H2A Hydrogen Production Model: Version 3.2018 User Guide (DRAFT)

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The H2A Production Model analyzes the technical and economic aspects of hydrogen-production technologies. The model estimates the hydrogen selling price (or levelized cost) using a standard discounted-cash-flow methodology and a specified after-tax internal rate of return from the production technology. Users have the option of accepting default technology input values—such as capital costs, operating costs, and capacity factor—from established H2A production technology cases or entering custom values. Users can also modify the model's financial inputs.

The H2A Production Model is actually two models, which are very similar. The primary difference is that the central model can perform carbon sequestration calculations, whereas the distributed model performs refueling station compression, storage, and dispensing calculations. The models and detailed technology cases can be downloaded from www.hydrogen.energy.gov/h2a_production.html.

Compared with the previous version (version 3.1), this new version (version 3.2018) of the H2A Production Model features several updates and improvements. Updated analyses include those related to carbon capture and sequestration; compression, storage, and dispensing (to reflect the latest Hydrogen Delivery Scenario Analysis Model [HDSAM]); and upstream emissions (to add time sensitivity and reflect the most recent Greenhouse gases, Regulated Emissions, and Energy use in Transportation [GREET] model). Monte Carlo analysis has been added to the *Risk Analysis* worksheet in the central model. The Annual Energy Outlook (AEO) 2017 reference case is now available in the model, and all AEO price projections are extrapolated through 2100 using the Joint Global Change Research Institute's GCAM (formerly MiniCAM) model. The reference year for calculations has been updated to 2016. For H2A technology cases, current cases have been changed to reflect a 2015 construction year and future cases to reflect a 2040 construction year. The central coal gasification and distributed ethanol reforming cases have been transitioned from H2A version 2 to version 3. Finally, key financial assumptions were calibrated with reported industry performance for percent equity financing, return on equity, interest rate, term of debt and new federal tax rate.

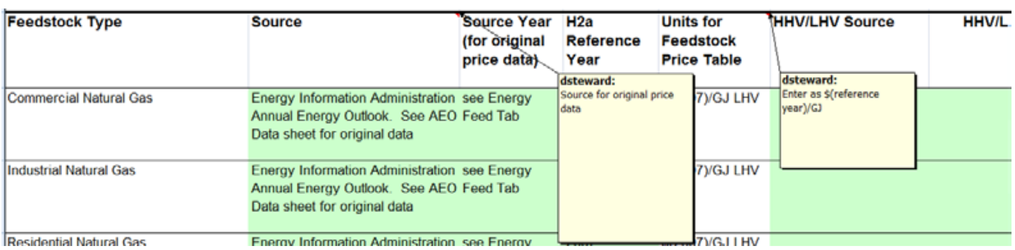
This *User Guide* introduces the basic elements of version 3.2018 of the H2A Production Model and then describes the function and use of each of its worksheets.

Contents

Tips & Troubleshooting

General Tips

- Before you start modifying the model, save the file under a new name. This will make it simple to go back to the unmodified model later if necessary.
- If the file you are working with accumulates numerous errors, or if you delete information that you later find you need, etc., it might be easier to discard the file and start afresh with the original version of the model and/or production technology case. If you have not kept an original version, download the model again from the H2A Web site: www.hydrogen.energy.gov/h2a_production.html.
- The model requires the use of macros. Make sure macro use is allowed in Excel.
- Throughout the model, orange cells are meant to accept static user-input values or user-defined equations, and blue cells are calculated automatically by the model. Use care if you overwrite the blue calculation cells with static values or your own equations; once overwritten, the original equation information is permanently deleted. Green cells are for user-input information and notes. Yellow cells contain H2A information and default values. Red cells indicate an error has occurred and inputs must be checked.
- Do not type values into cells with drop-down menus. Select only from values in the menu.
- If it is not obvious how to close or move on past a pop-up window, you can close it by clicking the in the upper right corner.
- Mouse over small red triangles for useful notes as shown below.



- The *Input_Sheet_Template* worksheet works best (has the least likelihood of errors) when you fill it out as completely as possible, starting with the top and working down. After filling out the worksheet completely, the model will automatically calculate the cost of hydrogen.

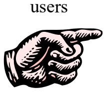
<u>User Guide Symbols</u>


CAUTION

Follow instructions carefully to prevent errors or unwanted results.


Advanced users

Skip this section if you are a novice user or want to perform only simple analyses.


TIP

Read for useful information.

Solutions to Commonly Encountered Problems

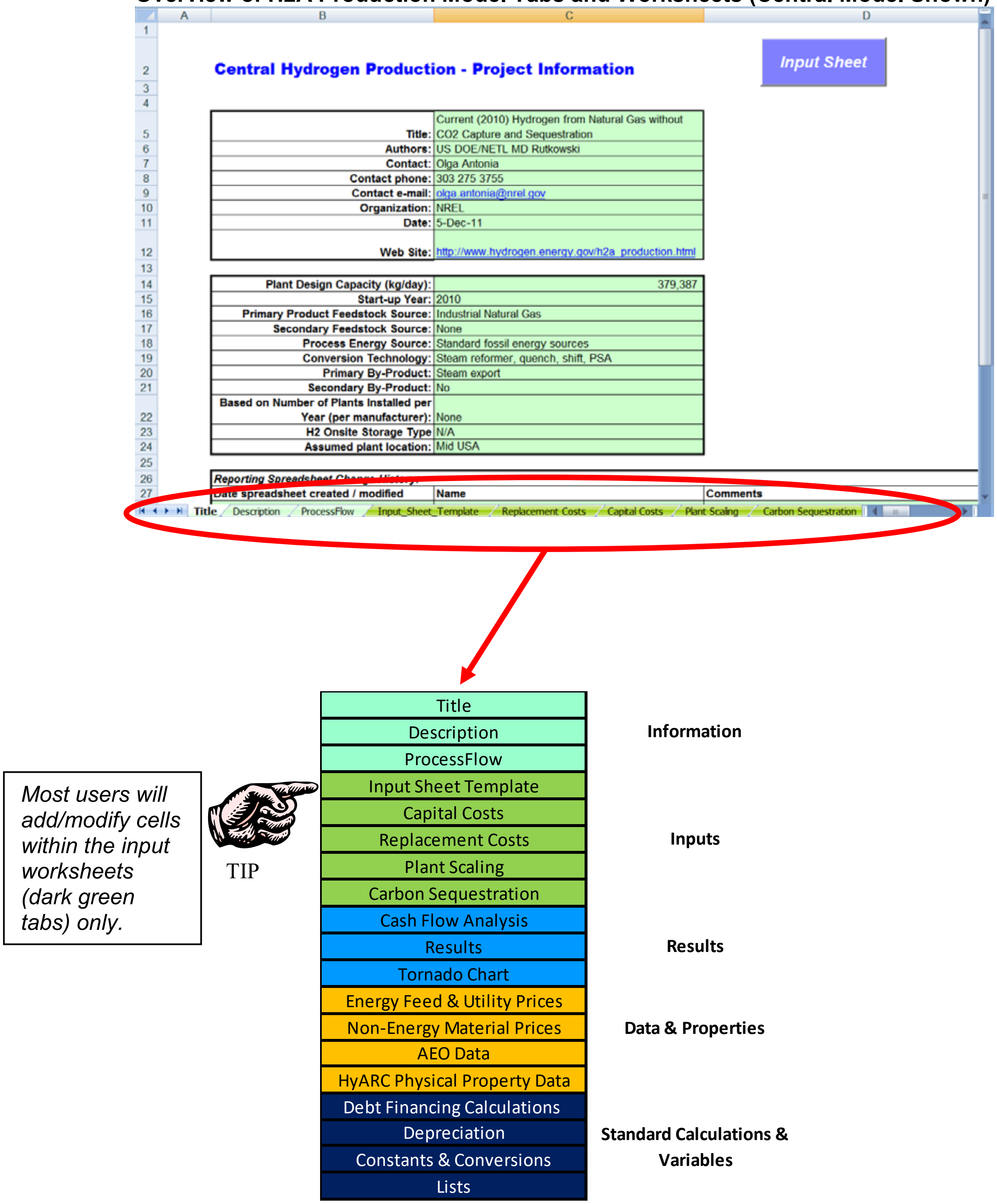
Problem	Possible Solution	Relevant Worksheets	User Guide Sections
1. Clicking the *Use Default Values* button unintentionally replaced some of your user-defined values.	To retain user-defined values while filling in blank cells with default values, click *No* in the *Use Default Values* pop-up window.	*Input_Sheet_Template* *Carbon Sequestration*	*Table of Contents* (p. 9)
2. After deleting energy feedstocks, utilities, and byproducts or other materials and byproducts in the *Input_Sheet_Template* worksheet using Microsoft Excel's delete functionality, you received null results.	Do not use Excel's delete functionality to delete entries under *Energy Feedstocks, Utilities, and Byproducts* or *Other Materials and Byproducts* within the *Input_Sheet_Template* worksheet. If you have used Excel's delete functionality in one or both of these sections, discard your current file and start afresh with the original version of the model and/or production technology case. In the future, make sure to use the H2A Model's *Delete* button to delete entries within these sections.	*Input_Sheet_Template*	*Energy Feedstocks, Utilities, and Byproducts* (p. 11) *Other Materials and Byproducts* (p. 14)
3. You did not perform the actions described in problem 2 above, but you still received null results.	Make sure to enter all critical values in the *Technical Operating Parameters and Specifications* and *Financial Input Values* sections before completing the rest of the *Input_Sheet_Template* worksheet. In particular, make sure values are present for reference year, startup year, and plant capacity.	*Input_Sheet_Template*	*Variable Operating Costs* (p. 14)

Problem	Possible Solution	Relevant Worksheets	User Guide Sections
4. You used the *Delete* button to delete an entry under *Energy Feedstocks, Utilities, and Byproducts* or *Other Materials and Byproducts*, and more entries—or different entries—were deleted than you had intended.	Be careful to choose the correct item from the *Delete* drop-down menu within the *H2A Toolkit*. It deletes all entries of the selected type.	*Input_Sheet_Template* *H2A Toolkit*	*Energy Feedstocks, Utilities, and Byproducts* (p. 11) *Other Materials and Byproducts* (p. 14)
5. You performed a sensitivity analysis, and the resulting tornado chart contained bad or nonsensical results.	Try switching the values you entered for the values "lowering" and "increasing" hydrogen cost. It is not always obvious how changing the value of a variable will affect the hydrogen price.	*Risk Analysis*	*Risk Analysis Worksheet* (p. 31)
6. You modified the *Lists* worksheet, and now the model does not work properly.	Do not add, delete, or change anything on the *Lists* worksheet. Modifying the lists can disable or introduce major errors into the model. If you have modified the lists, discard your current file and start afresh with the original version of the model and/or production technology case.	*Lists*	*Lists Worksheet* (p. 42)

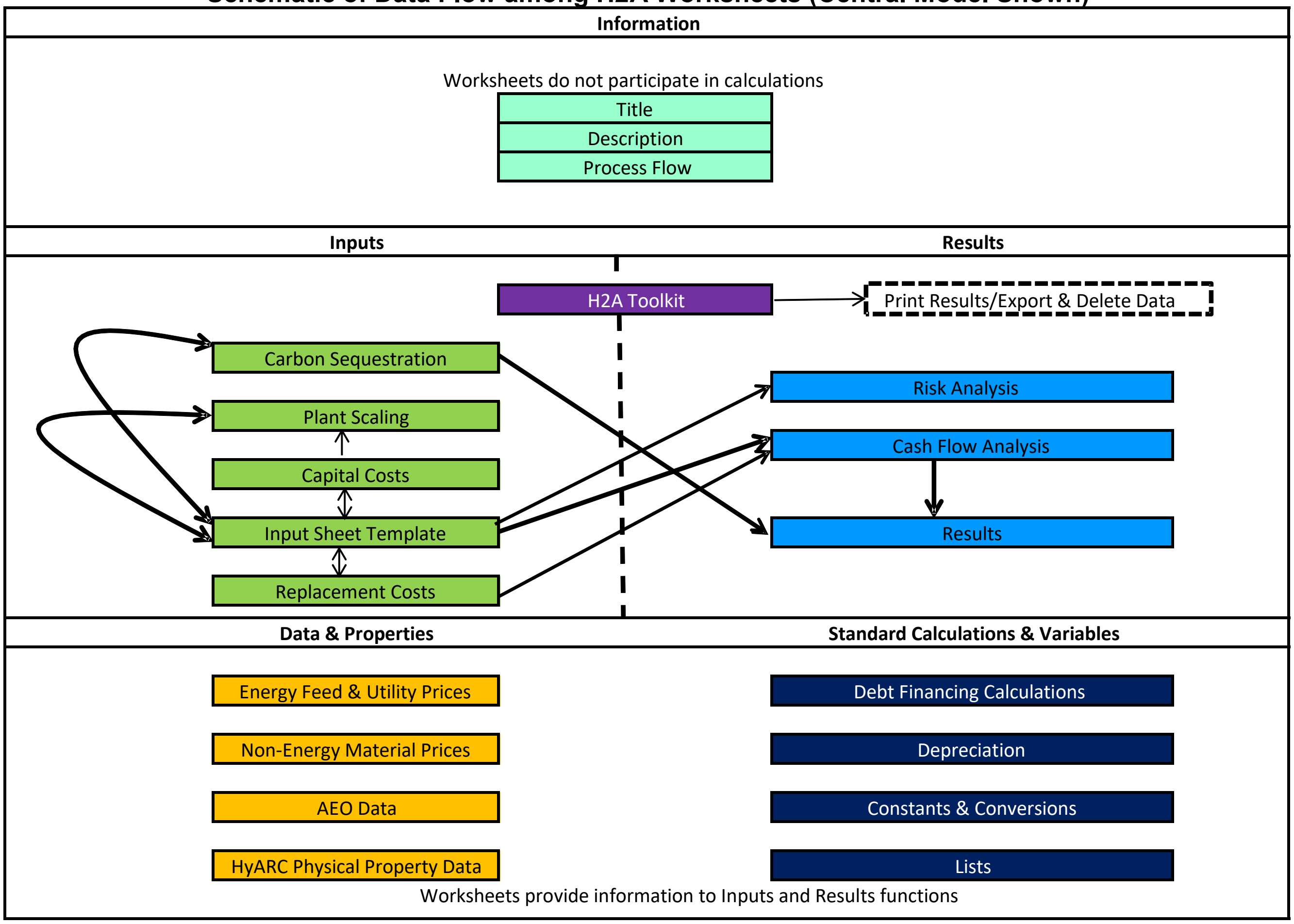
Quick Start: Getting Around

The spreadsheet is organized into numerous worksheets, which have tabs color coded according to their function, as shown below for the central model. The schematic on the following page shows a generalized data flow among the worksheets for the central model.

Overview of H2A Production Model Tabs and Worksheets (Central Model Shown)



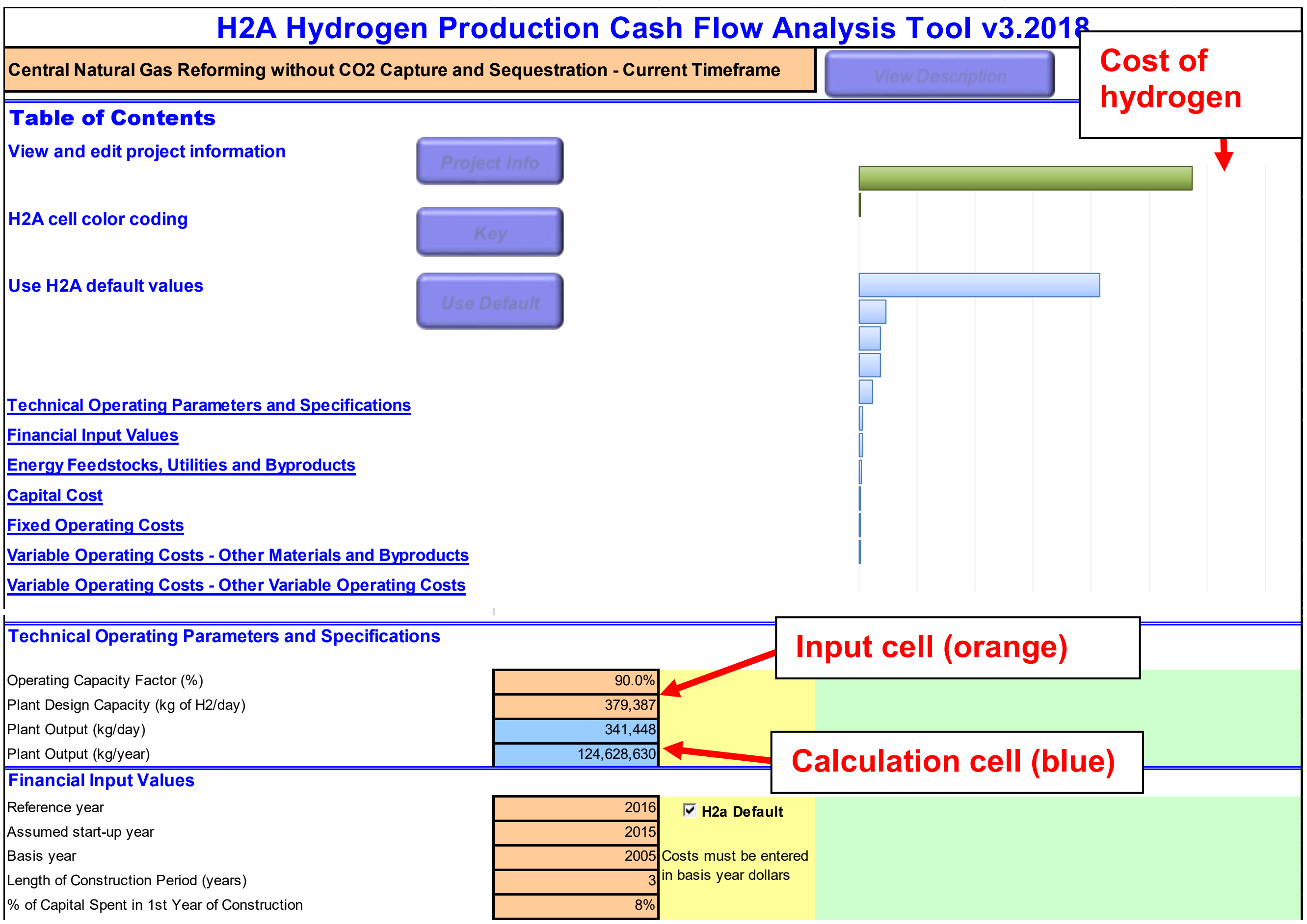
Schematic of Data Flow among H2A Worksheets (Central Model Shown)



Quick Start: Performing Simple Production Cost Analyses

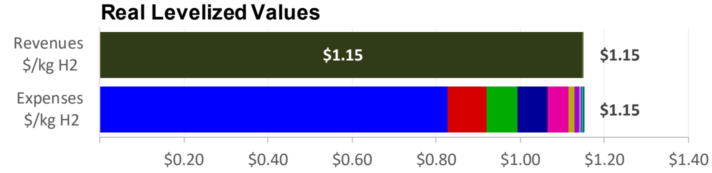
To perform a simple production cost analysis, select the *Input_Sheet_Template* tab. Accept the default (e.g., production technology case) values or enter new values into the orange cells. The contents of the blue cells are calculated automatically. Use the drop-down menus and buttons to enter information for *Energy Feedstocks, Utilities, and Byproducts* and *Other Materials and Byproducts*. Once all information is entered, the model will automatically calculate the cost of hydrogen. The *Real Levelized Values* chart at top right breaks down the total cost into individual components. Navigating to the *Results* tab will present detailed cost, energy, and emissions results.

Input_Sheet_Template Worksheet (Central Model Shown)



Results Worksheet (Central Model Shown)

Table of Contents



Cost of Hydrogen
Salvage Value
Byproduct Sales
Feedstock Cost
Other Variable Operating Costs
Initial Equity Depreciable Capital
Fixed Operating Cost
Debt Interest
Cash for Working Capital Reserve
Yearly Replacement Costs
Taxes
Principal Payment
Decommissioning Costs
Other Non-Depreciable Capital Costs
Other Raw Material Cost

H2a Analysis Results

COST RESULTS

Lang Factor	2.73

Specific Item Cost Calculation

Cost Component	Cost Contribution ($/kg)	Percentage of H2 Cost
Capital Costs	$0.15	13.5%
Decommissioning Costs	$0.00	0.1%
Fixed O&M	$0.07	6.3%
Feedstock Costs	$0.83	72.1%
Other Raw Material Costs	$0.00	0.0%
Byproduct Credits	$0.00	0.0%
Other Variable Costs (including utilities)	$0.09	8.0%
Total	$1.15	

Approximate Carbon Sequestration Costs*

Cost Component	Cost Contribution ($/ kg H2)	Cost Contribution ($/ tonne CO2 Sequestered)
Capital Costs	$0.00	#DIV/0!
O&M Cost	$0.00	#DIV/0!
Energy Cost	$0.00	#DIV/0!
Total	$0.00	#DIV/0!

*Carbon sequestration costs presented in this table do not include carbon capture capital and operating costs.

ENERGY

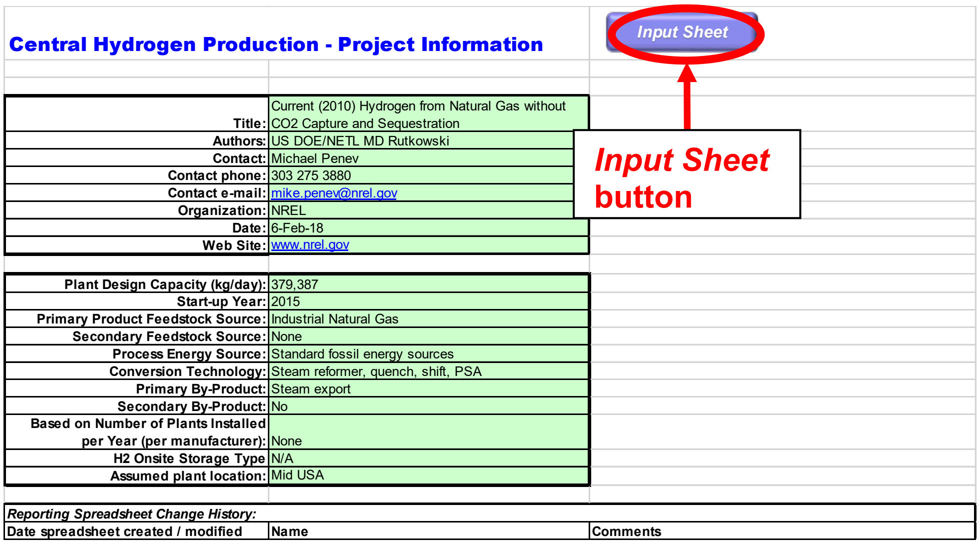
Energy Data

Feedstock	Energy Input (GJ/kg H2)	Energy Input (kWh/kg H2)	LHV (GJ/usage unit)	Usage (/kg H2)	Unit	Unit System Conversion Factor	Real levelized cost
Industrial Natural Gas	0.165	45.790	1.055	0.156	mmBtu	1	$ 5.60

Information Worksheets

Established H2A production technology cases contain information worksheets linked from the light-green tabs. These worksheets (*Title*, *Description*, and *ProcessFlow*) do not participate in the model's calculations but contain valuable information about the project file and the hydrogen production technology being modeled. Clicking the *Input Sheet* button on any of the information worksheets sends you to the *Input_Sheet_Template* worksheet to begin using the model.

