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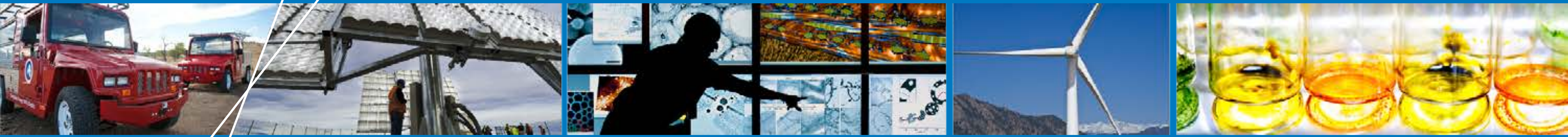
Overview of Two Hydrogen Energy Storage Studies: Wind Hydrogen in California and Blending in Natural Gas Pipelines



California Hydrogen Business Council, Hydrogen and Fuel Cell Summit

Marc W. Melaina, Ph.D.

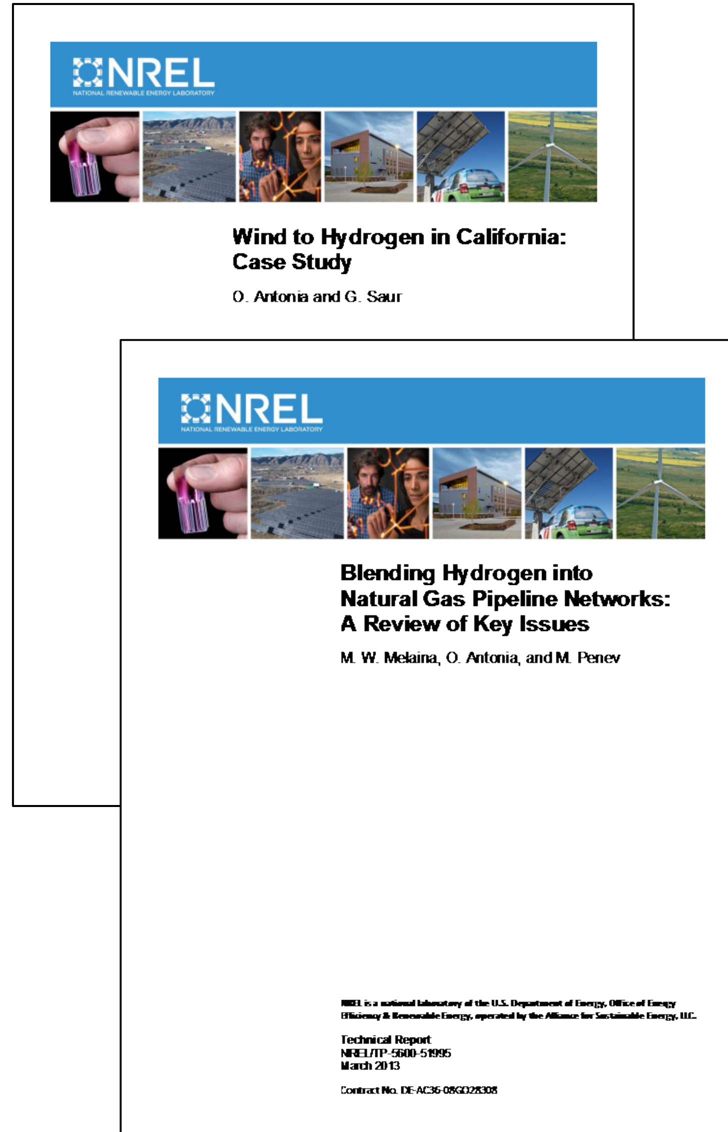
April 9, 2013

NREL/PR-5600-58514

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Presentation Overview

- **NREL has analyzed a wide range of hydrogen systems, with a focus on spatial analysis, early markets, and renewable pathways**
  - www.nrel.gov/hydrogen/proj_analysis.html
- **Wind hydrogen in California**
  - *Wind to Hydrogen in California: Case Study.* Olga Antonia and Genevieve Saur. (August 2012)
- **Blending in natural gas pipelines**
  - *Blending Hydrogen Into Natural Gas Pipeline Networks: A Review of Key Issues.* Marc Melaina, Olga Antonia, and Michael Penev. (March 2013)



