborator Elgowainy, A., Mintz, M. & Gillette, J. (2006). Hydrogen Delivery Scenario Analysis Model (HDSAM) V2.0. Argonne, IL: Argonne National Laborator	Inxed costs HDSAM version 2.02 calculation, Liquid H2 Terminal tab, cell B73: based on liquid storage capacity, terminal average flow
Hydrogen lost in terminal	2.8%		2.8%	Nexant, Inc. et al. (2008, May). H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results . Interim Report Section 2.2.14. DE-FG36- 05GO15032.	HDSAM parameter, recommendations from Nexant in conjuction with Air Liquide, GTI, Chevron, TIAX, ANL, PNNL and NREL (Nexant Report- Section 2.2.14)
Terminal total capital investment	\$191,649,060	2005\$	\$191,649,060	Nexant, Inc. et al. (2008, May). H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results . Interim Report Section 2.2.11.1. DE-FG36- 05GO15032.	CB&I (Nexant Report - Section 2.2.11.1)
Terminal electricity cost	\$565,492	2005\$ / yr	\$565,492	Elgowainy, A., Mintz, M. & Gillette, J. (2006). Hydrogen Delivery Scenario Analysis Model (HDSAM) V2.0. Argonne, IL: Argonne National Laborator	HDSAM version 2.02 calculation, Liquid H2 Terminal tab, cell B187: electricity prices are from EIA AEO 2005 and 2007
Terminal labor cost	\$588,708	2005\$ / vr	\$588,708	Nexant, Inc. et al. (2008, May). H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.2.1.3. DE-FG36- DGG015032	Bureau of Labor and Statistics (Nexant Report - Section 2.2.1.3)
Terminal total operating cost		2005\$ / yr	\$8,842,213	Elgowainy, A., Mintz, M. & Gillette, J. (2006). Hydrogen Delivery Scenario Analysis Model (HDSAM) V2.0. Argonne, IL: Argonne National Laborator	HDSAM version 2.02 calculation, Liquid H2 Terminal tab, cell B201: sum of total labor cost, total electricity cost and total other fixed costs
Truck Payload leaving terminal	4,372	kg / truckload	4,372	Nexant, Inc. et al. (2008, May). H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.1.8. DE-FG36- 05GO15032.	HDSAM calculation; default value (Nexant Report- Section 2.1.8)
Truck Trips	31,009	per year	31,009	Elgowainy, A., Mintz, M. & Gillette, J. (2006). Hydrogen Delivery Scenario Analysis Model (HDSAM) V2.0. Argonne, IL: Argonne National Laborator	HDSAM version 2.02 calculation, Truck - LH2 Delivery tab, cell B66: city yearly use(kg)*ref.station.mass efficiency(H2out/H2 in) / H2 delivered per trip (kg)
One-way distance per trip	49	miles / trip (one way)	157,840	Elgowainy, A., Mintz, M. & Gillette, J. (2006). Hydrogen Delivery Scenario Analysis Model (HDSAM) V2.0. Argonne, IL: Argonne National Laborator	HDSAM version 2.02 calculation, Truck - LH2 Delivery tab, cell B39: distance to the city gate + 1.5 * sqrt(city area)
Diesel for Truck Trips	3,837	m^3 / vr	3,837	Introduktiv 72.2. Programs, I.C. Populine reasonable and Education and Nexant, Inc. et al. (2008, May). H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.1.8. DE-FG36- 65GO15032.	HDSAM calculation, fuel consumption data from Nexant in conjuction with Air Liquide, GTI, Chevron, TIAX, ANL, PNNL and NREL (Nexant Report - Section 2.1.8)
Hydrogen Losses during loading / transport / unloading	6.1%		6.1%	Nexant, Inc. et al. (2008, May). H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results . Interim Report Section 2.2.14. DE-FG36- 05G015022	HDSAM parameter, recommendations from Nexant in conjuction with Air Liquide, GTI, Chevron, TIAX, ANL, PNNL and NREL (Nexant Report- Section 2.2.14)
Hydrogen Losses during liquefaction/loading / transport / unloading	10.08%		10.08%	Nexant, Inc. et al. (2008, May). H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results . Interim Report Section 2.2.14. DE-FG36- 05GO15032.	HDSAM parameter, recommendations from Nexant in conjuction with Air Liquide, GTI, Chevron, TIAX, ANL, PNNL and NREL (Nexant Report- Section 2.2.14)
Truck/trailer total capital investment	\$49,000,000	2005\$	\$49,000,000	Nevent Inc. et al. (2008, May) 1/24 Hudrogen Delivery Infectively Analysis Medale and	\$625,000 per each tank trailer and \$75,00 per each truck cab; recommendations from Nexant in conjuction with Air Liquide, GTI, Chevron, TIAX, ANL, PNNL and NREL
Truck/trailer electricity cost	50	2005\$ / vr	\$0	Elgowainy, A., Mintz, M. & Gillette, J. (2006). Hydrogen Delivery Scenario Analysis Model (HDSAM) V2.0. Argonne. IL: Argonne National Laborator	HDSAM calculation, electricity prices are from EIA AEO 2005 and 2007
Truck/trailer Diesel cost		2005\$ / yr	\$1,692,270	Electronica A. Minter M. & Cillette, J. (2008). Hudenson Delivery Separate Analysis Medel	HDSAM version 2.02 calculation, Truck - LH2 Delivery tab, cell B116: default milage - 6 mpg; diesel cost data are from EIA AEO 2005 and 2007
Truck/trailer labor cost	\$15,193,193		\$15,193,193	Nexant, Inc. et al. (2008, May). H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results . Interim Report Section 2.2.1.3. DE-FG36-	EIA AEO 2005 and 2007 Bureau of Labor and Statistics (Nexant Report - Section 2.2.1.3)
Truck/trailer total operating cost	004 004 000	2005\$ / yr 2005\$ / yr	\$21,691,089	05G015032. Elgowainy, A., Mintz, M. & Gillette, J. (2006). Hydrogen Delivery Scenario Analysis Model	HDSAM version 2.02 calculation, Truck - LH2 Delivery tab, cell B137: sum of total labor cost, total fuel cost and total othe
Distribution Station		2003ə / Yr		(HDSAM) V2.0. Argonne, IL: Argonne National Laborator	fixed costs
Liquid Receiving/Distributing Stations					
Hydrogen Dispensed at Forecourt Station	465,647	kg / station year	465,647	Elgowainy, A., Mintz, M. & Gillette, J. (2006). Hydrogen Delivery Scenario Analysis Model (HDSAM) V2.0. Argonne, IL: Argonne National Laborator	HDSAM version 2.02 calculation based on input: dispensing rate
Electricity Required by Forecourt Station	116,673	kWh / station year	116,673	Elgowainy, A., Mintz, M. & Gillette, J. (2006). Hydrogen Delivery Scenario Analysis Model (HDSAM) V2.0. Argonne, IL: Argonne National Laborator	HDSAM version 2.02 calculation based on pump power requirement (see equation in Design Data tab)
Design Capacity	1,516	kg H2 / day	1,516	Nexant, Inc. et al. (2008, May). H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.1.4. DE-FG36- 05G015032.	HDSAM calculation based on Chevron fueling profiles (Nexant Report-Section 2.1.4): = adjusted disp. Rate*(1+summer surge)*(1+Friday surge)
Operating Capacity	1.070	kg H2 / dav	1,278		Current forecourt H2A production from natural gas basis version 2.0.1; Input_Sheet_Template tab; Plant Output, cell C2
Capacity Factor	84%	ng na roof	84%	None	Calculation

				Referenced		
Parame	ter	Value	Units	Value	Reference	Comments
e	Site storage (liquid)	6,920	kg H2	6,920	Nexant, Inc. et al. (2008, May). H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.2.11.2. DE-FG36- 05GO15032.	HDSAM calculation based on number of deliveries per day (Nexant Report-Section 2.2.11.2)
ε	Site storage (gaseous)	453	ka H2	323	Nexant, Inc. et al. (2008, May). H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.3.2.4. DE-FG36- 05GO15032.	HDSAM calculation (Nexant Report - Section 2.3.2.4)
5	Site storage	486%	% of design H2 distribution		None	Calculation
C C	Dispensing Pressure	6,250	psi	6,250	Nexant, Inc. et al. (2008, May). H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results . Interim Report Section 2.3.2. DE-FG36- 05G015032.	HDSAM default (see Nexant Report-Section 2.3.2)
ŀ	łydrogen Losses due to leaks	1.34%		1.34%	Nexant, Inc. et al. (2008, May). H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results . Interim Report Section 2.2.14. DE-FG36- 05G015032.	HDSAM parameter, recommendations from Nexant in conjuction with Air Liquide, GTI, Chevron, TIAX, ANL, PNNL and NREL (Nexant Report - Section 2.2.14)
E	Distribution System total capital investment	\$2,073,185	2005\$ / station	\$2,073,185	Nexant, Inc. et al. (2008, May). H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results . Interim Report Section 2.2.4.2. DE-FG36- 05G015032.	Data from CP Industries, McMaster-Carr, Bechtel, Nexant manufacturer survey, Nexant recommendations (Nexant Repo Section 2.2.4.2)
C	Distribution System electricity cost	\$9,512	2005\$ / station yr	\$9,621	Nexant, Inc. et al. (2008, May). H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results . Interim Report Section 2.2.4.2. DE-FG36- 05G015032.	Data from CP Industries, McMaster-Carr, Bechtel, Nexant manufacturer survey, Nexant recommendations (Nexant Repo Section 2.2.4.2)
E	Distribution Labor Required	3,951	hr / station yr	3,942	Nexant, Inc. et al. (2008, May). H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results . Interim Report Section 2.2.1.3. DE-FG36- 05G015032.	HDSAM calculation (Nexant Report -Section 2.2.1.3)
C	Distribution System labor cost	\$39,513	2005\$ / station yr	\$39,416	Nexant, Inc. et al. (2008, May). H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results . Interim Report Section 2.2.1.3. DE-FG36- 05G015032.	Bureau of Labor and Statistics (Nexant Report - Section 2.2.1.3)
C	Distribution System total O&M cost	\$189,192	2005\$ / station yr	\$181,989	Nexant, Inc. et al. (2008, May). H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.2.1.2. DE-FG36- 05GO15032.	HDSAM calculations (Nexant Report - Section 2.2.1.2)
Other As	sumptions for WTW Calculations					
Share of R	FG in Total Gasoline Use	100%		100%	U.S. Department of Energy & U.S. Department of Transportation. (2006, December) <i>Hydrogen</i> Posture Plan An Inegrated Research, Development and Demonstration Plar.	Basis for posture plan
Type of Ox	vgenate in RFG	None		None	U.S. Department of Energy & U.S. Department of Transportation. (2006, December) Hydrogen Posture Plan An Inegrated Research, Development and Demonstration Plan	Basis for posture plan
O2 Conten		0%	wt %	0%	U.S. Department of Energy & U.S. Department of Transportation. (2006, December)Hydrogen	Basis for posture plan
	V VOCs (emissions) to GVs fueled with CG & RFG	0%		0%	Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1:	GREET default, Table 4.45 FCV: H2
Ratio of FC	V VOCs (evaporative) to GVs fueled with CG & RFG	0%		0%	Methodology, development, Use and Results. Argonne, IL: Argonne National Laboratory Wang, M.Q. (1999, August), GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Untradictional development (Jea and Result Argonne, III, Argonne II), and the second	GREET default, Table 4.45 FCV: H2
Ratio of FC	V CO emissions to GVs fueled with CG & RFG	0%		0%		GREET default, Table 4.45 FCV: H2
Ratio of FC	V NOx emissions to GVs fueled with CG & RFG	0%			Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1:	GREET default, Table 4.45 FCV: H2
Ratio of FC	V Exhaust PM10 emissions to GVs fueled with CG & RFG	0%		0%	Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology, development, Use and Results. Argonne, IL: Argonne National Laboratory	GREET default, Table 4.45 FCV: H2
Ratio of FC	V Brake & Tire Wear PM10 emissions to GVs fueled with CG & RFG	100%		100%	Wasa M.O. (1000, August) CREET 1.E. Transmodulian Eval Ovala Madel Valume 1	GREET default, page 197: vehicles within the same weight class have similar tire and brake wear emissions
Ratio of FC	V Exhaust PM2.5 emissions to GVs fueled with CG & RFG	0%		0%	Wang, M.Q. (2008, September 5). The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model, Version 1.8b. Argonne, IL: Argonne National Laboratory	GREET default-well-known fuel cell emissions (no PM2.5)
Ratio of FC	V Brake & Tire Wear PM2.5 emissions to GVs fueled with CG & RFG	100%		100%	Wang, M.Q. (2008, September 5). The Greenhouse Gases, Regualted Emissions, and Energy Use in Transportation (GREET) Model, Version 1.8b. Argonne, IL: Argonne National Laboratory	GREET default reasonable to assume FCV has same driving pattern as GV
Ratio of FC	V CH4 emissions to GVs fueled with CG & RFG	0%		0%	Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology, development, Use and Results. Argonne, IL: Argonne National Laboratory	GREET default, Table 4.45 FCV: H2
Ratio of FC	V N2O emissions to GVs fueled with CG & RFG	0%		0%	Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology, development, Use and Results, Argonne, IL: Argonne National Laboratory	GREET default, Table 4.45 FCV: H2
Marginal E	lectricity Generation Mix for Transportation Use	US Mix		US Mix	U.S. Department of Energy & U.S. Department of Transportation. (2006, December)Hydrogen Posture Plan An Inegrated Research, Development and Demonstration Plan.	Basis for posture plan
Results						
Levelized C	Cost	\$4.88	\$ / kg	\$4.38	Ruth, M. et al. (2009, March). Hydrogen Macro System Model User Guide. NREL/TP-6A1 44799. Golden, CO: National Renewable Energy Laboratory.	MSM Results
WTW Coal	Input	100	Btu / mile	534	44799, Golden, CO: National Renewable Energy Laboratory.	MSM Results
WTW Natu	ral Gas Input	3,911	Btu / mile	284	44799. Golden, CO: National Renewable Energy Laboratory.	MSM Results
WTW Petrr	bleum Input	249	Btu / mile	144	44799. Golden, CO: National Renewable Energy Laboratory.	MSM Results
WTW Foss	il Energy Input	2,044	Btu / mile	963	44799. Golden, CO: National Renewable Energy Laboratory.	MSM Results
WTW Tota	Energy Input	8,170	Btu / mile	5,302	44799. Golden, CO: National Renewable Energy Laboratory.	MSM Results
WTW CO2	Emissions	151	g / mile	58	44799. Golden, CO: National Renewable Energy Laboratory.	MSM Results
WTW CH4	Emissions	0	g / mile	C	Ruth, M. et al. (2009, March). Hydrogen Macro System Model User Guide. NREL/TP-6A1 44799. Golden, CO: National Renewable Energy Laboratory.	MSM Results
WTW N2O	Emissions	0	g / mile		Ruth, M. et al. (2009, March). Hydrogen Macro System Model User Guide. NREL/TP-6A1 44799. Golden, CO: National Renewable Energy Laboratory.	MSM Results
WTW GHC	Emissions	160	g / mile		Ruth, M. et al. (2009, March). Hydrogen Macro System Model User Guide. NREL/TP-6A1 44799. Golden, CO: National Renewable Energy Laboratory.	MSM Results

Appendix D — Biomass–Pipeline Supporting Tables and Figures

### Hydrogen Produced In Central Plant and Transported as Gas via Pipeline

Pump (\$/kg)



City Hydrogen Use: 344451 kg/day

In	puts	Graphic Depiction & Ass	sumptions	0	utputs
		♥ Biomass Production & De	livery	Biomass moisture content Woody biomass LHV	25% 16,811,019 Btu / dry ton
Coal Input from "Well" Natural Gas Input from "Well" Petroleum Input from "Well"	261 Btu / 116000Btu to Pump 418 Btu / 116000Btu to Pump 2,900 Btu / 116000Btu to Pump	Fraction of Woody Biomass (Remaining is Herf Grams of Nitrogen / dry ton biomass Grams of P2O5 / dry ton biomass Grams of K2O / dry ton biomass Herbicide use Insecticide use Average dist from farm to H2 production	baceous) 100% 709 331 24 g / dry ton 2 g / dry ton 40 miles	Biomass price at H2 production Levelized Cost of Biomass WTG CO2 Emissions WTG CH4 Emissions WTG QH2 Emissions WTG GHC Emissions	\$37.96 2005 \$ / dry ton \$0.56 2005\$ / kg H2 distributed -25,632 g / 116000Btu to Pump 0 g / 116000Btu to Pump 0 g / 116000Btu to Pump -25,590 g CO2 eq./ 116000 Btu
Biomass consumption Natural gas consumption Electricity consumption Process Water Consumption Natural gas price Electricity price Total Capital Investment Coal Input from "Well" Natural Gas Input from "Well"	12.8 kg (dry) / kg H2 produced 0.17 N m <sup>3</sup> /skg H2 produced 0.98 kWh / kg H2 \$0.340 2005\$ / N m <sup>3</sup> \$0.055 2005 \$/kWh \$154,644,297 2005\$ 6.063 Btu / 116000Btu to Pump 8.598 Btu / 116000Btu to Pump 3.623 Btu / 116000Btu to Pump	Hydrogen Production Central plant design capacity Capacity factor Process energy efficiency Electricity Mix US I After-tax IRR Assumed Plant Life	155,236 kg/day 90% 46.0%	Hydrogen Output Pressure Hydrogen Outlet Quality Total capital investment Electricity cost Natural Gas Cost Other operating costs Levelized Cost of Prod (excl feedst SMR CO2 Emissions SMR CH4 Emissions SMR OH6 Emissions	300 psi 1 \$3.03 2005\$ / annual kg H2 (effective \$0.05 2005\$ / kg H2 produced \$0.08 2005\$ / kg H2 produced \$1.07 2005\$ / kg H2 distributed 25,733 g / 116000Btu to Pump 3 g / 116000Btu to Pump 0 g / 116000Btu to Pump 25,839 g CO2 eq./ 116000 Btu
Electricity consumption for compressor Electricity consumption for geo storage Total electricity consumption Electricity price for compressor Electricity price for geologic storage	0.56 kWh / kg H2 0.51 kWh / kg H2 0.57 kWh / kg H2 \$0.056 2005\$ / kWh \$0.052 2005\$ / kWh \$0.052 2005\$ / kWh 3.306 Blu / 116000Blu to Pump 950 Blu / 116000Blu to Pump 246 Blu / 116000Blu to Pump	Pipelines for Delivery City Population Hydrogen Vehicle Penetration City hydrogen use Beologic Strage capacity Geologic Strage capacity Turuk #1-line length Turuk #2-line length Service-line length Number of service liness Hydrogen losses Hydrogen losses	r 1,247,364 people 50% 25,810,766 kg / yr 62 miles 3,762,787 kg H2 17 miles 40 miles 1.1 miles / line 270 1.12% 1.011	Total capital investment Electricity cost Levelized Cost of Delivery Delivery CO2 Emissions Delivery CH4 Emissions Delivery GH2 Emissions Delivery GHG Emissions	\$3.51 2005\$/annual kg distributed \$0.03 2005\$ / kg H2 \$0.92 2005\$ / kg H2 distributed 436 g / 116000Btu to Pump 1 g / 116000Btu to Pump 0 g / 116000Btu to Pump 452 g CO2 eq./ 116000 Btu
Electricity consumption Electricity price	3.04 kWh / kg H2 \$0.082 2005\$ / kWh	Forecourt Distribution	1	Hydrogen outlet pressure Basis Hydrogen Quantity	6,250 psi 116,000 Btu (116,000 Btu/gal non-oxyg
Coal input from "Well" Natural Gas Input from "Well" Petroleum input from "Well"	17,677 Btu / 116000Btu to Pump 5,078 Btu / 116000Btu to Pump 1,317 Btu / 116000Btu to Pump	Number of Distribution Stations Energy efficiency Number of Compression Steps Isentropic Efficiency Site storage Hydrogen losses Hydrogen losses	270 92% 4 65% 69% capacity 0.50% 1.005	Total capital investment Electricity cost Levelized Cost of Distribution CSD CO2 Emissions CSD CH4 Emissions CSD DKD Emissions CSD CH6 Emissions	\$6.89 2005\$/annual kg \$0.25 2005\$ / kg H2 \$1.69 2005\$ / kg H2 distributed 2.333 g / 116000Btu to Pump 3 g / 116000Btu to Pump 0 g / 116000Btu to Pump 2.419 g CO2 eq./ 116000 Btu
		Well-to-Pump Results         Coal input from "Well"         Natural Gas input from "Well"         Petroleum input from "Well"         Fossil Energy input from "Well"         Fossil Energy input from "Well"         WTP C42 Emissions         WTP V44 Emissions         WTP C44 Emissions         WTP C46 Emissions         WTP C46 Emissions         WTP C46 Emissions         WTP C40CS (emissions) to GVs         Ratio of FCV VOCS (evaporative) to GVs         Kueled with C63 & RF6         Ratio of FCV VOCs emissions to GVs         Kueled with C63 & RF6         Ratio of FCV VOCs emissions to GVs         Kueled with C63 & RF6         Ratio of FCV VCE kaust PM10 emissions to         GVS fueled with C63 & RF6         Ratio of FCV Exhaust PM10 emissions to         GVS fueled with C63 & RF6         Ratio of FCV Exhaust PM10 emissions to         GVS fueled with C63 & RF6         Ratio of FCV Exhaust PM10 emissions to         GVS fueled with C63 & RF6         Ratio of FCV VEX kaust PM10 emissions to	27,308 Btu / 116000 Btu 15,043 Btu / 116000 Btu 8,087 Btu / 116000 Btu 5,0437 Btu / 116000 Btu 0,875 g/ 116000 Btu 0 g/ 116000 Btu 3,127 116000 Btu 3,127 116000 Btu 3,127 116000 Btu 3,127 116000 Btu 0,127 11600 Btu 0,127 1		

Bio-Pipe Pathway Details R090209A 090806 v09.xis 202

Ratio of FCV Exhaust PM2.5 en to GVs fueled with CG & RFG

Weil-to-Wheel Results Coal Input from "Vell" Natural Gas Input from "Vell" Fossil Energy Input from "Vell" WTW C02 Emissions WTW C14 Emissions WTW N40 Emissions WTW 04G Emissions

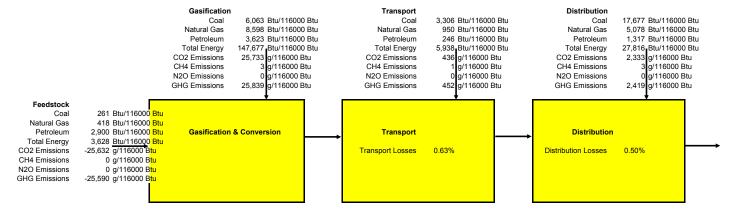
Levelized Cost of Hydrogen (\$/mi)

Ratio of FCV Brake & Tire Wear PM2.5 emissions to GVs fueled with GG & RFG Ratio of FCV CH4 emissions to GVs fueled with GG & RFG Ratio of FCV N20 emissions to GVs fueled with GG & RFG 0%

100% 0%

607 Btu / mi 335 Btu / mi 180 Btu / mi 1,122 Btu / mi 64 g / mi 0 g / mi 0 g / mi 70 g / mi

\$0.0941 2005 \$/mi



Total to Del	iver 116000 Btu Fuel	Check
Coal	27,308	27,308
Natural Gas	15,043	15,043
Petroleum	8,087	8,087
Total Energy	185,059	185,059
CO2 Emissions	2,870	2,875
CH4 Emissions	7	7
N2O Emissions	0	0
GHG Emissions	3,121	3,127

Paramet	ter		Value	Units	Reference	Comments
			Value	Units	Kelefelice	Commenta
ase Defi						
	ase Year	Technology	2005 Woody Biomass		N/A N/A	Default for Bio-Pipe Pathway study Default for Bio-Pipe Pathway study
Fo	orm of H2	2 During Delivery	Gas		N/A	Default for Bio-Pipe Pathway study
De	elivery Me	ode	Pipeline		N/A James, B.D. (2008, May 23). Current (2005) Steam Methan Reformer (SMR) at Forecourt	Default for Bio-Pipe Pathway study
Fo	orecourt S	Station Size	1278	kg/day	James, B.D. (2008, May 23). Current (2005) Steam Methan Reformer (SMR) at Forecourt 1500kg/day. Arlington, VA: Directed Technologies Inc.	Current forecourt H2A production from natural gas basis version 2.0.1; Input_Sheet_Template tab; Plant Output, cell C
Ve	ehicle Typ	pe	passenger cars		NA	Default for Bio-Pipe Pathway study
Ve	'ehicles' F	uel Economy	45.0	mile / gge	Rousseau, A. & Wallner, T. (2008, October 7). Prospects on Fuel Efficiency Improvements for Hydrogen Powered Vehicles . Argonne National Laboroatory presentation, Chicago, IL. Retreived from http://www.transportation.anl.gov/pdfs/HV/530.pdf	Calculated from data in the presentation. The fuel economy for today's average mid-size vehicle was estimated by the Powertrain Simulation Analysis Toolkit V 6.2 SP1, Summer 2008 (PSAT - http://www.transportation.anl.gov/modeling_simulation/PSAT/index.html). 45 mile/gge is the estimated on-road fuel economy which was determined by multiplying the projected EPA lab-rated fuel economy of 52.5 mile/gge by 0.85.
Market De	efinitior	n				
Ci	ity Popula	ation	1,247,364	people	U.S. Department of Energy & U.S. Department of Transportation. (2006, December/Hydrogen Posture Plan An Inegrated Research, Development and Demonstration Plan.	HDSAM City Selection; Scenario tab; Indianapolis, IN, cell B9
M	larket pen	netration	50%	(% vehicles in city)	U.S. Department of Energy & U.S. Department of Transportation. (2006, December)Hydrogen Posture Plan An Inegrated Research, Development and Demonstration Plan.	Basis for posture plan
N	lumber of	H2 vehicles in city	462,772	H2 vehicles / city	Elgowainy, A., Mintz, M. & Gillette, J. (2006)Hydrogen Delivery Scenario Analysis Model	Demand calculation by HDSAM version 2.02; Scenario tab; Number of H2 vehicles in city, cell F17
Mi	liles drive	n per vehicle	12,000	mile / vehicle year	Elgowainy, A., Mintz, M. & Gillette, J. (2006) Hydrogen Delivery Scenario Analysis Model	Key delivery input in HDSAM version 2.02; Scenario tab; Miles driven per year/ vehicle, cell C19
Ci	ity hydrog	gen use	344,451	ka / d	Elgowainy, A., Mintz, M. & Gillette, J. (2006) Hydrogen Delivery Scenario Analysis Model (HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	Demand calculation by HDSAM version 2.02; Scenario tab; City H2 daily use, cell F18 - based on number of hydrogen vehicles and miles/veh vr.
		H2 refueling stations in city	270	ng / u	(HDSAM) V2.0. Argonne, IL: Argonne National Laboratory Elgowainy, A., Mintz, M. & Gillette, J. (2006) <i>Hydrogen Delivery Scenario Analysis Model</i> (HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	venicies and miles/ven yr. Demand calculation by HDSAM version 2.02; Scenario tab; Number of H2 fueling stations in city, cell F19
N	lumber of	H2 stations/Number of gasoline stations	41%		Elgowainy, A., Mintz, M. & Gillette, J. (2006) Hydrogen Delivery Scenario Analysis Model (HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	Demand calculation by HDSAM version 2.02; Scenario tab; Number of H2 stations/Number of gasoline stations, cell F21
A	verage di	stance between stations (mi)	1.46	miles	Elgowainy, A., Mintz, M. & Gillette, J. (2006) <i>Hydrogen Delivery Scenario Analysis Model</i> (HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	Demand calculation by HDSAM version 2.02; Scenario tab; Average distance between stations, cell F22
Feedstoc	k Reco	very, Processing, & Transport		Timeo		
Biomass						
Pe	ercentage	e of Woody Biomass (Remainder is Herbaceous)	100%		Mann, M & Steward, D.M. (2008, May 28).Current (2005) Hydrogen from Biomass via Gasification and Catalytic Steam Reforming. Golden, CO: National Renewable Energy Laboraton	Current central H2A production via biomass gasification version 2.1.2 basis
Bi	iomass M	loisture Content	25%		Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology, development, Use and Results. Argonne, IL: Argonne National Laboratory.	Page 66
G	irams of N	Nitrogen / short ton biomass	709		M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walsh, 1998).	Equivalent to 75 lb N / ac in the maintenance year Year 3 or 4) which is reported by De La Torre Ugarte, 2003, App 3.1, assuming 6 dry tons biomass per acre, and harvesting once every 8 years. App 3.1 is for planting on cropland that was j
Gi	irams of P	205 / short ton biomass	189	g / dry ton	M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walsh, 1998)	used for traditional crops. Equivalent to 20 lb P / ac in the maintenance year (Year 3) which is in the range of 15-50 lb P / ac reported by De La Tor Ugarte, 2003, App 3.1, assuming 6 dry tons biomass per acre and harvesting once every 8 years
Gi	irams of K	(20 / short ton biomass	331	g / dry ton	M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walsh,	Equivalent to 35 lb K / ac in the maintenance year (Year 3) which is in the range of 15-50 lb K / ac reported by De La Tor
G	irams of h	nerbicide / short ton biomass	24	g / dry ton g / dry ton	1998). M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walsh, 1998).	Ugarte, 2003, App 3.1, assuming 6 dry tons biomass per acre and harvesting once every 8 years). Equivalent to 2 to herbickof 2 aci in the planting year which similar to the 2.0 bi glyboastel / ac reported by De La Torre Ugarte, 2000, App 3.2, assuming 6 dry tons biomass per acre and harvesting once every 8 years. Booth reported Trifluu (5 L/ha) and Metribuzin (395 g/ha). App 3.2 is for planting on currently idled cropland or cropland that was just used for pasture.
Gi	irams of ir	nsecticide / short ton biomass	2	g / dry ton	M. Walsh (personal communication via telephone and meeting between M. Wang and M. Walsh, 1998).	As a check, looked at Chastagner: Up to 56% of acreage annually sprayed with Dimethoate (Digon 400, 2-3 pints per ac up to 56% of acreage annually sprayed with Permethrin 2LB (Ambush, 64 ounces per acre); Up to 12% of acreage annually sprayed with Endosulfan 3 EC (24c WA-990025, 2 qts per acre).
Gi	frams of C	CO2 removed from atmosphere per dry ton woody biomass produ	iced -112,500	g / dry ton		GREET model default based on ANL personal communications
A	verage di	stance from farm to hydrogen production facility	40	miles	Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology, development, Use and Results. Argonne, IL: Argonne National Laboratory.	GREET basis: distance could be limited by transport costs?
Natural Gas	S			THE O		
N	G recover	ry efficiency	97.2%		Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology, development, Use and Results. Argonne, IL: Argonne National Laboratory.	GREET uses 97% which is comparable to several other models (Table 4.11)
NI	G used &	lost during recovery	0.35%		Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1:	
144	C used a	toot during receivery			Methodology, development, Use and Results. Argonne, IL: Argonne National Laboratory.	GREET basis
N	IG proces	sing energy efficiency	97.2%		Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology, development, Use and Results. Argonne, IL: Argonne National Laboratory.	GREET uses 97.5% which is comparable to several other models (Table 4.11)
N	IG used &	lost during processing	0.15%		Kirchgessner, D. A., Lott, R. A., Cowgill, R. M., Harrison, M. R. & Shires, T. M. (1996) Estimate of Methane Emissions from the U.S. Natural Gas Industry, EPA/Gas Research Institute paper. Retrieved from http://www.epa.gov/thrt/hief/ap42/ch14/related/methane.p	Volume lost from EPA/GRI paper and DOE/EIA-0573; future marginal increase is assumed to be less than current avera
N	IG used &	lost during transport	0.137	g / (MM Btu mil)	Kirchgessner, D. Å., Lott, R. Å., Cowgill, R. M., Harrison, M. R. & Shires, T. M. (1996) Estimate of Methane Emissions from the U.S. Natural Gas Industry, EPA/Gas Research Institute paper. Retrieved from http://www.epa.gov/titr/chief/ap4/2in14/ristaled/methane.p	Volume lost from EPA/GRI paper and DOE/EIA-0573; future marginal increase is assumed to be less than current avera
N	IG transpo	ort distance		miles	Wang, M.O. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology, development, Use and Results. Argonne, IL: Argonne National Laboratory.	GREET basis
Electricity	rid miv f-	r production	US Mix			Default
G			US MIX 1.20%		Energy Information Administration. (2007, February)Annual Energy Outlook 2007 with Projections to 2030. DOE/EIA-0383(2007). Washington, D.C. Retreived from	Default US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages calculat from total generation values reported with all renewables except biomass aggregated into the "Others (Carbon Neutral)"
		Biomass Fraction	51.70%		www.eia.doe.gov/oiaf/archive/aeo07/index.htr Energy Information Administration. (2007, February)Annual Energy Outlook 2007 with Projections to 2030. DOE/EIA-0383(2007). Washington, D.C. Retreived from	category US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages calculat from total generation values reported with all renewables except biomass aggregated into the "Others (Carbon Neutral)"
	0	Coal Fraction			www.eia.doe.gov/oiaf/archive/aeo07/index.htr Energy Information Administration. (2007, February)Annual Energy Outlook 2007 with	category US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages calculat
		Natural Gas Fraction	15.70%		Projections to 2030. DOE/EIA-0383(2007). Washington, D.C. Retreived from www.ela.doe.gov/oial/archive/aeo07/index.ht Energy Information Administration. (2007, February)Annual Energy Outlook 2007 with	from total generation values reported with all renewables except biomass aggregated into the "Others (Carbon Neutral)" category US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages calculat
1		Nuclear Fraction	20.30%		Projections to 2030. DOE/EIA-0383(2007). Veorual y Annual Energy Obiook 2007 with Projections to 2030. DOE/EIA-0383(2007). Washington, D.C. Retreived from www.eia.doe.gov/oiaffarchive/aeo07/index.htr	from total generation values reported with all renewables except biomass aggregated into the "Others (Carbon Neutral)"

Parameter		Value	Units	Reference	Comments
		2.90%		Energy Information Administration. (2007, February)Annual Energy Outlook 2007 with Projections to 2030. DOE/EIA-0383(2007). Washington, D.C. Retreived from	US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages calculate from total generation values reported with all renewables except biomass aggregated into the "Others (Carbon Neutral)"
	Residual Oil Fraction			www.eia.doe.gov/oiaf/archive/aeo07/index.htr Energy Information Administration. (2007, February)Annual Energy Outlook 2007 with	category US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages calculat
	Others (Carbon Neutral)	8.20%		Projections to 2030. DDE/EIA-0383(2007). Washington, D.C. Retreived from www.eia.doe.gov/oiaf/archive/aeo07/index.htr	to give time. Neutration releases by generation data from balles bury a bio using the 2000 timetratine. Fercentages various from total generation values reported with all renewables except biomass aggregated into the "Others (Carbon Neutral)" category
2 Production	n				
Produc	tion Facility Average Output	139,712	kg / facility d (after capacity factor is included)	Spath, P., Aden, A., Eggeman, T., Ringer, M., Wallace, B. & Jechura, J. (2005, Ma)@iomass to Hydrogen Production Detailed Design and Economics Utilizing the Battelle Columbus Laboratory Indirectly-Heated Gasifier. Section 3.0. NREL/TP-510-37408. Golden, CO. National Renewable Energy Laboratory	Design feed rate for current design plant of 2000 bone dry metric tonne biomass per day (see Section 3.0)
	Corresponding capacity factor	90%		Mann, M., & Steward, D.M. (2008, May 28) Current (2005) Hydrogen from Biomass via Gasification and Catalytic Steam Reforming. Golden, CO: National Renewable Energy Laboratot,	Current central H2A production from biomass basis version 2.1.2; Input_Sheet_Template tab; Operating Capacity Facto cell C21
Total C	apital Investment	\$154,644,297	2005 \$	Spath, P., Aden, A., Eggeman, T., Ringer, M., Wallace, B. & Jechura, J. (2005, May@iomass to Hydrogen Production Detailed Design and Economics Utilizing the Battelle Columbus Laboratory Indirectly-Heated Gasifier. Table 10. NREL/TP-510-37408. Golden, CO: National Renewable Energy Laboratory	Total installed capital cost of \$102M (\$2002) (see Table 10, Current Design) was escalated to \$2005 dollars. Capital co for additional compression was removed to maintain consistency with H2A central model assumptions.
Biomas	ss feedstock consumption	12.8	kg (dry) / kg H2	Spath, P., Aden, A., Eggeman, T., Ringer, M., Wallace, B. & Jechura, J. (2005, May@iomass to Hydrogen Production Detailed Design and Economics Utilizing the Battelle Columbus Laboratory Indirectly-Heated Gasifier. Appendex A. NREL/TP-510-37408. Golden, CO: National Renewable Energy Laboratory	Biomass usage calculated from plant efficiency of 45.6%. The LHV for woody biomass is taken from HyARC, and is high (8406 Btu/lb v. 8060 Btu/lb) than used in Spath. Appendix A - Design Report: Current Case; Hydrogen Yield = 70.4 kg/r US ton feedstock
Biomas	ss feedstock cost	\$37.96	2005\$ / dry short ton	Hess, R., Denney, K., Wright, C., Radtke, C., Perlack, W. (2007, April 18-19)Cellulosic Biomass Feedstocks for Renewable Bioenergy. EERE presentation to the National Academy of Sciences Commettee on Resource Needs for Fuel Cell and Hydrogen, Washington, D.C.	Feedstock price is taken from the Biomass Program 2012 Target price of \$35/ton (\$2002) escalated to \$2005
Biomas	ss LHV	16,811,019	Btu / dry ton	Hydrogen Analysis Resource Center. (2008, September 5)Lower and Higher Heating Values of Hydrogen and Fuels. Retrieved from http://hydrogen.pnl.gov/cocoon/morf/hydrogen/article/401	LHV of Farmed Trees (dry basis); 19.551 MJ/kg
Natural	gas feedstock consumption	0.00	normal m^3 / kg H2 produced	Mann, M., & Steward, D.M. (2008, May 28). Current (2005) Hydrogen from Biomass via Gasification and Catalytic Steam Reforming. Golden, CO: National Renewable Energy Laboratoty	Current central H2A production from biomass basis version 2.1.2; Results tab; Energy Data
Natural	I Gas LHV	34,714	Btu / normal m^3	Hydrogen Analysis Resource Center. (2008, September 5)Lower and Higher Heating Values of Hydrogen and Fuels. Retrieved from http://hydrogen.pnl.gov/coccon/morf/hydrogen/article/401	LHV of Natural Gas; 983 Btuff3
Natural	I gas utility consumption	0.17	normal m^3 / kg H2 produced	Spath, P., Aden, A., Eggeman, T., Ringer, M., Wallace, B. & Jechura, J. (2005, May@iomass to Hydrogen Production Detailed Design and Economics Utilizing the Battelle Columbus Laboratory Indirectly-Heated Gasifier: Appendex A. NREL/TP-510-37408. Golden, CO: National Renewable Energy Laboratory	Natural gas usage from overall energy balance; Appendix C, A401: stream 427 = 1669 lb/hr; Appendix C, A501: stream 424 = 14260 lb/hr; conversion vields 0.15 (not 0.17)
Natural	gas utility price	\$0.340	2005\$ / Nm^3	Energy Information Administation. (2005, February)Annual Energy Outlook 2005 With Projections to 2025. DOE/EIA-0383(2005). Washington, D.C.: U.S. Department of Energy.	Commercial natural gas price from AEO 2005 "High A" case for startup year (2005). Escalated from 2003 dollars to 200 dollars. File downloaded from http://www.eia.doe.gov/oiaf/aeo/index.html (file name aeo_hw-3.xls)
Natural	gas utility pressure	N/A	kPa	None	Not in H2A or GREET
		#VALUE!	psi		conversion calculation
	ty feedstock consumption	0.00	kWh / kg H2	Mann, M., & Steward, D.M. (2008, May 28).Current (2005) Hydrogen from Biomass via Gasification and Catalytic Steam Reforming. Golden, CO: National Renewable Energy Laboratoty	Current central H2A production from biomass basis version 2.1.2; Results tab; Energy Data
Electric	ity utility consumption (both production and compression)	0.98	kWh / kg H2	Spath, P., Aden, A., Eggeman, T., Ringer, M., Wallace, B. & Jechura, J. (2005, May Biomass to	Sum of feedstock + utility
Electric	ty utility consumption (production only)	0.98	kWh / kg H2	Spati, F., Aueti, A., Eggeritari, I., Kniger, M., Waiake, B. & Jectura, J. (2005, waypointies: 0 Hydrogen Production Detailed Design and Economics Utilizing the Battelle Columbus Laboratory Indirectly-Heated Gasifier. NREL/TP-510-37408. Golden, CO: National Renewable Energy Laboratory.	Electricity usage from overall energy balance with energy usage for hydrogen compression (3899 kW) removed. Apper A. Total Plant Electricity = 5.5 kWn/kg H2. Electricity consumption reduced in H2A because Spath has hydrogen prod at 360 psi and H2A's standard is 300 psi.
Electric	sity Utility Price	0.0555	2005 \$/kWh	Energy Information Administation. (2005, February)Annual Energy Outlook 2005 With Projections to 2025. DOE/EIA-0383(2005). Washington, D.C.: U.S. Department of Energy.	Industrial electricity price from AEO 2005 "High A" case for startup year (2005). Escalated from 2003 dollars to 2005 dollars. File downloaded from http://www.eia.doe.gov/oiaf/aeo/index.html (file name aeo_hw-3.xls)
Proces	s Water Consumption	1.32	gal / kg H2	Spath, P., Aden, A., Eggeman, T., Ringer, M., Wallace, B. & Jechura, J. (2005, May@iomass to Hydrogen Production Detailed Design and Economics Utilizing the Battelle Columbus Laboratory Indirectly-Heated Gasifier. NREL/TP-510-37408. Golden, CO: National Renewable Energy Laboratory.	Appendix C, A202: stream 218 = 738 lb/hr; Appendix C, A601: stream 620 = 102749 lb/hr; Appendix C, A701: stream 71 = 131921 lb/hr
	Consumption for Cooling	0.00008		Spath, P., Aden, A., Eggeman, T., Ringer, M., Wallace, B. & Jechura, J. (2005, May@iomass to Hydrogen Production Detailed Design and Economics Utilizing the Battelle Columbus Laboratory Indirectly-Heated Gasifier. NREL/TP-510-37408. Golden, CO: National Renewable Energy Laboratory.	Assume all make-up water is process water
	ity co-product production		kWh / kg H2 kg / kg H2	None None	All electricity co-product used internally N/A
	co-product production		kg / kg H2	None	N/A
Total A	nnual Fixed Operating Costs	\$10,391,486	2005\$ / yr	Spath, P., Aden, A., Eggeman, T., Ringer, M., Wallace, B. & Jechura, J. (2005, May@iomass to Hydrogen Production Detailed Design and Economics Utilizing the Battelle Columbus Laboratory Indirectly-Heated Gasifier: Section 9.2. NREL/TP-510-37408. Golden, CO: National Renewable Energy Laboratory	Section 9.2 Fixed Operating Costs. Costs were escalated from \$2002 to \$2005 dollars.
Total A	nnual Variable Operating Costs	\$43,162,900		Spath, P., Aden, A., Eggeman, T., Ringer, M., Wallace, B. & Jechura, J. (2005, May@iomass to Hydrogen Production Detailed Design and Economics Utilizing the Battelle Columbus Laboratory Indirectly-Heated Gasifier. Table 13. NREL/TP-510-37408. Golden, CO: National Renewable Energy Laboratory	Table 13: Variable Operating Costs. Costs were escalated from \$2002 to \$2005 dollars.
Total A	nnual Operating Costs	\$53,554,386	2005\$ / yr	N/A	Addition of Annual Total Fixed Operating Costs and Total Annual Variable Operating Costs
Produc Share (	tion energy efficiency (does not include electricity for forecourt compres of process fuel - biomass	ssio 46.0% 93.1%		N/A N/A	Calculated from H2A values Calculated from H2A values
Share of	of process fuel - coal	0.0%		N/A	Calculated from H2A values
Share of	of process fuel - natural gas	2.5%		N/A	Calculated from H2A values
	of process fuel - ethanol of process fuel - electricity	0.0%		N/A N/A	Calculated from H2A values Calculated from H2A values
	en outlet pressure (before CSD)	300		Spath, P., Aden, A., Eggeman, T., Ringer, M., Wallace, B. & Jechura, J. (2005, May@iomass to Hydrogen Production Detailed Design and Economics Utilizing the Battelle Columbus Laboratory Indirectly-Heated Gasifier. NREL/TP-510-37408. Golden, CO: National Renewable Energy Laboratory.	Calculated inter Track addess Final compression step modeled in the analysis was removed for the H2A case study to maintain consistency with H2A default value. Spath's compression was to 360 psi and H2A standard is 300 psi. Reducing the compression reduced t electricity use.