Example Title Worksheet (Central Natural Gas with no CO_2 Capture and Sequestration)



Central Hydrogen Production - Project Information

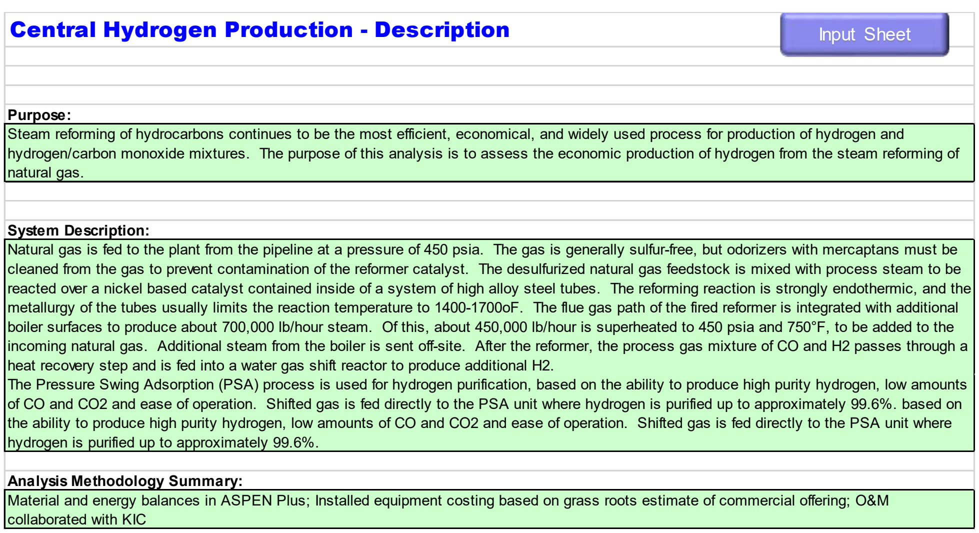
Title:	Current (2010) Hydrogen from Natural Gas without CO2 Capture and Sequestration
Authors:	US DOE/NETL MD Rutkowski
Contact:	Michael Penev
Contact phone:	303 275 3880
Contact e-mail:	mike.penev@nrel.gov
Organization:	NREL
Date:	6-Feb-18
Web Site:	www.nrel.gov

Plant Design Capacity (kg/day):	379,387
Start-up Year:	2015
Primary Product Feedstock Source:	Industrial Natural Gas
Secondary Feedstock Source:	None
Process Energy Source:	Standard fossil energy sources
Conversion Technology:	Steam reformer, quench, shift, PSA
Primary By-Product:	Steam export
Secondary By-Product:	No
Based on Number of Plants Installed per Year (per manufacturer):	None
H2 Onsite Storage Type	N/A
Assumed plant location:	Mid USA

Reporting Spreadsheet Change History:

Date spreadsheet created / modified	Name	Comments

Example Description Worksheet (Central Natural Gas with no CO_2 Capture and Sequestration)



Central Hydrogen Production - Description

Purpose:

Steam reforming of hydrocarbons continues to be the most efficient, economical, and widely used process for production of hydrogen and hydrogen/carbon monoxide mixtures. The purpose of this analysis is to assess the economic production of hydrogen from the steam reforming of natural gas.

System Description:

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 of a system of high alloy steel tubes. The reforming reaction is strongly endothermic, and the metallurgy of the tubes usually limits the reaction temperature to 1400-1700oF. 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. After the reformer, the process gas mixture of CO and H2 passes through a heat recovery step and is fed into a water gas shift reactor to produce additional H2.
The Pressure Swing Adsorption (PSA) process is used for hydrogen purification, based on the ability to produce high purity hydrogen, low amounts of CO and CO2 and ease of operation. Shifted gas is fed directly to the PSA unit where hydrogen is purified up to approximately 99.6%. based on the ability to produce high purity hydrogen, low amounts of CO and CO2 and ease of operation. Shifted gas is fed directly to the PSA unit where hydrogen is purified up to approximately 99.6%.

Analysis Methodology Summary:

Material and energy balances in ASPEN Plus; Installed equipment costing based on grass roots estimate of commercial offering; O&M collaborated with KIC

Input_Sheet_Template Worksheet

The *Input_Sheet_Template* worksheet is the H2A Model's primary user interface (see the screen capture on page 6). The sections below describe each of the seven sections of the *Input_Sheet_Template* worksheet in sequence as they appear in the worksheet as well as the *H2A Toolkit* (see page 25 for details on the *H2A Toolkit*). You use the *Input_Sheet_Template* worksheet to input the data the model uses for calculations, perform analyses, and access the automated functions of the model through the *H2A Toolkit* utility. After you fill out the worksheet, the model automatically calculates the cost of hydrogen. The chart at the top of the worksheet will update if any orange cells are modified. Throughout the worksheet, entries in the *Notes* column describe calculations being performed or offer guidance on user inputs.

Project Description

The first line of the *Input_Sheet_Template* worksheet lists the name of the H2A file you are using. Click the *View Description* button to view a brief project description (see page 8 for a sample *Description* worksheet).

Table of Contents

At the top of the *Table of Contents* are three buttons. The *Project Info* button sends you to the *Title* worksheet. The *Key* button describes the color coding used in the H2A Model.

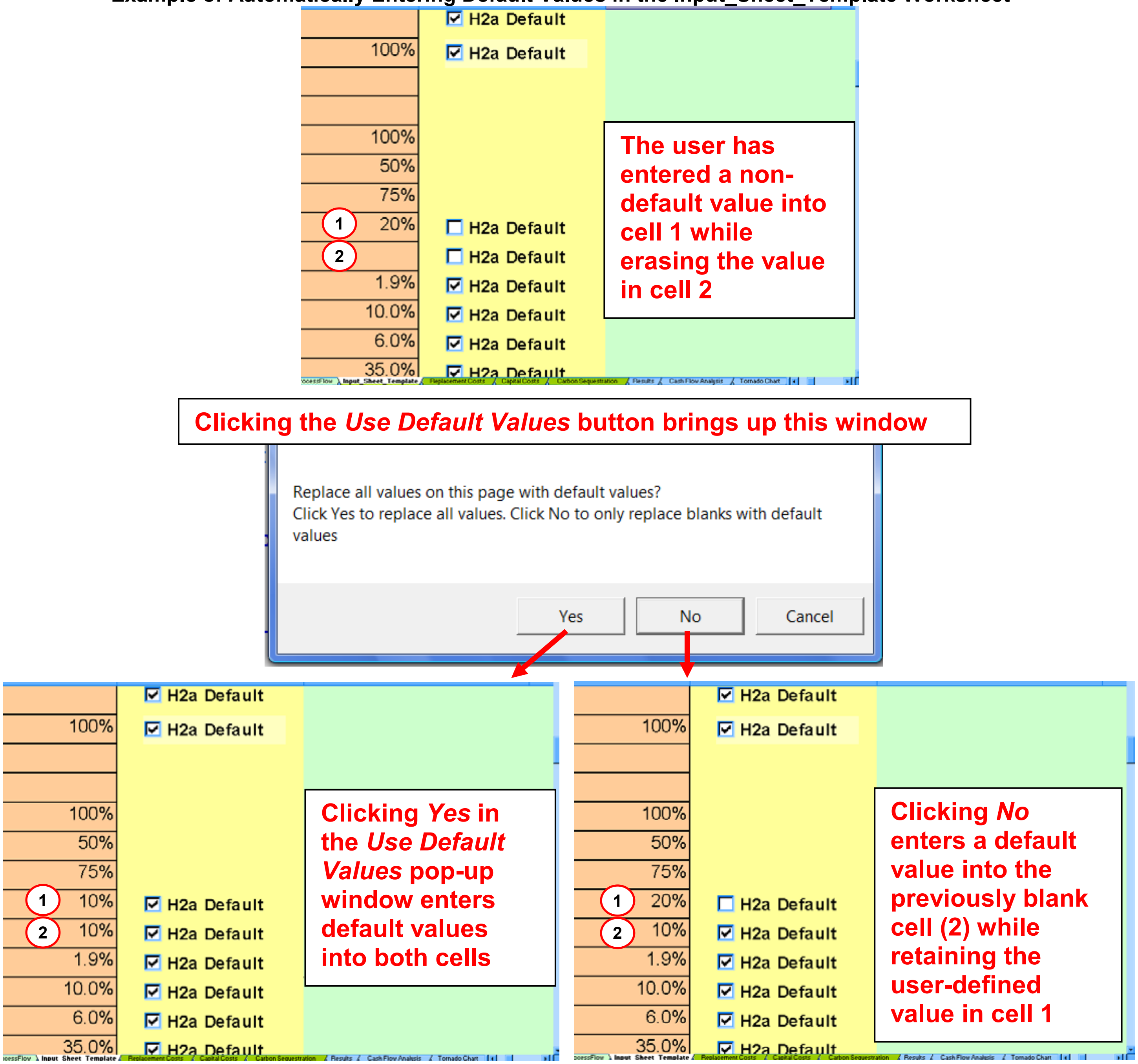
The *Use Default Values* button links to a pop-up window, which provides two options for automatically using H2A default values. Clicking *Yes* replaces all *Input_Sheet_Template* inputs for which default values exist with the default values. Clicking *No* enters default values only for those inputs that have default values and are blank (see illustration on page 10). Be careful when using this button so as not to replace values unintentionally.

CAUTION

Beneath the column of buttons, the *Table of Contents* links to the major sections of the *Input_Sheet_Template* worksheet, which are described in the subsequent sections of this *User Guide*. These sections (which vary slightly in order and wording between the central and distributed model) include the following:

- *Technical Operating Parameters and Specifications*
- *Financial Input Values*
- *Energy Feedstocks, Utilities, and Byproducts*
- *Capital Cost*
- *Fixed Operating Costs*
- *Variable Operating Costs - Other Materials and Byproducts*
- *Variable Operating Costs - Other Variable Operating Costs.*

Example of Automatically Entering Default Values in the Input_Sheet_Template Worksheet



Technical Operating Parameters and Specifications

Here you define the hydrogen output of your plant. For the central model, enter values for capacity factor and plant design capacity. For the distributed model, also enter information for summer surge, Friday average, and outages.

Financial Input Values

Here you define the financial characteristics of your plant. Several of the fields have an "H2a Default" checkbox adjacent to them. Checking this box automatically fills the cell with the H2A Model default value for that input. The fields *Length of Construction Period*, *Depreciation*

Schedule Length, and *Depreciation Type* have drop-down menus containing predefined values. Select a value from the drop-down menu for these fields; values not listed in the drop-down menus cannot be entered. The only field calculated by the model within the *Financial Input Values* section is *Total Tax Rate*, shown in blue.

Two very important fields in this section are *Reference Year* and *Basis Year*. Throughout the *Input_Sheet_Template* worksheet, you will enter financial values in basis year dollars, and the model will convert the values to reference year dollars. For example, if you have plant costs in 2005 dollars, you set the basis year to 2005 and enter capital cost values in 2005 dollars throughout the worksheet (in the appropriate orange input cells). Then, if you want cost results in, for example, 2016 dollars, you set the reference year to 2016, and the model automatically converts the 2005-dollar inputs to 2016 dollars based on plant scaling (see page 18) and escalation factors.

Energy Feedstocks, Utilities, and Byproducts

Energy feedstocks, utilities, and byproducts are variable operating costs. The inputs for this section follow the *Financial Input Values* section in the central model, and they follow the *Fixed Operating Costs* section in the distributed model. This section allows you to define energy feedstock, utility, and byproduct costs and credits—up to four of each type. Each element is added by first defining it using the drop-down menus and data entry fields, then clicking the *Add* button.

The first drop-down menu selects the price data table that will be used to calculate feedstock, energy, and byproduct costs and credits. These EIA data are drawn from the model's *Energy Feed & Utility Prices* worksheet (see page 34). Select one of the tables from the drop-down menu:

- *AEO_2009_Reference_Case*
- *AEO_2013_Reference Case*
- *AEO_2013_High_Price_Case*
- *AEO_2014_Reference_Case*
- *AEO_2017_Reference_Case*


CAUTION

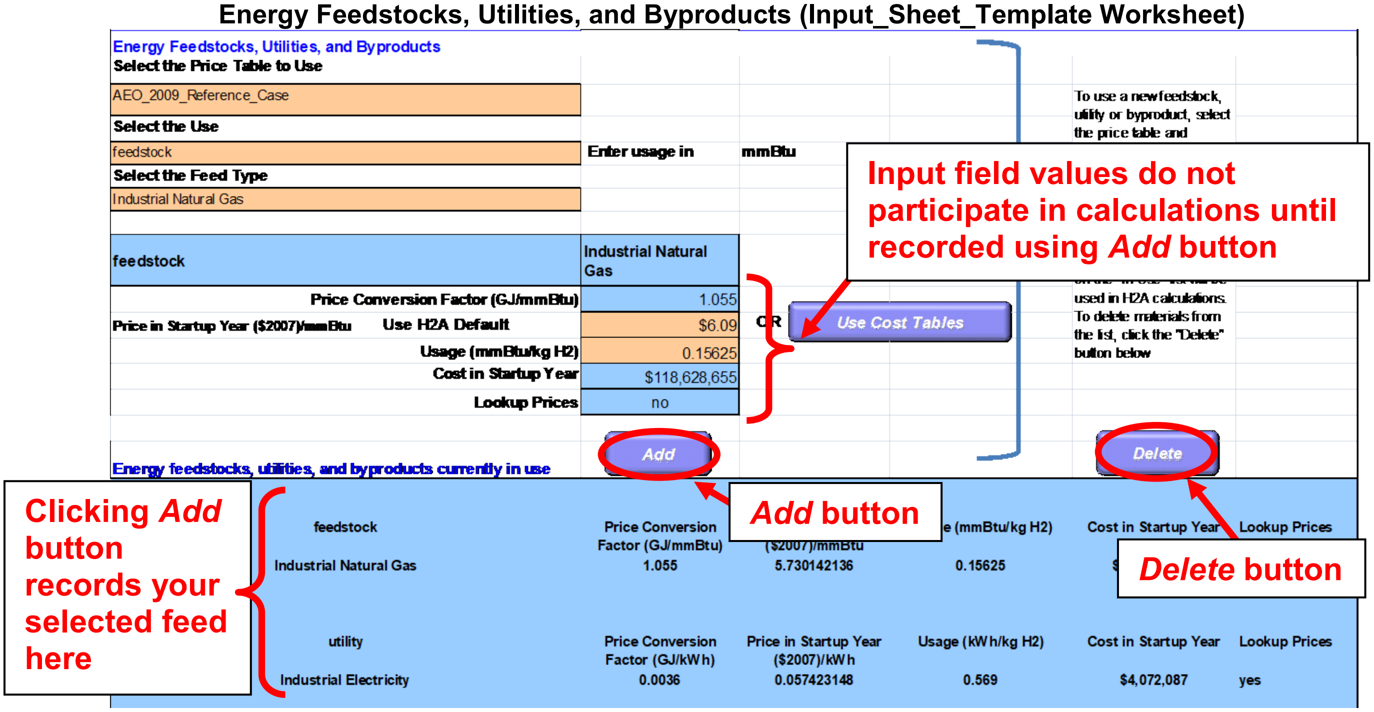
The U.S. Department of Energy (DOE) has selected the *AEO 2017 Reference Case* as the default for all H2A production technology cases. For more information on the price data, see *Energy Feed & Utility Prices* on page 36. Note, you must use only one price table for each analysis, i.e., you must use the same price table for each energy feedstock, utility, and byproduct you enter.

Use the next two drop-down menus to select use (feedstock, utility, or byproduct) and type. The lower heating value (LHV) is automatically drawn from the *HyARC Physical Property Data* worksheet, *Table A* (see page 37).

Next, accept the shown *Price in Startup Year* or click the *Enter Cost Manually* button—which toggles to the *Use Cost Tables* button—to use the default value or enter your own (see the screen capture on page 12). If you accept the original *Price in Startup Year* or click the *Use Cost Tables* button, the model looks up the price for each year of the analysis in the selected price table and inflates that value using the inflation rate entered in the *Financial Input Values* section. If you click the *Enter Cost Manually* button and accept the default value or enter your own, the model inflates that price over the analysis period. For *Usage/Production*, enter the amount of energy or material required to produce a kilogram of hydrogen for sale—or the amount of byproduct produced per kilogram of hydrogen produced—in the unit shown. Once these fields are completed, click the *Add* button, which records your entry as shown below.

Remember that a feedstock, utility, or byproduct does not become part of the model's calculations until you click the *Add* button and the entry is recorded. Values present in the input fields but not recorded in this manner do not participate in the calculations. Established H2A production technology cases include recorded feedstock, utility, and byproduct values. Some also include unrecorded values in the input fields (for example, see the screen capture below). You can disregard these unrecorded values or select new values (then click the *Add* button) if you wish to add your own feedstocks, utilities, or byproducts.

Energy Feedstocks, Utilities, and Byproducts (Input_Sheet_Template Worksheet)



To delete entries, click the *Delete* button, which pulls up the *Toolkit* menu. Use the drop-down menu under *Editing* to select the type of entry you want to delete. Then click the *Delete* button. This deletes all entries of the selected type. For example, if you had selected three energy byproducts, choosing *Energy Byproduct* from the drop-down menu and clicking the *Delete* button will delete all three.


CAUTION

When deleting entries, you must use the *Delete* button. Do not delete rows using Excel's delete function. Also, be careful to choose the correct item from the *Delete* menu within the *Toolkit*. It can delete not only the energy feedstocks, utilities, and byproducts selected in this section, but also the other materials and byproducts selected in the *Variable Operating Costs* section (page 14).

The model uses the selected entries to calculate total energy feedstock and utilities costs and byproduct credits in the startup year; these values appear in the three blue cells at the bottom of the *Energy Feedstocks, Utilities, and Byproducts* section but are not used in the cash-flow calculations. You can view the values being used in the cash-flow calculations for every year of the analysis in the *Cash Flow Analysis* worksheet.

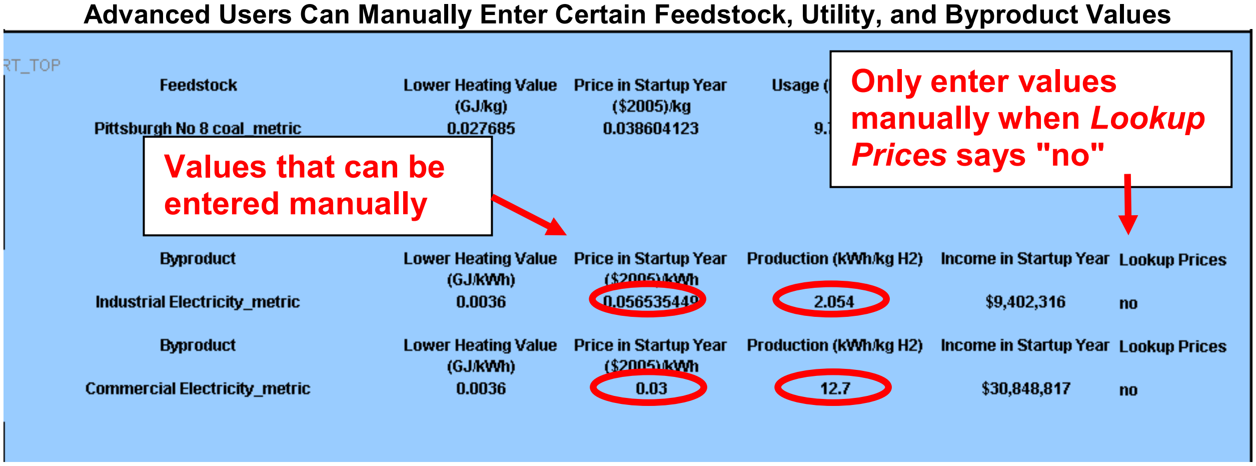
Advanced users only

If desired, advanced users can change the units applied to each material selected in this section. For example, the units for natural gas feedstock could be changed from Nm3 to scf. This requires changes be made elsewhere in the model. Go to the *HyARC Physical Property Data* worksheet, *Table A*, and change the unit in the column *H2A Usage Input Unit/ kg H2*. In the column *H2A LHV (GJ/ H2A usage input unit)*, enter the numerical value of the LHV corresponding to the new input unit; the LHV must be entered as GJ/usage unit for metric values and mmBtu/usage unit for English values. Check that the calculated results are consistent with the new-unit input values.

Advanced users only

Advanced users can take advantage of a shortcut in this section. If you want to perform numerous modeling runs—for example, by modeling the hydrogen costs resulting from an array of feedstock, utility, and byproduct input price and production/usage values—you can save time by typing values directly into certain Excel cells instead of using the model's *Add* and *Delete* functions every time. Initially, add your chosen feedstocks, utilities, and byproducts using the *Add* function. If you want to vary items by typing over values, click the *Enter Cost Manually* button for those items and enter your own price; this automatically changes the *Lookup Prices* field to "no." After completing the rest of the model's sections and recording the resulting hydrogen cost, return to the *Energy Feedstocks, Utilities, and Byproducts* section. For any items with "no" in the *Lookup Prices* field, you can manually replace the values for *Usage*/*Production* and *Price in Startup Year*—simply type over the existing values.

Advanced Users Can Manually Enter Certain Feedstock, Utility, and Byproduct Values



Capital Costs

Here you define the capital costs of your plant. For the central model, click the *View/Edit* button. This takes you to the *Capital Costs* worksheet for data entry (see page 17). When you are done, click the *Input Sheet* button to return to the *Input_Sheet_Template* worksheet. In that worksheet, clicking the *Link to Detail Sheet* button (which toggles with an *Unlink* button) takes you to the *Carbon Sequestration* worksheet (see page 21) to calculate detailed capital costs for that function. Once all applicable fields of the Capital Costs section within the *Input_Sheet_Template* worksheet are filled with inputs and calculated values, the model calculates *Total Depreciable Capital Costs*, *Total Non-Depreciable Capital Costs*, and *Total Capital Costs*.

For the distributed model, the process is similar. Under the *Capital Costs - Hydrogen Production Facility* section within the *Input_Sheet_Template* worksheet, click the *Detailed Capital Costs* button. This will send you to the *Capital Costs* worksheet, where you can enter production-related capital cost values. After you return to the *Input_Sheet_Template* worksheet, enter the remaining values in the *Capital Costs - Hydrogen Production Facility* section. Then, under the *H2A Compression, Storage, and Dispensing Capital Cost* section, click the *View Detail* button. This sends you to the *Refueling Station - GH2* worksheet, where you can specify your station's compression, storage, and dispensing capital costs.

Fixed Operating Costs

Here you define your plant's fixed operating costs. Once values are entered or calculated for each field, the model calculates *Total Fixed Operating Costs*.

Variable Operating Costs

Here you define process material costs and other variable operating costs and the value of non-energy byproducts. The parts of the *Variable Operating Costs* section are *Other Materials and Byproducts* and *Other Variable Operating Costs* (the order and wording vary slightly between the central model and the distributed model). To prevent model errors, enter all critical values in the *Technical Operating Parameters and Specifications* (page 10) and *Financial Input Values* (page 10) sections before completing these subsections.

Make sure values are present for reference year, startup year, & plant capacity

TIP

<u>Other Materials and Byproducts</u>

This subsection (see screen capture on next page) works in a fashion similar to the *Energy Feedstocks, Utilities, and Byproducts* function described on page 11. It allows you to define up to three non-energy input materials and three byproducts. Each element is added by first defining it using the drop-down menu and data entry fields, then clicking the *Add* button.