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Wind to Hydrogen in California: Case Study

O. Antonia and G. Saur

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Blending Hydrogen into Natural Gas Pipeline Networks: A Review of Key Issues

M. W. Melaina, O. Antonia, and M. Penev

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Technical Report
NREL/TP-5600-51995
March 2013

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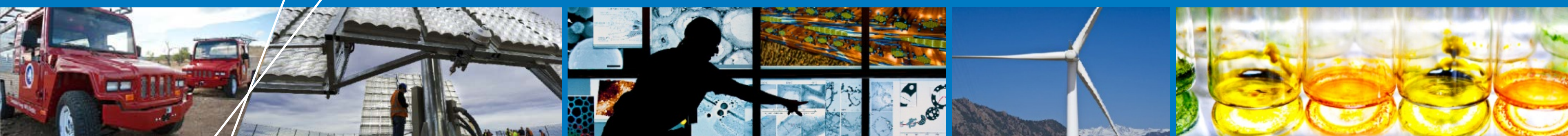


Wind Hydrogen in California: Case Study

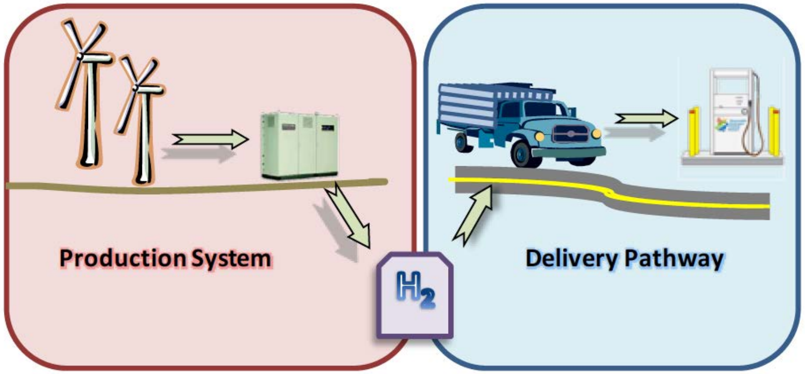
Wind to Hydrogen in California: Case Study.
Olga Antonia and Genevieve Saur. (August 2012)

