H2A DELIVERY SCENARIO ANALYSIS MODEL VERSION 2.0* (HDSAM 2.0) USER'S MANUAL

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1.0 OVERVIEW

Development of hydrogen production and delivery technologies, and their associated infrastructure, requires a robust suite of analytical tools to guide R&D decisions, provide transparency, and permit expert review. To this end, the US Department of Energy's (DOE's) Office of Fuel Cells, Hydrogen and Infrastructure Technologies initiated the H2A Project. This report documents one of the tools developed under that project, the Hydrogen Delivery Scenario Analysis Model (HDSAM), an Excel-based model that estimates the cost of delivering hydrogen from a centralized production facility to a hydrogen-fueled vehicle.

1.1 Approach

Like other H2A-developed tools, the HDSAM uses an engineering economics approach to cost estimation. For a given scenario (discussed below) a set of "components" (e.g., compressors, storage vessels, tube-trailers, etc.) are specified, sized and linked into a simulated delivery system or pathway. Financial, economic and technological assumptions are then used to compute the cost of those components and their overall contribution to the delivered cost of hydrogen.

Like its predecessor (HDSAM 1.0), HDSAM Version 2.0 contains many default values that represent currently available technology and costs. In many cases these parameters can be changed by the user to simulate advancements in technology and in future costs.

1.2 Scope of Hydrogen Delivery

For modeling purposes, hydrogen delivery is defined as the entire process of moving hydrogen from the gate of a central production plant onto a vehicle. Thus, delivery includes all transport, storage and conditioning activities from the outlet of a centralized hydrogen-production facility to and including a fuel station which stores, dispenses and, in some cases, further conditions the hydrogen. Hydrogen delivery could also include compression, storage and dispensing of hydrogen produced on site at a fuel station (i.e., distributed production). The current version of HDSAM (Version 2.0) does not model distributed production scenarios. Future versions of the model will include this option.

1.3 Delivery Scenarios

In HDSAM, the user defines a scenario by selecting a market type (urban, rural interstate, or a combination of the two), specifying its size and the market penetration of hydrogen-fueled vehicles in the population of light-duty vehicles, and selecting a delivery mode or modes. Market size can vary from an urbanized area of 50,000 persons to one of over 20 million, or from an interstate highway segment of 10 mi to 300 mi (1000 mi for pipeline delivery); market penetration can vary from 1 to 100 percent; and delivery can be via gaseous tube-trailer, liquid hydrogen truck or gaseous pipeline from the hydrogen production plant all the way to the fuel station, or via pipeline to the edge of the urban area (city gate) and then via liquid or gas truck to the station. In HDSAM 2.0, this first delivery segment is called transmission; the second is called distribution.

The user can further define a scenario by changing a number of other default values, including the distance from a central production facility to the city gate, the fuel economy and annual utilization (i.e., miles driven per vehicle per year) of hydrogen-fueled light-duty vehicles, motorization rate (i.e., vehicles per person), financial assumptions, and the average number of light-duty vehicles served by each gasoline refueling station. Thus, delivery scenarios are combinations of (a) markets, (b) market penetration and (c) delivery mode with an associated set of assumptions about market demand and infrastructure. The user also must select the capacity of the hydrogen fuel stations that are to be considered in the scenario. HDSAM Version 2.0 allows the user to select stations of a design capacity from 50kg/day to 6000 kg/day. (See Section 4.2.1 for some special case limitations on the station refueling capacity.)

1.4 Delivery Pathways

In HDSAM, user selection of a delivery mode invokes an associated chain of delivery "components" or processes.[1] For example, if the user selects liquid hydrogen truck transmission and distribution for a given market and penetration rate, the model calculates not only the number and cost of the trucks required to deliver the fuel to fuel stations but also the cost of appropriately-sized liquefiers, terminal storage, liquid pumps, vaporizers, etc. Collectively, these major steps or "components" are known as a pathway.

Figure 1 illustrates the three pathways contained in Version 1.0 of the Model; Figure 2 illustrates the nine pathways contained in Version 2.0. Note that because delivery is now split into transmission and distribution, loading, conditioning and storage activities normally associated with a terminal need not occur immediately adjacent to the production plant.[2] Rather, this transshipment point occurs at the city gate. Note also that fuel station capacity is no longer limited to 100 or 1500 kg/day, but can now vary from 50 to 6000 kg/day. (See Section 4.2.1 for some special case limitations on the station refueling capacity.)

[1] These steps or processes correspond to individual component spreadsheets or tabs within the HDSAM. These tabs, which were originally developed for a separate model (known as the H2A Delivery Components Model, see discussion in Section 2.2), are shown at the bottom of the HDSAM workbook so the user can view their contents. However, because some cells which are user defined in the H2A Delivery Components Model are now calculated within HDSAM, the color of these cells has been changed from tan (i.e., the color-code for input cells) to blue (i.e., the color-code for calculated cells) in the HDSAM. As noted in Section 4 of this Guide, while the user may no longer change default values within the respective components tab, such changes may still be made from the SCENARIO or INPUTS tab.

[2] For illustrative purposes, these facilities are drawn as icons in the "black box" production facilities shown in Figure 1.

In HDSAM, a production plant need not be defined more specifically than as a centralized facility producing 300-psi hydrogen which then enters a delivery system composed of conditioning facilities (e.g., compressors, liquefiers), storage facilities (e.g., terminals or geologic caverns), and various types of pipelines or trucks. Like petroleum product terminals, hydrogen terminals are modeled as transshipment locations where bulk hydrogen is stored, conditioned (as needed), and broken down for local delivery via a mode that brings the hydrogen fuel to retail locations.

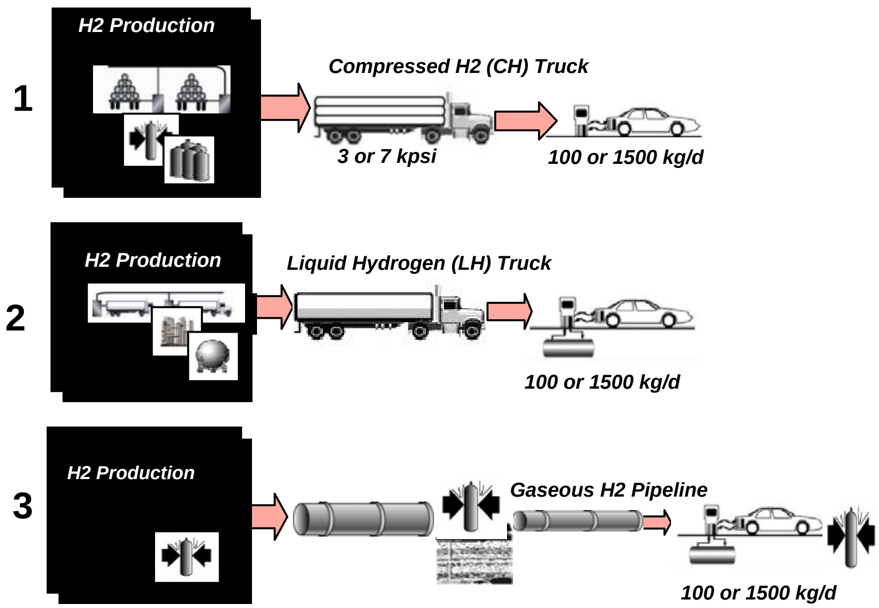


Figure 1. Delivery Pathways in HDSAM Version 1.0

In subsequent versions of the model, the pathways shown in Fig. 2 will be expanded to include hydrogen production, truck or pipeline delivery of hydrogen carriers, and dispensing of cryo-compressed hydrogen and of gaseous hydrogen at pressures above 5000 psi. It should be noted that a pathway with compressed H2 delivery at 7000 psi is included in Version 1.0 but not in Version 2.0 (where delivery tubes cannot exceed a maximum of 5000 psi). Cost information for the 7000 psi tubes in Version 1.0 was very uncertain since the necessary technologies are not currently available. Thus, in developing Version 2.0, the H2A Delivery Team decided to limit tube pressures so cost and performance data would better represent current high-pressure tube technologies.