This subsection requires fewer user choices than the *Energy Feedstocks, Utilities, and Byproducts* function does. You do not need to select price tables; prices are automatically drawn from the lists on the *Non-Energy Material Prices* worksheet, or you can enter your own price by clicking the *Enter Cost Manually/Use Cost Tables* button.

You can add materials to the drop-down menu simply by going to the *Non-Energy Material Prices* worksheet and adding information for the new material in the rows underneath the existing information. See *Non-Energy Material Prices Worksheet* on page 35 for an illustration. This is also where you can modify the material prices if desired.

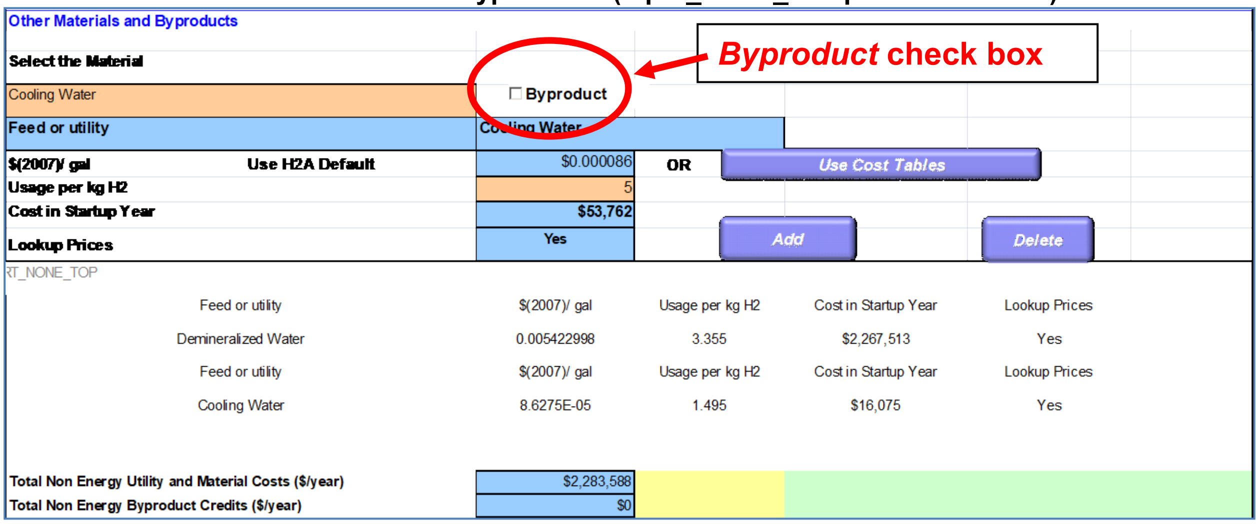
CAUTION

When deleting entries, you must use the *Delete* button. Do <u>not</u> delete the rows using Excel's delete functionality. Also, be careful to choose the correct item from the *Delete* drop-down menu within the *H2A Toolkit*. It can delete not only the other materials and byproducts selected in this subsection, but also the energy feedstocks, utilities, and byproducts selected previously (see page 11).

Advanced users only

Advanced users can take advantage of a shortcut in this section by typing values directly into certain Excel cells instead of using the model's *Add* and *Delete* functions every time. This is done in a fashion similar to that in the *Energy Feedstocks, Utilities, and Byproducts* section—see page 13 for instructions.

Other Materials and Byproducts (Input_Sheet_Template Worksheet)



Other Variable Operating Costs

This subsection defines additional variable operating costs. Fill in the appropriate input (orange) cells. The factor you enter in the field *Total Unplanned Replacement Capital Cost Factor* is transferred to the *Replacement Costs* worksheet (see page 16), which calculates replacement costs based on this factor and the value for total depreciable capital costs (see *Capital Costs*, page 13). Clicking the *Enter Specific Costs* button takes you to the *Replacement Costs* worksheet, where you can specify additional replacement costs.

In the central model, the field *CO2 sequestration O&M costs and credits* is filled in automatically if you linked to the *Carbon Sequestration* worksheet in the *Capital Costs* section (see page 13). Once you have entered all the information you want to enter, scroll to the top of the *Input_Sheet_Template* worksheet to find the calculated cost of hydrogen and individual cost components. You can then navigate to the *Results* worksheet, which displays the cost analysis in a more detailed format.

Replacement Costs Worksheet

The *Replacement Costs* worksheet is the source of replacement cost information for the cash flow analysis calculations. It accounts for planned and unplanned replacement costs.

Enter planned replacement costs in basis year dollars—do not inflate.

TIP

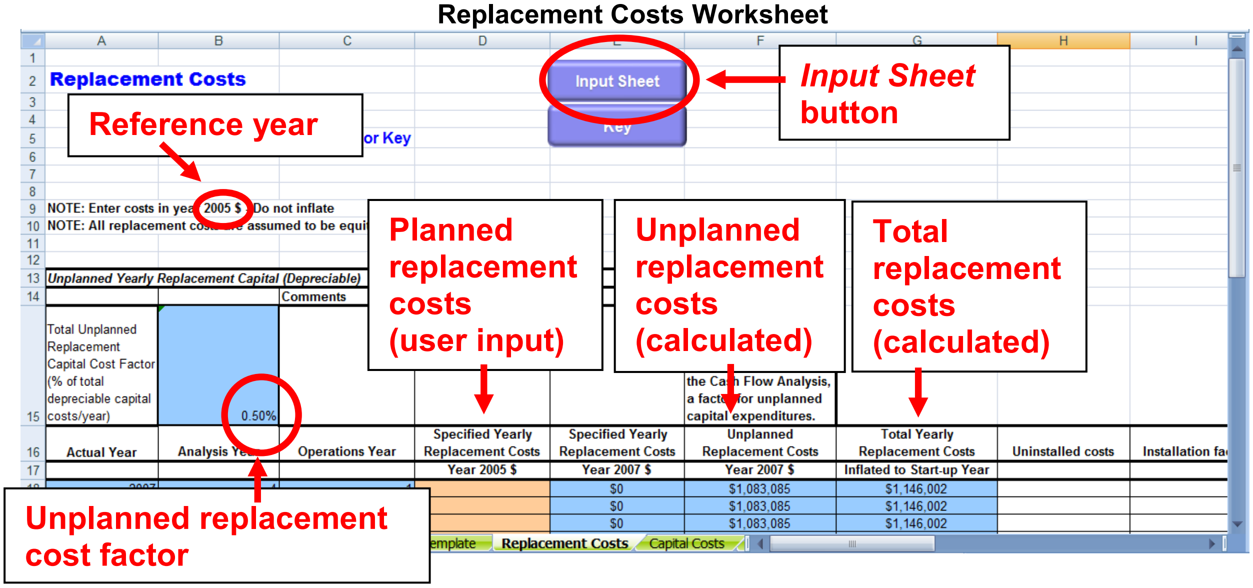
Enter planned replacement costs (in basis year $) for each year in the *Specified Yearly Replacement Costs* column. The values in the *Unplanned Replacement Costs* column are calculated automatically in the following way:

1) The *Total Unplanned Replacement Capital Cost Factor* you entered in the *Other Variable Operating Costs* subsection of the *Input_Sheet_Template* worksheet (see page 15) is automatically imported into the *Replacement Costs* worksheet (in the uppermost blue cell; see screen capture below). Clicking the *Input Sheet* button sends you directly to the relevant cost factor cell in the *Input_Sheet_Template* worksheet.

2) This cost factor is multiplied times the *Total Depreciable Capital Costs* value from the *Input_Sheet_Template* worksheet (see page 13); the result is automatically entered for each year in the *Unplanned Replacement Costs* column.

The inflation-adjusted sum of the specified (i.e., planned) and unplanned replacement costs is automatically entered into the *Total Yearly Replacement Costs* column. When finished, click the *Input Sheet* button to return to the *Input_Sheet_Template* worksheet.

Replacement Costs Worksheet

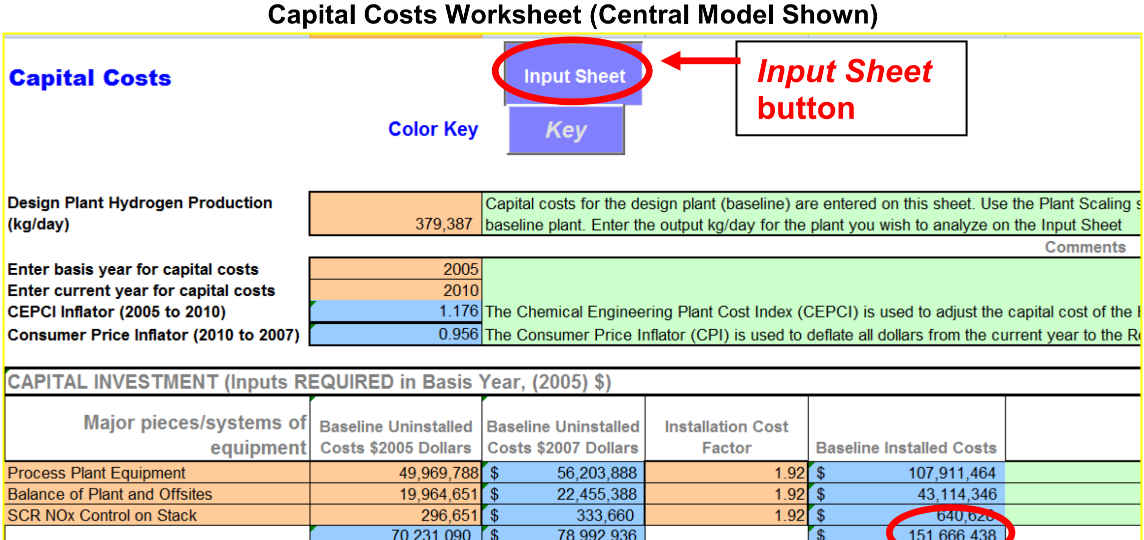


Capital Costs Worksheet

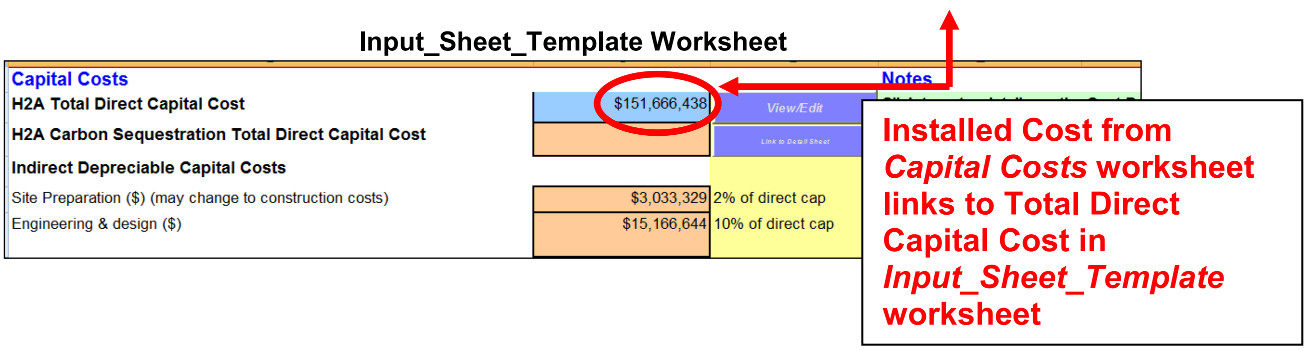
The *Capital Costs* worksheet accepts inputs for individual capital costs and calculates total direct capital cost. This total direct capital cost is then imported into the *Capital Costs* section of the *Input_Sheet_Template* worksheet (see page 13). This is the direct capital cost of the production equipment not including carbon sequestration equipment, in the central model (see page 21), and not including compression, storage, and dispensing equipment, in the distributed model (see page 23).

In the central model, activate the *Capital Costs* worksheet by clicking the *View/Edit* button next to the *H2A Total Direct Capital Cost* field in the *Capital Costs* section of the *Input_Sheet_Template* worksheet. In the distributed model, activate the *Capital Costs* worksheet by clicking the *Detailed Capital Costs* button next to the *H2A Production Process Total Direct Capital Cost* field in the *Capital Costs - Hydrogen Production Facility* section of the *Input_Sheet_Template* worksheet. Enter the names of capital equipment items in the column *Major pieces/systems of equipment*. Enter uninstalled costs for each item in the column *Baseline Uninstalled Costs*. Under the column *Installation Cost Factor*, enter values by which the uninstalled costs of each item will be multiplied to give installed costs. The model automatically calculates total installed direct capital cost in the *Baseline Installed Costs* column. In the central model, the user can also redefine the default baseline hydrogen production value, which is used for plant-scaling purposes. When you are finished inputting values, click the *Input Sheet* button at top to return to the *Input_Sheet_Template* worksheet, where the total capital cost will appear; the screen captures below show the link.

Capital Costs Worksheet (Central Model Shown)



Input_Sheet_Template Worksheet



Plant Scaling Worksheet

The H2A Model is designed to determine the levelized cost of hydrogen from a facility with a specific hydrogen production capacity. Similarly, established H2A production technology cases model facilities with specific production capacities. The *Plant Scaling* worksheet makes it easy to analyze facilities with different production capacities. Complete the following steps in the order shown. Note that step 3 is only used for the distributed model.

1) Set Baseline Plant Values (*Input_Sheet_Template*, *Capital Costs, and Plant Scaling* Worksheets)
Baseline plant values are imported into the *Plant Scaling* worksheet from the *Input_Sheet_Template* and *Capital Costs* worksheets, so the first step is to fill out those worksheets completely (see pages 9 and 17). Once you have finished, go to the *Plant Scaling* worksheet. Within the *Plant Scaling* worksheet, the first cell (*Baseline Design Capacity*) and the baseline value cells in the *Capital Investment* section are automatically imported from the *Capital Costs* worksheet in the central model; in the distributed model the *Baseline Design Capacity* is set to 1,500 kg/day.

2) Establish Scaling Parameters (*Plant Scaling* Worksheet)
Within the *Plant Scaling* worksheet, accept or create scaling parameters. In the *Plant Scaling Factors* section, accept the *Default Scaling Factor Exponent* or enter a new one.

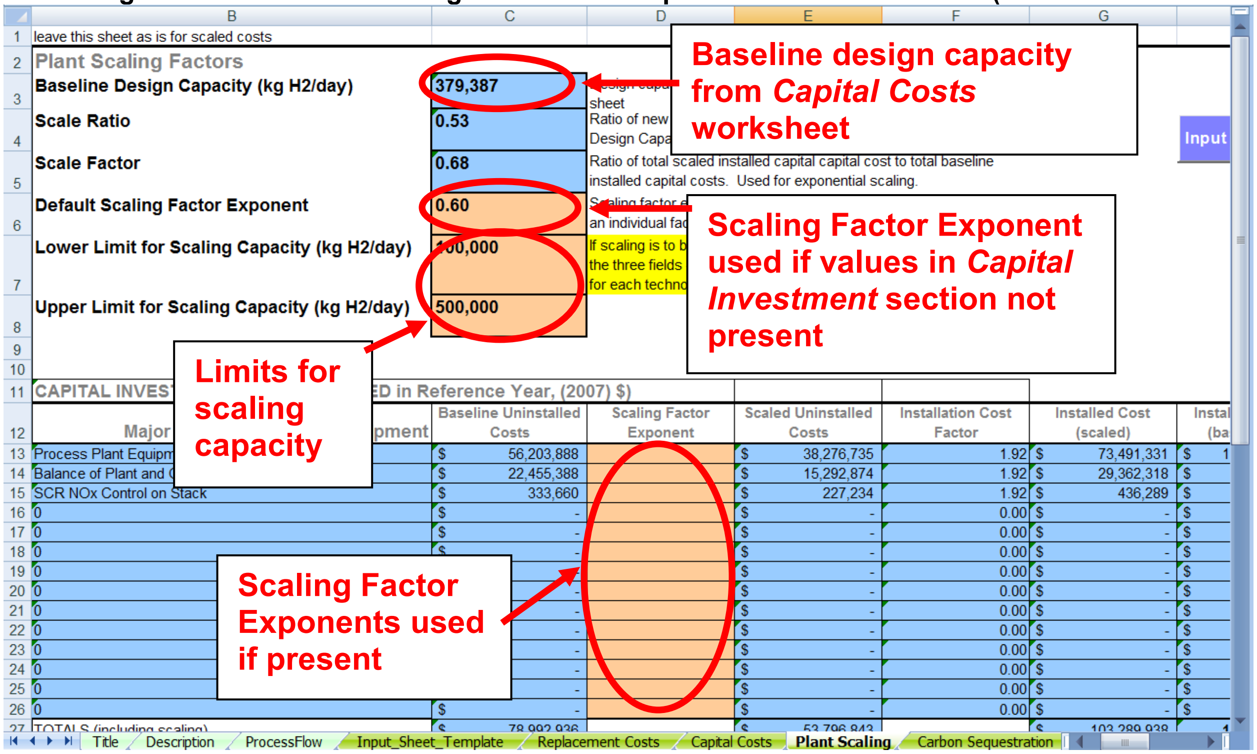
Changing the Scaling Factor Exponent changes how the cost of each item of capital equipment varies in relation to the Scale Ratio (the ratio of new design capacity to baseline design capacity) as follows:

$$\text{Scaled Cost} = \text{Baseline Cost} \times \text{Scale Ratio}^{\text{Scaling Factor Exponent}}$$

For example, a Scaling Factor Exponent of 1.0 means the cost of the equipment increases by the same ratio as the increase in plant capacity. Scaling Factor Exponents are typically 1.0 or less. If values for individual pieces of equipment are entered in the column *Scaling Factor Exponent* within the *Capital Investment* section, those values are used in the scaling calculations. If a value is not present in this column for a given item, the *Default Scaling Factor Exponent* in the *Plant Scaling Factors* section is used.

The *Lower Limit for Scaling Capacity* and *Upper Limit for Scaling Capacity* fields define the capacity range within which the scaling you are defining is valid. The model will alert you if you attempt to scale your plant capacity outside the range you specify.

Plant Scaling Worksheet: Plant Scaling Factors and Capital Investment Sections (Central Model Shown)



3) Specify Plant Scaling Methods (*Plant Scaling* Worksheet, distributed model only)

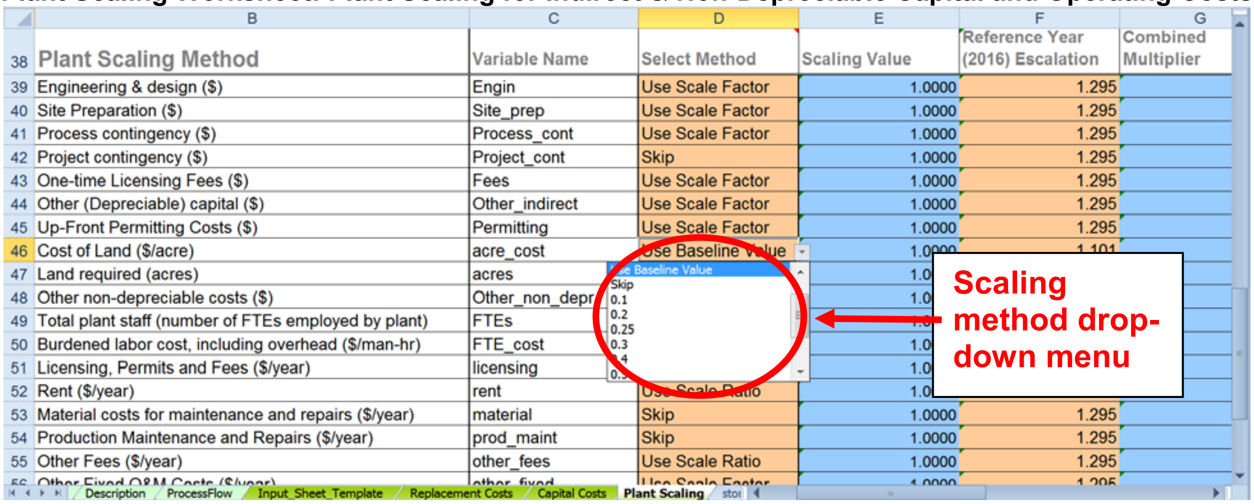
After you have added Scaling Factor Exponents to the *Plant Scaling Factors* and *Capital Investment* sections, go down to the next section to accept or define scaling parameters for indirect and non-depreciable capital costs and operating costs.

For each item in the table, choose one of the following scaling methods from the drop-down menus in the *Select Method* column:

- *Use Scale Ratio*—uses the scale ratio to scale the item cost in relation to plant capacity (i.e., linearly) (Scaled Value = Baseline Value × Scale Ratio)
- *Use Scale Factor*—uses the scale factor (the ratio of total scaled installed capital cost to total baseline installed capital cost) to scale the item cost in relation to plant capital cost (i.e., scale with capital costs) (Scaled Value = Baseline Value × Scale Factor)
- *Use Baseline Value*—uses the shown baseline value with no scaling
- *Skip*—skips the value, does not change the cell value or equation
- Use scale ratio with scaling factor exponent—uses the number you select from the drop-down menu (0.1, 0.2, etc.) as the scaling factor exponent, to scale the value in relation to the scale ratio as follows: Scaled Value = Baseline Cost × Scale Ratio$^{\text{Scaling Factor Exponent}}$

The next column (*Scaling Value*) calculates the scaling value for each cost based on the scaling method you selected and the scaled plant capacity (see step 4 below). The *Reference Year Escalation* column lists the escalation factors that the model will apply to each value to convert basis-year dollars to reference-year dollars, and the *Combined Multiplier* column shows the combined effect of the scaling value multiplied times the escalation value. Once you have selected scaling methods for all items, return to the *Input_Sheet_Template* worksheet.