arameter	,	Value	Units	Reference	Comments
Hydrogen quality before transport		99.9%		Spath, P., Aden, A., Eggeman, T., Ringer, M., Wallace, B. & Jechura, J. (2005, MayBiomass to Hydrogen Production Detailed Design and Economics Utilizing the Battelle Columbus Laboratory Indirectly-Heated Gastier. NELITP-510-37408. Golden, CO: National Renewable Energy	
incial Parameters			% H2	Laboratory.	
After-tax Real IRR		10%		Mann, M., & Steward, D.M. (2008, May 28). Current (2005) Hydrogen from Biomass via Gasification and Catalytic Steam Reforming. Golden, CO: National Renewable Energy Laboratoty	Current central H2A production from biomass basis version 2.1.2; Input_Sheet_Template tab; After-tax Real IRR, cell (
Plant Life		40	years	Mann, M., & Steward, D.M. (2008, May 28). Current (2005) Hydrogen from Biomass via Gasification and Catalytic Steam Reforming. Golden, CO: National Renewable Energy Laboratoty	Current central H2A production from biomass basis version 2.1.2; Input_Sheet_Template tab; Plant life, cell C34
Federal Tax Rate		35.0%		Mann, M., & Steward, D.M. (2008, May 28). Current (2005) Hydrogen from Biomass via Gasification and Catalytic Steam Reforming. Golden, CO: National Renewable Energy Laboratory	
State Tax Rate		6.0%		Mann, M., & Steward, D.M. (2008, May 28). Current (2005) Hydrogen from Biomass via Gasification and Catalytic Steam Reforming. Golden, CC: National Renewable Energy Laboratory	
Total Tax Rate		38.9%		Mann, M., & Steward, D.M. (2008, May 28). Current (2005) Hydrogen from Biomass via Gasification and Catalytic Steam Reforming. Golden, CO: National Renewable Energy Laboratory	
Fraction Equity		100%		Mann, M., & Steward, D.M. (2008, May 28). Current (2005) Hydrogen from Biomass via Gasification and Catalytic Steam Reforming. Golden, CO: National Renewable Energy Laboratory	
ansport, Delivery, and Storage Er	nergy Requirements				
eline Delivery				Elgowainy, A., Mintz, M. & Gillette, J. (2006) Hydrogen Delivery Scenario Analysis Model	HDSAM version 2.02 calculation based on input parameters: city, market penetration, dispensing rate (PEAK FLOW R
Average Hydrogen Flowrate (Enter	ing System)	348,364	kg/hr	(HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	THRU TRANSMISSION SYSTEM=CITY PEAK DEMAND/TRANSMISIION PIPELINE MASS EFFICIENCY/REF.STATION MASS EFFICIENCY)
Average Hydrogen Flowrate (Distributed)		344,451	kg/hr	Elgowainy, A., Mintz, M. & Gillette, J. (2006) Hydrogen Delivery Scenario Analysis Model	HDSAM version 2.02 calculation based on input parameters: city, market penetration, dispensing rate (Ave. daily use DAILY USE/TOTAL PIPELINE MASS EFFICIENCY/REF.STATION MASS EFFICIENCY)
Summer Surge: % above the Syste	m Average Daily Demand	10%	% above Average Daily Demand	Elaswoiny, A. Mintz, M. & Cillotto, J. (2006) Hudrogen Delivery Seenerie Analysis Medel	HDSAM default, Scenario Parameters tab, cell B90
Friday Peak		8%	% above Average Daily Demand	Electronic A. Mintz, M. & Cillette, J. (2006) Hudrogen Delivery Secondria Applysic Medel	HDSAM default, Scenario Parameters tab, cell B92
Peak Hydrogen Flowrate		381,192	kg/hr		HDSAM version 2.02 calculation based on input parameters: city, market penetration, dispensing rate (PEAK FLOWR THRU DISTRIBUTION SYSTEM-CITY PEAK DEMAND/DISTRIBUTION PIPELINE MASS EFFICIENCY/REF_STATION MASS EFFICIENCY)
Total Capital Investment for Compr	essors	\$27,199,794		05GQ15032	Disscussions with Bechtel and Air Liquide (Nexant report - Section 2.2.5)
Hydrogen Losses from Compresso	rs	0.50%		Electronic A Mintz M & Cillette J (2006) Hudrogen Delivery Seenerie Analysis Medel	HDSAM default, Refueling Station - Gaseous H2 tab, cell B79
Compressor Electricity Demand		70,343,075	kWh / year	Nexant, Inc. et al. (2008, May).H2A Hydrogen Delivery Infrastructure Analysis Models and	Based on vendor data from Neuman&Esser, Burckhardt Compression, Ariel Compressors, Dresser-Rand (Nexant rep Section 2.2.5)
Compressor Electricity Demand		0.5591	kWh / kg H2	Nexant, Inc. et al. (2008, May).H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results . Interim Report Section 2.2.5. DE-FG36- 05GO15032.	Based on vendor data from Neuman&Esser, Burckhardt Compression, Ariel Compressors, Dresser-Rand (see Nexanl report - Section 2.2.5)
Compressor Electricity Cost		\$0.056	2005\$ / kWh	Energy Information Administration. (2007, February)Annual Energy Outlook 2007 with Projections to 2030. DOE/EIA-0383(2007). Washington, D.C. Retreived from www.eia.doe.gov/oiafarchive/aeo07/index.ht	EIA AEO 2005 and 2007
Total Capital Investment for Pipelin	e System \$	\$377,283,372		Nexant, Inc. et al. (2008, May).H2A Hydrogen Delivery Infrastructure Analysis Models and	HDSAM version 2.02 calculations based on data from GTI, Bechtel, Air Liquide, UC Davis (Nexant Report -Section 2.
Hydrogen Losses from Pipelines		0.10%		Elgowainy, A., Mintz, M. & Gillette, J. (2006) Hydrogen Delivery Scenario Analysis Model (HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	
Number of transmission pipelines		1		Electronic A Mintz M & Cillette 1 (2006) Hudrogen Delivery Seenerie Applysic Medel	Default in HDSAM version 2.02
Transmission pipeline diameter		11.00	in	Gas Processors Supplier Association. (2004). GPSA Engineering Data Book, 12th Edition. Tulsa, OK. Retrieved from http://gpaglobal.org/gpsa/book.php	HDSAM version 2.02 calculation: Panhandle B equation, H2 Pipeline tab, cell B83
Transmission pipeline inlet pressure	e	999	psi	05G015032.	Recommendations from Nexant in conjuction with Air Liquide, GTI, Chevron, TIAX, ANL, PNNL and NREL (Nexant R Section 2.1.6)
Transmission pipeline outlet pressu	re	705	psi	05G015032.	Recommendations from Nexant in conjuction with Air Liquide, GTI, Chevron, TIAX, ANL, PNNL and NREL (Nexant R Section 2.1.6)
Transmission pipeline temperature		25	c	05GO15032.	Recommendations from Nexant in conjuction with Air Liquide, GTI, Chevron, TIAX, ANL, PNNL and NREL (Nexant R Section 2.1.6)
Transmission pipeline length		62	miles	Elgowainy, A., Mintz, M. & Gillette, J. (2006) Hydrogen Delivery Scenario Analysis Model (HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	HDSAM version 2.02 calculation based on input parameter: city, Scenario Parameters tab, cell F167
Number of trunk pipelines		4		Elgowainy, A., Mintz, M. & Gillette, J. (2006) Hydrogen Delivery Scenario Analysis Model	HDSAM version 2.02 calculation based on input data and HDSAM distribution model - not documented, H2 Pipeline ta cell B58
Trunk #1 pipeline diameter		7.25	in	Cas Processors Supplier Association. (2004). GPSA Engineering Data Book, 12th Edition. Tulsa, OK. Retrieved from http://gpaglobal.org/gpsa/book.php	HDSAM version 2.02 calculation: Panhandle B equation, H2 Pipeline tab, cell B84
Trunk #1 pipeline inlet pressure		603	psi	Nexant, Inc. et al. (2008, May).H2A Hydrogen Delivery Infrastructure Analysis Models and	Recommendations from Nexant in conjuction with Air Liquide, GTI, Chevron, TIAX, ANL, PNNL and NREL (Nexant R Section 2.1.6)
Trunk #1 pipeline outlet pressure		397	psi	Nexant, Inc. et al. (2008, May)-H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Ontions Analysis Results. Interim Paport Section 2.1.6. DE-EG36.	Recommendations from Nexant in conjuction with Air Liquide, GTI, Chevron, TIAX, ANL, PNNL and NREL (Nexant R Section 2.1.6)
Trunk #1 pipeline temperature		25	с	Nexant, Inc. et al. (2008, May) H2A Hydrogen Delivery Infrastructure Analysis Models and	Recommendations from Nexant in conjuction with Air Liquide, GTI, Chevron, TIAX, ANL, PNNL and NREL (Nexant Re Section 2.1.6)
Trunk #1 pipeline length		17	miles	Elgowainy, A., Mintz, M. & Gillette, J. (2006) Hydrogen Delivery Scenario Analysis Model	HDSAM version 2.02 calculation based on input data and HDSAM distribution model (discussions with Pacific Gas & Electric Company, San Francisco). Scenario Parameters tab, cell F168

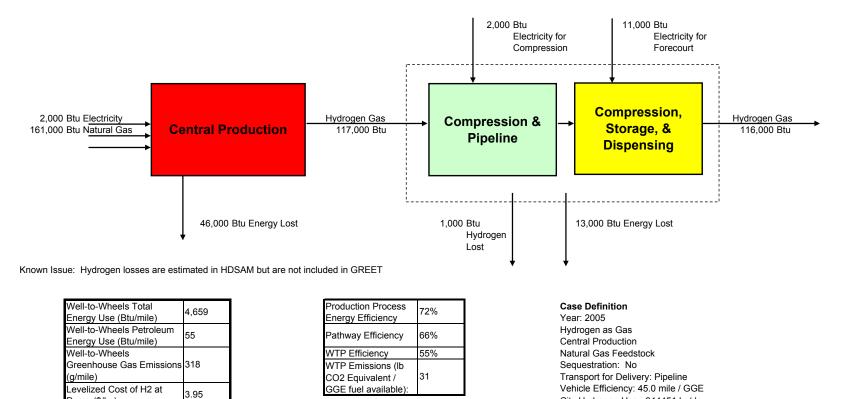
i					
Parameter		Value	Units	Reference Gas Processors Supplier Association. (2004). GPSA Engineering Data Book, 12th Edition. Tulsa,	Comments
Trunk #2 pipe	peline diameter	10.25 i	1	OK. Retrieved from http://gpaglobal.org/gpsa/book.php Nexant, Inc. et al. (2008, May):HZA Hydrogen Delivery Infrastructure Analysis Models and	HDSAM version 2.02 calculation: Panhandle B equation, H2 Pipeline tab, cell B85
Trunk #2 pipe	beline inlet pressure	588 p	si	Conventional Pathway Options Analysis Results . Interim Report Section 21.6. DE-FG36- OSOO 15032. Nexant, Inc. et al. (2008, May) H2A Hydrogen Delivery Infrastructure Analysis Models and	Recommendations from Nexant in conjuction with Air Liquide, GTI, Chevron, TIAX, ANL, PNNL and NREL (Nexant Repo Section 2.1.6)
Trunk #2 pipe	beline outlet pressure	397 p	si	Conventional Pathway Options Analysis Results . Interim Report Section 2.1.6. DE-FG36- 05GO15032.	Recommendations from Nexant in conjuction with Air Liquide, GTI, Chevron, TIAX, ANL, PNNL and NREL (Nexant Repo Section 2:1.6)
Trunk #2 pipe	beline temperature	25 C		Nexant, Inc. et al. (2008, May) H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results . Interim Report Section 2.1.6. DE-FG36- 05GO15032.	Recommendations from Nexant in conjuction with Air Liquide, GTI, Chevron, TIAX, ANL, PNNL and NREL (Nexant Repo Section 2.1.6)
Trunk #2 pipe	peline length	40 r	niles	Elgowainy, A., Mintz, M. & Gillette, J. (2006) <i>Hydrogen Delivery Scenario Analysis Model</i> (HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	HDSAM version 2.02 calculations based on input data and HDSAM distribution model - not documented, Scenario Parameters tab, cell F169
Trunk #3 pipr	peline diameter	12.25 i	1	Gas Processors Supplier Association. (2004). GPSA Engineering Data Book, 12th Edition. Tulsa, OK. Retrieved from http://gpaglobal.org/gpsa/book.php	HDSAM version 2.02 calculation: Panhandle B equation, H2 Pipeline tab, cell B86
Trunk #3 pipe	beline inlet pressure	573 p	si	Nexant, Inc. et al. (2008, May).H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results . Interim Report Section 2.1.6. DE-FG36- 05GO15032.	Recommendations from Nexant in conjuction with Air Liquide, GTI, Chevron, TIAX, ANL, PNNL and NREL (Nexant Repo Section 2.1.6)
Trunk #3 pipe	beline outlet pressure	397 p	si	Nexant, Inc. et al. (2008, May) H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results . Interim Report Section 2.1.6. DE-FG36- 05GO15032.	Recommendations from Nexant in conjuction with Air Liquide, GTI, Chevron, TIAX, ANL, PNNL and NREL (Nexant Repo Section 2.1.6)
Trunk #3 pipe	peline temperature	25 (		Nexant, Inc. et al. (2008, May) H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results . Interim Report Section 2.1.6. DE-FG36- 05GO15032.	Recommendations from Nexant in conjuction with Air Liquide, GTI, Chevron, TIAX, ANL, PNNL and NREL (Nexant Repo Section 2.1.6)
Trunk #3 pipe	peline length	65 r	niles	Elgowainy, A., Mintz, M. & Gillette, J. (2006) <i>Hydrogen Delivery Scenario Analysis Model</i> ( <i>HDSAM</i> ) V2.0. Argonne, IL: Argonne National Laboratory	HDSAM version 2.02 calculations based on input data and HDSAM distribution model - not documented, Scenario Parameters tab, cell F170
Trunk #4 pipe	beline diameter	10.75 ii	1	Gas Processors Supplier Association. (2004). GPSA Engineering Data Book, 12th Edition. Tulsa, OK. Retrieved from http://gpaglobal.org/gpsa/book.php	HDSAM version 2.02 calculation: Panhandle B equation, H2 Pipeline tab, cell B87
Trunk #4 pipe	beline inlet pressure	558 p	si	Nexant, Inc. et al. (2008, May) H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results . Interim Report Section 2.1.6. DE-FG36- 05GO15032.	Recommendations from Nexant in conjuction with Air Liquide, GTI, Chevron, TIAX, ANL, PNNL and NREL (Nexant Repo Section 2.1.6)
Trunk #4 pipe	beline outlet pressure	397 p	si	Nexant, Inc. et al. (2008, May) H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results . Interim Report Section 2.1.6. DE-FG36- 05GO15032.	Recommendations from Nexant in conjuction with Air Liquide, GTI, Chevron, TIAX, ANL, PNNL and NREL (Nexant Repo Section 2.1.6)
Trunk #4 pipe	peline temperature	25 (		Nexant, Inc. et al. (2008, May) H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results . Interim Report Section 2.1.6. DE-FG36- 05GO15032.	Recommendations from Nexant in conjuction with Air Liquide, GTI, Chevron, TIAX, ANL, PNNL and NREL (Nexant Repo Section 2.1.6)
Trunk #4 pipe	peline length	90 r	niles	Elgowainy, A., Mintz, M. & Gillette, J. (2006) Hydrogen Delivery Scenario Analysis Model (HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	HDSAM version 2.02 calculations based on input data and HDSAM distribution model - not documented, Scenario Parameters tab, cell F171
Number of se	ervice pipelines	270		Elgowainy, A., Mintz, M. & Gillette, J. (2006) <i>Hydrogen Delivery Scenario Analysis Model</i> (HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	HDSAM version 2.02 calculations based on input data and HDSAM distribution model (discussions with Pacific Gas & Electric Company, San Francisco), H2 Pipeline tab, cell B67
Service pipeli	eline diameter	<b>1</b> ii	1	Gas Processors Supplier Association. (2004). GPSA Engineering Data Book, 12th Edition. Tulsa, OK. Retrieved from http://gpaglobal.org/gpsa/book.php	HDSAM version 2.02 calculation: Panhandle B equation, H2 Pipeline tab, cell B88
Service pipel	line inlet pressure	382 p	si	Nexant, Inc. et al. (2008, May) H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results . Interim Report Section 2.1.6. DE-FG36- 05G015032.	Recommendations from Nexant in conjuction with Air Liquide, GTI, Chevron, TIAX, ANL, PNNL and NREL (Nexant Repo Section 2.1.6)
Service pipel	line outlet pressure	294 p	si	Nexant, Inc. et al. (2008, May) H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results . Interim Report Section 2.1.6. DE-FG36- 05GO15032.	Recommendations from Nexant in conjuction with Air Liquide, GTI, Chevron, TIAX, ANL, PNNL and NREL (Nexant Repo Section 2.1.6)
Service pipel	line temperature	25 C		Nexant, Inc. et al. (2008, May) H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results . Interim Report Section 2.1.6. DE-FG36- 05GO15032.	Recommendations from Nexant in conjuction with Air Liquide, GTI, Chevron, TIAX, ANL, PNNL and NREL (Nexant Repo Section 2.1.6)
Service pipeli	line length	1.1 r	niles	Elgowainy, A., Mintz, M. & Gillette, J. (2006) <i>Hydrogen Delivery Scenario Analysis Model</i> (HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	HDSAM version 2.02 calculations based on input data and HDSAM distribution model (discussions with Pacific Gas & Electric Company, San Francisco), H2 Pipeline tab, cell B68
Pipeline Geo	ologic Storage Total Capital Investment	\$36,988,376		Nexant, Inc. et al. (2008, May) H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results . Interim Report Section 2.2.12. DE-FG36- 05GO15032.	HDSAM version 2.02 calculations (cost data from ConocoPhilips and Saltville natural gas storage facility in Virginiase (Nexant Report - Section 2.2.12)
Hydrogen Lo	osses from Geologic Storage	0.02%		Elgowainy, A., Mintz, M. & Gillette, J. (2006) <i>Hydrogen Delivery Scenario Analysis Model</i> (HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	
a seriege sta	prage Capacity	41,864,765 n		Calculation Elgowainy, A., Mintz, M. & Gillette, J. (2006)Hydrogen Delivery Scenario Analysis Model	
Geologic Stor	orage Design Capacity	3,762,787 k	g H2	(HDSAM) V2.0. Argonne, IL: Argonne National Laboratory Nexant, Inc. et al. (2008, May).H2A Hydrogen Delivery Infrastructure Analysis Models and	HDSAM version 2.02 calculation, Gaseous H2 Geological Stroage tab, cell B105
Geologic Stor	orage Electricity Demand	961,465 k	Wh / year	Conventional Pathway Options Analysis Results . Interim Report Section 2.12. DE-FG36- OSO-0502. Nexant, Inc. et al. (2008, May).H2A Hydrogen Delivery Infrastructure Analysis Models and	HDSAM version 2.02 calculations (cost data from ConocoPhilips and Saltville natural gas storage facility in Virginiase (Nexant Report- Sections 2.2.12 and 2.2.5)
Geologic Stor	orage Electricity Demand	0.0076 k	Wh / kg H2	Conventional Pathway Options Analysis Results . Interim Report Section 2.2.12. DE-FG36- 05GO15032.	HDSAM version 2.02 calculations (cost data from ConocoPhilips and Saltville natural gas storage facility in Virginiase (Nexant Report- Sections 2.2.12 and 2.2.5)
Geologic Sto	orage Electricity Cost	<b>\$0.052</b> 2	005\$ / kWh	Energy Information Administration. (2005, January)Annual Energy Outlook 2005 with Projections to 2025. DOE/EIA-0383(2005). Washington, D.C. Retreived from http://www.eia.doe.gov/oid/archive/aeo05/index.ht	EIA AEO 2005
Distribution Statio	on				
Gaseous Receiving/Di	Distributing Stations				
Hydrogen Dis	ispensed at Forecourt Station	465,647 k	g / station year	Elgowainy, A., Mintz, M. & Gillette, J. (2006) <i>Hydrogen Delivery Scenario Analysis Model</i> ( <i>HDSAM</i> ) V2.0. Argonne, IL: Argonne National Laboratory	HDSAM version 2.02 calculation, Refueling Station - Gaseous H2 tab, cell B138
Electricity Re	equired by Forecourt Station	1,416,755 k	Wh / station year	Elgowainy, A., Mintz, M. & Gillette, J. (2006) <i>Hydrogen Delivery Scenario Analysis Model</i> ( <i>HDSAM</i> ) V2.0. Argonne, IL: Argonne National Laboratory	HDSAM version 2.02 calculation, Refueling Station - Gaseous H2 tab, cell B263
Number of C	Compressor Stages	4 5	stages in compressor	Elgowainy, A., Mintz, M. & Gillette, J. (2006) <i>Hydrogen Delivery Scenario Analysis Model</i> (HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	HDSAM version 2.02 default, Refueling Station - Gaseous H2 tab, cell B67
Compressor	r Isentropic Efficiency	65%		Elgowainy, A., Mintz, M. & Gillette, J. (2006) <i>Hydrogen Delivery Scenario Analysis Model</i> ( <i>HDSAM</i> ) V2.0. Argonne, IL: Argonne National Laboratory	HDSAM version 2.02 default, Refueling Station - Gaseous H2 tab, cell B69
Design Capa	acity	1,516 k	g H2 / day	Nexant, Inc. et al. (2008, May) H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results . Interim Report Section 2.1.4. DE-FG36- 05GO15032.	HDSAM version 2.02 calculation based on Chevron fueling profiles (Nexant Report - Section 2.1.4): = adjusted disp. Rate*(1+summer surge)*(1+Friday surge), Refueling Station - Gaseous H2 tab, cell B32
Operating Ca	apacity	1,278	g H2 / day	Elgowainy, A., Mintz, M. & Gillette, J. (2006) Hydrogen Delivery Scenario Analysis Model (HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	Adjusted dispensing rate=city use/number of stations/utilization factor, Refueling Station - Gaseous H2 tab, cell B33

Parameter	Tester	Value	Units	Reference	Comments
Capacity I		84%		Nexant, Inc. et al. (2008, May).H2A Hydrogen Delivery Infrastructure Analysis Models and	calculation
Site storage (Low Pressure)		470	kg H2	Conventional Pathway Options Analysis Results . Interim Report Section 2.2.3. DE-FG36- 05GO15032.	HDSAM version 2.02 calculation (Nexant Report - Section 2.2.3), Refueling Station - Gaseous H2 tab, cell B123
Site storage (Cascade)		582	kg H2	Nexant, Inc. et al. (2008, May) H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results . Interim Report Section 2.3.2.4 DE-FG36- 05G015032.	HDSAM calculations (Nexant Report - Section 2.3.2.4), Refueling Station - Gaseous H2 tab, cell B122
Site stora	ge		% of design H2 distribution	N/A	calculation
Dispensin	Dispensing Pressure		psi	Nexant, Inc. et al. (2008, May) H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results . Interim Report Section 2.2.3. DE-FG36- 05G015032.	HDSAM version 2.02 default (see Nexant Report-Section 2.3.2), Refueling Station - Gaseous H2 tab, cell B58
Hydrogen	Losses due to leaks	0.50%		Elgowainy, A., Mintz, M. & Gillette, J. (2006) Hydrogen Delivery Scenario Analysis Model (HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	HDSAM version 2.02 default, Refueling Station - Gaseous H2 tab, cell B79
Electrical Voltage Supply Requirement		480	Volts	Nexant, Inc. et al. (2008, May) H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.2.5. DE-FG36- 05GO15032.	HDSAM version 2.02 calculation (see Nexant Report - Sections 2.2.5 and 2.2.6), Refueling Station - Gaseous H2 tab, ce B137
Distributio	n System total capital investment	\$3,117,483	2005\$ / station	Nexant, Inc. et al. (2008, May) H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results . Interim Report Section 2.2.5.2. DE-FG36- 05G015032.	Nexant Report - Section 2.2.5.2
Distributio	n System electricity cost	\$115,508	2005\$ / station yr	Elgowainy, A., Mintz, M. & Gillette, J. (2006) Hydrogen Delivery Scenario Analysis Model (HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	HDSAM version 2.02 calculation, Refueling Station - Gaseous H2 tab, cell B267
Distributio	n Labor Required	3,951	hr / station yr	Elgowainy, A., Mintz, M. & Gillette, J. (2006) <i>Hydrogen Delivery Scenario Analysis Model</i> (HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	HDSAM version 2.02 calculation, Refueling Station - Gaseous H2 tab, cell B259
Distributio	n System labor cost	\$39,513	2005\$ / station yr	Nexant, Inc. et al. (2008, May) H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results . Interim Report Section 2.2.1.3. DE-FG36- 05GO15032.	Bureau of Labor and Statistics (Nexant Report - Section 2.2.1.3), Refueling Station - Gaseous H2 tab, cell B260
Distribution System total O&M cost		\$298,898	2005\$ / station yr	Nexant, Inc. et al. (2008, May),H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results . Interim Report Section 2.2.1.2. DE-FG36- 05GO15032.	HDSAM version 2.02 calculations (Nexant Report - Section 2.2.1.2), Refueling Station - Gaseous H2 tab, cell B283
Other Assumpti	ons for WTW Calculations				
Share of RFG in Tot	al Gasoline Use	100%		U.S. Department of Energy & U.S. Department of Transportation. (2006, December)Hydrogen Posture Plan An Inegrated Research, Development and Demonstration Plan.	Basis for posture plan
Type of Oxygenate i	n RFG	None		U.S. Department of Energy & U.S. Department of Transportation. (2006, December)Hydrogen Posture Plan An Inegrated Research, Development and Demonstration Plan.	Basis for posture plan
O2 Content in RFG		0%	wt %	U.S. Department of Energy & U.S. Department of Transportation. (2006, December/Hydrogen Posture Plan An Inegrated Research, Development and Demonstration Plan.	Basis for posture plan
Ratio of FCV VOCs (emissions) to GVs fueled with CG & RFG		0%		Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology, development, Use and Results. Argonne, IL: Argonne National Laboratory.	GREET default, Table 4.45 FCV: H2
Ratio of FCV VOCs	(evaporative) to GVs fueled with CG & RFG	0%		Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology, development, Use and Results. Argonne, IL: Argonne National Laboratory.	GREET default, Table 4.45 FCV: H2
Ratio of FCV CO em	issions to GVs fueled with CG & RFG	0%		Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology, development, Use and Results. Argonne, IL: Argonne National Laboratory.	GREET default, Table 4.45 FCV: H2
Ratio of FCV NOx e	missions to GVs fueled with CG & RFG	0%		Wang, M.C. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology, development, Use and Results. Argonne, IL: Argonne National Laboratory.	GREET default, Table 4.45 FCV: H2
Ratio of FCV Exhau	st PM10 emissions to GVs fueled with CG & RFG	0%		Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology, development, Use and Results. Argonne, IL: Argonne National Laboratory.	GREET default, Table 4.45 FCV: H2
Ratio of FCV Brake	& Tire Wear PM10 emissions to GVs fueled with CG & RFG	100%		Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1:	GREET default, page 197: vehicles within the same weight class have similar tire and brake wear emissions
Ratio of FCV Exhaust PM2.5 emissions to GVs fueled with CG & RFG		0%		Methodology, development, Use and Results. Argonne. IL: Argonne National Laboratory. Wang, M.O. (2008, September 5). The Greenhouse Gases, Regualted Emissions, and Energy Use in Transportation (GREET) Model, Version 1.8b. Argonne, IL: Argonne National Laboratory.	GREET default:well-known fuel cell emissions (no PM2.5)
Ratio of FCV Brake & Tire Wear PM2.5 emissions to GVs fueled with CG & RFG		100%		Wang, M.Q. (2008, September 5). The Greenhouse Gases, Regualted Emissions, and Energy Use in Transportation (GREET) Model, Version 1.8b. Argonne, IL: Argonne National Laboratory.	GREET default:reasonable to assume FCV has same driving pattern as GV
Ratio of FCV CH4 e	missions to GVs fueled with CG & RFG	0%		Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology, development, Use and Results. Argonne, IL: Argonne National Laboratory.	GREET default, Table 4.45 FCV: H2
Ratio of FCV N2O e	missions to GVs fueled with CG & RFG	0%		Wernoboology, development, Use and results: Argonine, IL: Argonine National Caboratory. Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology, development, Use and Results. Argonne, IL: Argonine National Laboratory.	GREET default, Table 4.45 FCV: H2
Marginal Electricity Generation Mix for Transportation Use		US Mix		U.S. Department of Energy & U.S. Department of Transportation. (2006, December)Hydrogen	Basis for posture plan
Results	·····			Posture Plan An Inegrated Research, Development and Demonstration Plan.	
Levelized Cost		\$4.23	• / I	Ruth, M. et al. (2009, March). Hydrogen Macro System Model User Guide. NREL/TP-6A1-44799	
		607		Golden, CO: National Renewable Energy Laboratory. Ruth, M. et al. (2009, March). Hydrogen Macro System Model User Guide. NREL/TP-6A1-44799	MSM Results
WTW Coal Input		225	Btu / mile	Golden, CO: National Renewable Energy Laboratory. Ruth, M. et al. (2009, March). Hydrogen Macro System Model User Guide. NREL/TP-6A1-44799	MSM Results
WTW Natural Gas Input			Btu / mile	Golden, CO: National Renewable Energy Laboratory. Ruth, M. et al. (2009, March). Hydrogen Macro System Model User Guide. NREL/TP-6A1-44799	MSM Results
WTW Petroleum Input			Btu / mile	Golden, CO: National Renewable Energy Laboratory. Ruth, M. et al. (2009, March). Hydrogen Macro System Model User Guide. NREL/TP-6A1-44799	MSM Results
WTW Fossil Energy Input			Btu / mile	Golden, CO: National Renewable Energy Laboratory. Ruth, M. et al. (2009, March). Hydrogen Macro System Model User Guide. NREL/TP-6A1-44799	MSM Results
WTW Total Energy Input		6,695	Btu / mile	Ruth, M. et al. (2009, March). Hydrogen Macro System Model User Guide. NREL/TP-6A1-44799 Golden, CO: National Renewable Energy Laboratory. Ruth, M. et al. (2009, March). Hydrogen Macro System Model User Guide. NREL/TP-6A1-44799	MSM Results
WTW CO2 Emissions		64	g / mile	Golden, CO: National Renewable Energy Laboratory.	MSM Results
WTW CH4 Emissions		0	g / mile	Ruth, M. et al. (2009, March). Hydrogen Macro System Model User Guide. NREL/TP-6A1-44799 Golden, CO: National Renewable Energy Laboratory.	MSM Results
WTW N2O Emissions		0	g / mile	Ruth, M. et al. (2009, March). Hydrogen Macro System Model User Guide. NREL/TP-6A1-44799 Golden, CO: National Renewable Energy Laboratory.	MSM Results
WTW GHG Emissio			g / mile	Ruth, M. et al. (2009, March). Hydrogen Macro System Model User Guide. NREL/TP-6A1-44799 Golden, CO: National Renewable Energy Laboratory.	MSM Results
		1			

Appendix E — Natural Gas–Pipeline Supporting Tables and Figures

#### Hydrogen Produced In Central Plant and Transported as Gas via Pipeline

Pump (\$/kg)



