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Production of Hydrogen at the Forecourt Using Off-Peak Electricity

June 2005

J.I. Levene

Prepared for the U.S. Department of Energy Hydrogen, Fuel Cells & Infrastructure Technologies Program in fulfillment of the FY 2005 NREL Milestone 3.2.1.5 Final Report on the Design and Cost of Electrolysis Scenario Options

Milestone Report
NREL/MP-560-38354
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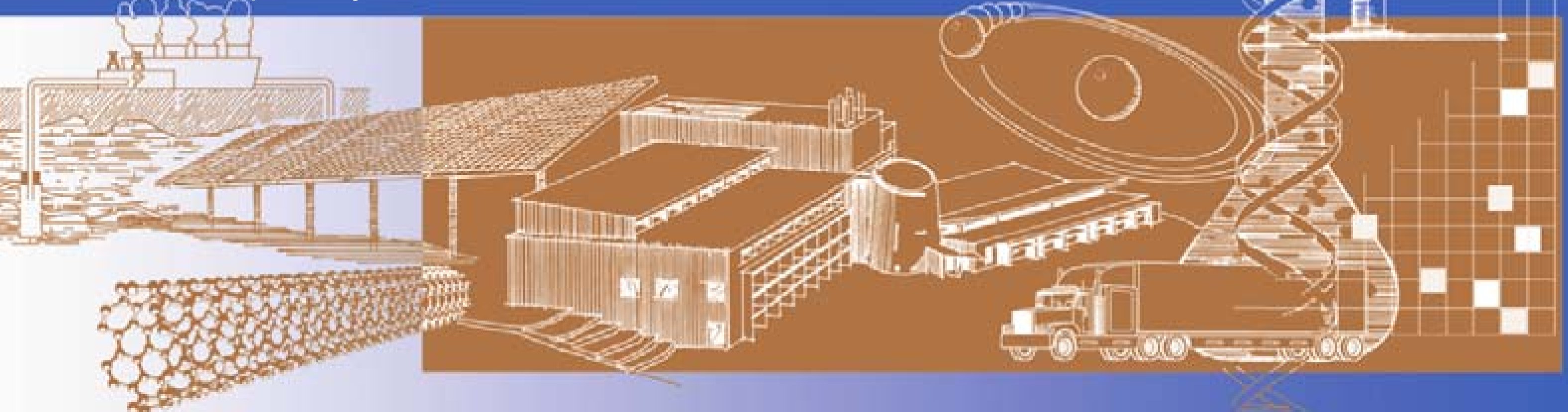

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1. Executive Summary

One of the driving costs of hydrogen production via electrolysis is the price of electricity. Often, when analyzing electrolysis, one of the ways researchers and analysts suggest lowering the price of the hydrogen produced is to use off-peak electricity. However, using off-peak electricity does not mean that the price of electricity can be lowered, and the system remains the same. When using off-peak electricity, the electrolysis system must change; for example, additional electrolyzer capacity is needed and additional storage is needed. The Hydrogen from Off-Peak Electricity (HOPE) model was developed to understand the system changes necessary, and resulting cost differences when using off-peak electricity. The HOPE model determines the most economic hydrogen production system configuration for a given electricity pricing structure and hydrogen demand. With this model, electricity-pricing data and hydrogen demand data can be quickly examined for the least cost configuration for hydrogen production via electrolysis. The model can use either 24-hour electricity pricing structures, which accounts for daily variations, or annual 8760-hour annual data sets, which account for seasonal and daily variations.

The system modeled in this analysis is a forecourt electrolysis system designed to produce 1500 kg/day of hydrogen production with varying hourly demand. The system components include an electrolyzer system, a compressor, storage tanks, and a dispensing unit.

In order to determine the optimal system configuration for hydrogen production using off-peak electricity, the HOPE model combines a hydrogen/electric optimization and the Department of Energy's (DOE) Hydrogen Analysis (H2A) model as the back end cash flow calculator. The hydrogen/electricity optimization uses hourly electricity pricing and demand data over the course of a single year, and optimizes the system by minimizing the number of electrolyzers and the number of storage tanks while ensuring the fuel demand is met every hour out of the day, either through hydrogen production or stored hydrogen.

Four analysis stages were used to understand the effects of using off-peak electricity in a forecourt electrolysis system. In the first stage an analysis was run using electricity prices ranging from \$0.01/kWh to \$0.24/kWh varied hourly. Three cases were run: the electricity price was varied from high to low, low to high, and randomly. Some interesting conclusions can be drawn from this analysis stage. The number of hours electricity is available during the day determines the size of the electrolyzer and the size of the compressor, regardless of when the electricity is available. The differences in the three cases come about in the storage requirement. This is because storage requirements change either because hydrogen is produced, and there is no demand, or when there is a hydrogen demand, but no hydrogen is being produced.

In the second analysis stage, three simple electricity pricing cases were run to determine if using off-peak electricity can result in lower hydrogen prices. The electricity price range for the cases was set to $0.04/kWh during 21 hours out of the day, and during the other three hours of the day, the price was $0.08/kWh, $0.09/kWh or $0.10/kWh. Off-peak electricity only resulted in lower hydrogen price when the peak was $0.10/kWh for the 21-hour/3-hour split. This analysis stage shows the importance of the size of the peak when using off-peak electricity. The heuristic used in this analysis, is that that high peak electricity prices are necessary to produce hydrogen at a lower price using off-peak electricity.

In stage 3 of the analysis, two cases were run using two different electricity pricing structures where the electricity prices varied from $0.01/kWh - $0.20/kWh. Both electricity price ranges were run for four different sets of capital cost and efficiency scenarios to develop and understanding of how technology improvements can change the price of hydrogen and the system optimization. The results of this analysis stage show that as the system costs decrease and efficiencies improve, the resulting hydrogen price using off-peak electricity is lower.

In stage 4 of the analysis, the model was used to test actual 8760-hour real time pricing data that were obtained from ISO New England. The goal of this stage was to determine if using off-peak electricity results in a lower hydrogen price when electricity prices vary daily and annually. This analysis stage shows that if utilities disrupt power to electrolysis units during peak electricity demands for a few hours out of the year the price of hydrogen is not adversely affected. However, it appears as though using off-peak electricity for more than a few hours of peak shaving leads to a higher hydrogen price. This is partially due to the storage assumptions made with this version of the HOPE model, which work well for 24-hour electricity price ranges, but need to be improved for 8760 price ranges. Modifications should be made to the model to better account for the storage needs and resulting hydrogen prices during seasonal peak electricity pricing periods.

The HOPE model provides the capability to determine the best off-peak pricing structure for the production of hydrogen using both 24 hour and 8760 hour data; it determines how hydrogen production system configurations change with different electricity price distributions; it determines if off-peak electricity can lead to a lower hydrogen price; it evaluates how system improvements change the hydrogen production system and the optimum off peak pricing structure; and it can provide data to help calculate how best to run an electrolysis hydrogen production system for a given electricity pricing structure and demand curve. In short, this model can help answer the question for any site: does using off-peak electricity for electrolysis lead to lower hydrogen prices? Also, the HOPE model can help clarify under what conditions different locations can meet the DOE hydrogen cost targets of $2 - $3/kg of hydrogen using forecourt electrolysis.

