H2A Production Model, Version 2.0
User Guide

DRAFT

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The H2A Production Model analyzes the technical and economic aspects of central and forecourt hydrogen production technologies. Using a standard discounted cash flow rate of return methodology, it determines the minimum hydrogen selling price (or levelized cost), including 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.

This new version of the H2A Production Model features enhanced usability and functionality. Input fields are consolidated and simplified. New capabilities include performing sensitivity analyses and scaling analyses to various plant sizes.

The model is actually two models: one Microsoft Excel spreadsheet to analyze central hydrogen production technologies and another to analyze forecourt hydrogen production technologies. The two models are very similar; the primary difference is that the central model performs carbon sequestration calculations, whereas the forecourt model performs refueling station compression, storage, and dispensing calculations.

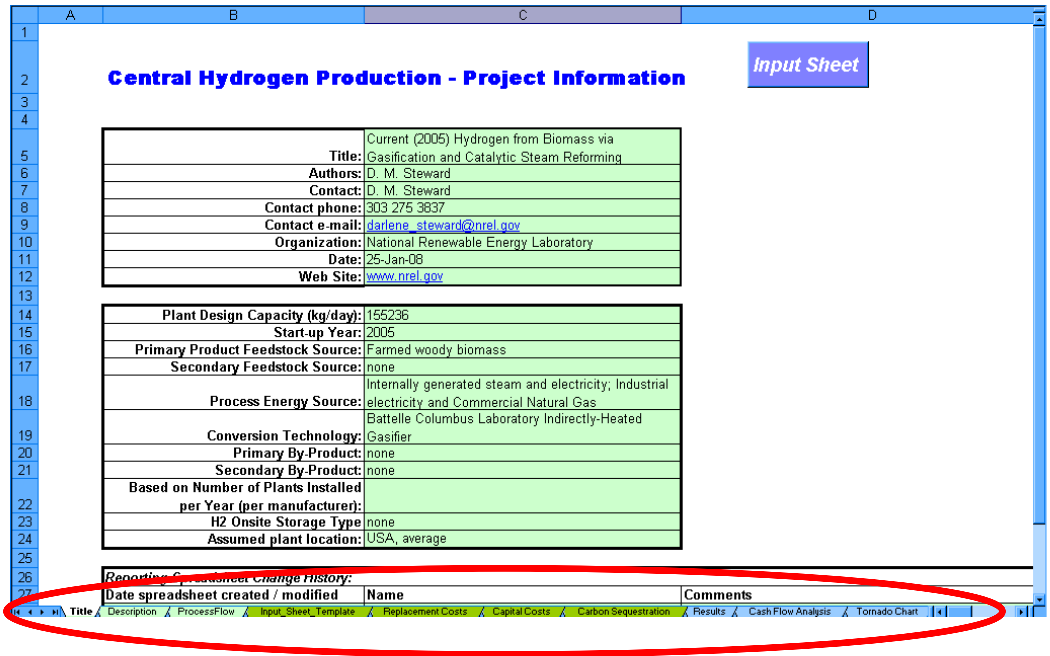
This *User Guide* helps users already familiar with the basic tenets of H2A hydrogen production cost analysis get started using the new version of the model. It introduces the basic elements of the model then describes the function and use of each of its worksheets. More detailed and explanatory instructional materials are being developed.

Contents

Quick Start: Getting Around

The spreadsheet is organized into 19 or more worksheets, which have tabs color coded according to their function, as shown below. The schematic on the following page shows a generalized data flow among the worksheets.

Overview of H2A Production Model Tabs and Worksheets

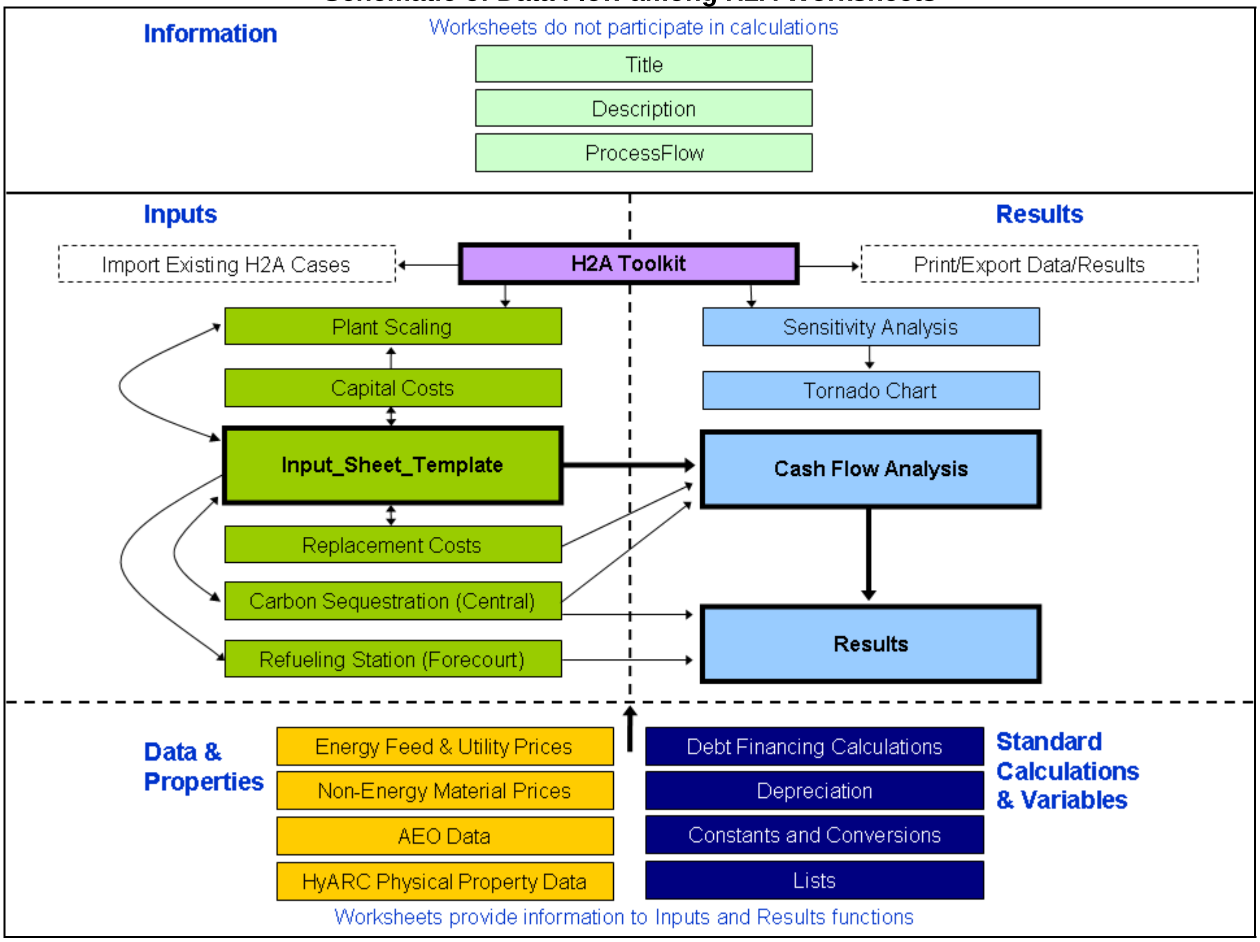


Worksheet tab	Group
Title	Information
Description	
ProcessFlow	
Input_Sheet_Template	Inputs
Replacement Costs	
Capital Costs	
Plant Scaling	
Refueling Station [forecourt model only]	
Carbon Sequestration [central model only]	
Results	Results
Cash Flow Analysis	
Tornado Chart	
Sensitivity_Analysis	
Energy Feed & Utility Prices	Data & Properties
Non-Energy Material Prices	
AEO Data	
HyARC Physical Property Data	
Debt Financing Calculations	Standard Calculations & Variables
Depreciation	
Constants and Conversions	
Lists	

Most users will add/modify cells within the Input worksheets (dark green tabs) only.

TIP

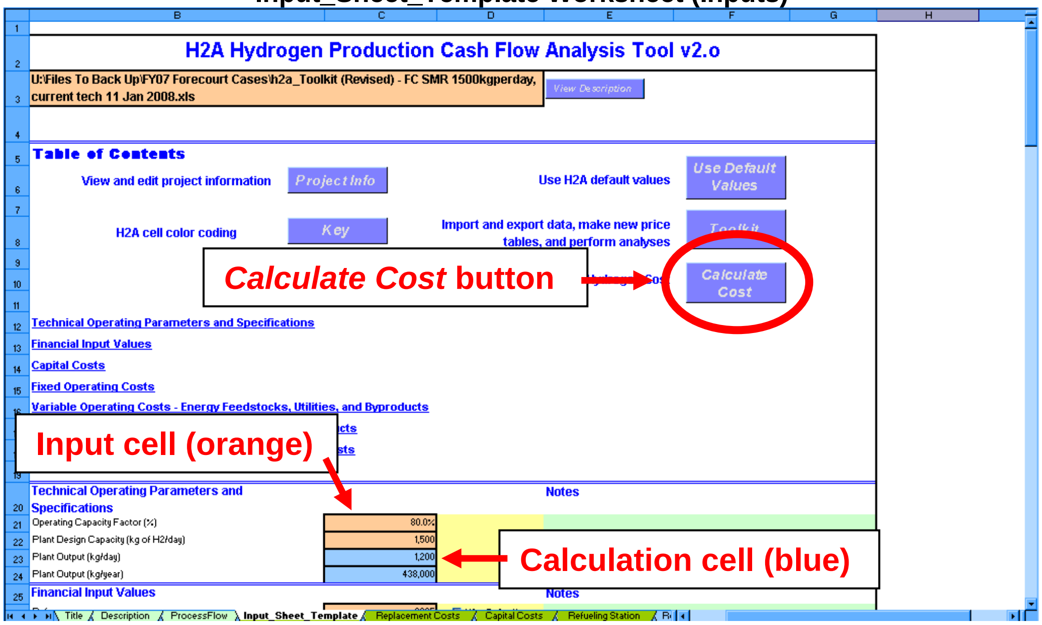
Schematic of Data Flow among H2A Worksheets



Quick Start: Performing Simple Production Cost Analyses

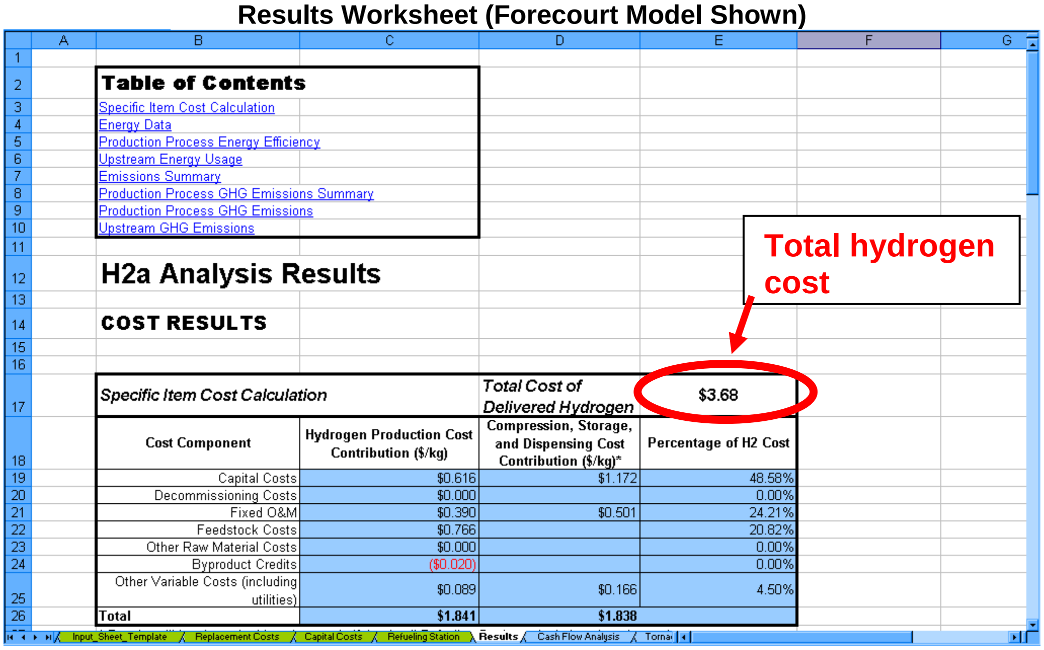
To perform a simple production cost analysis, select the *Input_Sheet_Template* tab. Accept the default (e.g., production technology case) values or enter new values into the orange cells. The contents of the blue cells are calculated automatically. Use the drop-down menus and buttons to enter information for *Energy Feedstocks, Utilities, and Byproducts* and *Other Materials and Byproducts*. Once all information is entered, click the *Calculate Cost* button at the top of the worksheet.

Input_Sheet_Template Worksheet (Inputs)



Clicking the *Calculate Cost* button sends you to the *Results* worksheet, which displays the production cost, energy, and emissions results.

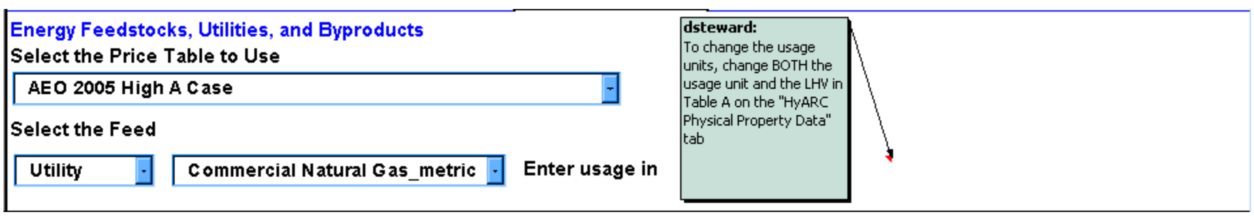
Results Worksheet (Forecourt Model Shown)



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, 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.
- 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.
- 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 (i.e., 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, click the *Calculate Cost* button at top to view results.
- Tabs for the *Plant Scaling* and *Tornado Chart* worksheets do not appear until you initiate their use. See pages 23 and 39 for details.

<u>User Guide Symbols</u>


CAUTION

Follow instructions carefully to prevent errors or unwanted results.


Advanced users only

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* *Refueling Station*	*Table of Contents* (p. 13)
2. After adding energy feedstocks, utilities, and byproducts in the *Input_Sheet_Template* worksheet, you received an error message and null results when you clicked the *Calculate Cost* button.	Make sure you use the same price table for each energy feedstock, utility, and byproduct you add. Using different price tables creates an error in the calculations.	*Input_Sheet_Template*	*Energy Feedstocks, Utilities, and Byproducts* (p. 15)
3. 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 an error message and null results when you clicked the *Calculate Cost* button.	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. 15) *Other Materials and Byproducts* (p. 19)

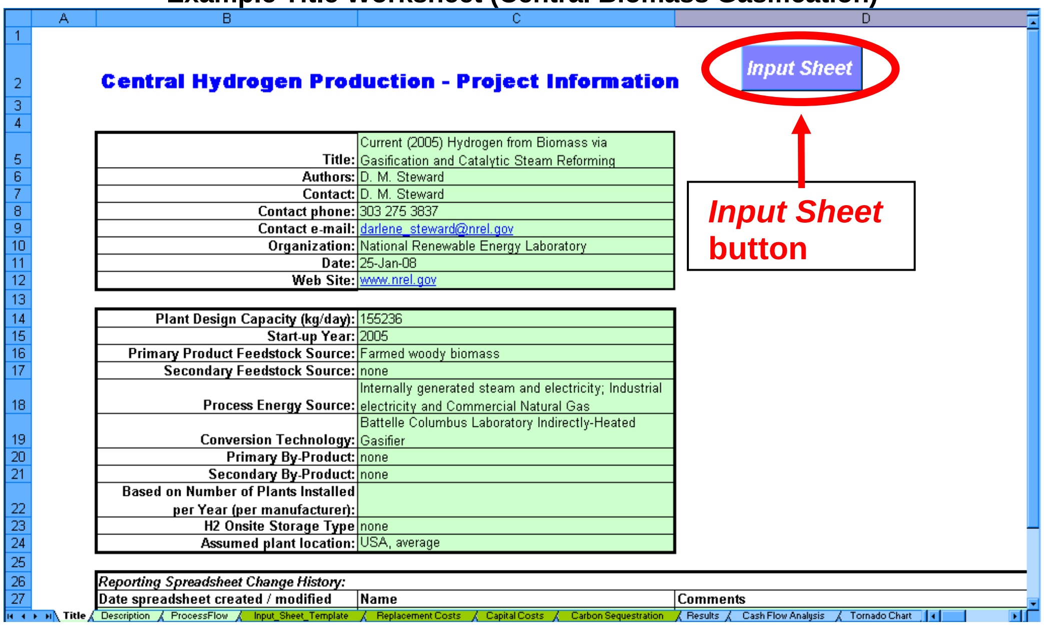
Problem	Possible Solution	Relevant Worksheets	User Guide Sections
4. You did not perform the actions described in problems 2 and 3 above, but you still received an error message when you clicked the *Calculate Cost* button.	Make sure to enter all critical values in the *Technical Operating Parameters and Specifications* and *Financial Input Values* sections before completing the rest of the *Input_Sheet_Template* worksheet and calculating cost. In particular, make sure values are present for reference year, startup year, and plant capacity.	*Input_Sheet_Template*	*Variable Operating Costs* (p. 18)
5. 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. 15) *Other Materials and Byproducts* (p. 19) *Delete Feed, Utility, and Byproduct Inputs* (p. 32)
6. You performed a sensitivity analysis, and the resulting tornado chart contained bad or nonsensical results.	Try switching the values you entered for "Value Reducing Hydrogen Price" and "Value Increasing Hydrogen Price" within the *Sensitivity Analysis* window. It is not always obvious how changing the value of a variable will affect the hydrogen price.	*H2A Toolkit* *Tornado Chart* *Sensitivity Analysis*	*Performing Sensitivity Analyses* (p. 33)

Problem	Possible Solution	Relevant Worksheets	User Guide Sections
7. You added your own energy feedstock, utility, or byproduct using the *Energy Feed & Utility Prices* worksheet, but your new item did not appear in the *Energy Feedstocks, Utilities, and Byproducts* section within the *Input_Sheet_Template* worksheet.	First, "refresh" the *Energy Feedstocks, Utilities, and Byproducts* section by selecting another price table from the drop-down menu then selecting the table in which your new item was added; use the next two drop-down menus to check if your item now appears. If your item still does not appear, go to the *HyARC Physical Property Data* worksheet, *Table A*, and make sure the item has values in every required column.	*Input_Sheet_Template* *Energy Feed & Utility Prices* *HyARC Physical Property Data*	*Energy Feed & Utility Prices Worksheet* (p. 41)
8. 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. 50)

Information Worksheets

Established H2A production technology cases contain information worksheets linked from the light-green tabs. These worksheets 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 Biomass Gasification)



Central Hydrogen Production - Project Information

Input Sheet

Input Sheet button

Title:	Current (2005) Hydrogen from Biomass via Gasification and Catalytic Steam Reforming
Authors:	D. M. Steward
Contact:	D. M. Steward
Contact phone:	303 275 3837
Contact e-mail:	darlene_steward@nrel.gov
Organization:	National Renewable Energy Laboratory
Date:	25-Jan-08
Web Site:	www.nrel.gov

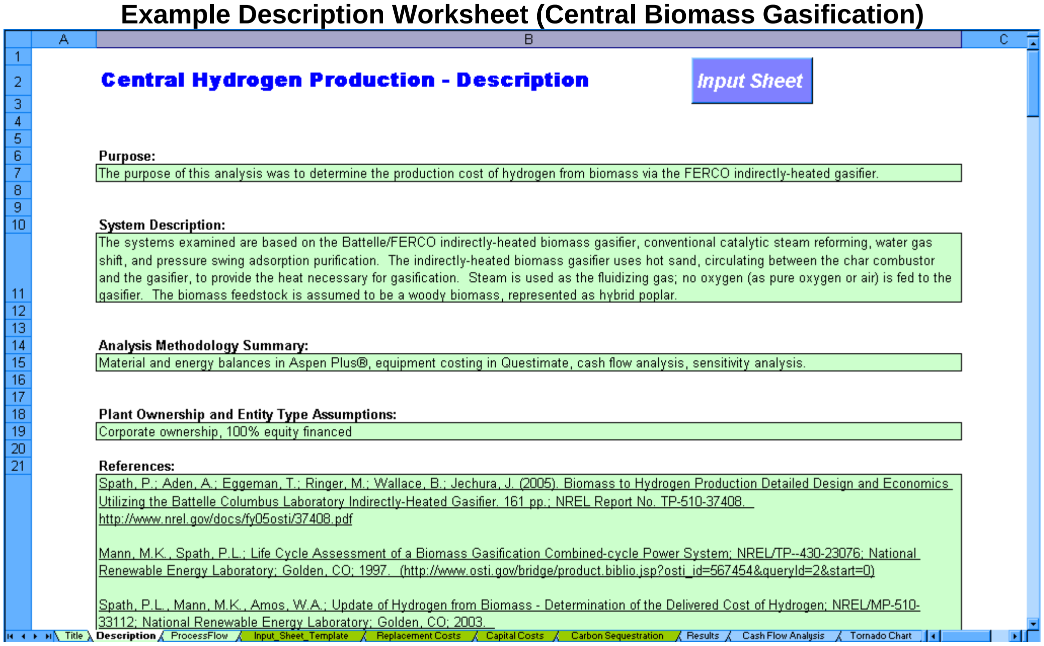
Plant Design Capacity (kg/day):	155236
Start-up Year:	2005
Primary Product Feedstock Source:	Farmed woody biomass
Secondary Feedstock Source:	none
Process Energy Source:	Internally generated steam and electricity; Industrial electricity and Commercial Natural Gas
Conversion Technology:	Battelle Columbus Laboratory Indirectly-Heated Gasifier
Primary By-Product:	none
Secondary By-Product:	none
Based on Number of Plants Installed per Year (per manufacturer):	
H2 Onsite Storage Type	none
Assumed plant location:	USA, average

Reporting Spreadsheet Change History:

Date spreadsheet created / modified	Name	Comments

Title / Description / ProcessFlow / Input_Sheet_Template / Replacement Costs / Capital Costs / Carbon Sequestration / Results / Cash Flow Analysis / Tornado Chart

Example Description Worksheet (Central Biomass Gasification)



Central Hydrogen Production - Description

Input Sheet

Purpose:

The purpose of this analysis was to determine the production cost of hydrogen from biomass via the FERCO indirectly-heated gasifier.

System Description:

The systems examined are based on the Battelle/FERCO indirectly-heated biomass gasifier, conventional catalytic steam reforming, water gas shift, and pressure swing adsorption purification. The indirectly-heated biomass gasifier uses hot sand, circulating between the char combustor and the gasifier, to provide the heat necessary for gasification. Steam is used as the fluidizing gas; no oxygen (as pure oxygen or air) is fed to the gasifier. The biomass feedstock is assumed to be a woody biomass, represented as hybrid poplar.

Analysis Methodology Summary:

Material and energy balances in Aspen Plus®, equipment costing in Questimate, cash flow analysis, sensitivity analysis.