City Hydrogen Use: 344451 kg/day

In Record, Records, Literatori, No. No. 2003     Avegage / descriptions (a) and (a) and (b) and (b) and (b) and (b)	Ing	outs	Graphic Depiction & Ass	sumptions	C	Dutputs
Note optimized based of an optimized based			NG Recovery Efficiency NG emitted & combusted during recovery NG processing energy efficiency NG emitted & combusted during processin	97.2% 0.35% 97.2% 0.15%	NG Quality at Delivery	Average of gas companies \$0.243 2005 \$ / Nm^3
Backet groups         B.5 Montage         B. Set Montage         Project	Natural Gas Input from "Well"	122,927 Btu / 116000Btu to Pump	NG transport distance	500 miles	WTG CH4 Emissions WTG N2O Emissions	16 g / 116000Btu to Pump 0 g / 116000Btu to Pump
Opport Product         5.50 / 1 + 1          Opport Product         3.50 / 1 + 1          Set of the Product Produc	Electricity consumption	0.57 kWh / kg H2	Hydrogen Productio	1		Not Available psi 1
School Statistics         Statistististics	Cooling Water Consumption	5.66 L / kg H2 \$0.0555 2005 \$/kWh	Capacity factor Process energy efficiency Electricity Mix After-tax IRR	90% 71.9% US Mix 10%	Electricity cost Other operating costs	\$0.03 2005\$ / kg H2 produced \$0.08 2005\$ / kg H2 produced
Bis data (particular)     0.01 (Mn / g) = 1 (M / G / G / G / G / G / G / G / G / G /	Natural Gas Input from "Well"	47,416 Btu / 116000Btu to Pump		40 years	SMR CH4 Emissions SMR N2O Emissions	7 g / 116000Btu to Pump 0 g / 116000Btu to Pump
Electicity note for compressor Beside you for for compressor	Electricity consumption for geo storage	0.01 kWh / kg H2	Pipelines for Deliver	,		
Case Ingent Wert         3.368 Bur / 10000Bus Pharps         Phate of envice Res         70         Delivery 0.44 Emissions         1 3/ 15000Bus Pharps           Exclusion from Wert         3.06 Bur / 10000Bus Pharps         11276         Delivery 0.44 Emissions         1 3/ 15000Bus Pharps           Exclusion from Wert         3.06 Bur / 10000Bus Pharps         11276         Delivery 0.44 Emissions         1 3/ 15000Bus Pharps           Exclusion from Wert         3.06 Bur / 10000Bus Pharps         Processmelter         3.06 Bur / 10000Bus Pharps         4.250 Plant         Bellery 0.44 Emissions         1 3/ 15000Bus Pharps         4.250 Plant         Burlery 0.44 Emissions         4.250 Plant         4.250 Plant         115.000 Bus Pharps         4.250 Plant         Burlery 0.44 Emissions         4.250 Plant         115.000 Bus Pharps         4.250 Plant         Burlery 0.44 Emissions         4.250 Plant         Burlery 0.44 Emissions         4.250 Plant         115.000 Bus Pharps         4.250 Plant         Burlery 0.44 Emissions         4.250 Plant         Burlery 0.44 Emissions         1.250 Plant         Burlery 0.44 Emissions         1.250 Plant         4.250 Plant         Exclusion 0.250 Plant         4.250 Plant         Exclusion 0.250 Plant         4.250 Plant         Exclusion 0.250 Plant         Exclusin 0.250 Plant		\$0.056 2005\$ / kWh	Hydrogen Vehicle Penetration City hydrogen use 1 Distance from City to Production Facility Geologic storage capacity Trunk #1-line length Trunk #2-line length	50% 25,810,766 kg / yr 62 miles 3,762,787 kg H2 17 miles 40 miles		·
Electricity pros ' S0.082 2005 / Whith Pump Electricity pros ' S0.082 2005 / Whith Pump Coal input from 'Weit'' 77.777 Bb / 11000Bb lu Pump Peterdeum input from 'Weit'' 77.777 Bb / 11000Bb lu Pump Peterdeum input from 'Weit'' 77.777 Bb / 11000Bb lu Pump Peterdeum input from 'Weit'' 77.777 Bb / 11000Bb lu Pump Peterdeum input from 'Weit'' 74.7778 Bb / 11000Bb lu Pump Peterdeum input from 'Weit'' 74.778 Bb / 11000Bb lu Pump Peterdeum input from 'Weit'' 74.778 Bb / 11000Bb lu Pump Peterdeum input from 'Weit'' 74.778 Bb / 11000Bb lu Pump Peterdeum input from 'Weit'' 74.778 Bb / 11000Bb lu Pump Peterdeum input from 'Weit'' 74.778 Bb / 11000Bb lu Pump Peterdeum input from 'Weit''' 74.778 Bb / 1100	Natural Gas Input from "Well"	950 Btu / 116000Btu to Pump	Number of service lines	270	Delivery CH4 Emissions Delivery N2O Emissions	1 g / 116000Btu to Pump 0 g / 116000Btu to Pump
Call light from 'Well'     17.677 Bb // 11000Bb to Pump 5.078 Bb // 11000Bb to Pump 5.07			Forecourt Distributio	ı		
Weiling Case with the second	Natural Gas Input from "Well"	5,078 Btu / 116000Btu to Pump	Energy efficiency Number of Compression Steps Isentropic Efficiency Site storage	92% 4 65% 69% capacity	Electricity cost Levelized Cost of Distribution CSD CO2 Emissions CSD CH4 Emissions CSD N2O Emissions	\$0.25 2005\$ / kg H2 \$1.69 2005\$ / kg H2 distributed 2,333 g / 116000Btu to Pump 3 g / 116000Btu to Pump 0 g / 116000Btu to Pump
Fuel Economy45.0 mi / GGERatio of FCV VOCs (emissions) to GVsRatio of FCV VOCs (emissions) to GVsRatio of FCV VOCs (evaporative) to GVsRatio of FCV CO emissions to GVsRatio of FCV CO emissions to GVsRatio of FCV NDx emissions to GVsRatio of FCV NDx emissions to GVsRatio of FCV NDx emissions to GVsRatio of FCV Schueled with CG & RFGGVs fueled with CG & RFGO%Ratio of FCV Exhaust PM10 emissions to GVs fueled with CG & RFGRatio of FCV Exhaust PM10 emissions to GVs fueled with CG & RFGRatio of FCV Exhaust PM10 emissions to GVs fueled with CG & RFGRatio of FCV Exhaust PM10 emissions to GVs fueled with CG & RFGRatio of FCV Exhaust PM2.5 emissions to GVs fueled with CG & RFGRatio of FCV CH4 emissions to GVs fueled with CG & RFGRatio of FCV CH4 emissions to GVs fueled with CG & RFGRatio of FCV CH4 emissions to GVs fueled with CG & RFGRatio of FCV CH4 emissions to GVs fueled with CG & RFGRatio of FCV CH4 emissions to GVsRatio of FCV RDA emissions to GVsRatio FCV R			Coal Input from "Well" Natural Gas Input from Well" Petroleum Input from "Well" Fossil Energy Input from "Well" WTP CO2 Emissions WTP CH4 Emissions WTP CH6 Emissions	176,371 Btu / 116000 Btu 2,489 Btu / 116000 Btu 203,535 Btu / 116000 Btu 13,599 g / 116000 Btu 26 g / 116000 Btu 0 g / 116000 Btu 14,283 116000 Btu		
Ratio of FCV Exhaust PM10 emissions to GV's fueled with CG & RFG       0%         Ratio of FCV Brake & Tire Wear PM10 emissions to GV's fueled with CG & RFG       100%         Ratio of FCV Exhaust PM2.5 emissions to GV's fueled with CG & RFG       0%         Ratio of FCV Brake & Tire Wear PM2.5 emissions to GV's fueled with CG & RFG       0%         Ratio of FCV CH-Variate & Tire Wear PM2.5 emissions to GV's fueled with CG & RFG       100%         Ratio of FCV CH-Variate & Tire Wear PM2.5 emissions to GV's fueled with CG & RFG       0%         Ratio of FCV CH-H emissions to GV's fueled with CG & RFG       0%         Ratio of FCV CH-H emissions to GV's       0%         Ratio of FCV NDE emissions to GV's       0%			Fuel Economy Ratio of FCV VOCs (emissions) to GVs fueled with CG & RFG Ratio of FCV VOCs (evaporative) to GVs fueled with CG & RFG Ratio of FCV CO emissions to GVs fueled with CG & RFG Ratio of FCV NOx emissions to GVs	0% 0% 0%		
emissions to GVs fueled with CG & RFG       100%         Ratio of FCV Exhaust PM2.5 emissions to GVs fueled with CG & RFG       0%         Ratio of FCV Brake & Tire Wear PM2.5 emissions to GVs fueled with CG & RFG       100%         Ratio of FCV CH4 emissions to GVs fueled with CG & RFG       0%         Ratio of FCV CH4 emissions to GVs       0%         fueled with CG & RFG       0%         Ratio of FCV CH4 emissions to GVs       0%         fueled with CG & RFG       0%         Ratio of FCV CH4 emissions to GVs       0%			Ratio of FCV Exhaust PM10 emissions to			
to GVs fueled with CG & RFG 0% Ratio of FCV Brake & Tire Wear PM2.5 emissions to GVs fueled with CG & RFG 100% Ratio of FCV CH4 emissions to GVs fueled with CG & RFG 0% Ratio of FCV N20 emissions to GVs			emissions to GVs fueled with CG & RFG	100%		
emissions to GVs fueled with CG & RFG 100% Rabio of FCV CH4 emissions to GVs fueled with CG & RFG 0% Rabio of FCV N2O emissions to GVs			to GVs fueled with CG & RFG	0%		
			emissions to GVs fueled with CG & RFG Ratio of FCV CH4 emissions to GVs fueled with CG & RFG			

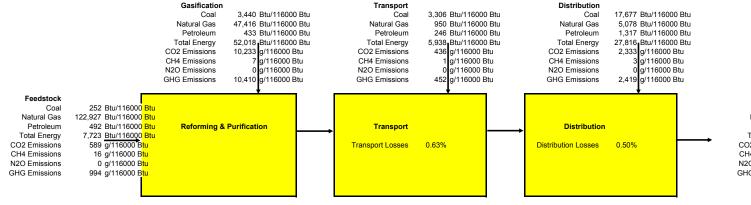
NG-Pipe Pathway Details R090304E 090821 v09.xls 211

Well-to-Wheel Results Coal Input from "Well" Natural Gas Input from "Well" Petroleum Input from "Well" Fossil Energy Input from "Well" WTW CO2 Emissions WTW CH4 Emissions WTW QBHG Emissions

Levelized Cost of Hydrogen (\$/mi)

549 Btu / mi 3,922 Btu / mi 55 Btu / mi 4,527 Btu / mi 302 g / mi 1 g / mi 0 g / mi 318 g / mi

\$0.0878 2005 \$/mi



Total to Del	iver 116000 Btu Fuel	Check
Coal	24,676	24,676
Natural Gas	176,371	176,371
Petroleum	2,489	2,489
Total Energy	93,495	93,495
CO2 Emissions	13,591	13,599
CH4 Emissions	26	26
N2O Emissions	0	0
GHG Emissions	14,276	14,283

# NG-Pipe Pathway Details R090304E 090821 v09.xls 212

Darama	tor		Value	l Inite	Bafaranaa	Commente
Parame	ler		Value	Units	Reference	Comments
Case Def	inition					
B	lase Year		2005		None	Default for NG-Pipe Pathway study
P	roduction	Technology	Natural Gas		None	Default for NG-Pipe Pathway study
Fi	orm of H2 elivery M	2 During Delivery	Gas Pipeline		None None	Default for NG-Pipe Pathway study Default for NG-Pipe Pathway study
		Station Size	1278	kaldov	James, B.D. (2008, May 23). Current (2005) Steam Methan Reformer (SMR) at Forecourt	Current forecourt H2A production from natural gas basis version 2.0.1; Input_Sheet_Template tab; Plant Output, cell C23
				kg/day	1500kg/day. Arlington, VA: Directed Technologies Inc.	
V	ehicle Ty	pe	passenger cars		None	Default for NG-Pipe Pathway study
V	'ehicles' F	uel Economy	45.0	mile / gge	Rousseau, A. & Wallner, T. (2008, October 7) Prospects on Fuel Efficiency Improvements for Hydrogen Powered Vehicles. Argonne National Laboroatory presentation, Chicago, IL. Retreiven from http://www.transportation.anl.gov/pdfs/HV/S30.pdf	Calculated from data in the presentation. The fuel economy for today's average mid-size vehicle was estimated by the Powertrain Simulation Analysis Toolkit V 6.2 SP1, Summer 2008 (PSAT - http://www.transportation.ani.gov/modeling_simulation/PSAT/index.html). 45 mile/gge is the estimated on-road fuel econom which was determined by multiplying the projected EPA lab-rated fuel economy of 62.5 mile/gge by 0.85.
Market De	efinitio	n				
с	ity Popula	ation	1,247,364		Elgowainy, A., Mintz, M. & Gillette, J. (2006) <i>Hydrogen Delivery Scenario Analysis Model</i> ( <i>HDSAM</i> ) V2.0. Argonne, IL: Argonne National Laboratory	HDSAM City Selection; Scenario tab; Indianapolis, IN, cell B9
м	larket per	netration	50%	(% vehicles in city)	U.S. Department of Energy & U.S. Department of Transportation. (2006, December/Hydrogen Posture Plan An Inegrated Research, Development and Demonstration Plan.	Basis for posture plan
N	lumber of	H2 vehicles in city	462 772	H2 vehicles / city	Elgowainy, A., Mintz, M. & Gillette, J. (2006) Hydrogen Delivery Scenario Analysis Model	Demand calculation by HDSAM version 2.02; Scenario tab; Number of H2 vehicles in city, cell F17
					(HDSAM) V2.0. Argonne, IL: Argonne National Laboratory Elgowainy, A., Mintz, M. & Gillette, J. (2006)Hydrogen Delivery Scenario Analysis Model	
м	liles drive	n per vehicle	12,000	mile / vehicle year	(HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	Key delivery input in HDSAM version 2.02; Scenario tab; Miles driven per year/ vehicle, cell C19
с	ity hydrog	pen use	344,451		Elgowainy, A., Mintz, M. & Gillette, J. (2006) Hydrogen Delivery Scenario Analysis Model	Demand calculation by HDSAM version 2.02; Scenario tab; City H2 daily use, cell F18
				kg / d	(HDSAM) V2.0. Argonne, IL: Argonne National Laboratory Elgowainy, A., Mintz, M. & Gillette, J. (2006)Hydrogen Delivery Scenario Analysis Model	
N	lumber of	H2 refueling stations in city	270		(HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	Demand calculation by HDSAM version 2.02; Scenario tab; Number of H2 fueling stations in city, cell F19
N	lumber of	H2 stations/Number of gasoline stations	41%		Elgowainy, A., Mintz, M. & Gillette, J. (2006) <i>Hydrogen Delivery Scenario Analysis Model</i> ( <i>HDSAM</i> ) V2.0. Argonne, IL: Argonne National Laboratory	Demand calculation by HDSAM version 2.02; Scenario tab; Number of H2 stations/Number of gasoline stations, cell F21
A	verage di	istance between stations (mi)	1.46	miles	Elgowainy, A., Mintz, M. & Gillette, J. (2006) <i>Hydrogen Delivery Scenario Analysis Model</i> (HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	Demand calculation by HDSAM version 2.02; Scenario tab; Average distance between stations, cell F22
Faadataa		Braansian & Tasaanat				
		very, Processing, & Transport				
Natural Gas	S					
N	IG recove	ry efficiency	97.2%		Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology, development, Use and Results. Argonne, IL: Argonne National Laboratory.	Table 4.11
N	C upod 8	lost during recovery	0.35%		Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1:	
N	IG used a	a lost during recovery	0.35%		Methodology, development, Use and Results. Argonne, IL: Argonne National Laboratory.	
N	IG proces	sing energy efficiency	97.2%		Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology, development, Use and Results. Argonne, IL: Argonne National Laboratory.	
N	IG used 8	k lost during processing	0.15%		Kirchgessner, D. A., Lott, R. A., Cowgill, R. M., Harrison, M. R. & Shires, T. M. (1996)Estimate of Methane Emissions from the U.S. Natural Gas Industry, EPA/Gas Research Institute paper. Retrieved from http://www.epa.gov/ttn/chiel/ap42/ch14/related/methane.pdf.	Volume lost from EPA/GRI paper by Kirchgessner er al (1996) and DOE/EIA-0573; future marginal increase is assumed t less than current average
N	IG used 8	k lost during transport	0.14	g / (MM Btu mil)	Kirchgessner, D. A., Lott, R. A., Cowgill, R. M., Harrison, M. R. & Shires, T. M. (1996/Estimate of Methane Emissions from the U.S. Natural Gas Industry, EPA/Gas Research Institute paper. Retrieved from http://www.epa.gov/ttn/chiel/ap42/ch14/related/methane.pdf.	GREET 97% is comparable to several other models: volume lost from EPA/GRI paper by Kirchgessner et al (1996) and DOE/EIA-0573; future marginal increase is assumed to be less than current average
	IG transp	ort distance	500	miles	Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology, development, Use and Results. Argonne, IL: Argonne National Laboratory.	
Electricity	Srid mix fo	production	US Mix		None	Default for NG-Pipe Pathway study
Ŭ		, production	OC MIX		Energy Information Administration. (2007, February)Annual Energy Outlook 2007 with	US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages calculate
		Biomass Fraction	1.2%		Projections to 2030. DOE/EIA-0383(2007). Washington, D.C. Retreived from	from total generation values reported with all renewables except biomass aggregated into the "Others (Carbon Neutral)"
			1.2%		www.eia.doe.gov/oiaf/archive/aeo07/index.htr Energy Information Administration. (2007, February)Annual Energy Outlook 2007 with	category US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages calculate
		Coal Fraction			Projections to 2030. DOE/EIA-0383(2007). Washington, D.C. Retreived from	from total generation values reported with all renewables except biomass aggregated into the "Others (Carbon Neutral)"
			51.7%		www.eia.doe.gov/oiaf/archive/aeo07/index.htr Energy Information Administration. (2007, February)Annual Energy Outlook 2007 with	category US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages calculate
		Natural Gas Fraction			Projections to 2030. DOE/EIA-0383(2007). Washington, D.C. Retreived from	from total generation values reported with all renewables except biomass aggregated into the "Others (Carbon Neutral)"
			15.7%		www.eia.doe.gov/oiaf/archive/aeo07/index.htr	category
		Nuclear Fraction			Energy Information Administration. (2007, February)Annual Energy Outlook 2007 with Projections to 2030. DOE/EIA-0383(2007). Washington, D.C. Retreived from	US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages calculate from total generation values reported with all renewables except biomass aggregated into the "Others (Carbon Neutral)"
	ľ		20.3%		www.eia.doe.gov/oiaf/archive/aeo07/index.htr	category
					Energy Information Administration. (2007, February)Annual Energy Outlook 2007 with	US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages calculate
		Residual Oil Fraction	2.9%		Projections to 2030. DOE/EIA-0383(2007). Washington, D.C. Retreived from www.eia.doe.gov/oiaf/archive/aeo07/index.htr	from total generation values reported with all renewables except biomass aggregated into the "Others (Carbon Neutral)" category
			2.370		Energy Information Administration. (2007, February)Annual Energy Outlook 2007 with	US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages calculate
	1	Others (Carbon Neutral)	0.00		Projections to 2030. DOE/EIA-0383(2007). Washington, D.C. Retreived from	from total generation values reported with all renewables except biomass aggregated into the "Others (Carbon Neutral)"
6	arid mix fo	or pipeline compressors	US Mix		www.eia.doe.gov/oiaf/archive/aeo07/index.htr None	category Default for NG-Pipe Pathway study
G	Grid mix fo	r compression at distribution	US Mix		None	Default for NG-Pipe Pathway study
H2 Produ	iction					
- 1					Rutkowski, M. (2008, Sept 22).Current (2005) Hydrogen from Natural Gas without CO2 Capture	
P		Facility Average Output		kg / facility d (after capacity factor is included)	and Sequestration . Golden, CO: National Renewable Energy Laboratoty.	Current central H2A production from NG basis version 2.1.1; Input Sheet Template tab; cell C23
		Corresponding capacity factor	90%		H2A Production model default	Current central H2A production from NG basis version 2.1.1; Input Sheet Template tab; cell C98; SMR Costs based on
		tal Investment	\$180,543,901			

Parameter		Value	Units	Reference	Comments
Parameter		value	Units	Reference	
Natural gas	feedstock consumption	4.50	normal m^3 / kg H2 produced	Rutkowski, M. (2008, Sept 22). Current (2005) Hydrogen from Natural Gas without CO2 Capture and Sequestration. Golden, CO: National Renewable Energy Laboratoty.	scale Contock-rimitips (Ecosis) gasmer, conventional gas cooling, commercian sinu conversion and acto gas bearing, commercial sultivinci ad technology, and commercial pressure swing adsorption (PSA). The EGas gasifier is the gasifier of choice for this study since it has been operated on both bituminous and sub-bituminous coals." Uses Aspen Plus® Model, Haldor Topsoe commercial catalyst spec., UOP commercial PSA design spec.
Natural Gas	s feedstock cost	\$ 0.243	2005\$ / Nm^3	Industrial natural gas price from AEO 2005 "High A" case for startup year (2005). Escalated fron 2003 dollars to 2005 dollars. File downloaded from http://www.eia.doe.gov/oiaf/aeo/index.html (that and the provide of	AEO 2005 High A Case - Industrial price; Escalated from 2003 dollars to 2005 dollars. File downloaded from http://www.eia.doe.gov/oiaf/aeo/index.html (file name aeo_hw-3.xis)
Natural Gas	s LHV	34,714	Btu / normal m^3 - review units	Hydrogen Analysis Resource Center. (2008, September 5)Lower and Higher Heating Values of Hydrogen and Fuels. Retrieved from http://hydrogen.pnl.gov/coccon/mort/hydrogen/article/401	LHV of Natural Gas; 983 Btu/ft3
Natural gas	utility consumption	0.00	normal m^3 / kg H2 produced	Rutkowski, M. (2008, Sept 22). Current (2005) Hydrogen from Natural Gas without CO2 Capture and Sequestration. Golden, CO: National Renewable Energy Laboratoty.	
Electricity fe	eedstock consumption	0.00	kWh / kg H2	Rutkowski, M. (2008, Sept 22).Current (2005) Hydrogen from Natural Gas without CO2 Capture and Sequestration. Golden, CO: National Renewable Energy Laboratoty.	
Electricity u	tility consumption (both production and compression)	0.57	kWh / kg H2	Colculation	Sum of production and CSD consumption of "utility" electricity (does not include "feedstock" electricity)
Electricity u	tility consumption (production only)	0.57	kWh / kg H2	Rutkowski, M. (2008, Sept 22). Current (2005) Hydrogen from Natural Gas without CO2 Capture	Current central H2A production from NG basis version 2.1.1; Input Sheet Template tab; cell E69
Electricity U	Itility Price	0.0555	2005 \$/kWh	Industrial electricity price from AEO 2005 "High A" case for startup year (2005). Escalated from 2003 dollars to 2005 dollars. File downloaded from http://www.eia.doe.gov/oiaf/aeo/index.html (f	A AEO 2005 High A Case - Industrial price; Escalated from 2003 dollars to 2005 dollars. File downloaded from http://www.eia.doe.gov/oiaf/aeolindex.html (file name aeo hw-3.xls)
Process Wa	ater Consumption	3.36	gal / kg H2	Rutkowski, M. (2008, Sept 22).Current (2005) Hydrogen from Natural Gas without CO2 Capture and Sequestration, Colden, CO: National Renewable Energy Laboratory	Current central H2A production from NG basis version 2.1.1; Input Sheet Template tab; cell D128
		1.50		Rutkowski, M. (2008, Sept 22). Current (2005) Hydrogen from Natural Gas without CO2 Capture	Current central H2A production from NG basis version 2.1.1; Input Sheet Template tab; cell D130
	sumption for Cooling		gal / kg H2	and Sequestration . Golden, CO: National Renewable Energy Laboratoty.	Content Central (12-5 production noni inco pasis version 2.1.1, input Sneet Template (ab), Cell D 150
	o-product production product production		kWh / kg H2 kg / kg H2	N/A N/A	
	roduct production		kg / kg H2	N/A	
Total Annua	al Fixed Operating Costs	<b>\$</b> 6,916,975	2005\$ / yr	Rutkowski, M. (2008, Sept 22).Current (2005) Hydrogen from Natural Gas without CO2 Capture and Sequestration. Golden, CO: National Renewable Energy Laboratoty.	Current central H2A production from NG basis version 2.1.1; Input Sheet Template tab; cell C114
	al Variable Operating Costs	\$144,393,400		Rutkowski, M. (2008, Sept 22). Current (2005) Hydrogen from Natural Gas without CO2 Capture and Sequestration. Golden, CO: National Renewable Energy Laboratoty.	Current central H2A production from NG basis version 2.1.1; Input Sheet Template tab; cell C153
Total Annua Production	al Operating Costs energy efficiency (does not include electricity for forecourt compressio	\$151,310,375 71,9%	2005\$ / yr	None Calculated from H2A values	Addtion of Annual Total Fixed Operating Costs and Total Annual Variable Operating Costs Calculated from H2A values
	pcess fuel - biomass	0.0%		Calculated from H2A values	Calculated from H2A values
	pcess fuel - coal	0.0%		Calculated from H2A values	Calculated from H2A values
Share of pro	pocess fuel - natural gas pocess fuel - ethanol	4.4%		Calculated from H2A values Calculated from H2A values	Calculated from H2A values Calculated from H2A values
Share of pro	ocess fuel - etnanoi	0.0%		Calculated from H2A values	Calculated from H2A values
Hydrogen o	utlet pressure (before CSD)	Not Available	psi	None	
Hydrogen q	uality before transport	99.6%	% H2	Rutkowski, M. (2008, Sept 22). Current (2005) Hydrogen from Natural Gas without CO2 Capture and Sequestration. Golden, CO: National Renewable Energy Laboratoty.	discussed in the process description
Financial Parameters After-tax Re	al IRR	10%		James, B.D. (2008, May 23). Current (2005) Steam Methan Reformer (SMR) at Forecourt	Current central H2A production from SMR basis version 2.0.1; Input_Sheet_Template tab; After-tax Real IRR, cell C47
Plant Life		40		1500kg/day. Arlington, VA: Directed Technologies Inc. James, B.D. (2008, May 23). Current (2005) Steam Methan Reformer (SMR) at Forecourt	Current central H2A production from SMR basis version 2.0.1; Input_Sheet_Template tab; Plant life, cell C34
Federal Tax	< Rate	35.0%	years	1500kg/day. Arlington, VA: Directed Technologies Inc. James, B.D. (2008, May 23). Current (2005) Stearn Methan Reformer (SMR) at Forecourt 1500kg/day. Arlington, VA: Directed Technologies Inc.	Current central H2A production from SMR basis version 2.0.1; Input_Sheet_Template tab; Federal taxes, cell C49
State Tax R	tate	6.0%		James, B.J. 2006, May 23). Current (2005) Steam Methan Reformer (SMR) at Forecourt 1500kg/day. Arlington, VA: Directed Technologies Inc.	Current central H2A production from SMR basis version 2.0.1; Input_Sheet_Template tab; State taxes, cell C48
Total Tax R	ate	38.9%		James, B.D. (2008, May 23). Current (2005) Steam Methan Reformer (SMR) at Forecourt 1500kg/day. Artington, VA: Directed Technologies Inc.	Current central H2A production from SMR basis version 2.0.1; Input_Sheet_Template tab; Total tax Rate, cell C50
Frection Eq	uity	100%		James, B.D. (2008, May 23). Current (2005) Steam Methan Reformer (SMR) at Forecourt 1500kg/day. Artington, VA: Directed Technologies Inc.	Current central H2A production from SMR basis version 2.0.1; Input_Sheet_Template tab; Equity Financing, cell C38
Transport, Delive	ery, and Storage Energy Requirements				
Pipeline Delivery	•				
	drogen Flowrate (Entering System)	348,364	kg/hr	Elgowainy, A., Mintz, M. & Gillette, J. (2006) <i>Hydrogen Delivery Scenario Analysis Model</i> ( <i>HDSAM</i> ) V2.0. Argonne, IL: Argonne National Laboratory	HDSAM calculation based on input parameters: city, market penetration, dispensing rate (PEAK FLOW RATE THRU TRANSMISIIION SYSTEM=CITY PEAK DEMAND/TRANSMISIION PIPELINE MASS EFFICIENCY/REF.STATION MASS EFFICIENCY)
Average Hy	rdrogen Flowrate (Distributed)	344,451	kg/hr	Elgowainy, A., Mintz, M. & Gillette, J. (2006) <i>Hydrogen Delivery Scenario Analysis Model</i> ( <i>HDSAM</i> ) V2.0. Argonne, IL: Argonne National Laboratory	MASS EFFICIENCY HDSAM calculation based on input parameters: city, market penetration, dispensing rate (Ave. daily use=CITY DAILY USE/TOTAL PIPELINE MASS EFFICIENCY/REF.STATION MASS EFFICIENCY)
Summer Su	rrge: % above the System Average Daily Demand	10%	% above Average Daily Demand	Nexant, Inc. et al. (2008, May) H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results . Interim Report Section 2.1.9. DE-FG36- 05GO15032.	Nexant Report - Section 2.1.9
Friday Peak	χ.	8%	% above Average Daily Demand	Nexant, Inc. et al. (2008, May) H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results . Interim Report Section 2.1.9. DE-FG36- 05GO15032.	Nexant Report - Section 2.1.9
Peak Hydro	gen Flowrate	381,192	kg/hr	Elgowainy, A., Mintz, M. & Gillette, J. (2006) <i>Hydrogen Delivery Scenario Analysis Model</i> ( <i>HDSAM</i> ) V2.0. Argonne, IL: Argonne National Laboratory	HDSAM calculation based on input parameters: city, market penetration, dispensing rate (PEAK FLOWRATE THRU DISTRIBUTION SYSTEM=CITY PEAK DEMAND/DISTRIBUTION PIPELINE MASS EFFICIENCY/REF.STATION MASS EFFICIENCY)
Total Capita	al Investment for Compressors	\$27,199,794		Elgowainy, A., Mintz, M. & Gillette, J. (2006) Hydrogen Delivery Scenario Analysis Model (HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	HDSAM calculations, data from disscussions with Bechtel and Air Liquide (see ref. in Nexant report - Section 2.2.5)
Hydrogen L	osses from Compressors	0.50%		Nexant, Inc. et al. (2008, May) H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results . Interim Report Section 2.2.14. DE-FG36- 05GO15032.	Table 2.26
Compresso	r Electricity Demand	70,343,075	kWh / year	Nexant, Inc. et al. (2008, May).H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results . Interim Report Section 2.2.5. DE-FG36- 05GO15032.	HDSAM calculations - data from Nexant recommendations (based on vendor data from Neuman&Esser, Burckhardt Compression, Ariel Compressors, Dresser-Rand - see Nexant report - Section 2.2.5)
Compresso	r Electricity Demand	0.5591	kWh / kg H2	Nexant, Inc. et al. (2008, May) H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results . Interim Report Section 2.2.5. DE-FG36- 05GO15032.	HDSAM calculations - data from Nexant recommendations (based on vendor data from Neuman&Esser, Burckhardt Compression, Ariel Compressors, Dresser-Rand - see Nexant report - Section 2.2.5)

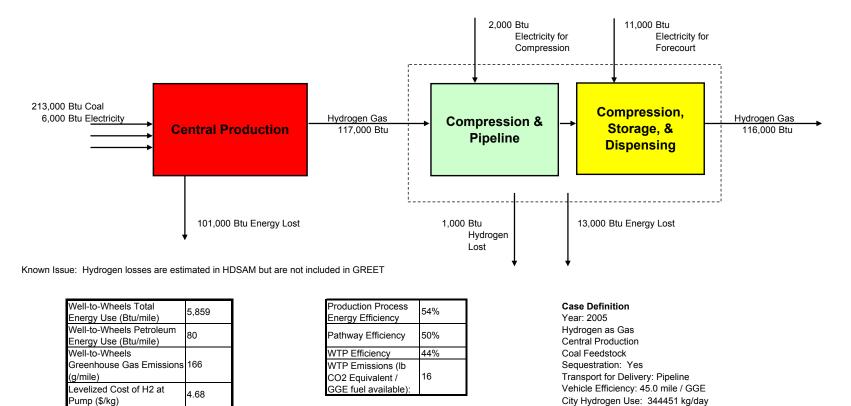
Parameter		Value	Units	Reference	Comments
Compresso	or Electricity Cost	\$0.056	2005\$ / kWh	Energy Information Administration. (2005, January)Annual Energy Outlook 2005 with Projections to 2025. DOE/EIA-0383(2005). Washington, D.C. Retreived from http://www.eia.doe.gov/oiaf/archive/aeo05/index.ht	EIA AEO 2005 and 2007
Total Capit	al Investment for Pipeline System	\$377,283,372		Nexant, Inc. et al. (2008, May).H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.2.2. DE-FG36- 05G015032.	HDSAM calculations based on data from GTI, Bechtel, Air Liquide, UC Davis (Nexant Report -Section 2.2.2)
Hydrogen I	Losses from Pipelines	0.10%		Nexant, Inc. et al. (2008, May) H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results . Interim Report Section 2.2.14. DE-FG36- 05G015032.	Calculated based upon natural gas pipelines; Nexant report - Section 2.2.14
Number of	transmission pipelines	1		Elgowainy, A., Mintz, M. & Gillette, J. (2006) <i>Hydrogen Delivery Scenario Analysis Model</i> ( <i>HDSAM</i> ) V2.0. Argonne, IL: Argonne National Laboratory	Default in HDSAM
Transmissi	on pipeline diameter	11.00	in	Elgowainy, A., Mintz, M. & Gillette, J. (2006) Hydrogen Delivery Scenario Analysis Model (HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	HDSAM Calculation: Panhandle B equation (Gas Processors Supplier Association, Engineering Data Book, 11th Edition, 1998, http://gpsa.gasprocessors.com)
Transmissi	on pipeline inlet pressure	999	psi	Nexant, Inc. et al. (2008, May) H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.1.6. DE-FG36- 05G015032.	Recommendations from Nexant in conjuction with Air Liquide, GTI, Chevron, TIAX, ANL, PNNL and NREL - see Nexant Report - Section 2.1.6)
Transmissi	on pipeline outlet pressure	705	psi	Nexant, Inc. et al. (2008, May).H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.1.6. DE-FG36- 05G015032.	Recommendations from Nexant in conjuction with Air Liquide, GTI, Chevron, TIAX, ANL, PNNL and NREL - see Nexant Report - Section 2.1.6)
Transmissi	on pipeline temperature	25	с	Nexant, Inc. et al. (2008, May).H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.1.6. DE-FG36- 05G015032.	Recommendations from Nexant in conjuction with Air Liquide, GTI, Chevron, TIAX, ANL, PNNL and NREL - see Nexant Report - Section 2.1.6)
Transmissi	on pipeline length	62	miles	Elgowainy, A., Mintz, M. & Gillette, J. (2006) Hydrogen Delivery Scenario Analysis Model (HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	Based on input parameter: city
Number of	trunk pipelines	4		Nexant, Inc. et al. (2008, May) H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results . DE-FG38-05G015032.	HOSAM calculations based on input data and HDSAM distribution model - not documented; "The pipeline model includes u to four trunk lines within a given metropolitan area with service lines extending from the trunk lines to the refueling stations. The model iterates on the number and location of trunk lines within a given metropolitan area until an optimum distribution configuration is obtained at a minimum cost." Nexant (2006) sect 2.4.3, 2.1.6, 2.2.2
Trunk #1 p	ipeline diameter	7.25	in	Nexant (2008) Section 2.4.3, 2.1.6, 2.2.2; H2A Delivery Components User Guide (2006) sect 5.15.4	HDSAM Calculation: Panhandle B equation (Gas Processors Supplier Association, Engineering Data Book, 11th Edition, 1998, http://gpsa.gasprocessors.com)
Trunk #1 p	peline inlet pressure	603	psi	Nexant, Inc. et al. (2008, May).H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results . Interim Report Section 2.1.6. DE-FG36- 05G015032.	Recommendations from Nexant in conjuction with Air Liquide, GTI, Chevron, TIAX, ANL, PNNL and NREL - see Nexant Report - Section 2.1.6)
Trunk #1 p	peline outlet pressure	397	psi	Nexant, Inc. et al. (2008, May) H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results . Interim Report Section 2.1.6. DE-FG36- 05G015032.	Recommendations from Nexant in conjuction with Air Liquide, GTI, Chevron, TIAX, ANL, PNNL and NREL - see Nexant Report - Section 2.1.6)
Trunk #1 p	peline temperature	25	с	Nexant, Inc. et al. (2008, May) H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results . Interim Report Section 2.1.6. DE-FG36- 05G015032.	Recommendations from Nexant in conjuction with Air Liquide, GTI, Chevron, TIAX, ANL, PNNL and NREL - see Nexant Report - Section 2.1.6)
Trunk #1 p	peline length	17	miles	Elgowainy, A., Mintz, M. & Gillette, J. (2006) Hydrogen Delivery Scenario Analysis Model (HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	HDSAM calculations based on input data and HDSAM distribution model (discussions with Pacific Gas & Electric Company, San Francisco)
Trunk #2 p	peline diameter	10.25	in	Nexant (2008) Section 2.4.3, 2.1.6, 2.2.2; H2A Delivery Components User Guide (2006) sect 5.15.4	HDSAM Calculation: Panhandle B equation (Gas Processors Supplier Association, Engineering Data Book, 11th Edition, 1998, http://qpsa.qasprocessors.com)
Trunk #2 p	peline inlet pressure	588	psi	Nexant, Inc. et al. (2008, May) H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results . Interim Report Section 2.1.6. DE-FG36- 05G015032.	Recommendations from Nexant in conjuction with Air Liquide, GTI, Chevron, TIAX, ANL, PNNL and NREL - see Nexant Report - Section 2.1.6)
Trunk #2 p	peline outlet pressure	397	psi	Nexant, Inc. et al. (2008, May).H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.1.6. DE-FG36- 05G015032.	Recommendations from Nexant in conjuction with Air Liquide, GTI, Chevron, TIAX, ANL, PNNL and NREL - see Nexant Report - Section 2.1.6)
Trunk #2 p	ipeline temperature	25	с	Nexant, Inc. et al. (2008, May) H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results . Interim Report Section 2.1.6. DE-FG36- 05G015032.	Recommendations from Nexant in conjuction with Air Liquide, GTI, Chevron, TIAX, ANL, PNNL and NREL - see Nexant Report - Section 2.1.6)
	peline length	40	miles	Nexant (2008) Section 2.4.3, 2.1.6, 2.2.2 Nexant (2008) Section 2.4.3, 2.1.6, 2.2.2; H2A Delivery Components User Guide (2006) sect	HDSAM calculations based on input data and HDSAM distribution model - not documented HDSAM Calculation: Panhandle B equation (Gas Processors Supplier Association, Engineering Data Book, 11th Edition,
Trunk #3 p	peline diameter	12.25	in	Nexant, Inc. et al. (2008, May) H2A Hydrogen Delivery Infrastructure Analysis Models and	1998, http://gpsa.gasprocessors.com)
Trunk #3 p	peline inlet pressure	573	psi	Conventional Pathway Options Analysis Results . Interim Report Section 2.1.6. DE-FG36- 05GO15032.	Recommendations from Nexant in conjuction with Air Liquide, GTI, Chevron, TIAX, ANL, PNNL and NREL - see Nexant Report - Section 2.1.6)
Trunk #3 p	peline outlet pressure	397	psi	Nexant, Inc. et al. (2008, May).H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.1.6. DE-FG36- 05G015032.	Recommendations from Nexant in conjuction with Air Liquide, GTI, Chevron, TIAX, ANL, PNNL and NREL - see Nexant Report - Section 2.1.6)
	peline temperature	25	с	Nexant, Inc. et al. (2008, May).H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.1.6. DE-FG36- 05G015032.	Recommendations from Nexant in conjuction with Air Liquide, GTI, Chevron, TIAX, ANL, PNNL and NREL - see Nexant Report-Section 2.1.6)
	peline length	65	miles	Nexant (2008) Section 2.4.3, 2.1.6, 2.2.2 Nexant (2008) Section 2.4.3, 2.1.6, 2.2.2; H2A Delivery Components User Guide (2006) sect	HDSAM calculations based on input data and HDSAM distribution model - not documented HDSAM Calculation: Panhandle B equation (Gas Processors Supplier Association, Engineering Data Book, 11th Edition,
Trunk #4 p	peline diameter	10.75	in	5.15.4	1998, http://gpsa.gasprocessors.com)
Trunk #4 p	peline inlet pressure	558	psi	Nexant, Inc. et al. (2008, May).H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.1.6. DE-FG36- 05G015032.	Recommendations from Nexant in conjuction with Air Liquide, GTI, Chevron, TIAX, ANL, PNNL and NREL - see Nexant Report - Section 2.1.6)
Trunk #4 p	peline outlet pressure	397	psi	Nexant, Inc. et al. (2008, May).H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.1.6. DE-FG36- 05G015032.	Recommendations from Nexant in conjuction with Air Liquide, GTI, Chevron, TIAX, ANL, PNNL and NREL - see Nexant Report - Section 2.1.6)
Trunk #4 p	peline temperature	25	с	Nexant, Inc. et al. (2008, May) H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.1.6. DE-FG36- 05G015032.	Recommendations from Nexant in conjuction with Air Liquide, GTI, Chevron, TIAX, ANL, PNNL and NREL - see Nexant Report - Section 2.1.6)
Trunk #4 p	peline length		miles	Nexant (2008) Section 2.4.3, 2.1.6, 2.2.2	HDSAM calculations based on input data and HDSAM distribution model - not documented
Number of	service pipelines	270		Elgowainy, A., Mintz, M. & Gillette, J. (2006) <i>Hydrogen Delivery Scenario Analysis Model</i> ( <i>HDSAM</i> ) V2.0. Argonne, IL: Argonne National Laboratory	HDSAM calculations based on input data and HDSAM distribution model (discussions with Pacific Gas & Electric Compan San Francisco)
Service pip	eline diameter	1	in	Elgowainy, A., Mintz, M. & Gillette, J. (2006) <i>Hydrogen Delivery Scenario Analysis Model</i> (HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	HDSAM Calculation: Panhandle B equation (Gas Processors Supplier Association, Engineering Data Book, 11th Edition, 1998, http://gpsa.gasprocessors.com)
Service pip	eline inlet pressure	382	psi	Nexant, Inc. et al. (2008, May) H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results . Interim Report Section 2.1.6. DE-FG36- 05G015032.	Recommendations from Nexant in conjuction with Air Liquide, GTI, Chevron, TIAX, ANL, PNNL and NREL - see Nexant Report - Section 2.1.6)