2. Overview

The purpose of this analysis is to examine the production of hydrogen via electrolysis at the forecourt station using off-peak electricity. The goal of the analysis is to understand if hydrogen can be made more economically using off-peak electricity than by using electricity 24 hours a day. As a result, the Hydrogen from Off-Peak Electricity (HOPE) model was developed to find the system configuration that leads to the most economic production of hydrogen for a given electricity pricing structure and hydrogen demand.

The model can use either 24-hour electricity pricing structures, which account for daily variations, or annual 8760 electricity pricing structures, which account for seasonal and daily variations. The 24-hour pricing structure allows for hypothetical pricing structures to be tested in order to better understand when, in general, using off-peak electricity results in a lower hydrogen price. The 8760 pricing structure allows for actual hourly pricing data from utilities to be used to determine the best electricity usage for any location.

The model was used to run several analysis cases to determine the optimum hydrogen system configuration for several 24-hour electricity pricing structures. These helped to develop an understanding of when, in general, off peak pricing results in a lower hydrogen price.

The model was then used to test actual 8760 real time pricing data that were downloaded from ISO New England. These data provide pricing information from 950 different locations including hubs, hub nodes, load zones and network nodes. These data were then entered into a database where the data could be summarized into usable datasets. The 8760 data were extracted from the database for the two network nodes with the highest and lowest electricity price averages. These data were then entered into the model, and the optimum electricity usage and resulting hydrogen selling price was determined for each node.

3. Introduction

When studying hydrogen production via electrolysis, electricity is a driving cost in the price of hydrogen. One of the ways researchers and analysts often suggest lowering the cost of the hydrogen produced from electrolysis is by using off-peak electricity. However, when using off-peak electricity, the price of electricity cannot just be lowered, resulting in a lower cost of hydrogen. Using off-peak electricity means using electricity less hours out of the day. This means the electrolyzer would have to be upsized to produce the same amount of hydrogen over the course of a day or year, but its capacity factor would be lower. In addition, in a forecourt situation, more storage would be needed to meet the demands of the station if hydrogen was being produced when there was no demand, or if there was a demand, but no hydrogen was being produced.

The HOPE model was built to determine if off-peak electricity could be used to produce lower cost hydrogen via electrolysis. It takes into account hydrogen demand curves, electricity pricing throughout an entire year, and hydrogen storage when using off-peak electricity and calculates a hydrogen price. That price can then be compared to a system using electricity 24 hours a day to see if using off-peak electricity is economically attractive.

4. Assumptions

A set of standard assumptions was used for all analyses run. The most critical assumption made in this analysis is that the electrolyzers at the forecourt, requiring around 3.3 MW per station, will be able to pay real time electricity rates, which vary hourly. As the hydrogen economy evolves, utilities will need to determine if such time-of-day pricing structures for such installations is appropriate.

However, assuming such pricing is possible, several other assumptions need to be clarified. The first is that the system being modeled is a forecourt hydrogen production station with onsite electrolysis. This system is to meet the demands of 1500 kg/day of hydrogen production, and the demand varies from hour to hour throughout the day. The demand profile, shown in Figure 1, is the same as the profile used in the H2A forecourt models. However, different demand profiles can be entered into the model and tested if desired. Note that for this demand profile, hydrogen is needed most during the hours from 7-8 a.m. and 5-6 p.m.

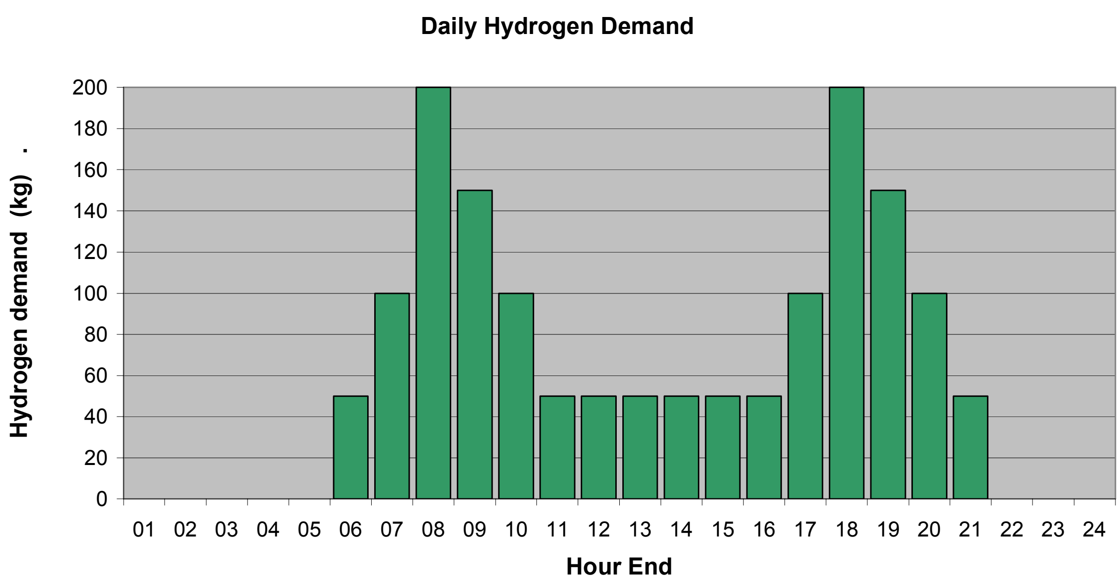


Figure 1: Assumed daily hydrogen demand distribution

The system is modeled using four Scenarios. These Scenarios represent different levels of cost and technological advancements in electrolysis, compression and storage technologies. Scenario 1 represents the technologies as they exist in 2005. Scenario 2 represents a less expensive electrolysis unit that has a lower energy requirement. In addition, the number of compressors required, and thus cost, is halved as the units become more reliable. It is also assumed that hydrogen can be stored at lower costs. Scenario 3 represents a further reduction in electrolyzer cost, and an additional reduction in the energy needs of the electrolyzer (i.e., higher efficiency). Hydrogen is also produced at a higher pressure from the electrolyzer, so compression needs are reduced. Also, costs of the compressors are reduced. Finally, there is a further reduction in storage costs. Scenario 4 represents the most optimistic set of assumptions with a further reduction in electrolyzer capital cost, an additional decrease in electrolyzer energy requirements, and the electrochemical compression of hydrogen to 6500 psi in the electrolysis unit without external compression.