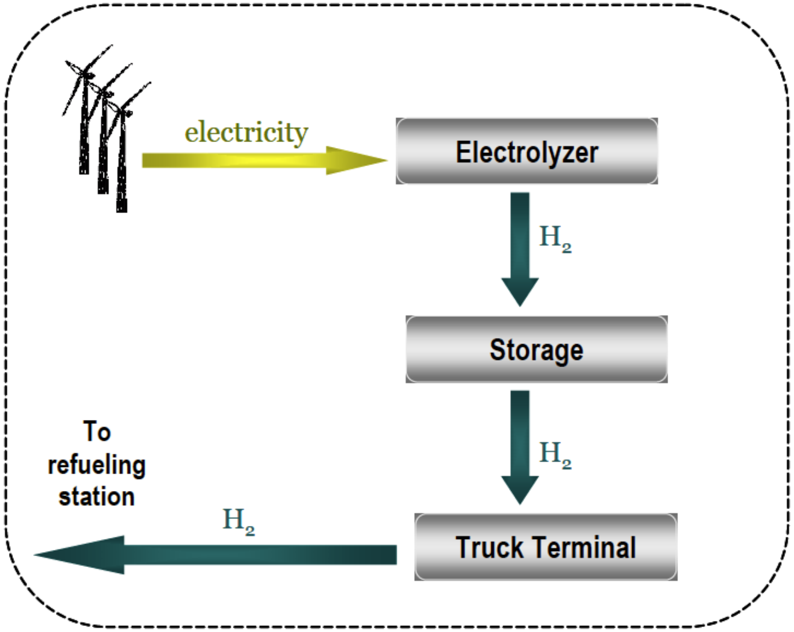
Techno-Economic Analysis Case Study

Contents

Major Model Input Assumptions

- **The analysis is a hypothetical techno-economic cost estimate developed using NREL's H2A cost models.**
  - Results are a first-cut estimate for an ideal system (not a proposed project).
- **The optimized wind farm uses 61 turbines (3 MW each) with total nameplate capacity of 183 MW using NREL's H2A cost models.**
  - Uninstalled turbine cost: $1270/kW
  - Total capital: $431 million
  - Total operating cost: $15.6 million/yr
- **Stand-alone supply system**
  - At 40,000 kg/day demand, the cavern size is about 32 days of the demand.



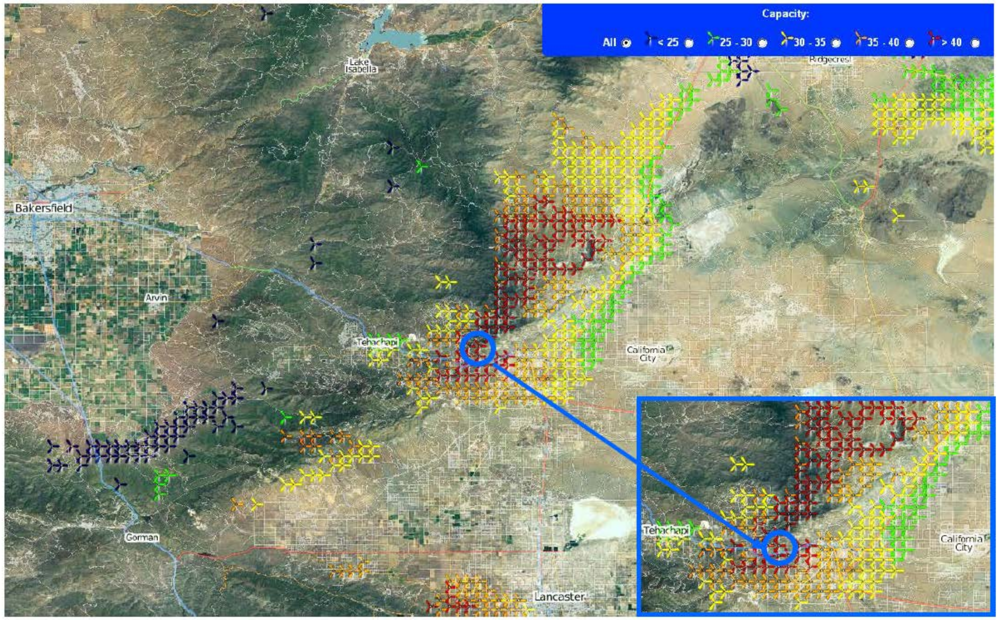


Ideal Wind Site Location With High Capacity Factor

Wind Site Location:

Mojave Desert (35.13 N, 118.27W)

- Average wind speed:
  9.2 m/s at 100 m
- Annual capacity factor: 43.2%
  - Energy produced / max.



Results are not typical of wind hydrogen in general. The average cost of wind energy would increase if the cheapest locations are converted to hydrogen.