Param	eter	Value	Units	Reference	Comments
	Service pipeline outlet pressure	294	psi	Nexant, Inc. et al. (2008, May),H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.1.6. DE-FG36- 05G015032.	Recommendations from Nexant in conjuction with Air Liquide, GTI, Chevron, TIAX, ANL, PNNL and NREL - see Nexant Report - Section 2.1.6)
	Service pipeline temperature	25	с	Nexant, Inc. et al. (2008, May) H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results . Interim Report Section 2.1.6. DE-FG36- 05GO15032.	Recommendations from Nexant in conjuction with Air Liquide, GTI, Chevron, TIAX, ANL, PNNL and NREL - see Nexant Report - Section 2.1.6)
	Service pipeline length	1.1	miles	Elgowainy, A., Mintz, M. & Gillette, J. (2006) <i>Hydrogen Delivery Scenario Analysis Model</i> ( <i>HDSAM</i> ) V2.0. Argonne, IL: Argonne National Laboratory	HDSAM calculations based on input data and HDSAM distribution model (discussions with Pacific Gas & Electric Company San Francisco)
	Pipeline Geologic Storage Total Capital Investment	\$36,988,376		Nexant, Inc. et al. (2008, May) H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results . Interim Report Section 2.2.12. DE-FG36- 05G015032.	HDSAM calculations (cost data from ConocoPhilips and Saltville natural gas storage facility in Virginiase Nexant Report- Section 2.2.12)
	Hydrogen Losses from Geologic Storage	0.02%		H2A Components Model User Guide, Section 6.5; Duke Energy, 2005; US EPA, 2003; Natural Resources Canada	
	Geologic Storage Capacity	41,864,765	m^3	H2A Components Model User Guide, Section 6.5; Duke Energy, 2005; US EPA, 2003; Natural Resources Canada	
	Geologic Storage Design Capacity	3,762,787	kg H2	H2A Components Model User Guide, Section 6.5; Duke Energy, 2005; US EPA, 2003; Natural Resources Canada	
	Geologic Storage Electricity Demand	961,465	kWh / year	Nexant (2008) Section 2.2.12, 2.2.5	HDSAM calculations (cost data from ConocoPhilips and Saltville natural gas storage facility in Virginiase Nexant Report- Sections 2.2.12 and 2.2.5)
	Geologic Storage Electricity Demand	0.0076	kWh / kg H2	Nexant (2008) Section 2.2.12, 2.2.5	HDSAM calculations (cost data from ConocoPhilips and Saltville natural gas storage facility in Virginiase Nexant Report- Sections 2.2.12 and 2.2.5)
	Geologic Storage Electricity Cost	\$0.052	2005\$ / kWh	Energy Information Administration. (2005, January)Annual Energy Outlook 2005 with Projections to 2025. DOE/EIA-0383(2005). Washington, D.C. Retreived from http://www.sia.doe.gov/oiafarchive/aeo05/index.ht	EIA AEO 2005
Distribu	ution Station				
Gaseous	Receiving/Distributing Stations				
	Hydrogen Dispensed at Forecourt Station	465,647	kg / station year	Elgowainy, A., Mintz, M. & Gillette, J. (2006) <i>Hydrogen Delivery Scenario Analysis Model</i> (HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	HDSAM version 2.02 calculation, Refueling Station - Gaseous H2 tab, cell B138
	Electricity Required by Forecourt Station	1,416,755	kWh / station year	(HDSAM) V2.0. Auguite, IL: Auguite Valuational Laboratory Elgowainy, A., Mintz, M. & Gillette, J. (2006) Hydrogen Delivery Scenario Analysis Model (HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	HDSAM version 2.02 calculation, Refueling Station - Gaseous H2 tab, cell B263
	Number of Compressor Stages	4	Stages in compressor	Elgowainy A., Mintz, M. & Gillette, J. (2006)Hydrogen Delivery Scenario Analysis Model (HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	HDSAM version 2.02 default, Refueling Station - Gaseous H2 tab, cell B67
	Compressor Isentropic Efficiency	65%	Stages in compressor	Elgowainy, A., Mintz, M. & Gillette, J. (2006) Hydrogen Delivery Scenario Analysis Model	HDSAM version 2.02 default, Refueling Station - Gaseous H2 tab, cell B69
	Design Capacity	1,516	kg H2 / day	(HDSAM) V2.0. Argonne, IL: Argonne National Laboratory Nexant, Inc. et al. (2008, May)/H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results . Interim Report Section 2.1.4. DE-FG36- 05G015032	HDSAM version 2.02 calculation based on Chevron fueling profiles (Nexant Report - Section 2.1.4): = adjusted disp. Rater(1+summer surge)'(1+Friday surge), Refueling Station - Gaseous H2 tab, cell B32
	Operating Capacity	1,278	kg H2 / day	Elgowainy, A., Mintz, M. & Gillette, J. (2006) <i>Hydrogen Delivery Scenario Analysis Model</i> ( <i>HDSAM</i> ) V2.0. Argonne, IL: Argonne National Laboratory	Adjusted dispensing rate=city use/number of stations/utilization factor, Refueling Station - Gaseous H2 tab, cell B33
	Capacity Factor	84%			calculation
	Site storage (Low Pressure)	470	kg H2	Nexant, Inc. et al. (2008, May).H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results . Interim Report Section 2.2.3. DE-FG36- 05GO15032.	HDSAM version 2.02 calculation (Nexant Report - Section 2.2.3), Refueling Station - Gaseous H2 tab, cell B123
	Site storage (Cascade)	582	kg H2	Nexant, Inc. et al. (2008, May).H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results . Interim Report Section 2.3.2.4 DE-FG36- 05G015032.	HDSAM calculations (Nexant Report - Section 2.3.2.4), Refueling Station - Gaseous H2 tab, cell B122
	Site storage	69%	% of design H2 distribution		calculation
	Dispensing Pressure	6,250	psi	Nexant, Inc. et al. (2008, May),H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results . Interim Report Section 2.2.3. DE-FG36- 05G015032.	HDSAM version 2.02 default (see Nexant Report-Section 2.3.2), Refueling Station - Gaseous H2 tab, cell B58
	Hydrogen Losses due to leaks	0.50%	3	Elgowainy, A., Mintz, M. & Gillette, J. (2006) <i>Hydrogen Delivery Scenario Analysis Model</i> ( <i>HDSAM</i> ) V2.0. Argonne, IL: Argonne National Laboratory	HDSAM version 2.02 default, Refueling Station - Gaseous H2 tab, cell B79
	Electrical Voltage Supply Requirement	480	Volts	Nexant, Inc. et al. (2008, May).H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results . Interim Report Section 2.2.5. DE-FG36- 05G015032.	HDSAM version 2.02 calculation (see Nexant Report - Sections 2.2.5 and 2.2.6), Refueling Station - Gaseous H2 tab, cell B137
	Distribution System total capital investment	\$3,117,483	2005\$ / station	Nexant, Inc. et al. (2008, May) H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results . Interim Report Section 2.2.5.2. DE-FG36- 05GO15032.	Nexant Report - Section 2.2.5.2
	Distribution System electricity cost	\$115,508	2005\$ / station yr	Elgowainy, A., Mintz, M. & Gillette, J. (2006) <i>Hydrogen Delivery Scenario Analysis Model</i> ( <i>HDSAM</i> ) V2.0. Argonne, IL: Argonne National Laboratory	HDSAM version 2.02 calculation, Refueling Station - Gaseous H2 tab, cell B267
	Distribution Labor Required	3,951	hr / station yr	Elgowainy, A., Mintz, M. & Gillette, J. (2006) Hydrogen Delivery Scenario Analysis Model (HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	HDSAM version 2.02 calculation, Refueling Station - Gaseous H2 tab, cell B259
	Distribution System labor cost	\$39,513	2005\$ / station yr	Nexant, Inc. et al. (2008, May) H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results . Interim Report Section 2.2.1.3. DE-FG36- 05G015032.	Bureau of Labor and Statistics (Nexant Report - Section 2.2.1.3), Refueling Station - Gaseous H2 tab, cell B260
	Distribution System total O&M cost	\$298,898	2005\$ / station yr	Description 15022. Nexant, Inc. et al. (2008, May).H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results . Interim Report Section 2.2.1.2. DE-FG36- 05GO1532.	HDSAM version 2.02 calculations (Nexant Report - Section 2.2.1.2), Refueling Station - Gaseous H2 tab, cell B283
Other A	ssumptions for WTW Calculations		Looop, sullion y	00001002.	
Share of P	RFG in Total Gasoline Use	100%		U.S. Department of Energy & U.S. Department of Transportation. (2006, December)r/ydrogen Posture Plan An Inegrated Research, Development and Demonstration Plan.	Basis for posture plan
	xygenate in RFG	None		U.S. Department of Energy & U.S. Department of Transportation. (2006, December/Hydrogen Posture Plan An Inegrated Research, Development and Demonstration Plan.	Basis for posture plan
		0%		U.S. Department of Energy & U.S. Department of Transportation. (2006, December)Hydrogen	Basis for posture plan
	nt in RFG CV VOCs (emissions) to GVs fueled with CG & RFG	0%	wt %	Posture Plan An Inegrated Research, Development and Demonstration Plan. Wang, M.Q. (1999, August), GREET 1.5 - Transportation Fuel-Cycle Model Volume 1:	GREET default, Table 4.45 FCV: H2
	CV VOCs (evaporative) to GVs fueled with CG & RFG	0%		Methodology, development, Use and Results. Argonne, IL: Argonne National Laboratory. Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1:	GREET default Table 4 45 ECV: H2
	CV VOCs (evaporative) to GVs fueled with CG & RFG	0%		Methodology, development, Use and Results. Argonne, IL: Argonne National Laboratory. Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1:	GREET default, Table 4.45 FCV: H2 GREET default, Table 4.45 FCV: H2
				Methodology, development, Use and Results. Argonne, IL: Argonne National Laboratory. Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1:	
Ratio of F	CV NOx emissions to GVs fueled with CG & RFG	0%		Methodology, development, Use and Results. Argonne, IL: Argonne National Laboratory.	GREET default, Table 4.45 FCV: H2

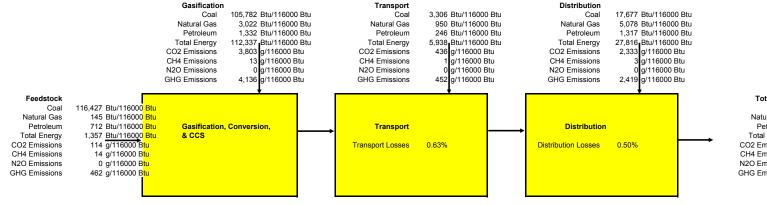
arameter	Value	Units	Reference	Comments
		Onits	Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1:	
tio of FCV Exhaust PM10 emissions to GVs fueled with CG & RFG	0%		Methodology, development, Use and Results. Argonne, IL: Argonne National Laboratory.	GREET default, Table 4.45 FCV: H2
atio of FCV Brake & Tire Wear PM10 emissions to GVs fueled with CG & RFG	100%		Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1:	
atio of FCV Brake & Tire wear PM10 emissions to GVs fueled with CG & RFG	100%		Methodology, development, Use and Results. Argonne, IL: Argonne National Laboratory.	GREET default, page 197: vehicles within the same weight class have similar tire and brake wear emissions
			Wang, M.Q. (2008, September 5). The Greenhouse Gases, Regualted Emissions, and Energy	
atio of FCV Exhaust PM2.5 emissions to GVs fueled with CG & RFG	0%		Use in Transportation (GREET) Model, Version 1.8b. Argonne, IL: Argonne National Laborator	ry. GREET default:well-known fuel cell emissions (no PM2.5)
			Wang, M.Q. (2008, September 5). The Greenhouse Gases, Requalted Emissions, and Energy	
atio of FCV Brake & Tire Wear PM2.5 emissions to GVs fueled with CG & RFG	100%		Use in Transportation (GREET) Model, Version 1.8b. Argonne, IL: Argonne National Laborator	ry. GREET default:reasonable to assume FCV has same driving pattern as GV
atio of FCV CH4 emissions to GVs fueled with CG & RFG	0%		Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1:	GREET default. Table 4.45 FCV: H2
tito of 1 GV GTH emissions to GVs fueled Will GG & RFG	0%		Methodology, development, Use and Results. Argonne, IL: Argonne National Laboratory.	OKEET deladit, Table 4.431 OV. TZ
atio of FCV N2O emissions to GVs fueled with CG & RFG	0%		Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1:	GREET default, Table 4.45 FCV: H2
			Methodology, development, Use and Results. Argonne, IL: Argonne National Laboratory.	
arginal Electricity Generation Mix for Transportation Use	US Mix		U.S. Department of Energy & U.S. Department of Transportation. (2006, December)Hydrogen Posture Plan An Inegrated Research. Development and Demonstration Plan.	Basis for posture plan
			Posture Plan An Inegrated Research, Development and Demonstration Plan.	
esults				
velized Cost	ea.or		Ruth, M. et al. (2009, March). Hydrogen Macro System Model User Guide. NREL/TP-6A1-447	99
Velized Cost	\$3.95	\$ / kg	Golden, CO: National Renewable Energy Laboratory.	MSM Results
	540		Ruth, M. et al. (2009, March). Hydrogen Macro System Model User Guide. NREL/TP-6A1-447	
TW Coal Input	010	Btu / mile	Golden, CO: National Renewable Energy Laboratory.	MSM Results
	3 922		Ruth, M. et al. (2009, March). Hydrogen Macro System Model User Guide. NREL/TP-6A1-447	
FW Natural Gas Input		Btu / mile	Golden, CO: National Renewable Energy Laboratory.	MSM Results
THE	55	Btu / mile	Ruth, M. et al. (2009, March). Hydrogen Macro System Model User Guide. NREL/TP-6A1-447	99 MSM Results
TW Petroleum Input			Golden, CO: National Renewable Energy Laboratory. Ruth, M. et al. (2009, March). Hydrogen Macro System Model User Guide. NREL/TP-6A1-447	
TW Fossil Energy Input	4,527	Btu / mile	Golden, CO: National Renewable Energy Laboratory.	MSM Results
rw rossii chorgy input		Did / Tillio	Ruth, M. et al. (2009, March). Hydrogen Macro System Model User Guide. NREL/TP-6A1-447	
TW Total Energy Input	4,659	Btu / mile	Golden, CO: National Renewable Energy Laboratory.	MSM Results
w rotar chorgy input		bid / mile	Ruth, M. et al. (2009, March). Hydrogen Macro System Model User Guide. NREL/TP-6A1-447	
TW CO2 Emissions	302	a / mile	Golden, CO: National Renewable Energy Laboratory.	MSM Results
		<b>v</b>	Ruth, M. et al. (2009, March). Hydrogen Macro System Model User Guide. NREL/TP-6A1-447	
TW CH4 Emissions	1	g / mile	Golden, CO: National Renewable Energy Laboratory.	MSM Results
		**	Ruth, M. et al. (2009, March). Hydrogen Macro System Model User Guide. NREL/TP-6A1-447	99
TW N2O Emissions	0	g / mile	Golden, CO: National Renewable Energy Laboratory.	MSM Results
			Ruth, M. et al. (2009, March). Hydrogen Macro System Model User Guide. NREL/TP-6A1-447	
FW GHG Emissions	318	g / mile	Golden, CO: National Renewable Energy Laboratory.	MSM Results

Appendix F — Coal–Pipeline with Carbon Capture and Sequestration Supporting Tables and Figures

#### Hydrogen Produced In Central Plant and Transported as Gas via Pipeline



In	puts	Graphic Depiction &	Assumptions	Ou	tputs
		Coal Mining & De	livery		
Coal Input from "Weil" Natural Gas Input from "Weil" Petroleum Input from "Weil"	116,427 Blu / 116000Blu to Pump 145 Blu / 116000Blu to Pump 712 Blu / 116000Blu to Pump	Energy Recovery Energy Used Diesel Used Electricity Used	99.3% 7049 Btu / MMBtu Coal 2048 Btu / MMBtu Coal 2048 Btu / MMBtu Coal 2019 Btu / MMBtu Coal 2019 Btu / MMBtu Coal 2019 Delivered	Coal price at H2 production Levelized Cost of Coal WTG CO2 Emissions WTG CH4 Emissions WTG N20 Emissions	\$33.98 2005 \$ / short ton \$0.31 2005\$ / kg H2 distributed 114 g / 116000Btu to Pump 14 g / 116000Btu to Pump 0 g / 116000Btu to Pump 46 g CO2 eq / 116000 Btu
Coal consumption Natural gas consumption Electricity consumption Process Water Consumption Electricity price	7.8 kg / kg H2 produced 0.00 N m^3/kg H2 produced 1.72 kWh / kg H2 11.02 L / kg H2 \$0.0555 2005 \$/kWh	Hydrogen Productio Central plant design capacity Capacity factor Process energy efficiency	307,673 kg/day 90% 53.6%	Hydrogen Output Pressure Total capital investment Electricity cost Natural Gas Cost	300 psi \$6.84 2005\$ / annual kg H2 (effectiv \$0.10 2005\$ / kg H2 produced \$0.00 2005\$ / kg H2 produced
Total Capital Investment	\$691,377,851 2005\$	Electricity Mix After-tax IRR Assumed Plant Life	US Mix 10% 40	Other operating costs Levelized Cost of Prod (excl feedst	\$0.38 2005\$ / kg H2 produced \$1.76 2005\$ / kg H2 distributed
Coal Input from "Well" Natural Gas Input from "Well" Petroleum Input from "Well"	105,782 Btu / 116000Btu to Pump 3,022 Btu / 116000Btu to Pump 1,332 Btu / 116000Btu to Pump	CO2 Captured for sequestration CO2 Pipeline Length Number of injection wells Injection well depth	90% 100 miles 1 1524 m	H2 Prod CO2 Emissions H2 Prod CH4 Emissions H2 Prod N2O Emissions H2 Prod GHG Emissions	3,803 g / 116000Btu to Pump 13 g / 116000Btu to Pump 0 g / 116000Btu to Pump 4,136 g CO2 eq./ 116000 Btu
Electricity consumption for compressor Electricity consumption for geo storage Total electricity consumption Electricity price for compressor	0.56 kWh / kg H2 0.01 kWh / kg H2 0.57 kWh / kg H2 \$0.056 2005\$ / kWh	Pipelines for Deli City Population		Total capital investment Electricity cost	\$3.51 2005\$/annual kg distributed \$0.03 2005\$ / kg H2
Electricity price for geologic storage	\$0.052 2005\$ / KWh	City Population Hydrogen Vehicle Penetration City hydrogen use Distance from City to Production Facility Geologic storage capacity Trunk #1-line length Trunk #2-line length	1,247,364 people 50% 125,810,766 kg / yr 62 miles 3,762,787 kg H2 17 miles 40 miles	Levelized Cost of Delivery	\$0.92 2005\$ / kg H2 distributed
Coal Input from "Well" Natural Gas Input from "Well" Petroleum Input from "Well"	3,306 Btu / 116000Btu to Pump 950 Btu / 116000Btu to Pump 246 Btu / 116000Btu to Pump	Service-line length Number of service lines Hydrogen losses Hydrogen loss factor	1.1 miles / line 270 1.12% 1.011	Delivery CO2 Emissions Delivery CH4 Emissions Delivery N2O Emissions Delivery GHG Emissions	436 g / 116000Btu to Pump 1 g / 116000Btu to Pump 0 g / 116000Btu to Pump 452 g CO2 eq./ 116000 Btu
Electricity consumption Electricity price	3.04 kWh / kg H2 \$0.082 2005\$ / kWh	Forecourt Distrib	ution	Hydrogen outlet pressure Basis Hydrogen Quantity	6,250 psi 116,000 Btu (116,000 Btu/gal non-oxy
Electricity price	\$0.002 2003\$ / KWII			Total capital investment	\$6.69 2005\$/annual kg
		Number of Distribution Stations Energy efficiency Number of Compression Steps	270 92% 4	Electricity cost Levelized Cost of Distribution	\$0.25 2005\$ / kg H2 \$1.69 2005\$ / kg H2 distributed
Coal Input from "Well" Natural Gas Input from "Well" Petroleum Input from "Well"	17,677 Btu / 116000Btu to Pump 5,078 Btu / 116000Btu to Pump 1,317 Btu / 116000Btu to Pump	Isentropic Efficiency Site storage Hydrogen losses Hydrogen loss factor	65% 69% capacity 0.50% 1.005	CSD CO2 Emissions CSD CH4 Emissions CSD N20 Emissions CSD GHG Emissions	2,333 g / 116000Btu to Pump 3 g / 116000Btu to Pump 0 g / 116000Btu to Pump 2,419 g CO2 eq./ 116000 Btu
		Well-to-Pump Results Coal Input from "Well" Natural Gas Input from "Well" Petroleum Input from "Well" Fossil Energy Input from "Well" WTP CO2 Emissions WTP CA4 Emissions WTP AGE Emissions WTP GHG Emissions Levelized Cost of Hydrogen (\$/kg)	243,192 Btu / 116000 Btu 9,194 Btu / 116000 Btu 3,608 Btu / 116000 Btu 25,994 Btu / 116000 Btu 6,694 g/ 116000 Btu 31 g/ 116000 Btu 0 g/ 116000 Btu 7,477 116000 Btu \$4.68 2005 \$/ kg		
		Vehicle Fuel Economy Ratio of FCV VOCs (emissions) to GVs	45.0 mi / GGE		
		fueled with CG & RFG Ratio of FCV VOCs (evaporative) to GVs	0%		
		fueled with CG & RFG Ratio of FCV CO emissions to GVs fueled with CG & RFG	0%		
		Ratio of FCV NOx emissions to GVs fueled with CG & RFG	0%		
		Ratio of FCV Exhaust PM10 emissions to GVs fueled with CG & RFG	0%		
		Ratio of FCV Brake & Tire Wear PM10 emissions to GVs fueled with CG & RFG	100%		
		Ratio of FCV Exhaust PM2.5 emissions to GVs fueled with CG & RFG	0%		
		Ratio of FCV Brake & Tire Wear PM2.5 emissions to GVs fueled with CG & RFG Ratio of FCV CH4 emissions to GVs	100%		
		fueled with CG & RFG Ratio of FCV N2O emissions to GVs	0%		
		Tueled with CG & RFG Well-to-Wheel Results Coal Input from "Well" Natural Gas Input from "Well" Petroleum Input from "Well" Fossil Energy Input from "Well" WTW C02 Emissions WTW C14 Emissions WTW ADG Emissions WTW GHG Emissions Langing Cast of Madaenes (#mi)	0% 5,408 Btu / mi 204 Btu / mi 5,693 Btu / mi 149 g/ mi 1 g / mi 166 g / mi 166 g / mi		
		Levelized Cost of Hydrogen (\$/mi)	\$0.1040 2005 \$/mi		



Total to De	liver 116000 Btu Fuel	Check
Coal	243,192	243,192
Natural Gas	9,194	9,194
Petroleum	3,608	3,608
Total Energy	147,448	147,448
CO2 Emissions	6,687	6,694
CH4 Emissions	31	31
N2O Emissions	0	0
GHG Emissions	7,470	7,477

# Coal-Pipe Pathway Details R090819G2C 090827 v09.xls 221

Param	eter	Value	Units	Reference	Comments
Case D	efinition				
	Base Year	2005	5	None	Default for Coal-Pipe Pathway study
	Production Technology	Coal Gas		None	Default for Coal-Pipe Pathway study Default for Coal-Pipe Pathway study
	Form of H2 During Delivery Delivery Mode	Pipeline		None	Default for Coal-Pipe Pathway study Default for Coal-Pipe Pathway study
	Forecourt Station Size	1278	kg/day	James, B.D. (2008, May 23). Current (2005) Steam Methan Reformer (SMR) at Forecourt	Current forecourt H2A production from natural gas basis version 2.0.1; Input_Sheet_Template tab; Plant Output, cell C
	Vehicle Type	passenger cars	5,	1500kg/day . Arlington, VA: Directed Technologies Inc. None	Default for Coal-Pipe Pathway study
	Vehicles' Fuel Economy		) mile / gge	Rousseau, A. & Wallner, T. (2008, October 7) Prospects on Fuel Efficiency Improvements for Hydrogen Powered Vehicles . Argonne National Laboroatory presentation, Chicago, IL. Retreived from http://www.transportation.anl.gov/pdfs/HV/IS30.pdf	Calculated from data in the presentation. The fuel economy for today's average mid-size vehicle was estimated by the Downertrain Simulation Analysis Toolkit V.6.2 SP1 Summer 2008 (JSSAT -
Market	Definition				
	City Population	1,247,364	people	Elgowainy, A., Mintz, M. & Gillette, J. (2006) <i>Hydrogen Delivery Scenario Analysis Model</i> ( <i>HDSAM</i> ) V2.0. Argonne, IL: Argonne National Laboratory	HDSAM City Selection; Scenario tab; Indianapolis, IN, cell B9
	Market penetration	50%	(% vehicles in city)	U.S. Department of Energy & U.S. Department of Transportation. (2006, December)Hydrogen Posture Plan An Inegrated Research, Development and Demonstration Plan.	Basis for posture plan
	Number of H2 vehicles in city	462.772	H2 vehicles / city	Posture Plan An Inegrated Research, Development and Demonstration Plan. Elgowainy, A., Mintz, M. & Gillette, J. (2006)Hydrogen Delivery Scenario Analysis Model	Demand calculation by HDSAM version 2.02; Scenario tab; Number of H2 vehicles in city, cell F17
	Miles driven per vehicle		mile / vehicle year	Elgowainy, A., Mintz, M. & Gillette, J. (2006) Hydrogen Delivery Scenario Analysis Model	Key delivery input in HDSAM version 2.02; Scenario tab; Miles driven per year/ vehicle, cell C19
	City hydrogen use	344,451	ka / d	Elgowainy, A., Mintz, M. & Gillette, J. (2006) <i>Hydrogen Delivery Scenario Analysis Model</i> (HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	Demand calculation by HDSAM version 2.02; Scenario tab; City H2 daily use, cell F18
	Number of H2 refueling stations in city	270	ng, s	Elgowainy, A., Mintz, M. & Gillette, J. (2006) Hydrogen Delivery Scenario Analysis Model	Demand calculation by HDSAM version 2.02; Scenario tab; Number of H2 fueling stations in city, cell F19
	number of Fiz reliabiling stations in city		1	(HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	Demand calculation by FIDSAM Version 2.02, Scenario tao, Number of FI2 fueling stations In City, Cell F19
	Number of H2 stations/Number of gasoline stations	41%	2	Elgowainy, A., Mintz, M. & Gillette, J. (2006) Hydrogen Delivery Scenario Analysis Model (HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	Demand calculation by HDSAM version 2.02; Scenario tab; Number of H2 stations/Number of gasoline stations, cell F2
	Average distance between stations (mi)	1.46		Elgowainy, A., Mintz, M. & Gillette, J. (2006) Hydrogen Delivery Scenario Analysis Model	Demand calculation by HDSAM version 2.02; Scenario tab; Average distance between stations, cell F22
Feedst	ock Recovery, Processing, & Transport		miles	(HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	
Electricit	v				
	Grid mix for production	US Mix		None	Default for Coal-Pipe Pathway study
	Biomass Fraction	1.2%		Energy Information Administration. (2007, February)Annual Energy Outlook 2007 with Projections to 2030. DOE/EIA-0383(2007). Washington, D.C. Retreived from www.eia.doe.gov/oia/farchive/aeo07/index.htr	US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages calcula from total generation values reported with all renewables except biomass aggregated into the "Others (Carbon Neutral) category
	Coal Fraction	51.7%		Energy Information Administration. (2007, February)Annual Energy Outlook 2007 with Projections to 2030. DDE/EIA-0383(2007). Washington, D.C. Retreived from www.eia.doc.gov/oiaffarchive/aeo07/index.htr	US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages calcula from total generation values reported with all renewables except biomass aggregated into the "Others (Carbon Neutral) category
	Natural Gas Fraction	15.7%		Energy Information Administration. (2007, February)Annual Energy Outlook 2007 with Projections to 2030. DCE/EIA-0383(2007). Washington, D.C. Retreived from www.eia.doe.gov/oiafarchive/aeo07/index.ht	US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages calculat from total generation values reported with all renewables except biomass aggregated into the "Others (Carbon Neutral)" category
	Nuclear Fraction	20.3%		Energy Information Administration. (2007, February)Annual Energy Outlook 2007 with Projections to 2030. DOE/EIA-0383(2007). Washington, D.C. Retreived from www.eia.doe.gov/oiaf/archive/aeo07/index.htr	US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages calcula from total generation values reported with all renewables except biomass aggregated into the "Others (Carbon Neutral) category
	Residual Oil Fraction	2.9%		Energy Information Administration. (2007, February)Annual Energy Outlook 2007 with Projections to 2030. DOE/EIA-0383(2007). Washington, D.C. Retreived from www.eia.doe.gov/loid/archive/aeo07/index.ht	US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages calculat from total generation values reported with all renewables except biomass aggregated into the "Others (Carbon Neutral)" category
	Others (Carbon Neutral)	8.2%		Energy Information Administration. (2007, February)Annual Energy Outlook 2007 with Projections to 2030. DOE/ELA-0383(2007). Washington, D.C. Retreived from www.eia.doe.gov/oialfarchive/aeo07/index.htr	US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages calculat from total generation values reported with all renewables except biomass aggregated into the "Others (Carbon Neutral)" category
	Grid mix for pipeline compressors Grid mix for compression at distribution	US Mix US Mix		None	Default for Coal-Pipe Pathway study Default for Coal-Pipe Pathway study
Coal	In this for compression at distribution	US MIX			Delauli loi Guai-ripe Falliway Study
	Energy efficiency of coal mining and delivery			Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1:	GREET default, Coal Tab B18
	Energy requirement for coal mining and delivery	99.3% 7049	Btu / MMBtu	Methodology, development, Use and Results. Argonne, IL: Argonne National Laboratory. None	Calculated from energy efficiency of coal mining and delivery, cell D53
	Share of Resid Oil for coal mining & delivery			Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1:	GREET default, Coal Tab B22
		7.0%		Methodology, development, Use and Results. Argonne, IL: Argonne National Laboratory. Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1:	
	Share of Diesel for coal mining & delivery	56.0%		Methodology, development, Use and Results. Argonne, IL: Argonne National Laboratory.	GREET default, Coal Tab B23
	Share of Gasoline for coal mining & delivery	3.0%	,	Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology, development, Use and Results. Argonne, IL: Argonne National Laboratory.	GREET default, Coal Tab B24
	Share of Natural Gas for coal mining & delivery	1.0%		Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology, development, Use and Results. Argonne, IL: Argonne National Laboratory.	GREET default, Coal Tab B25
	Share of Coal for coal mining & delivery	9.0%		Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology, development, Use and Results. Argonne, IL: Argonne National Laboratory.	GREET default, Coal Tab B26
	Share of Electricity for coal mining & delivery	24.0%		Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology, development, Use and Results. Argonne, IL: Argonne National Laboratory.	GREET default, Coal Tab B27
	Resid Oil requirement for coal mining and delivery	493	Btu / MMBtu	None	Calculated from share of reisd oil for coal mining and delivery (cell D55) times energy requirement for coal mining and delivery (cell D54)
		400	Btu / MMBtu	None	Calculated from share of diesel for coal mining & delivery (cell D56) times energy requirement for coal mining and deliver (cell D54)
	Diesel requirement for coal mining and delivery	3948			
	Diesel requirement for coal mining and delivery Gasoline requirement for coal mining and delivery		Btu / MMBtu	None	Calculated from share of gasoline for coal mining and delivery (cell D57) times energy requirement for coal mining and delivery (cell D54)
		211		None None	delivery (cell D54) Calculated from share of reisd oil for natural gas mining and delivery (cell D58) times energy requirement for coal mining
	Gasoline requirement for coal mining and delivery	211	Btu / MMBtu		delivery (cell D54) Calculated from share of reisd oil for natural gas mining and delivery (cell D58) times energy requirement for coal mining and delivery (cell D54)
	Gasoline requirement for coal mining and delivery Natural Gas requirement for coal mining and delivery	211 70 634	Btu / MMBtu Btu / MMBtu	None	delivery (cell D54) Calculated from share of reisd oil for natural gas mining and delivery (cell D58) times energy requirement for coal mining and delivery (cell D54) Calculated from share of coal for coal mining and delivery (cell D59) times energy requirement for coal mining and delive

Parameter		Value	Units	Reference	Comments
Productio	n Facility Average Output	276,906	kg / facility d (after capacity factor is included)	Rutkowski, M. (2008, May 28). Current (2005) Hydrogen from Coal with CO2 Capture and Storage . Golden, CO: National Renewable Energy Laboratoty.	Current central H2A production from coal basis version 2.1.1; Input_Sheet_Template tab; C23
	Corresponding capacity factor	90%		Rutkowski, M. (2008, May 28). Current (2005) Hydrogen from Coal with CO2 Capture and	Current central H2A production from coal basis version 2.1.1; Input_Sheet_Template tab; Operating Capacity Factor, c
				Storage . Golden, CO: National Renewable Energy Laboratoty. Spath, P., Aden, A., Eggeman, T., Ringer, M., Wallace, B. & Jechura, J. (2005, May@iomass to	621
Total Cap	ital Investment	\$691,377,851	2005 \$	Hydrogen Production Detailed Design and Economics Utilizing the Battelle Columbus Laboratory Indirectly-Heated Gasifier. Table 10. NRELTP-510-37408. Golden, CO: National Renewable Energy Laboratory	Total installed capital cost of \$102M (\$2002) (see Table 10, Current Design) was escalated to \$2005 dollars. Capital co for additional compression was removed to maintain consistency with H2A central model assumptions.
Pittsburgh	#8 coal feedstock consumption	7.8	kg / kg H2	Rutkowski, M. (2008, May 28). Current (2005) Hydrogen from Coal with CO2 Capture and Storage . Golden, CO: National Renewable Energy Laboratoty.	Current central H2A production from coal basis version 2.1.1; Results tab; Energy Data
Pittsburgh	#8 coal feedstock cost	\$33.98	2005 \$/ton	Rutkowski, M. (2008, May 28). Current (2005) Hydrogen from Coal with CO2 Capture and Storage. Golden, CO: National Renewable Energy Laboratoty.	
Pittsburgh	#8 coal LHV	23,824,506	Btu / ton	Coal Composition for Coal Gasification to Hydrogen in Central Plants: Pittsburgh No. 8 Bituminou Coal (from M. Rutkowski of Parsons, December 2003).	\$
Natural ga	as feedstock consumption	0.00	normal m^3 / kg H2 produced	Rutkowski, M. (2008, May 28). Current (2005) Hydrogen from Coal with CO2 Capture and Storage. Golden, CO: National Renewable Energy Laboratoty.	Current central H2A production from coal basis version 2.1.1; Results tab; Energy Data
Natural ga	as utility consumption	0.00	normal m^3 / kg H2 produced	Rutkowski, M. (2008, May 28). Current (2005) Hydrogen from Coal with CO2 Capture and Storage . Golden, CO: National Renewable Energy Laboratoty.	
Electricity	feedstock consumption	0.00	kWh / kg H2	Rutkowski, M. (2008, May 28). Current (2005) Hydrogen from Coal with CO2 Capture and Storage . Golden, CO: National Renewable Energy Laboratoty.	Current central H2A production from coal basis version 2.1.1; Results tab; Energy Data
Electricity	utility consumption (both production, carbon capture & transport, and co		kWh / kg H2	Rutkowski, M. (2008, May 28). Current (2005) Hydrogen from Coal with CO2 Capture and Storage . Golden, CO: National Renewable Energy Laboratoty.	Current central H2A production from coal basis version 2.1.1; Results tab; Energy Data
Electricity	utility consumption (production only)		kWh / kg H2	Rutkowski, M. (2008, May 28). Current (2005) Hydrogen from Coal with CO2 Capture and Storage . Golden, CO: National Renewable Energy Laboratoty.	Current central H2A production from coal basis version 2.1.1; Results tab; Energy Data
Process V	Vater Consumption	2.91	gal / kg H2	Rutkowski, M. (2008, May 28). Current (2005) Hydrogen from Coal with CO2 Capture and Storage . Golden, CO: National Renewable Energy Laboratoty.	Current central H2A production from coal basis version 2.1.1; Input Sheet Template: D126
	nsumption for Cooling	0.00000		Rutkowski, M. (2008, May 28). Current (2005) Hydrogen from Coal with CO2 Capture and Storage . Golden, CO: National Renewable Energy Laboratoty.	N/A
Electricity	co-product production		kWh / kg H2	None	N/A
	p-product production	0.0	kg / kg H2	None	N/A
	product production		kg / kg H2	None Rutkowski, M. (2008, May 28). Current (2005) Hydrogen from Coal with CO2 Capture and	N/A
	ual Fixed Operating Costs	\$28,653,073		Rutkowski, M. (2006, May 26). Current (2005) Hydrogen from Coal with CO2 Capture and Rutkowski, M. (2008, May 28). Current (2005) Hydrogen from Coal with CO2 Capture and	Current central H2A production from coal basis version 2.1.1; Input Sheet Template tab; Total Fixed Cost Data Current central H2A production from coal basis version 2.1.1; Input Sheet Template tab; Other Variable Operating Cost
	ual Variable Operating Costs	\$37,340,700		Storage . Golden, CO: National Renewable Energy Laboratoty.	Data
Total Ann	ual Operating Costs (includes CCS)	\$79,129,540	2005\$ / yr	None	Addition of Annual Total Fixed Operating Costs and Total Annual Variable Operating Costs
	n energy efficiency (does not include electricity for forecourt compressio process fuel - biomass	53.6% 0.0%		Calculated from H2A values Calculated from H2A values	Calculated from H2A values Calculated from H2A values
	process fuel - coal	94.0%		Calculated from H2A values	Calculated from H2A values
	process fuel - natural gas	6.0%		Calculated from H2A values	Calculated from H2A values
	process fuel - ethanol	0.0%		Calculated from H2A values	Calculated from H2A values
	process fuel - electricity	0.0%		Calculated from H2A values Rutkowski, M. (2008, May 28). Current (2005) Hydrogen from Coal with CO2 Capture and	Calculated from H2A values
	outlet pressure (before CSD)	300	psi	Storage - Golden, CO: National Renewable Energy Laboratoty. Rutkowski, M. (2008, May 28). Current (2005) Hydrogen from Coal with CO2 Capture and Rutkowski, M. (2008, May 28). Current (2005) Hydrogen from Coal with CO2 Capture and	From comments in Current central H2A production from coal basis version 2.1.1; Process Flow tab; E13
Hydrogen Carbon Capture and	quality before transport	99.8%	% H2	Storage . Golden, CO: National Renewable Energy Laboratoty.	From comments in Current central H2A production from coal basis version 2.1.1; Process Flow tab; E14
	ured for Sequestration	90%		Rutkowski, M. (2008, May 28). Current (2005) Hydrogen from Coal with CO2 Capture and	Current eacher 1004 and unline form and havin unrice 0.4.4. Online Convertentian table call CO0
	utility consumption (carbon capture, transport, & sequestration only)			Storage . Golden, CO: National Renewable Energy Laboratoty. Rutkowski, M. (2008, May 28). Current (2005) Hydrogen from Coal with CO2 Capture and	Current central H2A production from coal basis version 2.1.1; Carbon Sequestration tab; cell C28 Current central H2A production from coal basis version 2.1.1; Carbon Sequestration tab; cell C25
	Utility Price for carbon capture and transport	\$0.055	kWh / kg H2	Storage . Golden, CO: National Renewable Energy Laboratoty. Rutkowski, M. (2008, May 28). Current (2005) Hydrogen from Coal with CO2 Capture and	Current central H2A production from coal basis version 2.1.1; Carbon Sequestration tab; cell C24
	ual Fixed Operating Costs	\$3,492,544	2005 \$/kWh 2005\$ / vr	Storage . Golden, CO: National Renewable Energy Laboratoty. Rutkowski, M. (2008, May 28). Current (2005) Hydrogen from Coal with CO2 Capture and	Current central H2A production from coal basis version 2.1.1; Carbon Sequestration tab; cell J37
	ual Variable Operating Costs	\$9,643,224		Storage . Golden, CO: National Renewable Energy Laboratoty. Rutkowski, M. (2008, May 28). Current (2005) Hydrogen from Coal with CO2 Capture and	Current central H2A production from coal basis version 2.1.1: Carbon Sequestration tab: cell J31
	sor electricity requirement	22,044	-	Storage . Golden, CO: National Renewable Energy Laboratoty. Rutkowski, M. (2008, May 28). Current (2005) Hydrogen from Coal with CO2 Capture and	Current central H2A production from coal basis version 2.1.1; Carbon Sequestration tab; cell C47
	required to flow to sequestration site and be sequestered	15.0	kW	Storage . Golden, CO: National Renewable Energy Laboratoty. Rutkowski, M. (2008, May 28). Current (2005) Hydrogen from Coal with CO2 Capture and	Current central H2A production from coal basis version 2.1.1; Carbon Sequestration tab; cell C51
	Efficiency	74.0%	Мра	Storage . Golden, CO: National Renewable Energy Laboratoty. Rutkowski, M. (2008, May 28). Current (2005) Hydrogen from Coal with CO2 Capture and	Current central H2A production from coal basis version 2.1.1; Carbon Sequestration tab; cell C51 Current central H2A production from coal basis version 2.1.1; Carbon Sequestration tab; cell C54
	line Length	100		Storage . Golden, CO: National Renewable Energy Laboratoty. Rutkowski, M. (2008, May 28). Current (2005) Hydrogen from Coal with CO2 Capture and	Current central H2A production from coal basis version 2.1.1; Carbon Sequestration tab; cell C34 Current central H2A production from coal basis version 2.1.1; Carbon Sequestration tab; cell C39
		<20%	miles	Storage . Golden, CO: National Renewable Energy Laboratoty. Rutkowski, M. (2008, May 28). Current (2005) Hydrogen from Coal with CO2 Capture and	Current central H2A production from coal basis version 2.1.1; Carbon Sequestration tab; cell C39 Current central H2A production from coal basis version 2.1.1; Carbon Sequestration tab; cell C37
	f injection wells	Mountainous 1		Storage . Golden, CO: National Renewable Energy Laboratoty. Rutkowski, M. (2008, May 28). Current (2005) Hydrogen from Coal with CO2 Capture and	Current central H2A production from coal basis version 2.1.1; Carbon Sequestration tab; cell C37 Current central H2A production from coal basis version 2.1.1; Carbon Sequestration tab; cell C34
Well dept		1524		Storage . Golden, CO: National Renewable Energy Laboratoty. Rutkowski, M. (2008, May 28). Current (2005) Hydrogen from Coal with CO2 Capture and	Current central H2A production from coal basis version 2.1.1; Carbon Sequestration tab; cell C34
Financial Parameter		1524	m	Storage . Golden, CO: National Renewable Energy Laboratoty.	Content central rize producion non our basis version 2.1.1, carbon sequestration tab, cell 0.55
After-tax I		10%		Rutkowski, M. (2008, May 28). Current (2005) Hydrogen from Coal with CO2 Capture and Storage . Golden, CO: National Renewable Energy Laboratoty.	Current central H2A production from coal basis version 2.1.1; Input_Sheet_Template tab; After-tax Real IRR, cell C47
Plant Life		40	years	Rutkowski, M. (2008, May 28). Current (2005) Hydrogen from Coal with CO2 Capture and Storage . Golden, CO: National Renewable Energy Laboratoty.	Current central H2A production from coal basis version 2.1.1; Input_Sheet_Template tab; Plant life, cell C34
Federal T	ax Rate	35.0%		Rutkowski, M. (2008, May 28). Current (2005) Hydrogen from Coal with CO2 Capture and Storage . Golden, CO: National Renewable Energy Laboratoty.	Current central H2A production from biomass basis version 2.1.1; Input_Sheet_Template tab; Federal taxes, cell C49
State Tax	Rate	6.0%		Rutkowski, M. (2008, May 28). Current (2005) Hydrogen from Coal with CO2 Capture and Storage . Golden, CO: National Renewable Energy Laboratoty.	Current central H2A production from coal basis version 2.1.2; Input_Sheet_Template tab; State taxes, cell C48
Total Tax	Rate	38.9%		Rutkowski, M. (2008, May 28). Current (2005) Hydrogen from Coal with CO2 Capture and Storage . Golden, CO: National Renewable Energy Laboratoty.	Current central H2A production from coal basis version 2.1.1; Input_Sheet_Template tab; Total tax Rate, cell C50
Frection E	quity	100%		Rutkowski, M. (2008, May 28). Current (2005) Hydrogen from Coal with CO2 Capture and Storage . Golden, CO: National Renewable Energy Laboratoty.	Current central H2A production from coal basis version 2.1.1; Input_Sheet_Template tab; Equity Financing, cell C38
Transport, Deliv	very, and Storage Energy Requirements				
Pipeline Delivery					
-permo bonnoly				1	1