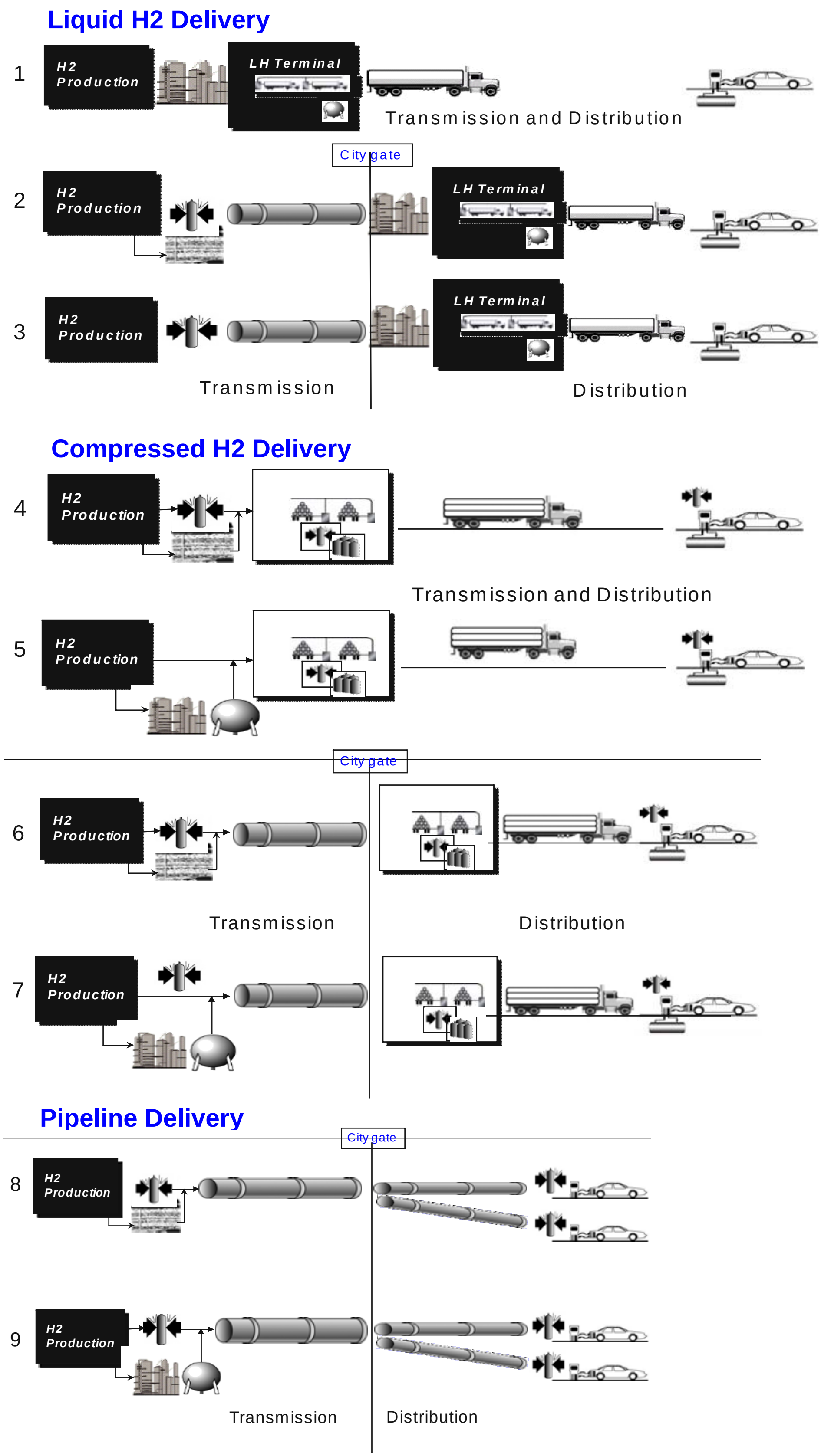


Figure 2. Delivery Pathways in HDSAM Version 2.0

For the nine pathways shown in Figure 2, these components include:

Liquid H2 Delivery

1. Central production → liquefier → LH2 terminal (including liquid storage for plant outages) → LH2 truck transmission & distribution → LH2 fuel station

2. Central production → compressor → geologic storage for plant outages → transmission pipeline → liquefier → LH2 terminal → LH2 truck distribution → LH2 fuel station

3. Central production → compressor → transmission pipeline → liquefier → LH2 terminal (including liquid storage for plant outages) → LH2 truck distribution → LH2 fuel station

Compressed H2 Delivery

4. Central production → compressor → geologic storage for plant outages → GH2 terminal → GH2 truck transmission & distribution → GH2 fuel station

5. Central production → liquefier → liquid storage for plant outages → GH2 terminal → GH2 truck transmission & distribution → GH2 fuel station

6. Central production → compressor → geologic storage for plant outages → transmission pipeline → GH2 terminal → GH2 truck distribution → GH2 fuel station

7. Central production → liquefier → liquid storage for plant outages → transmission pipeline → GH2 terminal → GH2 truck distribution → GH2 fuel station

Pipeline Delivery

8. Central production → compressor → geologic storage for plant outages → transmission & distribution pipeline → GH2 fuel station

9. Central production → liquefier → liquid storage for plant outages → transmission & distribution pipeline → GH2 station

Note that other combined delivery modes are theoretically possible but are not considered in Version 2.0. For example, liquid H2 transmission followed by pipeline distribution could be a desirable short-term scenario (i.e., using an existing natural gas distribution system),but it is not considered to be a long-term, high-demand option and is thus not considered in HDSAM Version 2.0.

1.5 Model Tab Structure

HDSAM 2.0 includes the following individual color-coded tabs or spreadsheets:

- TITLE (dark grey)
- SCENARIO (green)
- INPUTS (tan)
- RESULTS SUMMARY (blue)
- ENERGY & GHG RESULTS SUMMARY (blue)
- CF RESULTS (blue)
- REFUELING STATION – GASEOUS H2 (light grey)
- REFUELING STATION – LIQUID H2 (light grey)
- COMPRESSED GAS H2 TERMINAL (aqua)
- COMPRESSED H2 TRUCK (aqua)
- H2 LIQUEFIER (pink)
- LIQUID H2 TERMINAL (pink)
- TRUCK – LH2 DELIVERY (pink)
- H2 COMPRESSOR (gold)
- GASEOUS H2 GEOLOGIC STORAGE (gold)
- H2 PIPELINE (gold)
- SCENARIO PARAMETERS (orange)
- FINANCIAL INPUTS (light yellow)
- MACRS_DEPR. TABLE (light yellow)
- FEEDSTOCK & UTILITY PRICES (light yellow)
- PHYSICAL PROPERTY DATA (light yellow)
- GREET DATA (dark yellow)
- COST DATA (white)
- DESIGN DATA (white)

Most users will be concerned with the TITLE, SCENARIO, INPUTS, RESULTS SUMMARY, ENERGY & GHG RESULTS SUMMARY and CF RESULTS tabs. These are the tabs in which users can input assumptions and/or review results. The TITLE and SCENARIO tabs permit users to name and broadly define a scenario in terms of market type and size, market penetration, bulk storage (liquid or geologic) for production outage, fuel station size, delivery distance and mode by means of a series of option (radio) buttons, text boxes and drop-down menus. Once a scenario has been broadly defined, the model can be triggered using a command button on the SCENARIO tab to calculate delivery cost (in $/kg). Additional “default” inputs and calculated values, which further specify the delivery scenario, are then displayed in color-coded cells on the SCENARIO and INPUTS tabs. The user can override the default values (in the tan-colored cells) but not the calculated values (in the blue-colored cells). Subsequently, whenever the user makes a selection or changes the default inputs, he/she must click the “Calculate” button in the SCENARIO tab to initiate a re-calculation. Upon completion of each calculation, the model displays summary results and intermediate calculations on the SCENARIO tab, and detailed results on the RESULTS SUMMARY, ENERGY & GHG RESULTS

SUMMARY and CF RESULTS tabs. Additional details on these tabs are presented in Section 4 of this Guide.

Most of the other tabs in the HDSAM are nearly identical to those in the H2A Delivery Components Model (http://www.hydrogen.energy.gov/h2a_delivery.html). The key difference between the two models occurs from the necessity to link relevant components within HDSAM so that they have the correct flow of input and output capacities among the components and to properly account for losses. These linkages are described in Section 4 of this Users Guide.

1.6 Financial Assumptions

All H2A-developed tools have a common set of default financial assumptions. In HDSAM, these are contained in the FINANCIAL INPUTS tab. In order to easily model alternative financial assumptions, key variables and their default values are also contained in the SCENARIO and INPUTS tabs where the user may override the H2A defaults. Financial assumptions contained on the INPUTS tab include:

- debt ratio (i.e., investment share financed with debt)
- debt interest rate (%) and period (yrs)
- construction period (yrs)
- salvage value (%)
- decommissioning value (%)
- start-up period (yrs)
- % revenue, fixed and variable costs during start-up period.

A nominal Internal Rate of Return (IRR) is calculated and displayed within the FINANCIAL INPUTS tab based on an assumed real after-tax discount rate (10% is the default H2A rate). The latter can be user-specified resulting in an alternative IRR.

On the INPUTS tab, these financial variables are listed for each component being modeled in the delivery pathway. Hence, although common financial assumptions are specified in the FINANCIAL INPUTS spreadsheet, scenarios can be specified in which market participants have different financial strategies.

Since capital cost accounts for a large fraction of the total cost of delivering hydrogen, the internal rate of return (IRR) strongly affects the calculated results. The default financial parameters in all H2A-developed tools result in an IRR of 10% real (12.1% nominal). This rate is linked to another H2A assumption – that 100% of capital is obtained through equity financing. The financial parameters are based on historic return on equity (ROE, adjusted for inflation) for large-capitalization companies,[3] as well as ROI and ROE statistics for major energy producers. For further discussion of financial

[3] Based on *Stocks, Bonds, Bills and Inflation 2003 Yearbook* (Ibbotson Associates 2003), the inflation-adjusted return on stocks of large capitalization companies, averaged 9% over the period 1926-2002.

assumptions in the H2A models, see http://www.hydrogen.energy.gov/h2a_production.html.

1.7 Other User Inputs

On the SCENARIO tab, the user can override default values for the distance between the hydrogen production facility and the edge of an urban market (city gate), annual light-duty-vehicle utilization, the fuel economy of hydrogen-fueled vehicles, the population and land area of an urban area, the motorization rate (i.e., vehicles per person), and several parameters related to daily and seasonal hydrogen supply and demand. These latter inputs include the number days of annual scheduled production plant outage, the number of days of peak season demand, the percent that peak season demand exceeds average annual demand, the percent that peak daily demand exceeds average daily demand and a scale factor to reflect how closely hydrogen hourly demand tracks typical gasoline demand. (For a additional discussion of hydrogen supply and demand inputs see Section 4.2.)

Note that these user inputs are in addition to the key parameters defined at the top of the page via radio buttons and sliding cursors used to define the broad outlines of the scenario of interest. These latter additional inputs are: (a) market type (urban, rural interstate, or a combination of the two), (b) a measure of market size (either a specific urban area which the user selects from a drop-down menu, a user-entered population for a generic urbanized area, or the length of a single interstate highway segment to be served), (c) market penetration (i.e., the share of total light-duty vehicles operating on hydrogen fuel in the market of interest), (d) transmission and distribution mode(s), (e) size of hydrogen fuel stations (in terms of kg/day dispensed), and (f) type of bulk storage (either gaseous hydrogen in geologic storage or above-ground liquid hydrogen) to be used for production plant outages and summer demand surges.

1.8 Discounted Cash Flow Analysis

Discounted cash flow (DCF) is computed on each of the component tabs and summed over all the components in the pathway to estimate the total contribution of delivery to the cost of hydrogen. DCF includes capital, utilities, taxes, operating expenses, and other cash flows. DCF is calculated for each analysis year to generate a table of annual cash flow which, with an after-tax nominal Internal Rate of Return (IRR), is used to calculate the Net Present Value (NPV) of the cash flows.

The cost contribution of each component is that which generates a Net Present Value of zero. In other words, HDSAM estimates the cost of hydrogen delivery such that the sum of the revenue cash flows, including the return on capital, and expense cash flows, results in a Net Present Value of zero. Note also that these costs represent only delivery and dispensing (i.e., production costs are excluded).