Plant Ownership and Entity Type Assumptions:

Corporate ownership, 100% equity financed

References:

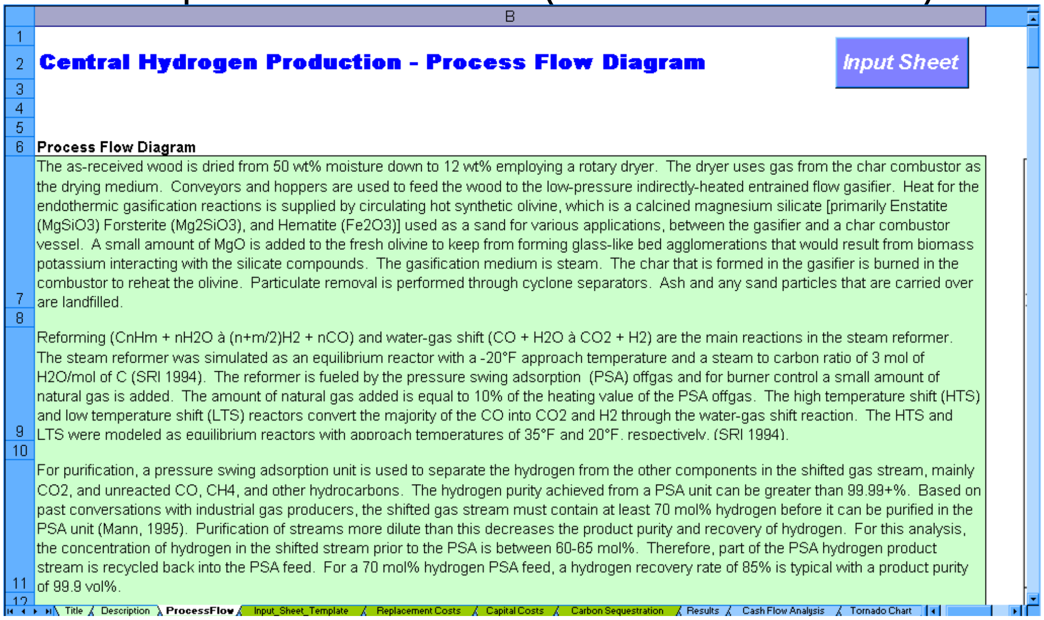
Spath, P.; Aden, A.; Eggeman, T.; Ringer, M.; Wallace, B.; Jechura, J. (2005). Biomass to Hydrogen Production Detailed Design and Economics Utilizing the Battelle Columbus Laboratory Indirectly-Heated Gasifier. 161 pp.; NREL Report No. TP-510-37408. http://www.nrel.gov/docs/fy05osti/37408.pdf

Mann, M.K., Spath, P.L.; Life Cycle Assessment of a Biomass Gasification Combined-cycle Power System; NREL/TP--430-23076; National Renewable Energy Laboratory; Golden, CO; 1997. (http://www.osti.gov/bridge/product.biblio.jsp?osti_id=567454&queryId=2&start=0)

Spath, P.L., Mann, M.K., Amos, W.A.; Update of Hydrogen from Biomass - Determination of the Delivered Cost of Hydrogen; NREL/MP-510-33112; National Renewable Energy Laboratory; Golden, CO; 2003.

Title / Description / ProcessFlow / Input_Sheet_Template / Replacement Costs / Capital Costs / Carbon Sequestration / Results / Cash Flow Analysis / Tornado Chart

Example ProcessFlow Worksheet (Central Biomass Gasification)



Central Hydrogen Production - Process Flow Diagram

Input Sheet

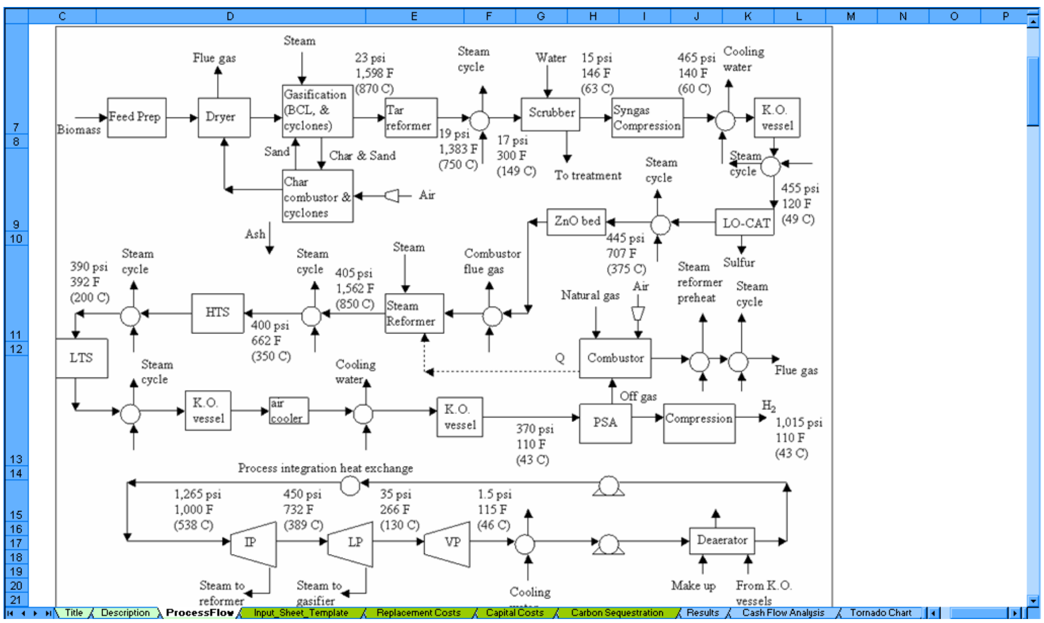
Process Flow Diagram

The as-received wood is dried from 50 wt% moisture down to 12 wt% employing a rotary dryer. The dryer uses gas from the char combustor as the drying medium. Conveyors and hoppers are used to feed the wood to the low-pressure indirectly-heated entrained flow gasifier. Heat for the endothermic gasification reactions is supplied by circulating hot synthetic olivine, which is a calcined magnesium silicate [primarily Enstatite (MgSiO3) Forsterite (Mg2SiO3), and Hematite (Fe2O3)] used as a sand for various applications, between the gasifier and a char combustor vessel. A small amount of MgO is added to the fresh olivine to keep from forming glass-like bed agglomerations that would result from biomass potassium interacting with the silicate compounds. The gasification medium is steam. The char that is formed in the gasifier is burned in the combustor to reheat the olivine. Particulate removal is performed through cyclone separators. Ash and any sand particles that are carried over are landfilled.

Reforming (CnHm + nH2O à (n+m/2)H2 + nCO) and water-gas shift (CO + H2O à CO2 + H2) are the main reactions in the steam reformer. The steam reformer was simulated as an equilibrium reactor with a -20°F approach temperature and a steam to carbon ratio of 3 mol of H2O/mol of C (SRI 1994). The reformer is fueled by the pressure swing adsorption (PSA) offgas and for burner control a small amount of natural gas is added. The amount of natural gas added is equal to 10% of the heating value of the PSA offgas. The high temperature shift (HTS) and low temperature shift (LTS) reactors convert the majority of the CO into CO2 and H2 through the water-gas shift reaction. The HTS and LTS were modeled as equilibrium reactors with approach temperatures of 35°F and 20°F, respectively. (SRI 1994).

For purification, a pressure swing adsorption unit is used to separate the hydrogen from the other components in the shifted gas stream, mainly CO2, and unreacted CO, CH4, and other hydrocarbons. The hydrogen purity achieved from a PSA unit can be greater than 99.99+%. Based on past conversations with industrial gas producers, the shifted gas stream must contain at least 70 mol% hydrogen before it can be purified in the PSA unit (Mann, 1995). Purification of streams more dilute than this decreases the product purity and recovery of hydrogen. For this analysis, the concentration of hydrogen in the shifted stream prior to the PSA is between 60-65 mol%. Therefore, part of the PSA hydrogen product stream is recycled back into the PSA feed. For a 70 mol% hydrogen PSA feed, a hydrogen recovery rate of 85% is typical with a product purity of 99.9 vol%.

Title | Description | ProcessFlow | Input_Sheet_Template | Replacement Costs | Capital Costs | Carbon Sequestration | Results | Cash Flow Analysis | Tornado Chart



Title | Description | ProcessFlow | Input_Sheet_Template | Replacement Costs | Capital Costs | Carbon Sequestration | Results | Cash Flow Analysis | Tornado Chart

Input_Sheet_Template Worksheet

The *Input_Sheet_Template* worksheet is the H2A Model's primary user interface. You use this worksheet to input data the model uses for calculations, perform analyses, and access the automated functions of the model through the *H2A Toolkit* utility. After filling out the worksheet, you click the *Calculate Cost* button to calculate and view results. The worksheet is organized into seven main sections plus the *Toolkit*, which are described below (see page 30 for details on the *H2A Toolkit*). 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 and date of the H2A file you are using. Click the *View Description* button to view a brief project description and history of updates in the *Title* worksheet (see page 11 for a sample *Title* worksheet).

Table of Contents

At the top of the *Table of Contents* are five 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 14). Be careful when using this button so as not to replace values unintentionally.


CAUTION

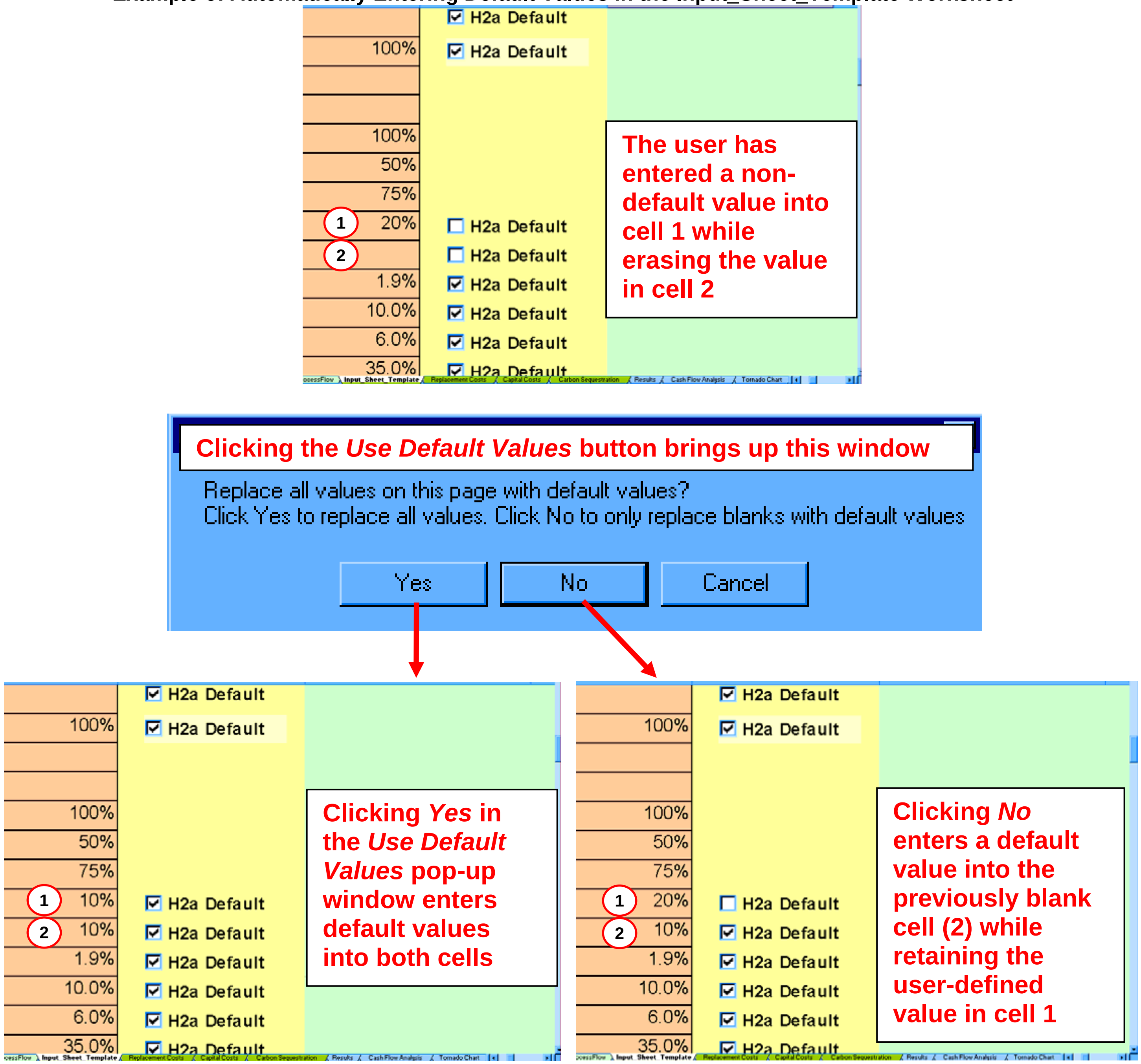
The *Toolkit* button brings up the *H2A Toolkit* window. Although this button is at the top of the worksheet, typically it is not the first thing you need to use—you will use it to perform a variety of important functions as described under *H2A Toolkit* (page 30) and in several other sections of this *User Guide*.

Use the *Calculate Cost* button after completing all necessary sections of the *Input_Sheet_Template* worksheet and associated worksheets. For illustrations, read through the rest of this section or see *Quick Start: Performing Simple Production Cost Analyses* (page 6).

Beneath the row 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* (the order of sections varies slightly between central and forecourt models):

- *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. Enter values for capacity factor and plant design capacity. The model uses these values to calculate plant output.

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 *Reference Year*, *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 is *Total Tax Rate*.

Energy Feedstocks, Utilities, and Byproducts

This important section follows the *Financial Input Values* section in the central model and is part of the *Variable Operating Costs* section (see page 18) in the forecourt model. It 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 U.S. Energy Information Administration (EIA) data are drawn from the model's *Energy Feed & Utility Prices* worksheet (see page 41). Select one of the tables from the drop-down menu. The U.S. Department of Energy (DOE) has selected the *AEO 2005 High A Case* as the standard for all H2A production technology cases. For more information on the AEO data, see *AEO Data Worksheet* on page 44. 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.

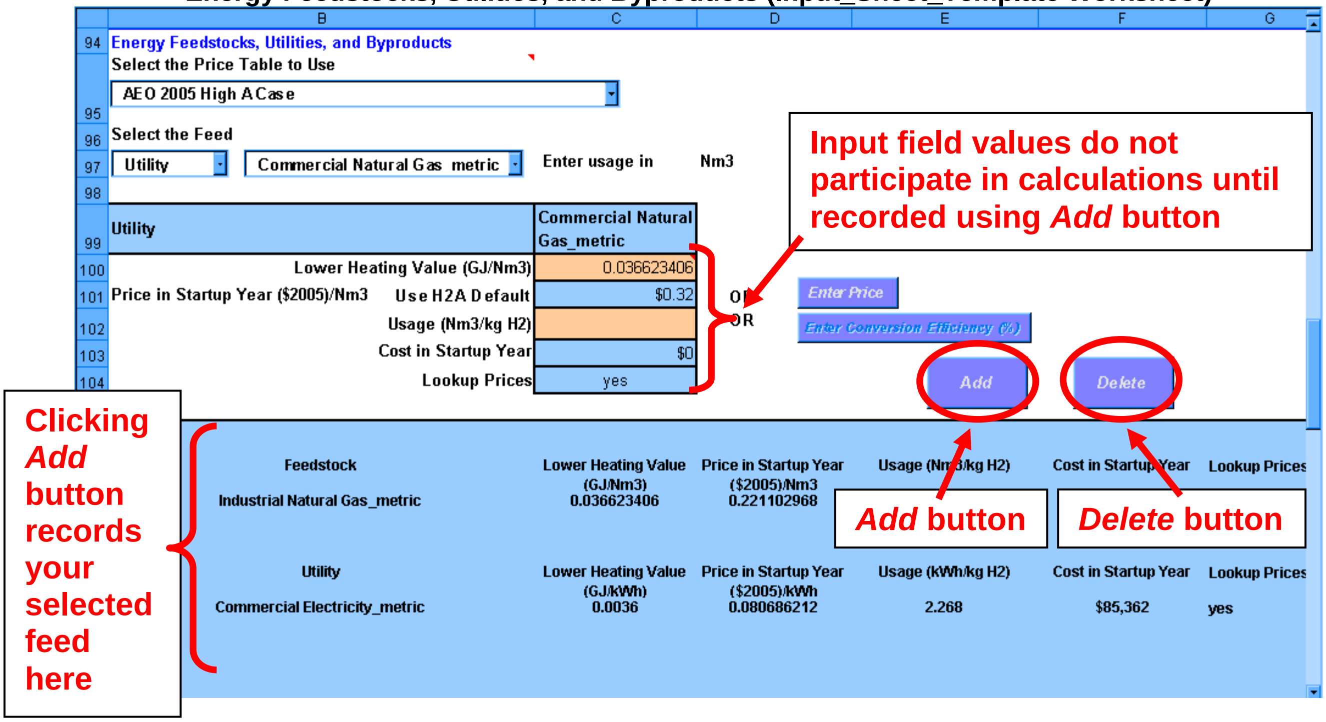
CAUTION

Use the next two drop-down menus to select feedstocks, utility inputs, and byproducts; see *Energy Feed & Utility Prices Worksheet* on page 41 for an easy way to add items that are not already in these menus. The lower heating value (LHV) is automatically drawn from the *HyARC Physical Property Data* worksheet, *Table A* (see page 45).

Next, accept the shown *Price in Startup Year* or click the *Enter Price* button to enter a different price. If you accept the *Price in Startup Year*, 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 enter your own price, 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 (kg, kWh, Nm3, or L). For feedstock, you can click the *Enter Conversion Efficiency (%)* button to enter the feedstock conversion efficiency. (Note this is the efficiency of feedstock conversion only; if there are other energy inputs, the overall plant energy efficiency will be lower.) Once these fields are completed, click the *Add* button, which records your entry as shown in the screen capture on page 16.

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 on page 16). 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, it is critical to use the *Delete* button. Do not delete the rows using Excel's delete functionality. Also, be careful to choose the correct item from the *Delete* drop-down 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 18).

The model uses the selected entries to automatically 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 section but are not used in the cash-flow calculations. You can view the yearly values being used in the cash-flow calculations in the lowermost table of the *Cash Flow Analysis* worksheet (see the bottom screen capture in the schematic on page 18).

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 or mmBtu/ H2A usage input unit)*,

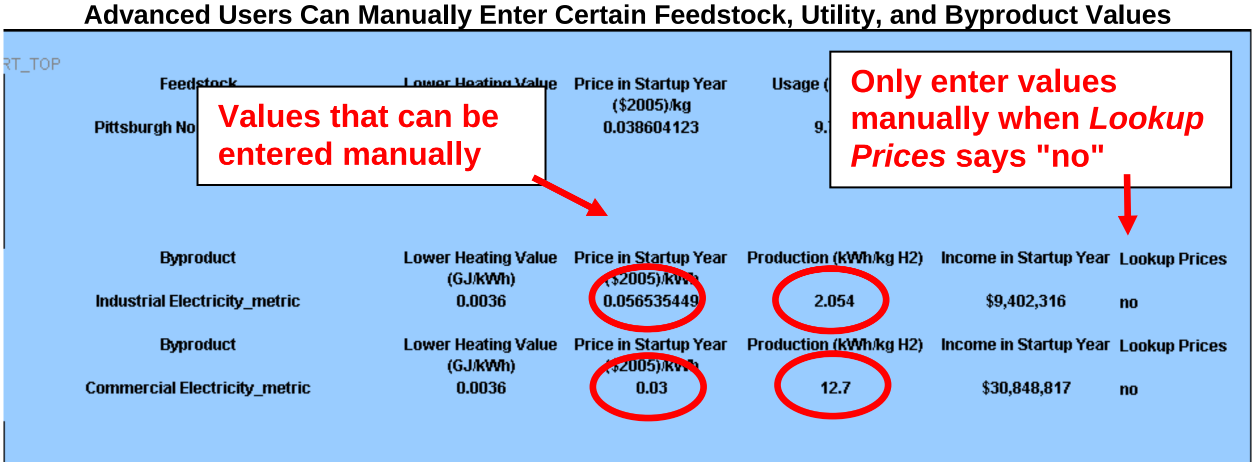
Advanced users only

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 accord with the new-unit input values.

Advanced users only

Advanced users also 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. For those items you will want to vary by typing over values, click the *Enter Price* button 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. Once you have finished typing in values, click the *Calculate Cost* button to see the resulting hydrogen cost.

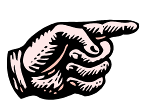
Advanced Users Can Manually Enter Certain Feedstock, Utility, and Byproduct Values



Capital Costs

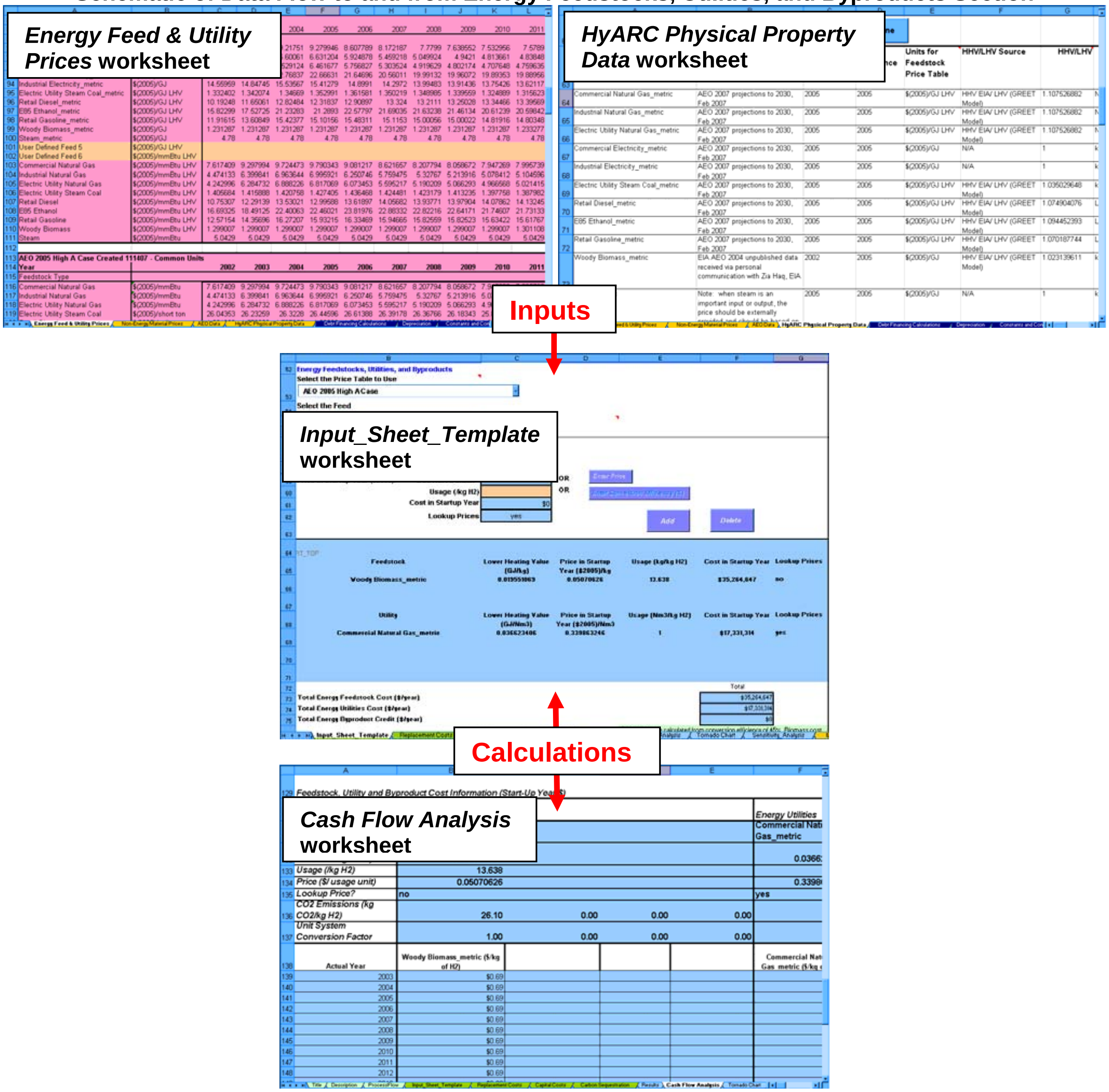
Here you define the capital costs of your plant. For quick analyses, enter the total direct capital costs in the first input cell. When developing cases or detailed analyses, entering detailed capital costs is recommended. Click the first *Link to Detail Sheet* button, which takes you to the *Capital Costs* worksheet for data entry (see page 22). Clicking the second *Link to Detail Sheet* button takes you to the *Carbon Sequestration* worksheet (in the central model; see page 26) or the *Refueling Station* worksheet (in the forecourt model; see page 28) to calculate detailed capital costs for those functions. Note that some of the orange input fields can contain suggested equations. You can overwrite these with your own static values or equations. Once all applicable fields are filled with inputs and calculated values, the model calculates *Total Depreciable Capital Costs*, *Total Non-Depreciable Capital Costs*, and *Total Capital Costs*.