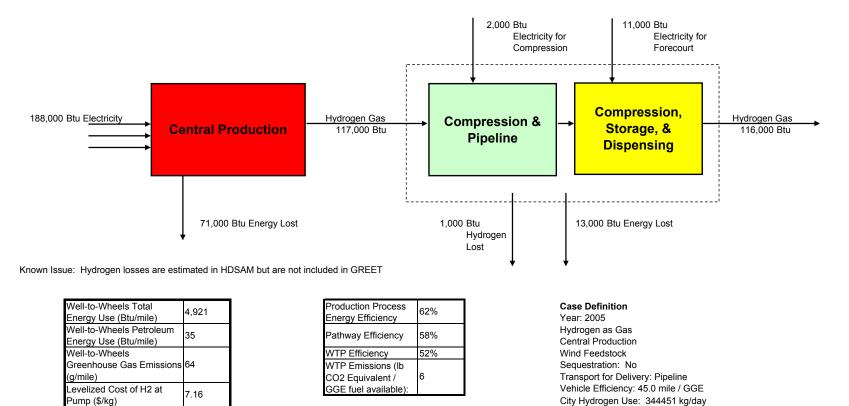
Parameter	Value	Units	Reference	Comments
Average Hydrogen Flowrate (Entering S	System) 348,364	↓kg/hr	Elgowainy, A., Mintz, M. & Gillette, J. (2006) <i>Hydrogen Delivery Scenario Analysis Model</i> (HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	HDSAM version 2.02 calculation based on input parameters: city, market penetration, dispensing rate (PEAK FLOW RAT THRU TRANSMISSION SYSTEM=CITY PEAK DEMAND/TRANSMISIION PIPELINE MASS EFFICIENCY/REF.STATION MASS EFFICIENCY)
Average Hydrogen Flowrate (Distributed	d) 344,45 <sup>-</sup>	l kg/hr	Elgowainy, A., Mintz, M. & Gillette, J. (2006) <i>Hydrogen Delivery Scenario Analysis Model</i> (HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	HDSAM version 2.02 calculation based on input parameters: city, market penetration, dispensing rate (Ave. daily use=CI DAILY USE/TOTAL PIPELINE MASS FEE(CIENCY/REF STATION MASS FEE(CIENCY)
Summer Surge: % above the System Av	verage Daily Demand 10%	% above Average Daily Demand	Elgowainy, A., Mintz, M. & Gillette, J. (2006)Hydrogen Delivery Scenario Analysis Model (HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	HDSAM default, Scenario Parameters tab, cell B90
Friday Peak	8%	% above Average Daily Demand	Elgowainy, A., Mintz, M. & Gillette, J. (2006) Hydrogen Delivery Scenario Analysis Model	HDSAM default, Scenario Parameters tab, cell B92
Peak Hydrogen Flowrate	381,192		(HDSAM) V2.0. Argonne, IL: Argonne National Laboratory Elgowainy, A., Mintz, M. & Gillette, J. (2006)/Hydrogen Delivery Scenario Analysis Model (HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	HDSAM version 2.02 calculation based on input parameters: city, market penetration, dispensing rate (PEAK FLOWRAT THRU DISTRIBUTION SYSTEM=CITY PEAK DEMAND/DISTRIBUTION PIPELINE MASS
Total Capital Investment for Compresso	rs \$27,199,794	4	Nexant, Inc. et al. (2008, May).H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results . Interim Report Section 2.2.5. DE-FG36-	EFFICIENCY/REF.STATION MASS EFFICIENCY) Disscussions with Bechtel and Air Liquide (Nexant report - Section 2.2.5)
Hydrogen Losses from Compressors	0.50%		05GO15032. Elgowainy, A., Mintz, M. & Gillette, J. (2006)Hydrogen Delivery Scenario Analysis Model	HDSAM default, Refueling Station - Gaseous H2 tab, cell B79
Hydrogen Losses from Compressors	0.50%		(HDSAM) V2.0. Argonne, IL: Argonne National Laboratory Nexant, Inc. et al. (2008, May) H2A Hydrogen Delivery Infrastructure Analysis Models and	
Compressor Electricity Demand	70,343,075	5 kWh / year	Conventional Pathway Options Analysis Results . Interim Report Section 2.2.5. DE-FG36- 05GO15032.	Based on vendor data from Neuman&Esser, Burckhardt Compression, Ariel Compressors, Dresser-Rand (Nexant report Section 2.2.5)
Compressor Electricity Demand	0.559	l kWh / kg H2	Nexant, Inc. et al. (2008, May), H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results . Interim Report Section 2.2.5. DE-FG36- 05GO15032.	Based on vendor data from Neuman&Esser, Burckhardt Compression, Ariel Compressors, Dresser-Rand (see Nexant report - Section 2.2.5)
Compressor Electricity Cost	\$0.056	2005\$ / kWh	Energy Information Administration. (2007, February)Annual Energy Outlook 2007 with Projections to 2030. DOE/EIA-0383(2007). Washington, D.C. Retreived from www.eia.doe.gov/ioidfarchive/aeo07/index.htr	EIA AEO 2005 and 2007
Total Capital Investment for Pipeline Sy	stem \$377,283,372	2	Nexant, Inc. et al. (2008, May) H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results . Interim Report Section 2.2.2. DE-FG36- 05GO15032.	HDSAM version 2.02 calculations based on data from GTI, Bechtel, Air Liquide, UC Davis (Nexant Report -Section 2.2.2
Hydrogen Losses from Pipelines	0.10%		Elgowainy, A., Mintz, M. & Gillette, J. (2006) Hydrogen Delivery Scenario Analysis Model (HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	
Number of transmission pipelines		1	Elgowainy, A., Mintz, M. & Gillette, J. (2006)Hydrogen Delivery Scenario Analysis Model (HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	Default in HDSAM version 2.02
Transmission pipeline diameter	11.00	) in	Gas Processors Supplier Association. (2004). GPSA Engineering Data Book, 12th Edition. Tulsa,	HDSAM version 2.02 calculation: Panhandle B equation, H2 Pipeline tab, cell B83
Transmission pipeline inlet pressure		psi	OK. Retrieved from http://gpaglobal.org/gpsa/book.php Nexant, nc. et al. (2008, May)/H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results . Interim Report Section 2.1.6. DE-FG36- nGG015632	Recommendations from Nexant in conjuction with Air Liquide, GTI, Chevron, TIAX, ANL, PNNL and NREL (Nexant Repc Section 2.1.6)
Transmission pipeline outlet pressure	70:	5 psi	UNSUT5U32. Nexani, Inc. et al. (2008, May).H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.1.6. DE-FG36- 05GO15032.	Recommendations from Nexant in conjuction with Air Liquide, GTI, Chevron, TIAX, ANL, PNNL and NREL (Nexant Repo Section 2.1.6)
Transmission pipeline temperature	25	5 C	Nexant, Inc. et al. (2008, May) H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results . Interim Report Section 2.1.6. DE-FG36- 05GO15032.	Recommendations from Nexant in conjuction with Air Liquide, GTI, Chevron, TIAX, ANL, PNNL and NREL (Nexant Repo Section 2.1.6)
Transmission pipeline length	62	2 miles	Elgowainy, A., Mintz, M. & Gillette, J. (2006) <i>Hydrogen Delivery Scenario Analysis Model</i> (HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	HDSAM version 2.02 calculation based on input parameter: city, Scenario Parameters tab, cell F167
Number of trunk pipelines	4	4	Elgowainy, A., Mintz, M. & Gillette, J. (2006) Hydrogen Delivery Scenario Analysis Model (HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	HDSAM version 2.02 calculation based on input data and HDSAM distribution model - not documented, H2 Pipeline tab, cell B58
Trunk #1 pipeline diameter	7.25	5 in	Gas Processors Supplier Association. (2004). GPSA Engineering Data Book, 12th Edition. Tulsa,	HDSAM version 2.02 calculation: Panhandle B equation, H2 Pipeline tab, cell B84
Trunk #1 pipeline inlet pressure	603	s psi	OK. Retrieved from http://gpaglobal.org/gpsa/book.php Nexant, nc. et al. (2008, May)/H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results . Interim Report Section 2.1.6. DE-FG36- 05GO15032.	Recommendations from Nexant in conjuction with Air Liquide, GTI, Chevron, TIAX, ANL, PNNL and NREL (Nexant Repo Section 2.1.6)
Trunk #1 pipeline outlet pressure	391	7 psi	Decorption and the second s	Recommendations from Nexant in conjuction with Air Liquide, GTI, Chevron, TIAX, ANL, PNNL and NREL (Nexant Repo Section 2.1.6)
Trunk #1 pipeline temperature	2:	s c	Decorption and the second s	Recommendations from Nexant in conjuction with Air Liquide, GTI, Chevron, TIAX, ANL, PNNL and NREL (Nexant Repc Section 2.1.6)
Trunk #1 pipeline length	11	7 miles	Elgowainy, A., Mintz, M. & Gillette, J. (2006) Hydrogen Delivery Scenario Analysis Model	HDSAM version 2.02 calculation based on input data and HDSAM distribution model (discussions with Pacific Gas &
Trunk #2 pipeline diameter	10.25	in	(HDSAM) V2.0. Argonne, IL: Argonne National Laboratory Gas Processors Supplier Association. (2004). GPSA Engineering Data Book, 12th Edition. Tulsa,	Electric Company, San Francisco), Scenario Parameters tab, cell F168 HDSAM version 2.02 calculation: Panhandle B equation, H2 Pipeline tab, cell B85
Trunk #2 pipeline inlet pressure		3 psi	OK. Retrieved from http://gpaglobal.org/gpas/book.php Nexant, Inc. et al. (2008, May).H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.1.6. DE-FG36-	Recommendations from Nexant in conjuction with Air Liquide, GTI, Chevron, TIAX, ANL, PNNL and NREL (Nexant Repo
Trunk #2 pipeline outlet pressure	391	7 psi	05GO15032. Nexant, Inc. et al. (2008, May) H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results . Interim Report Section 2.1.6. DE-FG36-	Recommendations from Nexant in conjuction with Air Liquide, GTI, Chevron, TIAX, ANL, PNNL and NREL (Nexant Repo Section 2.1.6)
Trunk #2 pipeline temperature	22	s c	05GO15032. Nexant, Inc. et al. (2008, May) H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results . Interim Report Section 2.1.6. DE-FG36-	Recommendations from Nexant in conjuction with Air Liquide, GTI, Chevron, TIAX, ANL, PNNL and NREL (Nexant Repo Section 2.1.6)
Trunk #2 pipeline length	40	) miles	05GO15032. Elgowainy, A., Mintz, M. & Gillette, J. (2006) Hydrogen Delivery Scenario Analysis Model	HDSAM version 2.02 calculations based on input data and HDSAM distribution model - not documented, Scenario Parameters tab. cell F169
Trunk #3 pipeline diameter	12.25	in	(HDSAM) V2.0. Argonne, IL: Argonne National Laboratory Gas Processors Supplier Association. (2004). GPSA Engineering Data Book, 12th Edition. Tulsa, OV. Detrived fore the Uncertainty and the track the track of the Company of the Co	
Trunk #3 pipeline inlet pressure		s psi	OK. Retrieved from http://gpaglobal.org/gpsa/book.php Nexant, Inc. et al. (2008, May) H24 Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results . Interim Report Section 2.1.6. DE-FG36-	Recommendations from Nexant in conjuction with Air Liquide, GTI, Chevron, TIAX, ANL, PNNL and NREL (Nexant Repo Section 2.1.6)
Trunk #3 pipeline outlet pressure	397	7 psi	05GO15032. Nexant. Inc. et al. (2008, May) H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results . Interim Report Section 2.1.6. DE-FG36- concernent of the Analysis Results . Interim Report Section 2.1.6. DE-FG36- concernent of the Analysis Results . Interim Report Section 2.1.6. DE-FG36- concernent of the Analysis Results . Interim Report Section 2.1.6. DE-FG36- concernent of the Analysis Results . Interim Report Section 2.1.6. DE-FG36- concernent of the Analysis Results . Interim Report Section 2.1.6. DE-FG36- concernent of the Analysis Results . Interim Report Section 2.1.6. DE-FG36- concernent of the Analysis Results . Interim Report Section 2.1.6. DE-FG36- concernent of the Analysis Results . Interim Report Section 2.1.6. DE-FG36- concernent of the Analysis Results . Interim Report Section 2.1.6. DE-FG36- concernent of the Results . Interim Report Section 2.1.6. DE-FG36- concernent of the Results . Interim Report Section 2.1.6. DE-FG36- concernent of the Results . Interim Report Section 2.1.6. DE-FG36- concernent of the Results . Interim Report Section 2.1.6. DE-FG36- concernent of the Results . Interim Report Section 2.1.6. DE-FG36- concernent of the Results . Interim Results .	Recommendations from Nexant in conjuction with Air Liquide, GTI, Chevron, TIAX, ANL, PNNL and NREL (Nexant Repo Section 2.1.6)
Trunk #3 pipeline temperature	25	s c	05GO15032. Nexani, Inc. et al. (2008, May).H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results . Interim Report Section 2.1.6. DE-FG36- 05GO15032.	, Recommendations from Nexant in conjuction with Air Liquide, GTI, Chevron, TIAX, ANL, PNNL and NREL (Nexant Repo Section 2.1.6)
Trunk #3 pipeline length		5 miles	Elgowainy, A., Mintz, M. & Gillette, J. (2006) Hydrogen Delivery Scenario Analysis Model	HDSAM version 2.02 calculations based on input data and HDSAM distribution model - not documented, Scenario

Test is gates name         Set is gate name         <			Value	ملاحل	Boferrara	Compression
Image of the product of the			Value	Units		Comments
Interpretation process of the second seco	I runk #4 pipeline diameter		10.75 in	1	OK. Retrieved from http://gpaglobal.org/gpsa/book.php	
Inversion         And A gate in degradem         And A gate in degradm         And A gate in degradem         <	Trunk #4 pipeline inlet pressure		558 pr	JSİ	Conventional Pathway Options Analysis Results . Interim Report Section 2.1.6. DE-FG36- 05GO15032.	
Note 4 genes impactation         C         Constraint frame, factor 4, and a field on the factor4, and a field on the factor 4, and a field on the fa	Trunk #4 pipeline outlet pressure		397 pr	JSI	Conventional Pathway Options Analysis Results . Interim Report Section 2.1.6. DE-FG36- 05GO15032.	Recommendations from Nexant in conjuction with Air Liquide, GTI, Chevron, TIAX, ANL, PNNL and NREL (Nexant Repo Section 2.1.6)
Inter young with youn	Trunk #4 pipeline temperature		25 C	5	Conventional Pathway Options Analysis Results . Interim Report Section 2.1.6. DE-FG36- 05GO15032.	
Number of stratung plotted         Control         Performance	Trunk #4 pipeline length		90 m	niles	(HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	
Interpretation     Constrained in the pretation service of the pretation of the pr	Number of service pipelines		270		(HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	HDSAM version 2.02 calculations based on input data and HDSAM distribution model (discussions with Pacific Gas & Electric Company, San Francisco), H2 Pipeline tab, cell B67
Image: Series prefer and pressure     Series prefer and pres	Service pipeline diameter		1 in	n	Gas Processors Supplier Association. (2004). GPSA Engineering Data Book, 12th Edition. Tulsa, OK. Retrieved from http://gpaglobal.org/gpsa/book.php	HDSAM version 2.02 calculation: Panhandle B equation, H2 Pipeline tab, cell B88
Backs polish and produce         Backs polish polish polish and polish poli	Service pipeline inlet pressure		382 p:	Jsi	Nexant, Inc. et al. (2008, May) H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.1.6. DE-FG36- 05GO15032.	Recommendations from Nexant in conjuction with Air Liquide, GTI, Chevron, TIAX, ANL, PNNL and NREL (Nexant Repo Section 2.1.6)
Image: Source particle segments with the spectra segments as the spectra segments and the spectra segments as the spectra segments and the spectra segments as the spectra segments and the spectra segments	Service pipeline outlet pressure		294 p:	)Sİ	Conventional Pathway Options Analysis Results . Interim Report Section 2.1.6. DE-FG36- 05GO15032.	Recommendations from Nexant in conjuction with Air Liquide, GTI, Chevron, TIAX, ANL, PNNL and NREL (Nexant Repo Section 2.1.6)
Bits / Depind english         Bits / Depind english         Bits / Depind english         Bits / Depind english           Paperie desingt: Storage 143 (2004) Instantent         \$50.983.70         Commission / Phaney / Depins / Link rainer Roots (Storage 112) E-FSS         Commission / Phaney / Depins / Link rainer Roots (Storage 112) E-FSS         Commission / Phaney / Depins / Link rainer Roots (Storage 112) E-FSS         Commission / Phaney / Depins / Link rainer Root (Storage 112) E-FSS         Commission / Phaney / Depins / Link rainer Root (Storage 112) E-FSS         Commission / Phaney / Depins / Link rainer Root (Storage 112) E-FSS         Commission / Phaney / Depins / Link rainer Root (Storage 112) E-FSS         Commission / Phaney / Depins / Link rainer Root (Storage 112) E-FSS         Commission / Phaney / Depins / Link rainer Root (Storage 112) E-FSS         Commission / Phaney / Depins / Link rainer Root (Storage 112) E-FSS         Commission / Phaney / Depins / Link rainer Root (Storage 112) E-FSS         Commission / Phaney / Depins / Link rainer Root (Storage 112) E-FSS         Commission / Phaney / Depins / Link rainer Root (Storage 112) E-FSS         Commission / Phaney / Depins / Link rainer Root (Storage 112) E-FSS         Commission / Phaney / Depins / Link rainer Root (Storage 112) E-FSS         Commission / Phaney / Depins / Link rainer Root (Storage 112) E-FSS         Commission / Phaney / Depins / Link rainer Root (Storage 112) E-FSS         Commission / Phaney / Depins / Link rainer Root (Storage 112) E-FSS         Commission / Phaney / Depins / Link rainer Root (Storage 112) E-FSS         Commission / Phaney / Depins / Link rainer Root (Storage 112) E-FSS         Commission / Phaney / Depins / Link rainer Root (Stor	Service pipeline temperature		25 C	2	Conventional Pathway Options Analysis Results . Interim Report Section 2.1.6. DE-FG36- 05GO15032.	
Period         Period         Concentration         Concentration         Period	Service pipeline length		1.1 m	niles	(HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	HDSAM version 2.02 calculations based on input data and HDSAM distribution model (discussions with Pacific Gas & Electric Company, San Francisco), H2 Pipeline tab, cell B68
Implicit         Data         (p253)/(p25)/	Pipeline Geologic Storage Total Capital Investment	ant	\$36,988,376		Conventional Pathway Options Analysis Results . Interim Report Section 2.2.12. DE-FG36- 05GO15032.	HDSAM version 2.02 calculations (cost data from ConocoPhilips and Saltville natural gas storage facility in Virginiase (Nexant Report - Section 2.2.12)
Conscip_Strage_Design_Capacity         3.782.71 bit 10         Sport August Augu					(HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	
Image:         Desktyp:         Number of the state of						HDSAM version 2.02 calculation. Gaseous H2 Geological Stroage tab. cell B105
Convertional Planning Option Advances Planning Option Advances Report Report Secure Advances Report Report Planning Option Planning Option Planning Optin Planning Option Planning Opting Planning Opting Planning Optio					Nexant, Inc. et al. (2008, May).H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results . Interim Report Section 2.2.12. DE-FG36-	HDSAM version 2.02 calculations (cost data from ConocoPhilips and Saltville natural gas storage facility in Virginiase
Distribution         Distribution         Image: Constraint of Amage: Constraint of Constraint	Geologic Storage Electricity Demand		0.0076 k <sup>1</sup>	:Wh / kg H2	Conventional Pathway Options Analysis Results . Interim Report Section 2.2.12. DE-FG36- 05GO15032.	
Best by Each Ming Distributing Station         Memory A. Marcz, M. & Science, J. (2005)/pdrogen Dalvery Scenario Analysis Model         Memory Scenario Analysis Model         Messal Laccomptee         Messal Laccomptee <t< td=""><td>Geologic Storage Electricity Cost</td><th></th><td>\$0.052 20</td><td>2005\$ / kWh</td><td>Energy Information Administration. (2005, January)Annual Energy Outlook 2005 with Projections</td><td>EIA AEO 2005</td></t<>	Geologic Storage Electricity Cost		\$0.052 20	2005\$ / kWh	Energy Information Administration. (2005, January)Annual Energy Outlook 2005 with Projections	EIA AEO 2005
Image: Hydrogen Dispensed at Forecourt Station     1486.47     Hydrogen Dispensed at Forecourt Station     1486.47     Hydrogen Dispensed at Forecourt Station     1486.37     Hydrogen Dispensed At Spran Dispense Di	ibution Station					
minipulsage     mini	ous Receiving/Distributing Stations				Electronic A. Mintz, M. & Cillette, L. (2006) Hudesson Delivery Sessoria Analysis Model	
Electroly Hequres by Portcourt Station         (H18/SP         Wh/ station year         (PDSAM/ V2.0. Argonne, L: Argonne National Laboratory			ĸ	(g / station year	(HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	
Number       Stages in compressor       (HDSAM) V2.0. Argonne, IL: Argonne National Laboral Laboral Lab cell B69         Compressor Isentropic Efficiency       655       Elgowary, A. Mitz, M. & Gilletto, J. (2006) Hydrogen Delivery Steamin Analysis Model Into Aux Benders Aux Data Cell B69       HDSAM version 2.02 default, Returning Studion - Gaseous H2 tab, cell B69         Design Capacity       1,358       kg H2 / day       Elgowary, A. Mitz, M. & Gilletto, J. (2006) Hydrogen Delivery Infrastructure Analysis Model Aux Benders Aux Deliver, Mitz, M. & Gilletto, J. (2006) Hydrogen Delivery Infrastructure Analysis Model Aux Benders Aux Deliver, Mitz Aux Deliver,	Electricity Required by Forecourt Station		1,416,755 kl	Wh / station year	(HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	HDSAM version 2.02 calculation, Refueling Station - Gaseous H2 tab, cell B263
Configescal feating, Euclarity       Units       (HDSAM V2.0. Argome, IL: Argome National Laboratory       HDSAM Vector 2.0. actuation based on Pizzo fuel and Structure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.1.4. DE-FG38- discretional Pathway Options Analysis Results. Interim Report Section 2.1.4. DE-FG38- discretional Pathway Options Analysis Results. Interim Report Section 2.1.4. DE-FG38- discretional Pathway Options Analysis Results. Interim Report Section 2.1.4. DE-FG38- discretional Pathway Options Analysis Results. Interim Report Section 2.1.4. DE-FG38- discretional Pathway Options Analysis Results. Interim Report Section 2.1.4. DE-FG38- discretional Pathway Options Analysis Results. Interim Report Section 2.2.3. Refueling Station - Gaseous H2 tab, col Capacity Factor       Adjusted dispensing rate-city use/number of stations/utilization factor, Refueling Station - Gaseous H2 tab, col Capacity Factor         Site storage (Cascade)       470       Nexant. Inc. et al. (2008, May) H2A Hydrogen Delivery Infrastructure Analysis Models an Conventional Pathway Options Analysis Results. Interim Report Section 2.3.2.4 DE-FG38- discretional Pathway Options Analysis Results. Interim Report Section 2.3.2.4 DE-FG38- discretional Pathway Options Analysis Results. Interim Report Section 2.3.2.4 DE-FG38- discretional Pathway Options Analysis Results. Interim Report Section 2.3.2.4 DE-FG38- discretional Pathway Options Analysis Results. Interim Report Section 2.3.2.4 DE-FG38- discretional Pathway Options Analysis Results. Interim Report Section 2.3.2.4 DE-FG38- discretional Pathway Options Analysis Results. Interim Report Section 2.2.3. DE-FG38- discretional Pathway Options Analysis Results. Interim Report Section 2.2.3. DE-FG38- discretional Pathway Options Analysis Results. Interim Report Section 2.2.3. DE-FG38- discretional Pathway Options Analysis Results.	Number of Compressor Stages			Stages in compressor	(HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	HDSAM version 2.02 default, Refueling Station - Gaseous H2 tab, cell B67
Design Capacity         1,516 bit plu2 / day         Conventional Pathway Options Analysis Results : Interim Report Section 2.1.4. DE-FG3s- discontrained analysis Model         Conventional Pathway Options Analysis Results : Interim Report Section 2.1.4. DE-FG3s- discontrained analysis Model         Relativity Station - Gaseous H2 bab, col discontrained analysis Model           Operating Capacity         2005 / Hold Surger, A., Mitz, M. & Gillette, J. (2005) Hydrogen Delivery Infrastructure Analysis Model (HDSAM Version 2.0.2.0 EFG3s- bit storage (Low Pressure)         Adjusted dispensing rate=city userhumber of stations/utilization factor, Refueling Station - Gaseous H2 bab, col dispensing Pressure         Adjusted dispensing rate=city userhumber of stations/utilization factor, Refueling Station - Gaseous H2 bab, col dispensing Pressure         HDSAM version 2.0.2 calculation (Nexant Report - Section 2.2.3. DE-FG3s- bit storage (Cascade)         HDSAM version 2.0.2 calculation (Nexant Report - Section 2.3.2.4), Refueling Station - Gaseous H2 bab, col dispensing Pressure         HDSAM version 2.0.2 calculation (Nexant Report - Section 2.3.2.4), Refueling Station - Gaseous H2 bab, col dispensing Pressure         HDSAM version 2.0.2 calculation (Nexant Report - Section 2.3.2.4), Refueling Station - Gaseous H2 bab, col dispensing Pressure         HDSAM version 2.0.2 calculation (Nexant Report - Section 2.3.2.4), Refueling Station - Gaseous H2 bab, col dispensing Pressure         HDSAM version 2.0.2 default (see Nexant Report - Section 2.3.2.9), Refueling Station - Gaseous H2 bab, col dispensing Pressure         HDSAM version 2.0.2 default (see Nexant Report - Section 2.3.2.9), Refueling Station - Gaseous H2 bab, cel B79           Hydrogen Losses due to leaks         0.50%         Kearth, Re, et al.	Compressor Isentropic Efficiency		65%		(HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	HDSAM version 2.02 default, Refueling Station - Gaseous H2 tab, cell B69
Operating Capacity       (HDSAM) V2.0. Argonne, LL: Argonne National Laboratory       Application usperising framework of stations during during of stations during	Design Capacity		1,516 ki	<g day<="" h2="" td=""><td>Conventional Pathway Options Analysis Results . Interim Report Section 2.1.4. DE-FG36- 05GO15032.</td><td>HDSAM version 2.02 calculation based on Chevron fueling profiles (Nexant Report - Section 2.1.4): = adjusted disp. Rate'(1+summer surge)'(1+Friday surge), Refueling Station - Gaseous H2 tab, cell B32</td></g>	Conventional Pathway Options Analysis Results . Interim Report Section 2.1.4. DE-FG36- 05GO15032.	HDSAM version 2.02 calculation based on Chevron fueling profiles (Nexant Report - Section 2.1.4): = adjusted disp. Rate'(1+summer surge)'(1+Friday surge), Refueling Station - Gaseous H2 tab, cell B32
Site storage (Low Pressure)         Nexant, Inc. et al. (2008, May), H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.3.2.4 DE-FG36- Bise storage (Cascade)         HDSAM version 2.02 calculation (Nexant Report - Section 2.2.3), Refueling Station Dispensing Pressure           Site storage         691 bis         692 bis         Nexant, Inc. et al. (2008, May), H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.3.2.4 DE-FG36- Bis         HDSAM version 2.02 calculation (Nexant Report - Section 2.3.2.4), Refueling Station - Gaseou Conventional Pathway Options Analysis Results. Interim Report Section 2.3.2.4 DE-FG36- Bis         HDSAM version 2.02 calculation (Nexant Report - Section 2.3.2.4), Refueling Station - Gaseou Conventional Pathway Options Analysis Results. Interim Report Section 2.3.2.5 DE-FG36- Bis         HDSAM version 2.02 default (see Nexant Report - Section 2.3.2.1), Refueling Station - Gaseous H2 tab, cell B79           Hydrogen Losses due to leaks         0.50%         Eligovarity, A., Mintz, M. & Gillette, J. (2006)Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.2.5. DE-FG36- psi         HDSAM version 2.02 default, Refueling Station - Gaseous H2 tab, cell B79           Electrical Voltage Supply Requirement         480         Nexant, Inc. et al. (2008, May) H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.2.5. DE-FG36- Volts         HDSAM version 2.02 calculation (see Nexant Report - Sections 2.2.5. def B13AM version 2.02 calculation (see Nexant Report - Sections 2.2			K	<g day<="" h2="" td=""><td>Elgowainy, A., Mintz, M. &amp; Gillette, J. (2006)<i>Hydrogen Delivery Scenario Analysis Model</i> (HDSAM) V2.0. Argonne, IL: Argonne National Laboratory</td><td>Adjusted dispensing rate=city use/number of stations/utilization factor, Refueling Station - Gaseous H2 tab, cell B33</td></g>	Elgowainy, A., Mintz, M. & Gillette, J. (2006) <i>Hydrogen Delivery Scenario Analysis Model</i> (HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	Adjusted dispensing rate=city use/number of stations/utilization factor, Refueling Station - Gaseous H2 tab, cell B33
Site storage (Cascade)       Nexant, Inc. et al. (2008, May) H2A. Hydrogen Delivery Infrastructure Analysis Models and Dispensing Pressure       Dispensing Pressure       Abstract Inc. et al. (2008, May) H2A. Hydrogen Delivery Infrastructure Analysis Models and Dispensing Pressure       Dispensing Pressure       Abstract Inc. et al. (2008, May) H2A. Hydrogen Delivery Infrastructure Analysis Models and Dispensing Pressure       Dispensing Pressure       Conventional Pathway Options Analysis Results. Interim Report Section 2.3.2.4 Models and Dispensing Pressure       HDSAM decluations (Nexant Report - Section 2.3.2.4), Refueling Station - Gaseous H2 tab, cell B79         Hydrogen Loses due to leaks       0.50%       Conventional Pathway Options Analysis Results. Interim Report Section 2.2.5. DE-FG36- psi       HDSAM version 2.02 default, Refueling Station - Gaseous H2 tab, cell B79         Electrical Voltage Supply Requirement       480       Nexamt, Inc. et al. (2008, May) H2A Hydrogen Delivery Infrastructure Analysis Models and Distribution System total capital investment       S3.117,483       Nexamt, Inc. et al. (2008, May) H2A Hydrogen Delivery Infrastructure Analysis Models and Distribution System electricity cost       Nexamt, Inc. et al. (2008, May) H2A Hydrogen Delivery Infrastructure Analysis Models and Distribution System electricity cost       HDSAM version 2.02 default, Refueling Station - Gaseous H2 tab, cell B79         Instructure Analysis Models and Distribution System electricity cost       S3.117,483       Nexamt, Inc. et al. (2008, May) H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.2.5. DE-FG36- B103M       Nexamt Report - Secti			470		Conventional Pathway Options Analysis Results . Interim Report Section 2.2.3. DE-FG36-	calculation HDSAM version 2.02 calculation (Nexant Report - Section 2.2.3), Refueling Station - Gaseous H2 tab, cell B123
Site storage       69% % of design H2 distribution       Nexant, Inc. et al. (2008, May) H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.2.3. DE-FG36- Biglowarry, A., Mintz, M. & Gillette, J. (2006) Hydrogen Delivery Infrastructure Analysis Model and Conventional Pathway Options Analysis Results. Interim Report Section 2.2.3. DE-FG36- Biglowarry, A., Mintz, M. & Gillette, J. (2006) Hydrogen Delivery Infrastructure Analysis Model and Conventional Pathway Options Analysis Results. Interim Report Section 2.2.3. DE-FG36- Biglowarry, A., Mintz, M. & Gillette, J. (2006) Hydrogen Delivery Infrastructure Analysis Model and Conventional Pathway Options Analysis Results. Interim Report Section 2.2.5. DE-FG36- Biglowarry A., Mintz, M. & Gillette, J. (2006) Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.2.5. DE-FG36- Biglowarry A., Mintz, M. & Gillette, J. (2006, May) H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.2.5. DE-FG36- Biglowarry A., Mintz, M. & Gillette, J. (2006) Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.2.5. DE-FG36- Biglowarry A. Mintz, M. & Gillette, J. (2006) Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.2.5. DE-FG36- Biglowarry A. Mintz, M. & Gillette, J. (2006) Hydrogen Delivery Infrastructure Analysis Model Distribution System total capital investment       Saiting and Saiting and S	Site storage (Cascade)			ka H2	Nexant, Inc. et al. (2008, May).H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results . Interim Report Section 2.3.2.4 DE-FG36-	HDSAM calculations (Nexant Report - Section 2.3.2.4), Refueling Station - Gaseous H2 tab, cell B122
Dispensing Pressure         6,250 psi         Conventional Pathway Options Analysis Results. Interim Report Section 2.2.3. DE-FG36- Biological Society         HDSAM version 2.02 default (see Nexant Report-Section 2.3.2), Refueling Station - GSO(15032           Hydrogen Losses due to leaks         0.50%         Elgowainy, A., Mintz, M. & Gillette, J. (2006) Hydrogen Delivery Scenario Analysis Models and (HDSAM) V2.0. Argonne, IL: Argonne National Laboratory (HDSAM)	Site storage					calculation
Implified     Conventional Pathway Options Analysis Results . Interim Report Section 2.2.5.0E-FG36-     HOSAM Version 2.02 celulatin, Returning Station - Gaseous H2 tab, cell B79       Implified     Nexant, Inc. et al. (2008, May) H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results . Interim Report Section 2.2.5.0E-FG36-     HOSAM Version 2.02 celulation (see Nexant Report - Sections 2.2.5.0), E137       Implified     Distribution System total capital investment     \$3,117,483     Nexant, Inc. et al. (2008, May) H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results . Interim Report Section 2.2.5.0E-FG36-     Nexant Report - Section 2.2.5.2       Implified     Distribution System total capital investment     \$3,117,483     Nexant Inc. et al. (2008, May) H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results . Interim Report Section 2.2.5.2     Nexant Report - Section 2.2.5.2       Implified     Distribution System total capital investment     \$3,117,483     Nexant Inc. et al. (2008, May) H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results . Interim Report Section 2.2.5.2     Nexant Report - Section 2.2.5.2       Implified     Distribution System electricity cost     \$115,609     2005 / station yr     HDSAM Version 2.02 celulation, Retueling Station - Gaseous H2 tab, cell B267       Implified     Volti     Elgowainy A. Mintz, M. & Gilletter, J. (2009) Hydrogen Delivery Coenario Analysis Model     HDSAM Version 2.02 calculation, Retueling Station - Gaseous H2 tab, cell	Dispensing Pressure		6,250 p	osi	Conventional Pathway Options Analysis Results . Interim Report Section 2.2.3. DE-FG36- 05GO15032.	HDSAM version 2.02 default (see Nexant Report-Section 2.3.2), Refueling Station - Gaseous H2 tab, cell B58
Electrical Voltage Supply Requirement         Conventional Pathway Options Analysis Results. Interim Report Section 2.2.5. DE-FG36.         HISAM version 2.0.2 calculation (see Nexant Report - Sections 2.2.5. p. Fig. 501)           Distribution System total capital investment         \$3,117,483         Nexant, Inc. et al. (2008, May) H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.2.5. DE-FG36.         Nexant Report - Section 2.2.5. DE-FG36.           Distribution System total capital investment         \$3,117,483         Nexant, Inc. et al. (2008, May) H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.2.5. DE-FG36.         Nexant Report - Section 2.2.5. DE-FG36.           Distribution System electricity cost         \$15,509         2005 / station yr         HDSAM V2.0. Argonne, IL: Argonne National Laboratory         HDSAM version 2.02 calculation, Refueling Station - Gaseous H2 tab, cell B267	Hydrogen Losses due to leaks		0.50%		(HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	HDSAM version 2.02 default, Refueling Station - Gaseous H2 tab, cell B79
Distribution System total capital investment       \$3,117,483       Conventional Pathway Options Analysis Results. Interim Report Section 2.2.5.2. DE-FG36- 0560/0502.       Nexant Report - Section 2.2.5.2         Distribution System electricity cost       \$115,000       Elgowainy, A., Mintz, M. & Gillette, J. (2006)/Hydrogen Delivery Scenario Analysis Model       HDSAM version 2.02 calculation, Refueling Station - Gaseous H2 tab, cell B267         Unstribution System electricity cost       \$115,000       Elgowainy, A., Mintz, M. & Gillette, J. (2006)/Hydrogen Delivery Scenario Analysis Model       HDSAM version 2.02 calculation, Refueling Station - Gaseous H2 tab, cell B267	Electrical Voltage Supply Requirement			Volts	Conventional Pathway Options Analysis Results . Interim Report Section 2.2.5. DE-FG36- 05GO15032.	HDSAM version 2.02 calculation (see Nexant Report - Sections 2.2.5 and 2.2.6), Refueling Station - Gaseous H2 tab, ce B137
Usinibulian system recularly cost. 41/10/04 [2005] / station yr (//DSA/I) V2.0. Angonen, Li. Angonen National Laboratory (//DSA/I) V2.0. Angonen, Li. Angonen National Laboratory (//DSA/IV 20. Angonen, Li. Angonen National Laboratory (///DSA/IV 20. Angonen, Li. Angonen National Laboratory (////) (///////) (//////) (//////) (/////) (/////) (/////) (/////) (////) (////) (////) (////) (////) (////) (////) (///) (///) (///) (////) (///) (///) (////) (/	Distribution System total capital investment			2005\$ / station	Conventional Pathway Options Analysis Results . Interim Report Section 2.2.5.2. DE-FG36- 05GO15032.	Nexant Report - Section 2.2.5.2
Elgowainy, A., Mintz, M. & Gillette, J. (2006) Hydrogen Delivery Scenario Analysis Model	Distribution System electricity cost		\$115,508 <sub>20</sub>	2005\$ / station yr	(HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	HDSAM version 2.02 calculation, Refueling Station - Gaseous H2 tab, cell B267
Ustroution Labor Required 3.951 hr / station yr (HDSAM) V2.0. Argonne, IL: Argonne National Laboratory HDSAM Version 2.02 calculation, Retueling Station - Gaseous H2 tab, Cell B259	Distribution Labor Required		3,951 hr	nr / station yr	Elgowainy, A., Mintz, M. & Gillette, J. (2006) Hydrogen Delivery Scenario Analysis Model (HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	HDSAM version 2.02 calculation, Refueling Station - Gaseous H2 tab, cell B259
Nexant, Inc. et al. (2008, May).H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results . Interim Report Section 2.2.1.3. DE-FG36- 2005\$ / station yr 05G015032.	Distribution System labor cost			2005\$ / station yr	Nexant, Inc. et al. (2008, May) H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results . Interim Report Section 2.2.1.3. DE-FG36- 05G015032.	Bureau of Labor and Statistics (Nexant Report - Section 2.2.1.3), Refueling Station - Gaseous H2 tab, cell B260
Nexant, Inc. et al. (2008, May) H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results . Interim Report Section 2.2.1.2. DE-FG36- 2005\$ / station yr USGO15032.	Distribution System total O&M cost			2005\$ / station yr	Conventional Pathway Options Analysis Results . Interim Report Section 2.2.1.2. DE-FG36-	HDSAM version 2.02 calculations (Nexant Report - Section 2.2.1.2), Refueling Station - Gaseous H2 tab, cell B283