Plant Scaling Worksheet: Plant Scaling for Indirect & Non-Depreciable Capital and Operating Costs

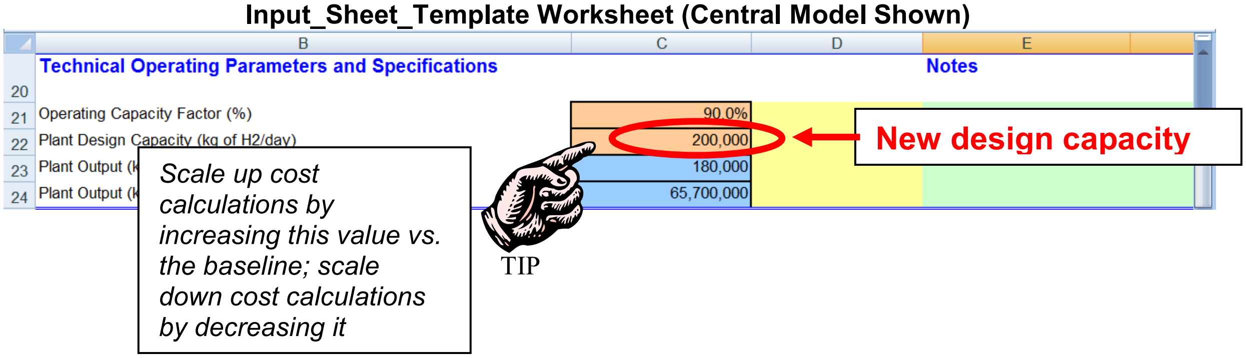


	B	C	D	E	F	G
38	Plant Scaling Method	Variable Name	Select Method	Scaling Value	Reference Year (2016) Escalation	Combined Multiplier
39	Engineering & design ($)	Engin	Use Scale Factor	1.0000	1.295	
40	Site Preparation ($)	Site_prep	Use Scale Factor	1.0000	1.295	
41	Process contingency ($)	Process_cont	Use Scale Factor	1.0000	1.295	
42	Project contingency ($)	Project_cont	Skip	1.0000	1.295	
43	One-time Licensing Fees ($)	Fees	Use Scale Factor	1.0000	1.295	
44	Other (Depreciable) capital ($)	Other_indirect	Use Scale Factor	1.0000	1.295	
45	Up-Front Permitting Costs ($)	Permitting	Use Scale Factor	1.0000	1.295	
46	Cost of Land ($/acre)	acre_cost	Use Baseline Value	1.0000	1.101	
47	Land required (acres)	acres		1.0		
48	Other non-depreciable costs ($)	Other_non_depr		1.0		
49	Total plant staff (number of FTEs employed by plant)	FTEs				
50	Burdened labor cost, including overhead ($/man-hr)	FTE_cost		1.0		
51	Licensing, Permits and Fees ($/year)	licensing		1.0		
52	Rent ($/year)	rent	Use Scale Ratio	1.0		
53	Material costs for maintenance and repairs ($/year)	material	Skip	1.0000	1.295	
54	Production Maintenance and Repairs ($/year)	prod_maint	Skip	1.0000	1.295	
55	Other Fees ($/year)	other_fees	Use Scale Ratio	1.0000	1.295	
56	Other Fixed O&M Costs ($/year)	other_fixed	Use Scale Factor	1.0000	1.295	

4) Set Scaled Plant Capacity (*Input_Sheet_Template* Worksheet)

Within the *Input_Sheet_Template* worksheet, enter a value for your new plant's design capacity in the *Technical Operating Parameters and Specifications* section (see screen capture below). If this value is larger than the baseline design capacity (as defined in the *Capital Costs* worksheet), the scale factor and ratio will be greater than 1.00. If it is smaller, the scale factor and ratio will be less than 1.00. Once you have entered this value, the cost values in the *Input_Sheet_Template* and *Plant Scaling* worksheets are scaled automatically according to the parameters you set in the *Plant Scaling* worksheet (step 2 above). The model will calculate the new cost of hydrogen automatically after these values have been entered.

Input_Sheet_Template Worksheet (Central Model Shown)



	B	C	D	E
	Technical Operating Parameters and Specifications			Notes
20				
21	Operating Capacity Factor (%)	90.0%		
22	Plant Design Capacity (kg of H2/day)	200,000		
23	Plant Output (k	180,000		
24	Plant Output (k	65,700,000		

Turning Off Plant Scaling

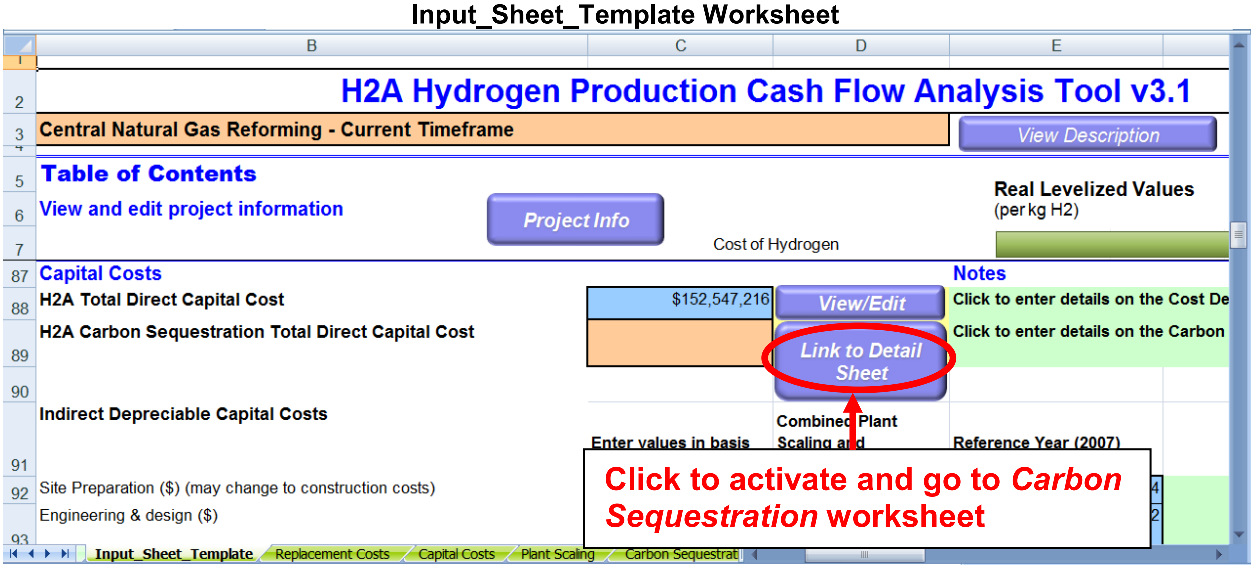
To turn off plant scaling, reset the plant design capacity in the *Technical Operating Parameters and Specifications* section of the *Input_Sheet_Template* worksheet (see screen capture above) to be equal to the *Design Plant Hydrogen Production* value within the *Capital Costs* worksheet (for the central model) or 1,500 kg/day (for the distributed model). Your plant characteristics will revert to the previously established baseline values.

Carbon Sequestration Worksheet (Central Model)

This worksheet is the source of values for carbon sequestration capital, operating, and electrical costs as well as carbon sequestration efficiency (proportion of carbon emissions captured from hydrogen production feedstocks) and energy use. It calculates costs for CO_2 compression, transportation to the sequestration site, and injection. Costs for CO_2 capture are assumed to be included in the production facility's capital and operating costs and are not included in this worksheet. Further, the worksheet only covers CO_2 emissions from the hydrogen production feedstocks, not CO_2 emissions from fuels used as utilities (e.g., natural gas used in a heater).

Before completing the *Carbon Sequestration* worksheet, specify all feedstocks and utilities in the *Input_Sheet_Template* worksheet (see *Energy Feedstocks, Utilities, and Byproducts*, page 11). After you have specified the feedstocks and utilities, activate the *Carbon Sequestration* worksheet by clicking the *Link to Detail Sheet* button next to the *H2A Carbon Sequestration Total Direct Capital Cost* field in the *Capital Costs* section of the *Input_Sheet_Template* worksheet (see screen capture below).

Input_Sheet_Template Worksheet

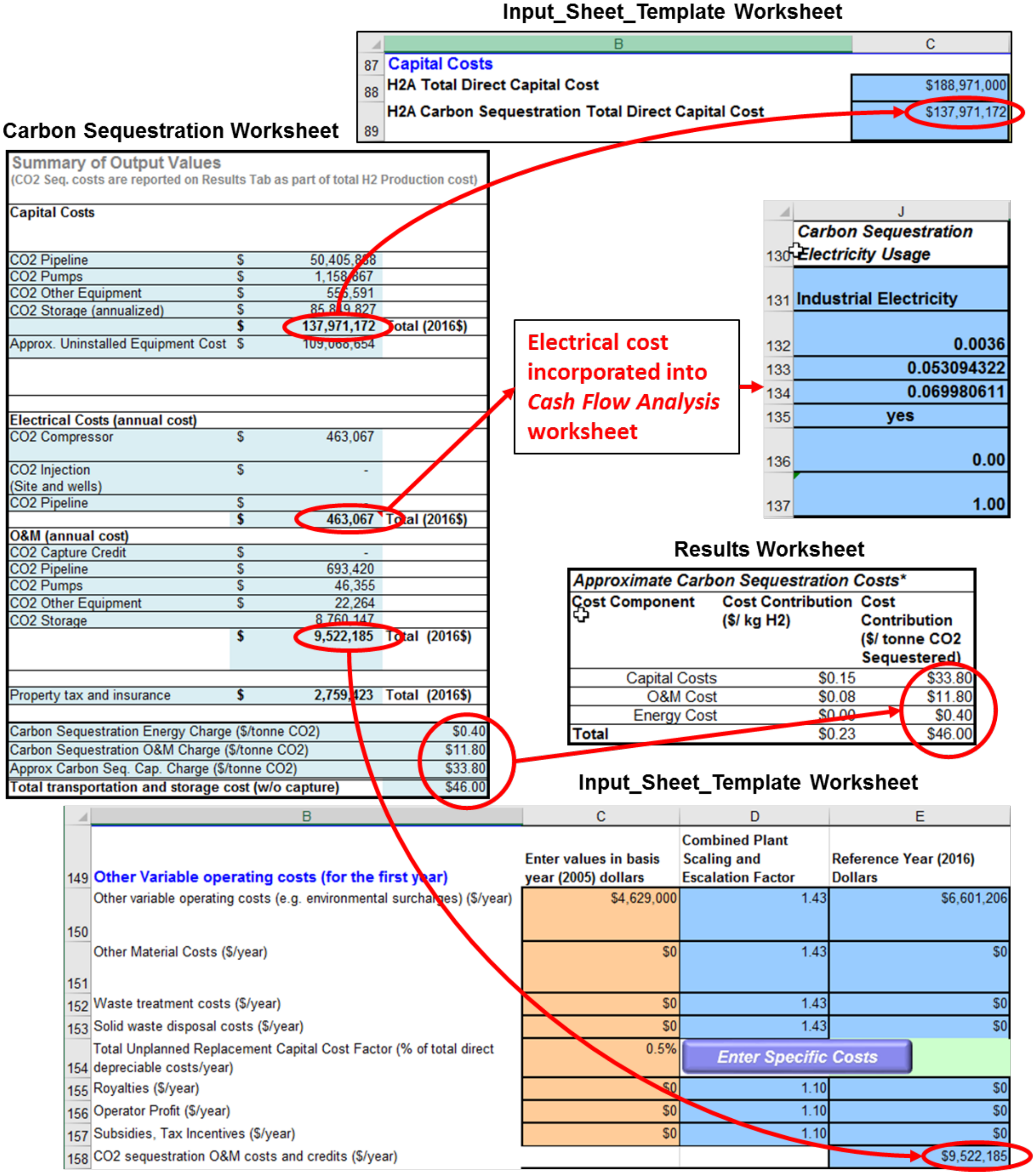


Clicking the *Link to Detail Sheet* button sends you to the *Carbon Sequestration* worksheet. At the top of the worksheet are notes, three self-explanatory buttons (see page 9 for a description of the *Use Default Values* functionality), and links to tables within the worksheet. You will input values only into the *Carbon Sequestration Input Values* table; complete or accept the default values for the orange-shaded fields. The other tables display the calculations and results based on your inputs. When you are finished inputting values, click the *Input Sheet* button at top to return to the *Input_Sheet_Template* worksheet.

The cost results (seen in the *Summary of Output Values* table) are the source of carbon transmission and storage direct capital costs, operation and maintenance costs and credits within the *Input_Sheet_Template* worksheet, and electricity use, which is used in the cash flow analysis—see the schematic below. The calculations also feed the carbon sequestration cost, energy use, and emissions results within the *Results* worksheet.

See Appendix 1 (page 44) for more information about the carbon sequestration inputs, outputs, and calculations used in this worksheet plus references for further reading.

Schematic of Cost Outputs from Carbon Sequestration Worksheet to Other H2A Worksheets

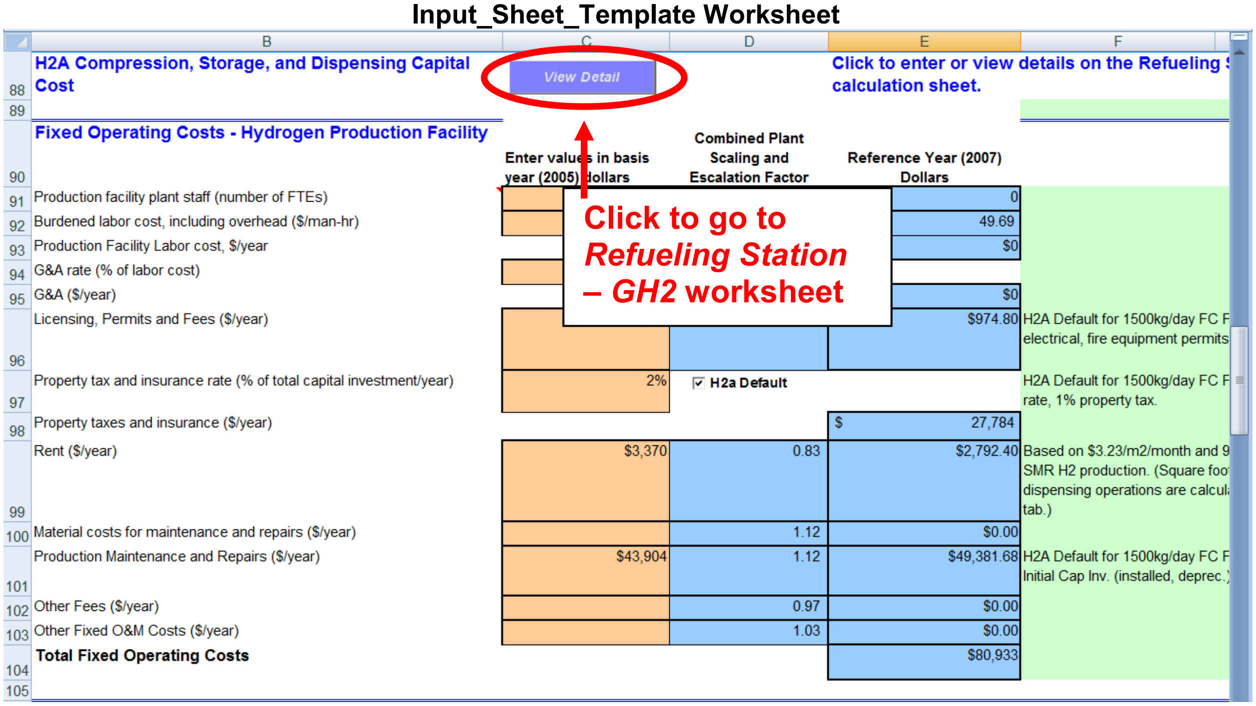


Refueling Station – GH2 Worksheet (Distributed Model)

This extensive worksheet calculates the optimal cost for compressing, storing, and dispensing hydrogen at a refueling station with a convenience store. Costs are calculated per kilogram of hydrogen dispensed. The average capacity can be varied up to 6,000 kg/day. Because the capital, fixed, and operating costs vary along with the varying capacity, none of the variables included in this worksheet appear in the *Plant Scaling* worksheet.

Go to the *Refueling Station – GH2* worksheet by clicking the *View Detail* button next to the *H2A Compression, Storage, and Dispensing Capital Cost* field in the *Input_Sheet_Template* worksheet (see screen capture below).

Input_Sheet_Template Worksheet



At the top of the *Refueling Station – GH2* worksheet are cost, performance, energy, and emissions results for the refueling station. These are based on the default values/user inputs (orange fields) and calculations (blue fields) contained in the subsequent tables on the worksheet. When you are finished accepting default values and inputting custom values as desired, return to the *Input_Sheet_Template* worksheet to finish specifying your facility.

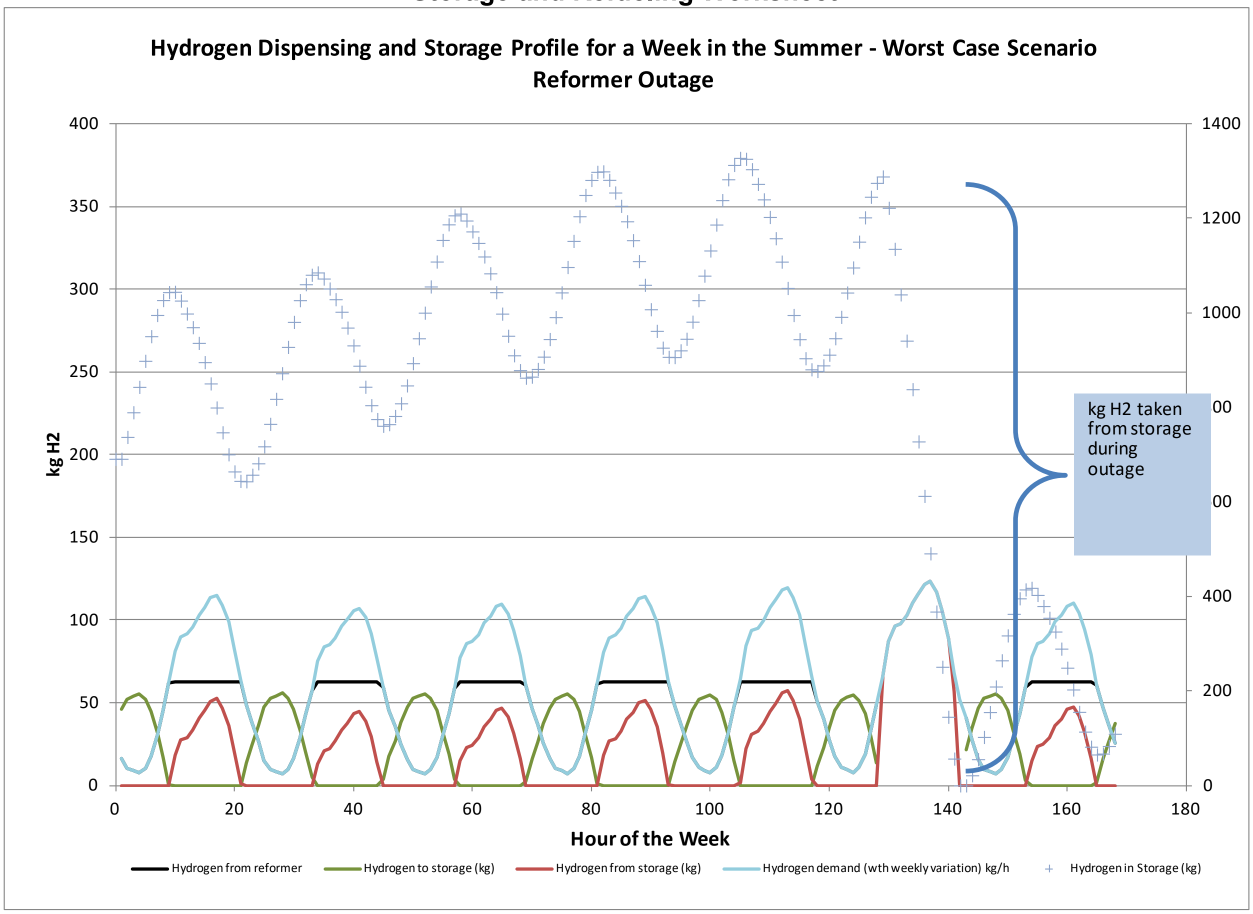
When you calculate your facility's costs, the *Refueling Station – GH2* cost results are transferred to the *Results* worksheet—see the schematic below. The *Refueling Station – GH2* worksheet also provides the values needed to calculate energy use and emissions due to compression, storage, and dispensing.

See Appendix 2 (page 51) for more information about the version 3 refueling station inputs, outputs, and calculations plus references for further reading.

Storage and Refueling Worksheet (Distributed Model)

The *Storage and Refueling* worksheet graphically profiles the operation of the modeled hydrogen dispensing and storage system. The profile is for a week in the summer with a worst-case-scenario reformer outage. It shows how stored hydrogen is used to compensate for the reformer outage. The data are drawn from the *Refueling Station – GH2* worksheet. No user input is required.

Storage and Refueling Worksheet



H2A Toolkit

The *H2A Toolkit* is not an Excel worksheet—it is a pop-up window accessed by the *Delete* buttons within the *Input_Sheet_Template* worksheet. The *Toolkit* performs a number of functions:

- Printing and exporting inputs and results
- Editing input parameters

Printing and Exporting Inputs and Results

Clicking the *Print Input Report* and *Print Result Report* buttons automatically prints information from the *Input_Sheet_Template* and *Results* worksheets, respectively. Automatic printing does not work with all printers. If it does not work for you, simply go to the worksheet you would like to print, click *File* at the top of your Excel window, and then click *Print*.

You can also export the inputs and results from your analysis to an Excel file. Click the *Export Data* button. Click *Yes* in the pop-up window that asks if you want to save your file. After you save the file, it will close automatically. The resulting file contains input and result values in an easily importable format, which you can bring into other analysis models.

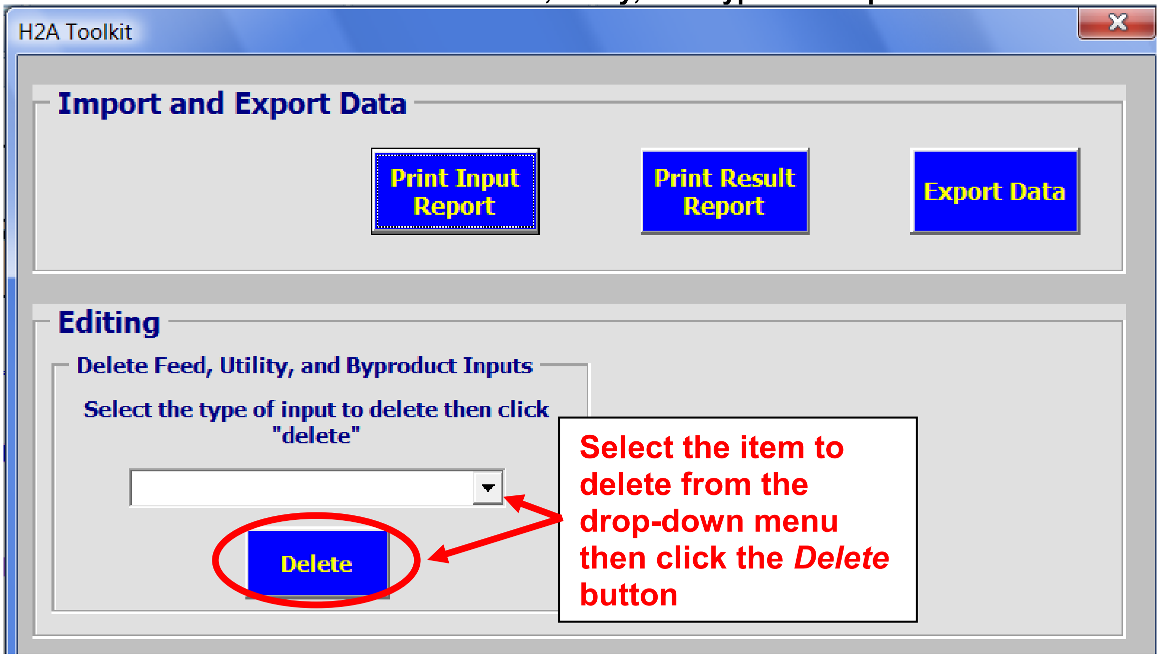
Editing: Delete Feed, Utility, and Byproduct Inputs

This function deletes items that have been added to the *Energy Feedstocks, Utilities, and Byproducts* and *Other Materials and Byproducts* sections within the *Input_Sheet_Template* worksheet (see pages 11 and 14). Use the drop-down menu under *Editing* to select the type of item you want to delete. Then click the *Delete* button. This deletes all items of the selected type. For example, if you had selected three energy byproducts, choosing *Energy Byproduct* from the drop-down menu and clicking the *Delete* button will delete all three.