1.9 User Interface

As noted above, HDSAM estimates the levelized cost to deliver hydrogen in quantities sufficient to meet a given level of market demand. Like other H2A-developed tools, HDSAM applies a common set of financial assumptions (although, as noted above, the user can change these assumptions), runs in a Microsoft Excel environment and, to the extent possible, produces “transparent” results. Unlike other H2A tools, HDSAM incorporates a graphical user interface (GUI) to assist the user in selecting and analyzing alternative scenarios and estimating the cost of individual components within them. Details of the GUI are discussed in Sections 3.1.2 and 4.2.

2.0 BACKGROUND

2.1 Origins of HDSAM

Although a number of analyses of hydrogen production and delivery infrastructures have been conducted and have produced important insights into technical and cost barriers, most studies have failed to provide the guidance needed for Research and Development (R&D) decisions. In particular, findings have appeared inconsistent or conflicting because of differences in the analytical base (e.g., whether the analysis is based on current or advanced technologies, on targets or empirical results, on “real world’ or simulated duty cycles, etc.), or in the many economic, financial and technological assumptions used in the analysis. As a result, analytical results have not always contributed the rigor desired for oversight and guidance of the hydrogen program.

The H2A (or Hydrogen Analysis) project was initiated to remedy this problem. Begun in 2003, H2A sought to improve transparency and consistency so researchers and program managers could better understand similarities and differences among efforts, and industry could better validate results. To that end, DOE leveraged the talents and capabilities of analysts from several national laboratories, universities and the private sector, forming two teams to develop a set of tools for production and delivery analysis. More information on H2A can be found at www.hydrogen.energy.gov.

The H2A Delivery team was charged with developing tools to model the cost contribution of all activities/components between the central production of hydrogen and its use on-board a vehicle. Two tools have been developed – the Delivery Components Model and the Delivery Scenarios Model. Versions 2.0 of both models are available at the above web address. This report documents Version 2.0 of the **Delivery Scenarios Model**.

The H2A teams were supplemented by a group of Key Industrial Collaborators (KIC) who attended H2A meetings, reviewed draft documents, provided “rules of thumb” for default assumptions, and reviewed “beta” or test versions of H2A-developed tools. In addition to contributing their own technical expertise, KIC members provided access to their organization’s publicly available knowledge base. The resulting tools benefited greatly from this input.

2.2 Relationship to the Hydrogen Delivery Components Model

HDSAM has been constructed to be similar to and consistent with the Hydrogen Delivery Components Model. In effect, the ‘component’ spreadsheets (or tabs) within the Delivery Components Model are embedded in HDSAM, which, in turn, links them into appropriate combinations to define a delivery pathway, size the individual components consistent with a scenario’s demand estimate, and calculate the cost associated with delivering a given quantity of hydrogen via the specified pathway. For a more complete understanding of how the components within HDSAM are modeled, users should consult the Delivery Components Model Users' Guide which contains additional detail on the tabs within that Model (see http://www.hydrogen.energy.gov/h2a_delivery.html).

Once a delivery pathway has been defined, HDSAM links the applicable components so that each individual component is sized to permit the entire pathway to deliver enough hydrogen to satisfy market demand. It is in this feature that the HDSAM expands upon the Components Model to allow analysis of a completely integrated delivery pathway. HDSAM uses technical and operational efficiencies along with an endogenous estimate of hydrogen demand (determined in the SCENARIO PARAMETERS tab, see following discussion) as the basis for sizing each component. For example, the capacity required for a terminal/storage depot is first estimated from average daily customer demand, and then increased to account for (a) seasonal demand variations and peak surges, (b) hydrogen losses in storage and handling, and (c) routine storage. Similar adjustments in required capacity are made to other components throughout the pathway so that each pathway's design capacity is sufficient to satisfy peak demand. HDSAM automatically makes these capacity adjustments based on input provided in the SCENARIO and INPUTS tabs.

3.0 TABS AND OPERATIONS

3.1 Key Tabs

In addition to tabs for each of the delivery components which are described elsewhere (see http://www.hydrogen.energy.gov/h2a_delivery.html), HDSAM contains four key tabs where users can input assumptions and review results. These are the TITLE, SCENARIO, INPUTS and RESULTS SUMMARY tabs. Note that all other tabs are available to users only for viewing and information purposes. Users are cautioned that changes made to any of these latter tabs may result in inconsistent behavior of the model. Users can trace calculations by using the "Formula Auditing" tool on a particular cell in a component tab, but may not override the entry that appears in any cell from within that tab. Instead, users must enter inputs on the SCENARIO or INPUTS tabs which are then passed to the input cells of the appropriate component tabs.

3.1.1 TITLE Tab

The first tab in HDSAM, the TITLE tab, is strictly for user convenience and consistency with other H2A-developed tools. It has no effect on calculations. The tab notes the color-coding convention used to distinguish different types of cells within the spreadsheet (see Section 4). It also allows users to identify themselves, to describe the purpose of a particular run and to document when the inputs were specified or modified. This information can be very helpful if a large number of cases are to be evaluated.

3.1.2 SCENARIO Tab

The second tab in HDSAM is the SCENARIO tab. The following paragraphs describe some of the main features within the SCENARIO tab (Section 4.2 includes more detailed information). In the SCENARIO tab, the user defines the basic parameters of the scenario to be evaluated, including market type and size, a market penetration rate, and a delivery mode(s).

<u>Market Selection</u>

Version 2.0 allows three market options – "Urban", "Rural Interstate", or "Combined". If the user selects "Urban" market, a scroll-down menu appears with an instruction to select either a particular urbanized area from those listed or to enter a population for a "generic" urbanized area. The "Rural Interstate" market assumes that hydrogen can be dispensed most cost-effectively from stations located along rural interstate highways which can serve both local and thru traffic. The "Combined" market assumes that both intra- and inter-urban traffic will be served from stations located in urban areas and along interstate highways.

The “Rural Interstate” option is further defined to consist of up to four interstate highway segments of equal, user-specified length. In cases where more than one segment is to be evaluated, it is assumed that the production facility and the terminal (if appropriate) are located at the intersection of the equal-length interstate segments.

Market Penetration

The other demand-related input on the SCENARIO tab is “H2 Vehicle Penetration”, expressed as a percent. This value represents the percentage of total light-duty vehicles operating within the particular market that are assumed to be hydrogen-fueled. As described later in this Guide, this information is passed to the SCENARIO PARAMETERS tab where a variety of parameters used throughout the model are calculated. Chief among these parameters is daily hydrogen demand (expressed in kg/day) which is used to size the individual components in the selected pathway. Other key parameters (also calculated in the SCENARIO PARAMETERS tab) are the number of fuel stations within the given “Urban” or “Rural Interstate” market and the average distance between these stations. Based on information from the PHYSICAL PROPERTY DATA tab, the SCENARIO PARAMETERS tab also determines the number of trucks and trailers that are needed to deliver hydrogen to meet the daily demand. These calculations are fed, as appropriate, to the component tabs which estimate the cost of delivering hydrogen to the required number of refueling stations.

Transmission Mode

In HDSAM 2.0, transmission is defined as the bulk transport of hydrogen from a central production facility to a transshipment point (generally a hydrogen depot or terminal) where it is transferred to another mode for local distribution. In this version of HDSAM, three transmission modes may be examined – pressurized tube-trailer trucks, cryogenic liquid-hydrogen tanker trucks, and gaseous pipelines sized to carry hydrogen with user-specified pressure losses in the system.

Distribution Mode

Distribution is defined as delivery from a city gate to local hydrogen fuel stations. In HDSAM 2.0 three distribution modes may be examined – pressurized tube-trailer trucks, cryogenic liquid-hydrogen tanker trucks, and gaseous pipelines. Because of inherent economies, if users specify a liquid or gaseous truck transmission scenario, the model will automatically select the same mode for distribution. However, if users select pipeline transmission, they will also need to specify one of the three choices for local distribution. If either of the truck distribution modes is selected along with pipeline transmission, it is assumed that the required terminal will be located at the city gate. If truck transmission is selected, the terminal is assumed to be located immediately adjacent to the production facility.

Supply for Outage and Peak Surge Demands

HDSAM 2.0 explicitly models the incremental hydrogen required for production plant outages and peak surges. As a reference case, outages are assumed to occur once per year for 10 days (a default value that can be changed). Surges are also assumed to occur once per year during the peak summer driving season. A default surge of 10% above the average daily demand is assumed but this too is a default that can be changed by the user. Users must choose whether to augment supplies with either liquid or gaseous storage for these two periods. If a liquid hydrogen delivery scenario has been specified, the model automatically selects liquid storage.

Fuel Station Capacity

The last piece of basic input on the SCENARIO tab is fuel station capacity. HDSAM 2.0 characterizes 5,000 psi gaseous hydrogen fuel stations dispensing 50 kg/day to 6,000 kg/day. The user can generally select any capacity in this range by either sliding the associated cursor or entering a specific quantity. However, user choice of station size can be constrained by the capacity of the distribution mode. Specifically, if a user specifies gaseous truck distribution and selects a station capacity that would result in more than two tube-trailer deliveries per station per day, HDSAM will generate an error message requiring the user to choose a lower station capacity. (See Section 4.2.1 for additional information regarding this limitation.)

Other Inputs

A summary of “Key Delivery Inputs and Assumptions” is also displayed on the SCENARIO tab. This summary allows the user to quickly review basic inputs to the selected scenario. Many of the displayed parameters are “default” or recommended values, which users can change as they see fit (see Section 1.7 for a list of these inputs and Section 4.2 for further discussion).

Outputs

Selected results are also displayed on the SCENARIO tab. Delivery cost, as calculated within the model, is displayed in $/kg, where the denominator represents annual kilograms of hydrogen demand by the ultimate consumer. Other outputs displayed on this tab include average daily hydrogen demand, number of hydrogen-fueled vehicles in the specific scenario, infrastructure requirements of the selected delivery mode(s) (e.g., number of trucks and tube-trailers, miles of transmission, trunk and service pipelines, etc.), and features of the delivery system (e.g., number of hydrogen fuel stations, percent of all fuel stations at which hydrogen is dispensed, average distance between hydrogen stations).

As noted above, in Version 2.0 of HDSAM hydrogen transmission and distribution are accomplished via separate calculations. Thus, if a user selects pipeline for transmission and one of the truck modes for distribution (Pathways 2, 3, 6 or 7), the calculation includes a transmission pipeline, a terminal, liquid or gaseous trucks, and whatever storage has been specified to handle outages and peak demand. If truck delivery is selected for transmission and distribution (Pathways 1, 4 or 5), the analysis assumes that a truck terminal/storage depot will be built immediately adjacent to the hydrogen production facility. This terminal will include compression (if applicable), storage, and loading equipment. If a user selects pipeline transmission and delivery (Pathways 8 or 9), the model calculates appropriate pipe diameters for all parts of the pathway and requirements for compression. The selected storage option to cover production plant outages and demand surges is assumed to be located adjacent to the production facility.