Table 1: Analysis Scenarios

Scenario number	1	2	3	4
Electrolyzer Cost, 1046 kg/day ($/kW)	740	400	300	200
Electrolyzer Energy Requirement (kWh/kg H_2)	53.4	47.9	44.7	43.0
Storage Tank Cost, 85 kg ($/tank)	100,000	40,000	26,000	26,000
Compressor Cost, 1500 kg ($/compression system)	600,000	300,000	100,000	0
Compressor Electricity requirement (kWh/kg H_2)	2.09	2.09	2.09	0
Dispensing Cost ($ for a system with 3 dispensers)	67,000	67,000	67,000	67,000
Control and Safety Equipment ($)	19,000	19,000	19,000	19,000

The assumptions in Table 1 are derived from the following sources (Note that all costs are uninstalled costs):

- Electrolyzer cost and efficiency assumptions
    - Scenario 1 is based on a quote from an electrolyzer vendor.
    - Scenarios 2 and 3 are based on the assumptions used in the H2A mid and long term electrolysis cases.
    - The Scenario 4 assumption for electrolyzer cost is the lowest cost presented in the Department of Energy's (DOE) Hydrogen, Fuel Cells, and Infrastructure Technologies (HFC&IT) Program's May 2005 Multi Year Program Plan (MYPP), and the electrolyzer energy requirements are the best-case sensitivity value used in H2A electrolyzer sensitivity analysis for the long term.
- Storage tank costs
    - Scenario 1 are based on quotes for 85 kg 6500 psi storage tanks in 2005.
    - Scenarios 2, 3 and 4 are based on the storage costs in the H2A forecourt assumptions.
- Compressor costs

- All Scenario costs come from delivery analysts in the HFC&IT program
    - Scenario 1 assumptions represent two 1500 kg/day compressors which are needed due to their unreliability in 2005
    - A single compressor in Scenario 2
    - An advanced compressor combined with some electrochemical compression in the electrolyzer in Scenario 3
    - Complete electrochemical compression in the electrolyzer in Scenario 4.
- Electricity requirement for compression and dispensing, control and safety equipment costs come from the H2A forecourt assumptions.

In addition to the above capital cost assumptions, it is assumed that the electrolyzer cell stack needs to be replaced at 30% of the installed capital cost every 10 years, and the entire compression system needs to be replaced every 10 years.

The hydrogen price was determined using the H2A model. The assumptions used in the H2A model for all Scenarios are detailed in Table 2.

Table 2: H2A Assumptions

Parameter	Assumption
Process Parameters	
Primary Feedstock	Electricity and Water
Electricity Used	Industrial Electricity
Conversion Technology	Electrolysis
Financial Parameters	
Start-up Year	2005
After-Tax Real IRR (%)	10
Depreciation Type	MACRS
Depreciation Schedule Length (No. of Years)	20
Analysis Period (years)	40
Plant Life (years)	40
Assumed Inflation Rate (%)	1.9
State Income Taxes (%)	6
Federal Income Taxes (%)	35
Effective Tax Rate (%)	38.9
% Equity Financing	100
Length of Construction Period (years)	1
% of Capital Spent in 1st Year of Construction	100
Start-up Time (years)	1
% of Revenues During Start-up (%)	75
% of Variable Operating Costs During Start-up (%)	75
% of Fixed Operating Costs During Start-up (%)	100

Parameter	Assumption
Salvage Value of Capital (% of Total Capital Investment)	10
Decommissioning Costs (% of Total Capital Investment)	10
Replacement Capital Parameters	
Electrolyzer cell stack lifetime (years)	10
Electrolyzer cell stack replacement cost (% of initial cost)	30%
Compressor lifetime (years until 100% replacement)	10
Indirect Depreciable Capital Parameters	
Buildings (% of fixed capital investment)	14
Yard Improvements (% of fixed capital investment)	3.5
Construction (% of fixed capital investment)	9
Engineering and design (% of fixed capital investment)	8
Contingency (% of fixed capital investment)	25
Non Depreciable Capital Parameters	
Land ($/acre)	5,000
O&M Parameters	
Burdened Labor ($/hour)	50
Overhead and G&A (% of labor cost)	20
Property Tax (% of depreciable capital costs)	1
Insurance Rate (% of depreciable capital costs)	1

Note that for this analysis, fractional pieces of equipment are used because the analysis is based on sizes of equipment that are available in 2005 and this analysis should not be constrained by the sizes of equipment currently available.

5. System design

The system modeled in this analysis is a forecourt electrolysis system. It consists of the following:

- An electrolyzer system, or multiple electrolyzers, sized to meet the demand of the forecourt system. The electrolyzer system consists of the transformer, thyristor, electrolyzer unit, lye tank, feed water demineralizer, hydrogen scrubber, gas holder, deoxidizer, and a twin tower drying unit.
- A compressor to compress the hydrogen to approximately 6500 psi sized to meet the maximum hourly flow rate of the system
- Storage tanks for 6500 psi hydrogen sized to meet the demands of the forecourt system when the electrolyzer isn't running
- Dispensing unit for fueling, consisting of 3 dispensing pumps

With regards to feedstock, raw materials, and utilities, the following are needed.

- The system feedstock is considered to be electricity, which is needed for the electrolyzer system at a value equal to the electrolyzer energy requirement seen in Table 1.
- Water for electrolysis, is used at a rate of 11.13 L/kg of hydrogen.
- Cooling water is used at a rate of 1100 L/kg of hydrogen.
- Compressed inert gas is needed for system purges.

- A 25% solution of potassium hydroxide is needed for the electrolyte, and is replaced annually.
- 2.09 kWh of electricity is needed per kilogram of hydrogen compressed, as seen in Table 1.

For a more thorough overview of the electrolysis system, see the milestone report, “Summary of Electrolytic Hydrogen” by Johanna Ivy.

6. Modeling system

The assumption made going into this study was that whether or not using off-peak electricity is economical would be based largely on three variables: average electricity price, capacity factor for the electrolyzer, and capital cost. Those parameters are related in the following way:

- The use of off-peak electricity first affects the average cost of electricity. For example: a location may have a peak price of $0.20/kWh for one hour out of the day, and $0.04/kWh pricing the rest of the day. For this location, the average electricity price would be $0.046/kWh for the entire day, but only $0.04/kWh if the peak hour were dropped.
- This then affects the second parameter, capacity factor. If electricity is used all day, the electrolyzer runs 100% of the time it is available. Assuming each electrolysis unit is available 97% of the time, the capacity factor when the electrolyzer runs 24 hours a day is 97%. However, if the electrolyzer isn’t used during a single peak hour, the capacity factor drops to 93%. This means that 7% of the time the electrolyzer is not in use. In addition, it means that during that 7% of the time, hydrogen must be available in storage to meet the demands for that hour when hydrogen is not being produced.
- This leads to the effect of the third parameter: capital cost. When the electrolyzer is only used 93% of the time, more electrolyzers are needed to meet the demands of the system and produce the same amount of hydrogen during the resulting run hours. In addition, more storage is needed so that hydrogen is available in storage to meet the demands when the electrolyzer is not running. Finally, additional compressors are needed to meet the larger production rates of the additional electrolyzers. Producing hydrogen using off peak power only results in a lower hydrogen price when the decrease in the average electricity price offsets, or more than offsets, the additional cost of the equipment due to the decrease in the capacity factor of the electrolysis unit.