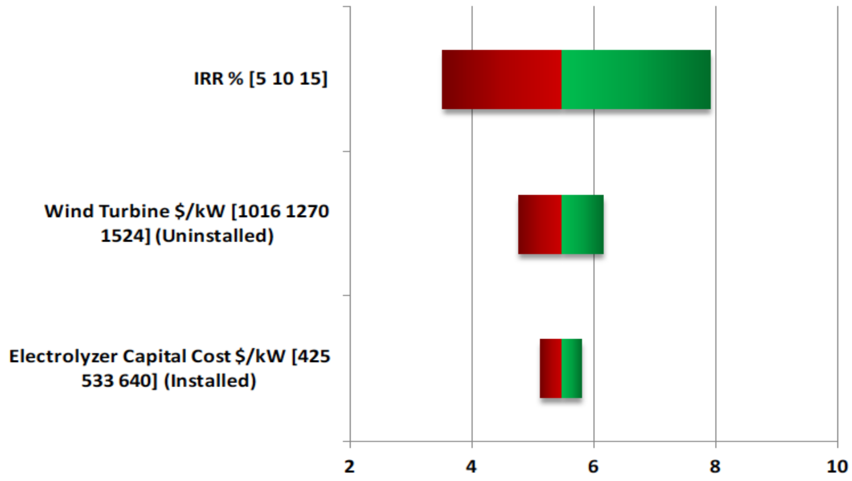
H2A Cost Models Allow Hourly Analysis and Sensitivities on Technical and Financial Inputs

The analytic framework allows for an exploration of a range of variables and sensitivity analyses. Some examples are shown below.

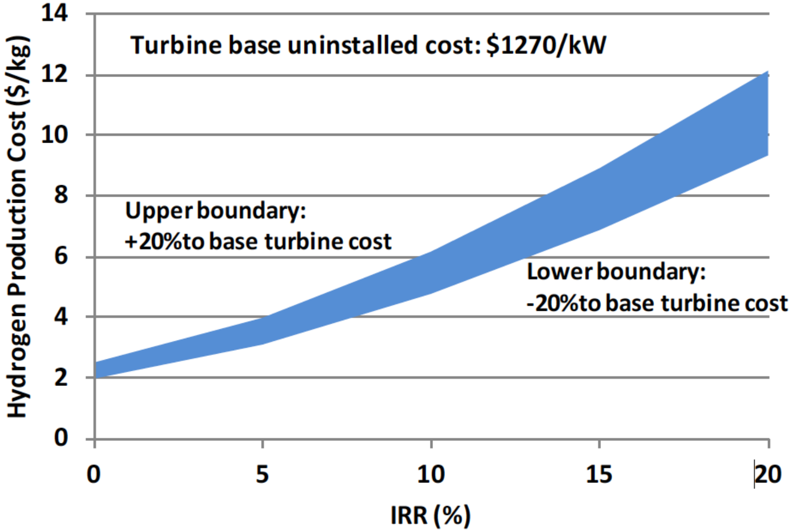
Equipment Replacement Summary

Equipment	Replacement Period (years)	Replacement Cost
Wind Turbines	20	20% initial installed capital cost
Electrolyzer	7	25% initial uninstalled capital cost
Terminal Equipment	20	evaluated by Equation 1
Truck Cab	5	evaluated by Equation 1
Truck Trailer	20	evaluated by Equation 1
Dispenser	10	evaluated by Equation 1