3.1.3 INPUTS Tab

Once the user has selected a delivery option, HDSAM prepares a scenario-specific INPUTS tab. This tab contains all inputs required for each of the major components that comprise the selected delivery pathway. The reader is referred to Figure 2 for illustrations and descriptions of the nine potential pathways.

HDSAM automatically "populates" the INPUTS tab with a set of tables containing all inputs required to run each tab in the selected pathway. The default or reference values in these tables represent typical operating or design conditions for the facilities in question, or values defined within the H2A Program to be reference case conditions. The user can change any value in a tan (light brown) colored cell. Blue cells are calculated values and should not be changed by the user. Note that values on HDSAM's INPUTS tab may differ from values on the corresponding tab of the Hydrogen Delivery Components Model; fill colors of the two cells may also differ. This occurs because many of the inputs in the Components Model must be calculated within HDSAM to ensure that the components of a given scenario are consistently linked. Such linkages are described in greater detail elsewhere in this Guide.

A table of "General Economic Assumptions" is also included in the INPUTS tab. This table provides H2A default values for tax rates, discount rate, startup year, and length of analysis period. These values are applied to all components within the delivery pathway.

Section 4.3 of this Guide describes additional features of the INPUTS tab.

3.1.4 RESULTS SUMMARY Tab

This tab provides more detailed results than those found on the SCENARIO tab, but excludes results of intermediate calculations. Tables and figures show the contribution of each major component to hydrogen delivery cost (in $/kg), permitting the user to identify major cost contributors across a range of scenarios or for a particular scenario of interest.

In the RESULTS SUMMARY tab, delivery costs are summarized in several ways. First, results are presented for each major component in the pathway. Thus, for example, for pipeline delivery with geologic storage for plant outages, cost is broken down into contributions from transmission pipelines (the lines connecting production facilities with trunk or "main" pipelines), distribution pipelines (the trunk or "main" lines as well as smaller-diameter service lines leading directly to a fuel station), main or central compressors, geologic storage caverns, and fuel stations. Within each of these components, costs are further broken down into capital, energy/fuel, and non-energy O&M categories. A pie chart of this latter breakdown is provided.

The second set of results on the RESULTS SUMMARY tab is a breakdown of delivery cost by function. Functions include compression or liquefaction, storage, other terminal costs (if applicable), transport, and fuel station. Within each of these categories, additional breakdowns are provided for capital, energy/fuel, and non-energy O&M costs. A pie chart of delivery cost by function is provided on this tab.

Additional details of the RESULTS SUMMARY tab are provided in Section 4.4 of this Guide.

3.1.5 ENERGY AND GHG RESULTS SUMMARY Tab

The ability to generate estimates of energy and greenhouse gas (GHG) emissions for alternative delivery pathways is one of the major enhancements of Version 2.0 of HDSAM. The model now contains tables of energy and GHG emission factors from the GREET 1.7 model (GREET DATA tab) which apply to a number of production and delivery processes. Depending on the delivery pathway, HDSAM selects the appropriate factors to compute total energy, fossil energy, petroleum use, and GHG emissions for that pathway.

In the ENERGY AND GHG RESULTS SUMMARY tab, results are displayed in several tables and figures. Energy and GHG emissions are disaggregated by major component and onsite versus upstream location. Onsite results correspond to energy use (or emissions) at the terminal, fuel station, liquefaction plant or truck; upstream results are most relevant for electricity where energy and emissions are produced at a central power station. Unless changed by the user, electricity emission factors use GREET 1.7 defaults which reflect the average US generation mix.

3.1.6 SCENARIO PARAMETERS Tab

The SCENARIO PARAMETERS tab provides the linkage between the scenario-defining variables of the SCENARIO and INPUTS tabs and the appropriate component tabs. Note that this tab is available to users only for viewing and information purposes. Users are cautioned that any changes made to this tab may result in inconsistent behavior of the model. As stated above, all user inputs should be made in the SCENARIO and INPUTS tabs. Six initial tables are contained on the SCENARIO PARAMETERS tab. One table summarizes fuel station design parameters such as daily capacity and service ratio (i.e., number of vehicles per station). With the exception of the service ratio, where the default value represents a US average, the data in this table are taken from other tabs in HDSAM. A second table displays energy densities of gasoline and hydrogen fuel. These data are taken from the PHYSICAL PARAMETERS tab. A third table provides DOE estimates for key features of hydrogen-fueled light-duty vehicles (e.g., annual utilization and fuel economy) and a fourth displays characteristics of trucks used to carry liquid or compressed hydrogen to fuel stations. Information in this latter table includes average truck speed, fuel economy, diesel fuel cost,[4] driver cost, tank volume and carrying capacity, capital costs for cab and trailer, loading and unloading times, and (for liquid hydrogen delivery) boil-off rates during various activities. Values in this table are predominately "best engineering estimates" based on DOE studies and from the KIC and other industry experts.

Table 5 on the SCENARIO PARAMETERS tab provides geographic information on two city sizes that are no longer used in the model. It is included in Version 2.0 for historical reasons. Table 6 provides information on production facilities, liquefaction, compression, and storage. This latter table is not "live", but is included in Version 2.0 as a placeholder for ultimately linking the delivery model (HDSAM) with production cost models, thereby permitting a full "Cost of Hydrogen" analysis on a consistent basis. Information required for compression, liquefaction, etc. for a scenario of interest is provided on the SCENARIO or INPUTS tab.

The most important part of the SCENARIO PARAMETERS tab is the section titled "Delivery Scenario Assumptions and Demand Calculations". Here, values from the SCENARIO and INPUTS tabs are used to calculate and display information on hydrogen demand. For example, population and hydrogen light-duty vehicle (LDV) penetration from the SCENARIO tab are used to calculate the number of hydrogen vehicles, which in turn is used to determine average demand (in kg of hydrogen per day), the number of hydrogen refueling stations required, and the average quantity of hydrogen dispensed from each station. The latter parameter is based on user selection (on the SCENARIO tab) of a fuel station capacity and the optimization of compressor and storage costs. It should be noted that the model will adjust the capacity factor so that a whole number of fuel stations is realized. This adjustment is typically quite small with the adjusted capacity factor typically rounding to 100%. Other information summarized in this table includes truck speed, availability and distance from the production facility to the market. These values are either taken directly from other HDSAM tabs or calculated from other inputs. Therefore, users should not change the values contained in this table from within the SCENARIO PARAMETERS tab. Instead, users should make all desired changes on the SCENARIO and/or INPUTS tabs.

The next set of tables on the SCENARIO PARAMETERS tab summarize demand – in terms of values specified by the user in the SCENARIO tab and those calculated within

[4] Users must change this value on the INPUTS tab. Values on the FEEDSTOCK & UTILITY PRICES tab (blue coded cells) are for information purposes only.

the model. Peak and average daily demand are calculated based on user inputs and data sets internal to the model. The number of fuel stations is estimated and displayed in this table, as is the average distance between stations in the market area. For truck delivery scenarios, average round-trip travel time is estimated and used to determine the number of truck tractors (cabs) and trailers needed to meet the hydrogen demand. For urban pipeline scenarios, the model determines the lowest cost number of trunk “rings” or main pipelines (up to 4 are allowed in Version 2.0), positions them at the appropriate distance(s) from the demand center, and calculates pipe diameters based on user-supplied (or default) pressure drops. Similar parameters are calculated for rural interstate scenarios. Depending on the scenario and the descriptive parameters on the SCENARIO tab, the model sets the appropriate parameters in the SCENARIO PARAMETERS tab. This information is then provided to the appropriate components tabs to properly size all components and subcomponents, and to develop cost estimates for each component.

Section 4.5 of this Guide includes additional information regarding the SCENARIO PARAMETERS tab.

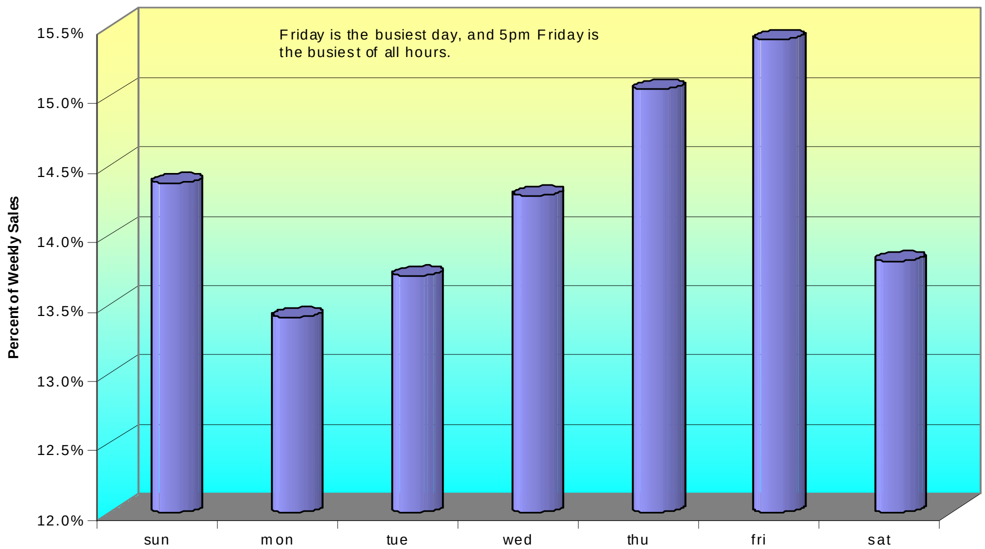
3.1.7 Other Tabs

The remaining tabs in HDSAM are very similar to those in the H2A Delivery Components Model. As noted earlier, a major difference between the two models is that in HDSAM design capacities are calculated within the model rather than input by the user. Within HDSAM, design capacities are initially computed to accommodate demand, but capacities are then increased to allow for hydrogen losses within the pathway, for the availability of the individual components, and for peak surges. For example, the amount of hydrogen the system must be able to deliver to fuel stations must equal peak consumer demand plus all losses that occur within the delivery pathway, plus a sufficient supply for buffer storage to accommodate production plant outages, plus anticipated downtime in major components. Thus, for example, the number of trucks needed to deliver the proper amount of hydrogen to fuel stations must include a sufficient number of spares to account for break downs or scheduled maintenance, as well as losses at the fuel station. Similarly, liquefiers must be sized to meet customer demand, to compensate for downtime, and to account for losses at the fuel station, during truck loading and unloading, and in storage at the terminal. In short, all components must be sized to deliver the proper quantity of hydrogen over the course of a year.