To model the effects of the above three parameters and find the optimal system configuration for hydrogen production using off-peak electricity, the HOPE model combines the H2A model with a hydrogen/electric optimization.

The following terms are used throughout the report, and are presented for clarification:

- Scenario: As seen in table 1, a Scenario is a set of assumptions with regards to capital cost and energy needs of the system. The H2A model is run using the Scenario assumptions.
- Case: Cases represent an electricity pricing structure for which an optimized system and a resulting hydrogen price is solved. Each Case is run using a single Scenario, but a Case can be run with more then one Scenario to determine how capital cost reductions and system efficiencies affect the resulting optimized system and hydrogen price. The result of a Case is the optimized hydrogen system, and the hydrogen selling price resulting from that system
- Run: A Run is a system optimization and resulting hydrogen price for a single Price Point in a Case. So if a Case had electricity prices that ranged from $0.01/kWh to $0.05/kWh, you could have Runs where the Price Point was $0.01/kWh, $0.02/kWh and $0.05/kWh. Many Runs make up a Case, and the Run with the lowest hydrogen price is the optimized result for any given Case.
- Price Point: an electricity price that defines the range of electricity prices used in a Run. All electricity prices less then or equal to the Price Point are used. For example, if a three-hour electricity price range was $0.02, $0.04 and $0.06/kWh, and the Price Point was $0.04/kWh, two hours would be used for the Run, $0.02/kWh and $0.04/kWh.

The hydrogen/electricity optimization side of the HOPE model uses hourly electricity pricing and demand data over the course of a single year, and optimizes the system by minimizing the number of electrolyzers and the number of storage tanks while ensuring the fuel demand is met every hour out of the day, either through hydrogen production or stored hydrogen. A Price Point is used to set the electricity price at or below which hydrogen will be produced. The number of electrolyzers, storage tanks and compressors, along with the average electricity price, capacity factor and plant design capacity are calculated for various Price Points in an electricity pricing structure. The equipment data, average electricity price, capacity factor and plant design capacity for each Price Point are fed into the H2A model and a price of hydrogen is calculated. The hydrogen prices for various Price Points can then be compared and the optimum system for a particular electricity pricing structure can be obtained. A flowchart of how the HOPE model works is presented in Figure 2.

Table 3 details the parameters that are fed into the H2A model from the hydrogen/electricity optimization:

Table 3: Parameters passed from the hydrogen/electricity optimization side of HOPE to the H2A model.

Parameter	Description
Plant design capacity (kg/day)	The optimization model changes the number of electrolyzers, so that the plant output meets the hourly demand of the forecourt. The number of electrolyzers changes the plant design capacity
Operating capacity factor (%)	The optimization model calculates the operating capacity factor of the system, given the number of electrolyzers and the hours when the electrolyzers are being used to produce hydrogen, when electricity prices are below the electricity Price Point.
Plant Output (kg H2/year)	The plant output is a calculation that is the product of the plant design capacity and the operating capacity factor. The plant output is approximately 550,000 kg/year, which is the amount of hydrogen the forecourt station demands in a year. The only variation of this number occurs from the potential for an initial amount of hydrogen charged to the system to meet early hours of demand and does not need to be produced.
Number of Electrolyzers	The optimization model changes the number of electrolyzers so that the hydrogen available from the electrolyzers and storage tanks meets the hourly demand of the forecourt. The number of electrolyzers needed is based on the hours when the electrolyzers are being used to produce hydrogen, when electricity prices are below the electricity Price Point.
Number of 85 kg storage tanks	The optimization model changes the number of storage tanks so that the hydrogen available from the electrolyzers and storage tanks meets the hourly demand of the forecourt.
Number of 1500 kg compressors	The optimization model sizes the compressors to meet the maximum hourly flow rate of hydrogen being produced.
Electricity feedstock cost	The electricity feedstock costs are the average of all hourly electricity prices less than or equal to the electricity Price Point in the model.

The required hydrogen selling price, along with the cost contributions, such as capital costs, fixed operation and maintenance (O&M), and feedstock costs, are fed from the H2A model back into the hydrogen/electricity optimization model for each electricity Price Point. These results can then be analyzed to determine if it is advantageous to use off-peak electricity for the electricity price range and demand curve entered. If the hydrogen price is lower using off-peak electricity than using electricity 24 hours a day, there is an advantage to using off-peak electricity.