Orange cells are overwritten automatically when you import a new case (pg 24) or use the cell variable in plant scaling (pg 17).



TIP

Schematic of Data Flow to and from Energy Feedstocks, Utilities, and Byproducts Section



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*. In the forecourt model, enter information for the staff needed to run the hydrogen production equipment in the first two cells and for the filling station staff in the fourth and fifth cells. If you linked to the *Refueling Station* worksheet in the *Capital Cost* section (see above), the storage and dispensing labor costs will be set to zero here.

Variable Operating Costs

Here you define process material costs and other variable operating costs and the value of non-energy byproducts. In the forecourt model, this section also contains the function for defining energy feedstocks, utilities, and byproducts; this function is described for both the central and forecourt models on page 15. The remaining parts of the *Variable Operating Costs* section are *Other Materials and Byproducts* and *Other Variable Operating Costs*. To prevent model errors, enter all critical values in the *Technical Operating Parameters and Specifications* (page 14) and *Financial Input Values* (page 14) sections before completing these sub-sections.

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

TIP

Other Materials and Byproducts

This sub-section works in a similar fashion as the *Energy Feedstocks, Utilities, and Byproducts* function described on page 15. 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 menus and data entry fields, then clicking the *Add* button.

This sub-section requires fewer user choices than the *Energy Feedstocks, Utilities, and Byproducts* function. 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 Price* button.

The *Byproduct* check box allows you to switch between materials consumed as process inputs (which incur costs) and materials produced as byproducts (which produce income/credits). When the box is unchecked, the material in the drop-down menu (cooling water, demineralized water, etc.) is labeled as a feed or utility, and the number you input is usage per kilogram of hydrogen produced for sale. When the box is checked, the material in the drop-down menu is labeled as a byproduct, and the number you input is production per kilogram of hydrogen.

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 43 for an illustration. This is also where you can modify the material prices if desired.

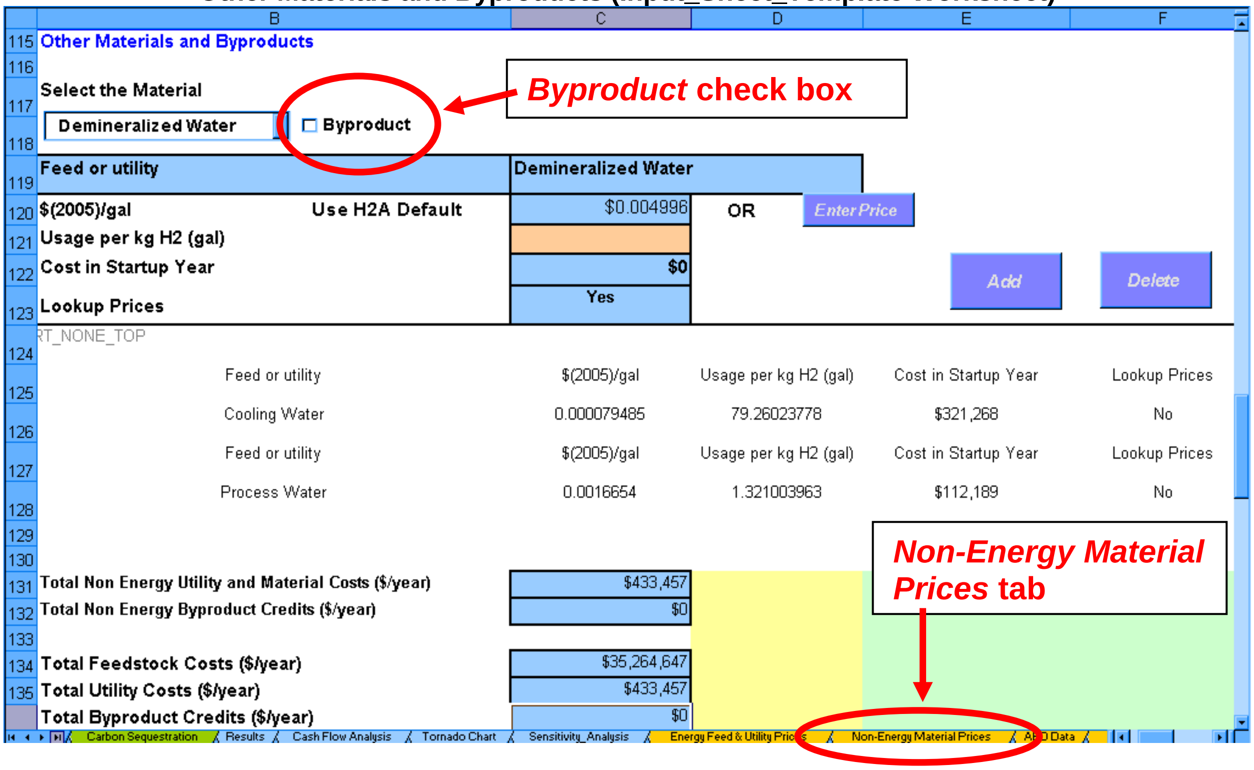
CAUTION

When deleting entries, it is critical to 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 sub-section, but also the energy feedstocks, utilities, and byproducts selected previously (see page 15).

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 similar fashion as for the *Energy Feedstocks, Utilities, and Byproducts* section—see page 17 for instructions.

Advanced users only

Other Materials and Byproducts (Input_Sheet_Template Worksheet)



Other Variable Operating Costs

This sub-section 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 21), which calculates replacement costs based on this factor and the value for total depreciable capital costs (see *Capital Costs*, page 17). Clicking the *Enter Specific Costs* button takes you to the *Replacement Costs* worksheet, where you can specify additional replacement costs.

For 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 17). For the forecourt model, the field *Refueling Station O&M costs* shows a value of zero if you linked to the *Refueling Station* worksheet in the *Capital Costs* section (see page 17). Note, these O&M costs are not actually zero; rather, a separate cash flow analysis is performed for the refueling station (compression, storage, and dispensing), and the results are presented in a separate column in the *Results* worksheet.

Once you have entered all the information you want to enter, scroll to the top of the *Input_Sheet_Template* worksheet and click the *Calculate Cost* button. This sends you to the *Results* worksheet, which displays results as illustrated under *Quick Start: Performing Simple Cost Analyses* (page 6).

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 reference year dollars—do not inflate.

TIP

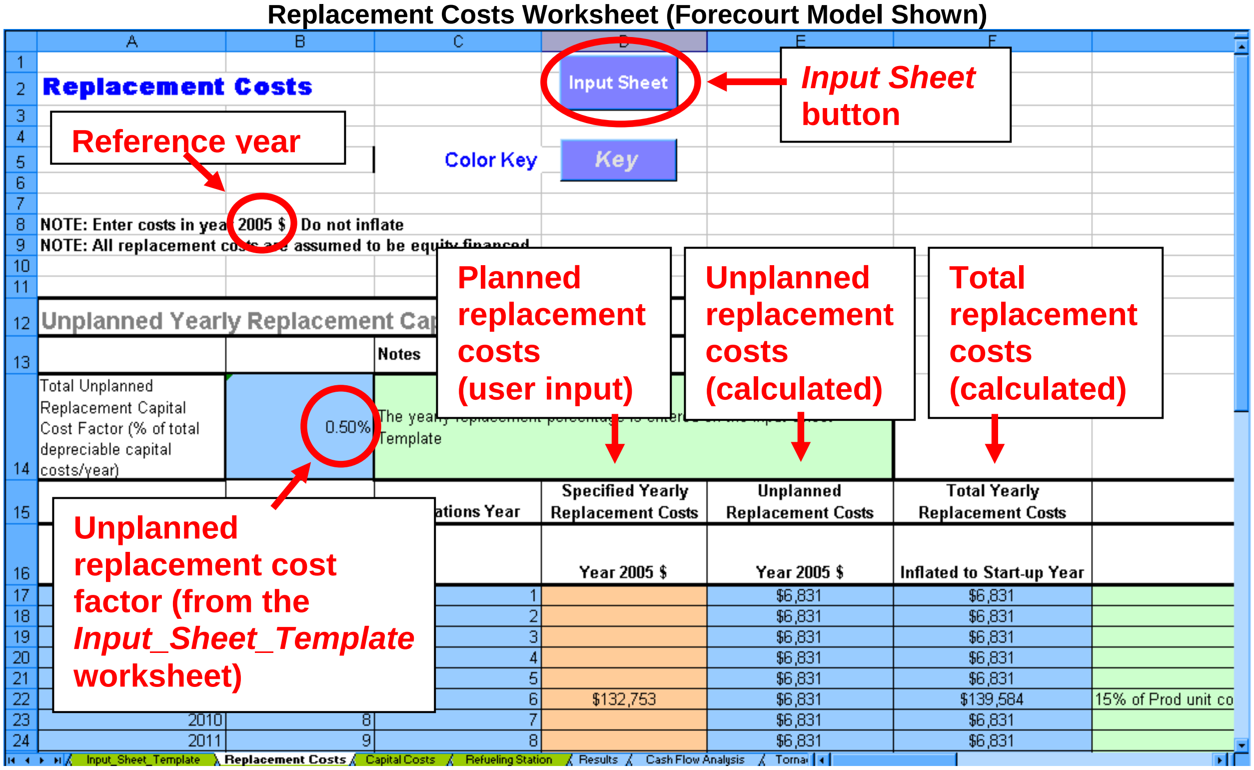
Enter planned replacement costs (in reference year $) for each year in the *Specified Yearly Replacement Costs* column. The values in the *Unplanned Replacement Costs* column are calculated automatically in the following way:

1) The *Total Unplanned Replacement Capital Cost Factor* you entered in the *Other Variable Operating Costs* sub-section of the *Input_Sheet_Template* worksheet (see page 20) 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 17); 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 (Forecourt Model Shown)

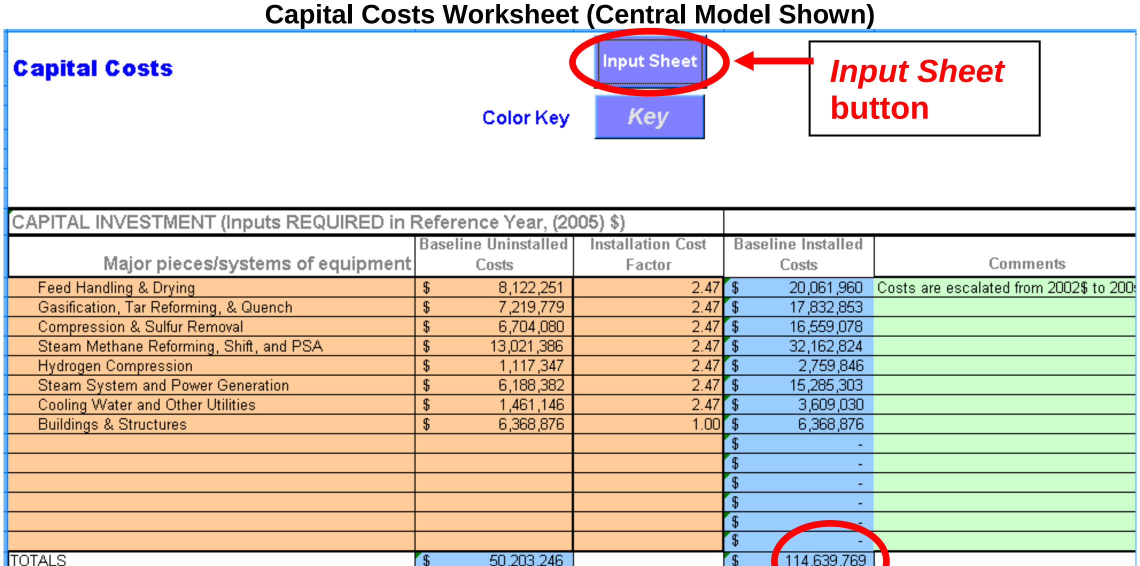


Capital Costs Worksheet

The *Capital Costs* worksheet accepts inputs for individual capital costs and calculates total direct capital cost. This total direct capital cost can then be imported into the *Capital Costs* section of the *Input_Sheet_Template* worksheet (see page 17). For the central model, this is the direct capital cost of the production equipment not including carbon sequestration equipment (see page 26 for carbon sequestration calculations). For the forecourt model, it is the direct capital cost of the production unit plus compression, storage, and dispensing if you choose to enter these costs using this worksheet; see page 28 for instructions on calculating optimal compression, storage, and dispensing costs using the *Refueling Station* worksheet.

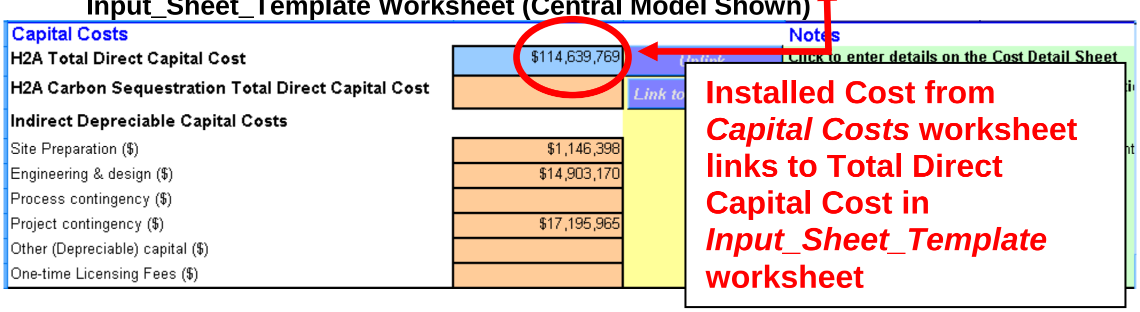
Activate the *Capital Costs* worksheet by clicking the *Link to Detail Sheet* button next to the *H2A Total Direct Capital Cost* (for the central model) or *H2A Production Process Total Direct Capital Cost* (for the forecourt model) field in the *Capital Costs* section of the *Input_Sheet_Template* worksheet. 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. 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 linkage.

Capital Costs Worksheet (Central Model Shown)



CAPITAL INVESTMENT (Inputs REQUIRED in Reference Year, (2005) $)				
Major pieces/systems of equipment	Baseline Uninstalled Costs	Installation Cost Factor	Baseline Installed Costs	Comments
Feed Handling & Drying	$ 8,122,251	2.47	$ 20,061,960	Costs are escalated from 2002$ to 200
Gasification, Tar Reforming, & Quench	$ 7,219,779	2.47	$ 17,832,853	
Compression & Sulfur Removal	$ 6,704,080	2.47	$ 16,559,078	
Steam Methane Reforming, Shift, and PSA	$ 13,021,386	2.47	$ 32,162,824	
Hydrogen Compression	$ 1,117,347	2.47	$ 2,759,846	
Steam System and Power Generation	$ 6,188,382	2.47	$ 15,285,303	
Cooling Water and Other Utilities	$ 1,461,146	2.47	$ 3,609,030	
Buildings & Structures	$ 6,368,876	1.00	$ 6,368,876	
			$ -	
			$ -	
			$ -	
			$ -	
			$ -	
			$ -	
TOTALS	$ 50,203,246		$ 114,639,769	

Input_Sheet_Template Worksheet (Central Model Shown)



H2A Total Direct Capital Cost	$114,639,769
H2A Carbon Sequestration Total Direct Capital Cost	
Indirect Depreciable Capital Costs	
Site Preparation ($)	$1,146,398
Engineering & design ($)	$14,903,170
Process contingency ($)	
Project contingency ($)	$17,195,965
Other (Depreciable) capital ($)	
One-time Licensing Fees ($)	

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:

1) Set Baseline Plant Values (*Input_Sheet_Template* Worksheet & *H2A Toolkit*)
Baseline plant values are imported into the *Plant Scaling* worksheet from the *Input_Sheet_Template* worksheet, so the first step is to fill out the *Input_Sheet_Template* worksheet completely (see page 13). Once you have finished, open the *H2A Toolkit* (by clicking the *Toolkit* button at the top of the *Input_Sheet_Template* worksheet) and click the *Set up Plant Scaling* button. Clicking this button exports values from the *Input_Sheet_Template* worksheet into the *Plant Scaling* worksheet (the *Plant Scaling* worksheet tab appears when you click the button), specifically into the first cell (*Baseline Design Capacity*) in the *Plant Scaling Factors* section and the baseline value cells within the *Capital Investment* and *Plant Scaling Method* sections.

2) Establish Scaling Parameters (*Plant Scaling* Worksheet)
After you click the *Set up Plant Scaling* button and answer *OK* to the query, you are sent to the *Plant Scaling* worksheet, where you establish your scaling parameters. In the *Plant Scaling Factors* section, accept the *Default Scaling Factor Exponent* or enter a new one.

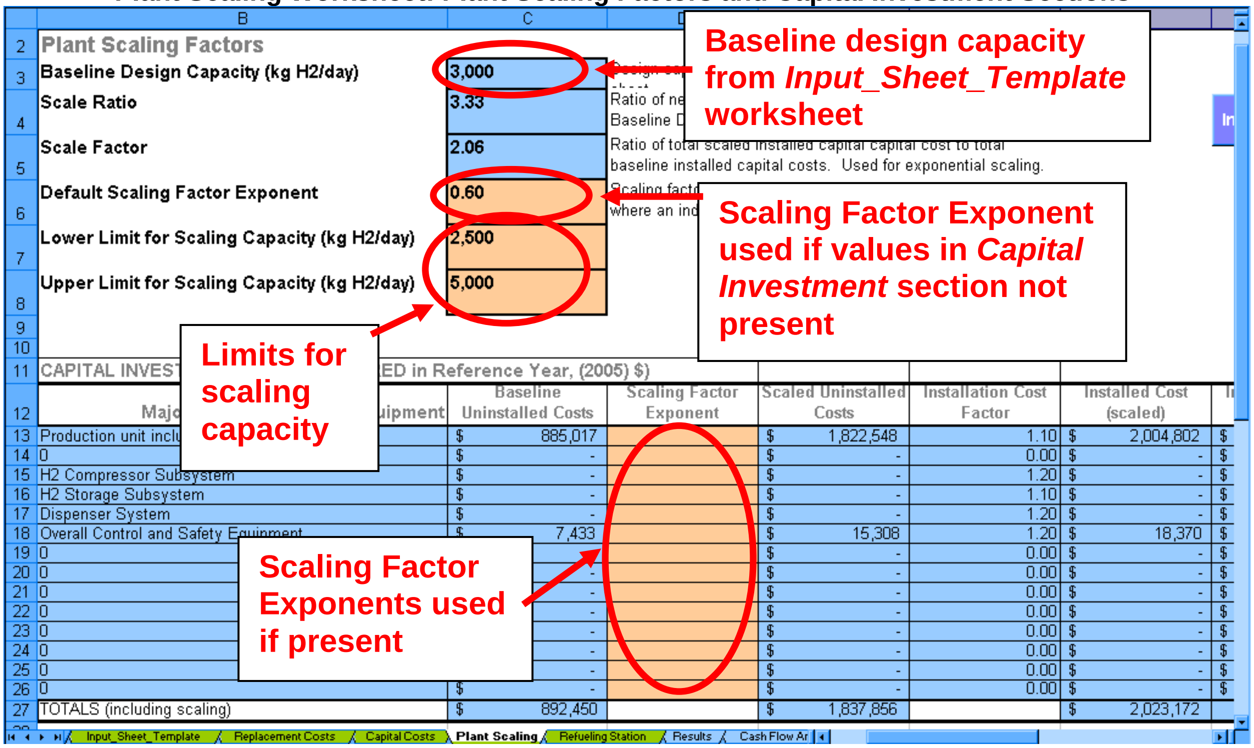
Changing the Scaling Factor Exponent changes how the cost of each item of capital equipment varies in relation to the Scale Ratio (the ratio of new design capacity to baseline design capacity) as follows:

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

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 when you click the *Calculate Cost* button (in step 3, see below) if you attempt to scale your plant capacity outside the range you specify.

Plant Scaling Worksheet: Plant Scaling Factors and Capital Investment Sections



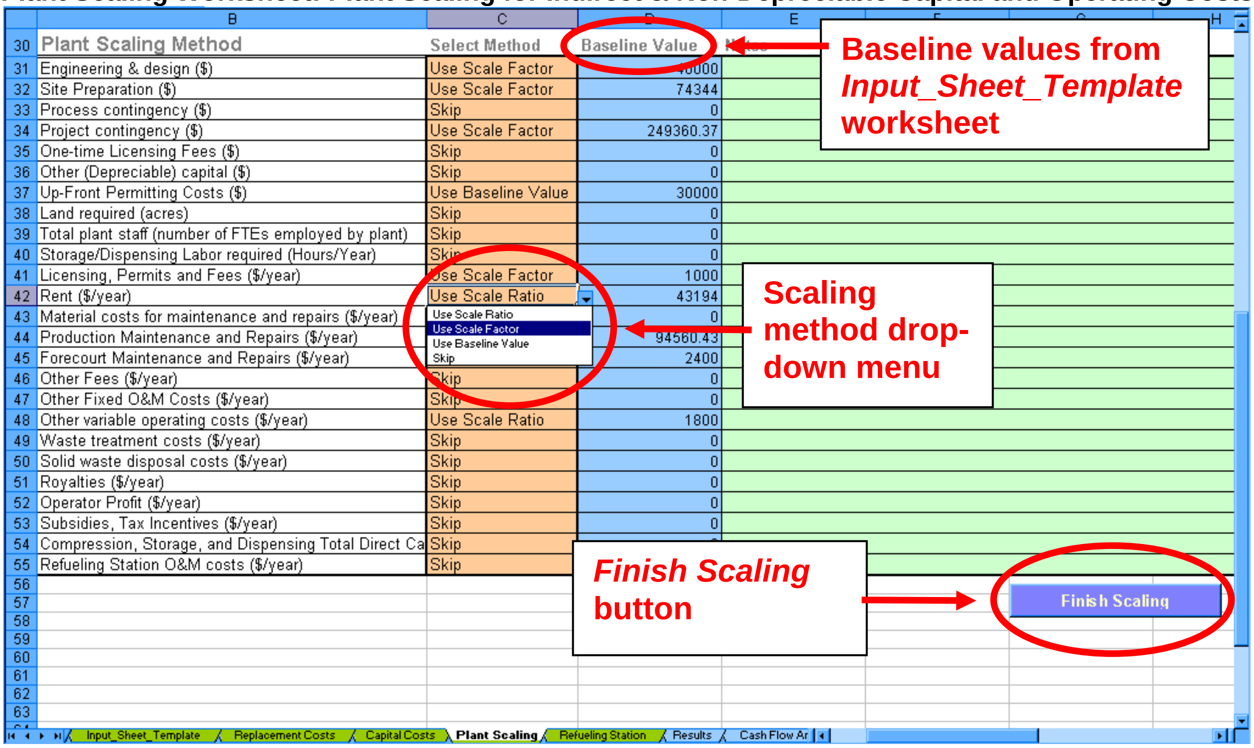
After you have added Scaling Factor Exponents to the *Plant Scaling Factors* and *Capital Investment* sections, go down to the next section to define scaling parameters for indirect and non-depreciable capital costs and operating costs. The baseline values for these items (Engineering & Design, Site Preparation, etc.) were imported from the *Input_Sheet_Template* worksheet. Note that, in the forecourt model, the variables used in the *Refueling Station* worksheet are scaled within that worksheet and, therefore, do not appear in the *Plant Scaling* worksheet.