3.2 Analytical Methodology

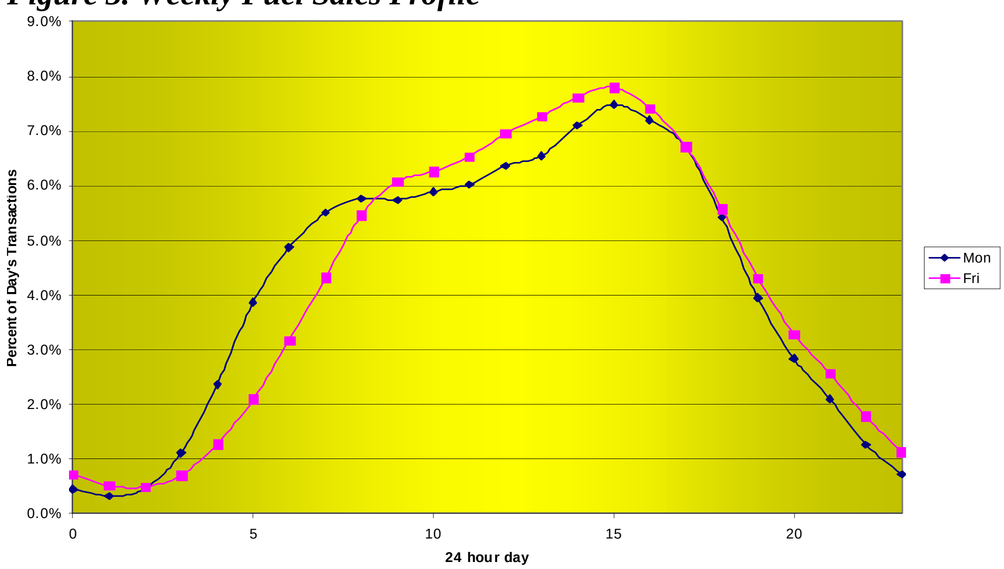
Once all inputs have been defined on the SCENARIO and INPUTS tabs and the user clicks the "Calculate" button, the model computes consumer demand and links the appropriate component tabs to define the delivery pathway. The scenario screen is refreshed to show demand and permit users to enter additional inputs. Upon depressing the “Calculate” button a second time, HDSAM calculates H2 delivery cost. (If the user is doing a series of scenarios, the “Calculate” button need only be pressed once for each scenario after the first one.) Along with this, the model also calculates losses for each major component in the pathway, adjusts flows upstream of that component to compensate, and computes peak season demand, which is used to size upstream components (seasonal factors include the length of the peak summer driving season and the percent increase in peak to average demand).

Peak hourly demand, which is used to size refueling station components, is then computed from weekly and daily demand profiles (see Figs. 3 and 4). The profiles in these figures represent information from industry experts and are the default profiles in Version 2.0. A knowledgeable user can alter these profiles by changing the appropriate input data on the SCENARIO tab.



Source: Chevron, Inc.

Figure 3. Weekly Fuel Sales Profile



Source: Chevron, Inc.

Figure 4. Daily Fuel Demand Profiles (Monday and Friday)

Upstream components must also accommodate production plant outages. In HDSAM 2.0, the default value for routine maintenance and other planned outages is ten days which is assumed to occur during the winter when hydrogen fuel demand normally drops by about 10 percent. Since outages are planned, an alternative supply of hydrogen is drawn from bulk storage, in either geologic caverns or cryogenic vessels. Figure 5 shows the default relationship between seasonal demand (solid turquoise line), production (solid red line), and average hydrogen demand (dashed black line).

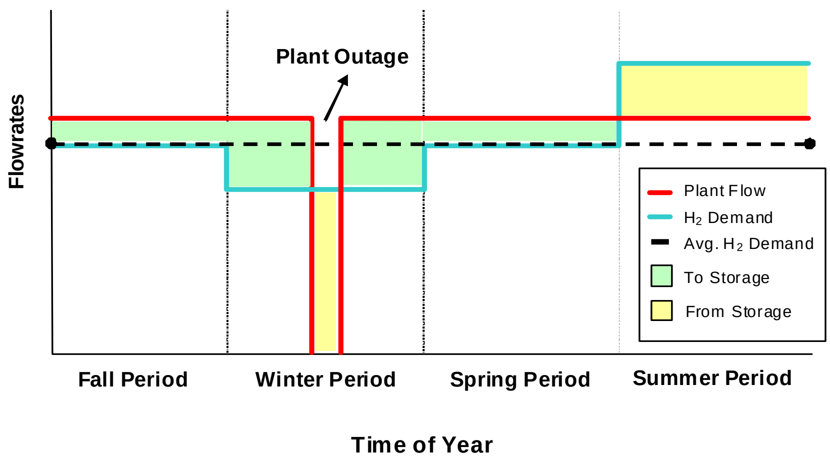


Figure 5. Seasonal Fuel Demand Profile and Flows to/from Storage

Unlike for plant outages, the incremental supply needed to satisfy daily demand peaks (Fig. 4) is met by on-site storage (at the fuel station). As shown in Figure 6, peak daily demand accounts for approximately a third of daily demand in HDSAM's default profile. Assuming that compressors and cascade charging systems operate at a steady rate, these systems must draw from site storage during demand peaks. Depending on delivery mode, site storage is assumed to be in standard tube trailers, or specialized cryogenic tanks and low pressure vessels (which are sized accordingly).

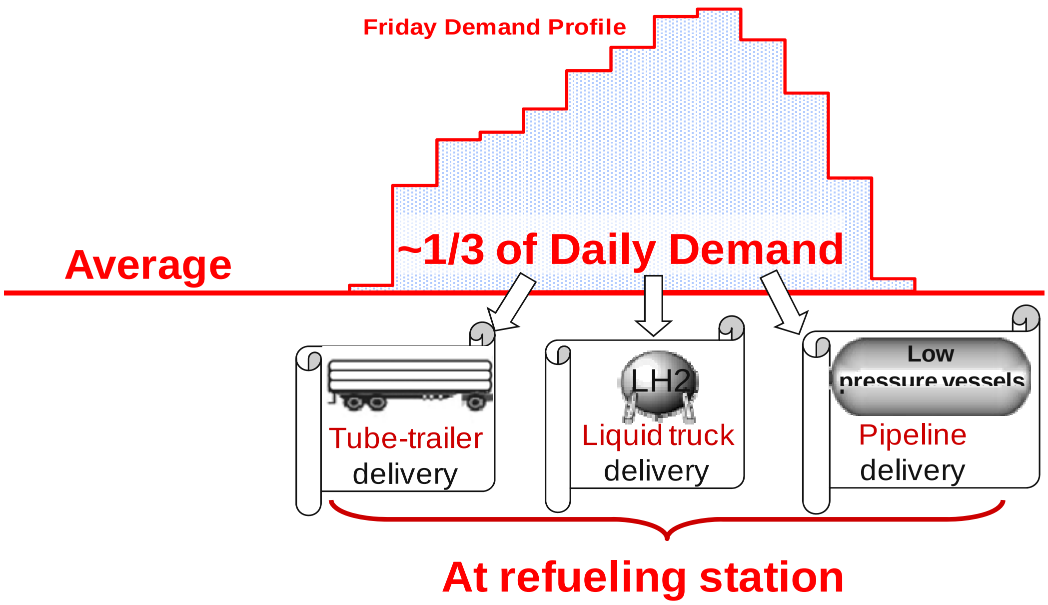


Figure 6. Average and Hourly Fuel Demand and Minimum On-Site Storage

The following discussion describes the logic and linkages among tabs used to model liquid hydrogen truck, compressed gas tube trailer and pipeline delivery pathways for Urban and Rural Interstate scenarios. See Section 4.2 for information on Combined-market scenarios.

3.2.1 Compressed Gas Tube-Trailer Delivery

Urban Market Scenarios (Pathways 4, 5, 6 or 7)

For compressed gas tube-trailer delivery, station size (as specified by the user in the SCENARIO tab) is passed to the REFUELING STATION-GASEOUS H2 tab which determines the number of dispensers required at each station. In Version 2.0 of HDSAM, the tube-trailer provides primary on-site storage which feeds the compressor and cascade charging system. Since the compressor and cascade system operate at a constant rate, on-site storage is used to accommodate peak demand (see Fig. 6).
Capital and operating costs for dispensers and ancillary equipment, the storage/cascade charging system, and forecourt compressors are estimated within the REFUELING STATION-GASEOUS H2 tab.

The number of trucks and trailers, and distances traveled are calculated in the SCENARIO PARAMETERS tab. This information is passed to the COMPRESSED H2 TRUCK tab where it is used to compute capital and operating costs of the delivery trucks, including the amount of diesel fuel required.

Peak demand, as calculated in the SCENARIO PARAMETERS tab (adjusted for peak surges and storage losses) is passed to the COMPRESSED GAS H2 TERMINAL tab to determine the design capacity of the terminal or depot where hydrogen is stored, compressed and loaded onto trailers for delivery to stations. The reader should recall from Figure 2 that for these pathways, storage for production plant outages and demand surges can be either as a liquid in cryogenic storage tanks or as a gas in a geologic formation. Such storage is further assumed to be immediately adjacent to the production facility. The terminal's storage requirement is determined by peak daily demand and user-input days of summer peak demand and production plant outage. This tab then determines the number of truck-filling bays required at the terminal, the capacities of storage tanks and compressors (consistent with other input and calculated information), and the resulting capital and operating costs associated with the terminal.

For Pathways 4 and 5, the total cost associated with compressed gas pathways is the sum of the costs estimated in the REFUELING STATION-GASEOUS H2 tab, the COMPRESSED H2 TRUCK tab, and the COMPRESSED GAS H2 TERMINAL tab plus the cost of liquid or geologic storage for production plant outages and summer demand surges. For Pathways 6 and 7, the cost of the transmission pipeline and the associated compression equipment is also included in the total cost of hydrogen delivery.