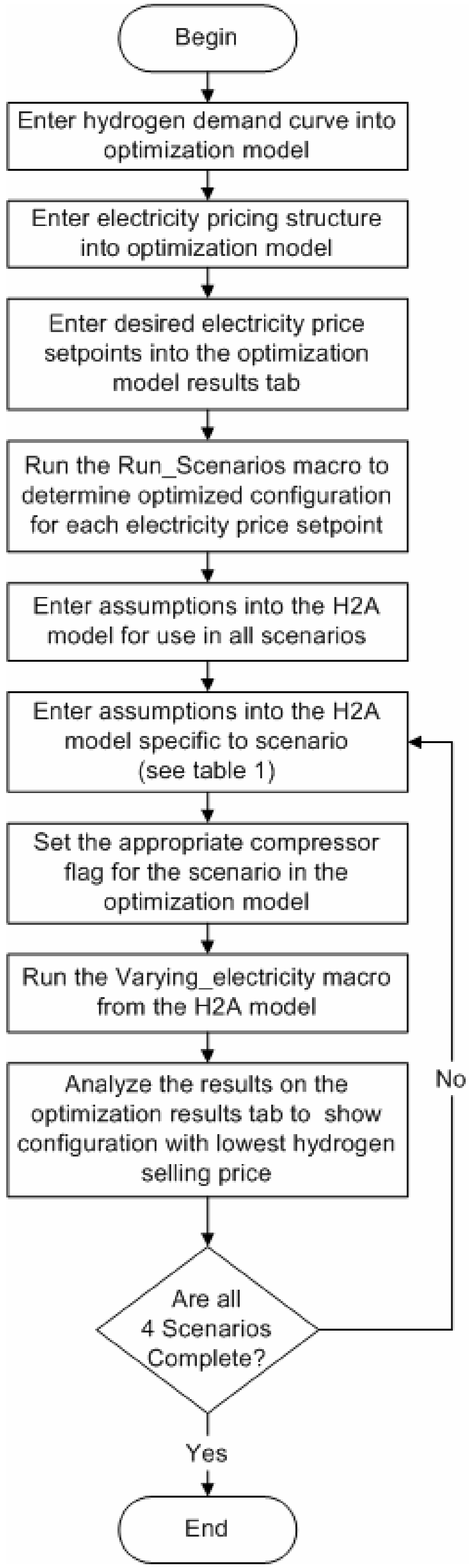


Figure 2: Hope Model Flowchart

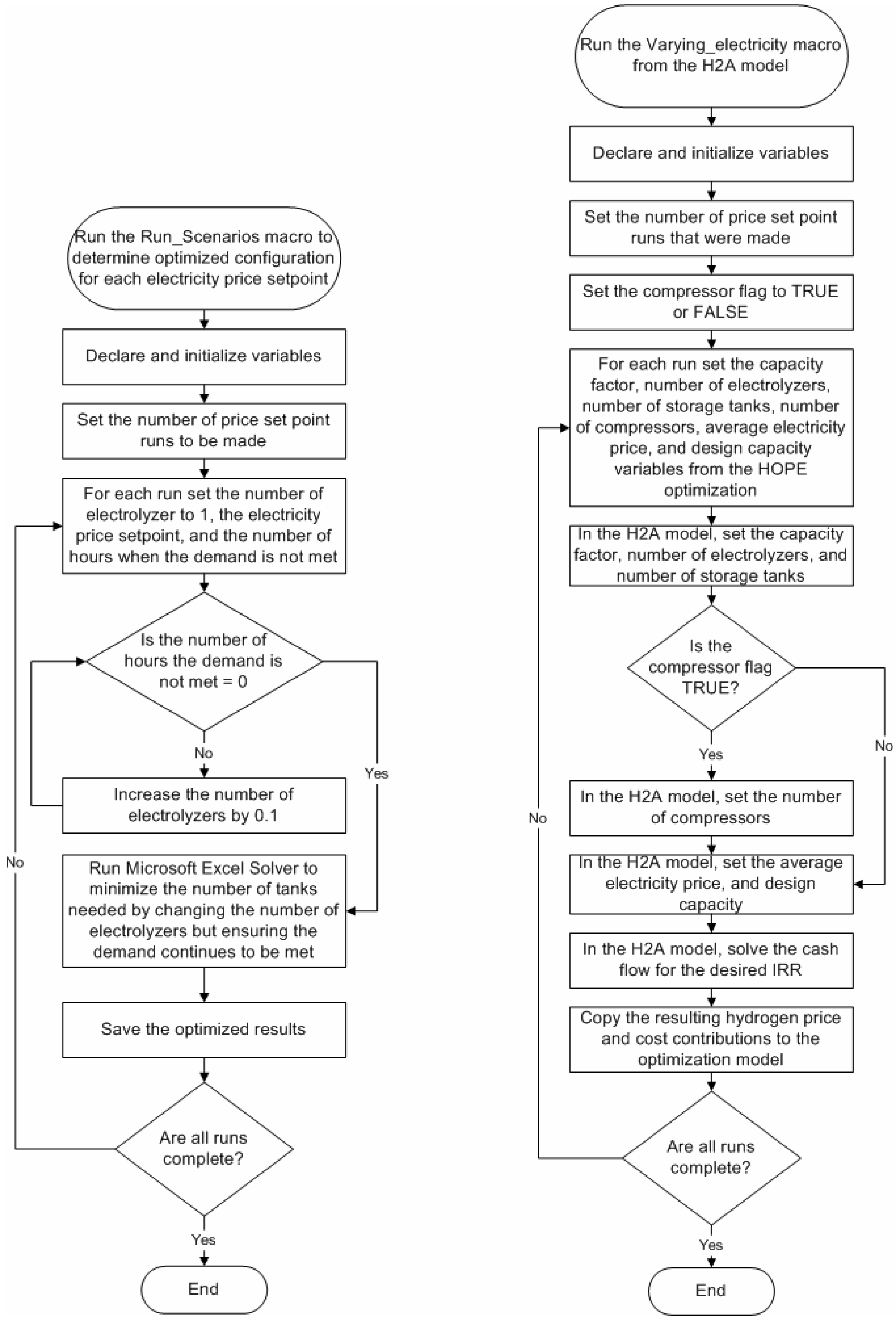


Figure 2: Hope Model Flowchart (continued)

7. Analysis Stages

In order to understand the effects of using off-peak electricity on a hydrogen production electrolysis system, four different stages of analysis were conducted. In the first stage, different electricity price distributions were used for the same electricity price range to determine if just changing when electricity peaks occur changes the hydrogen production system configuration. In the second stage, Cases were run to see if off-peak electricity could lead to a lower hydrogen price. In the third stage, Cases were run through all four Scenarios in order to determine the effect of system improvements when using 24-hour electricity price distributions. All three of the first stages use 24-hour electricity price ranges to understand how daily fluctuations in electricity price could affect hydrogen production costs. In the fourth stage, 8760 data was entered in the model to see how both daily and seasonal electricity price distribution affect the use of off-peak electricity to produce hydrogen.

a. Stage 1 - Effect of Electricity Price Distribution on System Configuration

Initially, unrealistic, but easy to understand Cases were run, in order to see if there were differences in hydrogen systems with the same electricity price ranges, but different distributions of prices during the day. Three Cases were run. Each Case varied electricity prices each hour from $0.01/kWh to $0.24/kWh by one cent. In the first Case, the prices started at $0.01/kWh at midnight, and increased to $0.24/Wh by 11:00 p.m. In the second Case, the electricity prices were varied inversely to Case 1, with electricity prices starting at $0.24/kWh at midnight, and decreasing through the day to $0.01/kWh. The final Case randomly varied the electricity price from $0.01/kWh - $0.24/kWh throughout the day. For each Case, 24 Runs were analyzed with Price Points for electricity price ranging from $0.24/kWh to $0.01/kWh in order to see how just varying when hydrogen is produced affected the systems. A graph of each system's electricity price distribution, and the resulting system requirements can be seen in Figure 7.

Some interesting conclusions can be drawn from this analysis. First, regardless of when hydrogen is produced during the day, the number of hours electricity is available at or below a certain price determines the size of the electrolyzer and the size of the compressor. In other words, regardless of when in the day the electrolyzer runs if the Price Point was $0.18/kWh, the electrolyzer only ran 18 hours out of the day; in all three Cases two electrolyzers and 1.3 compressors were needed. Likewise, the design capacity of the plant, plant output, capacity factors, and average electricity price are the same for the same electricity Price Point across all three Cases.