Parameter		Value	Units	Reference	Comments
Other Assumption	ons for WTW Calculations				
Share of RFG in Tota	Il Gasoline Use	100%		U.S. Department of Energy & U.S. Department of Transportation. (2006, December/Hydrogen Posture Plan An Inegrated Research, Development and Demonstration Plan.	Basis for posture plan
Type of Oxygenate in	RFG	None		U.S. Department of Energy & U.S. Department of Transportation. (2006, DecemberHydrogen Posture Plan An Inegrated Research, Development and Demonstration Plan.	Basis for posture plan
O2 Content in RFG		0%	wt %	U.S. Department of Energy & U.S. Department of Transportation. (2006, December)Hydrogen Posture Plan An Inegrated Research, Development and Demonstration Plan.	Basis for posture plan
Ratio of FCV VOCs (	emissions) to GVs fueled with CG & RFG	0%		Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology, development, Use and Results. Argonne, IL: Argonne National Laboratory.	GREET default, Table 4.45 FCV: H2
Ratio of FCV VOCs (	evaporative) to GVs fueled with CG & RFG	0%		Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology, development, Use and Results. Argonne, IL: Argonne National Laboratory.	GREET default, Table 4.45 FCV: H2
Ratio of FCV CO em	issions to GVs fueled with CG & RFG	0%		Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology, development, Use and Results. Argonne, IL: Argonne National Laboratory.	GREET default, Table 4.45 FCV: H2
Ratio of FCV NOx er	nissions to GVs fueled with CG & RFG	0%		Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology, development, Use and Results. Argonne, IL: Argonne National Laboratory.	GREET default, Table 4.45 FCV: H2
Ratio of FCV Exhaus	t PM10 emissions to GVs fueled with CG & RFG	0%		Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology, development, Use and Results. Argonne, IL: Argonne National Laboratory.	GREET default, Table 4.45 FCV: H2
Ratio of FCV Brake &	Tire Wear PM10 emissions to GVs fueled with CG & RFG	100%		Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology, development, Use and Results. Argonne, IL: Argonne National Laboratory.	GREET default, page 197: vehicles within the same weight class have similar tire and brake wear emissions
Ratio of FCV Exhaus	t PM2.5 emissions to GVs fueled with CG & RFG	0%		Wang, M.Q. (2008, September 5). The Greenhouse Gases, Regualted Emissions, and Energy Use in Transportation (GREET) Model, Version 1.8b. Argonne, IL: Argonne National Laboratory.	GREET default:well-known fuel cell emissions (no PM2.5)
Ratio of FCV Brake &	Tire Wear PM2.5 emissions to GVs fueled with CG & RFG	100%		Wang, M.Q. (2008, September 5). The Greenhouse Gases, Regualted Emissions, and Energy Use in Transportation (GREET) Model, Version 1.8b. Argonne, IL: Argonne National Laboratory.	GREET default-reasonable to assume FCV has same driving pattern as GV
Ratio of FCV CH4 er	nissions to GVs fueled with CG & RFG	0%		Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology, development, Use and Results. Argonne, IL: Argonne National Laboratory.	GREET default, Table 4.45 FCV: H2
Ratio of FCV N2O er	nissions to GVs fueled with CG & RFG	0%		Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology, development, Use and Results. Argonne, IL: Argonne National Laboratory.	GREET default, Table 4.45 FCV: H2
Marginal Electricity G	eneration Mix for Transportation Use	US Mix		U.S. Department of Energy & U.S. Department of Transportation. (2006, December)Hydrogen Posture Plan An Inegrated Research, Development and Demonstration Plan.	Basis for posture plan
Results					
Levelized Cost		\$4.68	\$ / ka	Ruth, M. et al. (2009, March). Hydrogen Macro System Model User Guide. NREL/TP-6A1-44799 Golden, CO: National Renewable Energy Laboratory.	MSM Results
WTW Coal Input		5,408	Btu / mile	Ruth, M. et al. (2009, March). Hydrogen Macro System Model User Guide. NREL/TP-6A1-44799 Golden, CO: National Renewable Energy Laboratory.	MSM Results
WTW Natural Gas In	put	204	Btu / mile	Ruth, M. et al. (2009, March). Hydrogen Macro System Model User Guide. NREL/TP-6A1-44799 Golden, CO: National Renewable Energy Laboratory.	MSM Results
WTW Petroleum Inpi	ıt	80	Btu / mile	Ruth, M. et al. (2009, March). Hydrogen Macro System Model User Guide. NREL/TP-6A1-44799 Golden, CO: National Renewable Energy Laboratory.	MSM Results
WTW Fossil Energy	Input	5,693	Btu / mile	Ruth, M. et al. (2009, March). Hydrogen Macro System Model User Guide. NREL/TP-6A1-44799 Golden, CO: National Renewable Energy Laboratory.	MSM Results
WTW Total Energy In	nput	5,859	Btu / mile	Ruth, M. et al. (2009, March). Hydrogen Macro System Model User Guide. NREL/TP-6A1-44799 Golden, CO: National Renewable Energy Laboratory.	MSM Results
WTW CO2 Emission	8	149	g / mile	Ruth, M. et al. (2009, March). Hydrogen Macro System Model User Guide. NREL/TP-6A1-44799 Golden, CO: National Renewable Energy Laboratory.	MSM Results
WTW CH4 Emission	5	1	g / mile	Ruth, M. et al. (2009, March). Hydrogen Macro System Model User Guide. NREL/TP-6A1-44799 Golden, CO: National Renewable Energy Laboratory.	MSM Results
WTW N2O Emission	8	0	g / mile	Ruth, M. et al. (2009, March). Hydrogen Macro System Model User Guide. NREL/TP-6A1-44799 Golden, CO: National Renewable Energy Laboratory.	MSM Results
WTW GHG Emission	IS	166	g / mile	Ruth, M. et al. (2009, March). Hydrogen Macro System Model User Guide. NREL/TP-6A1-44799 Golden, CO: National Renewable Energy Laboratory.	MSM Results

Appendix G — Wind Electrolysis–Pipeline Supporting Tables and Figures

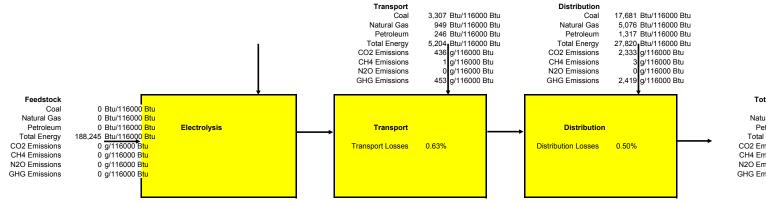
#### Hydrogen Produced In Central Plant and Transported as Gas via Pipeline



In	iputs	Graphic Depiction & Assumptions	Outputs
		Wind Electricity Wind-generated electricity on the grid is assumed. The electrolyzers are not necessarily co-located with the wind	farm.
			Electricity price at H2 production \$0.055 2005 \$ / short ton Levelized Cost of Wind Electricity \$2.99 2005\$ / kg H2 distributed
Coal Input from "Well" Natural Gas Input from "Well" Petroleum Input from "Well"	0 Btu / 116000Btu to Pump 0 Btu / 116000Btu to Pump 0 Btu / 116000Btu to Pump		WTG C02 Emissions         0 g / 116000Btu to Pump           WTG CH4 Emissions         0 g / 116000Btu to Pump           WTG N20 Emissions         0 g / 116000Btu to Pump           WTG GHG Emissions         0 g / 116000Btu to Pump
Electricity consumption	53.48 kWh / kg H2	Hydrogen Production	Hydrogen Output Pressure 450 psi
Process Water Consumption	11.1 L / kg H2	Central plant design capacity 52,300 kg/	
Cooling Water Consumption Electrolyzer Cost Total Capital Investment	1112 L / kg H2 675 \$ / kW \$110,432,050 2005\$	Capacity factor 97% Process energy efficiency 62.3% Electricity Mix Mind Electricity After-tax IRR 10% Assumed Plant Life 40	Electricity cost \$2.96 2005 / kg H2 produced Other operating costs \$0.38 2005 / kg H2 produced Levelized Cost of Prod (excl feedst \$1.56 2005\$ / kg H2 distributed
Coal Input from "Well" Natural Gas Input from "Well" Petroleum Input from "Well"	0 Btu / 116000Btu to Pump 0 Btu / 116000Btu to Pump 0 Btu / 116000Btu to Pump		H2 Prod CO2 Emissions     0 g / 116000Btu to Pump       H2 Prod CH4 Emissions     0 g / 116000Btu to Pump       H2 Prod N20 Emissions     0 g / 116000Btu to Pump       H2 Prod GHG Emissions     0 g CO2 eq./ 116000 Btu
Electricity consumption for compressor Electricity consumption for geo storage	0.56 kWh / kg H2 0.01 kWh / kg H2	Pipelines for Delivery	Total capital investment \$3.51 2005\$/annual kg distributed Electricity cost \$0.03 2005\$ / kg H2
Total electricity consumption Electricity price for compressor Electricity price for geologic storage	0.57 kWh / kg H2 \$0.056 2005\$ / kWh \$0.052 2005\$ / kWh	City Population         1.247.364 pe           Hydrogen Vehicle Penetration         50%           City hydrogen use         125,810,766 kg           Distance from City to Production Facility         62 mil           Geologic storage capacity         3,762,787 kg           Trunk # 1-ine length         17 mil	ple Levelized Cost of Delivery \$0.92 2005\$ / kg H2 distributed / yr es H2 es
Coal Input from "Well" Natural Gas Input from "Well" Petroleum Input from "Well"	3,307 Btu / 116000Btu to Pump 949 Btu / 116000Btu to Pump 246 Btu / 116000Btu to Pump	Trunk #2-line length         40 mil           Service-line length         1.1 mil           Number of service lines         270           Hydrogen losses         1.12%           Hydrogen loss factor         1.011	es / line Delivery CO2 Emissions 436 g / 116000Btu to Pump Delivery CH4 Emissions 1 g / 116000Btu to Pump Delivery N20 Emissions 0 g / 116000Btu to Pump Delivery GHG Emissions 453 g CO2 eq./ 116000 Btu
Electricity consumption Electricity price	3.04 kWh / kg H2 \$0.082 2005\$ / kWh	Forecourt Distribution	Hydrogen outlet pressure 6,250 psi Basis – Hydrogen Quantity 116,000 Btu (116,000 Btu/gal non-oxy
		Number of Distribution Stations         270           Energy efficiency         92%           Number of Compression Steps         4	Total capital investment     \$6.69 2005\$/annual kg       Electricity cost     \$0.25 2005\$ / kg H2       Levelized Cost of Distribution     \$1.69 2005\$ / kg H2 distributed
Coal Input from "Well" Natural Gas Input from "Well"	17,681 Btu / 116000Btu to Pump 5,076 Btu / 116000Btu to Pump	Isentropic Efficiency 65% Site storage 69% og Hydrogen losses 0.50% Hydrogen loss factor 1.005	Acity CSD CO2 Emissions 2,333 g / 116000Btu to Pump CSD CH4 Emissions 3 g / 116000Btu to Pump CSD N2O Emissions 0 g / 116000Btu to Pump
Petroleum Input from "Well"	1,317 Btu / 116000Btu to Pump	Natural Gas Input from "Well"         6,026 Bth           Petroleum Input from "Well"         1,564 Bth           Fossil Energy Input from "Well"         28,577 Bth           WTP CO2 Emissions         2,772 gth           WTP CH4 Emissions         4 g /	
		Vehicle           Fuel Economy         45.0 mil           Ratio of FCV VOCs (emissions) to GVs         0%           fueled with CG & RFG         0%           Ratio of FCV VOCs (evaporative) to GVs         0%           fueled with CG & RFG         0%           fueled with CG & RFG         0%           Ratio of FCV NOS (evaporative) to GVs         0%           fueled with CG & RFG         0%           Ratio of FCV NOS emissions to GVs         0%           fueled with CG & RFG         0%	/ GGE
		Ratio of FCV Exhaust PM10 emissions to GVs fueled with CG & RFG 0%	
		Ratio of FCV Brake & Tire Wear PM10 emissions to GVs fueled with CG & RFG 100% Ratio of FCV Exhaust PM2.5 emissions	
		Ratio of FCV Brake & Tire Wear PM10 emissions to GVs fueled with CG & RFG 100%	

Well-to-Wheel Results Coal Input from "Well" Natural Gas Input from "Well"

wen-to-wheel Results	
Coal Input from "Well"	467 Btu / mi
Natural Gas Input from "Well"	134 Btu / mi
Petroleum Input from "Well"	35 Btu / mi
Fossil Energy Input from "Well"	636 Btu / mi
WTW CO2 Emissions	62 g / mi
WTW CH4 Emissions	0 g / mi
WTW N2O Emissions	0 g / mi
WTW GHG Emissions	64 g / mi
Levelized Cost of Hydrogen (\$/mi)	\$0.1591 2005 \$/mi



Total to Del	liver 116000 Btu Fuel	Check
Coal	20,988	20,988
Natural Gas	6,026	6,026
Petroleum	1,564	1,564
Total Energy	221,268	221,268
CO2 Emissions	2,770	2,772
CH4 Emissions	4	4
N2O Emissions	0	0
GHG Emissions	2,872	2,874

Parameter .	N-1	11-21	Dife	0
Parameter	Value	Units	Reference	Comments
Case Definition				
Base Year	2005		None	Default for Wind-Pipe Pathway study
Production Technology Form of H2 During Delivery	Wind Gas		None	Default for Wind-Pipe Pathway study Default for Wind-Pipe Pathway study
Delivery Mode	Pipeline		None	Default for Wind-Pipe Pathway study
Forecourt Station Size	1278	kg/day	James, B.D. (2008, May 23). Current (2005) Steam Methan Reformer (SMR) at Forecourt	Current forecourt H2A production from natural gas basis version 2.0.1; Input_Sheet_Template tab; Plant Output, cell
Vehicle Type	passenger cars		1500kg/day. Arlington, VA: Directed Technologies Inc. None	C23 Default for Wind-Pipe Pathway study
Vehicles' Fuel Economy	45.0	mile / gge	Rousseau, A. & Wallner, T. (2008, October 7). Prospects on Fuel Efficiency Improvements for Hydrogen Powered Vehicles. Argonne National Laboroatory presentation, Chicago, IL. Retreived from http://www.transportation.anl.gov/pdfs/HV/530.pdf	Calculated from data in the presentation. The fuel economy for today's average mid-size vehicle was estimated by the Powertrain Simulation Analysis Toolkit V 62. SP1, Summer 2008 (PSAT - http://www.transportation.anl.gov/modeling_simulation/PSAT/index.htm). 45 mile/gge is the estimated on-road fuel economy which was determined by multiplying the projected EPA lab-rated fuel economy of 52.5 mile/gge by 0.85.
Market Definition				
City Population	1,247,364	people	Elgowainy, A., Mintz, M. & Gillette, J. (2006) Hydrogen Delivery Scenario Analysis Model (HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	HDSAM City Selection; Scenario tab; Indianapolis, IN, cell B9
Market penetration	50%	(% vehicles in city)	U.S. Department of Energy & U.S. Department of Transportation. (2006, December). Hydrogen Posture Plan An Inegrated Research, Development and Demonstration Plan.	Basis for posture plan
Number of H2 vehicles in city	462,772	H2 vehicles / city	Elgowainy, A., Mintz, M. & Gillette, J. (2006). Hydrogen Delivery Scenario Analysis Model (HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	Demand calculation by HDSAM version 2.02; Scenario tab; Number of H2 vehicles in city, cell F17
Miles driven per vehicle	12,000	mile / vehicle year	Elgowainy, A., Mintz, M. & Gillette, J. (2006). Hydrogen Delivery Scenario Analysis Model (HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	Key delivery input in HDSAM version 2.02; Scenario tab; Miles driven per year/ vehicle, cell C19
City hydrogen use	344,451	kg / d	Elgowainy, A., Mintz, M. & Gillette, J. (2006). Hydrogen Delivery Scenario Analysis Model (HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	Demand calculation by HDSAM version 2.02; Scenario tab; City H2 daily use, cell F18
Number of H2 refueling stations in city	270		Elgowainy, A., Mintz, M. & Gillette, J. (2006). Hydrogen Delivery Scenario Analysis Model (HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	Demand calculation by HDSAM version 2.02; Scenario tab; Number of H2 fueling stations in city, cell F19
Number of H2 stations/Number of gasoline stations	41%		Elgowainy, A., Mintz, M. & Gillette, J. (2006). Hydrogen Delivery Scenario Analysis Model (HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	Demand calculation by HDSAM version 2.02; Scenario tab; Number of H2 stations/Number of gasoline stations, cell F21
Average distance between stations (mi)	1.46	miles	Elgowainy, A., Mintz, M. & Gillette, J. (2006). Hydrogen Delivery Scenario Analysis Model (HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	Demand calculation by HDSAM version 2.02; Scenario tab; Average distance between stations, cell F22
Feedstock Recovery, Processing, & Transport				
Electricity (Utility)				
Grid mix for production & delivery utility electricity	US Mix		Energy Information Administration. (2007, February). Annual Energy Outlook 2007 with	US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages
Biomass Fraction	1.2%		Projections to 2030. DOE/EIA-0383(2007). Washington, D.C. Retreived from www.eia.doe.gov/oiaf/archive/aeo07/index.html	calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbo Neutral)" category
Coal Fraction	51.7%		Energy Information Administration. (2007, February). Annual Energy Outlook 2007 with Projections to 2030. DOE/EIA-0383(2007). Washington, D.C. Retreived from www.eia.doe.gov/loid/archive/aeo07/index.html	US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbo Neutral)" category
Natural Gas Fraction	15.7%		Energy Information Administration. (2007, February). Annual Energy Outlook 2007 with Projections to 2030. DOE/EIA-0383(2007). Washington, D.C. Retreived from www.eia.doe.gov/oiaf/archive/ae007/index.html	US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbo Neutral)" category
Nuclear Fraction	20.3%		Energy Information Administration. (2007, February). Annual Energy Outlook 2007 with Projections to 2030. DDE/EIA-0383(2007). Washington, D.C. Retreived from www.eia.doe.gov/oiaf/archive/aeo07/index.html	US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbo Neutral)" category
Residual Oil Fraction	2.9%		Energy Information Administration. (2007. February). Annual Energy Outlook 2007 with Projections to 2030. DOE/EIA-0383(2007). Washington, D.C. Retreived from www.eia.doe.gov/oiaf/archive/aeo07/index.html	US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbo Neutral)" category
Others (Carbon Neutral)	8.2%		Energy Information Administration. (2007, February). Annual Energy Outlook 2007 with Projections to 2030. DOE/EIA-0383(2007). Washington, D.C. Retreived from www.eia.doe.gov/oiaf/archive/ae007/index.html	US grid mix. National electricity generation data from tables D-7 & D-8 using the 2005 timeframe. Percentages calculated from total generation values reported with all renewables except biomass aggregated into the "Others (Carbo Neutral)" category
Grid mix for pipeline compressors	US Mix		None	Default for Wind-Pipe Pathway study
Grid mix for compression at distribution Electricity (Feedstock)	US Mix		None	Default for Wind-Pipe Pathway study
Grid mix for production	Wind Electricity		None	Default for Wind-Pipe Pathway study
H2 Production				
Production Facility Average Output		kg / facility d (after capacity factor is included)	Ramsden, T. (2008, May 28). Current (2005) Hydrogen from Central Grid Electrolysis. Golden, CO: National Renewable Energy Laboratory.	Current central H2A production from electricity basis version 2.1.2; Input_Sheet_Template tab; cell C23
Corresponding capacity factor	97%		Ramsden, T. (2008, May 28). Current (2005) Hydrogen from Central Grid Electrolysis. Golden, CO: National Renewable Energy Laboratory.	Current central H2A production from electricity basis version 2.1.2; Input_Sheet_Template tab; cell C21 Note that this technology is higher than others due to its simplicity
Total Capital Investment	\$110,432,050	2005 \$	Ramsden, T. (2008, May 28). Current (2005) Hydrogen from Central Grid Electrolysis. Golden, CO: National Renewable Energy Laboratory.	Current central H2A production from electricity basis version 2.1.2; Input_Sheet_Template tab; cell C96
Electricity feedstock consumption	53.5	kWh / kg H2	Ramsden, T. (2008, May 28). Current (2005) Hydrogen from Central Grid Electrolysis. Golden, CO: National Renewable Energy Laboratory.	Current central H2A production from electricity basis version 2.1.2; Input_Sheet_Template tab; cell E66; 62% Efficiency on LHV basis from Norsk Hydro Quote
Electricity feedstock cost	\$0.055	2005 \$/kWh	Energy Information Administation. (2005, February) Annual Energy Outlook 2005 With Projections to 2025. DOE/EIA-0383(2005). Washington, D.C.: U.S. Department of Energy.	Assumed that wind electricity price would match industrial electricity price from AEO 2005 "High A" case for startup year (2005). Escalated from 2003 dollars to 2005 dollars. File downloaded from http://www.eia.doe.gov/oiaf/aeo/index.html (file name aeo_hw-3.xis)
Electricity utility consumption (both production, carbon capture & transport, and o		kWh / kg H2		All electricity is considered feedstock.
Electricity utility consumption (production only) Process Water Consumption	0.00 2.94	kWh / kg H2 gal / kg H2	Ramsden, T. (2008, July 2). Current (2005) Hydrogen Production from Distributed Grid Electrolysis. Golden, CO: National Renewable Energy Laboratory.	All electricity is considered feedstock. Current central H2A production from electricity basis version 2.1.2; Input_Sheet_Template tab; cell D126. Value from Norsk Hydro Quote (2002) 11 per Nm3 H2 At 89.9 g H2/Nm3 and 3.785L/gal, this equals 2.939 gal/kg
	294		Ramsden, T. (2008, July 2). Current (2005) Hydrogen Production from Distributed Grid	Current central H2A production from electricity basis version 2.1.2; Input_Sheet_Template tab; cell D128; ASPEN
Water Consumption for Cooling	201	gal / kg H2	Electrolysis . Golden, CO: National Renewable Energy Laboratory.	modeling - see ProcessFlow sheet for details (Mike Penev) in Ramsden, 2008.

Parameter	Value	Units	Reference	Comments
Compressed Inert Gas	0.023	Nm^3 / kg H2	Ramsden, T. (2008, July 2). Current (2005) Hydrogen Production from Distributed Grid Electrolysis. Golden, CO: National Renewable Energy Laboratory.	Current central H2A production from electricity basis version 2.1.2; Input_Sheet_Template tab; cell D130
Electricity co-product production		kWh / kg H2	Elositolysic. Solden, CO. Hallonar Honowable Energy Eaboratory.	N/A
Oxygen co-product production		kg / kg H2		N/A
Steam co-product production		kg / kg H2	Remarkers T. (2009, July 2), Current (2005) Mudaness Breduction from Distributed Crid	N/A Current control UDA production from electricity basic upraion 2.4.2) Control Control to COL CO2. Taken from a Narak
Electrolyzer Equipment Cost (Uninstalled)	\$675	\$ / kW	Ramsden, T. (2008, July 2). Current (2005) Hydrogen Production from Distributed Grid Electrolysis . Golden, CO: National Renewable Energy Laboratory.	Current central H2A production from electricity basis version 2.1.2; Capital Costs tab; Cell C32 - Taken from a Norsk Hydro Quote
Total Annual Fixed Operating Costs	\$5,413,991	2005\$ / yr	Ramsden, T. (2008, July 2). Current (2005) Hydrogen Production from Distributed Grid Electrolysis . Golden, CO: National Renewable Energy Laboratory.	Current central H2A production from electricity basis version 2.1.2; Input_Sheet_Template tab; cell "fixed" = C112
Total Annual Variable Operating Costs	\$55,873,500	-	Ramsden, T. (2008, July 2). Current (2005) Hydrogen Production from Distributed Grid Electrolysis. Golden, CO: National Renewable Energy Laboratory.	Current central H2A production from electricity basis version 2.1.2; Input_Sheet_Template tab; cell "total_var" = C153
Total Annual Operating Costs	\$61,287,491	2005\$ / yr	Calculation	Sum of fixed and variable operating costs
Production energy efficiency (does not include electricity for CSD)	62.3%		Calculated from H2A values Ramsden, T. (2008, July 2). Current (2005) Hydrogen Production from Distributed Grid	Calculated from H2A values based on Electricity requirement which was stated in Norsk Hydro Quote
Hydrogen outlet pressure (before CSD)	450	psi	Electrolysis. Golden, CO: National Renewable Energy Laboratory.	Discussion on Description tab
Hydrogen quality before transport	99.990%	% H2	D. Steward (personal communication).	
inancial Parameters				
After-tax Real IRR	10%		Mann, M., & Steward, D.M. (2008, May 28). Current (2005) Hydrogen from Biomass via Gasification and Catalytic Steam Reforming. Golden, CO: National Renewable Energy Laboratory.	Current central H2A production from biomass basis version 2.1.2; Input_Sheet_Template tab; After-tax Real IRR, cell C47
Plant Life	40	years	Mann, M., & Steward, D.M. (2008, May 28). Current (2005) Hydrogen from Biomass via Gasification and Catalytic Steam Reforming. Golden, CO: National Renewable Energy Laboratory.	Current central H2A production from biomass basis version 2.1.2; Input_Sheet_Template tab; Plant life, cell C34
Federal Tax Rate	35.0%		Mann, M., & Steward, D.M. (2008, May 28). Current (2005) Hydrogen from Biomass via Gasification and Catalytic Steam Reforming. Golden, CO: National Renewable Energy Laboratory.	Current central H2A production from biomass basis version 2.1.2; Input_Sheet_Template tab; Federal taxes, cell C49
State Tax Rate	6.0%		Mann, M., & Steward, D.M. (2008, May 28). Current (2005) Hydrogen from Biomass via Gasification and Catalytic Steam Reforming. Golden, CO: National Renewable Energy Laboratory.	Current central H2A production from biomass basis version 2.1.2; Input_Sheet_Template tab; State taxes, cell C48
Total Tax Rate	38.9%		Mann, M., & Steward, D.M. (2008, May 28). Current (2005) Hydrogen from Biomass via Gasification and Catalytic Steam Reforming. Golden, CO: National Renewable Energy Laboratory.	Current central H2A production from biomass basis version 2.1.2; Input_Sheet_Template tab; Total tax Rate, cell C50
Frection Equity	100%		Mann, M., & Steward, D.M. (2008, May 28). Current (2005) Hydrogen from Biomass via Gasification and Catalytic Steam Reforming. Golden, CO: National Renewable Energy Laboratory.	Current central H2A production from biomass basis version 2.1.2; Input_Sheet_Template tab; Equity Financing, cell C
Transport, Delivery, and Storage Energy Requirements				
Pipeline Delivery				
Average Hydrogen Flowrate (Entering System)	348,364	kg/hr	Elgowainy, A., Mintz, M. & Gillette, J. (2006) <i>Hydrogen Delivery Scenario Analysis Model</i> (HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	HDSAM calculation based on input parameters: city, market penetration, dispensing rate (PEAK FLOW RATE THRU TRANSMISIIION SYSTEM=CITY PEAK DEMAND/TRANSMISIION PIPELINE MASS EFFICIENCY/REF.STATION MASS EFFICIENCY)
Average Hydrogen Flowrate (Distributed)	344,451	kg/hr	Elgowainy, A., Mintz, M. & Gillette, J. (2006) <i>Hydrogen Delivery Scenario Analysis Model</i> (HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	HDSAM calculation based on input parameters: city, market penetration, dispensing rate (Ave. daily use=CITY DAILY USE/TOTAL PIPELINE MASS EFFICIENCY/REF.STATION MASS EFFICIENCY)
Summer Surge: % above the System Average Daily Demand	10%	% above Average Daily Demand	Nexant, Inc. et al. (2008, May), H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.1.9. DE-FG36- 05G015032.	Nexant Report - Section 2.1.9
Friday Peak	8%	% above Average Daily Demand	Nexant, Inc. et al. (2008, May). H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.1.9. DE-FG36- 05GO15032.	Nexant Report - Section 2.1.9
Peak Hydrogen Flowrate	381,192	kg/hr	Elgowainy, A., Mintz, M. & Gillette, J. (2006) <i>Hydrogen Delivery Scenario Analysis Model</i> (HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	HDSAM calculation based on input parameters: city, market penetration, dispensing rate (PEAK FLOWRATE THRU DISTRIBUTION SYSTEM=CITY PEAK DEMAND/DISTRIBUTION PIPELINE MASS EFFICIENCY/REF.STATION MAS EFFICIENCY)
Total Capital Investment for Compressors	\$27,199,794		Elgowainy, A., Mintz, M. & Gillette, J. (2006) <i>Hydrogen Delivery Scenario Analysis Model</i> (HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	HDSAM calculations, data from disscussions with Bechtel and Air Liquide (see ref. in Nexant report - Section 2.2.5)
Hydrogen Losses from Compressors	0.50%		Nexant, Inc. et al. (2008, May). H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.2.14. DE-FG36- 05G015032.	Table 2.26
Compressor Electricity Demand	70,343,075	kWh / year	Nexant, Inc. et al. (2008, May).H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.2.5. DE-FG36- 05GO15032.	HDSAM calculations - data from Nexant recommendations (based on vendor data from Neuman&Esser, Burckhardt Compression, Ariel Compressors, Dresser-Rand - see Nexant report - Section 2.2.5)
Compressor Electricity Demand	0.5591	kWh / kg H2	Nexant, Inc. et al. (2008, May). H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.2.5. DE-FG36- 05G015032.	HDSAM calculations - data from Nexant recommendations (based on vendor data from Neuman&Esser, Burckhardt Compression, Ariel Compressors, Dresser-Rand - see Nexant report - Section 2.2.5)
Compressor Electricity Cost	\$0.056	2005\$ / kWh	Energy Information Administration. (2005, January) Annual Energy Outlook 2005 with Projections to 2025. DOE/EIA-0383(2005). Washington, D.C. Retreived from http://www.eia.doe.gov/oiaf/archive/aeo05/index.html	EIA AEO 2005 and 2007
Total Capital Investment for Pipeline System	\$377,283,372		Nexant, Inc. et al. (2008, May).H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.2.2. DE-FG36- 05G015032.	HDSAM calculations based on data from GTI, Bechtel, Air Liquide, UC Davis (Nexant Report -Section 2.2.2)
Hydrogen Losses from Pipelines	0.10%		Nexant, Inc. et al. (2008, May).H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.2.14. DE-FG36- 05G015032.	Calculated based upon natural gas pipelines; Nexant report - Section 2.2.14
Number of transmission pipelines	1		Elgowainy, A., Mintz, M. & Gillette, J. (2006) Hydrogen Delivery Scenario Analysis Model (HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	Default in HDSAM
Transmission pipeline diameter	11.00	in	Elgowainy, A., Mintz, M. & Gillette, J. (2006) <i>Hydrogen Delivery Scenario Analysis Model</i> ( <i>HDSAM</i> ) V2.0. Argonne, IL: Argonne National Laboratory	HDSAM Calculation: Panhandle B equation (Gas Processors Supplier Association, Engineering Data Book, 11th Edition 1998, http://gpsa.gasprocessors.com)
Transmission pipeline inlet pressure	999	psi	Interstanty 22.5 regiones, i.e. Anglonie reasonal Education of Mexant, Inc. et al. (2008, May), IP2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.1.6. DE-FG36-05GO15032.	Recommendations from Nexant in conjuction with Air Liquide, GTI, Chevron, TIAX, ANL, PNNL and NREL - see Nexan Report - Section 2.1.6)
Transmission pipeline outlet pressure	705	psi	Desort 10022. Nexant, Inc. et al. (2008, May).H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.1.6. DE-FG36- 05GO15032.	Recommendations from Nexant in conjuction with Air Liquide, GTI, Chevron, TIAX, ANL, PNNL and NREL - see Nexar Report - Section 2.1.6)

Parameter	Value	Units	Reference	Comments
Transmission pipeline temperature	25	с	Nexant, Inc. et al. (2008, May).H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.1.6. DE-FG36- 05GO15032.	Recommendations from Nexant in conjuction with Air Liquide, GTI, Chevron, TIAX, ANL, PNNL and NREL - see Nexa Report - Section 2.1.6)
Transmission pipeline length	62	miles	Elgowainy, A., Mintz, M. & Gillette, J. (2006) <i>Hydrogen Delivery Scenario Analysis Model</i> (HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	Based on input parameter: city
Number of trunk pipelines	4		Nexant, Inc. et al. (2008, May). H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. DE-FG36-05G015032.	HDSAM calculations based on input data and HDSAM distribution model - not documented; "The pipeline model inclu up to four trunk lines within a given metropolitan area with service lines extending from the trunk lines to the reflueling stations. The model iterates on the number and location of trunk lines within a given metropolitan area until an optimur distribution configuration is obtained at a minimum cost." Nexant (2008) sect 2.4.3, 2.1.6, 2.2.2
Trunk #1 pipeline diameter	7.25	in	Nexant (2008) Section 2.4.3, 2.1.6, 2.2.2; H2A Delivery Components User Guide (2006) sect 5.15.4	HDSAM Calculation: Panhandle B equation (Gas Processors Supplier Association, Engineering Data Book, 11th Editit 1998, http://gpsa.gasprocessors.com) Equations and explanations can be found in Component Delivery User Guide.
Trunk #1 pipeline inlet pressure	603	psi	Nexant, Inc. et al. (2008, May).H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.1.6. DE-FG36- 05GO15032.	Recommendations from Nexant in conjuction with Air Liquide, GTI, Chevron, TIAX, ANL, PNNL and NREL - see Nexa Report - Section 2.1.6)
Trunk #1 pipeline outlet pressure	397	psi	Nexant, Inc. et al. (2008, May). H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.1.6. DE-FG36- 06G015032.	Recommendations from Nexant in conjuction with Air Liquide, GTI, Chevron, TIAX, ANL, PNNL and NREL - see Nexa Report - Section 2.1.6)
Trunk #1 pipeline temperature	25	с	Nexant, Inc. et al. (2008, May).H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.1.6. DE-FG36- 05GO15032.	Recommendations from Nexant in conjuction with Air Liquide, GTI, Chevron, TIAX, ANL, PNNL and NREL - see Nexa Report - Section 2.1.6)
Trunk #1 pipeline length	17	miles	Elgowainy, A., Mintz, M. & Gillette, J. (2006) Hydrogen Delivery Scenario Analysis Model (HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	HDSAM calculations based on input data and HDSAM distribution model (discussions with Pacific Gas & Electr Company, San Francisco)
Trunk #2 pipeline diameter	10.25	in	Nexant (2008) Section 2.4.3, 2.1.6, 2.2.2; H2A Delivery Components User Guide (2006) sect 5.15.4	HDSAM Calculation: Panhandle B equation (Gas Processors Supplier Association, Engineering Data Book, 11th Editio 1998, http://gpsa.gasprocessors.com) Equations and explanations can be found in Component Delivery User Guide.
Trunk #2 pipeline inlet pressure	588	psi	Nexant, Inc. et al. (2008, May).H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.1.6. DE-FG36- 05GO15032.	Recommendations from Nexant in conjuction with Air Liquide, GTI, Chevron, TIAX, ANL, PNNL and NREL - see Nexan Report - Section 2.1.6)
Trunk #2 pipeline outlet pressure	397	psi	Nexant, Inc. et al. (2008, May).H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.1.6. DE-FG36- 05GO15032.	Recommendations from Nexant in conjuction with Air Liquide, GTI, Chevron, TIAX, ANL, PNNL and NREL - see Nexan Report - Section 2.1.6)
Trunk #2 pipeline temperature	25	с	Nexant, Inc. et al. (2008, May).H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.1.6. DE-FG36- 05GO15032.	Recommendations from Nexant in conjuction with Air Liquide, GTI, Chevron, TIAX, ANL, PNNL and NREL - see Nexan Report - Section 2.1.6)
Trunk #2 pipeline length	40	miles	Nexant (2008) Section 2.4.3, 2.1.6, 2.2.2	HDSAM calculations based on input data and HDSAM distribution model - not documented
Trunk #3 pipeline diameter	12.25	in	Nexant (2008) Section 2.4.3, 2.1.6, 2.2.2; H2A Delivery Components User Guide (2006) sect 5.15.4	HDSAM Calculation: Panhandle B equation (Gas Processors Supplier Association, Engineering Data Book, 11th Editit 1998, http://gpsa.gasprocessors.com) Equations and explanations can be found in Component Delivery User Guide.
Trunk #3 pipeline inlet pressure	573	psi	Nexant, Inc. et al. (2008, May).H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.1.6. DE-FG36- 05GO15032.	Recommendations from Nexant in conjuction with Air Liquide, GTI, Chevron, TIAX, ANL, PNNL and NREL - see Nexan Report - Section 2.1.6)
Trunk #3 pipeline outlet pressure	397	psi	Nexant, Inc. et al. (2008, May).H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.1.6. DE-FG36- 05GO15032.	Recommendations from Nexant in conjuction with Air Liquide, GTI, Chevron, TIAX, ANL, PNNL and NREL - see Nexan Report - Section 2.1.6)
Trunk #3 pipeline temperature	25		Nexant, Inc. et al. (2008, May).H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.1.6. DE-FG36- 05GO15032.	Recommendations from Nexant in conjuction with Air Liquide, GTI, Chevron, TIAX, ANL, PNNL and NREL - see Nexal Report - Section 2.1.6)
Trunk #3 pipeline length	65	miles	Nexant (2008) Section 2.4.3, 2.1.6, 2.2.2	HDSAM calculations based on input data and HDSAM distribution model - not documented
Trunk #4 pipeline diameter	10.75	in	Nexant (2008) Section 2.4.3, 2.1.6, 2.2.2; H2A Delivery Components User Guide (2006) sect 5.15.4	HDSAM Calculation: Panhandle B equation (Gas Processors Supplier Association, Engineering Data Book, 11th Editi 1998, http://gpsa.gasprocessors.com) Equations and explanations can be found in Component Delivery User Guide.
Trunk #4 pipeline inlet pressure	558	psi	Nexant, Inc. et al. (2008, May). H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.1.6. DE-FG36- 05GO15032.	Recommendations from Nexant in conjuction with Air Liquide, GTI, Chevron, TIAX, ANL, PNNL and NREL - see Nexa Report - Section 2.1.6)
Trunk #4 pipeline outlet pressure	397	psi	Nexant, Inc. et al. (2008, May). H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.1.6. DE-FG36- 05GO15032.	Recommendations from Nexant in conjuction with Air Liquide, GTI, Chevron, TIAX, ANL, PNNL and NREL - see Nexa Report - Section 2.1.6)
Trunk #4 pipeline temperature	25	-	Nexant, Inc. et al. (2008, May).H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.1.6. DE-FG36- 05GO15032.	Recommendations from Nexant in conjuction with Air Liquide, GTI, Chevron, TIAX, ANL, PNNL and NREL - see Nexan Report - Section 2.1.6)
Trunk #4 pipeline length		miles	Nexant (2008) Section 2.4.3, 2.1.6, 2.2.2	HDSAM calculations based on input data and HDSAM distribution model - not documented
Number of service pipelines	270		Elgowainy, A., Mintz, M. & Gillette, J. (2006) Hydrogen Delivery Scenario Analysis Model (HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	HDSAM calculations based on input data and HDSAM distribution model (discussions with Pacific Gas & Electric Company, San Francisco)
Service pipeline diameter	1	in	Elgowainy, A., Mintz, M. & Gillette, J. (2006) Hydrogen Delivery Scenario Analysis Model (HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	HDSAM Calculation: Panhandle B equation (Gas Processors Supplier Association, Engineering Data Book, 11th Edition 1998, http://gpsa.gasprocessors.com)
Service pipeline inlet pressure	382	psi	Incontrary sec. or substrate Lie Augustic Management and a substrate of the substrate of	Recommendations from Nexant in conjuction with Air Liquide, GTI, Chevron, TIAX, ANL, PNNL and NREL - see Nexa Report - Section 2.1.6)
Service pipeline outlet pressure	294	psi	Nexant, Inc. et al. (2008, May).H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.1.6. DE-FG36- 05GO15032.	Recommendations from Nexant in conjuction with Air Liquide, GTI, Chevron, TIAX, ANL, PNNL and NREL - see Nexa Report - Section 2.1.6)
Service pipeline temperature	25	с	Nexant, Inc. et al. (2008, May).H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.1.6. DE-FG36- 05GO15032.	Recommendations from Nexant in conjuction with Air Liquide, GTI, Chevron, TIAX, ANL, PNNL and NREL - see Nexan Report - Section 2.1.6)
Service pipeline length	1.1	miles	Elgowainy, A., Mintz, M. & Gillette, J. (2006) Hydrogen Delivery Scenario Analysis Model (HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	HDSAM calculations based on input data and HDSAM distribution model (discussions with Pacific Gas & Electric Company, San Francisco)
Pipeline Geologic Storage Total Capital Investment	\$36,988,376		Nexant, Inc. et al. (2008, May). H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.2.12. DE-FG36- 05G015032.	HDSAM calculations (cost data from ConocoPhilips and Saltville natural gas storage facility in Virginiase. Nexant Rep Section 2.2.12)
Hydrogen Losses from Geologic Storage	0.02%		H2A Components Model User Guide, Section 6.5; Duke Energy, 2005; US EPA, 2003; Natural	
Geologic Storage Capacity	41,864,765	m^3	H2A Components Model User Guide, Section 6.5; Duke Energy, 2005; US EPA, 2003; Natural	