<u>Rural Interstate Scenarios</u>

In HDSAM, "Rural Interstate" scenarios are modeled much like "Urban" scenarios. In these cases, users specify the number of interstate segments and the length of those segments. These selections are made on the SCENARIO tab. Users can select up to four interstate segments and a segment length (all segments are assumed to be of the same length) of up to 300 miles. This upper limit on segment length is based on the assumption that a single driver is assigned to each truck tractor and thus the maximum round-trip distance must be completed in one work day (14-hours driving time). The costs within the corresponding tab of the Delivery Components Model are estimated on this same premise.

If users select a single interstate segment, it is assumed that the hydrogen production facility and a truck terminal are located at one end of the segment and that fuel stations are distributed evenly along the segment so as to meet the specified hydrogen demand. Each fuel station is assumed to be at a user-specified distance off the interstate. Truck travel times are estimated on the basis of these assumptions and are, in turn, used to determine the number of truck tractors (or cabs) and trailers needed to meet demand.

If users select multiple interstate segments, the model assumes that all segments meet at one end-point (i.e., that the intersection of two segments forms an "I", three segments form a "T" and four segments form an "X"). Further, it is assumed that each segment is of the specified length, and the production facility and terminal are located at this intersection. It is also assumed that truck routes between segments are not allowed. For example, a delivery truck cannot make a stop in Segment 1 and then another in Segment

2 without first returning to the terminal at the segment intersection. All other assumptions and methods of analysis are the same as for a single segment.

Standard Pressure Tube-trailers

Conventional-technology hydrogen tube-trailers typically operate at roughly 2700 psi with capacities of 300-400 kg of hydrogen. Based on information from the KIC and other industry experts, it is not believed practical to make more than two deliveries to a single fuel station per day. As a result, this technology is limited to relatively small stations. In Version 2.0, users select a station size and the model computes the number of daily deliveries. If the result is greater than two, the model will return an error message prompting the user to reduce station size. See Section 4.2.1 for additional information regarding the limitation in gaseous refueling station capacity.

As noted earlier in this manual, HDSAM Version 1.0 allowed pressures of approximately 7000 psi but the cost and performance information are considered unreliable so this option was dropped in Version 2.0. Future versions of HDSAM may include a high-pressure cryogenic tube-trailer tab which will characterize tubes that can operate at pressures above 6,000 psi and deliver 600-800 or more kg of hydrogen.

3.2.2 Liquid Hydrogen Truck Delivery (Pathways 1, 2 or 3)

Urban Scenarios

Linkages for liquid hydrogen truck delivery scenarios are conceptually similar to those discussed above for compressed gas tube-trailer delivery. Tabs specific to the handling of cryogenic liquids are used instead of those associated with compressed gas but the analytical methodology is similar. An additional tab used in liquid delivery scenarios is the H2 LIQUEFIER tab which estimates the cost associated with liquefying hydrogen.

As with most major component tabs in HDSAM 2.0, liquefier design capacity is linked to peak hydrogen demand as determined in the SCENARIO PARAMETERS tab. Since the liquefier must also liquefy any hydrogen subsequently lost during storage, handling, transportation, dispensing, and for summer surges and production plant outages, its capacity is increased above the average demand to account for these additional loads.

Rural Interstate Scenarios

Liquid hydrogen truck delivery in “Rural Interstate” scenarios is evaluated in a manner similar to that described above for compressed gas tube-trailer delivery.

3.2.3 Pipeline Delivery (Pathways 8 or 9)

In pipeline delivery scenarios, average and peak hydrogen demand (and the number and relative location of fuel stations) are determined in the same manner as in gaseous truck delivery scenarios. However, there are key differences in how hydrogen is delivered to each station. The reader is reminded that pipeline distribution can only be selected in conjuction with pipeline transmission as it is deemed impractical to transport the hydrogen by truck to a city gate location and to then distribute the hydrogen via a local pipeline network. HDSAM Version 2.0 allows geologic or liquid hydrogen storage to be used for production plant outages and demand surges.

The following discussion is directed predominately toward Pathways 8 and 9 where pipelines are used as both the transmission and distribution modes. For cases involving truck delivery for distribution and pipeline for transmission, the following information on transmission pipelines is appropriate.

Urban Scenarios

For urban scenarios, pipeline pathways include three types of pipeline. The largest diameter pipe, referred to as transmission pipeline, extends from the production facility to the city gate. The diameter of this pipeline is a function of its length, peak hydrogen demand, and the pressure differential between the pipeline inlet at the production end and the pipeline outlet at the city gate. These parameters are entered on the INPUTS tab.

An intermediate-diameter pipeline is referred to as a "trunk" or "main" line. In effect, trunk lines create one or more rings within an urban area and are used to carry hydrogen from the transmission line, which terminates at the city gate, to the individual service pipelines which connect to each individual hydrogen fuel station.[5] Depending on the size of the urban area, there may be from one to four trunk lines. The model finds the least-cost combination of trunk and service lines and in doing so determines the number of trunk lines, their location (i.e., the radius of the trunk line(s) from the center of the urban area), length(s) and diameter(s); and the total length and diameter of service lines. These service lines are the third type of pipeline within a pipeline delivery scenario.

The pipeline system requires a compressor to increase hydrogen pressure from its production level (assumed to be 300 psi but the user can change this default value in the INPUTS tab) to the pressure at the terminus of the transmission line. The user can input this maximum pressure at the inlet of the transmission pipeline (the default value in Version 2.0 is 1000 psia). Design requirements for the pipeline central (main) compressor are then calculated as a function of the change in pressure and the peak hydrogen throughput (after accounting for losses in the pathway).

[5] Since pipelines are typically buried beneath streets or adjacent parkways and streets are typically laid out on a grid, the actual configuration is more like a square.

Rural Interstate Scenarios

In “Rural Interstate” scenarios only two types of pipeline are modeled -- a transmission pipeline to transport hydrogen from the production facility and along the interstate segment(s), and service lines connecting the transmission pipeline to each individual fuel station. As in the truck delivery scenarios, the production facility and the terminus of the transmission pipeline(s) are assumed to be at the end of a single segment or at the intersection of two or more segments. An implicit assumption in “Rural Interstate” scenarios is that geologic or liquid-hydrogen storage is at this same location.

Note that in “Rural Interstate” scenarios, pipelines can serve a larger market (defined by segment length) than trucks. Truck segment lengths are constrained by US Department of Transportation (DOT) rules which limit drivers to a maximum of 14 driving hours/day and the HDSAM assumption that a single driver is associated with each delivery. Hence, segment lengths are constrained to 300 miles (600 miles round trip). Longer segments are permitted for pipeline delivery since the limiting factor is the potential requirement for compressor booster stations which are not allowed in Version 2.0. Given other default inputs by the KIC and other industry experts, an upper limit of 1000 miles per segment has been established in HDSAM.

3.2.4 Storage

As noted in Figure 2, all pathways in HDSAM 2.0 include a long-term, high-capacity storage component. This storage is intended solely to provide a steady supply of hydrogen as is needed during production plant outages and/or demand surges. This storage may be in the form of gaseous-hydrogen in geologic formations or as liquid-hydrogen in large, cryogenic tanks. The storage option is user-specified on the SCENARIOS tab and key parameters (e.g., plant outage days per yr and demand surge data) are entered on that tab. (The geologic storage option is not allowed for the case of liquid H2 truck delivery). Multiplying these parameters by daily system demand (increased by hydrogen losses and equipment availabilities) yields the maximum quantity of hydrogen that must be stored to meet these demands. This value is used to determine the size of the storage facility. If geologic storage has been selected, a compressor is required to charge the hydrogen into the cavern. The same compressor is used to extract hydrogen from the cavern and push it into the pipeline. The GASEOUS H2 GEOLOGIC STORAGE tab determines the required capacities of the cavern and compressor, and their associated capital and operating costs. These costs are added to the costs of other components in the delivery pathway to determine the total cost of delivery with geological storage for plant outages. Similarly, if the liquid storage option has been selected, the model will size the liquefier and cryogenic storage tanks appropriately. Depending on the transmission mode selected, vaporizers and compressors may also be needed. If so, the model sizes these components appropriately, determines their estimated costs, and adds these costs to the total cost of delivered hydrogen.

4.0 DETAILED INSTRUCTIONS AND INFORMATION

Earlier sections of this Users Guide described the objectives of HDSAM and the basic methodologies used in estimating the cost of hydrogen delivery. Included in these descriptions are explanations of various inputs and outputs. The following sections (Sections 4.2–4.5) provide additional detail on the four principal tabs users will work with in the model. This detail is intended to enhance users' understanding of the range of applications and limitations of Version 2.0 of HDSAM, as well as aid the analyst in effectively and efficiently changing basic inputs to conduct a variety of analyses.

4.1 Color Coding

The cells in each tab of HDSAM are color coded to show the user which values are inputs to the model and which are not. The color-coding convention is the same as that used in other H2A-developed tools. Figure 2 is a screen capture showing the color-coding convention.

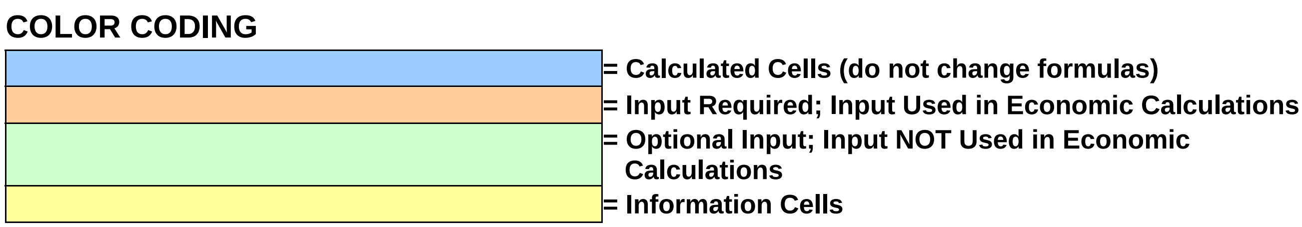


Figure 2. Color-Coding Convention in H2A Models

The blue cells in the model are calculated cells and cannot be changed by the user. When scrolling through the various tabs, a blue cell may be opened to see how a particular calculation is completed, but the formula itself cannot be changed. Note that the tabs at the bottom of the screen corresponding to the RESULTS SUMMARY and CF (Cash Flow) RESULTS spreadsheets are also colored blue to correspond to the color-coding convention.