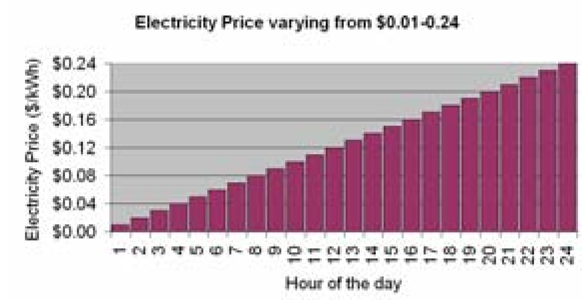
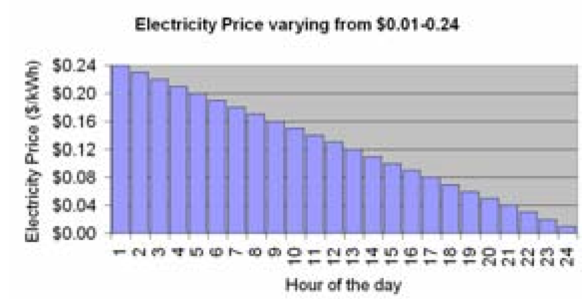
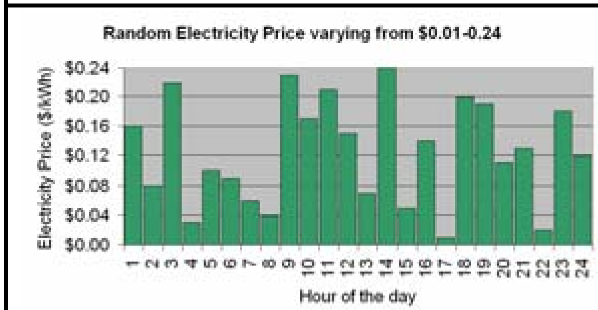
Electricity Pricing Case	Price Point Hours Operating	$0.24/kWh 24	$0.18/kWh 18	$0.12/KWh 12	$0.06/kWh 6	$0.01/kWh 1
	# Electrolyzers	1.5	2.0	2.7	5.9	35.43
	Max # of tanks	13.82	15.28	18.80	27.03	27.62
	Kg H2 Design capacity	560,000	750,000	1,040,000	2,300,000	13,500,000
	Kg H2 Plant output	550,000	550,000	550,000	550,000	550,000
	Capacity factor	97.0%	72.8%	52.5%	24.3%	4.0%
	Avg Electricity Price	0.125	0.095	0.070	0.035	0.010
	# Compressors	1.0	1.3	1.8	4.0	24.0
	# Electrolyzers	1.5	2.0	2.7	5.9	35.48
	Max # of tanks	13.82	10.00	10.00	18.00	18.00
	Kg H2 Design capacity	560,000	750,000	1,040,000	2,300,000	13,500,000
	Kg H2 Plant output	550,000	550,000	550,000	550,000	550,000
	Capacity factor	97.0%	72.8%	52.5%	24.3%	4.0%
	Avg Electricity Price	0.125	0.095	0.070	0.035	0.010
	# Compressors	1.0	1.3	1.8	4.0	24.0
	# Electrolyzers	1.5	2.0	2.7	5.9	35.48
	Max # of tanks	13.82	14.31	15.02	14.70	16.88
	Kg H2 Design capacity	560,000	750,000	1,040,000	2,300,000	13,500,000
	Kg H2 Plant output	550,000	550,000	550,000	550,000	550,000
	Capacity factor	97.0%	72.8%	52.5%	24.3%	4.0%
	Avg Electricity Price	0.125	0.095	0.070	0.035	0.010
	# Compressors	1.0	1.3	1.8	4.0	24.0

Figure 3: Effect of Electricity Price Distribution on System Design, $0.01-$0.24/kWh over 24-hour period

The storage requirement encompasses the differences between the systems. This is because storage is needed either to store hydrogen when there is no demand, or to have hydrogen in storage to meet a demand when there is no hydrogen being produced. Considering all three Cases where the Price Point for electricity is $0.18/kWh, and the system runs 18 hours out of the day, the maximum number of tanks needed for the system varies from 15 to 10 to 14 depending on when the electricity price is high and the system does not run.

Still considering the Price Point of $0.18/kWh, in the first Case, electricity prices are low during the first five hours of the day, and hydrogen is produced. However, there is no demand for the hydrogen during these hours, so the hydrogen must be stored (see Figure 1 for the hydrogen demand curves) In the second Case, when electricity price decreases during the day, the Price Point of $0.18/kWh eliminates five hours during the day when there is no demand for hydrogen, and one hour when there is low demand. As no hydrogen produced during these hours, and there is very little demand, and storage is only needed to meet the one-hour when there is a hydrogen demand. Finally, the third Case shows how a random distribution of electricity prices leads to a higher storage requirement than the second Case, but a lower storage requirement than the first Case. For one hour when hydrogen is not being produced, there is no demand, so no additional storage is needed. However, there is also some demand during two of the hours when hydrogen isn't being produced, so hydrogen storage is needed to meet that demand. So there are more hours when no hydrogen is produced when there is no demand, as compared to Case 1, which leads to a reduction in storage from Case 1. However, there are more hours when no hydrogen is produced but there is a demand as compared to Case 3, thus increasing the storage needs as compared to Case 3.

One item of note is that all of the Cases in Figure 7 were run with a standard assumption that the system started with ten 85 kg storage tanks of hydrogen charged with hydrogen at the beginning of the year. This was so that there was ample hydrogen in the system during early hours when hydrogen storage was not yet built up. However, in Case 2 for both the $0.18/kWh and $0.12/kWh Price Points, the maximum storage size was ten, and this maximum was determined by the size set by the initial tank charge assumption. Changing the initial tank charge assumption does not affect the overall conclusions of this analysis, but should be noted for future Cases when a hydrogen price is calculated, as an excess of storage tanks should not be included in costing analyses.

Once a basic understanding of how hydrogen systems vary with electricity price ranges and electricity price constraints, additional analysis stages were used to see if a pattern could be established as to when using off-peak electricity results in a lower hydrogen production price.

b. Stage 2 - Simple Electricity Pricing: When Does Off Peak Make Sense?

Three simple electricity-pricing Cases were run, using Scenario 1 prices as seen in Table 1. The electricity price range for the Cases was set to $0.04/kWh during 21 hours out of the day, and during the other three hours of the day, the price was varied from $0.08/kWh to $0.10/kWh. The Cases run were as follows:

Table 4: 3 Simple Electricity Pricing Structures

	Case 1	Case 2	Case 3
Hours 1- 12	$0.04/kWh	$0.04/kWh	$0.04/kWh
Hours 13 –15	$0.08/kWh	$0.09/kWh	$0.10/kWh
Hours 16 – 24	$0.04/kWh	$0.04/kWh	$0.04/kWh
Average Electricity Price all day	$0.045/kWh	$0.046/kWh	$0.048/kWh
Average Electricity price at $0.04/kWh Price Point	$0.04/kWh	$0.04/kWh	$0.04/kWh

Each of the Cases was first run with a Price Point high enough so the electrolyzer ran the entire day and used the average electricity price of the entire 24 hour day: 21 hours of $0.04/kWh electricity and 3 hours at the higher price. Then the Case was run where the Price Point was set to $0.04/kWh, so the electrolyzer only produced hydrogen 21 hours out of the day, and the average electricity price was $0.04/kWh. Note that this second Run should yield the same results for all three Cases, as it is the same system: an electrolyzer that runs 21 hours with $0.04/kWh electricity.