Parameter	Value 3 762 787	Units	Reference	Comments
Geologic Storage Design Capacity Geologic Storage Electricity Demand		kg H2 kWh / year	H2A Components Model User Guide, Section 6.5; Duke Energy, 2005; US EPA, 2003; Natural Nexant (2008) Section 2.2.12, 2.2.5	HDSAM calculations (cost data from ConocoPhilips and Saltville natural gas storage facility in Virginiase. Nexant Repo
,				Sections 2.2.12 and 2.2.5) HDSAM calculations (cost data from ConocoPhilips and Saltville natural gas storage facility in Virginiase. Nexant Repo
Geologic Storage Electricity Demand		kWh / kg H2	Nexant (2008) Section 2.2.12, 2.2.5	Sections 2.2.12 and 2.2.5)
Geologic Storage Electricity Cost	\$0.052	2005\$ / kWh		EIA AEO 2005
Distribution Station				
Gaseous Receiving/Distributing Stations				
Hydrogen Dispensed at Forecourt Station	465,647	kg / station year	Nexant (2008) Section 2.1.3, 2.1.5 Nexant, Inc. et al. (2008, May).H2A Hydrogen Delivery Infrastructure Analysis Models and	HDSAM calculation
Electricity Required by Forecourt Station	1,416,755	kWh / station year	Conventional Pathway Options Analysis Results. Interim Report Section 2.2.6. DE-FG36- 05GO15032.	HDSAM calculation
Number of Compressor Stages	4	Stages in compressor	Nexant, Inc. et al. (2008, May). H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.2.5. DE-FG36- 05G015032.	HDSAM default
Compressor Isentropic Efficiency	65%		Nexant 2008, Section 2.2.3.3, 2.2.5.2 Elgowainy, A., Mintz, M. & Gillette, J. (2006) Hydrogen Delivery Scenario Analysis Model	HDSAM default;small compressor isentropic efficiency 65%, large 88% HDSAM calculation based on Chevron fueling profiles (see Nexant Report-Section 2.1.4): = adjusted disp.
Design Capacity	1,516	kg H2 / day	(HDSAM) V2.0. Argonne, IL: Argonne National Laboratory	Rate*(1+summer surge)*(1+Friday surge)
Operating Capacity	1,278	kg H2 / day	Elgowainy, A., Mintz, M. & Gillette, J. (2006) <i>Hydrogen Delivery Scenario Analysis Model</i> ( <i>HDSAM</i> ) V2.0. Argonne, IL: Argonne National Laboratory Nexant, Inc. et al. (2008, <i>May</i> ). <i>H2A</i> Hydrogen Delivery Infrastructure Analysis Models and	adjusted dispensing rate=city use/numberof stations/utilization factor
Capacity Factor	84%		Conventional Pathway Options Analysis Results. Interim Report Section 2.1.5. DE-FG36- 05GO15032.	Calculation; according to Nexant report the station does not have a capacity factor (did in v1 H2A, not in v2) so not sure what the refers to.
Site storage (Low Pressure)	470	kg H2	Nexant, Inc. et al. (2008, May). H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.2.3. DE-FG36- 05G015032.	HDSAM calculation, see description in Nexant Report-Section 2.2.3
Site storage (Cascade)	582	kg H2	Nexant, Inc. et al. (2008, May). H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.3.2.4. DE-FG36- 05GO15032.	HDSAM calculations (see description in Nexant Report-Section 2.3.2.4)
Site storage	69%	% of design H2 distribution	Nexant 2008, Section 2.1.9, 2.2.3.4	calculation
Dispensing Pressure	6,250	psi	Nexant, Inc. et al. (2008, May).H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.3.2. DE-FG36- 05GO15032.	HDSAM Default (see Nexant Report-Section 2.3.2)
Hydrogen Losses due to leaks	0.50%		Elgowainy, A., Mintz, M. & Gillette, J. (2006) Hydrogen Delivery Scenario Analysis Model	
Electrical Voltage Supply Requirement	480	Volts	(HDSAM) V2.0. Argonne, IL: Argonne National Laboratory Nexant (2008) Section 2.2.5, 2.2.6	HDSAM calculation (see Nexant Report - Sections 2.2.5 and 2.2.6)
Distribution System total capital investment	\$3,117,483	2005\$ / station	Nexant, Inc. et al. (2008, May). H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.2.5.2. DE-FG36- 05G015032.	See Nexant Report-Section 2.2.5.2)
Distribution System electricity cost	\$115,508	2005\$ / station yr	Nexant, Inc. et al. (2008, May). H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.2.6. DE-FG36- 05G015032.	HDSAM calculation
Distribution Labor Required	3,951	hr / station yr	Nexant, Inc. et al. (2008, May). H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.2.1.3. DE-FG36- 05G015032.	HDSAM calculation
Distribution System labor cost	\$39,513	2005\$ / station yr	Nexant, Inc. et al. (2008, May). H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.2.1.3. DE-FG36- 05G015032.	Bureau of Labor and Statistics, Nexant Report - Section 2.2.1.3
Distribution System total O&M cost	\$298,898	2005\$ / station yr	Nexant, Inc. et al. (2008, May). H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results. Interim Report Section 2.2.1.2. DE-FG36- 05G015032.	HDSAM calculations - see recommendations in Nexant Report-Section 2.2.1.2
Other Assumptions for WTW Calculations				
	100%		U.S. Department of Energy & U.S. Department of Transportation. (2006, December). Hydrogen	Basis for posture plan
Share of RFG in Total Gasoline Use			Posture Plan An Inegrated Research, Development and Demonstration Plan. U.S. Department of Energy & U.S. Department of Transportation. (2006, December). Hydrogen	
Type of Oxygenate in RFG	None		Posture Plan An Inegrated Research, Development and Demonstration Plan.	Basis for posture plan
02 Content in RFG	0%	wt %	U.S. Department of Energy & U.S. Department of Transportation. (2006, December). Hydrogen Posture Plan An Inegrated Research, Development and Demonstration Plan.	Basis for posture plan
Ratio of FCV VOCs (emissions) to GVs fueled with CG & RFG	0%		Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1:	GREET default, Table 4.45 FCV: H2
	0%		Methodology, development, Use and Results. Argonne, IL: Argonne National Laboratory. Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1:	GREET default Table 4 45 ECV: H2
Ratio of FCV VOCs (evaporative) to GVs fueled with CG & RFG			Methodology, development, Use and Results. Argonne, IL: Argonne National Laboratory. Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1:	
Ratio of FCV CO emissions to GVs fueled with CG & RFG	0%		Methodology, development, Use and Results. Argonne, IL: Argonne National Laboratory.	GREET default, Table 4.45 FCV: H2
Ratio of FCV NOx emissions to GVs fueled with CG & RFG	0%		Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology, development, Use and Results. Argonne, IL: Argonne National Laboratory.	GREET default, Table 4.45 FCV: H2
Ratio of FCV Exhaust PM10 emissions to GVs fueled with CG & RFG	0%		Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology, development, Use and Results. Argonne, IL: Argonne National Laboratory.	GREET default, Table 4.45 FCV: H2
Ratio of FCV Brake & Tire Wear PM10 emissions to GVs fueled with CG & RFG	100%		Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology, development, Use and Results. Argonne, IL: Argonne National Laboratory.	GREET default, page 197: vehicles within the same weight class have similar tire and brake wear emissions
Ratio of FCV Exhaust PM2.5 emissions to GVs fueled with CG & RFG	0%		Mennology, development, ose and results regioner, it. regioner valoret abovatory. Wang, M.O. (2008, September 5). The Greenhouse Gases, Regualted Emissions, and Energy Use in Transportation (GREET) Model, Version 1.8b. Argonne, IL: Argonne National Laboratory.	GREET default:well-known fuel cell emissions (no PM2.5)
Ratio of FCV Brake & Tire Wear PM2.5 emissions to GVs fueled with CG & RFG	100%		Wang, M.Q. (2008, September 5). The Greenhouse Gases, Regualted Ernissions, and Energy Use in Transportation (GREET) Model, Version 1.8b. Argonne, IL: Argonne National Laboratory.	GREET default reasonable to assume FCV has same driving pattern as GV
Ratio of FCV CH4 emissions to GVs fueled with CG & RFG	0%		Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology, development, Use and Results. Argonne, IL: Argonne National Laboratory.	GREET default, Table 4.45 FCV: H2
			memoral age and results . Arguine, it. Arguine realitional cabolatory.	4

Parameter	Value Units		Comments
Ratio of FCV N2O emissions to GVs fueled with CG & RFG	0%	Wang, M.Q. (1999, August). GREET 1.5 - Transportation Fuel-Cycle Model Volume 1: Methodology, development, Use and Results. Argonne, IL: Argonne National Laboratory.	GREET default, Table 4.45 FCV: H2
Marginal Electricity Generation Mix for Transportation Use	US Mix	U.S. Department of Energy & U.S. Department of Transportation. (2006, December). Hydrogen Posture Plan An Inegrated Research, Development and Demonstration Plan.	Basis for posture plan
Results			
Levelized Cost	\$7.16 \$ / kg	Ruth, M. et al. (2009, March). Hydrogen Macro System Model User Guide. NREL/TP-6A1-44799 Golden, CO: National Renewable Energy Laboratory.	MSM Results
WTW Coal Input	467 Btu / mile	Ruth, M. et al. (2009, March). Hydrogen Macro System Model User Guide. NREL/TP-6A1-44799 Golden, CO: National Renewable Energy Laboratory.	MSM Results
WTW Natural Gas Input	134 Btu / mile	Ruth, M. et al. (2009, March). Hydrogen Macro System Model User Guide. NREL/TP-6A1-44799 Golden, CO: National Renewable Energy Laboratory.	MSM Results
WTW Petroleum Input	<sup>35</sup> Btu / mile	Ruth, M. et al. (2009, March). Hydrogen Macro System Model User Guide. NREL/TP-6A1-44799 Golden, CO: National Renewable Energy Laboratory.	MSM Results
WTW Fossil Energy Input	636 Btu / mile	Ruth, M. et al. (2009, March). Hydrogen Macro System Model User Guide. NREL/TP-6A1-44799 Golden, CO: National Renewable Energy Laboratory.	MSM Results
WTW Total Energy Input	4,921 Btu / mile	Ruth, M. et al. (2009, March). Hydrogen Macro System Model User Guide. NREL/TP-6A1-44799 Golden, CO: National Renewable Energy Laboratory.	MSM Results
WTW CO2 Emissions	62 g / mile	Ruth, M. et al. (2009, March). Hydrogen Macro System Model User Guide. NREL/TP-6A1-44799 Golden, CO: National Renewable Energy Laboratory.	MSM Results
WTW CH4 Emissions	0 g / mile	Ruth, M. et al. (2009, March). Hydrogen Macro System Model User Guide. NREL/TP-6A1-44799 Golden, CO: National Renewable Energy Laboratory.	MSM Results
WTW N2O Emissions	0 g / mile	Ruth, M. et al. (2009, March). Hydrogen Macro System Model User Guide. NREL/TP-6A1-44799 Golden, CO: National Renewable Energy Laboratory. Ruth, M. et al. (2009, March). Hydrogen Macro System Model User Guide. NREL/TP-6A1-44799	MSM Results
WTW GHG Emissions	<sup>64</sup> g / mile	Golden, CO: National Renewable Energy Laboratory.	MSM Results

### Appendix H — Platinum Resource Availability and Cost

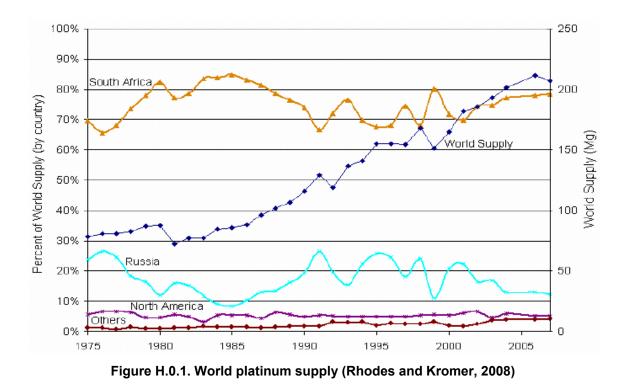
Although a lot of research is being done to reduce the platinum loading in proton exchange membrane (PEM) fuel cells, platinum catalyst is critical to the performance of current PEM fuel cell technology. Platinum catalyst was projected by TIAX (Kromer et. al, 2009) in 2008 to contribute 31% of the total fuel cell system factory cost. Current Pt loading in fuel cell vehicles (FCVs) is 32–45 g/vehicle. The DOE target is to reduce this loading to 15 g/FCV by 2015. The target for FCVs is still about fivefold greater than the Pt loading for internal combustion engine (ICE) vehicles: 2.5–3.3 g/vehicle (associated with the autocatalyst). At the 2007 average Pt price of \$1,300/troy ounce, 15 g Pt will cost ~\$750 (Rhodes and Kromer, 2008).

An implicit assumption in this study is that PEM FCVs will achieve cost parity with internal combustion engine vehicles. Although the cost and availability of platinum will not affect the hydrogen cost directly for the pathways studied, it will impact the cost of the FCV and, therefore, the rate at which FCVs can be commercialized. Demand for hydrogen will depend on the rate of FCV deployment, and the viability of various hydrogen production and delivery pathways will depend on hydrogen demand.

### Availability and Utilization

The Stillwater and East Boulder mines in Montana are the only primary platinum group metal (PGM) mines in the United States. During 2008, those mines produced 3,700 kg of platinum, which was down from 3,860 kg in 2007. An estimated 26,000 kg of PGMs were recovered from new and old scrap in 2008. Platinum imports for consumption were 181,000 and 195,000 kg for 2007 and 2008, respectively. The United States has a reserve of 900,000 kg and a reserve base of 2,000,000 kg of platinum (United States Geological Survey, 2009). The reserve base is the part of platinum that meets specified minimum physical and chemical criteria related to current mining and production practices, including grade, quality, thickness and depth. Reserves are the part of the reserve base that could be economically extracted or produced at the time of determination.

TIAX, LLC (Rhodes and Kromer, 2008) projected that world resources for all PGMs are ~160,000 Mg; platinum resources are ~76,000 Mg. South Africa produces ~80% of the world's platinum supply of ~200 Mg per year (Figure H.0.1). The historical growth rate of primary Pt demand (from 1960 to 2007) is 3 Mg/yr; recent growth rates (1999–2007) have been closer to 6–7 Mg/yr. (Primary Pt refers to platinum that is directly mined in contrast to secondary Pt, which is recycled.)



TIAX (Rhodes and Kromer, 2008) assessed worldwide platinum availability for FCVs and concluded that platinum resources are sufficient to meet significant FCV demand but that FCV demand growth may be constrained by primary platinum supply. Long-term projections for the global transportation sector were developed based on population projections, vehicle-per-capita scenarios, and projected ICE vehicle and FCV Pt requirements. Population projections and vehicle–per-capita projections were used to develop a total vehicle forecast, which included replacement demand and new demand. The total vehicle forecast and fuel cell and internal combustion powertrain Pt requirements were used to determine the FCV projection, which in turn was used to develop the Pt demand versus time. United Nations forecasts were used for the population projections. The EIA Annual Energy Outlook 2003 provided near-term annual vehicle per capita growth estimates.

Two scenarios were considered: 1) FCVs achieve market share of 50% in the global light-duty vehicle market by 2050, and 2) FCVs achieve market share of 80% in the global light-duty vehicle market by 2050 (Figure H.0.2). A growth rate in primary Pt demand of 12 Mg/yr would be necessary for the 50% scenario, and 23 Mg/yr would be needed to achieve the 80% scenario (Figure H.0.3). Annual primary platinum supply increased by an average of 3 Mg/yr from 1960 to 2007 with average increases of 6.3 Mg/yr from 1999 to 2004. The platinum industry developed plans in 2003 to expand production by 13 Mg/yr. Thus, the lower growth rate is considered achievable while the higher growth rate is considered beyond reasonable growth expectations (Rhodes and Kromer, 2008).

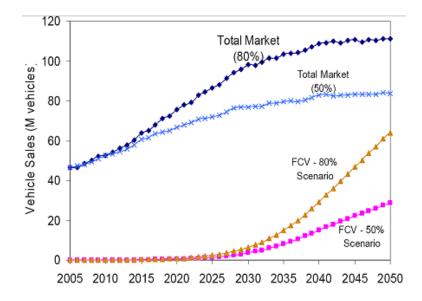


Figure H.0.2. Projected worldwide vehicle sales (Kromer, Rhodes, and Guernsey, 2008)

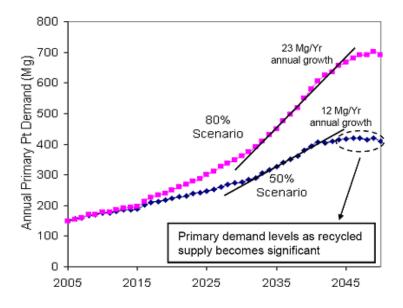


Figure H.0.3. Projected primary platinum demand (Kromer, Rhodes, and Guernsey, 2008)

#### Resource Cost

In 2008, platinum reached its all-time highest annual average price of \$1,680 per troy ounce. That price is up from \$1,308 per troy ounce in 2007 (United States Geological Survey, 2009).

## Appendix I — Enlarged Graphics

The following figures from the previous sections are enlarged in this section for ease of viewing.

- Figure 3.2.1. Efficiency in electricity generation from various sources (van Aart, 2004)
- Figure 3.2.2. Installed wind capacity as of April 2009 (National Renewable Energy Laboratory, 2009)
- Figure 3.2.3. U.S. wind resource map (National Renewable Energy Laboratory, 2009)
- Figure 3.5.2. Regional carbon sequestration partnerships and their respective validation carbon storage projects (National Energy Technology Laboratory, 2008)
- Table 4.1.1. Natural Gas Pipeline Mileage (Energy Information Administration, 2008e)
- Figure 4.1.3. Hypothetical pressures (psig) in distribution mains at maximum design flows (Vidas, 2007)
- Figure 5.1.1. Distributed natural gas reforming process flow diagram (James, 2008)
- Figure 5.2.1. Distributed electrolysis process flow diagram (Ramsden, 2008b)
- Figure 5.2.3. Distributed electrolysis process flow diagram cooling water detail (Ramsden, 2008b)
- Figure 5.3.1. Central biomass gasification flow diagram (Mann and Steward, 2008)
- Figure 9.1.2. Cost analysis inputs and high-level results for distributed natural gas pathway
- Figure 9.1.7. WTW emissions resulting from delivery of 116,000 Btu hydrogen using distributed natural gas pathway
- Figure 9.1.9. Production sensitivities for distributed natural gas pathway
- Figure 9.1.10. Production sensitivities for distributed natural gas pathway with advanced technology
- Figure 9.2.2. Cost analysis inputs and high-level results for distributed electricity pathway
- Figure 9.2.7. WTW emissions resulting from delivery of 116,000 Btu hydrogen using distributed electricity pathway
- Figure 9.2.9. Production sensitivities for distributed electrolysis pathway
- Figure 9.3.2. Cost analysis inputs and high-level results for central biomass–liquid truck delivery pathway
- Figure 9.3.7. WTW emissions resulting from delivery of 116,000 Btu hydrogen using central biomass–liquid truck delivery pathway
- Figure 9.3.9. Production sensitivities for central biomass-liquid truck delivery pathway
- Figure 9.4.2. Cost analysis inputs and high-level results for central biomass-pipeline delivery pathway
- Figure 9.4.7. WTW emissions resulting from delivery of 116,000 Btu hydrogen using central biomass–pipeline delivery pathway
- Figure 9.4.9. Production sensitivities for central biomass-pipeline delivery pathway

- Figure 9.5.2. Cost analysis inputs and high-level results for central natural gas-pipeline delivery pathway
- Figure 9.5.7. WTW emissions resulting from delivery of 116,000 Btu hydrogen using central natural gas–pipeline delivery pathway
- Figure 9.5.9. Production sensitivities for central natural gas-pipeline delivery pathway
- Figure 9.6.2. Cost analysis inputs and high-level results for central wind electricity–pipeline delivery pathway
- Figure 9.6.7. WTW emissions resulting from delivery of 116,000 Btu hydrogen using central wind electricity–pipeline delivery pathway
- Figure 9.6.9. Production sensitivities for central wind electrolysis-pipeline delivery pathway
- Figure 9.7.2. Cost analysis inputs and high-level results for central coal with CCS-pipeline delivery pathway
- Figure 9.7.7. WTW emissions resulting from delivery of 116,000 Btu hydrogen using central coal with CCS–pipeline delivery pathway
- Figure 9.7.9. Production sensitivities for central coal with CCS-pipeline delivery pathway
- Figure 10.0.3. WTW, pathway, and production efficiencies for seven hydrogen pathways, three crude oil-based fuel options, and two E85 options
- Figure 10.0.4. WTW petroleum energy use for seven hydrogen pathways, three crude oilbased fuel options, and two E85 options
- Figure 10.0.6. WTW GHG emissions for seven hydrogen pathways, three crude oil-based fuel options, and two E85 options
- Figure 10.0.9. Levelized costs/market prices with possible carbon taxes for seven hydrogen pathways, three crude oil-based fuel options, and two E85 options

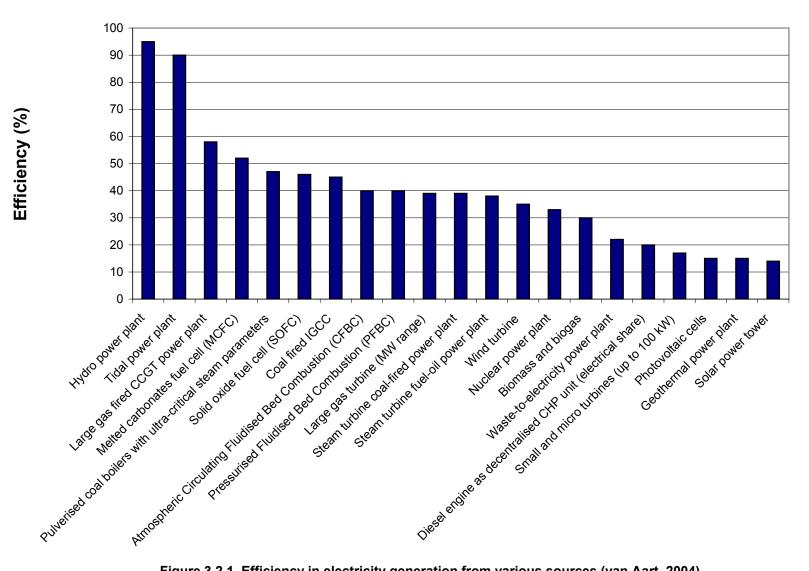


Figure 3.2.1. Efficiency in electricity generation from various sources (van Aart, 2004)

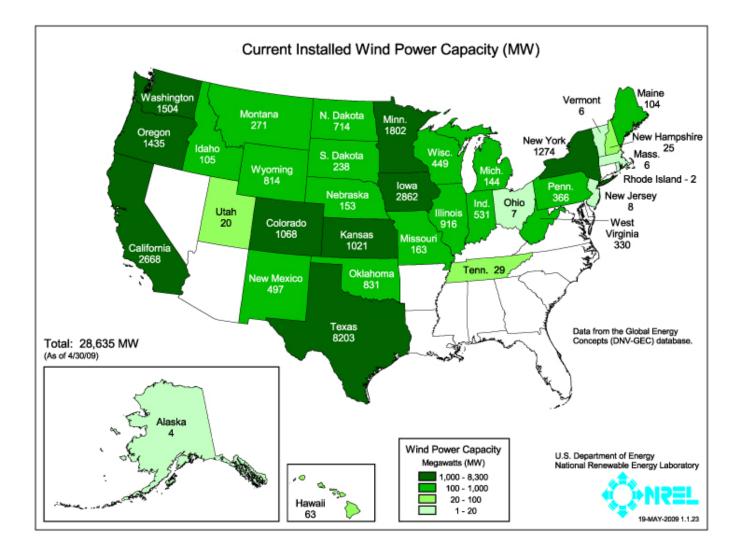


Figure 3.2.2. Installed wind capacity as of April 2009 (National Renewable Energy Laboratory, 2009)

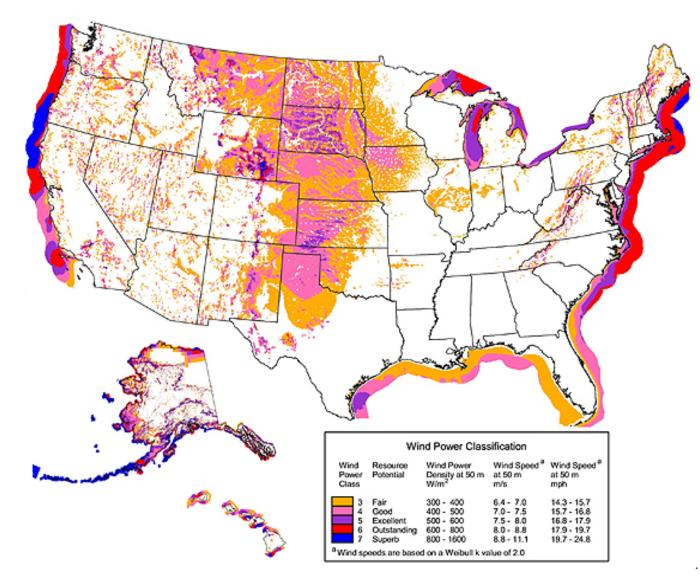


Figure 3.2.3. U.S. wind resource map (National Renewable Energy Laboratory, 2009)

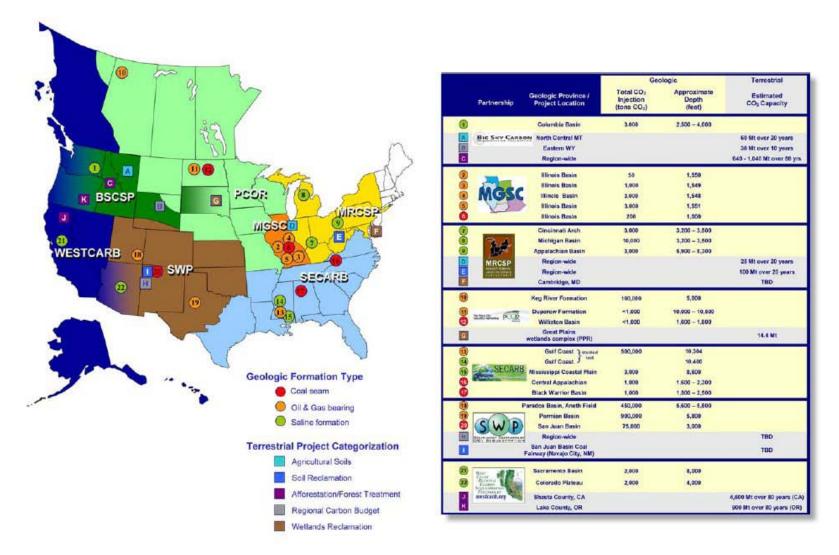


Figure 3.5.2. Regional carbon sequestration partnerships and their respective validation carbon storage projects (National Energy Technology Laboratory, 2008)

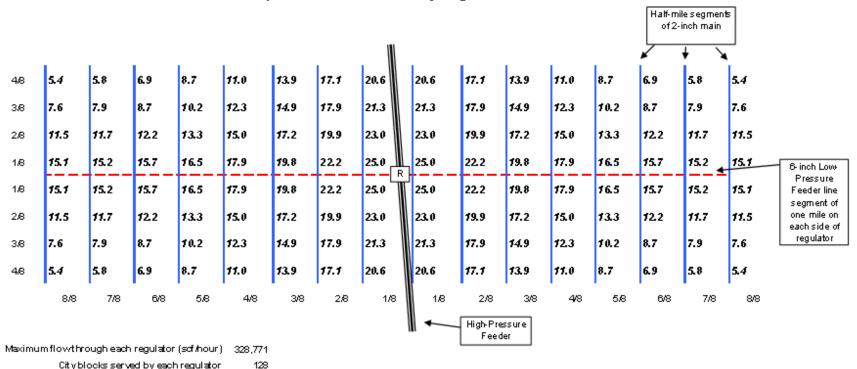
Region/	Pipeline	Region/	Pipeline	Region/	Pipeline	Region/	Pipeline	Region/	Pipeline	Region/	Pipeline
-	• •		•		•			3	•	-	
State	Mileage	State	Mileage	State	Mileage	State	Mileage	State	Meage	State	Mileage
Central		Midwest		Northeast		Southeast		Southwest		Western	
Colorado	7,803	Illinois	11,911	Connecticut	628	Alabama	4,818	Arkansas	6,267	Arizona	5,989
lowa	5,421	Indiana	4,704	Delaware	280	Florida	4,971	Louisiana	18,900	California	11,770
Kansas	15,386	Michigan	9,722	Maine	609	Georgia	3,483	New Mexico	6,756	Idaho	1,567
Missouri	3,944	Minnesota	4,447	Maryland/D C	1,022	Kentucky	6,892	Oklahoma	18,539	Nevada	1,469
Montana	3,861	Ohio	7,670	Massachusetts	972	Mississippi	9,784	Texas	58,588	Oregon	1,823
Nebraska	5,697	Wisconsin	3,471	New Hampshire	291	North Carolina	2,484		109,050	Washington	2,072
North Dakota	1,873		41,925	New Jersey	1,520	South Carolina	2,265				24,690
South Dakota	1,242			New York	5,018	Tennessee	4,304				
Utah	3,175			Pennsylvania	8,680		39,001	Gulf Mexico <sup>1</sup>	9,458		
Wyoming	7,902			Rhode Island	100						
	56,304			Vermont	71						
				Virginia	2,577			Total US Pipelir	ne Mileage		305,954
				West Virginia	3,758			Total Intersta	te <sup>1</sup>		217,306
				-	25,526			Total Non-int	erstate <sup>2</sup>		88,648
					,						,

Table 4.1.1. Natural Gas Pipeline Mileage (Energy Information Administration, 2008e)

<sup>1</sup> In the Gulf of Mexico some large-scale gathering systems are FERC jurisdictional and are therefore counted as interstate.

<sup>2</sup> Includes intrastate transmission and non-FERC iurisdictional large diameter gathering systems or headers. Local distribution company (LDC) mileage excluded. Note: All mileage is approximate. Includes looped pipeline segments. Approximately 73 percent of Interstate pipeline systems are made up of pipeline diameters exceeding 16 inches while only 34 percent of non-interstate pipeline systems are 16 inches or larger.

Source: Energy Information Administration, Gas Transportation Information System, Pipeline Map Files and Pipeline Projects Database.



## Two-Square Mile Area Served by Regulator Station

Cityblocks served by each regulator

Maximum flowper city block (scf /hour) 2,569



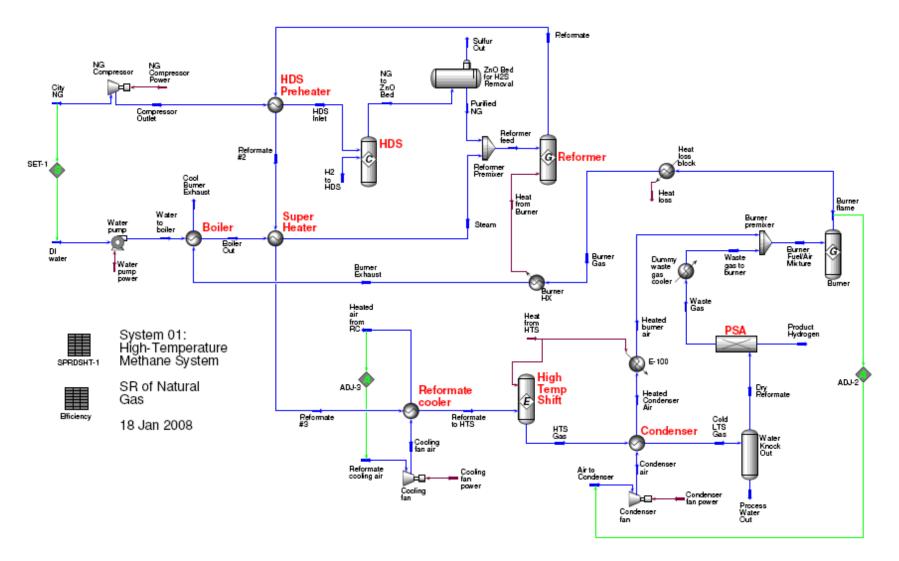


Figure 5.1.1. Distributed natural gas reforming process flow diagram (James, 2008)

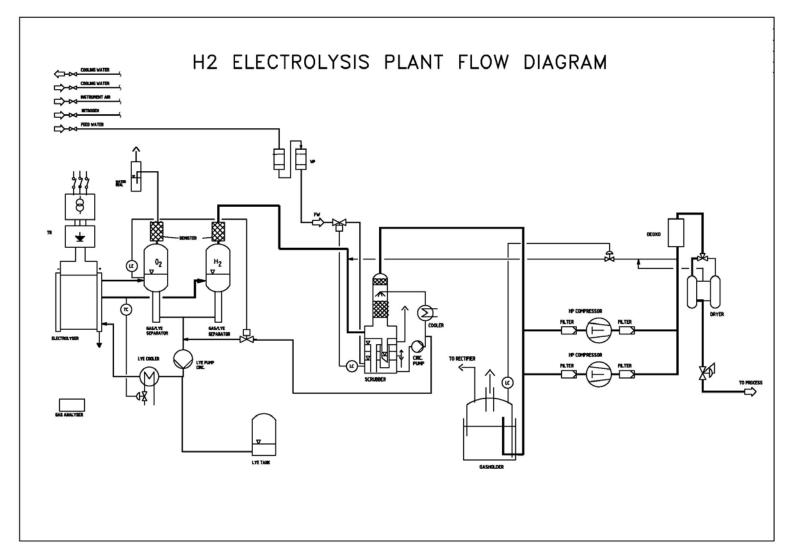


Figure 5.2.1. Distributed electrolysis process flow diagram (Ramsden, 2008b)

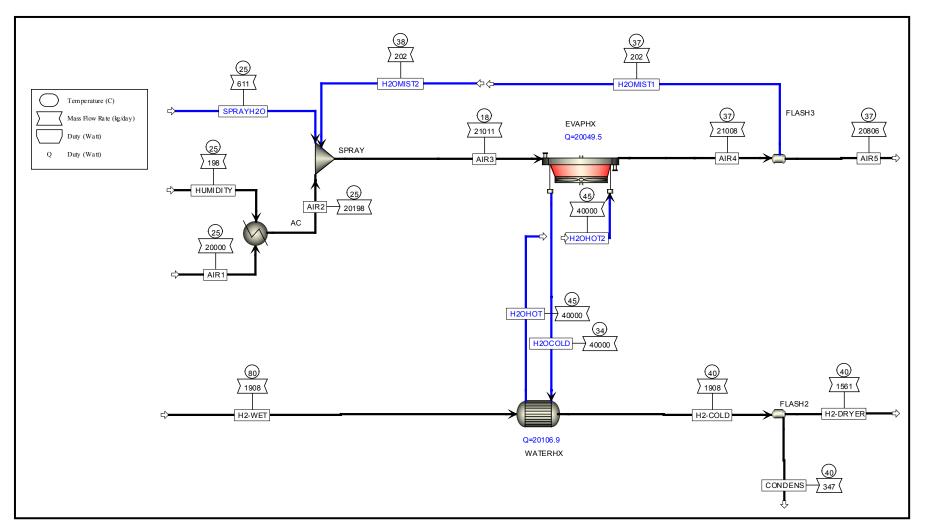


Figure 5.2.3. Distributed electrolysis process flow diagram cooling water detail (Ramsden, 2008b)

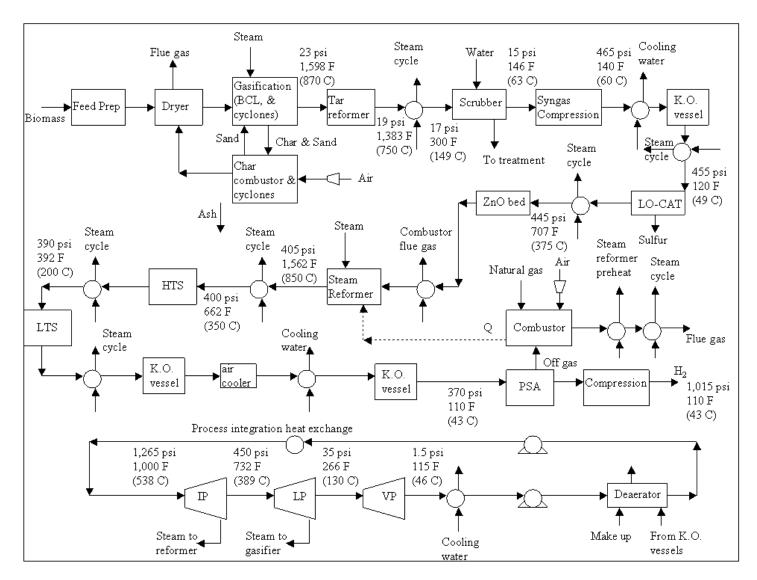
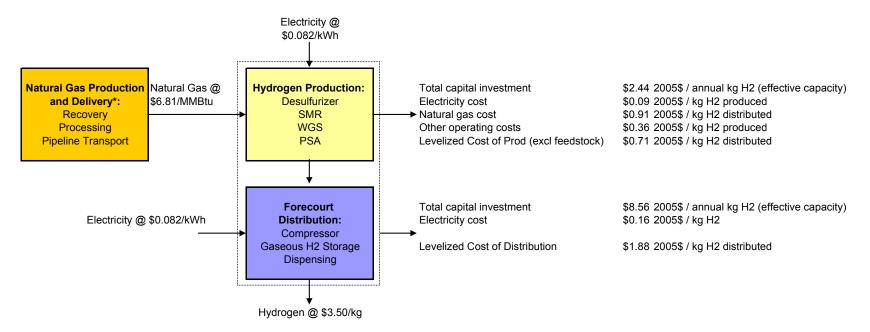


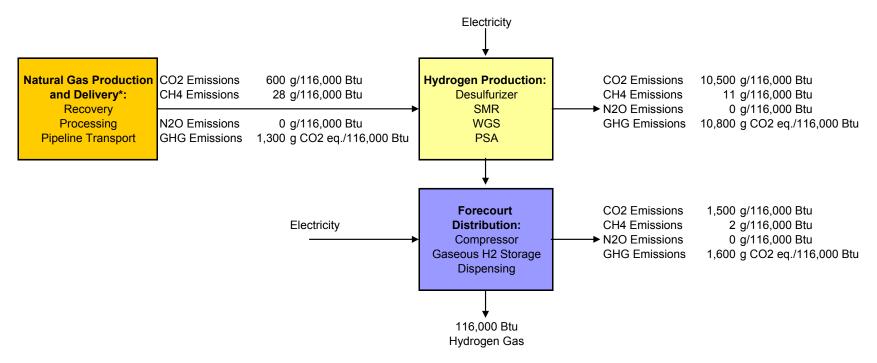
Figure 5.3.1. Central biomass gasification flow diagram (Mann and Steward, 2008)



\* This box represents the natural gas that is converted to hydrogen or otherwise consumed/lost as a process feedstock.