Hydrogen Production Cost Sensitivity to Select Variables



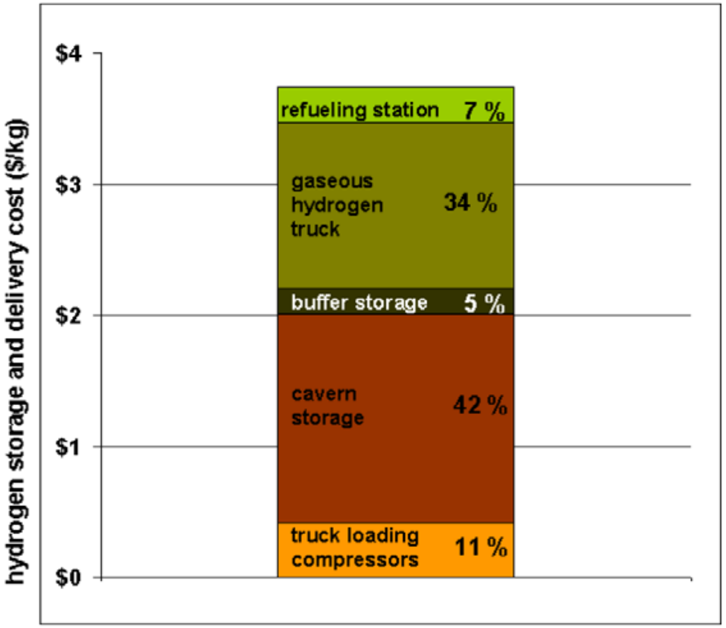
Hydrogen Production Cost Sensitivity for Increasing IRR



The IRR model input assumption has a significant influence on the cost of hydrogen.

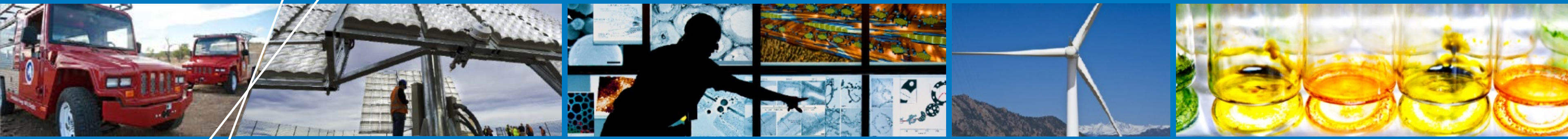
Summary Results

- The total cost of hydrogen produced from the electricity at the wind farm and delivered to and dispensed at the Los Angeles area refueling stations is $9.4/kg.
  - Production cost is $5.5/kg; storage and delivery cost is $3.9/kg.
- Including a production or incentive tax credit could reduce production costs to $4.4 or $4.2 per kg.
- An alternative scenario with lower and more variable supply (30,000 kg/d) can reduce storage and delivery capital.
  - Delivery costs drop by $0.9/kg.
- With fuel cell vehicles achieving twice the fuel economy of conventional gasoline vehicles, $9.4/kg translates to an equivalent per mile cost of approximately $4.70/gal gasoline.



Hydrogen storage and delivery costs for the base case scenario

Additional cost reductions would be needed to compete directly with gasoline.



Blending Hydrogen Into Natural Gas Pipeline Networks: A Review of Key Issues

Review of literature, including comparisons to U.S. conditions and pressure swing absorption (PSA) extraction cost estimates

Contents

This report relies heavily on the EU NaturalHy study: www.naturalhy.net

Report Summary Conclusions

From the Executive Summary:

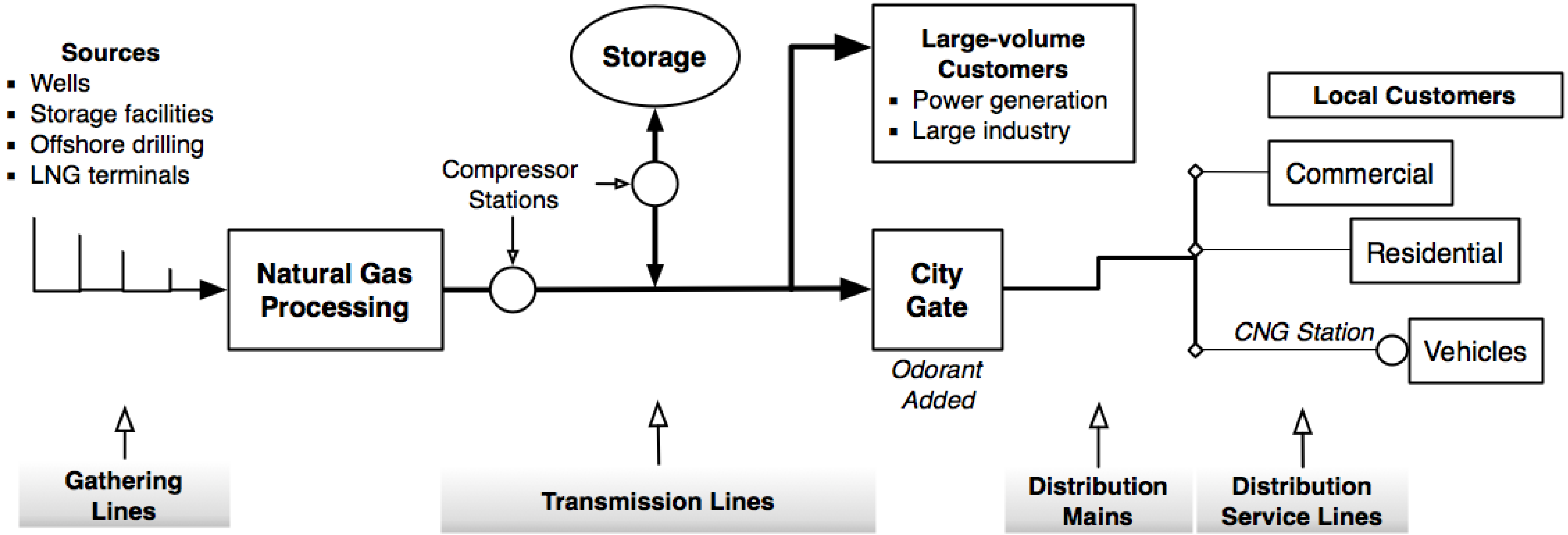
- "If implemented with relatively low concentrations, less than 5%–15% hydrogen by volume, this strategy of storing and delivering renewable energy to markets appears to be viable without significantly increasing risks associated with utilization of the gas blend in end-use devices (such as household appliances), overall public safety, or the durability and integrity of the existing natural gas pipeline network."

- "However, the appropriate blend concentration may vary significantly between pipeline network systems and natural gas compositions and must therefore be assessed on a case-by-case basis."

- "Any introduction of a hydrogen blend concentration would require extensive study, testing, and modifications to existing pipeline monitoring and maintenance practices (e.g., integrity management systems). Additional cost would be incurred as a result, and this cost must be weighed against the benefit of providing a more sustainable and low-carbon gas product to consumers."

How Would It Work?

- Multiple possibilities for injection, storage, and extraction
- Injection at transmission line (or cavern storage) and extraction (for high volumes) at city gate may be most promising for use in fuel cell electric vehicles

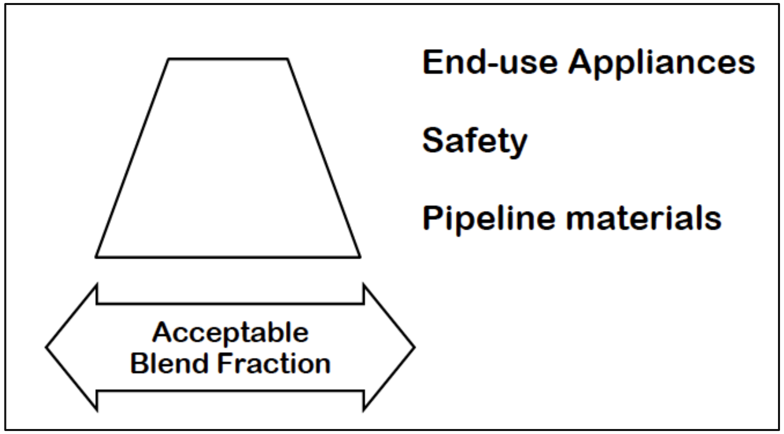


Report Reviews Seven Key Issues

1. Benefits of blending
2. Extent of the U.S. natural gas pipeline network
3. Impact on end-use systems
4. Safety
5. Material durability and integrity management
6. Leakage
7. Downstream extraction

Issues are interrelated, but discussed separately.