As in other H2A-developed models, the tan (light brown) cells require user input. However, unlike those models where the user must enter a value (if the cell is blank) or use the default supplied in the spreadsheet, HDSAM's graphical user interface (GUI) automatically enters input values consistent with all other scenario parameters selected by the user on other tabs. The key exceptions are the SCENARIO and INPUTS tabs which function more like the tan cells in the other models. On these two tabs, the user can enter values corresponding to the specific scenario being modeled. The model's internal error-detection system will return an error message if these user-specified inputs are beyond a reasonable range pre-programmed into the model. Note that the tab at the bottom of the screen for the INPUTS spreadsheet is also colored tan to correspond with the above-discussed color-coding convention.

The light green cells are typically used for comments and references. The information entered in these cells is beneficial to future users of the model, as it can assist in tracking assumptions and identifying the rationale for particular inputs.

The yellow cells, always on the right-hand side of the tables, provide miscellaneous information like empirical ranges for input values, references, and data sources.

In addition to these color-coding conventions, HDSAM also color-codes tabs appearing at the bottom of the screen so that the user can quickly and easily see which components are linked into particular transmission or distribution modes. Thus, all tabs involved in gaseous truck transmission or distribution are colored aqua, while those for liquid H2 are pink and those for pipeline are gold. The reader should note however, that the tabs associated with scenarios involving mixed mode delivery will not be all of the same color and that the tabs associated with geologic or liquid H2 storage may not be the same as the other tabs used in the scenario pathway. General information tabs (FINANCIAL INPUTS, MACRS, FEEDSTOCK & UTILITY PRICES and PHYSICAL PROPERTY DATA) are light yellow, the GREET DATA tab is bright yellow, the SCENARIO tab is aqua, the SCENARIO PARAMETERS tab is orange, and the TITLE tab is dark grey. Since the REFUELING STATION–GH2 and REFUELING STATION–LH2 tabs may be combined with several pathways, they are colored gray.

4.2 SCENARIO Tab

4.2.1 User Inputs Prior to Calculation

As described earlier, it is in the SCENARIO tab that the user specifies the principal parameters that define a scenario. Upon opening the tab, the user sees six major input blocks across the top of the screen. In the first block, titled “H2 Market”, the user selects an “Urban”, a “Rural Interstate”, or a “Combined” market. In the second, “Market Penetration”, block the user specifies the percentage of light-duty vehicles in the market that are hydrogen-fueled. This value can range from 1 to 100 percent and can be entered either by typing the value in the indicated cell or by using the slide bar located below the indicated value. The third and fourth blocks allow the user to select a delivery mode(s). As noted elsewhere in this Guide, Version 2.0 of HDSAM permits different delivery modes for transmission and distribution. However, some combinations are mutually exclusive and are not allowed in HDSAM 2.0. For example, pipeline distribution makes little sense without pipeline transmission and gaseous truck distribution makes little sense with liquid truck transmission.

If the user selects the “Urban” market option, a box titled “City Selection” appears on the SCENARIO tab. This box enables the user to select either a specific urbanized area from a drop-down menu or to enter a population for an unspecified, generic urbanized area. When using this option, the input population must be between 50,000 and 20,000,000. In selecting specific cities to be examined, the user should be aware that the only city-specific data contained in the model are population, land area, motorization (i.e., the number of LDVs per person) and utilization rate (i.e., annual miles/vehicle). No location-specific cost data are contained in HDSAM or its component parts.

The fifth major block on the SCENARIO tab sets hydrogen fuel station capacity. In Version 2.0, the user may select any value from 50 kg/day to 6,000 kg/day. Values outside this range will generate an error message. As noted elsewhere in this Guide, if the gaseous H2 truck distribution mode is selected, the model restricts the user from selecting fuel station capacities that will require more than two gaseous H2 truck drop-offs per day. This minimum gaseous refueling station capacity is dependent on the "Friday Peak" demand factor and the summer demand surge factor but is approximately 476 kg/day when using the default values for these parameters.

The sixth block requires the user to choose a method for storing hydrogen to accommodate production plant outages and summer demand peaks. Two options are provided: geologic storage, or liquefier and liquid storage. One combination is automatic and does not require user input. If the user selects a liquid hydrogen pathway, the liquefier and liquid storage option is automatically selected and cannot be over-ridden by the user.

Once the user has made all his/her selections, he/she must click the "Calculate" button on the SCENARIO tab for the model to accept these inputs and calculate. If all necessary information has been provided, an estimated delivery cost will appear in Cell C11. This value, expressed in $/kg of hydrogen delivered to the customer, is a levelized cost of delivery as defined in the H2A Program. See Section 1.6 for a more complete description of the financial calculations within HDSAM.

The SCENARIO tab in HDSAM 2.0 contains one additional option. If "Click Here to Save Results" is selected, a screen will appear instructing the user to name another Excel workbook. The results portion of the SCENARIO tab will appear as SHEET 1 of the resulting workbook. SHEETS 2-4 will be the RESULTS SUMMARY, ENERGY & GHG RESULTS SUMMARY and CF RESULTS, respectively.

4.2.2 Additional Inputs and Outputs

Following user selection of the above inputs, three additional blocks appear on the SCENARIO tab. The first block, titled "Key Delivery Inputs and Assumptions", includes both input and output data. Cell C15 displays the population of the urban area of interest. This value is the same as that contained in the "City Selection" box unless the user chooses to change it. If the user changes the population in this manner, the city area remains that of the chosen city but the user-input population is used in subsequent calculations. Cells C16, C18, and C19 allow the user to alter land area, vehicles per capita, and vehicle utilization, respectively. Cell C20 contains the distance between the hydrogen production facility and the urban area. It should be noted here that there are modeling limitations that necessitate some user discretion in choosing a value. For example, the pipeline delivery mode is based on the premise that a compressor is located at the pipeline inlet (at the production facility) but that no booster compressors are required on transmission or distribution lines. The model determines pipe diameters based on hydrogen flow rate, distance, and a user-specified pressure drop. Therefore, for hydrogen demands of realistic interest, calculated pipe diameters are within typical manufacturing capabilities for distances of up to 1000 miles. Truck delivery modes, however, pose a more stringent limitation on this parameter. Cost models within the appropriate Component tabs assume that a single driver delivers each load and that a round trip must be completed within one working day. Thus, a realistic limit to the parameter in Cell C20 is on the order of 300 miles for truck delivery scenarios.

Cell C21 contains a capacity parameter to "over-build" hydrogen fuel stations. If set to a value less than 100%, the model will reduce the average quantity of hydrogen dispensed per station by that factor although the capacities of the pathway components will be based on 100% of the input hydrogen demand. In effect, the model is imposing an over-capacity delivery system. This condition might exist in the early stages of a transition to hydrogen.

Cells C22-C26 set several demand parameters. Cell C22 specifies the number of days/yr that production plants are off-line for scheduled maintenance. The default value, 10 days, is equivalent to a 97% on-stream factor. Cells C23-C25 specify the sharpness of demand peaks – in other words, the percentage by which average daily demand in the peak season exceeds average daily demand (C23), the length of the peak demand season (C24), and the percentage by which peak daily (Friday) demand exceeds average daily demand (C25). Cell C26 also permits the user to adjust demand peaks, by modifying the steepness of the hourly demand profile. The default value (100%) represents the empirical Chevron hourly profile where peak demand is approximately double average demand (see Sec. 3.2). The user can lower this value to as little as 1%, representing almost no increment between peak and average hourly demand, or raise to several times peak demand, representing a very large increment between peak and average hourly demand.

Cell C27 represents average fuel economy of hydrogen-fueled vehicles and is used to determine daily H2 demand. The user can vary this parameter to determine the impact of improved fuel economy on delivery costs.

The remaining cell in this block (C17) is a simple determination of population density.

"Demand Calculations" are summarized in Cells F15-F21 of the SCENARIO tab. Since these are calculated values (blue color-coded cells), the user cannot change them. Parameters include average daily and annual hydrogen demand per vehicle, number of hydrogen-fueled LDVs, and average daily hydrogen demand; and number of hydrogen stations, average distance between them, and the ratio of hydrogen-capable stations to total gasoline stations. As noted throughout this Guide, the latter two parameters are particularly important for estimating infrastructure and equipment requirements for hydrogen delivery and, consequently, its cost.

The final output block on this tab (Cells C33-C37), "Delivery Mode Calculations", summarizes various details of the selected delivery mode. For pipeline delivery, this block contains lengths and diameters for each type of pipeline – transmission, ring (or trunk), and service – as well as results of calculations to determine the lowest cost number of rings. For truck delivery, the block includes round-trip travel time, annual deliveries, the maximum number of daily round-trips per truck, and the number of tractors (cabs) and trailers required to meet demand. For the special case of mixed-mode delivery, only the transmission pipeline distance is shown in this block.

4.2.3 Rural Interstate Scenarios

If the user selects a "Rural Interstate" market, most inputs and outputs on the SCENARIO tab are the same as those for "Urban" scenarios. There are, however, a couple of notable exceptions. One such exception is that the mixed-mode delivery option is not allowed for "Rural Interstate" scenarios. Initially, an "Interstate Selection" box appears and the user must enter the length of interstate segment to be examined. Segment lengths can vary from 10 to 300 miles for truck-delivery scenarios but can be up to1000 miles for pipeline scenarios. Following user-selection of segment length, the "Key Delivery Inputs and Assumptions" box displays this input, as well as the number of intersecting segments (the user may select up to four such segments), the average number of vehicle-miles traveled per highway-mile, the distance from the hydrogen fuel station to the interstate highway, the fuel economy of conventional light-duty vehicles, and several parameters defining production plant outages and demand peaks (see Sec 4.2.2). The user may change any of these inputs.

For "Rural Interstate" scenarios, the "Demand Calculations" box contains much the same information as for "Urban" scenarios. For the former, however, information on gasoline refueling stations along the interstate is also provided. Gasoline station information is calculated within the SCENARIO PARAMETERS tab (see Section 4.5). These values are significant in determining the number of gasoline stations on the interstate segments and thus the percentage of such stations that are hydrogen capable. Other information in this box includes peak and average hydrogen demand along the interstate, number of hydrogen-capable refueling stations and the percentage of total gasoline stations that are hydrogen-capable.