CAUTION

When deleting items, it is critical to use the *Toolkit's Delete* button. Do not delete the corresponding rows within the *Input_Sheet_Template* worksheet using Excel's delete function. Also, be careful to choose the correct item from the *Delete* drop-down menu. All items of the selected type are deleted within the *Energy Feedstocks, Utilities, and Byproducts* or *Other Materials and Byproducts* sections. Choosing "All" at the bottom of the drop-down menu deletes all energy and non-energy feeds, utilities, and byproducts.

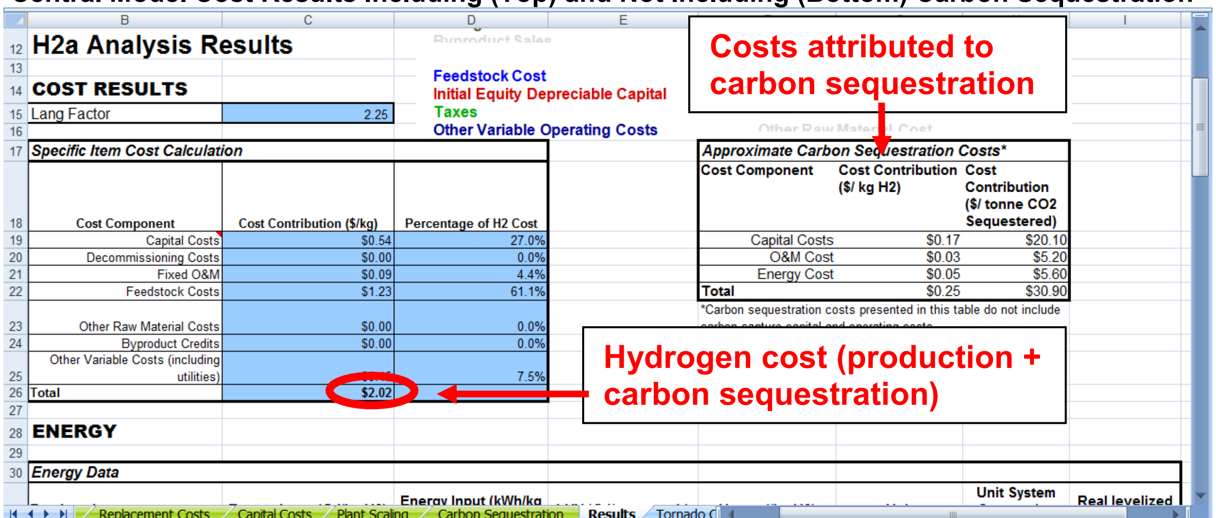
H2A Toolkit: Delete Feed, Utility, and Byproduct Inputs

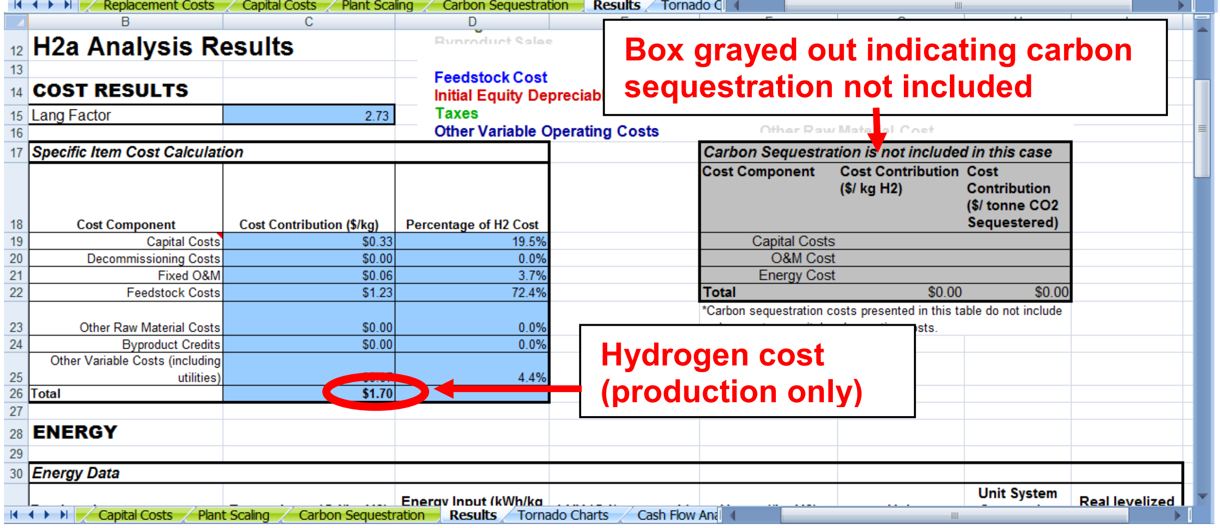


Results Worksheet

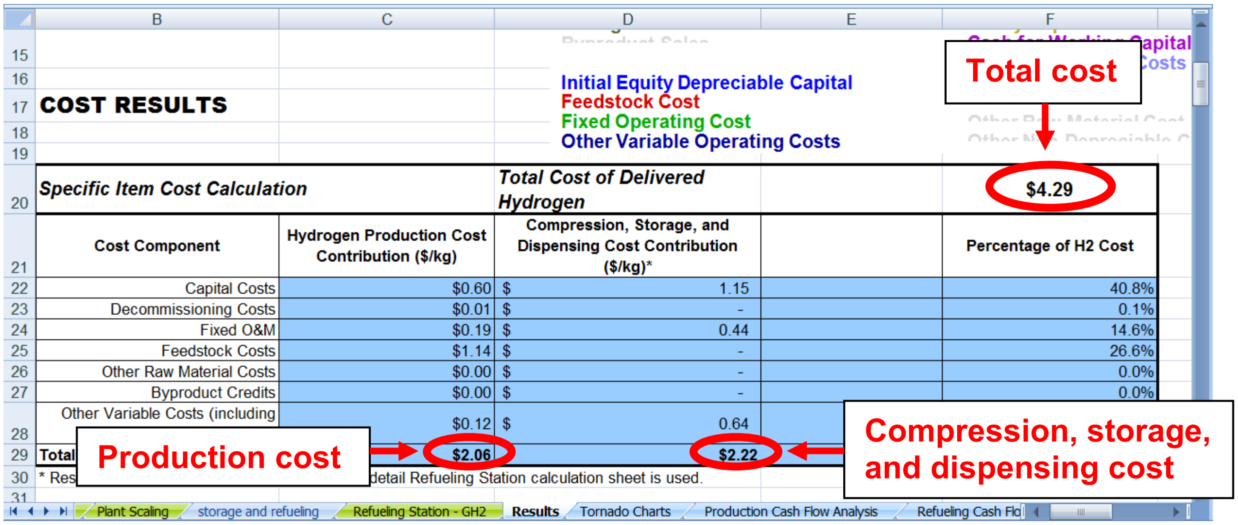
The *Results* worksheet tabulates the results of your H2A Model analysis. No user input is required within this worksheet. The hydrogen cost results are in the *Specific Item Cost Calculation* table at the top (see screen captures below). In the central model, the costs shown in the *Approximate Carbon Sequestration Costs* table are included in the total cost shown in the *Specific Item Cost Calculation* table. In the distributed model, in addition to total delivered hydrogen cost, the contributions from hydrogen production and from compression, storage, and dispensing are detailed.

Central Model Cost Results Including (Top) and Not Including (Bottom) Carbon Sequestration





Distributed Model Cost Results



COST RESULTS

Specific Item Cost Calculation		Total Cost of Delivered Hydrogen		$4.29
Cost Component	Hydrogen Production Cost Contribution ($/kg)	Compression, Storage, and Dispensing Cost Contribution ($/kg)*		Percentage of H2 Cost
Capital Costs	$0.60	$ 1.15		40.8%
Decommissioning Costs	$0.01	$ -		0.1%
Fixed O&M	$0.19	$ 0.44		14.6%
Feedstock Costs	$1.14	$ -		26.6%
Other Raw Material Costs	$0.00	$ -		0.0%
Byproduct Credits	$0.00	$ -		0.0%
Other Variable Costs (including	$0.12	$ 0.64		
Total	$2.06	$2.22		

* Res... detail Refueling Station calculation sheet is used.

The remaining tables show energy and emissions results. In the central model, the *Energy Data* table summarizes the energy inputs in the form of feedstocks, utilities, and carbon sequestration. It also summarizes the energy outputs in the form of hydrogen and byproducts. The *Production Process Energy Efficiency* table shows a percentage efficiency calculated by dividing energy outputs by energy inputs. Unless otherwise specified, efficiencies are reported on an LHV basis.

The *Upstream Energy Usage* table shows total, fossil fuel, and petroleum energy consumed by energy inputs during their upstream processing (e.g., natural gas extraction or coal-fired electricity generation). These estimates of upstream energy use are calculated based on the GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) Model. The GREET Model is continually being updated. For the most accurate upstream energy results, download and use the most recent GREET version at www.transportation.anl.gov/modeling_simulation/GREET.

The *Emissions Summary* table summarizes upstream and process greenhouse gas emissions. The next two tables—*Production Process GHG Emissions Summary* and *Production Process GHG Emissions*—detail the process greenhouse gas emissions. Note that the default is to have all process emissions counted as CO_2, as defined in the *HyARC Physical Property Data worksheet*, *Table A*. If you want to add information about CH_4 and N_2O emissions to the energy feeds, enter values in the last two columns of *Table A* (see screen capture below).

HyARC Physical Property Data Worksheet, Table A: Entering CH_4 and N_2O Values

	A	B	C	D	E	K	L	M	N
69	TABLE A - Energy Feedstock and Utility Properties Table			Done					
70	Feedstock Type	Source	Source Year (for original price data)	H2a Reference Year	Units for Feedstock Price Table	CO2 Emissions Factor (kg CO2 produced/GJ feed)	Unit System	CH4 Emissions Factor (kg CH4 produced/GJ or mmBtu feed)	N2O Emissions Factor (kg N2O produced/GJ or mmBtu feed)
71	Commercial Natural Gas	Energy Information Administration Annual Energy Outlook. See AEO Data sheet for original data	see Energy Feed Tab	2007	$(2007)/GJ LHV	56.32	Metric		
72	Industrial Natural Gas	Energy Information Administration Annual Energy Outlook. See AEO Data sheet for original data	see Energy Feed Tab	2007			Metric		
73	Residential Natural Gas	Energy Information Administration Annual Energy Outlook. See AEO Data sheet for original data	see Energy Feed Tab	2007			Metric		
74	Electric Utility Natural Gas	Energy Information Administration Annual Energy Outlook. See AEO Data sheet for original data	see Energy Feed Tab	2007	$(2007)/GJ LHV	56.32	Metric		
75	Bio Methane		see Energy Feed Tab	2007	$(2007)/GJ LHV	56.32	Metric		
76	Commercial Electricity	Energy Information Administration Annual Energy Outlook. See AEO Data sheet for original data	see Energy Feed Tab	2007	$(2007)/GJ	0.00	Metric		
77	Industrial Electricity	Energy Information Administration Annual Energy Outlook. See AEO Data sheet for original data	see Energy Feed Tab	2007	$(2007)/GJ	0.00	Metric		
78	Residential Electricity	Energy Information Administration Annual Energy Outlook. See AEO Data sheet for original data	see Energy Feed Tab	2007	$(2007)/GJ	0.00	Metric		
79	Electric Utility Steam Coal	Energy Information Administration Annual Energy Outlook. See AEO Data sheet for original data	see Energy Feed Tab	2007	$(2007)/GJ LHV	102.75	Metric		
	Metallurgical Coal	Energy Information Administration Annual Energy Outlook. See AEO	see Energy Feed Tab	2007	$(2007)/GJ LHV	102.75	Metric		

Enter CH_4 and N_2O values in these columns

AEO Data | HyARC Physical Property Data | Debt Financing Calculations | Depreciation | Constants and Conversions | Lists

Note: some table columns have been hidden for illustrative purposes.

The *Upstream GHG Emissions* table shows greenhouse gas emissions (CO_2, CH_4, N_2O, and total) produced by energy inputs during their upstream processing. These estimates of upstream emissions are calculated based on the GREET Model.

Results Worksheet, Upstream GHG Emissions Table (Central Model Shown)

	B	C	D	E	F
108	*Upstream GHG Emissions (kg/kg H2)*				
109	**Feedstock**	**CO2**	**CH4**	**N2O**	**Total GHG (CO2 eq)**
110	Industrial Natural Gas	0.785	2.14E-02	1.24E-05	1.324
111					
112					
113					
114	**Utility**				
115	Industrial Electricity	0.428	5.61E-04	5.84E-06	0.444
116					
117					
118					
119	**Carbon Sequestration**				
120	Industrial Electricity	0.608	7.96E-04	8.30E-06	0.630
121	**TOTAL**	1.820	2.28E-02	2.65E-05	2.398

In the distributed model, under the heading *Summary Energy Results*, total and onsite energy use are calculated for the production and refueling station elements of the facility. In addition, the facility's energy efficiency (energy output divided by energy input) is calculated. Unless otherwise specified, efficiencies are reported on an LHV basis.

Under the heading *Summary Emissions Results*, upstream and onsite greenhouse gas emissions results are tabulated. Next, a diagram summarizes system energy inputs and energy and emissions outputs. Estimates of upstream energy use and emissions are calculated based on the GREET Model.

Cash Flow Analysis Worksheet

The *Cash Flow Analysis* worksheet shows the inputs, outputs, and calculations of the discounted cash flow analysis used to generate the hydrogen cost results (see page 27). No user input is required within this worksheet.

The worksheet contains the following information, which is linked from a table of contents at the top:

- Discounted Cash Flow (DCF) Calculations
- Yearly Cash Flow Calculations
- Specific Item Cost Calculation
- Feedstock, Utility, and Byproduct Cost Information.

Note the distributed model contains two separate worksheets—*Production Cash Flow Analysis* and *Refueling Cash Flow Analysis*—which address cash flows for those two components separately.

Cash Flow Analysis Worksheet (Central Model Shown)

	A
2	**TABLE OF CONTENTS**
3	DCF Calculations
4	Yearly Cash Flow Calculations
5	Specific Item Cost Calculation
6	Feedstock, Utility, and Byproduct Cost Information

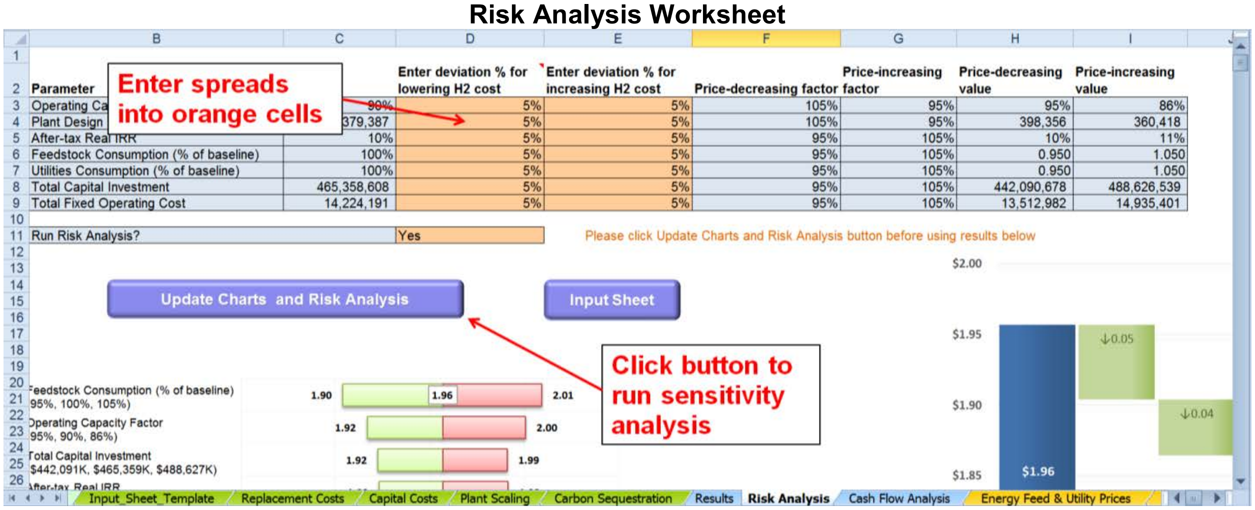
	A	B	C	D	E
15	***DCF CALCULATION INPUTS:***			***DCF CALCULATION OUTPUTS:***	
16	**Process**			**Hydrogen Cost (Year 2007 Real $/kg)**	**$1.940**
17	Actual Hydrogen Produced (kg/yr)	124,628,630		Hydrogen Cost (Start-up Year Nominal $/kg)	$2.052
18	Actual Hydrogen Energy Produced (MMBtu(LHV)/yr)	14,200,769		After Tax Real IRR	10.0%
19	Actual Hydrogen Energy Produced (MJ(LHV)/yr)	14,981,811,731		Pre Tax Real IRR	15.4%
20	Design Capacity (kg/day)	379,387		After Tax Nominal IRR	12.1%
21	Design Capacity (kg/yr)	138,476,255		Pre Tax Nominal IRR	17.6%

Capital Costs | Plant Scaling | Carbon Sequestration | Results | **Cash Flow Analysis** | Tornado Chart | Sensitivity_Analysis | Energy

Risk Analysis Worksheet

The *Risk Analysis* worksheet allows you to perform sensitivity analyses on different variables within the model. You can specify the desired spread for each variable by entering values into the orange cells. After all spreads have been specified, click the *Update Charts and Risk Analysis* button to perform the sensitivity analysis (see image below). The results of the sensitivity analysis are shown graphically in a “tornado chart.” The bars within the tornado chart show the range of minimum hydrogen-selling-price values obtained by entering—for each specified variable—a base value, a “lowering” value (a value that reduces the hydrogen price), and an “increasing” value (a value that increases the hydrogen price) while holding all other variables constant at their base values. In addition, the accompanying “waterfall chart” shows the cumulative impact each variable has on the cost of hydrogen. This function draws from the *Enter deviation % for lowering H2 cost* column only (the left column of orange cells). The blue bars show the baseline and adjusted costs of hydrogen resulting from the sensitivity analysis, while the green and orange bars show the impact of each sensitivity variable. Variable names and spreads are shown on the x-axis.

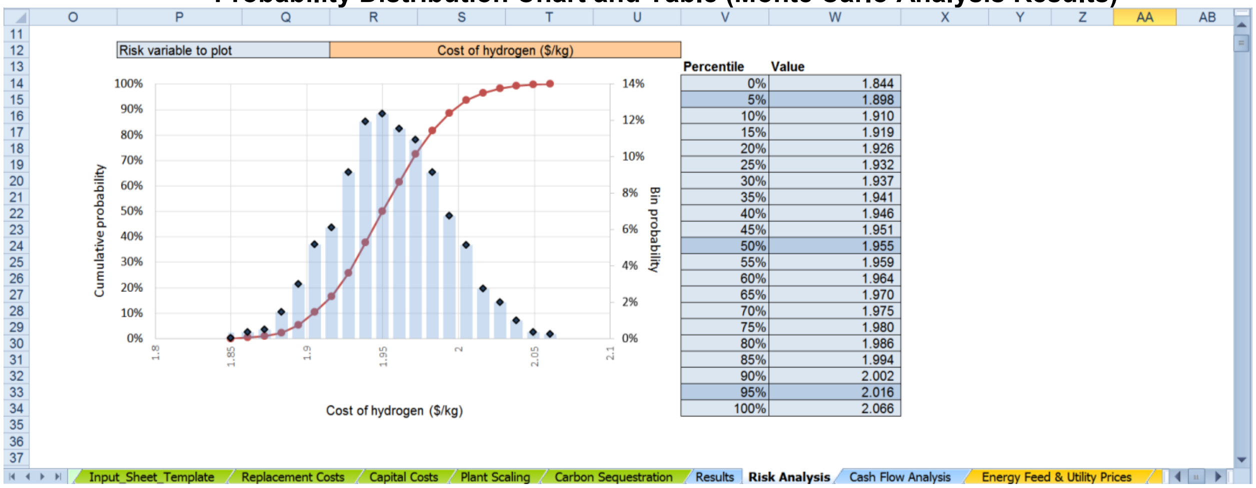
Risk Analysis Worksheet



Tornado (Top) and Waterfall (Bottom) Charts

In the central model, the risk analysis also includes Monte Carlo analysis. This analysis uses the nominal value, lowering value, and increasing value for each parameter to establish a triangular distribution. When the sensitivity analysis is run, H2A takes 2,000 random samples from each of the defined input distributions to calculate probability distributions for input parameters and results. Those probability distributions are shown in a chart and table to the right of the waterfall chart. A dropdown menu enables you to choose which risk variable to plot.

Probability Distribution Chart and Table (Monte Carlo Analysis Results)



Percentile	Value
0%	1.844
5%	1.898
10%	1.910
15%	1.919
20%	1.926
25%	1.932
30%	1.937
35%	1.941
40%	1.946
45%	1.951
50%	1.955
55%	1.959
60%	1.964
65%	1.970
70%	1.975
75%	1.980
80%	1.986
85%	1.994
90%	2.002
95%	2.016
100%	2.066

For established H2A technology cases, a default sensitivity analysis, tornado chart, waterfall chart, and Monte Carlo analysis (for central cases) are included. The input value ranges used in these analyses are based on feedback from analysts consulted as part of the H2A development process and on ongoing DOE research into the uncertainties inherent to the various hydrogen-production variables.

Energy Feed & Utility Prices Worksheet

The *Energy Feed & Utility Prices* worksheet is the source of price information for the *Energy Feedstocks, Utilities, and Byproducts* calculations within the *Input_Sheet_Template* worksheet (see page 11). It contains five tables, which list projected prices in $2016 for energy inputs/byproducts through the year 2100:

- *AEO_2009_Reference_Case*
- *AEO_2013_Reference_Case*
- *AEO_2013_High_Price_Case*
- *AEO_2014_Reference_Case*
- *AEO_2017_Reference_Case*

The *AEO_2017_Reference_Case* is the default for all established H2A production technology cases.

The raw prices used to make these tables—through the years 2030 (for the 2009 case), 2040 (for the 2013 and 2014 cases), and 2050 (for the 2017 case)—were drawn from the EIA's Annual Energy Outlook (AEO). Archived AEOs are available at www.eia.gov/oiaf/archive.html. The most recent AEO is available at www.eia.gov/forecasts/aeo. Prices in years beyond the AEO projections were projected using the Joint Global Change Research Institute's GCAM (formerly MiniCAM) model.