The most stringent conditions on the total hydrogen blend level (percent hydrogen by volume) are set by requirements for end-use appliances. The second and third most stringent conditions are safety and pipeline materials.



Benefits and Extent of U.S. Natural Gas System

Benefits of Blending

- Reduction in greenhouse-gas emissions if hydrogen is produced from low-carbon energy resources
- In some cases, blending could prove to be an economical means of expanding renewable energy production.
- A full cost/benefit analysis should include the social benefits (external to the market) and/or credits (internalized to the market) of renewable hydrogen pathways.

Extent of the U.S. Natural Gas Pipeline Network

- 2.44 million miles of pipeline, 400 underground storage facilities, and 1,400 compressor stations
- Enhanced domestic production methods suggest long-term competitiveness of natural gas.

"Hydrogen blending could become a widespread, long-term, and integral practice to supplement a critical domestic energy infrastructure."

Impact on End-Use Systems

Conditions determining a maximum hydrogen blend level that does not adversely influence appliance operation or safety vary significantly.

- These include the composition of the natural gas, the type of appliance (or engine), and the age of the appliance.
- The impact of hydrogen blends on industrial facilities must be addressed on a case-by-case basis, and stationary gas engines will likely require changes to control systems.

Ranges noted as being generally acceptable for end-use systems fall within 5% to 20% hydrogen, and most discussions note types of changes, precautions, or costs associated with higher blends.

- Florisson 2010; De Vries 2009; Haeseldonckx 2007; De Vries 2007; Schumra and Klingenberg 2005; Kelly and Hagler 1980

"Given the inertia behind any required changes to end-user appliances or industrial facilities, hydrogen blending likely would begin at very low concentrations and then increase gradually over time (if warranted) as required modifications for higher concentrations are addressed."

Safety and Material Durability and Integrity Management

Safety

- Multiple factors must be taken into consideration to assess the safety concerns associated with blending hydrogen into the existing U.S. natural gas system.
- It is difficult to make general claims about safety because of the large number of factors involved; detailed risk assessment results will likely vary from location to location.
- The report includes an appendix prepared by the Gas Technology Institute (GTI) to assess data specific to the U.S. natural gas supply system.

Material Durability and Integrity Management

- Pipeline durability can degrade with long-term exposure to high concentrations and high pressures.
- For blending, this is mostly a concern for high-pressure transmission pipelines.
- The accuracy of existing gas meters can be influenced.
- Increased leakage (and therefore monitoring) can be a concern.
- Changes to integrity management practices may incur an additional 10% cost to these activities. All requirements would be very case-specific.

Leakage and Downstream Extraction

Leakage

- Gas loss would increase, but would likely prove to be economically insignificant in most cases.
- Leakage into confined spaces (along distribution lines) may pose a safety risk, and could therefore require detection/monitoring to manage risks.