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

Once you have selected scaling methods for all items, click the *Finish Scaling* button.

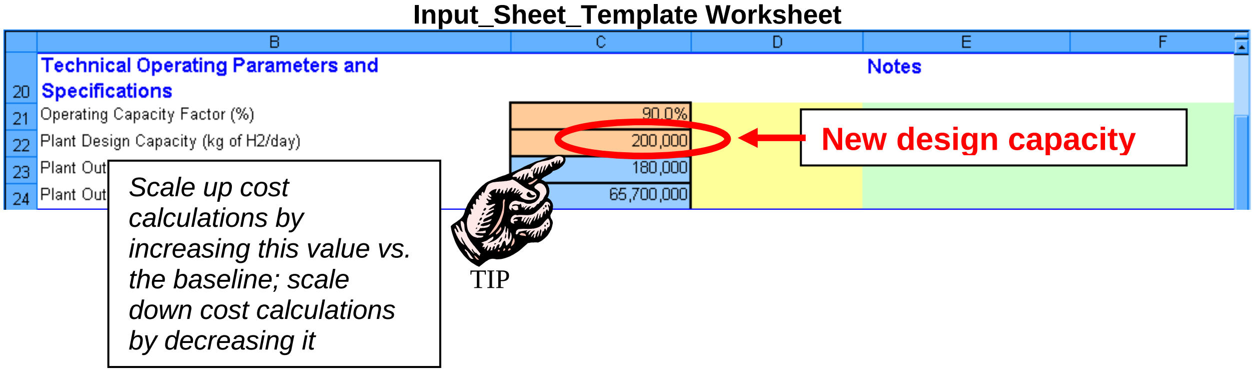
Plant Scaling Worksheet: Plant Scaling for Indirect & Non-Depreciable Capital and Operating Costs



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

After you click the *Finish Scaling* button, you are sent back to 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, 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). Click the *Calculate Cost* button to calculate the new hydrogen cost.

Input_Sheet_Template Worksheet



Turning Off Plant Scaling

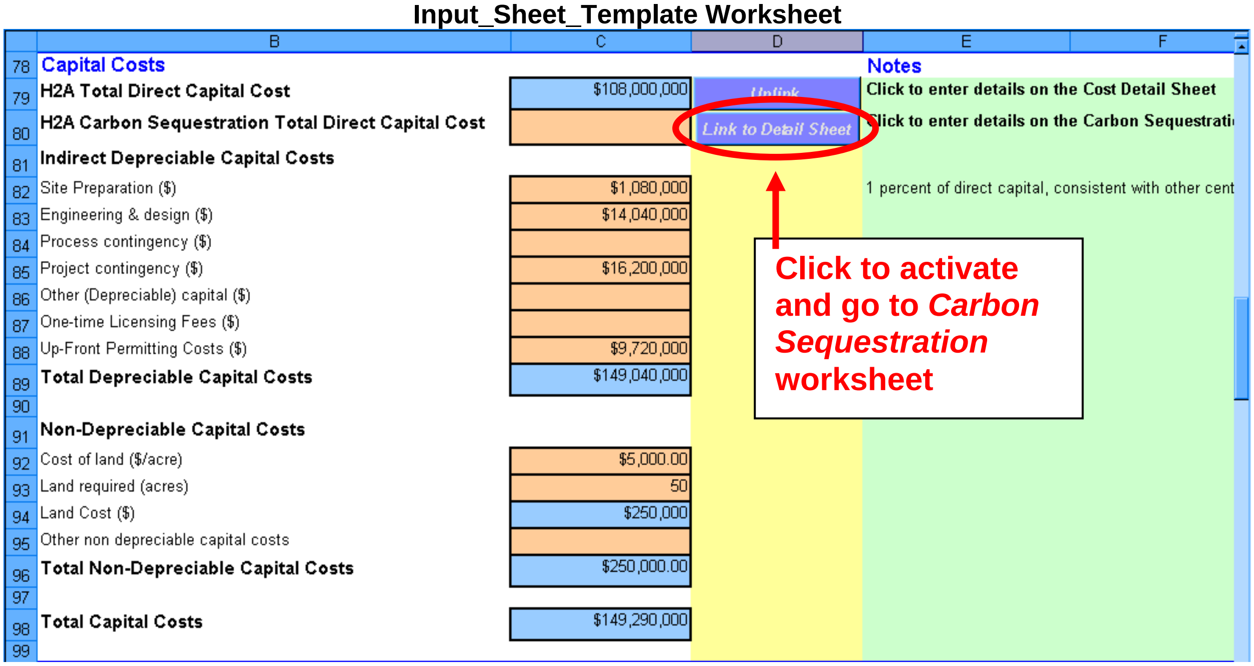
To turn off plant scaling, click the *Toolkit* button at the top of the *Input_Sheet_Template* worksheet, and click the *Turn Plant Scaling Off* button within the *H2A Toolkit*. Your plant characteristics will revert to the previously established baseline values.

Carbon Sequestration Worksheet (Central Model Only)

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 15). 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

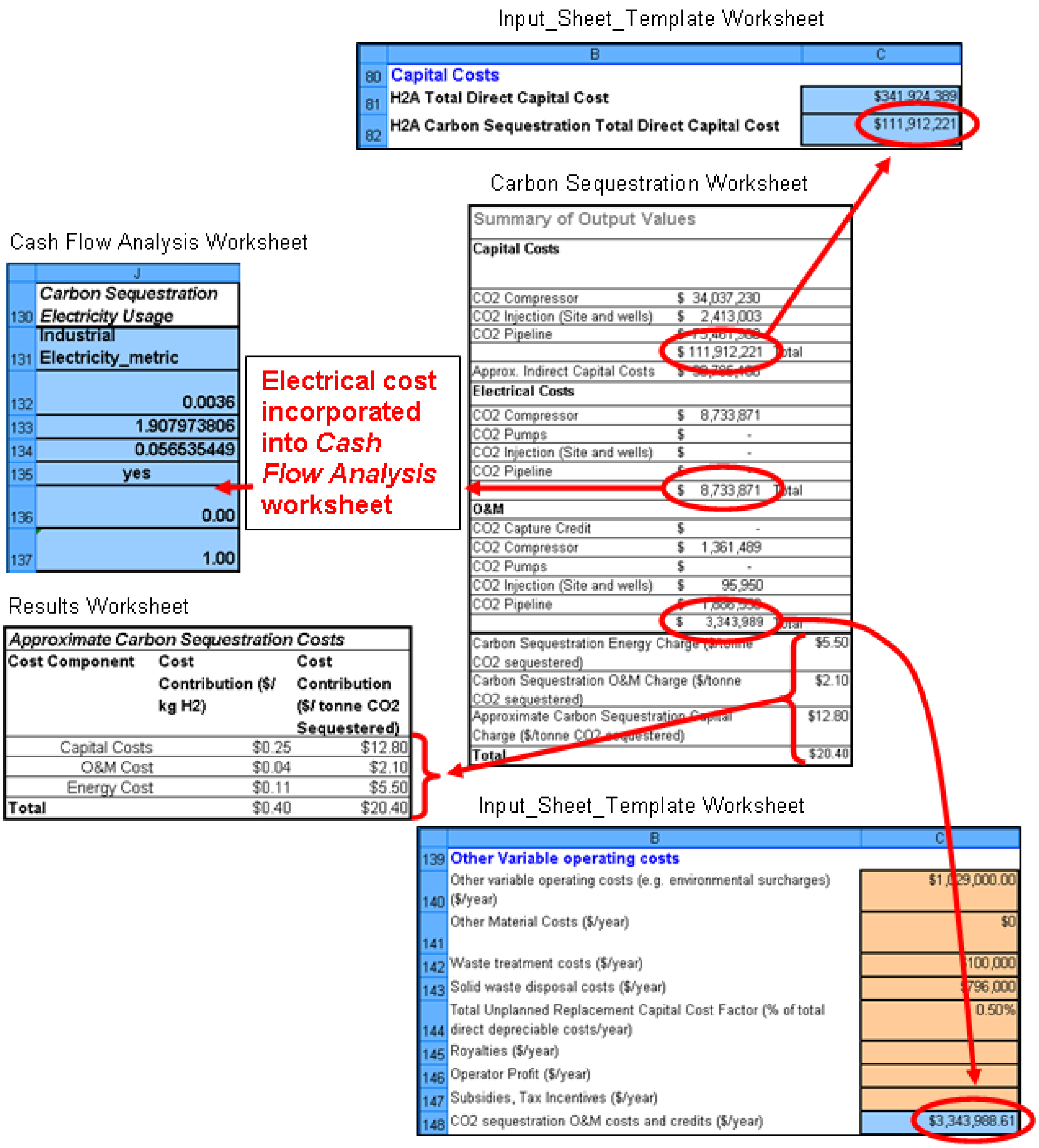


Clicking the *Link to Detail Sheet* button sends you to the *Carbon Sequestration* worksheet. At the top of the worksheet are notes, three self-explanatory buttons (see page 13 for a description of the *Use Default Values* functionality), and links to tables within the worksheet. Of the four tables, you will input values only into *Carbon Sequestration Input Values*; 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 sequestration direct capital cost and CO_2 sequestration operation and maintenance costs and credits within the *Input_Sheet_Template* worksheet as well as carbon sequestration 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 52) 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

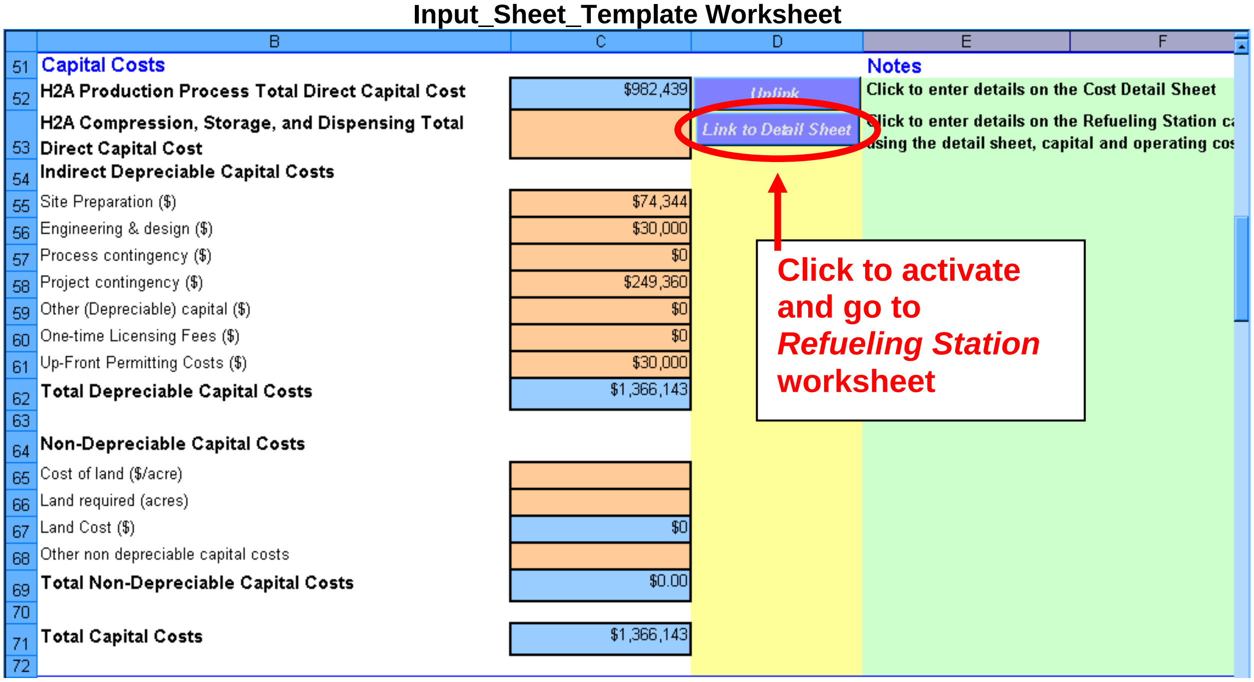


Refueling Station Worksheet (Forecourt Model Only)

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.

Activate the *Refueling Station* worksheet by clicking the *Link to Detail Sheet* button next to the *H2A Compression, Storage, and Dispensing Total Direct Capital Cost* field in the *Capital Costs* section of the *Input_Sheet_Template* worksheet (see screen capture below). When you have linked to the *Refueling Station* worksheet, the capital and operating costs for the model's cash flow analysis are calculated on that worksheet; thus, the corresponding fields within the *Capital Costs* and *Other Variable Operating Costs* sections of the *Input_Sheet_Template* worksheet show as zero.

Input_Sheet_Template Worksheet



Clicking the *Link to Detail Sheet* button sends you to the *Refueling Station* worksheet. At the top of the worksheet are notes, three self-explanatory buttons (see page 13 for a description of the *Use Default Values* functionality), and links to tables within the worksheet. The following six tables are designed to accept user inputs; complete or accept the default values for the orange-shaded fields:

- *Forecourt Specific Economic Assumptions*
- *Refueling Station Design Inputs*
- *Refueling Station Scenario Inputs*
- *CAPITAL INVESTMENT - Equipment Costs*
- *Other Compression, Storage, Dispensing Capital Costs*
- *Compression, Storage, Dispensing O&M Costs*

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 *Refueling Station* cost results (displayed in the *Calculation Outputs* table) are transferred to the *Results* worksheet—see the schematic below. The *Refueling Station* worksheet also provides the values needed to calculate energy use and emissions due to compression, storage, and dispensing.

See Appendix 2 (page 59) for more information about the refueling station inputs, outputs, and calculations used in this worksheet plus references for further reading.

Refueling Station Worksheet

Results - Cost Breakdown per kg H2	Compressor	Storage	Dispenser	Remainder of Station	Total
Gaseous Refueling Station Portion of the Delivered Real Levelized Hydrogen Cost (($2005)/kg of Hydrogen)	$0.84	$0.93	$0.03	$0.11	$1.93
Capital Cost Contribution to the Gaseous Refueling Station Portion of the Delivered Real Levelized Hydrogen Cost ($(2005)/kg of Hydrogen)	$0.50	$0.72	$0.03	$0.04	$1.29
Energy/Fuel Contribution to the Gaseous Refueling Station Portion of the Delivered Real Levelized Hydrogen Cost ($(2005)/kg of Hydrogen)	$0.16	$0.00	$0.00	$0.00	$0.16
Other Cost Contribution to the Gaseous Refueling Station Portion of the Delivered Real Levelized Hydrogen Cost ($(2005)/kg of Hydrogen)	$0.18	$0.21	$0.01	$0.07	$0.48
Results - Capital and Operating Costs	**Compressor**	**Storage**	**Dispenser**	**Remainder of Station**	**Total**
Total installed capital cost	$1,005,738	$2,050,294	$53,760	$203,249	$3,313,041
Yearly energy costs ($/y)					$73,679
Yearly operating costs excluding energy ($/y)					$220,622
Results - Other CSD Parameters					
CSD Mass Efficiency (H2 out/H2 in)	99.5%				
CSD System Energy Use (MJ/kg of H2 out)	7.083				
CSD System Energy Use (kWh/kg of H2 out)	1.967				
CSD System Energy Efficiency, LHV (%, H2 out/(H2 in + Energy/Fuel Use))	94.0%				
CSD labor requirement (FTE)	2.0				
Total Storage Volume (kg H2)	1741				
CSD Land Area (m^2)	1316				

Results Worksheet

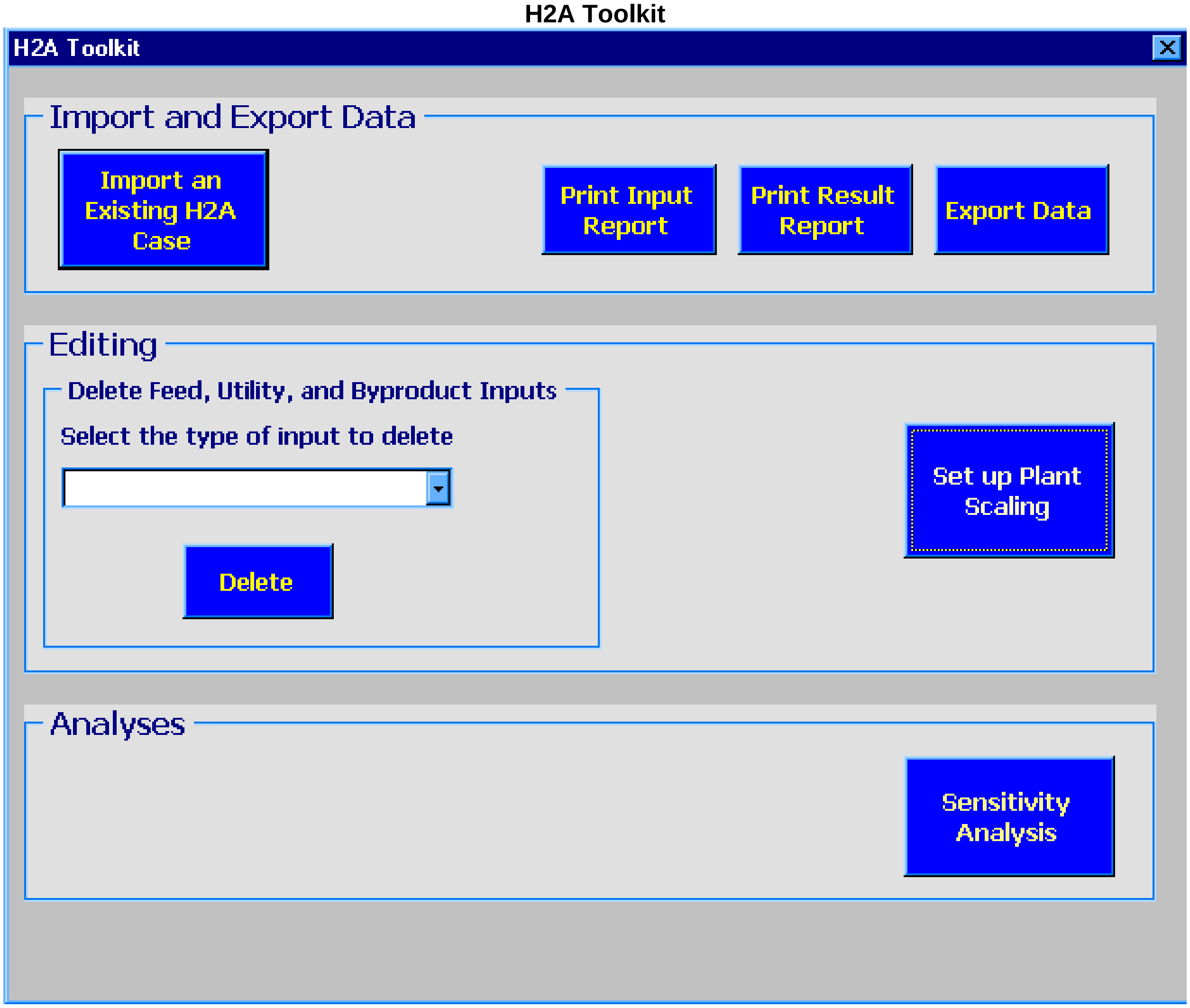
Specific Item Cost Calculation		*Total Cost of Delivered Hydrogen*	**$3.52**
Cost Component	**Hydrogen Production Cost Contribution ($/kg)**	**Compression, Storage, and Dispensing Cost Contribution ($/kg)***	**Percentage of H2 Cost**
Capital Costs	$0.315	$1.291	45.69%
Decommissioning Costs	$0.000		0.00%
Fixed O&M	$0.126	$0.475	17.11%
Feedstock Costs	$0.959		27.27%
Other Raw Material Costs	$0.000		0.00%
Byproduct Credits	$0.000		0.00%
Other Variable Costs (including utilities)	$0.190	$0.159	4.51%
Total	**$1.591**	**$1.925**	

H2A Toolkit

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

- Importing existing H2A cases
- Printing and exporting inputs and results
- Editing input parameters
- Setting up plant scaling
- Performing sensitivity analyses

H2A Toolkit



Importing Existing H2A Cases


CAUTION

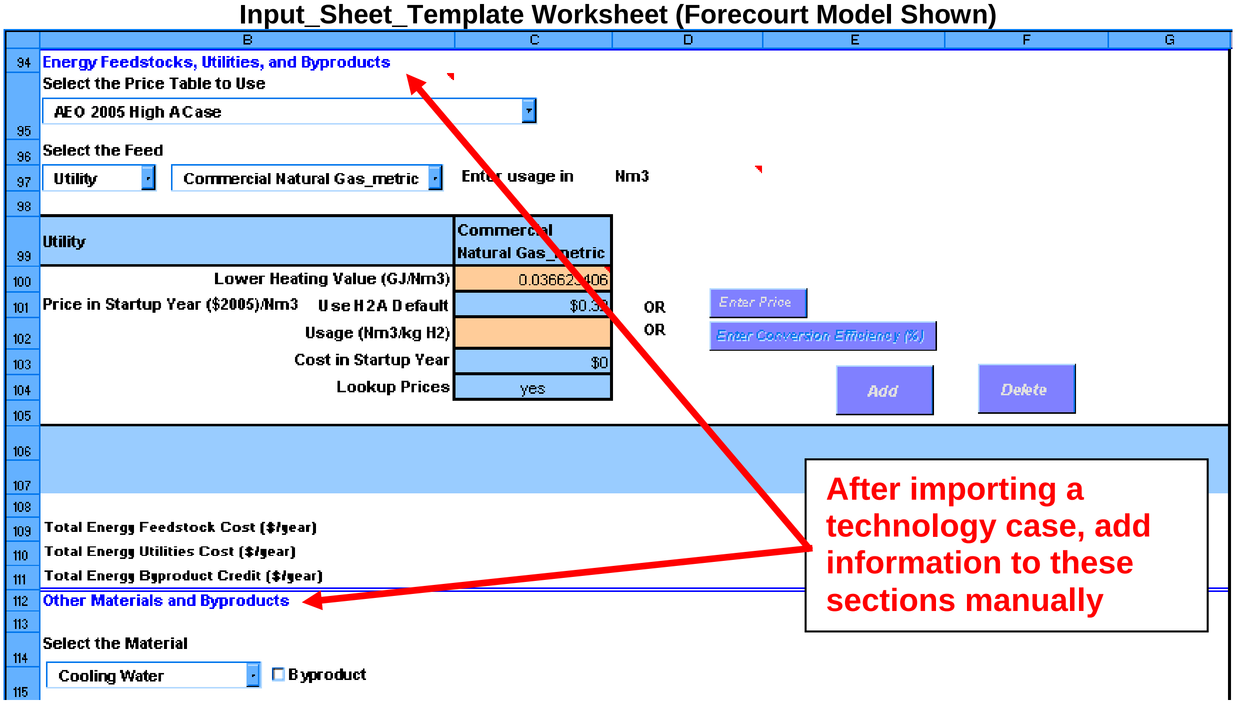
You can use the *H2A Toolkit* to import technology cases that are stored in previous versions of the H2A Model into the new version of the model. In the *Toolkit*, click the *Import an Existing H2A Case* button. A window will pop up, which states, "The values in the current case will be deleted." If you have any information in the current file that you want to save, click *Cancel* and save your file to a new name before proceeding. If your file does not need to be saved, click *OK*. Another window will pop up stating, "Data may exist in the sheet(s) selected for deletion. To permanently delete the data, press Delete." Instead of clicking the *Delete* button, click the *Cancel* button to proceed.