As with "Urban" scenarios, outputs in the "Delivery Mode Calculations" box depend on the delivery mode. For pipeline delivery, outputs include length of transmission and service pipelines.[6] For truck delivery, outputs include average round-trip time and distance, and the number of tractors and trailers required.

4.2.4 Combined Scenarios

For "Combined" scenarios, user inputs on the SCENARIO tab are largely the same as for "Urban" scenarios. Once entered, however, the resulting "Key Delivery Inputs and Assumptions", "Delivery Mode Calculations" and "Demand Calculations" boxes are somewhat different.

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[6] In Version 2.0, the former is the same as the user-specified segment length; the latter is the calculated number of stations times the user-specified service pipeline length (Cell C18).

In addition to providing standard information on the urban area selected, vehicle utilization and demand peaks, the “Key Delivery Inputs and Assumptions” box also contains interstate segment lengths, the average number of vehicle-miles traveled per highway-mile, and the distance from the hydrogen fuel station to the interstate highway. Note that the user is not able to select a segment length or number of intersecting segments in the same way as for “Rural Interstate” scenarios. For “Combined” scenarios, the default segment length is 300 miles. This value may be changed from within the “Key Delivery Inputs and Assumptions” box. The default number of intersecting segments is one. This value may be changed from the SCENARIO PARAMETERS tab.

For “Combined” scenarios, the “Delivery Mode Calculations” box contains only totals – total trucks, total miles of transmission and service pipelines. Similarly, the “Demand Calculations” box reports only average and peak hydrogen use, number of hydrogen stations and the percentage of stations in the urban market that provides hydrogen. For mixed mode delivery of pipeline transmission and truck distribution in combined markets, it is assumed that the truck terminal will be located at the city gate and that delivery to the refueling stations along the interstate will be via truck and not pipeline. An option to change this assumption is under consideration for future versions of HDSAM.

4.3 INPUTS Tab

In the INPUTS tab the user can modify the basic description and cost parameters of the various delivery components. Three types of inputs are displayed on the INPUTS tab. The first type is displayed in a block titled “General Economic Assumptions” (found in Cells B2 through B7) which contains startup year, reference-year dollars, real after-tax discount rate, analysis period, and state and federal tax rates. The user can modify any of these parameters. Based on this input, the model calculates the total tax rate which is noted in the blue color-coded Cell B8.

The second type of input, contained in cell E5, is the average number of light-duty vehicles that are serviced by a single gasoline station. In Version 2.0 of HDSAM this is 1,419, a value calculated by dividing the number of gasoline stations in operation by the number of LDVs on the road. (National Petroleum News 2006) A refueling station serving this many customers would pump on the order of 100,000 gals of gasoline per month. The sole objective of this parameter is to determine the number of gasoline refueling stations within an urban market area.

The third type of input on this tab is a series of blocks summarizing key features of the individual components in a pathway. As noted in Section 3.1.3 of this Guide, selection of a delivery mode causes the relevant contents of the corresponding component tabs to be displayed on the INPUTS tab. If a user wishes, he/she can change any input parameter associated with these components in the same manner as described in the Delivery Components Model Users Guide (see www.hydrogen.energy.gov). However, because some inputs to the Components Model are calculated in HDSAM or are linked to other components in the pathway, **the user may only change component inputs from within the INPUTS tab**. Parameters that are now calculated or linked in the components' tabs will not be included in the INPUTS tab (because they are no longer inputs in scenario applications).

4.4 RESULTS SUMMARY Tab

An overview of the RESULTS SUMMARY tab is provided in Section 3.1.4 of this Guide. As noted there, total delivery cost for the scenario being examined is summarized in two pie charts. The first shows the distribution by cost type — energy/fuel, capital, and other operating and maintenance (i.e., non-energy O&M). Figure 3 shows a typical breakdown of cost by type for a compressed gas truck delivery scenario.

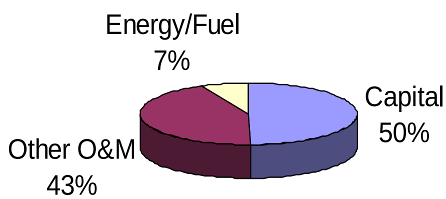

Figure 3. Breakdown of Delivery Cost by Type (Illustrative)

The second pie chart in the RESULTS SUMMARY tab shows a breakdown of cost by function. Figure 4 shows that breakdown for the same scenario described in Figure 3.

Note that in addition to these pie charts, the user can also use the normal display functions available within EXCEL to display cost breakdowns for each component in the pathway, e.g., for the terminal, for trucks/trailers, or for the refueling station (i.e., forecourt).

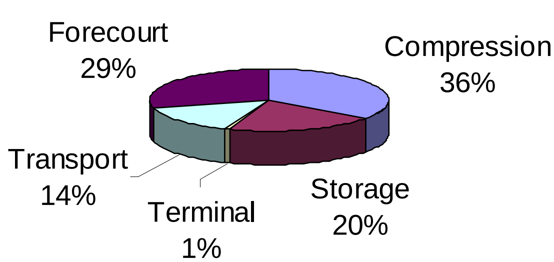

Figure 4. Breakdown of Delivery Cost by Function (Illustrative)

Whereas most cost results are displayed in terms of $/kg of hydrogen delivered to the customer, the RESULTS SUMMARY tab contains additional details and units. These appear on line 37 of the tab and consist of:

- Total initial capital investment
- Annual standard O&M cost (not including energy or fuel)

- Annual electrical energy consumption
- Fuel station land area
- Terminal land area (if applicable)
- Annual truck fuel consumption (if applicable)

4.5 SCENARIO PARAMETERS Tab

An overview of the SCENARIO PARAMETERS tab is provided in Section 3.1.6 of this Guide. As noted there, this tab determines average and peak hydrogen demand and thus drives the capacity requirement for each component in the delivery pathway. This tab is also used to determine the required number of hydrogen fuel stations, the distance between them, the required number of tractors and trailers, round-trip time and distance, and a variety of other parameters necessary to define the delivery pathway and estimate delivery costs.

The SCENARIO PARAMETERS tab consists of a series of blocks that contain information developed within the H2A Program. As the development of HDSAM evolved, some of the information contained in these blocks was replaced by other assumptions or analytical methodologies. Other blocks in this tab contain information that is not used in Version 2.0 of HDSAM but which could be relevant in future versions. Therefore, the various information blocks described below have been retained in Version 2.0 of HDSAM.

4.5.1 "Active" Cells

Tables 1, 2 and 4 in the Delivery Scenario Default Input Data block remain "active" in Version 2.0 of HDSAM. Table 1 presents refueling station inputs including capacity (in daily kg of H2 dispensed) the number of LDVs per gasoline station (see Sec. 4.3) and outputs like boiloff and compression losses. Table 2 presents data on the energy content of gasoline and hydrogen. This is used to estimate hydrogen demand. Table 4 contains data on trucks used for hydrogen delivery. This is used within the SCENARIO PARAMETERS tab to estimate the number of trucks required, their travel time, and other relevant parameters. Some of this information is also fed to the appropriate component tabs to estimate costs. The information in this table was developed primarily from industry experts (typically KIC members) and represents the best available collective knowledge. While the user can vary the assumptions in this table, it is highly recommended that the default values contained within HDSAM Version 2.0 be used.

Scenario-independent delivery and demand information is contained in cells B83 through B103. This information describes baseline conditions for determining hydrogen demand and is generally linked to corresponding data on other tabs within HDSAM. It is also used within this tab for delivery-specific calculations ultimately used to estimate delivery costs.

Rows 134-145 present input (repeated from previous rows in this tab) for the Compressed-Gas Delivery mode. Columns E and F present demand-specific results for compressed gas delivery. These results are obtained by combining the demand calculations (rows 83-103) with the compressed gas delivery information in rows 134-145. Appropriate information from this block is linked to the corresponding component tab for purposes of estimating delivery costs. Rows 149-159 provide the same information for liquid delivery applications. Column B shows basic input parameters and column F displays calculated results.

Cells B162-B179 display input information for pipeline delivery in urban applications. Calculated values are contained in cells F162-F182. These values are linked to the PIPELINE component tab.

<u>"Rural Interstate" Scenarios</u>

The above descriptions of calculated parameters are for "Urban" scenarios. Comparable information for "Rural Interstate" scenarios is presented in rows 189-210. Demand parameters are repeated in cells B189-194 and corresponding results for the various delivery modes are displayed in the remaining blocks. As with "Urban" scenarios, appropriate results from this tab are linked to the corresponding component tab for use in estimating delivery costs.

<u>"Combined" Scenarios</u>

Information for "Combined" scenarios is presented in rows 217-225. Note that all the information on "combined" scenarios displayed on the SCENARIO PARAMTERS tab is calculated (contained in blue color-coded cells).

4.5.2 "Inactive" Cells

Tables 5 and 6, as well as a number of other cell ranges are not linked to other parts of the model and the user is cautioned against attempting to enlist them in the process of defining a particular scenario.

Table 5 contains information on "Large" and "Small" cities. These two city sizes were the market sizes considered in the early development of HDSAM but have since been replaced by specific urbanized areas or generic urban areas with populations between 50,000 and 20,000,000 persons as described in Section 4.2. Table 5 is included in this tab solely for historical purposes.

Table 6 provides information on centralized hydrogen production. As with Table 5, this information was used in the early development of HDSAM but is not used in Version 2.0 of the model. However, future versions of HDSAM may link hydrogen production with delivery. Therefore Table 6 is included in this tab both for historical reasons and as a placeholder for potential application in future versions of HDSAM.

Hydrogen demand in an urban area is described in cells B118-B131. These cells also display the estimated number of hydrogen-capable refueling stations and the percent of total gasoline stations that are hydrogen-capable. Cells B130 and B131 show demand as a percentage of an assumed hydrogen production facility (cells F25 and F26) but these values have no real impact on the simulation results in the Version 2.0 framework.

5.0 Copyright Notice

References

Kelly, B. et al., *H2A Hydrogen Delivery Infrastructure Analysis Models and Conventional Pathway Options Analysis Results*, Nexant, Inc., Argonne National Laboratory, National Renewable Energy Laboratory, and Pacific Northwest National Laboratory, Interim Report, Contract DE-FG36-05GO15032, September 2008.

National Petroleum News, accessed Nov. 2007 at http://www.npnweb.com/uploads/researchdata/2006/USAnnualStationCount/06-stationcount.pdf.