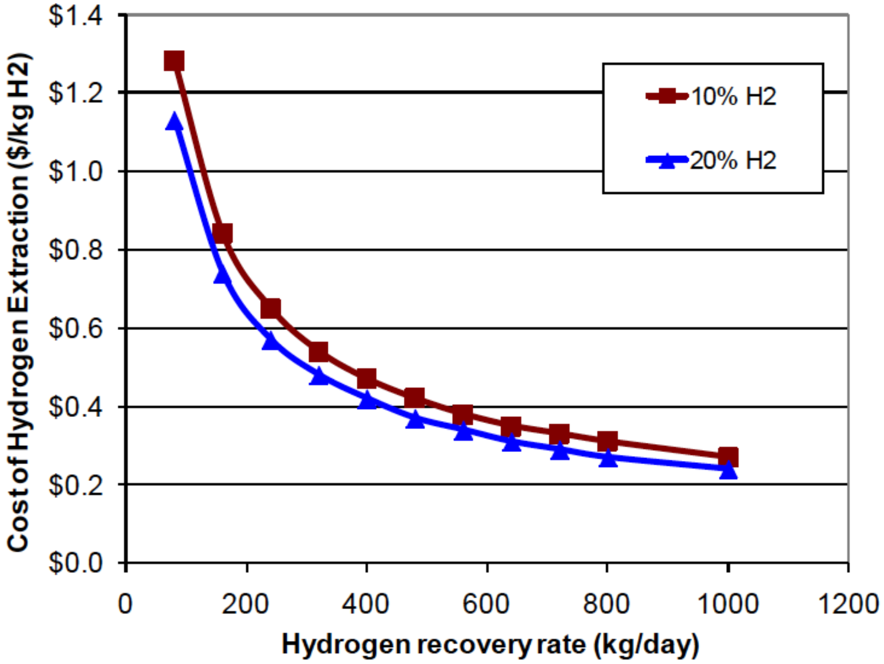
Downstream Extraction

- Three methods are discussed: PSA, membrane separation, and electrochemical hydrogen separation.
- PSA units with low hydrogen concentrations (<20%) would be large.
- PSA units appear to be economically practical only at pipeline pressure reduction stations where the pressure drop is synergistic with hydrogen separation.
  - Extraction with reinjection of NG into transmission: **$2.0-$8.3 per kg**
  - Extraction at pressure letdown stations: **$0.3-$1.3 per kg**
  - These costs would be added to production and (other) delivery costs.

These added costs are not excessive, and it appears that several thousand letdown stations are located in close proximity to large U.S. urban areas.

Cost Estimate for PSA Extraction System

- Cost of re-injecting natural gas into high-pressure transmission pipelines appears to be prohibitive.
  - Greater than $2/kg for 10% to 20% hydrogen and 300 psi pipeline
- Results below are for a system located at the city gate letdown station, taking advantage of pressure differential (300 down to 30 psi).



These additional costs could prove to be lower than other delivery options.

Figure 18. Estimated cost of hydrogen extraction by PSA unit at the pressure-reduction facility (from 300 psi to 30 psi).
Assumed hydrogen recovery factor is 80%.

Summary

Wind Hydrogen in California

- Cost estimates have been developed for large-scale, stand-alone, wind-hydrogen supply with delivery to a station in northern Los Angeles.
- Estimated cost of delivered hydrogen is $9.4/kg
- Production cost of $5.5/kg, and storage and delivery cost of $3.9/kg
- Roughly equivalent to ~$4.70/gal gasoline (assuming 2X fuel economy)
- Opportunities exist to reduce costs further through system integration and optimization

Blending Hydrogen Into Natural Gas Pipeline Systems

- Report is a review of seven key issues
- Appendix includes an assessment by GTI of U.S. conditions
- Requirements for end-use systems are most stringent on percent blend
- Extraction at pressure letdown stations, co-located at the city gate, could involve equipment costs as low as $0.3-$1.3 per kg
- Economic and technical feasibility is very site and system dependent

Acknowledgments

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- The report has benefited greatly from comments received from multiple reviewers of an earlier version.
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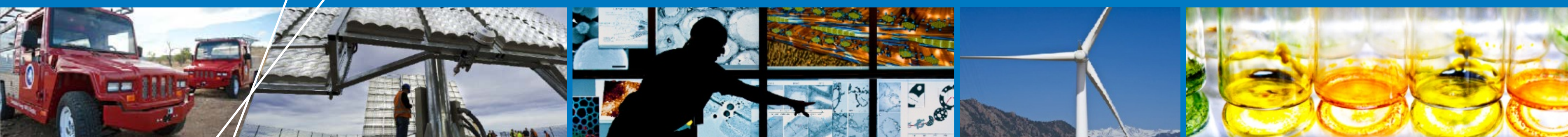

Questions?

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