The results of these Cases are seen in Figure 8. When the peak price of electricity is $0.08/kWh (the green bars) the price of hydrogen when producing 24 hours a day is $4.04/kg, and is $4.16/kg when using off-peak electricity 21 hours out of the day. This demonstrates that when the peak price of electricity is $0.08/kWh it is more expensive to use off-peak electricity to produce hydrogen when the electricity price is only $0.04/kWh. When the peak price of electricity rises to $0.09/kWh (the blue bars) the price of hydrogen continuously produced 24 hours a day is $4.10/kg, and is $4.16/kg using off-peak electricity. In this Case, the two prices are closer, as the $0.09/kWh peak raises the average electricity price by an additional $0.001/kWh, but using off-peak electricity is still more expensive. Finally, when the peak price rises to $0.10/kWh, the price of hydrogen produced using off-peak electricity is still $4.16/kg, but is $4.21/kg when produced 24 hours a day. This means it is $0.05/kg less expensive to produce hydrogen using off-peak electricity when the peak is $0.10/kWh.

How Hydrogen Price Varies with Peak Electricity Prices

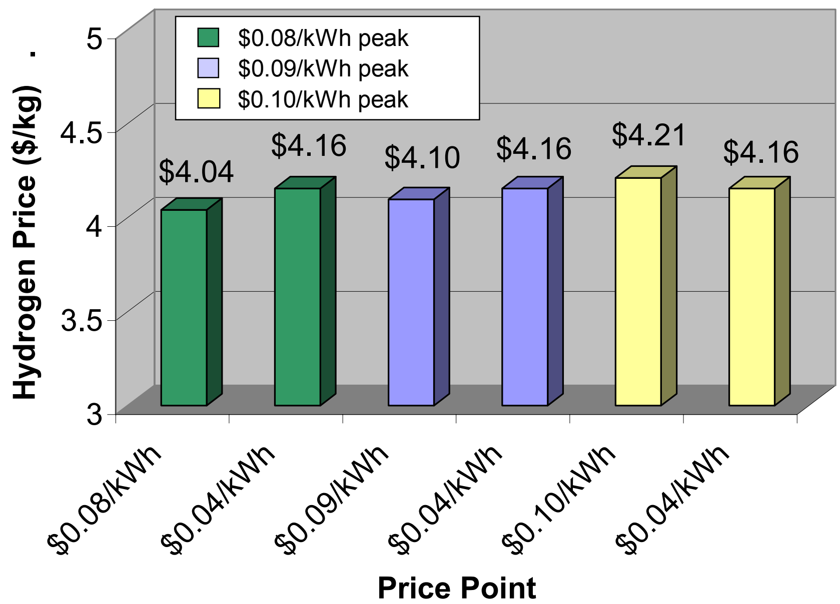


Figure 4: A simple example showing when using off-peak electricity lowers the hydrogen price

This simple analysis shows the importance of the size of the peak when using off-peak electricity. As a general rule of thumb moving forward in this analysis, it was assumed that if the peak price of a system is large enough, off-peak electricity should be used. However, if the difference between the peak price and the off peak price is just a few cents, it is unlikely to reduce the cost of hydrogen enough to warrant using off-peak electricity.

c. Stage 3 - Detailed 24 Hour Electricity Pricing Cases

In stage 3, two Cases were run using varying electricity prices over 24 hours. The electricity prices varied from $0.01/kWh - $0.20/kWh, and the hour-by-hour price range breakdown can be seen in Table 6. Both electricity price ranges were run through Scenarios 1 – 4 to develop and understanding of how technology improvements change the price of hydrogen in each Case.

The first Case uses an electricity price range with a 7-hour peak period where prices are $0.12/kWh, $0.16/kWh and $0.20/kWh. There is then a 10-hour shoulder period where electricity prices are $0.06/kWh and $0.04/kWh. Finally, there is a 7-hour off peak period when prices are $0.01/kWh. The prices and hours when the prices occur were chosen to give a good range of prices, a peak at the noontime, and a long off-peak period with low electricity prices.

The second Case uses an electricity price range with a 9-hour peak period where prices are $0.12/kWh, $0.16/kWh and $0.20/kWh. There is then a 6-hour shoulder period where electricity prices are $0.06/kWh and $0.04/kWh. Finally, there is a 9-hour off peak period when prices are $0.02/kWh or $0.01/kWh. This second electricity price range also has a good range of electricity prices, but the peak is between 3:00 and 4:00 p.m., and the peak period and off peak period are each an hour longer than in the first electricity price ranges.

Table 5: 24 Hour Electricity Price Ranges

Time of Day	Case 1 Electricity Price Range 1 ($/kWh)	Case 2 Electricity Price Range 2 ($/kWh)
12:00 AM	0.01	0.01
1:00 AM	0.01	0.01
2:00 AM	0.01	0.01
3:00 AM	0.01	0.01
4:00 AM	0.01	0.01
5:00 AM	0.04	0.01
6:00 AM	0.04	0.02
7:00 AM	0.06	0.02
8:00 AM	0.06	0.04
9:00 AM	0.12	0.06
10:00 AM	0.12	0.06
11:00 AM	0.12	0.12
12:00 PM	0.2	0.12
1:00 PM	0.16	0.16
2:00 PM	0.12	0.16
3:00 PM	0.12	0.2
4:00 PM	0.06	0.2
5:00 PM	0.06	0.12
6:00 PM	0.04	0.12
7:00 PM	0.04	0.12
8:00 PM	0.04	0.06
9:00 PM	0.04	0.06
10:00 PM	0.01	0.04
11:00 PM	0.01	0.02

Figure 9 below shows the results of the first Case. The figure is organized so that the assumptions common to all four Scenarios can be seen in the upper left-hand corner of the figure. The assumptions detail the Price Point, the average electricity price and the capacity factor for each of the six Runs completed for each Scenario. A Run is simply an optimization for a certain Price Point. So for example, Run 3 uses all electricity at $0.12/kWh and under, meaning that the system uses electricity 22 hours out of the day, from 12 a.m. to 11 a.m., and then from 2 p.m. until 11 p.m. This yields an average electricity price of $0.052 during the 22 hours the system runs, and a capacity factor of 89%. The capacity factor is calculated as the number of hours the electrolyzer is running (22 hours) divided by 24 hours (22/24) multiplied by the capacity factor of the electrolyzer, 97%. On the upper right-hand corner is the legend for all four graphs. There is one graph for each Scenario that shows the resulting hydrogen price for each Run, and the numbers on the x-axis correlate to the Run in the system assumptions. The number on the graph correlates to the lowest price hydrogen that can be produced from this system in each Scenario.

In each Scenario, with this hypothetical electricity price range, using off-peak electricity results in a lower hydrogen price. Scenario 1 has the lowest hydrogen price of $4.59/kg at Run 4, which corresponds to a $0.06/kWh electricity Price Point and a 69% capacity factor. If you consider the cost contribution bars, you can see that the capital cost contribution for Run 4 is higher than in Run 3, but the feedstock electricity price is lowered to the point that the overall cost of the hydrogen is lower. The capital cost contribution increases because the system is operating at a lower capacity factor, so more electrolyzer, storage and compression units are needed to meet the demand. In Run 5 the electricity feedstock cost contribution reduction no longer offsets the increased capital cost contribution. For a Run to result in lower hydrogen price then the previous Run, the growth of the capital cost bar needs to be more than offset by the reduction of the feedstock cost bar (electricity price) when compared to earlier Runs.