Energy Feed & Utility Prices Worksheet

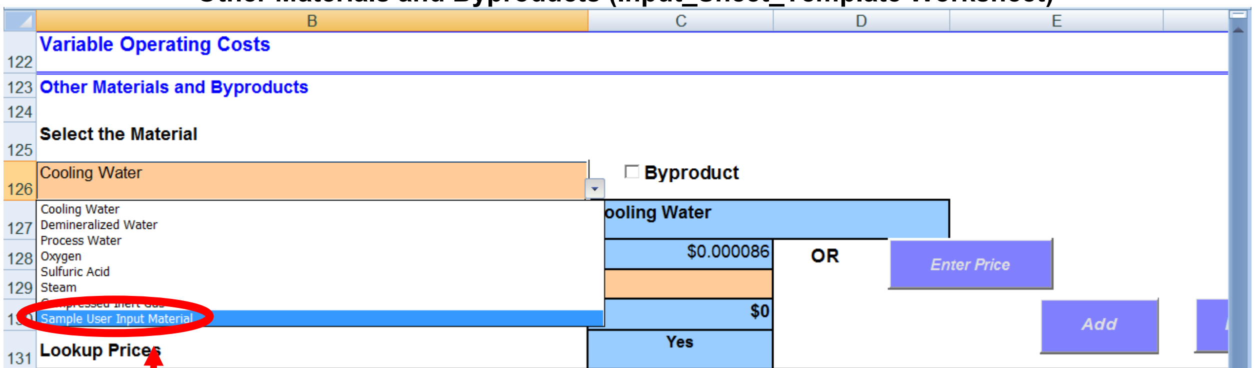
	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1														
2														
3														
4	**AEO_2009_Reference_Case**	**Prices are in $(2016)/GJ LHV**												
5	**Year**	**Source Data Year**	**Reference year Conversion**	**Display Units**	**Use Category**	**LHV (MJ/kg)**	**HHV (MJ/kg)**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**
6	Feedstock Type													
7	Residential Natural Gas	2007	1.1446	mmBtu	Feed Utility	47.14126905	52.22466124	16.4669	16.4669	16.4669	15.25424	15.59883	12.88212	13.45325
8	Commercial Natural Gas	2007	1.1446	mmBtu	Feed Utility	47.14126905	52.22466124	14.29861	14.29861	14.29861	13.20933	13.62876	10.70655	11.37726
9	Industrial Natural Gas	2007	1.1446	mmBtu	Feed Utility	47.14126905	52.22466124	9.560458	9.560458	9.560458	9.033017	10.57876	5.827775	6.609471
10	Electric Utility Natural Gas	2007	1.1446	mmBtu	Feed Utility	47.14126905	52.22466124	8.479379	8.479379	8.479379	8.436735	10.66331	5.475667	6.165219
11	Bio Methane	2007	1.1446	mmBtu	Feed Utility	47.14126905	52.22466124	14.22387	14.22387	14.22387	14.22387	14.22387	14.22387	14.22387
12	Woody Biomass	2005	1.2113	kg	Feed	19.55106924	20.58865638	1.54	1.54	1.54	1.54	1.54	1.54	1.54
13	Woody Biomass B2A	2007	1.1446	kg	Feed	19.55106924	20.58865638	4.36	4.36	4.36	4.36	4.10	3.76	3.50
14	Woody Biomass MYPP	2007	1.1446	kg	Feed	18.608		5.087134	5.087134	5.087134	5.087134	5.087134	5.087134	5.087134
15	Electric Utility Steam Coal	2007	1.1446	kg	Feed	22.732203	23.96761519	1.985314	1.985314	1.985314	2.03619	2.209007	2.267613	2.130288
16	Commercial Electricity	2007	1.1446	kWh	Feed Utility Byprod			30.78719	30.78719	30.78719	30.41123	31.52611	29.95233	26.94569
17	Industrial Electricity	2007	1.1446	kWh	Feed Utility Byprod			19.96429	19.96429	19.96429	20.20493	22.06208	20.78733	18.25795
18	Residential Electricity	2007	1.1446	kWh	Feed Utility Byprod			33.8582	33.8582	33.8582	33.83127	34.47233	33.34833	31.04769
19														
20														
21														
22	**AEO_2013_Reference_Case**	**Prices are in $(2016)/GJ LHV**												
23	**Year**	**Source Data Year**	**Reference year Conversion**	**Display Units**	**Use Category**	**LHV (MJ/kg)**	**HHV (MJ/kg)**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**

Cash Flow Analysis | Energy Feed & Utility Prices | Non-Energy Material Prices | AEO Data | HyARC Physical Property Data | Debt Financing Calculations | Depreciation | Consta

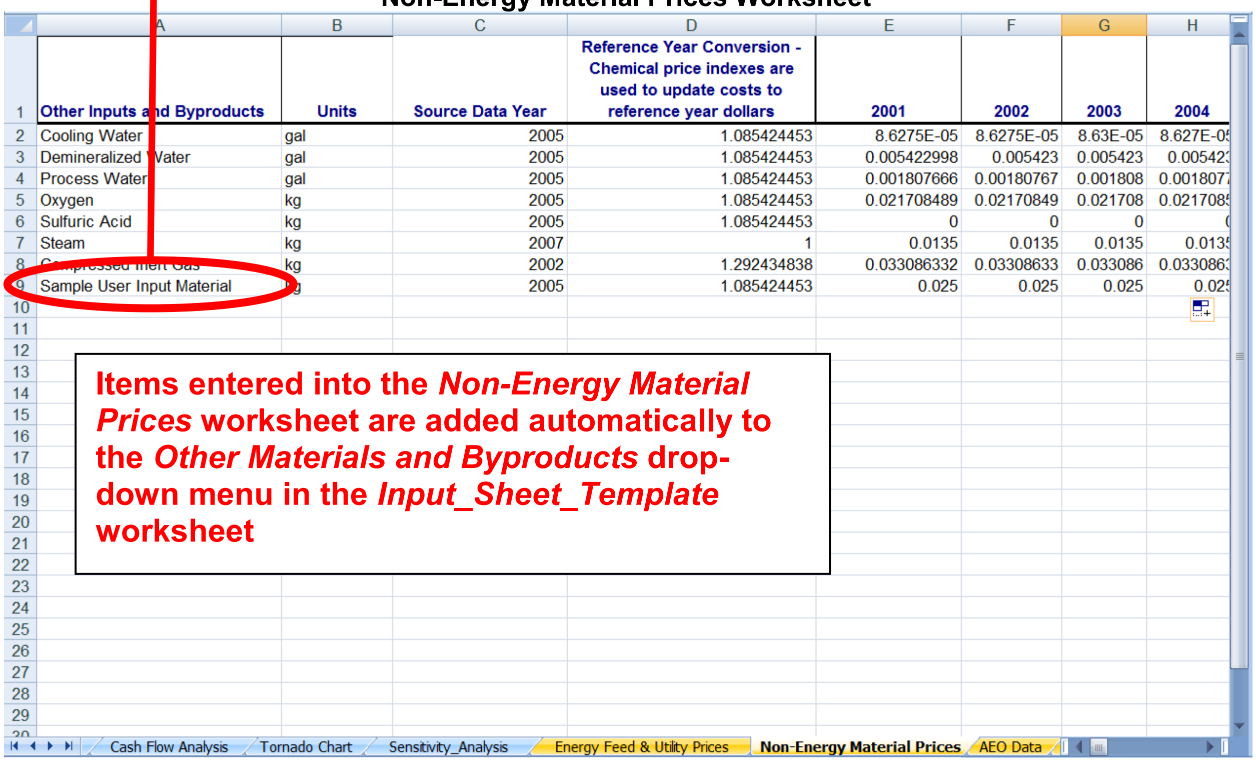
Non-Energy Material Prices Worksheet

The *Non-Energy Material Prices* worksheet is the source of price information for the *Other Materials and Byproducts* calculations within the *Input_Sheet_Template* worksheet (see page 14). Add new materials simply by adding information in the rows underneath the existing information. You can also modify the prices of materials here if desired.

Other Materials and Byproducts (Input_Sheet_Template Worksheet)



Non-Energy Material Prices Worksheet



Other Inputs and Byproducts	Units	Source Data Year	Reference Year Conversion - Chemical price indexes are used to update costs to reference year dollars	2001	2002	2003	2004
Cooling Water	gal	2005	1.085424453	8.6275E-05	8.6275E-05	8.63E-05	8.627E-0
Demineralized Water	gal	2005	1.085424453	0.005422998	0.005423	0.005423	0.00542
Process Water	gal	2005	1.085424453	0.001807666	0.00180767	0.001808	0.0018077
Oxygen	kg	2005	1.085424453	0.021708489	0.02170849	0.021708	0.0217085
Sulfuric Acid	kg	2005	1.085424453	0	0	0	0
Steam	kg	2007	1	0.0135	0.0135	0.0135	0.013
Compressed Inert Gas	kg	2002	1.292434838	0.033086332	0.03308633	0.033086	0.0330863
Sample User Input Material	kg	2005	1.085424453	0.025	0.025	0.025	0.02

Energy Feed & Utility Prices Worksheet

These tables are included for reference, but they do not perform any functions in the model.

Energy Feed & Utility Prices **Data Worksheet**

AEO_2017_Reference_Case	Prices are in $(2016)/GJ LHV											
Year	Source Data Year	Reference year Conversion	Display Units	Use Category	LHV (MJ/kg)	HHV (MJ/kg)	2004	2005	2006	2007	2008	2009
Feedstock Type												
Residential Natural Gas	2016	1.0000	mmBtu	Feed Utility	47.14126905	52.22466124	13.60488	15.57176	16.332	15.15567	15.78352	13.69149
Commercial Natural Gas	2016	1.0000	mmBtu	Feed Utility	47.14126905	52.22466124	11.93432	13.90423	14.27414	13.13955	13.89722	11.34567
Industrial Natural Gas	2016	1.0000	mmBtu	Feed Utility	47.14126905	52.22466124	8.264171	10.49561	9.361457	8.898743	10.96551	6.011173
Electric Utility Natural Gas	2016	1.0000	mmBtu	Feed Utility	47.14126905	52.22466124	8.416039	10.63048	10.2417	9.454915	10.43144	7.308143
Woody Biomass	2016	1.0000	kg	Feed Utility	19.55106924	20.58865638	5.096785	5.096785	5.096785	5.096785	5.096785	5.096785

HyARC Physical Property Data Worksheet

The *HyARC Physical Property Data* worksheet contains constants and conversions used in energy feedstock, utility, and greenhouse gas emissions calculations. Most users will not need to add or change information in this worksheet; however, *Tables A* and *C1* contain fields designed to accept user input.

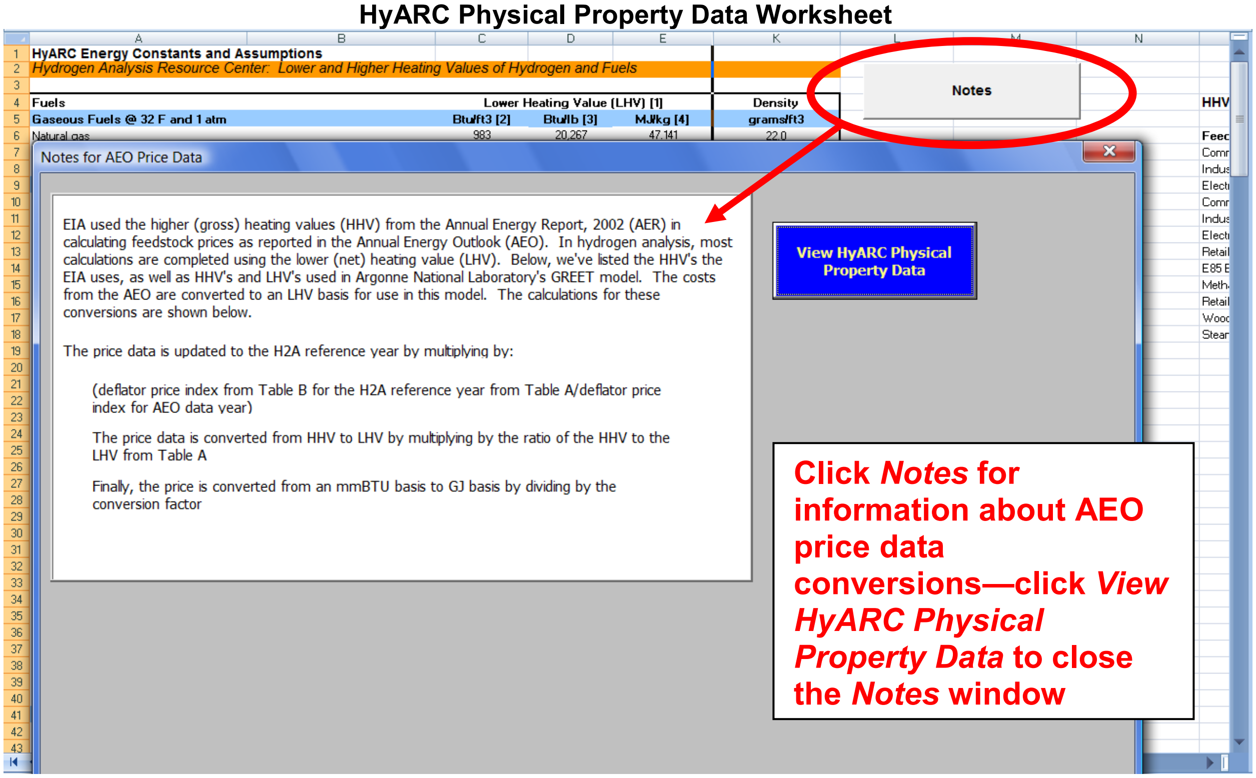
Advanced users only

Advanced users might have occasion to change information in *Table A*, the *Energy Feedstock and Utility Properties* table. For an example, see the "Advanced user" segment under *Energy Feedstocks, Utilities, and Byproducts* (page 13). Although you can add and modify items within *Table A*, do not delete any fields from the table completely; this could create serious errors.

CAUTION

Table C1 contains upstream energy and greenhouse gas emissions values for hydrogen feedstocks for hydrogen production facilities starting operations in 2010. *Table C2* contains the same information for plants starting operations in years 2020 and beyond. These tables are used to calculate the upstream energy use and greenhouse gas emissions shown on the *Results* worksheet (see page 27). Unless otherwise noted, all values in these tables are given as LHV.

HyARC Physical Property Data Worksheet



References

U.S. Department of Energy Hydrogen Program. *Hydrogen Analysis Resource Center—Hydrogen Properties*. Web Site, accessed 11/9/07. Washington, DC: U.S. Department of Energy. http://hydrogen.pnl.gov/cocoon/morf/hydrogen/article/401.

The values for the *HyARC Energy Constants and Assumptions* table were downloaded from this Web site.

U.S. Department of Energy Hydrogen Program. *Hydrogen Delivery Component Model version 2.0*. Washington, DC: U.S. Department of Energy.

The upstream energy and greenhouse gas emissions information in *Tables C1* and *C2* came from the Hydrogen Delivery Component Model, *Table 4a*. The ultimate source of the information is the GREET Model, version 1.8b.

Debt Financing Calculations Worksheet

If debt financing is selected on the *Input_Sheet_Template* worksheet, the *Debt Financing Calculations* worksheet amortizes the loan. The results are used in the H2A Model's cash flow analysis (see page 30). No user input is required within this worksheet.

Input_Sheet_Template Worksheet

	B	C	D	E
25	**Financial Input Values**			**Notes 6/2/2011**
26	Reference year	2007	☑ H2a Default	Capital costs will be entered in Referen
27	Assumed start-up year	2010		
28	Basis year	2005		
29	Length of Construction Period (years)	3		
30	% of Capital Spent in 1st Year of Construction	8%	8%	These values were changed to match E
31	% of Capital Spent in 2nd Year of Construction	60%	60%	
32	% of Capital Spent in 3rd Year of Construction	32%	32%	
33	% of Capital Spent in 4th Year of Construction			
34	Start-up Time (years)	1		
35	Plant life (years)	40		
36	Analysis period (years)	40		
37	Depreciation Schedule Length (years)	20		
38	Depreciation Type	MACRS	☑ H2a Default	
39	% Equity Financing	50%	☑ H	
40	Interest rate on debt, if applicable (%)	6.00%		
41	Debt period (years)	20		
42	% of Fixed Operating Costs During Start	75%		
43	% of Revenues During Start-up (%)	50%		
44	% of Variable Operating Costs During Start-up (%)	75%		
45	Decommissioning costs (% of depreciable capital investment)	10%	☑ H	
46	Salvage value (% of total capital investment)	10%	☑ H	
47	Inflation rate (%)	1.9%	☑ H	
48	After-tax Real IRR (%)	10.0%	☑ H	
49	State Taxes (%)	6.0%	☑ H	
50	Federal Taxes (%)	35.0%	☑ H	

Title / Description / ProcessFlow / **Input_Sheet_Template** / Replacement Costs / Capital Costs / Plant Scaling / Carbon Sequestration

Debt financing inputs

Any value < 100% in the *% Equity Financing* cell activates the *Debt Financing Calculations* worksheet

Debt Financing Calculations Worksheet Showing Amortization

ANNUAL LOAN CALCULATION (if debt financing is assumed)

	Analysis Year	Loan Year	Principal Owed	Annual Payment	Interest	Principal Payment	New Principal
14	1	1	$107,683,171	$9,388,310	$6,460,990	$2,927,319	$104,755,852
15	2	2	$104,755,852	$9,388,310	$6,285,351	$3,102,958	$101,652,893
16	3	3	$101,652,893	$9,388,310	$6,099,174	$3,289,136	$98,363,757
17	4	4	$98,363,757	$9,388,310	$5,901,825	$3,486,484	$94,877,273
18	5	5	$94,877,273	$9,388,310	$5,692,636	$3,695,673	$91,181,600
19	6	6	$91,181,600	$9,388,310	$5,470,896	$3,917,414	$87,264,186
20	7	7	$87,264,186	$9,388,310	$5,235,851	$4,152,458	$83,111,728
21	8	8	$83,111,728	$9,388,310	$4,986,704	$4,401,606	$78,710,122
22	9	9	$78,710,122	$9,388,310	$4,722,607	$4,665,702	$74,044,420
23	10	10	$74,044,420	$9,388,310	$4,442,665	$4,945,644	$69,098,775
24	11	11	$69,098,775	$9,388,310	$4,145,927	$5,242,383	$63,856,392
25	12	12	$63,856,392	$9,388,310	$3,831,384	$5,556,926	$58,299,466
26	13	13	$58,299,466	$9,388,310	$3,497,968	$5,890,342	$52,409,125
27	14	14	$52,409,125	$9,388,310	$3,144,547	$6,243,762	$46,165,363
28	15	15	$46,165,363	$9,388,310	$2,769,922	$6,618,388	$39,546,975
29	16	16	$39,546,975	$9,388,310	$2,372,819	$7,015,491	$32,531,484
30	17	17	$32,531,484	$9,388,310	$1,951,889	$7,436,420	$25,095,064
31	18	18	$25,095,064	$9,388,310	$1,505,704	$7,882,606	$17,212,458
32	19	19	$17,212,458	$9,388,310	$1,032,747	$8,355,562	$8,856,896
33	20	20	$8,856,896	$9,388,310	$531,414	$8,856,896	$0
34	21						
35	22						
36	23						
37	24						

AEO Data / HyARC Physical Property Data / **Debt Financing Calculations** / Depreciation / Constants and Conversions / Lists

Depreciation Worksheet

This worksheet calculates depreciation for use in the H2A Model's cash flow analysis (see page 30). No user input is required within this worksheet.

Input_Sheet_Template Worksheet

	B	C	D	E
25	**Financial Input Values**			**Notes 6/2/2011**
26	Reference year	2007	☑ H2a Default	Capital costs will be entered in Referen
27	Assumed start-up year	2010		
28	Basis year	2005		
29	Length of Construction Period (years)	3		
30	% of Capital Spent in 1st Year of Construction	8%	8%	These values were changed to match E
31	% of Capital Spent in 2nd Year of Construction	60%	60%	
32	% of Capital Spent in 3rd Year of Construction	32%	32%	
33	% of Capital Spent in 4th Year of Construction			
34	Start-up Time (years)	1		
35	Plant life (years)	40		
36	Analysis period (years)	40		
37	Depreciation Schedule Length (years)	20		
38	Depreciation Type	MACRS		
39	% Equity Financing	50%		
40	Interest rate on debt, if applicable (%)	6.00%		
41	Debt period (years)	20		
42	% of Fixed Operating Costs During Start-up (%)	75%		
43	% of Revenues During Start-up (%)	50%		
44	% of Variable Operating Costs During Start-up (%)	75%		
45	Decommissioning costs (% of depreciable capital investment)	10%	☑ H2a Default	
46	Salvage value (% of total capital investment)	10%	☑ H2a Default	
47	Inflation rate (%)	1.9%	☑ H2a Default	
48	After-tax Real IRR (%)	10.0%	☑ H2a Default	
49	State Taxes (%)	6.0%	☑ H2a Default	
50	Federal Taxes (%)	35.0%	☑ H2a Default	

Depreciation inputs

Title / Description / ProcessFlow / Input_Sheet_Template / Replacement Costs / Capital Costs / Plant Scaling / Carbon Sequestration

Depreciation Worksheet

	A	B
41	*Inputs from Cash-Input Sheet*	
42	Depreciation Type	MACRS
43	Depreciation Period (yrs)	20
44	Total Initial Depreciable Capital	$217,915,797

Values imported from *Input_Sheet_Template* worksheet

DEPRECIATION CALCULATION TABLE

48	Operation Year	Annual Depreciable Capital	1	2	3	4	5	6
49	-3	$0	$0	$0	$0	$0	$0	$0
50	-2	$0	$0	$0	$0	$0	$0	$0
51	-1	$217,915,797	$8,171,842	$15,731,341	$14,550,238	$13,460,659	$12,449,529	$11,516,850
52	1	$1,139,385	$42,727	$82,252	$76,077	$70,380	$65,093	$60,216
53	2	$1,161,033	$43,539	$83,815	$77,522	$71,717	$66,330	$61,361
54	3	$1,183,093	$44,366	$85,407	$78,995	$73,080	$67,590	$62,526
55	4	$1,205,571	$45,209	$87,030	$80,496	$74,468	$68,874	$63,714
56	5	$1,228,477	$46,068	$88,684	$82,025	$75,883	$70,183	$64,925
57	6	$1,251,818	$46,943	$90,369	$83,584	$77,325	$71,516	$66,159
58	7	$1,275,603	$47,835	$92,086	$85,172	$78,794	$72,875	$67,416
59	8	$1,299,839	$48,744	$93,835	$86,790	$80,291	$74,260	$68,697
60	9	$1,324,536	$49,670	$95,618	$88,439	$81,817	$75,671	$70,002
61	10	$1,349,702	$50,614	$97,435	$90,120	$83,371	$77,109	$71,332
62	11	$1,375,347	$51,576	$99,286	$91,832	$84,955	$78,574	$72,687
63	12	$1,401,478	$52,555	$101,173	$93,577	$86,569	$80,066	$74,068
64	13	$1,428,106	$53,554	$103,095	$95,355	$88,214	$81,588	$75,475
65	14	$1,455,241	$54,572	$105,054	$97,166	$89,890	$83,138	$76,909
66	15	$1,482,890	$55,608	$107,050	$99,013	$91,598	$84,718	$78,371

AEO Data / HyARC Physical Property Data / Debt Financing Calculations / Depreciation / Constants and Conversions / Lists

Constants and Conversions Worksheet

The constants and conversion factors listed on this worksheet are used in H2A calculations and included for users' reference. No user input is required within this worksheet.