Click *OK* on the next pop-up to select a case to import. Use the *Browse* window that appears to locate the technology case you want to import. Select the case and click *OK*. Values from the technology case you selected are automatically imported into the new model. During importation, the case you are importing data from will open, and a window will pop up asking if you want to save changes to it. Click the *No* button to close the case.

The model imports data by searching the technology case for variables present in the *Import_Variable_List* within the *Lists* worksheet (see page 50 for more information about the *Lists* worksheet). The model does not always find the target variables in this way; once the case is imported, review the input fields and fill in missing values manually by referring to the old version of the technology case. Commonly missed values include *Reference Year* and several of the *Indirect Depreciable Capital Costs* within the *Input_Sheet_Template* worksheet and *Specified Yearly Replacement Costs* within the *Replacement Costs* worksheet. The detailed capital cost breakdown (*Capital Costs* worksheet) and information worksheets are not imported.

You must also manually add information to the *Energy Feedstocks, Utilities, and Byproducts* and *Other Materials and Byproducts* sections within the *Input_Sheet_Template* worksheet; the automatic importation function does not capture this information. The old version of the model draws from the same price tables that are available in the new version, so this is a relatively easy process. See *Energy Feedstocks, Utilities, and Byproducts* (page 15) and *Other Materials and Byproducts* (page 19) for instructions on adding information to these sections.

Input_Sheet_Template Worksheet (Forecourt Model Shown)



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. You could also use the *Importing an Existing Case* function (see page 30) to import the values into another H2A Production Model file.

Editing Input Parameters

Two functions are available within the *H2A Toolkit's Editing* section: *Delete Feed, Utility, and Byproduct Inputs* and *Set up Plant Scaling*.

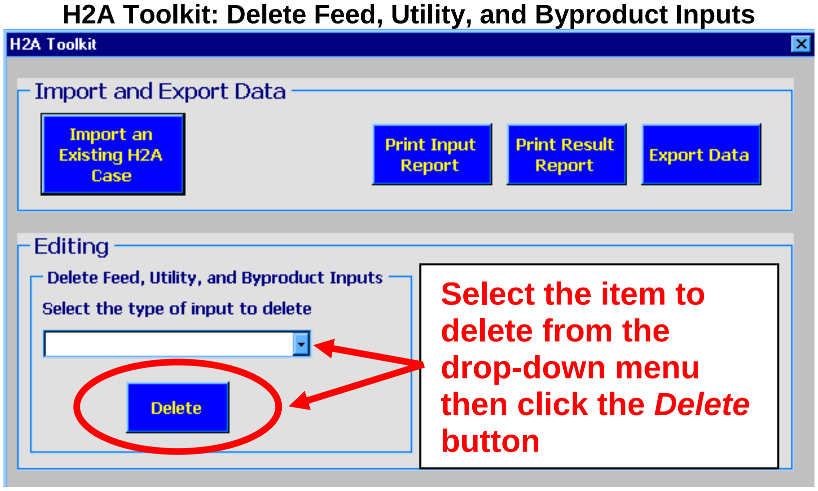
<u>Delete Feed, Utility, and Byproduct Inputs</u>

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 15 and 19). 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 <u>not</u> delete the corresponding rows within the *Input_Sheet_Template* worksheet using Excel's delete functionality. Also, be careful to choose the correct item from the *Delete* drop-down menu. <u>All</u> 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



Set up Plant Scaling

The *H2A Toolkit's Set up Plant Scaling* button is part of the process that scales your capital and operating costs to smaller or larger plant sizes. Do not click this button except as part of the scaling process. See *Plant Scaling Worksheet* (page 23) for details.

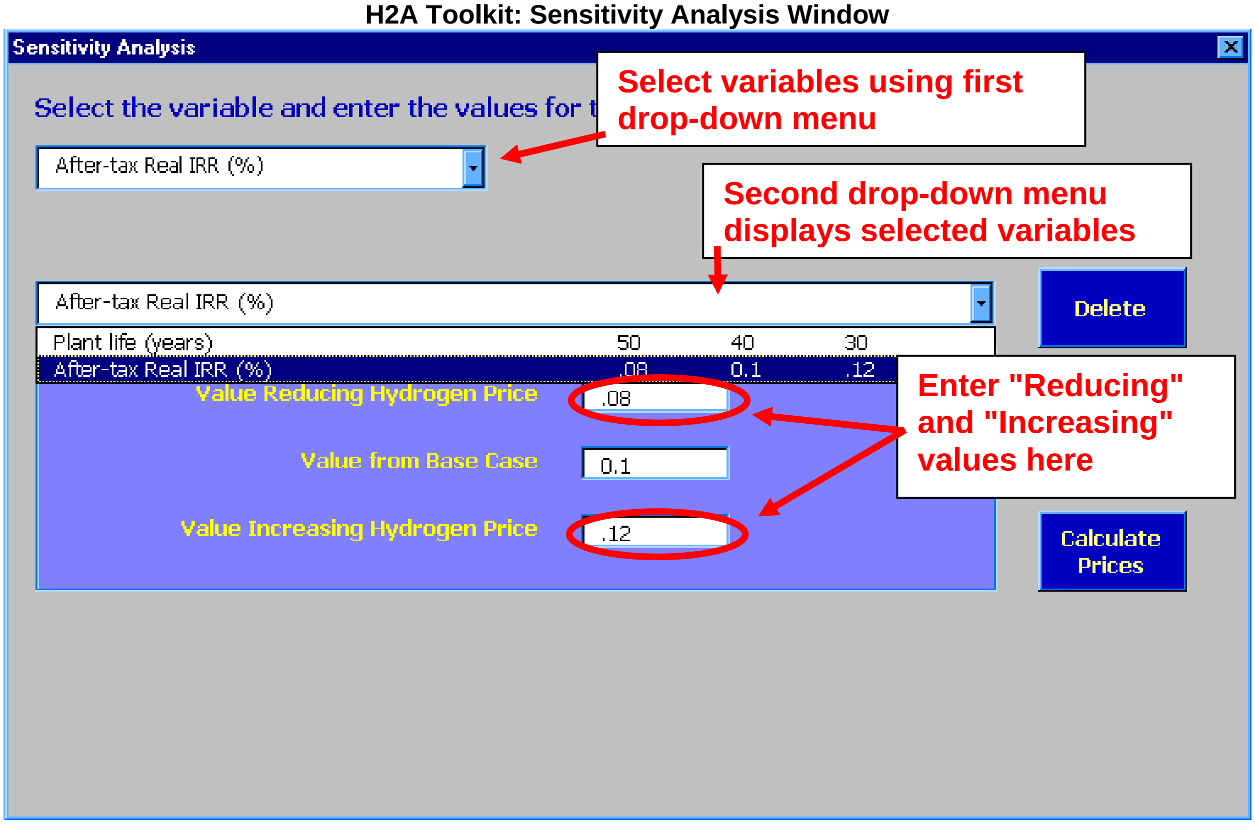
Performing Sensitivity Analyses

To perform a sensitivity analysis—which helps you understand how sensitive the cost of hydrogen is to changes in key input variables—click the *Sensitivity Analysis* button in the *H2A Toolkit*. In the *Sensitivity Analysis* window, use the first drop-down menu to select a variable you will use for the analysis (only variables that have a value in the base case will appear in the drop-down menu); simply highlighting the variable selects it and adds it to the second drop-down menu. With your variable now shown in the first line of the second drop-down menu, its value from the current case is displayed in the *Value from Base Case* field. Enter a value for *Value Reducing Hydrogen Price* and a value for *Value Increasing Hydrogen Price*. For example, for *After-tax Real IRR* with a base case value of 0.1, you might enter 0.08 for the *Value Reducing Hydrogen Price* and 0.12 for the *Value Increasing Hydrogen Price* (see screen capture below). Repeat this process for up to 50 variables.

> *It's not always obvious what will reduce vs. increase hydrogen price; if you get bad results (e.g., a blank tornado chart), switch your "Reducing" & "Increasing" values and try again.*

TIP

H2A Toolkit: Sensitivity Analysis Window



To delete a variable from the analysis, select the variable in the second drop-down menu and click the *Delete* button. Click *Yes* in the pop-up window that asks if you want to delete the variable. Remember, variables are added simply by highlighting them in the first drop-down menu, so check the second drop-down menu and delete unwanted variables before running your analysis. Also, make sure that three values are entered for each variable you do want to analyze.

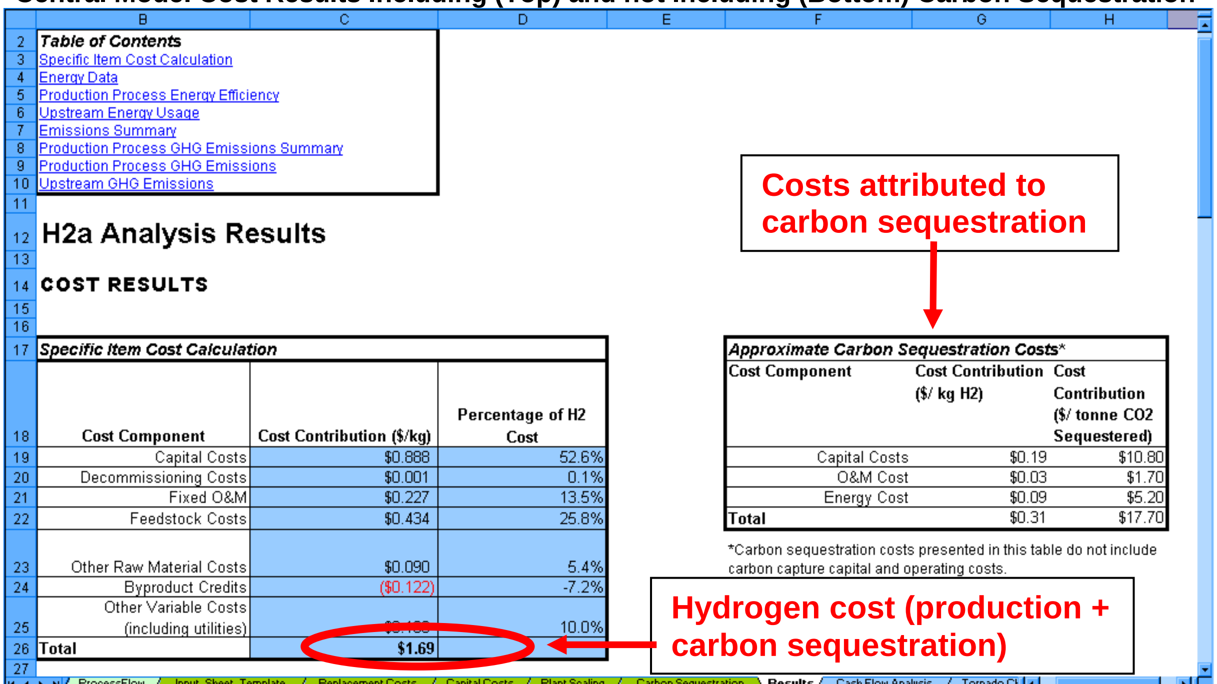
Once you are satisfied with the variables you have selected and the "Reducing" and "Increasing" values you have entered, click the *Calculate Prices* button. A pop-up window will state, "Data may exist in the sheet(s) selected for deletion. To permanently delete the data, press Delete." Click the *Delete* button. Next, close the *Sensitivity Analysis* window and *H2A Toolkit*. You are now in the *Sensitivity Analysis* worksheet (see page 40), where you see how much the minimum hydrogen selling price varies when your "Reducing" and "Increasing" values are entered into the model while holding all other variables constant at their base values. To the left of the *Sensitivity Analysis* tab is the *Tornado Chart* tab. The *Tornado Chart* worksheet shows the results of the sensitivity analysis graphically (see page 39).

If there were values in the *Sensitivity Analysis* and *Tornado Chart* worksheets before you performed your sensitivity analysis, they will be overwritten with your new results. Each time you perform a sensitivity analysis, the values in these worksheets are overwritten with the new values, so you can only have one set of values and one valid tornado chart at a time. If you want to create multiple sensitivity analyses/tornado charts, perform your first analysis then save your Excel file under a new name, perform your second analysis then save this file under a different name, and so forth.

Results Worksheet

The *Results* worksheet tabulates the results of your H2A Model analysis. No user input is required within this worksheet. You are sent here after you click the *Calculate Cost* button in the *Input_Sheet_Template* worksheet. The hydrogen cost results are in the *Specific Item Cost Calculation* table at the top (see screen captures below). Note that, 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.

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



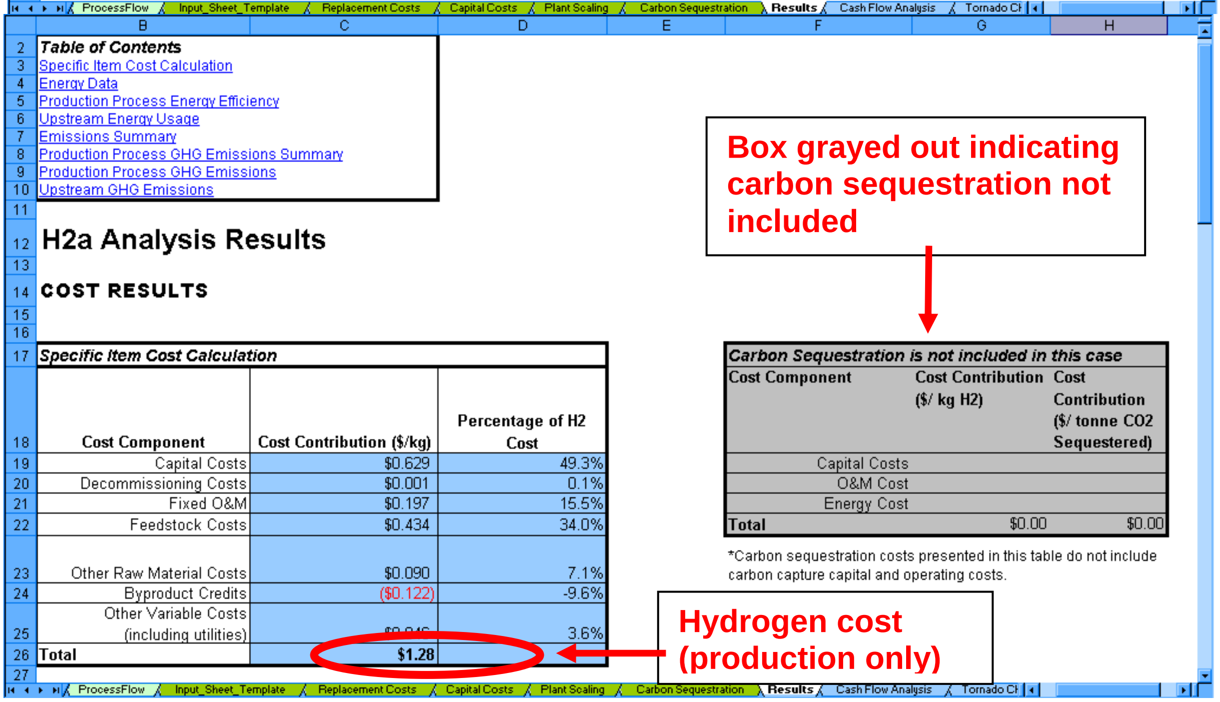
Specific Item Cost Calculation

Cost Component	Cost Contribution ($/kg)	Percentage of H2 Cost
Capital Costs	$0.888	52.6%
Decommissioning Costs	$0.001	0.1%
Fixed O&M	$0.227	13.5%
Feedstock Costs	$0.434	25.8%
Other Raw Material Costs	$0.090	5.4%
Byproduct Credits	($0.122)	-7.2%
Other Variable Costs (including utilities)	[illegible]	10.0%
Total	$1.69	

Approximate Carbon Sequestration Costs*

Cost Component	Cost Contribution ($/ kg H2)	Cost Contribution ($/ tonne CO2 Sequestered)
Capital Costs	$0.19	$10.80
O&M Cost	$0.03	$1.70
Energy Cost	$0.09	$5.20
Total	$0.31	$17.70

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



Specific Item Cost Calculation

Cost Component	Cost Contribution ($/kg)	Percentage of H2 Cost
Capital Costs	$0.629	49.3%
Decommissioning Costs	$0.001	0.1%
Fixed O&M	$0.197	15.5%
Feedstock Costs	$0.434	34.0%
Other Raw Material Costs	$0.090	7.1%
Byproduct Credits	($0.122)	-9.6%
Other Variable Costs (including utilities)	[illegible]	3.6%
Total	$1.28	

Carbon Sequestration is not included in this case

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

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

Forecourt Model Cost Results

Table of Contents

H2a Analysis Results

COST RESULTS

Hydrogen cost (production + compression, storage, and dispensing)

Specific Item Cost Calculation		*Total Cost of Delivered Hydrogen*	$3.68
Cost Component	**Hydrogen Production Cost Contribution ($/kg)**	**Compression, Storage, and Dispensing Cost Contribution ($/kg)***	**Percentage of H2 Cost**
Capital Costs	$0.616	$1.172	48.63%
Decommissioning Costs	$0.000		0.00%
Fixed O&M	$0.390	$0.501	24.24%
Feedstock Costs	$0.766		20.84%
Other Raw Material Costs	$0.000		0.00%
Byproduct Credits	($0.020)		0.00%
Other Variable Costs (including utilities)	$0.088	$0.164	4.45%
Total	**$1.839**	**$1.836**	

* Results will be shown in this column only if the detail Refueling Station calculation sheet is used.

The remaining tables show energy and emissions results. The *Energy Data* table summarizes the energy inputs in the form of feedstocks, utilities, carbon sequestration (for the central model), and compression, storage, and dispensing (for the forecourt model). It also summarizes the energy outputs in the form of hydrogen and byproducts. The *Production Process Energy Efficiency* (for the central model) and *Facility Energy Efficiency* (for the forecourt model) tables show 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, ethanol production, 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, version 1.7. 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/software/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	M	N
62	TABLE A - Energy Feedstock and Utility Properties Table			Done				
63	Feedstock Type	Source	Source Year (for original price data)	H2a Reference Year	Units for Feedstock Price Table	CO2 Emissions Factor (kg CO2 produced/GJ or mmBtu feed)	CH4 Emissions Factor (kg CH4 produced/GJ or mmBtu feed)	N2O Emissions Factor (kg N2O produced/GJ or mmBtu feed)
64	Commercial Natural Gas_metric	AEO 2007 projections to 2030, Feb 2007	2005	[illegible]	[illegible]	56.32		
65	Industrial Natural Gas_metric	AEO 2007 projections to 2030, Feb 2007	200			56.32		
66	Electric Utility Natural Gas_metric	AEO 2007 projections to 2030, Feb 2007	200			56.32		
67	Commercial Electricity_metric	AEO 2007 projections to 2030, Feb 2007	200			0.00		
68	Industrial Electricity_metric	AEO 2007 projections to 2030, Feb 2007	2005	2005	$(2005)/GJ	0.00		
69	Electric Utility Steam Coal_metric	AEO 2007 projections to 2030, Feb 2007	2005	2005	$(2005)/GJ LHV	102.75		
70	Retail Diesel_metric	AEO 2007 projections to 2030, Feb 2007	2005	2005	$(2005)/GJ LHV	74.12		
71	E85 Ethanol_metric	AEO 2007 projections to 2030, Feb 2007	2005	2005	$(2005)/GJ LHV	71.02		
72	Retail Gasoline_metric	AEO 2007 projections to 2030, Feb 2007	2005	2005	$(2005)/GJ LHV	72.83		
73	Woody Biomass_metric	EIA AEO 2004 unpublished data received via personal communication with Zia Haq, EIA	2002	2005	$(2005)/GJ	97.88		
74	Steam_metric	Note: when steam is an important input or output, the price should be externally provided and should be based on the specific characteristics of the steam needed or	2005	2005	$(2005)/GJ	0.00		
	Commercial Natural Gas		2005	2005	$(2005)/mmBtu	59.41		

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, version 1.7. The GREET Model is continually being updated; for the most accurate upstream emissions results, download and use the most recent GREET version at www.transportation.anl.gov/software/GREET.