It does not include natural gas used as a heating fuel or to produce electricity.





\* This box represents the natural gas that is converted to hydrogen or otherwise consumed/lost as a process feedstock.

It does not include natural gas used as a heating fuel or to produce electricity.

## Figure 9.1.7. WTW emissions resulting from delivery of 116,000 Btu hydrogen using distributed natural gas pathway

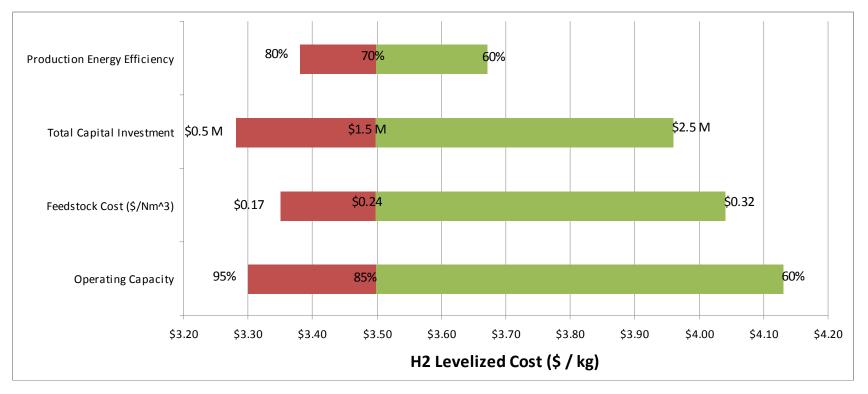


Figure 9.1.9. Production sensitivities for distributed natural gas pathway

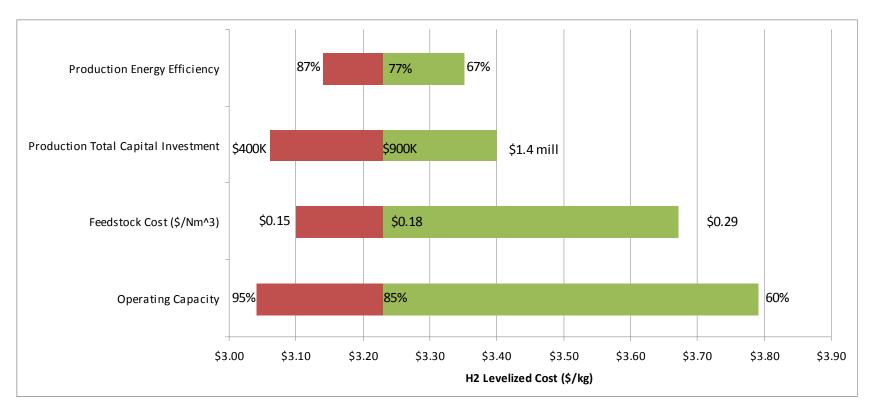


Figure 9.1.10. Production sensitivities for distributed natural gas pathway with advanced technology

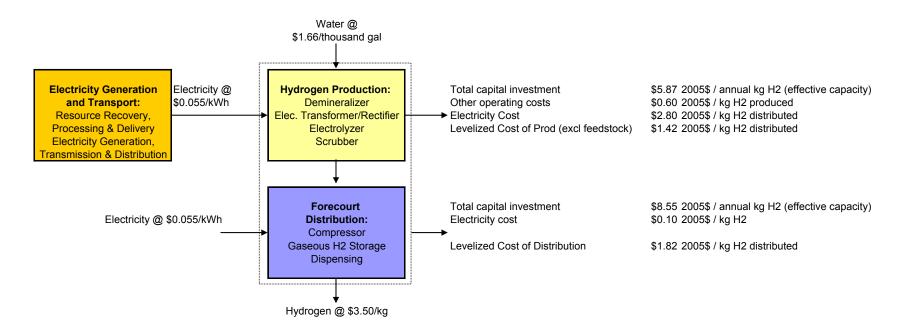
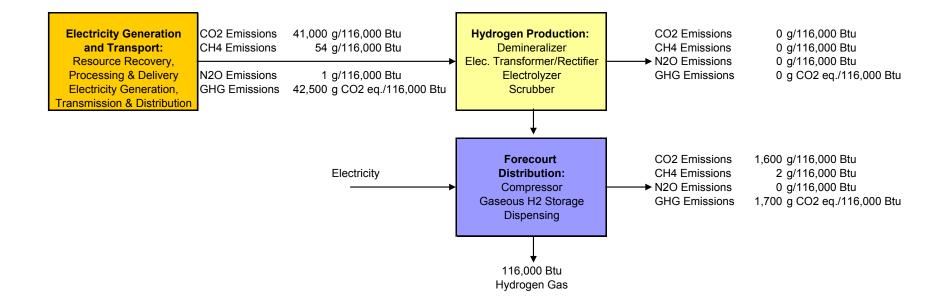
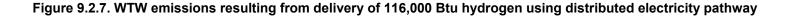


Figure 9.2.2. Cost analysis inputs and high-level results for distributed electricity pathway





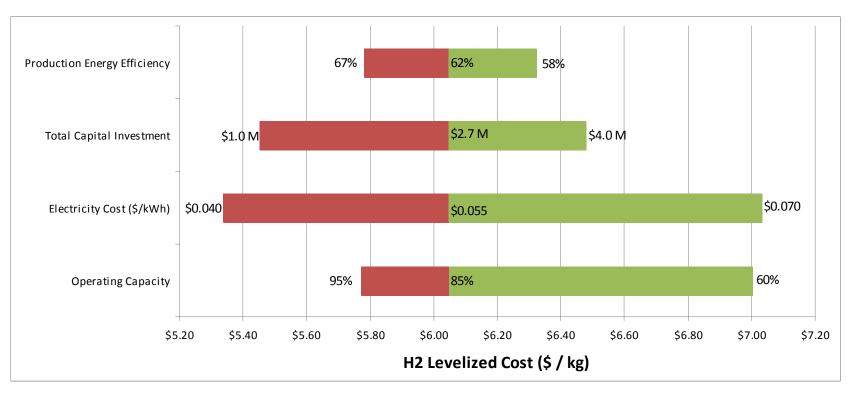


Figure 9.2.9. Production sensitivities for distributed electrolysis pathway

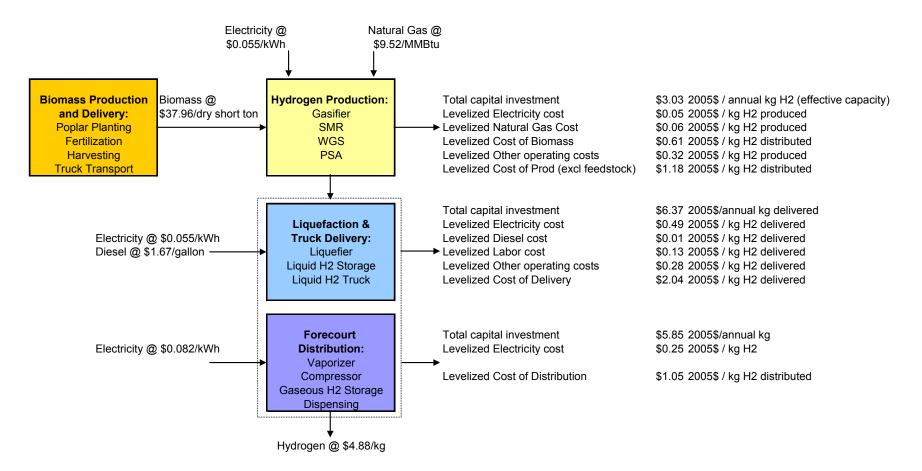
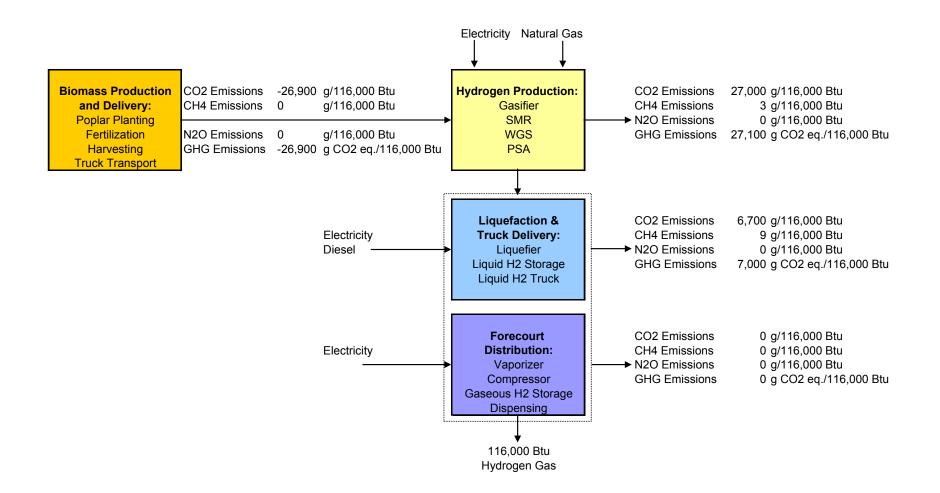


Figure 9.3.2. Cost analysis inputs and high-level results for central biomass-liquid truck delivery pathway





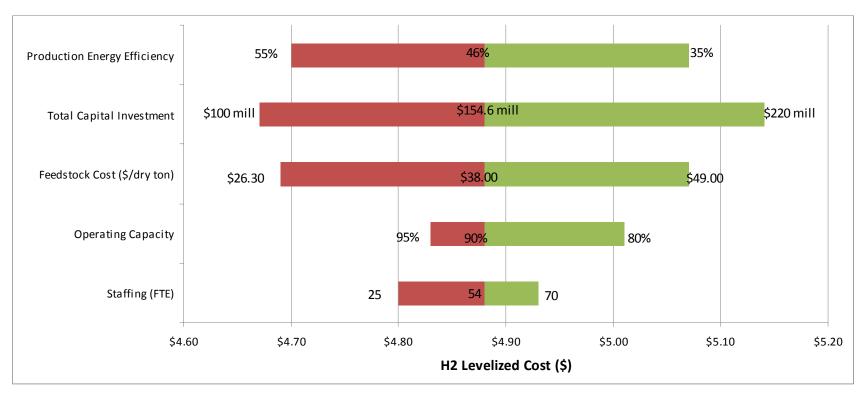


Figure 9.3.9. Production sensitivities for central biomass-liquid truck delivery pathway

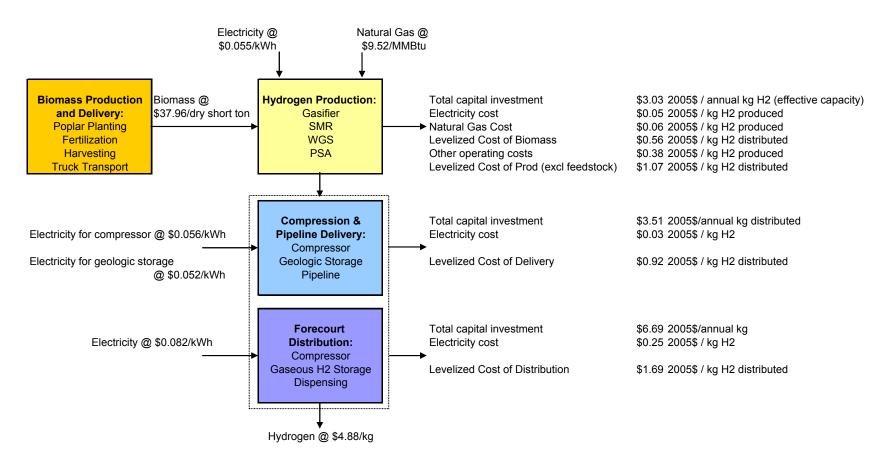
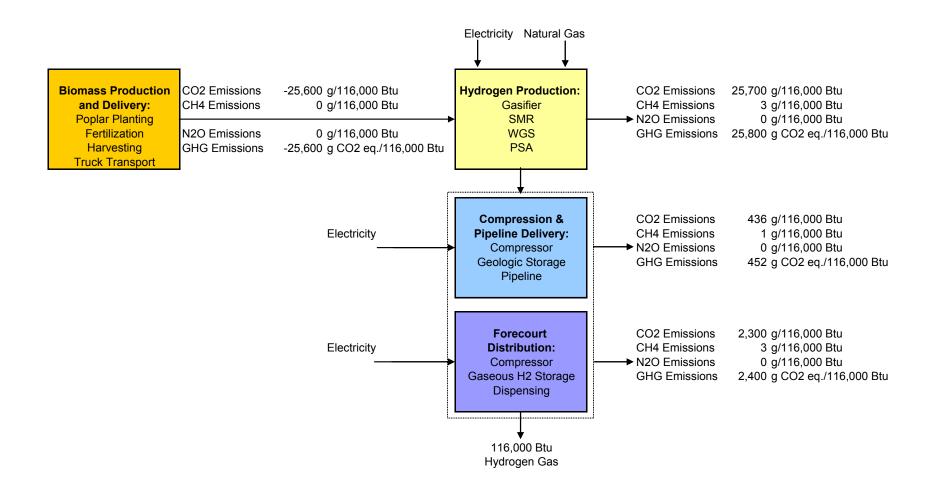


Figure 9.4.2. Cost analysis inputs and high-level results for central biomass-pipeline delivery pathway





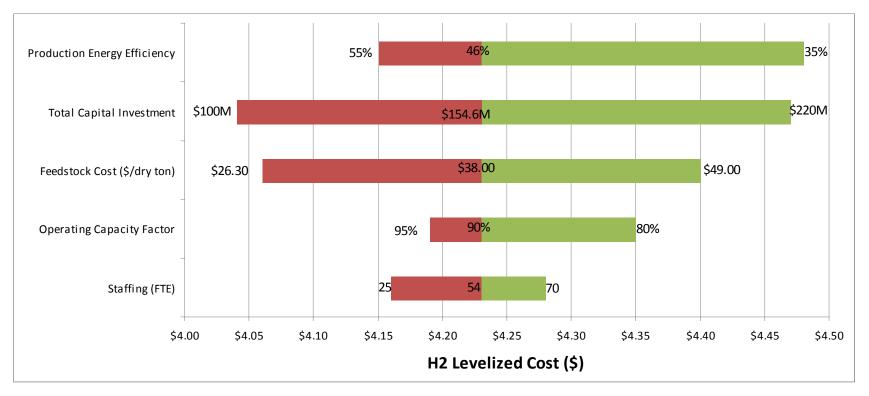
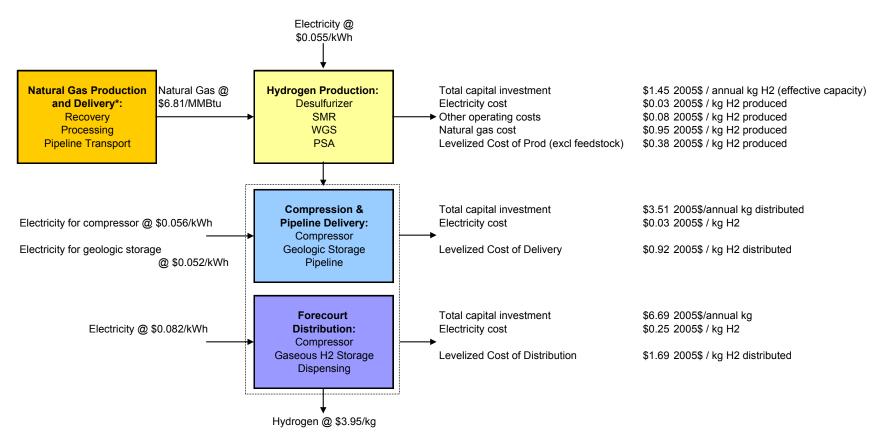
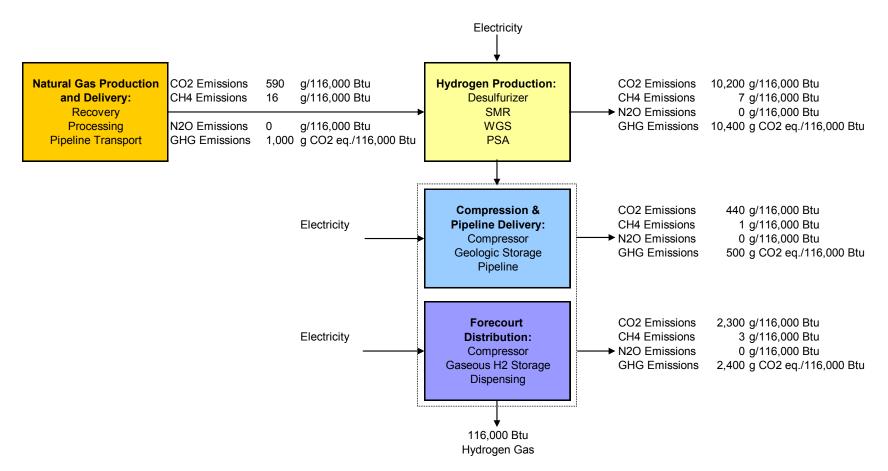


Figure 9.4.9. Production sensitivities for central biomass-pipeline delivery pathway



\* This box represents the natural gas that is converted to hydrogen or otherwise consumed/lost as a process feedstock. It does not include natural gas used as a heating fuel or to produce electricity.

## Figure 9.5.2. Cost analysis inputs and high-level results for central natural gas-pipeline delivery pathway



\* This box represents the natural gas that is converted to hydrogen or otherwise consumed/lost as a process feedstock. It does not include natural gas used as a heating fuel or to produce electricity.



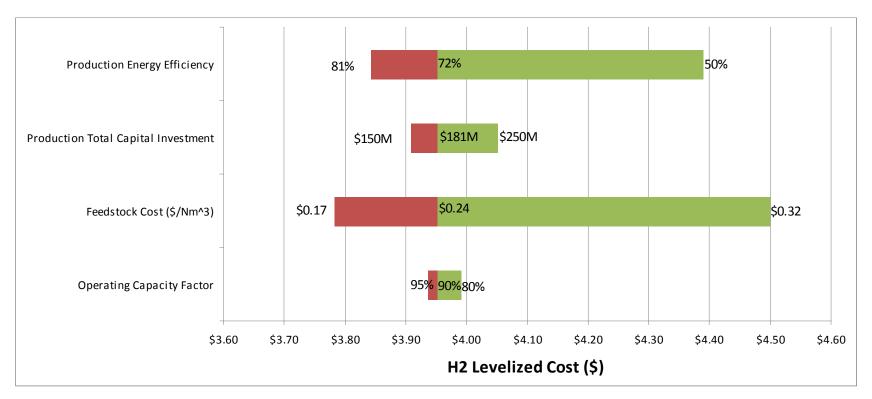


Figure 9.5.9. Production sensitivities for central natural gas-pipeline delivery pathway

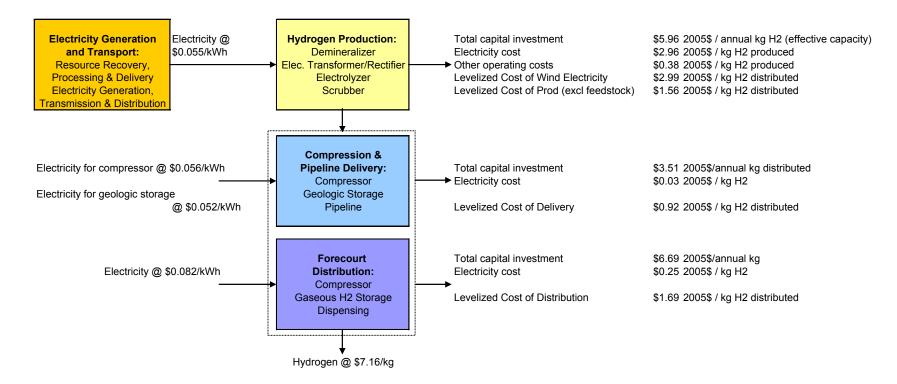


Figure 9.6.2. Cost analysis inputs and high-level results for central wind electricity-pipeline delivery pathway

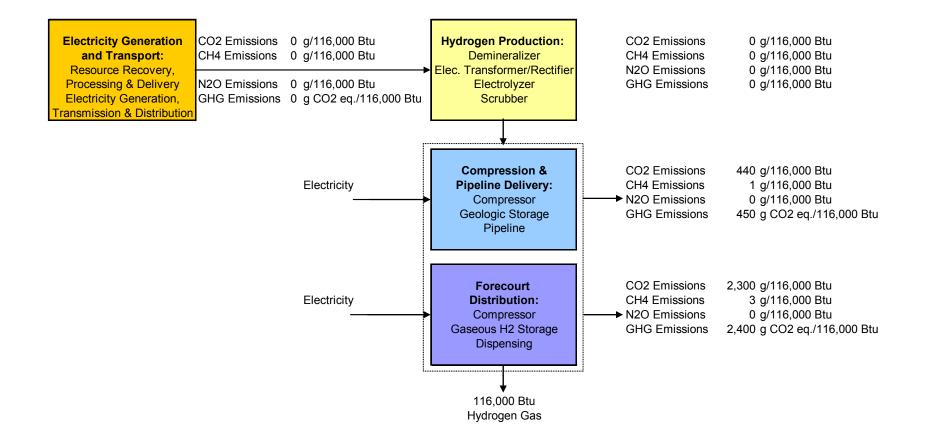


Figure 9.6.7. WTW emissions resulting from delivery of 116,000 Btu hydrogen using central wind electricity-pipeline delivery pathway

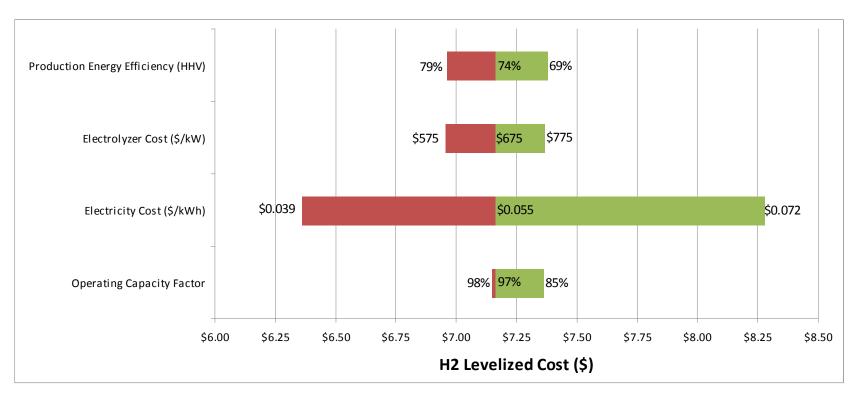
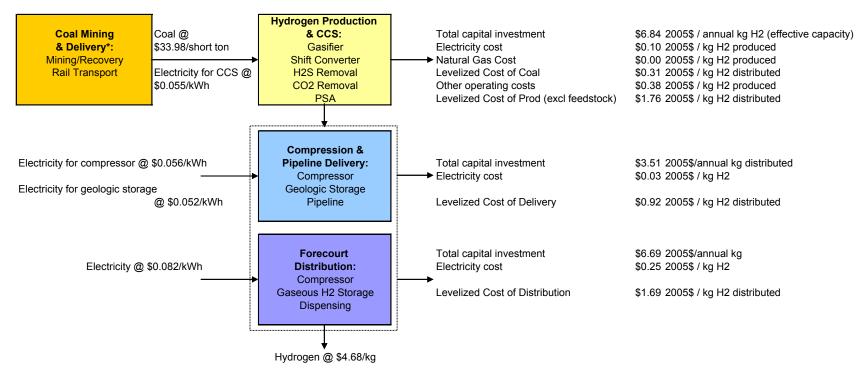
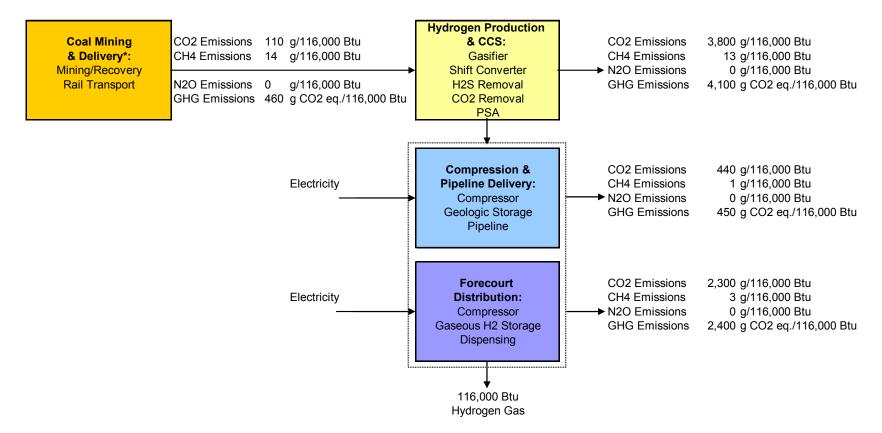


Figure 9.6.9. Production sensitivities for central wind electrolysis-pipeline delivery pathway



\* This box represents the coal that is converted to hydrogen or otherwise consumed/lost as a process feedstock. It does not include coal used as a heating fuel or to produce electricity.





\* This box represents the coal that is converted to hydrogen or otherwise consumed/lost as a process feedstock. It does not include coal used as a heating fuel or to produce electricity.

Figure 9.7.7. WTW emissions resulting from delivery of 116,000 Btu hydrogen using central coal with CCS-pipeline delivery pathway

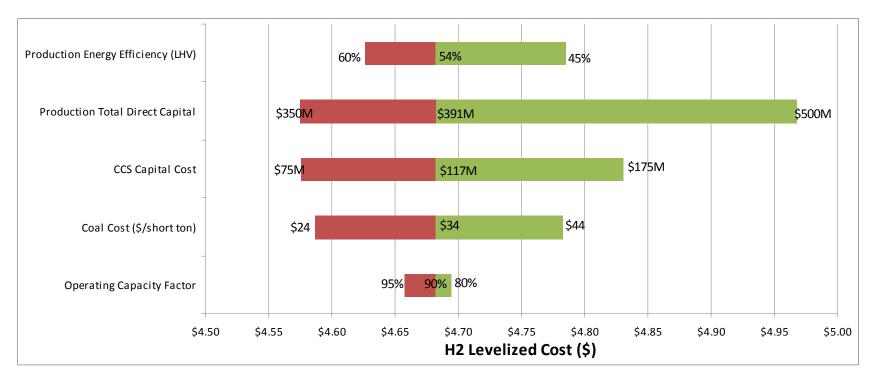


Figure 9.7.9. Production sensitivities for central coal with CCS-pipeline delivery pathway

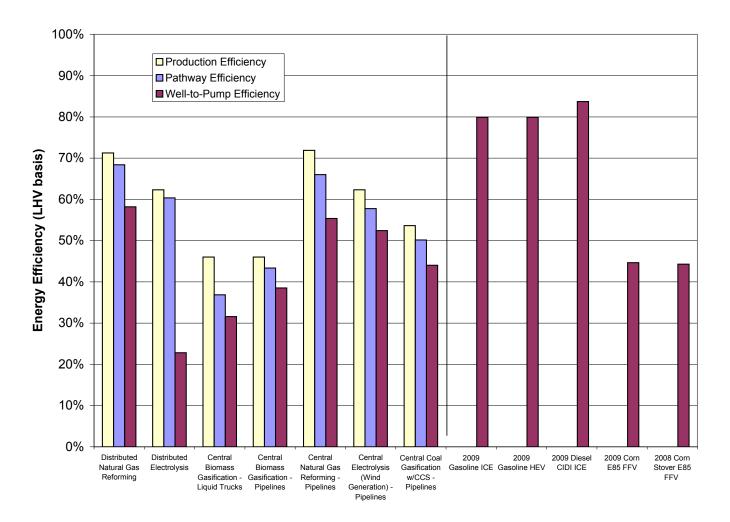


Figure 10.0.3. WTW, pathway, and production efficiencies for seven hydrogen pathways, three crude oil-based fuel options, and two E85 options

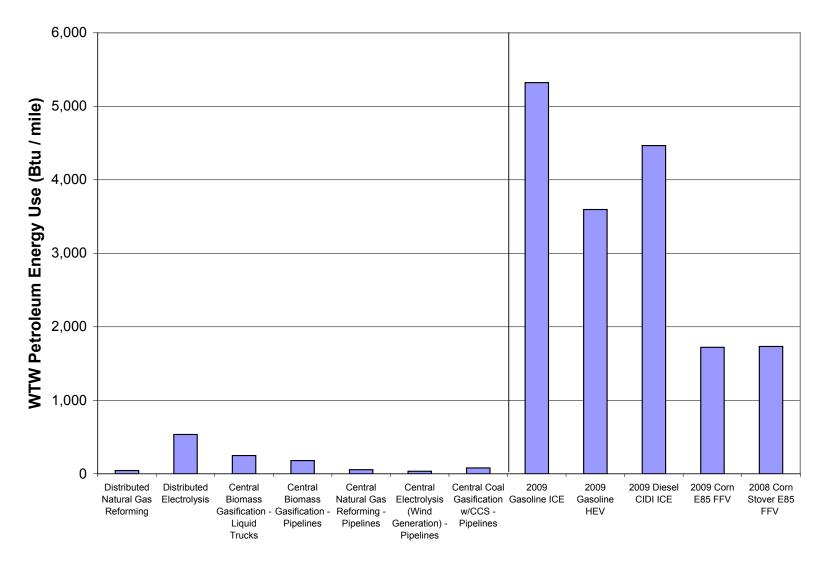
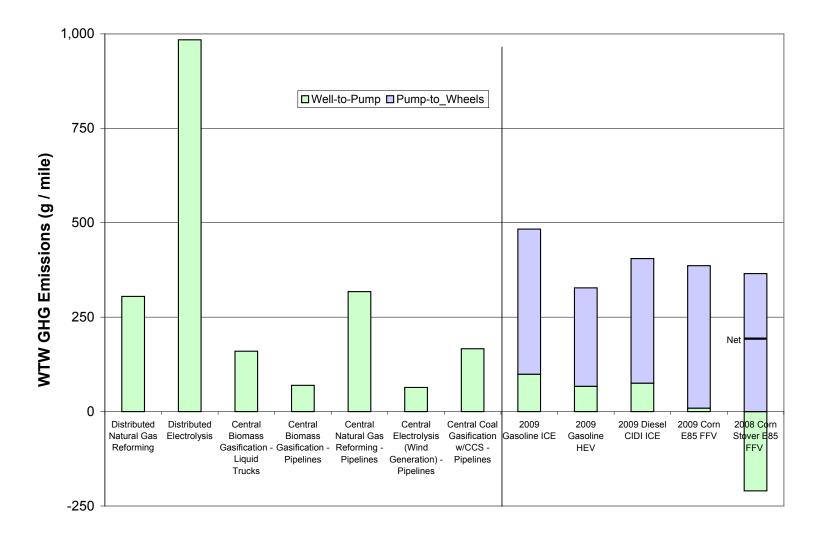


Figure 10.0.4. WTW petroleum energy use for seven hydrogen pathways, three crude oil-based fuel options, and two E85 options





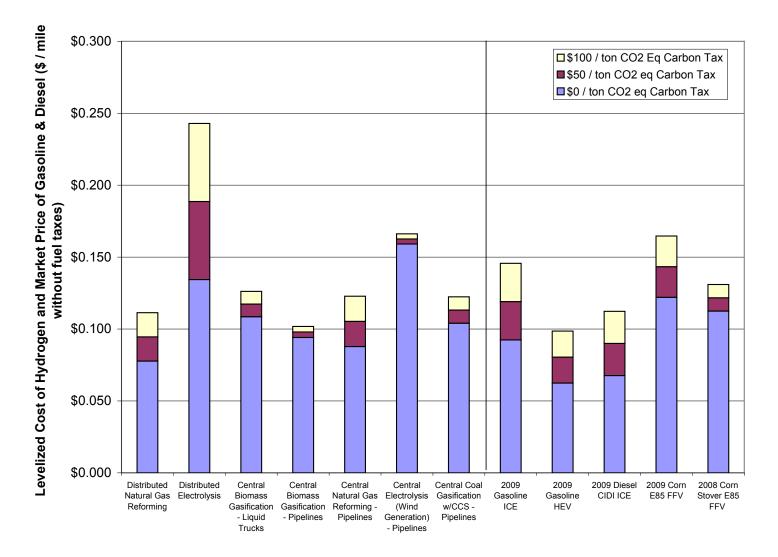


Figure 10.0.9. Levelized costs/market prices with possible carbon taxes for seven hydrogen pathways, three crude oil-based fuel options, and two E85 options

## Acronyms

°C °F AC atm BSCSP	degrees Celsius degrees Fahrenheit alternating current atmosphere Big Sky Carbon Sequestration Partnership
Btu	British thermal unit
CA	California
CCS	carbon capture and sequestration
CHP	combined heat and power
cm	centimeter
CO	carbon monoxide
$CO_2$	carbon dioxide
CSD	compression, storage, and dispensing
DC	direct current
DOE	Department of Energy
EIA	Energy Information Administration
EPA	Environmental Protection Agency
FAF2	Freight Analysis Framework 2
FCV	fuel cell vehicle
FL	Florida
FPITT	Fuel Pathway Integration Tech Team
gal	gallon
gge	gallon gasoline equivalent
GHG	greenhouse gas
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation
H2, H <sub>2</sub>	diatomic hydrogen
HEV	hybrid electric vehicle
HDSAM	H2A Delivery Scenario Analysis Model
HFCIT	Hydrogen, Fuel Cells and Infrastructure Technologies
HOF	hose occupied fraction
hr	hour
ICE	internal combustion engine
IGCC	integrated gasification combined cycle
kg	kilogram
kWh	kilowatt-hour
L	liter
lb	pound
MGSC	Midwest Geological Sequestration Consortium
mi	mile
MI	Michigan
MRCSP	Midwest Regional Carbon Sequestration Partnership
MSM	Macro-System Model
MT	metric ton

MW	megaWatt
MYPP	Multi-Year Program Plan
NG	natural gas
NOx	oxides of nitrogen
NREL	National Renewable Energy Laboratory
NV	Nevada
NY	New York
PA	Pennsylvania
PC	pulverized coal
PCOR	Plains CO <sub>2</sub> Reduction
PGM	platinum group metal
PM	particulate matter
ppm	parts per million
PSA	pressure swing adsorption
PSAT	Powertrain Simulation Analysis Toolkit
psi	pound per square inch
psia	pounds per square inch absolute
psig	pound per square inch gauge
SECARB	Southeast Regional Carbon Sequestration Partnership
SMR	steam methane reforming
SWP	Southwest Regional Partnership
TBW	tire and brake wear
TLR	transmission loading relief
TX	Texas
U.S.	United States
VOC	volatile organic compound
WESTCARB	West Coast Regional Carbon Sequestration Partnership
WGS	water-gas shift
wt%	weight percent
WTG	well-to-plant gate
WTP	well-to-pump
WTW	well-to-wheels

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1. REPORT DATE (DD-MM-YYYY)		ORT TYPE			3. DATES COVERED (From - To)		
September 2009	Tec	hnical Report					
4. TITLE AND SUBTITLE		•		5a. CON	ITRACT NUMBER		
Hydrogen Pathways: Cost, Well-to-Wheels Energy Use, and				DE-AC36-08-GO28308			
Emissions for the Current Technology Status of Seven Hydrogen							
Production, Delivery, and Dis	stribution	Scenarios		5b. GRANT NUMBER			
				5c. PRO	GRAM ELEMENT NUMBER		
6. AUTHOR(S)		5d PRO	5d. PROJECT NUMBER				
M. Ruth: NREL;				NREL/TP-6A1-46612			
M. Laffen and T.A. Timbario:	Alliance -	Technical Serv	ices. Inc.				
				5e. TASK NUMBER			
				HS07.1002			
				5f. WORK UNIT NUMBER			
7. PERFORMING ORGANIZATION N	AME(S) AN	D ADDRESS(ES)			8. PERFORMING ORGANIZATION		
National Renewable Energy	Laborator	ту			REPORT NUMBER		
1617 Cole Blvd.		-			NREL/TP-6A1-46612		
Golden, CO 80401-3393							
9. SPONSORING/MONITORING AGE	NCY NAME	E(S) AND ADDRES	SS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) NREL		
					11. SPONSORING/MONITORING AGENCY REPORT NUMBER		
12. DISTRIBUTION AVAILABILITY ST	ATEMENT						
National Technical Informatio		2					
U.S. Department of Commerce							
5285 Port Royal Road							
Springfield, VA 22161							
13. SUPPLEMENTARY NOTES							
AA ADOTDAOT (Maximum 000 Mi )							
14. ABSTRACT (Maximum 200 Words) Report of levelized cost in 2005 U.S. dollars, energy use, and GHG emission benefits of seven hydrogen production,							
delivery, and distribution path	iways.						
15. SUBJECT TERMS							
hydrogen pathways; well-to-wheels; hydrogen production; hydrogen delivery; hydrogen distribution; pathway							
scenarios; natural gas; electricity; biomass–liquid truck delivery; biomass–pipeline; natural gas–pipeline; wind							
electricity; coal							
16. SECURITY CLASSIFICATION OF:	1	7. LIMITATION		19a. NAME C	OF RESPONSIBLE PERSON		
	S PAGE	OF ABSTRACT	OF PAGES				
Unclassified Unclassified Uncl	assified	UL		19b. TELEPH	HONE NUMBER (Include area code)		
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Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18