Constants and Conversions Worksheet

	A	B	C	D	E	F
1	**To Convert From**	**To**	**Multiply by:**			
2	**General**					
3	miles	km	1.6093	km/mile		
4	gallons	liters	3.785	L/gal		
5	MPG	kWh/km	0.018263969	(kWh/km)/MPG		
6	scf	Nm3	0.026853	Nm3/scf	60 degrees F, 1 atm	
7	lb	kg	0.453514739	kg/lb		
8	ncf	Nm3	0.028317	Nm3/ncf	0 degrees C (32 F), 1 atm	
9	MPa	psi	145.038	psi/MPa		
10						
11	**Energy**					
12	MJ	kWh	0.277777778			
13	gallon of gasoline eq (GGE) -conventiona	kWh	34.02262529			
14	kg H2 (LHV)	GGE	0.979331964			
15	kg H2 (LHV)	kWh	33.39212175	33.3194444		
16	kg H2 (LHV)	GJ	0.120211638			
17	btu	kWh	0.000293083			
18	mmBTU	GJ	1.055			
19						
20						
21	**Greenhouse Gas Emissions Factors**		IPCC Fourth Assessment Report: Climate Change 2007 (http://www.ipcc.ch/publications_and_data/ar4/wg1/en/ch2			
22	CO2	1				
23	CH4	25				
24	N2O	298				
25						
26						
27	**Energy Feedstock Conversions**					
28	Usage unit	Conversion from $/GJ				
29	mmBtu	1.055				
30	kWh	0.0036				
31	GJ	1				
32						

AEO Data | HyARC Physical Property Data | Debt Financing Calculations | Depreciation | Constants and Conversions | Lists

Lists Worksheet

CAUTION

The *Lists* worksheet contains lists of variable labels that the H2A Production Model uses to perform all its calculations. Do not add, delete, or change anything on this worksheet. Modifying the lists could disable or introduce major errors into the model.

Lists Worksheet

	A	B	C	D	E	F	G	
1	**Cancelled**							
2								
3	**Use_Default**		**Yes_No**		**Temp_var_location**		**Sensitivity_Variables**	
4	Use H2A Value		Yes		**100000**		Operating Capacity Factor (fraction)	cap_fa
5	Enter Value		No				Plant Design Capacity (kg of H2/day)	design_
6							Assumed start-up year	startup_
7	**Add_As_List**		**Feed_Type_List**				Length of Construction Period (years)	constru
8	Feedstock		Feed				Start-up Time (years)	start_ti
9	Utility		Utility				Plant life (years)	plant_li
10	Byproduct		Feed Utility				Decommissioning costs (fraction of depreciable capital investment)	decom_
11			Feed Utility Byprod				Salvage value (fraction of total capital investment)	salvage
12			Byproduct				Inflation rate (fraction)	inflatio
13							After-tax Real IRR (fraction)	real_irr
14	**Delete_As_List**		**ColorList**				State Taxes (fraction)	state_ta
15	Energy Feedstock		Input				Federal Taxes (fraction)	fed_tax
16	Energy Utility		Calculated				WORKING CAPITAL (fraction of yearly change in operating costs)	Workin
17	Energy Byproduct		Error				Total Direct Capital Cost	direct_
18	Other Feed		Information				Total Capital Investment	total_ca
19	Other Byproduct		UserInfo				Total Fixed Operating Cost	fixed
20	All						Cost of land ($/acre)	acre_c
21							Labor Requirement (FTE)	FTEs
22							G&A rate (fraction of labor cost)	overhe
23	**Scaling_validation**						Property tax and insurance rate (fraction of total capital investment)	tax_ins
24	Use Scale Ratio						Rent ($/year)	rent
25	Use Scale Factor						Material costs for maintenance and repairs ($/year)	materia
26	Use Baseline Value						Production Maintenance and Repairs ($/year)	prod_m
27	Skip						Waste treatment costs ($/year)	waste_
28	0.1						Solid waste disposal costs ($/year)	solidwa
29	0.2						CO2 sequestration capital costs ($/year)	CO2_s
30	0.25						feedstock Industrial Natural Gas Usage	feedstc
31	0.3						utility Industrial Electricity Usage	utilityIn
32	0.4							
33	0.5							

AEO Data / HyARC Physical Property Data / Debt Financing Calculations / Depreciation / Constants and Conversions / **Lists**

Technical Support

Information related to the new H2A Production Model will be posted on the H2A Web site as it becomes publicly available: www.hydrogen.energy.gov/h2a_production.html. Visit the Web site to download copies of the model and technology cases.

For technical questions not answered by this guide or the Web site, contact:

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Appendix 1: Carbon Sequestration Calculations and Sources

This appendix briefly describes the inputs and calculations used within the *Carbon Sequestration* worksheet (which is used for the H2A central model only, see page 21). The calculations are based on the CO_2 Transport and Saline Storage cost models from the DOE Office of Fossil Energy's National Energy Technology Laboratory (NETL). See the sources listed in *References* at the end of this appendix for the model user guides, detailed descriptions of the model, and derivations of the calculations. The CO_2 transport and storage models use pumps because super-critical CO_2 exhibits liquid-like density at the pressures and temperatures of carbon sequestration.

The NETL CO_2 Transport cost model was built completely into the H2A model. The model includes the capital costs for purchasing and installing the pipeline, a surge tank, a control system, and the number of pumps needed (including booster pumps). The NETL CO_2 Saline Storage cost model segments costs by project stage (regional evaluation, site characterization, permitting, operations, and post-injection site care and closure) depending on site location and geologic structure and formation. Because H2A is agnostic to location, cost correlations were developed for each project stage based on the P50 cost across all formation locations (226 sites) assuming a general composite formation structure.

The *Carbon Sequestration* worksheet is divided into five tables:

Table	Purpose	User Input Required
Carbon Sequestration Information	Source of values for carbon sequestration calculations	No
Carbon Sequestration Input Values	Source of values for carbon sequestration calculations	Yes
Carbon Transport Calculations	Calculate carbon transportation results	No
Carbon Storage (Saline) Calculations	Calculate carbon storage results	No
Summary of Output Values	Display carbon sequestration results	No

See the screen captures of the tables below. The numbers on the left of each table correspond with the numbered descriptions of each field.

Carbon Sequestration Information

	Carbon Sequestration Information		
1	CO2 Produced from Feedstock (metric tons CO2/year)	1,153,600	CO2 emissions are based on the carbon content of the feed. See the Physical Properties Table for specific values
2	CO2 Produced from Feedstock (kg CO2/kg H2)	9.26	
3	CO2 Mass Flowrate (metric tons/day)	2844	
4	CO2 Mass Flowrate (G metric tons/year)	1.04	
5	Electricity Cost ($/kWh)	0.0700	Price for industrial electricity in the startup year
6	Carbon Sequestration Electricity Usage (kWh/kg H2)	0.0531	

1, 2. *CO2 Produced from Feedstock*—CO_2 emissions produced from the feedstock are calculated based on the properties of the feedstock and the amount of feedstock used in hydrogen production. The feedstock type and use information comes from the *Input_Sheet_Template* worksheet. The properties come from the *HyARC Physical Property Data* worksheet.

3, 4. *CO2 Mass Flowrate*—The CO_2 mass flow rate (the mass of CO_2 transported to the injection site each day) is calculated using the value for CO_2 produced from feedstock (**1**) and the carbon capture efficiency (**7**).

5. *Electricity Cost*—The industrial electricity cost is drawn from the *Energy Feed & Utility Prices* worksheet for each year of the calculations. The startup year cost is shown here.

6. *Carbon Sequestration Electricity Usage*—This value is calculated using the power requirement (**24**) from the *Carbon Sequestration Calculations* table (in the *Carbon Sequestration* worksheet) and the capacity factor and plant output from the *Input_Sheet_Template* worksheet.

Carbon Sequestration Input Values

Windows User:
Set to 0 to turn off carbon sequestration

	Carbon Sequestration Input Values			
	Process Design Parameters			
7	Carbon Capture Efficiency (%)	90.00%	☑ H2a Default	Set to 0 to turn off CCS
8	CO2 capture process outlet pressure (psia)	14.7	☑ H2a Default	Inlet pressure for CO2 transport (pump suction
9	Number of Pumps (H2 Production Site + Booster Pumps)	1	☑ H2a Default	
10	Pump Efficiency	75%	☑ H2a Default	
11	Pipeline Control System	Yes	☑ H2a Default	
12	CO2 Surge Tank	Yes	☑ H2a Default	
13	Pipeline length (miles)	100	☑ H2a Default	
14	Pipeline Elevation Change (ft)	0	☑ H2a Default	
15	Pipeline Nominal Diameter (in)	8		
	Process Conditions			
16	Pipeline Temperature (°F)	53	☑ H2a Default	Ground temperature
17	CO2 Density (kg/m3)	866		PR Equation of state: ρ_{CO2} = denPRCO2($v_{CO2\text{-}init}$, P_{ave}, $T_{Pipeline}$)
	Other Considerations			
18	CO2 capture credit ($/metric ton CO2 captured)	$0.00	☑ H2a Default	
19	Operation and maintenance factor for equipment (pumps, etc.)	0.040	☑ H2a Default	
	Finance Parameters			
20	After Tax Real Capital Recovery Factor	0.102		
21	Real Present Value of Depreciation	0.487		
22	Approx Capital Charge Rate	0.136		

7. *Carbon Capture Efficiency*—Input the percentage of CO_2 emissions captured here (note: only CO_2 emissions from feedstock processing can be captured). This value is used in the calculation of CO_2 mass flow rate (**3**). Setting this value to 0% turns off carbon sequestration. The default value is 90%.

8. *CO2 Capture Process Outlet Pressure*—Input the value for the pressure of CO_2 exiting the capture phase and entering the compression phase here. This value becomes the inlet pressure in the CO_2 compression calculations (**24**). The default value is 14.7 psia (atmospheric pressure).

9. *Number of Pumps (H2 Production Site + Booster Pumps)*—Input the number of pumps used along the pipeline including the pump at the site of hydrogen production as well as any booster pumps needed. This is used in the pipeline nominal diameter (**15**) and the pump cost (**24**) calculations. The default value is 1.

10. *Pump Efficiency*—Input the pipeline pump efficiency factor here. This is used in the pump cost calculations (**24**). The default value is 75%.

11. *Pipeline Control System*—Input whether or not the pipeline will have a control system. This value is used in the Other Equipment Costs (**25**). The default value is “Yes.”

12. *CO2 Surge Tank*—Input whether or not the pipeline will have a CO2 surge tank to accommodate fluctuations in process output or flowrate. This value is used in the Other Equipment Costs (**25**). The default value is “Yes.”

13. *Pipeline Length*—Input the pipeline length here. This value is used in the calculations for pipeline nominal diameter (**15**) and pipeline costs (**23**). The default value is 100 miles. Required CO_2 transportation distances (i.e., required pipeline lengths) vary by location.

14. *Pipeline Elevation Change*—Input the elevation change that the pipeline traverses as measured from the CO2 production site to the CO2 injection site to account for head pressure loss due to elevation differences. This value is used in the pipeline nominal diameter calculation (**15**). The default value is 0.

15. *Pipeline Nominal Diameter*—This is calculated based on the CO2 flowrate (**3**), the number of pumps (**9**), the pipeline length (**13**), the pipeline elevation change (**14**), pipeline temperature (**16**), and pipeline inlet and outlet pressures (**24**).

16. *Pipeline Temperature*—Input the pipeline temperature here. This value is used in the calculation for pipeline nominal diameter (**15**) and CO2 density (**17**). The default value is 53°F.

17. *CO2 Density*—The CO2 density is calculated here. This value is based on the pipeline temperature (**16**) and is used in the CO2 pump costs (**24**).

18. *CO2 Capture Credit*—Input the value for CO_2 capture credits here. If a value is entered, the credits offset operation and maintenance costs (**30**). The default value is zero.

19. *Operation and Maintenance Factor for Equipment (pumps, etc.)*—Input the equipment operation and maintenance factor here. This value is used in the CO2 pump costs (**24**) and CO2 other equipment costs (**25**). The default value is 0.04.

20–22. These factors (after tax real capital recovery factor, real present value of depreciation, and approximate capital charge rate) are automatically calculated using values from the *Input_Sheet_Template* worksheet and financial calculations. They are used in the carbon sequestration calculations for capital, electrical, and O&M cost per metric ton of CO_2 sequestered. The capital and operating costs for carbon sequestration are also included in the model’s discounted cash flow calculations—see the *Cash Flow Analysis* (page 30) and

Results (page 27) sections. The results shown on the *Results* worksheet are for the entire plant.

23–25. The *Carbon Transport Calculations* table shows the transportation cost calculations based on the input and calculation tables described above as well as default values and constants. The table is broken down by equipment associated with the transportation of CO2 from the production plant to the injection site including pipeline (**23**), pumps (**24**), and other equipment (**25**). Within each equipment category, the costs are further segmented into capital, operating, and utility costs. The cost basis is referenced next to each line item. See Morgan et al. (2014) for additional cost calculation details. Do not change any of the cells in this table directly.

26. The *Carbon Storage (Saline) Calculations* table shows the storage cost calculations based on the input and calculation tables described above as well as default values and constants. The storage costs are segmented by capital and operating expenses before being segmented further by project stage. The cost basis is referenced in the notes/references section of the table. See Grant et al. (2014) for additional cost calculation details. Do not change any of the cells in this table directly.

The calculations for the cost of carbon transport and storage per metric ton of CO_2 are based on the capital recovery factor (CRF) method rather than a rigorous discounted cash flow method, which is used for the H2A Model's hydrogen production calculations. Although the CRF method is not quite as rigorous, the results are comparable when the same economic parameters are used.

27–35. The *Summary of Outputs* table summarizes the major results of the carbon sequestration calculations. Costs are broken down into capital costs (**28**), utility costs (**29**), O&M costs (**30**), and property tax and insurance costs (**31**). These values are then combined and normalized by the metric tons of CO_2 sequestered (**32–34**). The total cost per metric ton of carbon sequestered is reported at the bottom of the table (**35**). Costs are shown in reference year dollars. Do not change any of the cells in this table directly.

Carbon Sequestration Calculations

	Carbon Transport Calculations		
23	**CO_2 Pipeline Costs (2016 USD)**		**Units**
	Capital Costs		
	Adjustment factor (Natural Gas Pipeline -> CO2 Pipeline)	1.00	
	Material Capital	7,416,658	2016$
	Labor	27,966,033	2016$
	Right of Way and Damages	4,735,517	2016$
	Miscellaneous (Surveying, engineering, supervision, etc.)	10,287,680	2016$
	Pipeline Capital Cost Per Mile	504,059	2016$/mile
	O&M Costs		
	Pipeline cost of $5000/mi-yr	693,420	2016$/year
24	**CO_2 Pump Costs**		
	Capital Costs		
	Inlet Pressure	15	psia
	Outlet Pressure	2176	psia
	Pump Power	839	kW
	Pump Fixed Cost	80,989	2016$
	Pump Variable Cost	1,077,878	2016$
	Pump Capital Cost	1,158,867	2016$
	Electricity Costs		
	Ecomp = elec cost*Wcomp*(capacity factor*24*365)*n_pumps	463,067	2015$/year
	Electricity consumption	0.053	kWh/kg H2
	O&M Costs		
	(Total Other Equipment Cost) * O&M Factor	46,354.68	2016$/year
25	**CO_2 Other Equipment Costs**		
	Capital Costs		
	CO2 Surge Tank	490,829	2016$
	Pipeline Process Control System	65,761	2016$
	O&M Costs		
	(Total Other Equipment Cost) * O&M Factor	22,264	2016$/year

	Carbon Storage (Saline) Calculations		
26	**CO_2 Storage Cost Breakdown (2007 USD)**		**Units**
	Capital Costs by Stage (Annual Cost of 40 year project in 2016$)		
	Regional Evaluation	109,498	2016$
	Site Characterization	67,506,648	2016$
	Permitting	18,233,681	2016$
	Ongoing Capital Expences		
	Operations	7,011,359	2016$/year
	Post Injection Site Care & Site Closure	6,132,903	2016$/year
	Total ongoing capital expenses	**13,144,262**	2016$/year
	Expense Costs by Stage		
	Regional Evaluation	-	2016$/year
	Site Characterization	11,503	2016$/year
	Permitting	2,912	2016$/year
	Operations	4,575,909	2016$/year
	Post Injection Site Care & Site Closure	4,169,822	2016$/year

Summary of Output Values

27	**Summary of Output Values** (CO2 Seq. costs are reported on Results Tab as part of total H2 Production cost)			
28	**Capital Costs**			
	CO2 Pipeline	$	50,405,888	
	CO2 Pumps	$	1,158,867	
	CO2 Other Equipment	$	556,591	
	CO2 Storage (annualized)	$	85,849,827	
		$	**137,971,172**	**Total (2016$)**
	Approx. Uninstalled Equipment Cost	$	109,068,654	
29	**Electrical Costs (annual cost)**			
	CO2 Compressor	$	463,067	
	CO2 Injection (Site and wells)	$	-	
	CO2 Pipeline	$	-	
		$	**463,067**	**Total (2016$)**
30	**O&M (annual cost)**			
	CO2 Capture Credit	$	-	
	CO2 Pipeline	$	693,420	
	CO2 Pumps	$	46,355	
	CO2 Other Equipment	$	22,264	
	CO2 Storage		8,760,147	
		$	**9,522,185**	**Total (2016$)**
31	Property tax and insurance	**$**	**2,759,423**	**Total (2016$)**
32	Carbon Sequestration Energy Charge ($/tonne CO2)			$0.40
33	Carbon Sequestration O&M Charge ($/tonne CO2)			$11.80
34	Approx Carbon Seq. Cap. Charge ($/tonne CO2)			$33.80
35	**Total transportation and storage cost (w/o capture)**			$46.00

References

The calculations used in the *Carbon Sequestration* worksheet were developed by the DOE Office of Fossil Energy's NETL. The carbon transportation and storage cost calculations are based on the following publications:

Morgan, D.; Grant, T.; Simpson, J.; Myles, P.; Poe, A.; Valenstein, J. (2014). *FE/NETL CO2 Transport Cost Model: Description and User's Manual*. Pittsburgh, PA: National Energy Technology Laboratory. https://www.netl.doe.gov/research/energy-analysis/search-publications/vuedetails?id=630

This study develops a mathematical model that estimates the costs of transporting liquid CO_2 using a pipeline. Pipeline costs are functions of pipeline length and diameter. Diameter is calculated dynamically based on the input pipeline length, flowrate, and allowable pressure drop. The pipeline network also includes options for surge tanks and a control system.

Grant, T.; Morgan, D.; Poe, A.; Valenstein, J. (2014). *FE/NETL CO2 Saline Storage Cost Model: User's Manual*. Pittsburgh, PA: National Energy Technology Laboratory. https://www.netl.doe.gov/research/energy-analysis/search-publications/vuedetails?id=529

This report develops a mathematical model to estimate the costs of injecting and storing CO_2 in saline formations. Saline formations were chosen owing to their large storage capacity, whereas other methods such as depleted oil and gas mines and un-mineable coal seams have limited locations and capacity for large-scale sequestration. The report breaks down carbon storage costs into five main categories: regional evaluation, site characterization, permitting, operations, and post-injection site care and site closure. Each category breaks down costs by line item and characterizes them as either capital or operating expenses. Finally, costs depend on both site location and geologic structure and formation.

Appendix 2: Distributed Model Version 3 Updates

Introduction

Version 2 of the H2A Production Model was released in 2008. Since then, multiple improvements were made, culminating in the release of version 3 in 2012. This appendix lists the major assumptions behind version 3 and details the rationale for the changes made since version 2. Although the changes discussed specifically apply to the current timeframe distributed steam methane reformer (SMR) production case, they are broadly applicable to the other distributed production cases. Table 1 summarizes version 3 improvements, which are detailed in the subsequent sections of this appendix.

Table 1. Summary of changes from H2A distributed model version 2 to version 3

	Version 2	Version 3
Hydrogen Compression, Storage and Dispensing		
Reformer sizing	Size set by user	Sized for peak hydrogen demand
Refueling pressure	5,000 psi	10,000 psi
General and Financial Input Values		
Reference year	2005	2007
Assumed start-up year*	2005	2010
Direct Capital Costs		
All direct capital costs	$2005	Escalated to $2007
Pressure swing adsorption	Previous H2A assumptions, $2005	Adjusted based on new PSA data and Nth-plant assumptions, escalated to $2007
Indirect Capital and Other Costs		
Site preparation	$74,344	$188,000
Engineering & design	$30,000	$50,000
Project contingency	5% of direct capital	15% of direct capital
Insurance costs	$0	TBD
Initial spares	$0	0.75% of total capital cost
Pre-paid royalties	$0	0.75% of total process cost
Installation	10% of uninstalled cost	17% of uninstalled cost
Feedstock Prices		
Feedstock price source	EIA (2005), $2003	EIA (2009), $2007; constant-price biomethane (Saur 2011)
Feedstock price reference year	2005	Conversion to reference year dollars for 2005–2010

*Current timeframe case

Hydrogen Compression, Storage, and Dispensing

The compression, storage, and dispensing (CSD) component is one of the primary differences between version 2 and version 3 of the H2A distributed model. Figure 1 illustrates the primary equipment for distributed hydrogen production and CSD. The H2A distributed model treats hydrogen production and CSD separately.

In version 2, the user set the design capacity of the onsite reformer, and the station components were sized to accommodate the output of the reformer. Enough hydrogen storage was provided to accommodate daily and weekly peaks in demand. In version 3, the user determines the desired output of the station, and the reformer is sized to produce enough hydrogen to meet peak demand. The primary consequence of this change is that fluctuations in hydrogen demand (e.g., high demand on a summer Friday afternoon) are met by making the reformer large enough to meet these peaks. When less hydrogen is needed, the reformer is operated at less than its design capacity. Onsite storage only provides hydrogen during planned and unplanned outages of the hydrogen production equipment. The other major CSD change is increasing the default refueling pressure from 5,000 psi (version 2) to 10,000 psi (version 3).

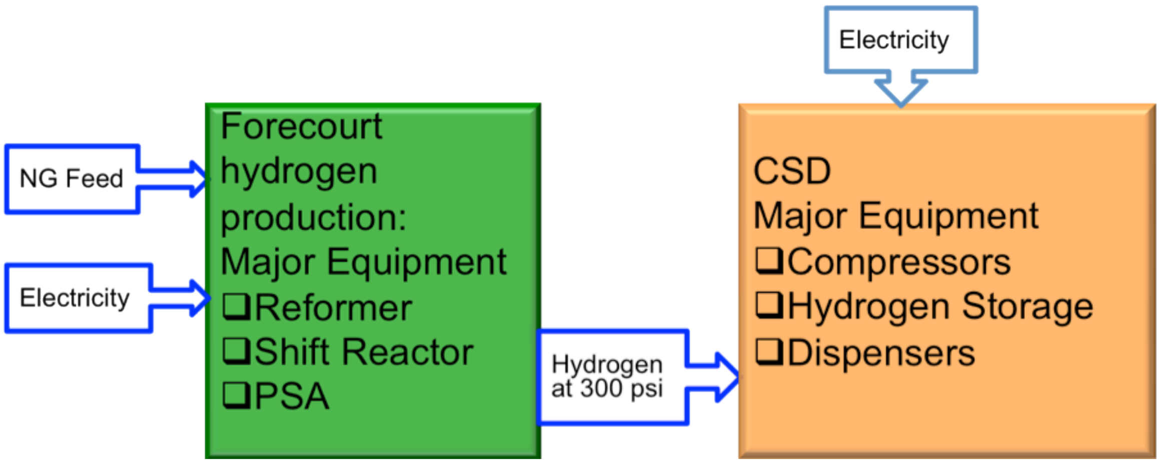

Figure 1. Schematic of distributed SMR hydrogen production and CSD

For distributed electrolysis, hydrogen is delivered from the production process to the compressors (CSD) at 435 psi. Savings in compressor capital and operating costs are credited to the production process.

Nth-Plant Assumptions

A number of the capital and installation cost-related improvements to version 3 of the model arise from an improved understanding of the “Nth-plant” concept. The nominal assumption when constructing distributed production cases is that the capital cost and plant operating parameters reflect Nth-plant conditions: a mature system that is functioning reliably in the field and has been produced in sufficiently high annual and cumulative volumes as to have a capital cost (and unit cost) close to its asymptotic limit.