Results Worksheet, Upstream GHG Emissions Table

	B	C	D	E	F	G
104	*Upstream GHG Emissions (kg/kg H2)*					
105	Feedstock	CO2	CH4	N2O	Total GHG (CO2 eq)	
106	Industrial Natural Gas_metric	1.759	3.61E-02	2.82E-05	2.599	
107						
108						
109						
110	Utility					
111	Commercial Electricity_metric	1.666	2.34E-03	2.58E-05	1.728	
112						
113						
114						
115	Compression, Storage and Dispensing					
116	Commercial Electricity_metric	1.445	2.03E-03	2.24E-05	1.499	
117	TOTAL	4.871	4.05E-02	7.65E-05	5.825	

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 35). 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

Cash Flow Analysis Worksheet

	A	B	C	D	E	F
1						
2	**TABLE OF CONTENTS**					
3	DCF Calculations					
4	Yearly Cash Flow Calculations					
5	Specific Item Cost Calculation					
6	Feedstock, Utility, and Byproduct Cost Information					
7						
8						
9						
10						
11						
12						
13						
14						
15	***DCF CALCULATION INPUTS:***			***DCF CALCULATION OUTPUTS:***		
16	**Process**			**Hydrogen Cost (Year 2005 Real $/kg)**	**$1.627**	
17	Actual Hydrogen Produced (kg/yr)	50,994,963		Hydrogen Cost (Start-up Year Nominal $/kg)	$1.627	
18	Actual Hydrogen Energy Produced (MMBtu(LHV)/yr)	5,799,667		After Tax Real IRR	10.0%	
19	Actual Hydrogen Energy Produced (MJ(LHV)/yr)	6,118,648,852		Pre Tax Real IRR	13.6%	
20	Design Capacity (kg/day)	155,236		After Tax Nominal IRR	12.1%	

Title / Description / ProcessFlow / Input_Sheet_Template / Replacement Costs / Capital Costs / Carbon Sequestration / Results / **Cash Flow Analysis** / Tornado Chart

Tornado Chart Worksheet

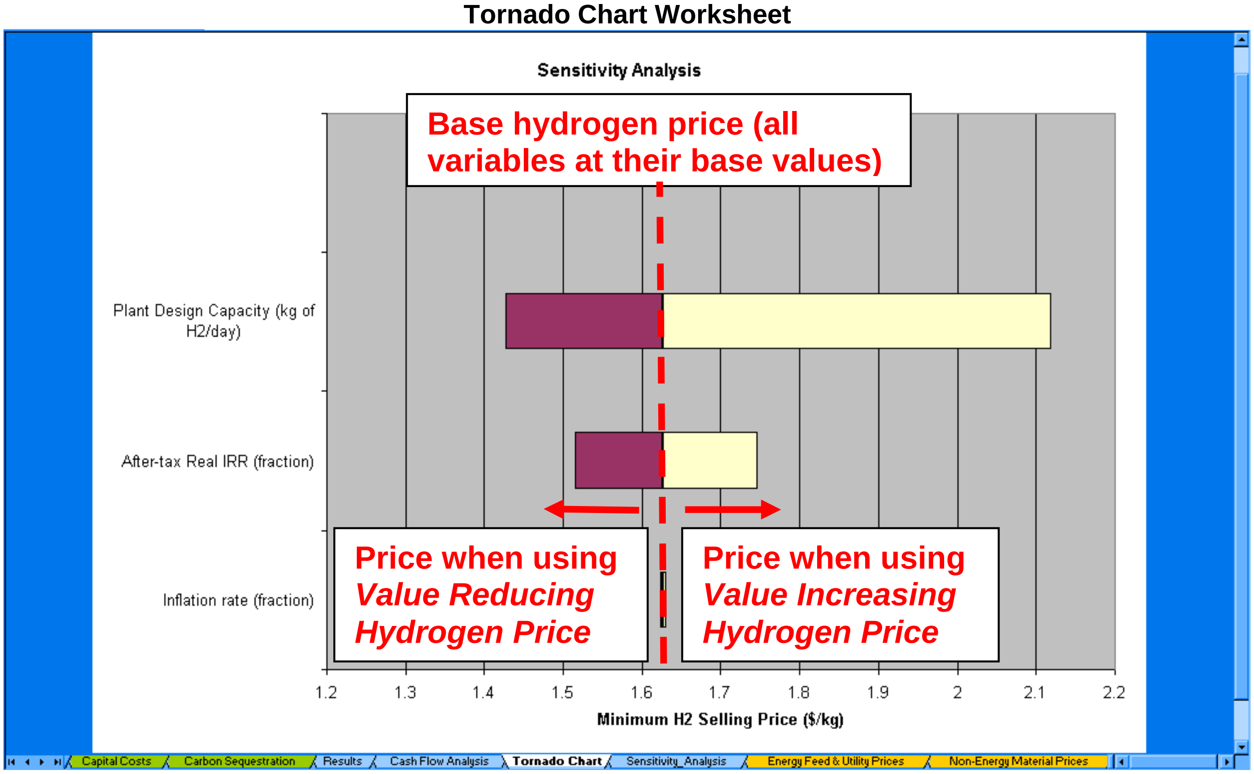
The *Tornado Chart* worksheet shows sensitivity analysis results graphically; see page 33 for information about performing sensitivity analyses and page 40 for the *Sensitivity_Analysis* worksheet, which shows the results numerically. The bars within the tornado chart show the range of minimum hydrogen selling price values obtained by entering—for each specified variable—a base value, a "reducing" value (i.e., a value that reduces the hydrogen price), and an "increasing" value (i.e., a value that increases the hydrogen price) while holding all other variables constant at their base values. No user input is required within this worksheet.

> *Unless you are using an H2A technology case that has a default tornado chart, the Tornado Chart tab will not appear until you perform your first sensitivity analysis.*

TIP

For established H2A production technology cases, a default sensitivity analysis/tornado chart is 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.

Tornado Chart Worksheet



Sensitivity_Analysis Worksheet

The *Sensitivity_Analysis* worksheet shows sensitivity analysis results numerically; see page 33 for information about performing sensitivity analyses and page 39 for the *Tornado Chart* worksheet, which shows the results graphically.

The worksheet's columns show the range of minimum hydrogen selling price values obtained by entering—for each specified variable—a nominal (i.e., base) value, a lower value (i.e., a value that reduces the hydrogen price), and an upper value (i.e., a value that increases the hydrogen price) while holding all other variables constant at their base values. The columns at the far right show the difference in price between the lower-value and upper-value hydrogen prices and the nominal-value price.

It is best not to modify anything directly within this worksheet. Use the *H2A Toolkit's* sensitivity analysis function (page 33) to make changes.

Sensitivity_Analysis Worksheet

	A	B	C	D	E	F	G	H	I	J
1		Lower value		Nominal value		Upper value				
2	**Variable Name**	**Value**	**Minimum H2 Selling Price ($/kg)**	**Value**	**Minimum H2 Selling Price ($/kg)**	**Value**	**Minimum H2 Selling Price ($/kg)**	**Lower Difference**	**Upper Difference**	
3	Labor Requirement (FTE)	35	1.7309	54	1.781	70	1.8231	0.0501	0.0421	
4	Operating Capacity Factor (fraction)	0.95	1.7341	0.9	1.781	0.8	1.8923	0.0469	0.1113	
5	Total Capital Investment	119431999	1.6751	149290000	1.781	194076999	1.9398	0.1059	0.1588	
6	Feedstock Woody Biomass_metric U:	10.542	1.6159	13.638	1.781	16.938	1.9569	0.1651	0.1759	
7	Feedstock Woody Biomass_metric Pr	0.033	1.5271	0.05070626	1.781	0.066	2.0003	0.2539	0.2193	
8								0	0	
9								0	0	
10								0	0	
11								0	0	
12								0	0	
13								0	0	
14								0	0	
15								0	0	
16								0	0	
17								0	0	
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22								0	0	
23								0	0	
24								0	0	
25								0	0	
26								0	0	
27								0	0	
28								0	0	
29								0	0	
30								0	0	
31								0	0	
32								0	0	

Replacement Costs / Capital Costs / Carbon Sequestration / Results / Cash Flow Analysis / Tornado Chart / **Sensitivity_Analysis** / Energy Feed & Utility Prices / Non

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 15). It contains three pairs of tables, which list projected prices in $2005 for 11 energy inputs/byproducts through the year 2070:

- *AEO 2007 Energy Prices* & *AEO 2007 Energy Prices Common Units*
- *AEO Reference Case 2005* & *AEO Reference Case 2005 Common Units*
- *AEO 2005 High A Case* & *AEO 2005 High A Case Common Units*

The *AEO 2005 High A Case* is the default for all established H2A production technology cases.

The raw prices used to make these tables, through the year 2025 (for AEO Reference Case 2005 and AEO 2005 High A Case) and 2030 (for AEO 2007 Energy Prices), were drawn from the EIA Annual Energy Outlook (AEO). The year 2026/2031–2070 prices were projected using Pacific Northwest National Laboratory's (PNNL's) Mini-CAM model. See *AEO Data Worksheet* (page 44) for more information.

You can add your own energy feedstocks, utilities, byproducts, and prices to the tables in the *Energy Feed & Utility Prices* worksheet. Complete the following steps (illustrated in the screen captures below):

1) In the table of your choice (i.e., any table but a "common units" table), scroll down to the orange-shaded rows labeled *User Defined Feed 1*, *User Defined Feed 2*, etc. in the *Feedstock Type* column. Overwrite one of these *User Defined Feed* labels with a name for your first item (feedstock, utility, or byproduct). Do not use special characters (such as parentheses) in the name. Fill in price values for each year in the reference year $/unit shown; you can change the unit, but it must be either $/GJ LHV or $/mmBtu LHV. Repeat the process for up to five more items (two user-defined feeds in each table).

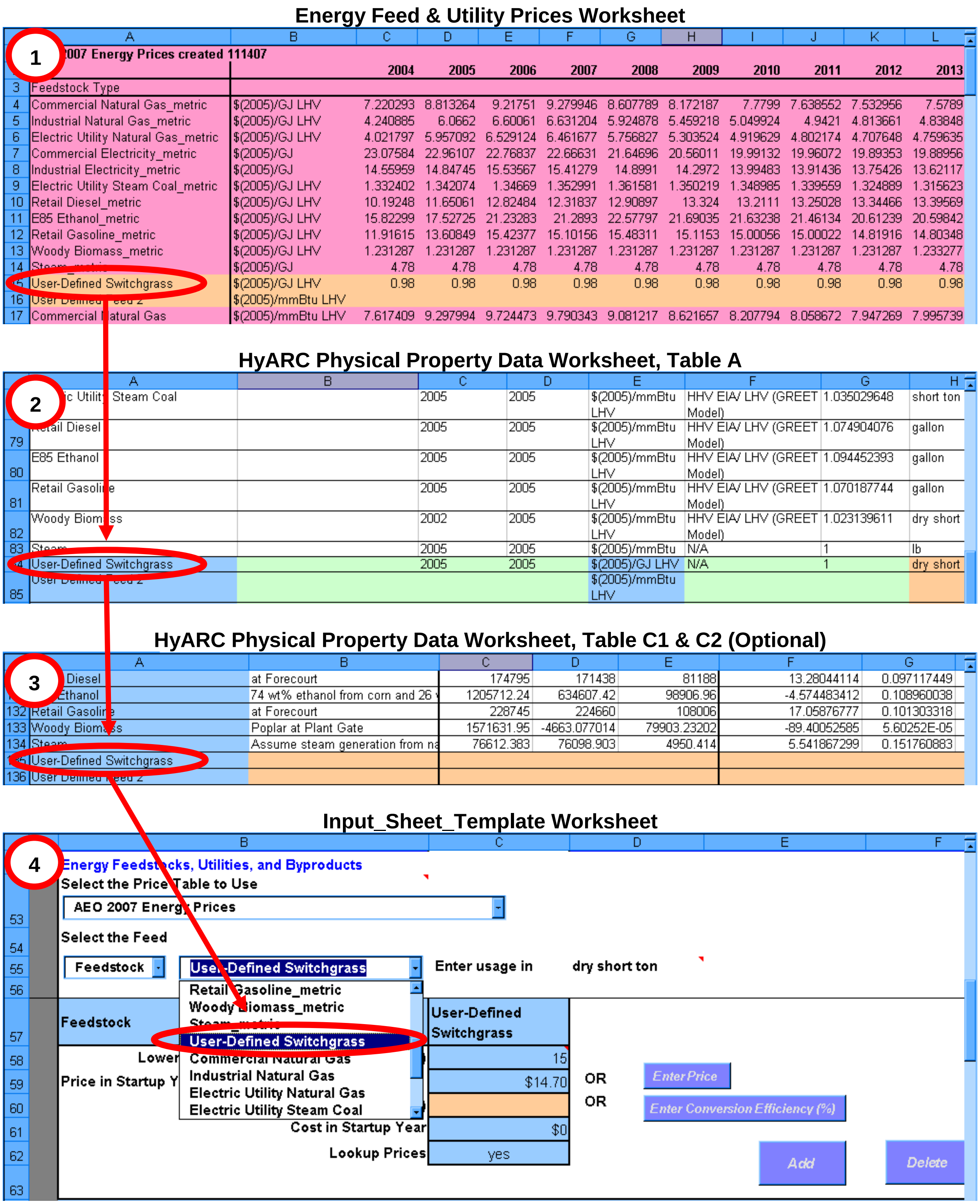
2) Go to the *HyARC Physical Property Data* worksheet, *Table A*. Your new item's name and units will appear automatically near the bottom of the table. Complete all orange-shaded cells for your new item. In the *List* column, select from the drop-down menu.

3) Optional step: If you want to add upstream energy and emissions values for your item, enter them next to the item's name near the bottom of *Table C1* (for startup years 2005–2019) and *C2* (for startup years 2020 and beyond).

4) Within the *Input_Sheet_Template* worksheet, "refresh" the *Energy Feedstocks, Utilities, and Byproducts* section by selecting another price table from the first drop-down menu then selecting the table in which your new item was added. Your new item will now appear as part of that table; find it using the two drop-down menus under the heading *Select the Feed*.

If your item does not appear, go back to the HyARC Physical Property Data worksheet, Table A, and make sure the item has values in every required column.

TIP



Energy Feed & Utility Prices Worksheet

	A	B	C	D	E	F	G	H	I	J	K	L
1	007 Energy Prices created 111407		2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
3	Feedstock Type											
4	Commercial Natural Gas_metric	$(2005)/GJ LHV	7.220293	8.813264	9.21751	9.279946	8.607789	8.172187	7.7799	7.638552	7.532956	7.5789
5	Industrial Natural Gas_metric	$(2005)/GJ LHV	4.240885	6.0662	6.60061	6.631204	5.924878	5.459218	5.049924	4.9421	4.813661	4.83848
6	Electric Utility Natural Gas_metric	$(2005)/GJ LHV	4.021797	5.957092	6.529124	6.461677	5.756827	5.303524	4.919629	4.802174	4.707648	4.759635
7	Commercial Electricity_metric	$(2005)/GJ	23.07584	22.96107	22.76837	22.66631	21.64696	20.56011	19.99132	19.96072	19.89353	19.88956
8	Industrial Electricity_metric	$(2005)/GJ	14.55959	14.84745	15.53567	15.41279	14.8991	14.2972	13.99483	13.91436	13.75426	13.62117
9	Electric Utility Steam Coal_metric	$(2005)/GJ LHV	1.332402	1.342074	1.34669	1.352991	1.361581	1.350219	1.348985	1.339559	1.324889	1.315623
10	Retail Diesel_metric	$(2005)/GJ LHV	10.19248	11.65061	12.82484	12.31837	12.90897	13.324	13.2111	13.25028	13.34466	13.39569
11	E85 Ethanol_metric	$(2005)/GJ LHV	15.82299	17.52725	21.23283	21.2893	22.57797	21.69035	21.63238	21.46134	20.61239	20.59842
12	Retail Gasoline_metric	$(2005)/GJ LHV	11.91615	13.60849	15.42377	15.10156	15.48311	15.1153	15.00056	15.00022	14.81916	14.80348
13	Woody Biomass_metric	$(2005)/GJ LHV	1.231287	1.231287	1.231287	1.231287	1.231287	1.231287	1.231287	1.231287	1.231287	1.233277
14	Steam_metric	$(2005)/GJ	4.78	4.78	4.78	4.78	4.78	4.78	4.78	4.78	4.78	4.78
15	User-Defined Switchgrass	$(2005)/GJ LHV	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98
16	User Defined Feed 2	$(2005)/mmBtu LHV										
17	Commercial Natural Gas	$(2005)/mmBtu LHV	7.617409	9.297994	9.724473	9.790343	9.081217	8.621657	8.207794	8.058672	7.947269	7.995739

HyARC Physical Property Data Worksheet, Table A

	A	B	C	D	E	F	G	H
	Electric Utility Steam Coal		2005	2005	$(2005)/mmBtu LHV	HHV EIA/ LHV (GREET Model)	1.035029648	short ton
79	Retail Diesel		2005	2005	$(2005)/mmBtu LHV	HHV EIA/ LHV (GREET Model)	1.074904076	gallon
80	E85 Ethanol		2005	2005	$(2005)/mmBtu LHV	HHV EIA/ LHV (GREET Model)	1.094452393	gallon
81	Retail Gasoline		2005	2005	$(2005)/mmBtu LHV	HHV EIA/ LHV (GREET Model)	1.070187744	gallon
82	Woody Biomass		2002	2005	$(2005)/mmBtu LHV	HHV EIA/ LHV (GREET Model)	1.023139611	dry short
83	Steam		2005	2005	$(2005)/mmBtu	N/A	1	lb
84	User-Defined Switchgrass		2005	2005	$(2005)/GJ LHV	N/A	1	dry short
85	User Defined Feed 2				$(2005)/mmBtu LHV			

HyARC Physical Property Data Worksheet, Table C1 & C2 (Optional)

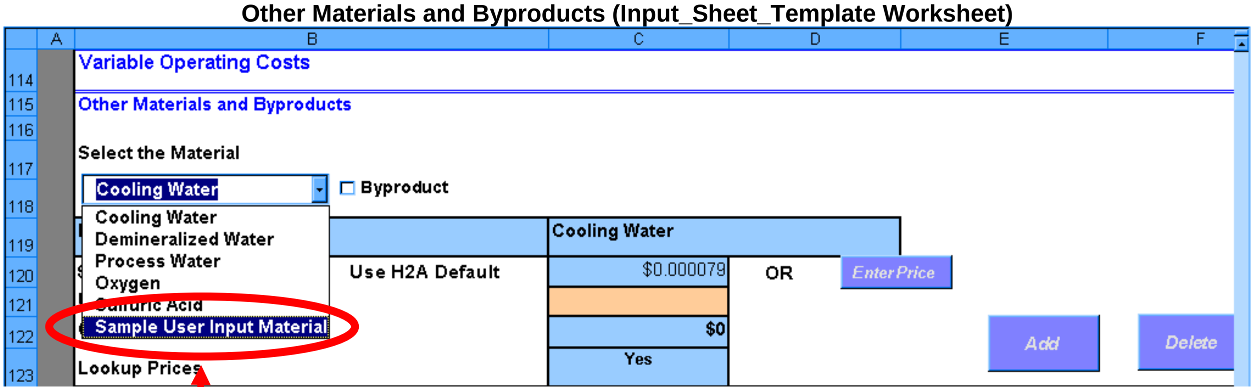
	A	B	C	D	E	F	G
	Retail Diesel	at Forecourt	174795	171438	81188	13.28044114	0.097117449
	E85 Ethanol	74 wt% ethanol from corn and 26	1205712.24	634607.42	98906.96	-4.574483412	0.108960038
132	Retail Gasoline	at Forecourt	228745	224660	108006	17.05876777	0.101303318
133	Woody Biomass	Poplar at Plant Gate	1571631.95	-4663.077014	79903.23202	-89.40052585	5.60252E-05
134	Steam	Assume steam generation from na	76612.383	76098.903	4950.414	5.541867299	0.151760883
135	User-Defined Switchgrass						
136	User Defined Feed 2						

Input_Sheet_Template Worksheet

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 19). 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	2001	2002	2003	2004	2005	2006	2007	2008
Cooling Water	$(2005)/gal	0.000079485	7.9485E-05	7.949E-05	7.949E-05	7.949E-05	7.95E-05	7.949E-05	7.949E-05
Demineralized Water	$(2005)/gal	0.0049962	0.0049962	0.0049962	0.0049962	0.0049962	0.004996	0.0049962	0.0049962
Process Water	$(2005)/gal	0.0016654	0.0016654	0.0016654	0.0016654	0.0016654	0.001665	0.0016654	0.0016654
Oxygen	$(2005)/kg	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Sulfuric Acid	$(2005)/kg	0	0	0	0	0	0	0	0
Sample User Input Material	$(2005)/kg	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.025

Items entered into the *Non-Energy Material Prices* worksheet are added automatically to the *Other Materials and Byproducts* drop-down menu in the *Input_Sheet_Template* worksheet

AEO Data Worksheet

The data in the *AEO Data* worksheet are the source of the energy price tables in the *Energy Feed & Utility Prices* worksheet (page 41). For typical users, no actions are required or recommended within this worksheet. The worksheet contains four tables:

- AEO 2007 Energy Prices
  - Based on report no. DOE/EIA-0383(2007), Table 3, *Energy Prices by Sector and Source*, release date full report February 2007
  - Prices given in $(2005)/mmBTU
- AEO Reference Case 2005
  - Based on report no. DOE/EIA-0383(2005), Table 3, *Energy Prices by Sector and Source*, release date full report January 2005
  - Prices given in $(2003)/mmBTU
- AEO 2005 High A Case
  - AEO 2005 Reference Case modified for high projected oil prices
  - Details in *Market Drivers*, www.eia.doe.gov/oiaf/archive/aeo05/index.html
  - Prices given in $(2003)/mmBTU
  - Default case for all H2A production technology cases.
- Price Ratios from PNNL Mini Climate Assessment Model (Mini-CAM)
  - Details at www.pnl.gov/gtsp/research/minicam.stm

The first three tables contain EIA AEO data and projections through year 2030 and projections for years 2031–2070 extrapolated using the AEO projections and Mini-CAM Model results.

AEO Data Worksheet

	A	B	C	D	E	F	G	H	I	J	
1	AEO 2007 Report #: DOE/EIA-0383(2007)										
2	Release date full report: February 2007										
3	Next release date full report: February 2008										
4											
5	Table 3. Energy Prices by Sector and Source										
6	(2005 dollars per million Btu, unless otherwise noted)										
7											
8											
9											
10				2004	2005	2006	2007	2008	2009	2010	2011
11											
12											
13	Residential										
14	Liquefied Petroleum Gases			18.2104111	19.293371	21.158409	24.540438	24.49481	23.960043	23.672392	23.2
15	Distillate Fuel Oil			12.8933477	14.727064	16.906725	17.448505	16.91049	15.836798	14.874867	14.0
16	Natural Gas			10.721179	12.428177	13.040691	11.834162	11.74102	11.250778	10.975987	10.5
17	Electricity			27.0989685	27.587885	27.636595	27.492031	27.36811	27.154861	26.912786	26.5
18	Commercial										
19	Distillate Fuel Oil			10.4802904	12.679383	14.632154	15.323599	14.43847	13.450114	12.718927	11.9
20	Residual Fuel Oil			6.24901056	8.4144115	10.100347	7.8816242	7.797915	7.6790781	7.5374599	7.06
21	Natural Gas			9.40245628	11.20282	11.378678	10.268854	10.15759	9.6297474	9.3356886	8.92
22	Electricity			24.5915394	25.251781	25.738388	25.337698	25.26854	24.918291	24.500483	23.8
23	Industrial 1/										
24	Liquefied Petroleum Gases			11.1755381	16.959982	18.957874	17.513134	17.38941	16.750248	16.423851	15.9
25	Distillate Fuel Oil			10.9898891	13.081453	15.140741	15.435568	14.29198	13.4233	12.948052	12.4
26	Residual Fuel Oil			5.77388954	7.7708011	9.3422022	9.8767166	10.08419	9.7906637	9.5023155	8.77
27	Natural Gas 2/			6.46885538	8.1627741	7.4494205	7.363225	7.290155	6.7422004	6.4267693	6.02
28	Metallurgical Coal			2.30784726	3.0599997	3.254849	3.2975256	3.287283	3.1889374	3.0940959	2.9
29	Other Industrial Coal			1.80300605	2.1500018	2.2005796	2.239264	2.245091	2.2358458	2.2614977	2.24
30	Coal to Liquids			N/A	N/A	N/A	N/A	N/A	N/A	N/A	0.88
31	Electricity			15.8847752	16.691057	18.258221	18.768579	18.85383	18.518166	18.014034	17.
32	Transportation										
33	Liquefied Petroleum Gases 3/			19.6766357	23.916117	26.805565	22.710955	22.75907	22.268847	24.343836	23.9

Sensitivity_Analysis / Energy Feed & Utility Prices / Non-Energy Material Prices / AEO Data / HyARC Physical Property Data / Debt Financing Calculations / Depreciatio

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*, *C1*, and *C2* contain fields designed to accept user input.