At low manufacturing rates, capital costs are high due to poor use of capital and relatively time-intensive manufacturing and assembly methods. As manufacturing rates increase, more efficient production methods become economical, capital cost (per unit output) decreases, and unit cost decreases. At extremely high manufacturing rates, all possible cost improvements have been achieved, and production rates are only increased by replicating process machinery. At those levels, capital cost per unit output becomes flat relative to manufacturing rate. For H2A production cases, Nth-plant conditions pertain to the point along the curve past the knee, where most cost reduction from high manufacturing rates has been achieved, but not necessarily the lowest cost at the highest manufacturing rate (see Figure 2).

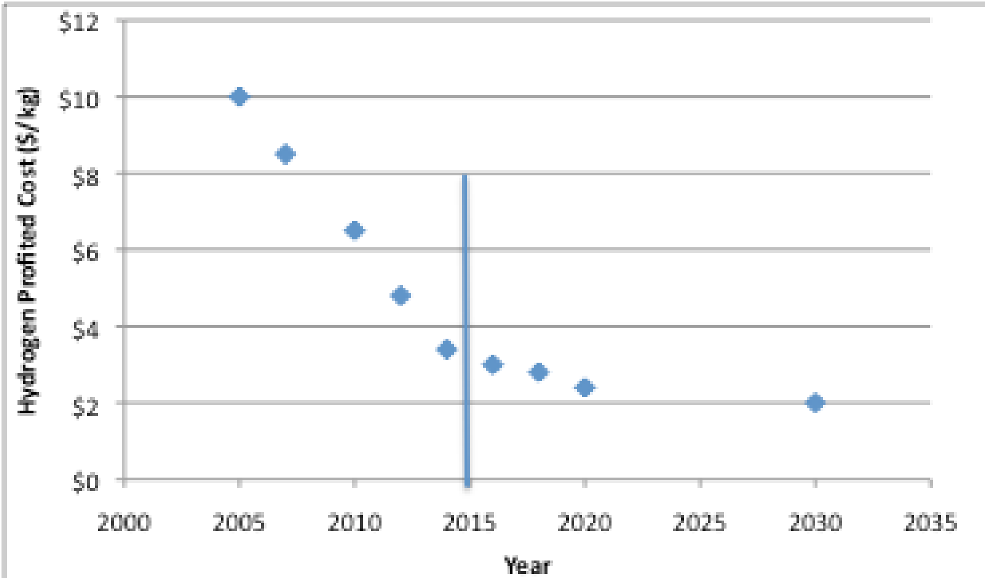

Figure 2. Hypothetical hydrogen production cost curve over time showing a technology readiness date of approximately 2015.

The Nth-plant assumption affects the H2A cost computations in two ways. The primary effect is to the estimated plant capital cost, which is calculated based on a relatively mature system produced in production quantities, not an initial or "one off" system. Incorporated into the capital cost estimate are factors such as bulk discounts on material costs, low-cost manufacturing and assembly methods made possible by serial production of the systems, efficient and streamlined business operations, and a lower profit margin consistent with a mature product that must be priced competitively with alternative systems.

The second effect to the H2A cost computation is the level of uncertainty and markup applied to the system. A new, unproven, and immature technology would be linked with a high cost contingency, high station engineering costs, extensive break-in period, relatively intensive manpower requirements, and high expected outage rate. The Nth-plant assumption is the opposite of this scenario: the values for the abovementioned parameters are based on a mature technology, mostly beyond early-phase field problems.

AACE Cost Guidance

The indirect capital costs for version 3 of the H2A distributed model were developed using guidance provided by the Association for the Advancement of Cost Engineering International (AACE International), a professional society dedicated to advancing, normalizing, and documenting the science of engineering cost estimation. AACE International publishes recommended guidance reports on a variety of subjects. The following are the two most relevant to H2A modeling:

- AACE International Recommended Practice No. 18R-97, "Cost Estimate Classification System – as Applied In Engineering, Procurement, and Construction for the Process Industries."
- AACE International Recommended Practice No. 16R-90, "Conducting Technical and Economic Evaluations – as Applied for the Process and Utility Industries."

Although these AACE International reports are excellent references, they apply primarily to one-of-a-kind engineering projects and do not necessarily capture the Nth-plant assumptions. Consequently, the AACE International practices are treated as guidance rather than hard rules in the H2A distributed model.

General and Financial Input Values

Version 3 has two differences in general and financial input values compared with version 2: reference year (i.e., base-year dollars) and assumed start-up year. These are shown in Table 2 and discussed in the subsections below.

Table 2. H2A distributed model version 3 differences in general and financial input values

Distributed Model Financial Input Values	Version 2	Version 3
Reference year	2005	2007
Assumed start-up year	2005	2010

Reference Year

The reference year determines the base-year dollars used in the model, i.e., the nominal-year currency in which hydrogen costs are reported. Version 2 reported hydrogen costs in 2005 dollars; version 3 reports them in 2007 dollars.

The way capital costs are adjusted for inflation affects the projected hydrogen cost. For version 3, capital costs are updated to 2010 dollars using the composite index of the *Chemical Engineering Magazine* Plant Cost Index (CEPCI). The composite index charts actual inflation in a basket of chemical plant cost categories (heat exchangers, piping, construction, labor, compressors, etc.) and thus narrowly calculates the annual increase in plant equipment and preparation costs. Once plant cost is determined in 2010 dollars, the value is deflated to 2007 dollars using the Consumer Price Index (CPI). The CPI is a broad measure of U.S. inflation and thus is appropriate for adjusting the generic buying power of money over time. Using the two indexes (CEPCI and CPI) together results in a current (2010) estimate of hydrogen costs stated in 2007 dollars. Table 3 shows indexes used to escalate the costs to 2007 dollars.

Table 3. General inflation, plant cost, and labor indexes used to escalate costs to 2007 dollars (tables are included in the H2A "HyARC Physical Properties Data" tab)

TABLE B - GDP Implicit Deflator Price Index
GDP Implcit Price Deflator (Index, 2005=100), Available from Short Term Energy Outlook,Table 1 November 2009
http://www.eia.doe.gov/emeu/steo/pub/contents.html

Year	Value
1992	76.537
1993	78.222
1994	79.867
1995	81.533
1996	83.083
1997	84.554
1998	85.507
1999	86.766
2000	88.648
2001	90.654
2002	92.113
2003	94.099
2004	96.769
2005	100
2006	103.263
2007	106.221
2008	108.5
2009	109.8
2010	111.1

TABLE B2 - Plant Cost Inde
From Chemical Engineering Magazine
Averaged Annual Index

Year	Value
1992	358.20
1993	359.20
1994	368.10
1995	381.10
1996	381.70
1997	386.50
1998	389.50
1999	390.60
2000	394.10
2001	394.30
2002	395.60
2003	402.00
2004	444.20
2005	468.20
2006	499.60
2007	525.40
2008	575.40
2009	521.90
2010	

TABLE B3 - Labor Index
From the Bureau of Labor Statistics
Average Hourly Earnings of

Year	Value
1992	13.70
1993	13.97
1994	14.33
1995	14.86
1996	15.37
1997	15.78
1998	16.23
1999	16.40
2000	17.09
2001	17.57
2002	17.97
2003	18.50
2004	19.17
2005	19.67
2006	19.60
2007	19.55
2008	19.50
2009	20.3
2010	

Assumed Start-up Year

The assumed version 3 current/near-term plant start-up year is 2010 (compared with a version 2 start-up year of 2005). Plants are assumed to be produced in quantities consistent with the Nth-plant assumption in 2010. Although this assumption may not be feasible, it is made so that the H2A cost estimates reflect a mature-system hydrogen price in the first year the technology could be fielded.

Direct Capital Costs

Direct capital costs were changed in version 3 based on escalating to 2007 dollars. In addition, the pressure swing adsorption (PSA) direct capital cost was adjusted in version 3 based on a better understanding of technology costs. Table 4 shows the direct capital cost changes made in version 3.

Table 4. H2A distributed model version 3 differences in direct capital costs ($2005 uninstalled costs are from version 2, $2007 uninstalled costs and installed costs are from version 3)

Major pieces/systems of equipment	Baseline Uninstalled Costs $2005 Dollars	Baseline Uninstalled Costs $2007 Dollars	Installation Cost Factor	Baseline Installed Costs
Water Feed System	$ 4,099	$ 4,599	1.17	$ 5,381
Primary Feed System	$ 10,428	$ 11,702	1.17	$ 13,691
Boiler	$ 27,802	$ 31,198	1.17	$ 36,502
Superheater	$ 5,562	$ 6,241	1.17	$ 7,302
HDS & Absorbent Bed	$ 6,107	$ 6,853	1.17	$ 8,019
Burner	$ 2,960	$ 3,322	1.17	$ 3,886
Reformer	$ 183,196	$ 205,577	1.17	$ 240,525
Water Gas Shift	$ 152,088	$ 170,669	1.17	$ 199,683
HDS Preheater	$ 3,144	$ 3,528	1.17	$ 4,128
Primary Air Feed System	$ 3,552	$ 3,986	1.17	$ 4,664
Reformate Cooler	$ 30,265	$ 33,963	1.17	$ 39,737
Condenser	$ 31,920	$ 35,819	1.17	$ 41,908
Air Feed System for Condenser	$ 667	$ 748	1.17	$ 876
Pressure Swing Adsorption Unit	$ 153,526	$ 172,282	1.17	$ 201,570
Water Purification	$ 31,645	$ 35,511	1.17	$ 41,548
Structural Supports	$ 17,908	$ 20,096	1.17	$ 23,512
Controls System	$ 32,506	$ 36,477	1.17	$ 42,678
System Assembly	$ 186,578	$ 209,373	1.17	$ 244,966
Miscellaneous	$ 79,075	$ 88,736	1.17	$ 103,821
		$ -		$ -
		$ -		$ -
		$ -		$ -
TOTALS	$ 963,027	$ 1,080,680		$ 1,264,396

PSA Cost

The version 3 capital cost scaling relationship is based on proprietary data from a PSA manufacturer, adjusted for parameters consistent with the Nth-plant assumption. Specifically, the PSA scaling relationship is based on purification of an SMR reformate stream (~75% H_2, 25% CO_2, dry gas) to "five nine" purity hydrogen gas, gross margins of 50%, approximately 100 systems produced per year, and no installation charges included in the cost. The capital cost of the PSA system is expected to scale with bed size, which in turn scales with hydrogen gas flow. Although the bed size grows linearly with hydrogen production rate, the overall cost scaling is highly non-linear owing to the relatively high cost fraction of valves and assembly. The following are the cost-scaling curve equations used:

$$\text{New PSA Cost} = BaseCost * \left(\frac{NewBedSize}{BaseBedSize}\right)^{CostFactor} = \$54{,}750 * \left(\frac{XX\ kgH_2/day}{115\ kgH_2/day}\right)^{0.4}$$

$$\text{For a 1500 kgH}_2\text{/dayPSAUnit} = \$54{,}750 * \left(\frac{1500\ kgH_2/day}{115 kgH_2/day}\right)^{0.4} = \$153{,}526$$

Indirect Capital and Other Costs

Indirect capital and other costs were changed in version 3 primarily based on AACE guidance and Nth-plant assumptions. The improvements to version 3 are summarized in Table 5 and discussed below.

Table 5. H2A distributed model version 3 differences in indirect capital and other costs

Field	Version 2	Version 3	Comment/Basis
Site preparation ($)	$74,344	$188,000	Based on AACE formula for foundations/misc. CA H_2 stations will provide valuable data.
Engineering & design ($)	$30,000	$50,000	
Process contingency ($)	$0	$0	AACE lists range as 0%–10% if “process is used commercially.”
Project contingency ($)	5% of direct capital	15% of direct capital	AACE recommends 25% but lists range of 15%–30%. Low end of range was selected because this is an Nth plant.
Initial spares	$0	0.75% of total capital cost	AACE recommends 0.5%–1.0%.
Pre-paid royalties	$0	0.75% of total project cost	AACE recommends 0.5%–1.0%.
Installation	10% of uninstalled cost	17% of uninstalled cost	Hybrid method partially based on AACE recommendations for setting of equipment.

Site Preparation

Site preparation refers to the physical preparation of the distributed plant location prior to installation of the hydrogen production equipment. It encompasses clearing and leveling the ground, cement foundations for the equipment, running electrical/gas/water lines to the site, and electricity upgrades (if necessary).

Site preparation for distributed production units is difficult to predict with accuracy given the scarcity of public production system installation cost data. Nth-plant considerations add additional uncertainty. However, costs for cement foundations are expected to be approximately the same whether for one-of-a-kind stations or modular/replicated stations. Only the station layout and engineering costs, and possibly the extent to which fluid connections can be simplified for rapid installation, would benefit from being the Nth plant. Consequently, site preparation costs are based heavily on “standard” costing methods and are not modified for the Nth-plant assumption.

Site preparation costs for distributed plants are based on a modification of AACE guidance. AACE presents guidance for “handling” and “setting,” which together sum to what H2A calls site preparation and installation. To isolate an AACE estimate for distributed system site preparation, the AACE estimates for “Foundations” and “Miscellaneous” are summed for the system category of “>150psi, >400F Gas Process.” AACE reports these costs as the following:

- Foundation materials: 5% of process costs
- Foundation labor: 6.65% of process costs
- Miscellaneous materials: 4% of process costs
- Miscellaneous labor: 3.2% of process costs.

This adds up to 18.85% of total process costs. Because the distributed production total process costs vary, but the site preparation costs may be approximately the same for multiple technologies, this percentage is applied to an average distributed process cost of $1M. This yields a site preparation cost of $188,000.

Process and Project Contingency

The AACE recommended practice is to include two types of contingencies in cost analysis: process contingency and project contingency. Contingencies cover omissions and unforeseen costs, and their magnitude generally decreases with detailed analysis or experience that leads to specific enumeration of costs. The process contingency adjusts for uncertainty in the technical performance due to limited design data. AACE indicates the process contingency range to be 0%–10% for commercial projects and 40%+ for new concepts with limited data. The H2A assumption is a 0% process contingency in keeping with the Nth-plant assumption of a well-vetted, commercial operation.

The project contingency covers additional cost that would be uncovered by a detailed costing analysis. AACE recommended practice is to set the project contingency at 15%–30% of project cost. The low end of the range, 15%, was selected for version 3 to project the most likely cost—rather than the upper-bound cost—for an Nth-plant system.

Initial Spares and Pre-Paid Royalties

For initial spare parts capital costs, the AACE recommends a range of 0.5%–1.0% of total project capital cost. The mid-point value (0.75%) is used in H2A version 3, whereas 0% was used in version 2.

For pre-paid royalties, the AACE recommends a range of 0.5%–1.0% of total project cost. The mid-point value (0.75%) is used in H2A version 3, whereas 0% was used in version 2.

Installation

Installation refers to the costs of transporting, placing, connecting, and verifying initial operation of system equipment. Installation costs for version 3 were raised to 17% of total direct uninstalled capital cost per the following breakdown:

- Sales tax 5% based on typical state sales tax
- Shipping 1% based on actual “Low-Rider” coast-to-coast transport of single large load
- Insurance 1% based on shipping insurance estimate
- Setting 10% based on ½ of AACE generic recommended value (reduced due to Nth-plant considerations).

Feedstock Prices

The H2A model requires current and projected future feedstock prices. The default set of projected feedstock prices is from the Energy Information Agency (EIA) Annual Energy Outlook (AEO) 2009 Reference Case (EIA 2009). AEO 2009 price projections are presented in 2007 dollars, so no escalation of the prices is required. In addition, the AEO 2009 High Price Case (EIA 2009) and the AEO 2010 Reference Case (EIA 2010) are available in the H2A model as pull-down menu options. Biomass is not included in the AEO projections, so biomass projections created by DOE’s Biomass Program are used. Table 6 shows the sources for feedstock prices and properties for version 2 and version 3.

To accommodate lifecycle modeling of hydrogen production facilities, the AEO price projections were extrapolated beyond the 2030 end date for the AEO data. The GCAM (formerly MiniCAM) model (Joint Global Change Research Institute 2011) was used to extrapolate out-year feedstock prices (Table 7).

Table 6. H2A distributed model version 3 differences in feedstock prices

Field	Description/Data Source for Version 2	Description/Data Source for Version 3
All feedstock prices except biomass and biomethane	EIA (2005): High A Case, Appendix C, Table 3 (Energy Prices by Sector and Source), 2003 dollars	EIA (2009): Reference Case (Stimulus Scenario), Table 3 (Energy Prices by Sector and Source), 2007 dollars
Biomass (farmed trees) prices	DOE (2011b), feedstock and utility price projections for 2001–2070, EIA units, 2005 dollars	DOE (2011c)
Biomethane prices	Not included in version 2	Saur (2011): $13.11/mmBtu, assumed constant through 2070, 2010 dollars
Price projections, 2031–2070	GCAM projections (Table 7)	GCAM projections except for biomethane, which is assumed constant
Conversion to reference year dollars, all feedstocks	2005 reference year	Conversion to reference year dollars automatically included in price tables for any reference year between 2005 and 2010
Conversion from HHV to LHV, all feedstocks	DOE (2011a)	Same as version 2

HHV—higher heating value; LHV—lower heating value.

Table 7. Price ratios from the GCAM model

	Ratio 2050 to 2035 Price	Ratio 2065 to 2050 Price	Extrapolated Ratio 2070 to 2065 Price
Coal Delivered to Utilities	1.044	1.028	1.009
Wellhead Gas	1.210	1.173	1.058
Gas Delivered to Utilities	1.170	1.149	1.050
Crude Oil Price	1.159	1.085	1.028
Delivered Diesel	1.159	1.085	1.028
Average Electricity	0.994	1.010	1.003
Dry Biomass at Farmgate	1.010	1.005	1.002
Ethanol	1.010	1.005	1.002

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Appendix 3: Central Model Default Values and Assumptions

The following default values and assumptions apply to the H2A central model, unless a specific technology case specifies otherwise:

Analysis Methodology	Discounted cash flow (DCF) model that calculates a levelized hydrogen cost yielding a prescribed IRR
Analysis Period	40 years
Average Burdened Labor Rate for Staff	$50/hour (2005 dollars)
Capacity Factor	90% with case exceptions
Central Storage	Optional buffer only as required for efficient operations
CO_2 Capture Credit	Not included in base cases (default value = 0)
CO_2 Production Taxes	Not included in base cases (default value = 0)
Construction Period and Cash Flow	Varies per case
Decommissioning	10% of initial capital, with case exceptions
Depreciation Type and Schedule for Initial Depreciable Capital Cost	MACRS: 20 years with case exceptions
Facility Life	40 years with case exceptions
G&A Rate	20% of the staff labor costs above
Hydrogen Pressure at Central Gate	300 psig; if higher pressure is inherent to the process, apply pumping power credit for pressure > 300 psig
Income Taxes	21% federal; 6% state; 25.74% total
Inflation Rate	1.9%, but with resultant price of hydrogen in reference year constant dollars
Interest Rate on Debt	3.7%
Land Cost	$50,000/acre purchased (2005 dollars)
O_2 Credit	Not included in base cases
Process Contingency	% adjustment to the total initial capital cost such that the result incorporates the mean or expected overall performance

Project Contingency	% adjustment to the total initial capital cost such that the result represents the mean or expected cost value; periodic replacement capital includes project contingency
Property Taxes and Business Insurance	2%/year of the total initial capital cost
Reference Financial Structure	40% equity with 8% after-tax real IRR; 60% debt with 3.7% interest rate (outstanding debt is constant throughout project length)[1]
Reference Year Dollars	2016 (can be adjusted 1992–2016)
Sales Tax	Not included on basis that facilities and related purchases are wholesale and through a general contractor entity
Salvage Value	10% of initial capital, with case exceptions
Sensitivity Variables and Ranges	Based on applying best judgment of 5% and 90% confidence limit extremes to the most significant baseline cost and performance parameters
Technology Development Stage	All cost estimates are based on mature, commercial facilities
Working Capital Rate[2]	15% of the annual change in total operating costs

[1] The default 8% real IRR value was derived from return-on-equity statistics (adjusted for inflation) for Praxair, Inc. and Air Products and Chemicals, Inc. during the period 2009–2017, which show a nominal return of approximately 10% (equivalent to an 8% real IRR) (Source: NREL, 2018, *Market Calibration of H2A Cost of Capital Parameters* [Internal Memo Report]). Because returns already account for corporate taxes, this value is an after-tax return. The use of the 8% real IRR is intended to reflect a steady-state situation in the future in which hydrogen is no longer a novel concept and a significant demand for hydrogen exists.

[2] Working capital is defined as a measure of a business' daily operating liquidity, calculated by subtracting current liabilities from current assets. Working capital is considered a part of operating capital, along with fixed assets such as facilities and equipment. It is also known as net working capital.

Appendix 4: Distributed Model Default Values and Assumptions

The following default values and assumptions apply to the H2A distributed model, unless a specific technology case specifies otherwise:

Analysis Methodology	Discounted cash flow (DCF) model that calculates a levelized hydrogen cost yielding a prescribed IRR
Analysis Period	20 years
Average Burdened Labor Rate for Staff	\$50/hour (2005 dollars) for production; \$12.06/hour (2007 dollars) for fueling station
Usage Factor	86%
Construction Period and Cash Flow	1 year
Decommissioning (% of depreciable capital investment)	10%
Depreciation Type and Schedule for Initial Depreciable Capital Cost	MACRS: 7 years
Facility Life	20 years with case exceptions
G&A Rate	20% of the staff labor costs above
Income Taxes	21% federal; 6% state; 25.74% total
Inflation Rate	1.9%, but with resultant price of hydrogen in reference year constant dollars
Interest Rate on Debt	3.7%
Land Cost	\$0.3/sqft/month for land rental
Process Contingency	% adjustment to the total initial capital cost such that the result incorporates the mean or expected overall performance
Project Contingency	% adjustment to the total initial capital cost such that the result represents the mean or expected cost value; periodic replacement capital includes project contingency
Property Taxes and Business Insurance	2%/year of the total initial capital cost
Reference Financial Structure	40% equity with 8% after-tax real IRR; 60% debt with 3.7% interest rate (outstanding debt is constant throughout project length)[3]

[3] The default 8% real IRR value was derived from return-on-equity statistics (adjusted for inflation) for Praxair, Inc. and Air Products and Chemicals, Inc. during the period 2009–2017, which show a nominal return of approximately 10%

Reference Year Dollars	2016 (can be adjusted 1992–2016)
Sales Tax	Not included on basis that facilities and related purchases are wholesale and through a general contractor entity
Salvage Value	10% of initial capital, with case exceptions
Sensitivity Variables and Ranges	Based on applying best judgment of 5% and 90% confidence limit extremes to the most significant baseline cost and performance parameters
Technology Development Stage	All cost estimates are based on mature, commercial facilities
Working Capital Rate[4]	15% of the annual change in total operating costs

(equivalent to an 8% real IRR) (Source: NREL, 2018, *Market Calibration of H2A Cost of Capital Parameters* [Internal Memo Report]). Because returns already account for corporate taxes, this value is an after-tax return. The use of the 8% real IRR is intended to reflect a steady-state situation in the future in which hydrogen is no longer a novel concept and a significant demand for hydrogen exists.

[4] Working capital is defined as a measure of a business' daily operating liquidity, calculated by subtracting current liabilities from current assets. Working capital is considered a part of operating capital, along with fixed assets such as facilities and equipment. It is also known as net working capital.