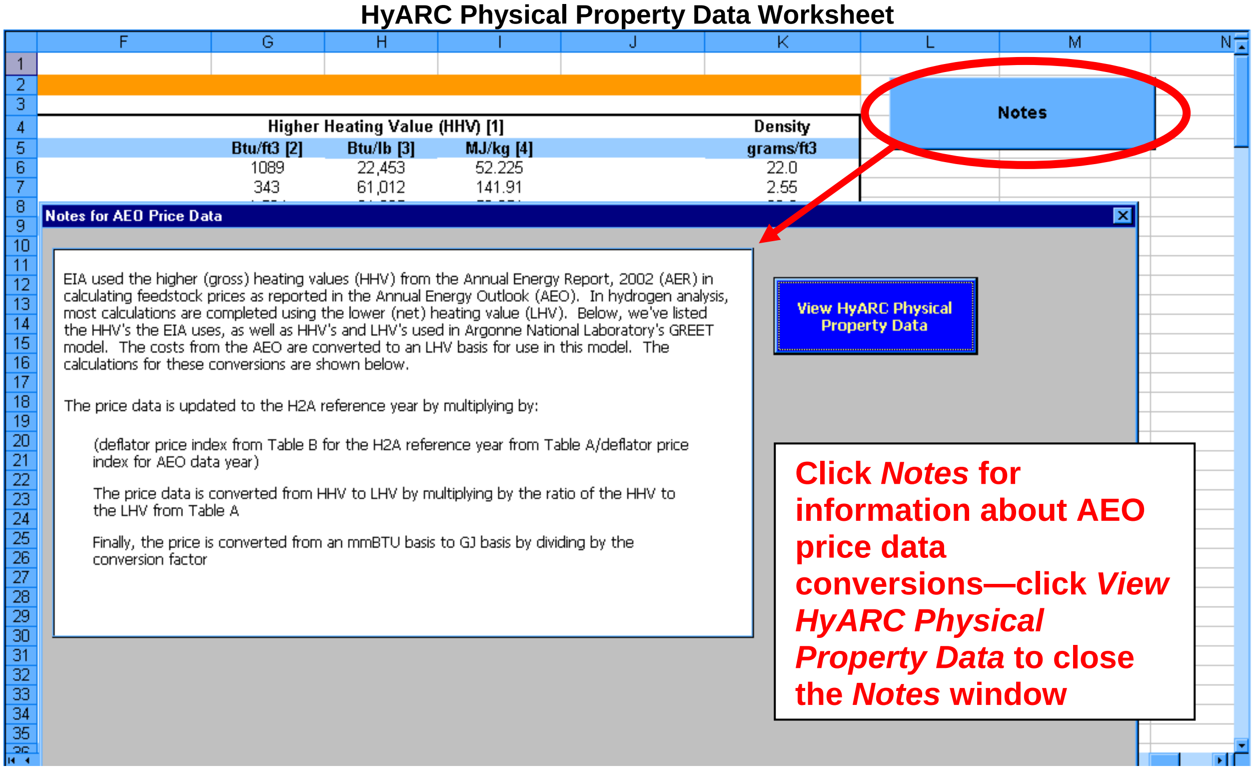
Advanced users only

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 16). You can also add new energy feedstocks, utilities, and byproducts to *Table A* using the *User Defined Feeds* within the *Energy Feed & Utility Prices* worksheet. See page 41 to learn how. 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 years 2005–2019. *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 35). See page 41 to learn how to enter values for user-defined energy feedstocks and utilities. 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.

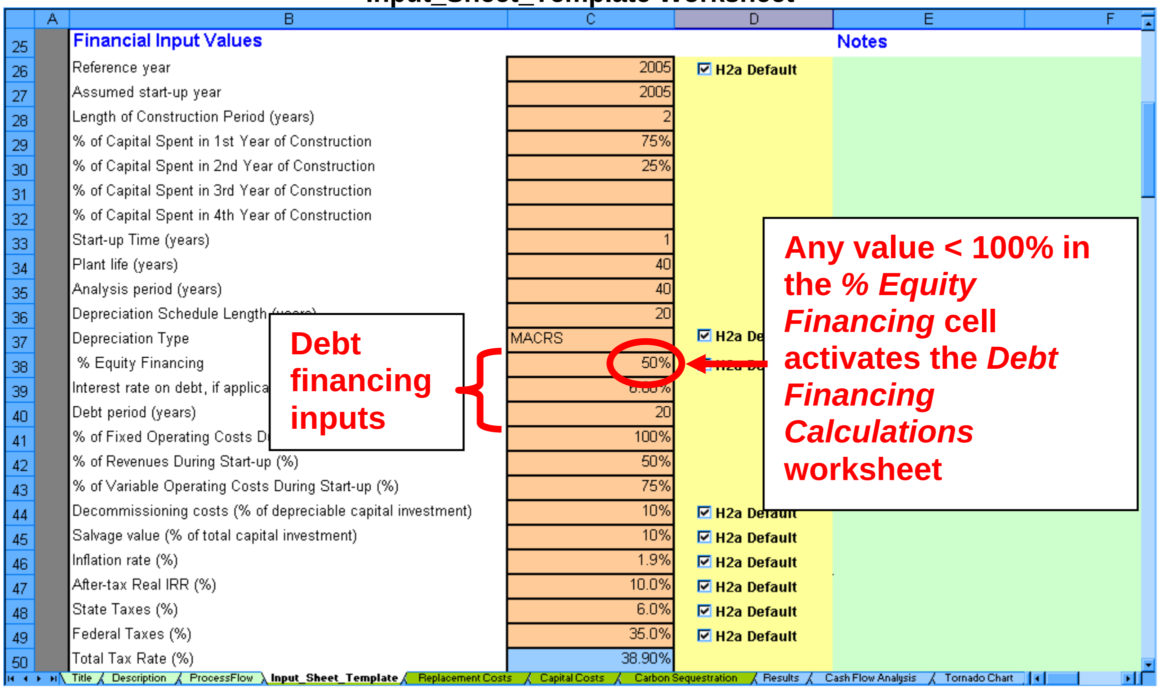
U.S. Department of Energy Hydrogen Program. *Hydrogen Delivery Component Model*. Version released 11/21/07. Washington, DC: U.S. Department of Energy.

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 1.7.

Debt Financing Calculations Worksheet

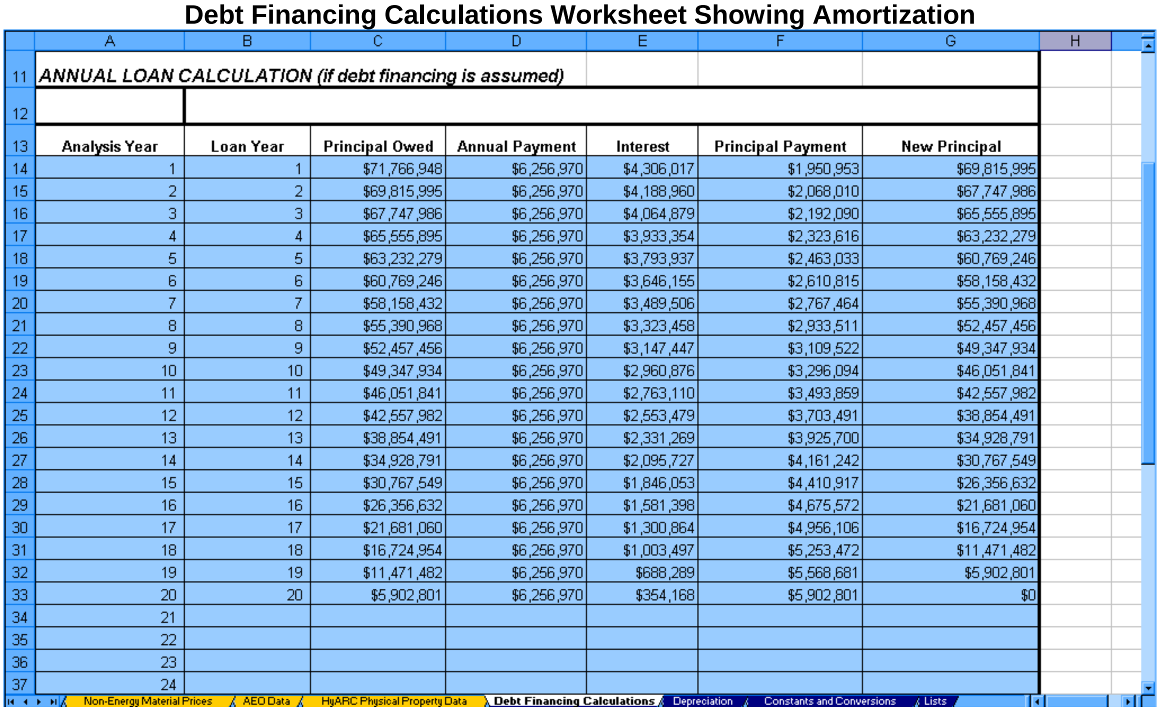
If debt financing is selected on the *Input_Sheet_Template* worksheet, the *Debt Financing Calculations* worksheet amortizes the loan. The results are used in the H2A Model's cash flow analysis (see page 38). No user input is required within this worksheet.

Input_Sheet_Template Worksheet



	Financial Input Values		Notes
26	Reference year	2005	☑ H2a Default
27	Assumed start-up year	2005	
28	Length of Construction Period (years)	2	
29	% of Capital Spent in 1st Year of Construction	75%	
30	% of Capital Spent in 2nd Year of Construction	25%	
31	% of Capital Spent in 3rd Year of Construction		
32	% of Capital Spent in 4th Year of Construction		
33	Start-up Time (years)	1	
34	Plant life (years)	40	
35	Analysis period (years)	40	
36	Depreciation Schedule Length (years)	20	
37	Depreciation Type	MACRS	☑ H2a De
38	% Equity Financing	50%	
39	Interest rate on debt, if applica	[illegible]	
40	Debt period (years)	20	
41	% of Fixed Operating Costs D	100%	
42	% of Revenues During Start-up (%)	50%	
43	% of Variable Operating Costs During Start-up (%)	75%	
44	Decommissioning costs (% of depreciable capital investment)	10%	☑ H2a Default
45	Salvage value (% of total capital investment)	10%	☑ H2a Default
46	Inflation rate (%)	1.9%	☑ H2a Default
47	After-tax Real IRR (%)	10.0%	☑ H2a Default
48	State Taxes (%)	6.0%	☑ H2a Default
49	Federal Taxes (%)	35.0%	☑ H2a Default
50	Total Tax Rate (%)	38.90%	

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
1	1	$71,766,948	$6,256,970	$4,306,017	$1,950,953	$69,815,995
2	2	$69,815,995	$6,256,970	$4,188,960	$2,068,010	$67,747,986
3	3	$67,747,986	$6,256,970	$4,064,879	$2,192,090	$65,555,895
4	4	$65,555,895	$6,256,970	$3,933,354	$2,323,616	$63,232,279
5	5	$63,232,279	$6,256,970	$3,793,937	$2,463,033	$60,769,246
6	6	$60,769,246	$6,256,970	$3,646,155	$2,610,815	$58,158,432
7	7	$58,158,432	$6,256,970	$3,489,506	$2,767,464	$55,390,968
8	8	$55,390,968	$6,256,970	$3,323,458	$2,933,511	$52,457,456
9	9	$52,457,456	$6,256,970	$3,147,447	$3,109,522	$49,347,934
10	10	$49,347,934	$6,256,970	$2,960,876	$3,296,094	$46,051,841
11	11	$46,051,841	$6,256,970	$2,763,110	$3,493,859	$42,557,982
12	12	$42,557,982	$6,256,970	$2,553,479	$3,703,491	$38,854,491
13	13	$38,854,491	$6,256,970	$2,331,269	$3,925,700	$34,928,791
14	14	$34,928,791	$6,256,970	$2,095,727	$4,161,242	$30,767,549
15	15	$30,767,549	$6,256,970	$1,846,053	$4,410,917	$26,356,632
16	16	$26,356,632	$6,256,970	$1,581,398	$4,675,572	$21,681,060
17	17	$21,681,060	$6,256,970	$1,300,864	$4,956,106	$16,724,954
18	18	$16,724,954	$6,256,970	$1,003,497	$5,253,472	$11,471,482
19	19	$11,471,482	$6,256,970	$688,289	$5,568,681	$5,902,801
20	20	$5,902,801	$6,256,970	$354,168	$5,902,801	$0
21						
22						
23						
24						

Depreciation Worksheet

This worksheet calculates depreciation for use in the H2A Model's cash flow analysis (see page 38). No user input is required within this worksheet.

Input_Sheet_Template Worksheet

Financial Input Values			Notes
Reference year	2005	☑ H2a Default	
Assumed start-up year	2005		
Length of Construction Period (years)	2		
% of Capital Spent in 1st Year of Construction	75%		
% of Capital Spent in 2nd Year of Construction	25%		
% of Capital Spent in 3rd Year of Construction			
% of Capital Spent in 4th Year of Construction			
Start-up Time (years)	1		
Plant life (years)	40		
Analysis period (years)	40		
Depreciation Schedule Length (years)	20		
Depreciation Type	MACRS	☑ H2a Default	
% Equity Financing	100%	☑ H2a Default	
Interest rate on debt, if applicable (%)			
Debt period (years)			
% of Fixed Operating Costs During Start-up (%)	100%		
% of Revenues During Start-up (%)	50%		
% of Variable Operating Costs During Start-up (%)	75%		
Decommissioning costs (% of depreciable capital investment)	10%	☑ H2a Default	
Salvage value (% of total capital investment)	10%	☑ H2a Default	
Inflation rate (%)	1.9%	☑ H2a Default	
After-tax Real IRR (%)	10.0%	☑ H2a Default	
State Taxes (%)	6.0%	☑ H2a Default	
Federal Taxes (%)	35.0%	☑ H2a Default	
Total Tax Rate (%)	38.90%		

Depreciation inputs

Title / Description / ProcessFlow / Input_Sheet_Template / Replacement Costs / Capital Costs / Carbon Sequestration / Results / Cash Flow Analysis / Tornado Chart

Depreciation Worksheet

Inputs from Cash-Input Sheet	
Depreciation Type	MACRS
Depreciation Period (yrs)	20
Total Initial Depreciable Capital	$144,215,682

Values imported from *Input_Sheet_Template* worksheet

DEPRECIATION CALCULATION TABLE

Operation Year	Annual Depreciable Capital	1	2	3	4	5	6
-2	$0	$0	$0	$0	$0	$0	$0
-1	$144,215,682	$5,408,088	$10,410,930	$9,629,281	$8,908,203	$8,239,042	$7,621,799
1	$745,200	$27,945	$53,796	$49,757	$46,031	$42,573	$39,384
2	$759,359	$28,476	$54,818	$50,702	$46,906	$43,382	$40,132
3	$773,787	$29,017	$55,860	$51,666	$47,797	$44,206	$40,895
4	$788,489	$29,568	$56,921	$52,647	$48,705	$45,046	$41,672
5	$803,470	$30,130	$58,002	$53,648	$49,630	$45,902	$42,463
6	$818,736	$30,703	$59,105	$54,667	$50,573	$46,774	$43,270
7	$834,292	$31,286	$60,228	$55,706	$51,534	$47,663	$44,092
8	$850,143	$31,880	$61,372	$56,764	$52,513	$48,569	$44,930
9	$866,296	$32,486	$62,538	$57,843	$53,511	$49,491	$45,784
10	$882,756	$33,103	$63,726	$58,942	$54,528	$50,432	$46,654
11	$899,528	$33,732	$64,937	$60,061	$55,564	$51,390	$47,540
12	$916,619	$34,373	$66,171	$61,203	$56,620	$52,366	$48,443
13	$934,035	$35,026	$67,428	$62,366	$57,695	$53,361	$49,364
14	$951,781	$35,692	$68,709	$63,550	$58,792	$54,375	$50,302
15	$969,865	$36,370	$70,015	$64,758	$59,909	$55,408	$51,257

Non-Energy Material Prices / 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
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
7	lb	kg	0.453514739	kg/lb
8	ncf	Nm3	0.028317	Nm3/ncf
9	MPa	psi	145.038	psi/MPa
10				
11	**Energy**			
12	MJ	kWh	0.277777778	
13	gallon of gasoline eq (GGE) -convention	kWh	34.02262529	
14	kg H2 (LHV)	GGE	0.979331964	
15	kg H2 (LHV)	kWh	33.32926599	33.3194444
16	kg H2 (LHV)	GJ	0.119985358	
17	btu	kWh	0.000293083	
18	mmBTU	GJ	1.055	
19				
20				
21	**Greenhouse Gas Emissions Factors**			
22	CO2	1		
23	CH4	23		
24	N2O	296		
25				
26				
27				
28				
29				
30				
31				
32				
33				

Non-Energy Material Prices / 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	H
1	**Cancelled**							
2								
3	**Use_Default**		**Yes_No**		**Temp_var_location**		**Sensitivity_Variables**	
4	Use H2A Value		Yes		**0.025**		Operating Capacity Factor (fraction)	cap_factor
5	Enter Value		No				Plant Design Capacity (kg of H2/day)	design_cap
6							Assumed start-up year	startup_yea
7	**Add_As_List**		**Feed_Type_List**				Length of Construction Period (years)	construct
8	Feedstock		Feed				Start-up Time (years)	start_time
9	Utility		Utility				Plant life (years)	plant_life
10	Byproduct		Feed Utility				Decommissioning costs (fraction of depreciable capital investment)	decom_per
11			Feed Utility Byprod				Salvage value (fraction of total capital investment)	salvage_pe
12			Byproduct				Inflation rate (fraction)	inflation_rat
13							After-tax Real IRR (fraction)	real_irr
14	**Delete_As_List**		**ColorList**				State Taxes (fraction)	state_tax_r
15	Energy Feedstock		Input				Federal Taxes (fraction)	fed_tax_rat
16	Energy Utility		Calculated				WORKING CAPITAL (fraction of yearly change in operating costs)	WorkingCa
17	Energy Byproduct		DropDown				Total Direct Capital Cost	direct_cap
18	Other Feed		Information				Total Capital Investment	total_cap
19	Other Byproduct		UserInfo				Cost of land ($/acre)	acre_cost
20	All						Labor Requirement (FTE)	FTEs
21							G&A rate (fraction of labor cost)	overhead_r
22							Property tax and insurance rate (fraction of total capital investment)	tax_ins_rat
23							Rent ($/year)	rent
24							Material costs for maintenance and repairs ($/year)	material
25							Production Maintenance and Repairs ($/year)	prod_maint
26							Waste treatment costs ($/year)	waste_treat
27							Solid waste disposal costs ($/year)	solidwaste_
28							CO2 sequestration capital costs ($/year)	CO2_seq
29							Feedstock Woody Biomass_metric Usage	Feedstock\
30							Feedstock Woody Biomass_metric Price	Feedstock\
31								
32								
33								
34								

Non-Energy Material Prices / 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:

Darlene Steward
National Renewable Energy Laboratory
303-275-3837
darlene_steward@nrel.gov

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 26). See the sources listed in *References* at the end of this appendix for detailed descriptions and derivations of the calculations. Note that McCollum and Ogden (2006) include CO_2 pumps in their carbon sequestration calculations as well as compressors. Because super-critical CO_2 exhibits liquid-like density at the pressures and temperatures of carbon sequestration, pumps or compressors can be used in this application. The choice of using pumps, compressors, or both depends on the scale of the carbon sequestration process. At the high production capacities of most H2A central model cases, the higher efficiency of compressors offsets their higher initial capital cost; industry feedback supports this contention. Therefore, the H2A central model includes only CO_2 compressors, rather than pumps, in its carbon sequestration calculations.

The *Carbon Sequestration* worksheet is divided into four 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 Sequestration Calculations	Calculate carbon sequestration 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)	1,330,800	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)	26.10	
3	CO2 Mass Flowrate (metric tons/day)	2916.82	
4	Electricity Cost ($/kWh)	0.0555	Price for industrial electricity in the startup year
5	Carbon Sequestration Electricity Usage (kWh/kg H2)	2.0185	

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. *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 (**6**).

4. *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.

5. *Carbon Sequestration Electricity Usage*—This value is calculated using the power requirement (**21**) 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

	Carbon Sequestration Input Values			
6	Carbon Capture Efficiency (%)	80.00%	☑ H2a Default	
7	CO2 capture process outlet pressure (psia)	14.7	☑ H2a Default	Inlet pressure for compression
8	CO2 capture credit ($/metric ton CO2 captured)	$0.00	☑ H2a Default	
9	Operation and maintenance factor for compressors and	0.040	☑ H2a Default	
10	Operation and maintenance factor for CO2 pipeline	0.025	☑ H2a Default	
11	Capital cost for site screening and evaluation (per well)	$1,857,773	☑ H2a Default	
12	Number of injection wells	1	☑ H2a Default	
13	Well depth (m)	1524	☑ H2a Default	
14	Location factor	1	☑ H2a Default	1 - USA,
15	Terrain Type	<20% Mountainous	☑ H2a Default	
16	Terrain factor	1.3		
17	Total CO2 pipeline length (miles)	100	☑ H2a Default	
18	After Tax Real Capital Recovery Factor	0.102		
19	Real Present Value of Depreciation	0.487		
20	Approx Capital Charge Rate	0.136		

6. *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**). The default value is 80%.

7. *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 $P_{initial}$ in the CO_2 compression calculations (**23**). The default value is 14.7 psia (atmospheric pressure).

8. *CO2 Capture Credit*—Input the value for CO_2 capture credits here. If a value is entered, the credits offset operation and maintenance costs (**29**). The default value is zero.

9. *Operation and Maintenance Factor for Compressors*—Input the compressor operation and maintenance factor here. The model multiplies this value times the compressor capital cost to determine annual compressor operation and maintenance cost (**24**). The default value is 0.04.

10. *Operation and Maintenance Factor for CO2 Pipeline*—Input the pipeline operation and maintenance factor here. The model multiplies this value times the pipeline capital cost to determine annual pipeline operation and maintenance cost (**28**). The default value is 0.025.

11. *Capital Cost for Site Screening and Evaluation (per well)*—Input the per-well capital cost for site screening and evaluation here. This value is multiplied times the number of wells to become C_{site} in the CO_2 compression calculations (**25**). The default value is $1,857,773.

12. *Number of Injection Wells*—Input the number of injection wells here. This value is used in the calculations for drilling and injection equipment capital costs as well as injection operation and maintenance costs (**25**, **26**). The default value is 1 well, which is the typical number needed for injecting 10,000 metric tons/day or less using a 0.15-m-diameter injection pipe. For an iterative process for calculating number of wells needed, see McCollum and Ogden (2006), page 15.

13. *Well Depth*—Input well depth here. This value is used in the calculations for drilling capital cost as well as injection operation and maintenance costs (**25**, **26**). The default value is 1,524 m, which is the base case for gas reservoirs in McCollum and Ogden (2006), page 15 (Table 3). Benson (2000) describes California oil and gas reservoirs as no deeper than 1,500 m.

14. *Location Factor*—Select a location factor from the drop-down menu. A location factor of 1 corresponds to location in the United States, Canada, Europe, Japan, or Australia. A location factor of 1.2 corresponds to location in the United Kingdom. This value is used in the calculation for pipeline capital cost; a higher location factor increases the cost (**27**). The default value is 1.

15, 16. *Terrain Type/Terrain Factor*—Select a terrain type from the drop-down menu. Each terrain type corresponds to a specific terrain factor, which is automatically entered into the *Terrain Factor* field as follows:

- cultivated land = 1.1
- grassland = 1
- wooded = 1.05
- jungle = 1.1
- stony desert = 1.1
- <20% mountainous = 1.3
- >50% mountainous = 1.5

This value is used in the calculation for pipeline capital cost; a higher terrain factor increases the cost (**27**). The default value is 1.3 (<20% mountainous).

17. *Total CO2 Pipeline Length*—Input total pipeline length here. This value is used in the calculation for pipeline capital cost (**27**). The default value is 100 miles. Required CO_2 transportation distances (i.e., required pipeline lengths) vary by location.

18–20. 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 38) and *Results* (page 35) sections. The results shown on the *Results* worksheet are for the entire plant.

21–28. The *Carbon Sequestration Calculations* table shows calculations based on the input and calculation tables described above as well as default values and constants. The upper half of the table (**21–24**) calculates compressor costs, including a power requirement calculation for multi-stage compression (**21**). The lower half of the table (**25–28**) calculates injection and pipeline costs. See McCollum and Ogden (2006) for details about the calculations. Do not change any of the cells in this table directly.

29. The *Summary of Outputs* table summarizes the major results of the carbon sequestration calculations. The costs are 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 here. Costs are shown in reference year dollars. Do not change any of the cells in this table directly.

The calculations for the cost of sequestration 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.

30. The approximate indirect capital costs due to carbon sequestration are calculated by multiplying total indirect capital costs by the ratio of carbon sequestration direct capital costs to total direct capital costs. This approximation is for information only; it does not participate in the model's calculations.

Carbon Sequestration Calculations

Carbon Sequestration Calculations

CO2 Compressor Costs

21 Power Requirement — 13,056 kW

Wsi = (1000/(24*3600))*(m*Zs*R*Tin/(M*his)*(ks/(ks-1))*[(CR)^((ks-1)/ks) - 1]

where

CRmax (maximum allowable compression ratio)	1.80	
Outlet Pressure Desired	15	MPa
N stages needed:	9	
Tin (inlet temperature)	323.15	K
hin (isentropic efficiency)	0.74	
CR needed	1.74	

Stage 1		**Stage 2**		**Stage 3**		
Z1 (compressability factor or CO2)	0.995	Z2	0.991	Z3	0.984	Z4
k1 (ratio of Specific Heats for CO2)	1.284	k2	1.288	k3	1.296	k4
Pinitial (stage inlet pressure) MPa	0.101	Pinitial	0.177	Pinitial	0.308	Pin
Pfinal (stage outlet pressure) MPa	0.177	Pfinal	0.308	Pfinal	0.536	Pfi
W1 (stage power) kW	1636.60	W2	1631.42	W3	1622.37	W4
Stage 5		**Stage 6**		**Stage 7**		
Z5	0.950	Z6	0.912	Z7	0.839	Z8
k5	1.340	k6	1.400	k7	1.549	k8
Pinitial	0.934	Pinitial	1.628	Pinitial	2.836	Pin
Pfinal	1.628	Pfinal	2.836	Pfinal	4.941	Pfi
W5	1578.34	W6	1527.86	W7	1434.22	W8
Stage 9		Stage 10		Stage 11		
Z9	0.400	Z10	0.410	Z11	0.410	Z12
k9	4.961	k10	3.207	k11	3.207	k12
Pinitial	8.609	Pinitial	15.000	Pinitial	26.135	Pin
Pfinal	15.000	Pfinal	26.135	Pfinal	45.538	Pfi
W9	777.45	W10	0.00	W11	0.00	W

22 **Electrical Costs** — $ **5,711,356** **$/yr**

Ecomp = electricity cost*Wcomp*(capacity factor*24*365)

23 **Capital Costs** — $ **28,950,657** **$**

Ccomp = mtrain*Ntrain*[(0.13x10^6)*(mtrain)^-0.71+(1.40x10^6)*(mtrain)^-0.60*ln(Pcut-off/Pinitial)]

where

mtrain (compressor train mass flow)	33.76	kg/s
Ntrain (number of paralel compressor trains)	1	
Pcut-off	2175.6	psi
Pinitial	14.7	psi

24 **O&M Costs** — $ **1,158,026** **$/yr**

O&Mannual = Ccomp*O&Mfactor

where

O&Mfactor — 0.04

CO2 Injection Costs

Capital Costs

25	**Capital cost of site screening and evaluation**	$ **1,857,773**	**$**
	Cequip = number of wells*[49,433*(CO2 flowrate/(280*Nwell))^0.5]	$ **159,549**	
	Cdrill = Nwell*10^6*0.1063*e^(0.0008*d)	$ **359,770**	
	Cinj = Csite+Cequip+Cdrill	$ **2,377,092**	

26 **O&M Costs**

O&Mdaily	$ 7,596	Nwell*7596
O&Mcons	$ 20,295	Nwell*20295
O&Msur	$ 49,769	Nwell*[15,420*(m/(280*Nwell))^0.5]
O&Msubsur	$ 7,087	Nwell*(5669*(d/1219))
O&Mtotal	$ **84,748**	**$/yr**

CO2 Pipeline Costs

27 Capital Cost Requirement

Ccap=location factor*terrain factor*pipeline length(m)*(9970*(CO2 flowrate^0.35)*(pipeline length(m)^0.13))	$ **65,465,510.85**	**$**
Pipeline capital cost per mile	$ **654,655.11**	**$/mi**

28 **O&M Costs**

O&Mannual = Ccap*O&Mfactor — $ **1,636,637.77** **$/yr**

Summary of Output Values

29	Summary of Output Values		
	Capital Costs		
	CO2 Compressor	$ 34,037,230	
	CO2 Injection (Site and wells)	$ 2,413,003	
	CO2 Pipeline	$ 75,461,988	
		$ 111,912,221	Total
30	Approx. Indirect Capital Costs	$ 38,785,188	
	Electrical Costs		
	CO2 Compressor	$ 8,733,871	
	CO2 Pumps	$ -	
	CO2 Injection (Site and wells)	$ -	
	CO2 Pipeline	$ -	
		$ 8,733,871	Total
	O&M		
	CO2 Capture Credit	$ -	
	CO2 Compressor	$ 1,361,489	
	CO2 Pumps	$ -	
	CO2 Injection (Site and wells)	$ 95,950	
	CO2 Pipeline	$ 1,886,550	
		$ 3,343,989	Total
	Carbon Sequestration Energy Charge ($/tonne CO2 sequestered)		$5.50
	Carbon Sequestration O&M Charge ($/tonne CO2 sequestered)		$2.10
	Approximate Carbon Sequestration Capital Charge ($/tonne CO2 sequestered)		$12.80
	Total		$20.40

References

The calculations used in the *Carbon Sequestration* worksheet were developed by Directed Technologies, Inc. and the National Renewable Energy Laboratory based on information from compressor/turbine manufacturer MAN Turbo and the following publications:

Benson, S.M. (2000). *Comparison of Three Options for Geologic Sequestration of CO2—A Case Study for California*. LBNL-46365. Berkeley, CA: Lawrence Berkeley National Laboratory. http://repositories.cdlib.org/lbnl/LBNL-46365.

This study examines the distribution of carbon emissions from fossil fuel power plants in California and their proximity to active or depleted oil and gas fields and brine formations—reservoirs that might be suitable for carbon sequestration. It also assesses the feasibility of sequestering CO_2 from California fossil fuel plants in these reservoirs.

Chen, S.G.; Lu, Y.; Rostam-Abadi, M.; Nyman, D.J.; Dracos, J.S.; Varagani, Rajani. (2004). *Carbon Dioxide Capture and Transportation Options in the Illinois Basin*. Champaign, IL: Illinois State Geological Survey. http://sequestration.org/publish/MGSC_year1report.pdf.

This report describes CO_2 capture options from large stationary emission sources in the Illinois Basin, focusing on coal-fired power plants. It includes information on pipeline costs.

McCollum, D.L.; Ogden, J.M. (2006). *Techno-Economic Models for Carbon Dioxide Compression, Transport, and Storage & Correlations for Estimating Carbon Dioxide Density and Viscosity*. UCD—ITS—RR—06-14. Davis, CA: Institute of Transportation Studies, University of California, Davis. http://hydrogen.its.ucdavis.edu/publications/2006pubs/resolveuid/7c6a2993156155db8d3209af679b4cdb.

This report is divided into three sections:

- *Techno-Economic Models for Carbon Dioxide Compression, Transport, and Storage* contains models for estimating the engineering requirements and costs of carbon capture and storage (CCS) infrastructure.
- *Simple Correlations for Estimating Carbon Dioxide Density and Viscosity as a Function of Temperature and Pressure* describes simple correlations—which are functions of only temperature and pressure—for estimating the density and viscosity of CO_2 within the range of operating temperatures and pressures that might be encountered in CCS applications.
- *Comparing Techno-Economic Models for Pipeline Transport of Carbon Dioxide* illustrates an approach used to compare several recent techno-economic models for estimating CO_2 pipeline sizes and costs, resulting in a new CO_2 pipeline capital cost model that is a function only of flow rate and pipeline length.

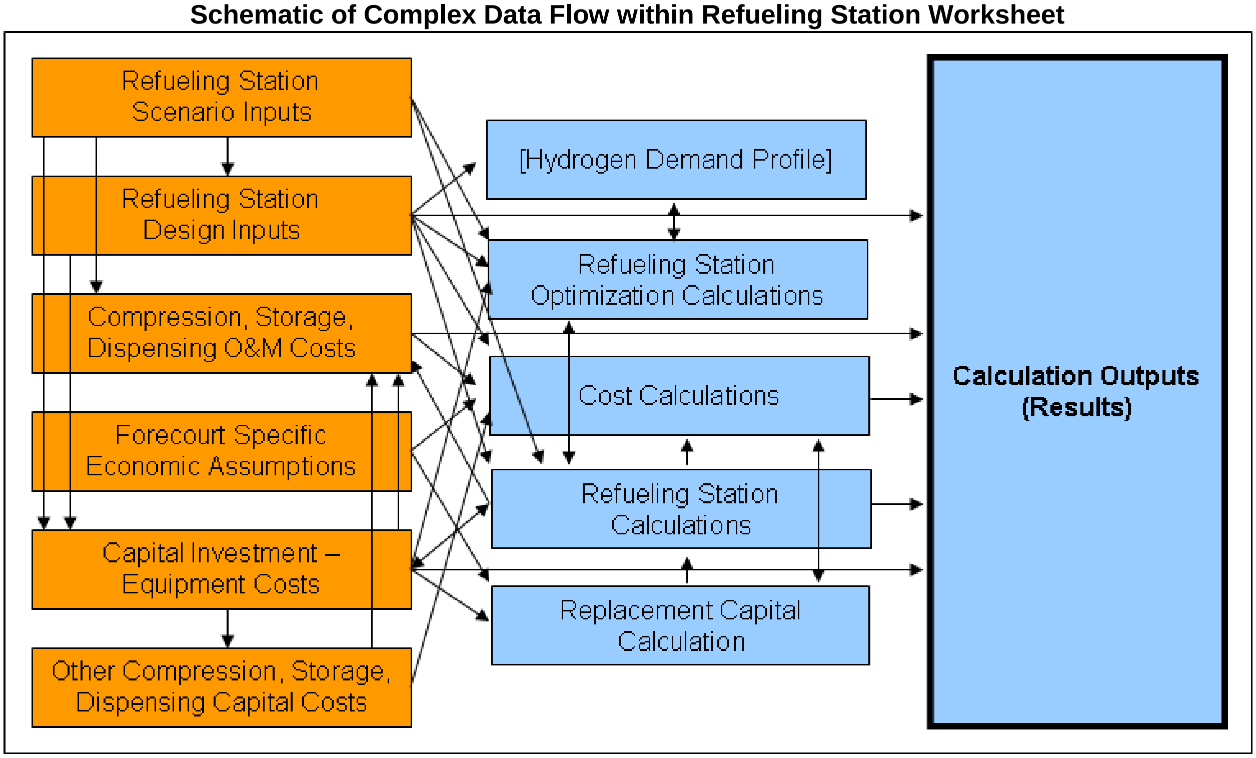
Appendix 2: Forecourt Hydrogen Delivery Calculations

This appendix briefly describes the inputs and calculations used within the *Refueling Station* worksheet (which is used for the H2A forecourt model only, see page 28). The *Refueling Station* worksheet is itself a relatively complex model (see schematic below); it is based on refueling station modeling from the H2A Delivery Components Model and the Hydrogen Delivery Scenario Analysis Model (HDSAM). It calculates optimal hydrogen compression, storage, and dispensing costs for a station with a capacity of up to 6,000 kg of hydrogen per day and a convenience store.

In contrast to the H2A Delivery Components Model, which assumes hydrogen is delivered via pipeline, the *Refueling Station* worksheet assumes hydrogen is produced onsite. Because hydrogen supply is more likely to be disrupted by planned and unplanned outages of the onsite production unit, additional storage is required; a user-input field (in the *Refueling Station Scenario Inputs* table) accounts for the additional low-pressure storage requirement. The default value is slightly more than one half (58.3%) of the plant's daily production capacity.

The table descriptions below give an overview of the worksheet's functions and some default values. See the sources listed in *References* at the end of this appendix for detailed information.

Schematic of Complex Data Flow within Refueling Station Worksheet



Note: The *Input_Sheet_Template* worksheet also provides inputs to the *Refueling Station* worksheet.

Calculation Outputs (Results)

The three *Calculation Outputs* tables summarize the major results of the *Refueling Station* calculations:

- *Results - Cost Breakdown per kg H2*
- *Results - Capital and Operating Costs*
- *Results - Other CSD Parameters*

The *Calculation Outputs* tables receive input from the *Refueling Station Design Inputs*; *Compression, Storage, Dispensing O&M Costs*; *Cost Calculations, Refueling Station Calculations*; and *Capital Investment—Equipment Costs* tables. No user input is required. The *Cost Breakdown per kg H2* results are output to the main H2A *Results* worksheet; see the schematic on page 29.

Forecourt Specific Economic Assumptions
Input or accept the default values for depreciation and component lifetime values here. The values are output to the *Cost Calculations* and *Replacement Capital Calculation* tables.

Refueling Station Design Inputs
Input refueling station design characteristics here. The default values assume a hydrogen pressure of 300 psi exiting the production process. The hydrogen is compressed to 2,500 psi for storage; this relatively low-pressure storage was found to be economical.

Using the default values, vehicles fueling at the station take a fill pressure of 5,000 psi after equilibration to standard temperature; thus, the default maximum cascade charging system pressure is 6,250 psi, which allows the vehicle to refuel within 3 minutes and allows for overpressure to compensate for temperature increases during refueling. The cascade charging system has three pressure vessels, each with a 21.3-kg capacity and a maximum pressure of 6,250 psi. There can be more than one bank of three cascade charging vessels depending on the size of the refueling station. To satisfy vehicle filling dynamics, each vessel operates under a different minimum pressure: 6,000, 4,350, and 2,000 psi. The default compressor values are described in Nexant et al. (2008).

The *Refueling Station Design Inputs* table receives input from the *Refueling Station Scenario Inputs* table. Its values are output to the *Refueling Station Optimization Calculations*, *Cost Calculations*, *Refueling Station Calculations*, and *Calculation Outputs* tables as well as the Hydrogen Demand Profile.

Refueling Station Scenario Inputs
Input details about the refueling station's design and operation here. About half the fields in the *Value* column contain notes that describe the meaning of the values; read them by selecting each field.

The default values are based on a station with six dispensers operating 18 hours per day (6:00 AM to 12:00 AM). The 58.3% low-pressure storage vessel excess capacity provides about a half day of backup storage for use during unplanned shutdowns.

The land area a hydrogen refueling station requires is determined by daily average fuel demand, setback distances (as determined by the National Fire Protection Association for safety purposes), and delivery method. For the purposes of characterizing the default station's area and storage vessel dimensions, the assumptions for a station with pipeline hydrogen delivery given in Nexant et al. (2008) were used.

The *Refueling Station Scenario Inputs* values output to the *Refueling Station Design Inputs*, *Refueling Station Calculations*, and *Refueling Station Optimization Calculations* tables.

Capital Investment—Equipment Costs
The top part of this table gives you the option of accepting H2A-defined compressor, dispenser, storage, and electrical costs or entering your own values. Select "yes" in the drop-down menu to accept the H2A costs as described in the *Notes* fields. If you select "yes" for all of the pieces of equipment, you do not need to provide further input to this table. If you select "no" for one or more pieces of equipment, you must input values in the bottom part of the table as described in the *Notes* fields.

The bottom part of the table calculates the installed cost of each piece of equipment and calculates total initial capital investment. Equipment characteristics in the *Value* column come from the *Refueling Station Scenario Inputs*, *Refueling Station Design Inputs*, and *Refueling Station Calculations* tables. The *Capital Investment—Equipment Costs* values output to the *Refueling Station Calculations*; *Refueling Station Optimization Calculations*; *Replacement Capital Calculation*; *Other Compression, Storage, Dispensing Capital Costs*; and *Calculation Outputs* tables.

Other Compression, Storage, Dispensing Capital Costs
Input or accept the default values for indirect compression, storage, and dispensing capital costs—as a percentage of the direct capital costs—in the orange cells. The blue cells automatically multiply the percentages by the total direct capital cost from the *Capital Investment—Equipment Costs* table. The *Total Capital Investment* value sums the direct and indirect capital costs. The *Total Land/Other Capital Costs* value (which sums the indirect costs) outputs to the *Cost Calculations* table.

Compression, Storage, Dispensing O&M Costs
Input labor and other operating and maintenance costs here. The default labor costs are based on a refueling station open 365 days per year, dispensing an average of 1,050 kg of hydrogen per day. The convenience store at such a station employs 1.5 people; 33% of the labor is associated with fuel dispensing. For stations with capacities other than 1,050 kg/day, labor hours scale linearly as a function of station size, i.e., labor hours per year = store hours per day × 365 × 0.33 × 1.5 × (station capacity/1,050). The labor rate is $10/hr plus 20% for overhead and G&A.

The *Compression, Storage, Dispensing O&M Costs* table receives input from the *Refueling Station Scenario Inputs*; *Capital Investment—Equipment Costs*; *Other Compression, Storage, Dispensing Capital Costs*; and *Refueling Station Calculations* tables as well as the *Input_Sheet_Template* worksheet. Its values are output to the *Cost Calculations* and *Calculation Outputs* tables.

Calculation Tables: Optimizing Refueling Station Design and Cost
The five tables following the *Compression, Storage, Dispensing O&M Costs* table work together to calculate optimal refueling station design, operation, and cost:

- *Refueling Station Calculations*

- *Refueling Station Optimization Calculations*
- *Cost Calculations*
- *Replacement Capital Calculation*
- Hydrogen Demand Profile (untitled table at bottom of worksheet)

No user input is required for these tables. The schematic on page 59 shows the data flow among the various calculation and input tables (the *Input_Sheet_Template* worksheet also provides data to the calculation tables).

The refueling station optimization calculations are based on the following inputs and assumptions:

- Chevron daily and hourly hydrogen demand profiles
- Assumed spike in demand at the beginning of each hour
- Cost of the compressor, cascade, and electrical upgrades
- Minimum and maximum pressures in each of the cascade vessels
- Vehicle filling dynamics (tank capacity, fill time, linger time, etc.)
- Number of compressors in operation and in standby modes
- Number of dispensers and the average hose occupied fraction during peak hour

The optimization methodology—from the H2A Delivery Models—is based on a simple logic. The amount of hydrogen and the pressures in each of the cascade vessels are tracked at the critical points of the demand profile, and a decision is made regarding the size of the compressor and cascade system to satisfy the demand with minimum cost. The selected design parameters are those that satisfy the demand profile at all of its critical points. See Nexant et al. (2008) for optimization methodology details.

References

Nexant et al. (scheduled publication 2008). *H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results*. DE-FG36-05GO15032. Washington, DC: U.S. Department of Energy. www.hydrogen.energy.gov/systems_analysis.html.

This report contains results of an analysis of infrastructure options for hydrogen delivery and distribution to refueling stations from central, semi-central, and distributed production facilities. The H2A Production Model's *Refueling Station* worksheet is based on the refueling station characteristics and calculations described in this report.

U.S. Department of Energy Hydrogen Program. *DOE H2A Delivery Analysis*. Web Site. Washington, DC: U.S. Department of Energy. www.hydrogen.energy.gov/h2a_delivery.html.

This Web site includes descriptions of the H2A Delivery Components Model and HDSAM as well as user's guides for both models.

Appendix 3: Default Values and Assumptions

The following default values and assumptions apply to the H2A central and forecourt models, 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 for central model; 20 years for forecourt model
Average Burdened Labor Rate for Staff	$50/hour for central model; $15/hour for forecourt model
Capacity Factor	90% for central model with case exceptions; 85.2% for forecourt model
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 for central model; 1 year for forecourt model
Co-produced and Cogenerated Electricity Price	$30/MWh
Decommissioning	10% of initial capital for central model, with case exceptions; 0% for forecourt model
Depreciation Type and Schedule for Initial Depreciable Capital Cost	MACRS: 20 years for central model with case exceptions; 5 years for compressors, 7 years for remainder of plant for forecourt model
Facility Life	40 years for central model with case exceptions; 20 years for forecourt model with case exceptions
Forecourt Compressed Hydrogen Storage	117% of maximum daily production
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
Hydrogen Purity	98% minimum; CO < 10 ppm, sulfur < 10 ppm
Hydrogen Storage Pressure at Forecourt	6,250 psig
Income Taxes	35% federal; 6% state; 38.9% effective

Inflation Rate	1.9%, but with resultant price of hydrogen in reference year constant dollars
Land Cost	\$5,000/acre purchased for central model; \$0.5/sqft/month for long-term lease for forecourt model
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	100% equity with 10% IRR; includes levelized hydrogen price plot for 0%–25% IRR; model allows debt financing
Reference Year Dollars	2005, to be adjusted at half-decade increments (e.g., 2005, 2010)
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 for central model, with case exceptions; 0% for forecourt model
Sensitivity Variables and Ranges	Based on applying best judgment of 10% and 90% confidence limit extremes to the most significant baseline cost and performance parameters
Technology Development Stage	All central and forecourt model cost estimates are based on mature, commercial facilities
Working Capital Rate	15% of the annual change in total operating costs

Appendix 4: Derivations and Definitions

Derivation of Forecourt Production Unit Operating Capacity Factor

The following calculations show how 85.2% was chosen as the standard operating capacity factor for forecourt production systems. (Source: Directed Technologies, Inc.)

$$\mathbf{CF} = \mathbf{100\% - R_{season} - R_{planned} - R_{unplanned} - R_{extra}}$$

Where:

CF = Operating capacity factor

$\mathbf{R_{season}}$ = CF reduction for seasonal loads (winter to summer)
Assumption = **10%**

$\mathbf{R_{planned}}$ = CF reduction for planned shutdown
7 days per year for planned system shutdown (annual maintenance, etc.)
$R_{planned}$ = 7 day/year ÷ 365 day/year = **1.92%**

$\mathbf{R_{unplanned}}$ = CF reduction for unplanned shutdowns
6 "expected" unplanned system shutdowns per year (equipment failure, power outage, etc.)
14 hr system down for each unplanned shutdown (average):
- 2 hr to react to shutdown (also allows unit to cool)
- 6 hr to get repair personnel to site
- 4 hr to effect repairs (assumes replacement parts are in hand)
- 2 hr to bring unit back to full power and monitor for proper performance

$R_{unplanned}$ = 6 shutdowns/year × (14 hr/shutdown ÷ 8,760 hr/year) = **0.96%**

$\mathbf{R_{extra}}$ = CF reduction for needing extra production capacity to refill storage tanks after unplanned shutdowns
H_2 storage for hourly/daily demand fluctuations determined by the Chevron supplied hourly demand load calculations in the HDSAM/H2A model
Chevron demand based on highest daily demand of highest weekly demand (Friday in summer)
1,500 kg/day maximum rating of forecourt production system
14 hr system down for each unplanned shutdown (average)
30 days of design time between unplanned shutdowns
R_{extra} = 14 hr/shutdown ÷ (30 days × 24 hr/day) = **1.94%**
H_2 storage for unplanned shutdowns = 14 hr/shutdown ÷ 24 hr/day × 1,500 kg/day = 875 kg

$$\mathbf{CF} = \mathbf{100\% - 10\% - 1.92\% - 0.96\% - 1.94\% = 85.2\%}$$

Definitions

Working capital — 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. Also known as net working capital.