In Scenario 2, the lowest price of hydrogen drops to $3.85/kg as the capital costs are reduced and electrolyzer efficiency is improved in Scenario 2. However, the lowest hydrogen price still occurs at Run 4 with a Price Point at $0.06/kWh of electricity. In Scenario 3, the capital cost reductions cause the lowest hydrogen price to drop to Run 5, an electricity price Price Point of $0.04/kWh and a capacity factor of 53%. This Run results in a hydrogen price of $2.70/kg, over a dollar cost reduction from Scenario 2. The reason the lowest price shifts to Run 5 is because for all Scenarios, the electricity cost contribution stays roughly the same. The decrease in electrolyzer efficiency makes the contributions slightly smaller, but not significantly. However, as the capital costs get smaller in Scenario 3, the capital cost contribution bars do not grow as much with the decrease in capacity factor, and smaller electricity cost contributions can offset the smaller increase in capital costs, which leads to an overall lower cost. In Scenario 4 the hydrogen price drops to $1.90 a kilogram, and Run 5 has the lowest hydrogen price, the same as Scenario 3. In summary, as the capital costs of the system decrease in Scenarios 2-4, using lower cost electricity becomes more advantageous.

The results of this analysis show that as the system costs reduce and efficiencies improve, the resulting hydrogen price using off-peak electricity is lower. In addition, these process improvements can lead to a shift in the Price Point where off-peak electricity becomes economically attractive. As the system improves, the Price Points, and thus capacity factors, can be lowered and hydrogen will be produced at a lower price. To validate the results seen in the first Case, a second Case was run with a second electricity price range. The results from this Case can be seen in Figure 10. Again, the analysis shows that in all four Scenarios using off-peak electricity results in a lower hydrogen price.

Assumptions							
Run	**Units**	**1**	**2**	**3**	**4**	**5**	**6**
Price Point	$/kWh	$0.20	$0.16	$0.12	$0.06	$0.04	$0.01
Avg. Electricity Price	$/kWh	$0.063	$0.057	$0.052	$0.032	$0.024	$0.010
Capacity Factor	%	97%	93%	89%	69%	53%	28%

Legend – Cost Contributions ($/kg)

	Other Variable Costs
	Other Raw Material
	Electricity Feedstock
	Fixed O&M
	Decommissioning
	Capital Cost

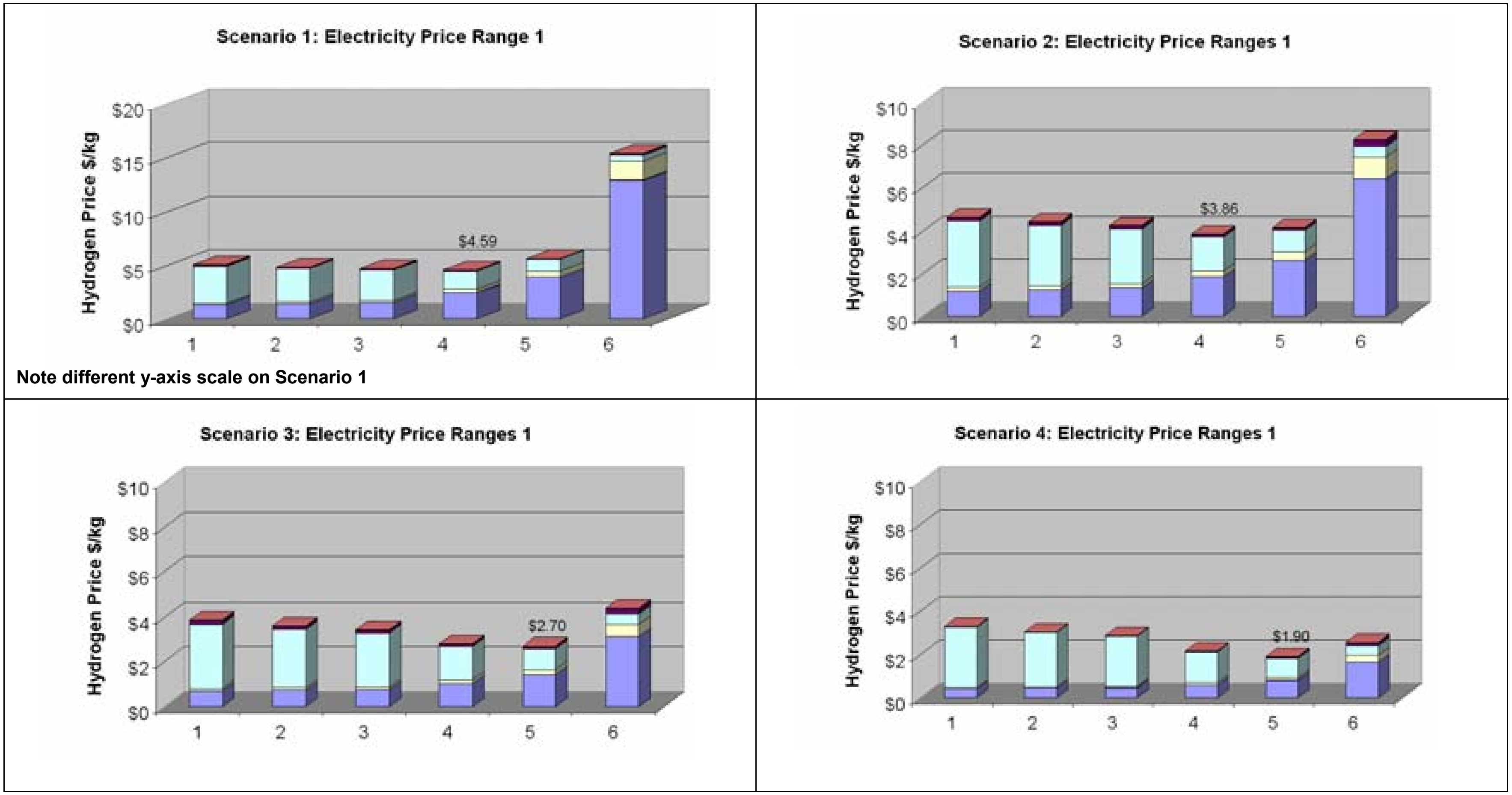


Figure 5: Assumptions, Legend and Cost Contribution Charts for Electricity Price Range 1 Case

Assumptions								
Run	**Units**	1	2	3	4	5	6	7
Price Point	$/kWh	$0.20	$0.1	$0.12	$0.06	$0.04	$0.02	$0.01
Avg. Electricity Price	$/kWh	$0.073	$0.062	$0.052	$0.029	$0.018	$0.013	$0.010
Capacity Factor	%	97%	89%	81%	61%	44%	36%	24%

Legend – Cost Contributions ($/kg)

	Other Variable Costs
	Other Raw Material
	Electricity Feedstock
	Fixed O&M
	Decommissioning
	Capital Cost

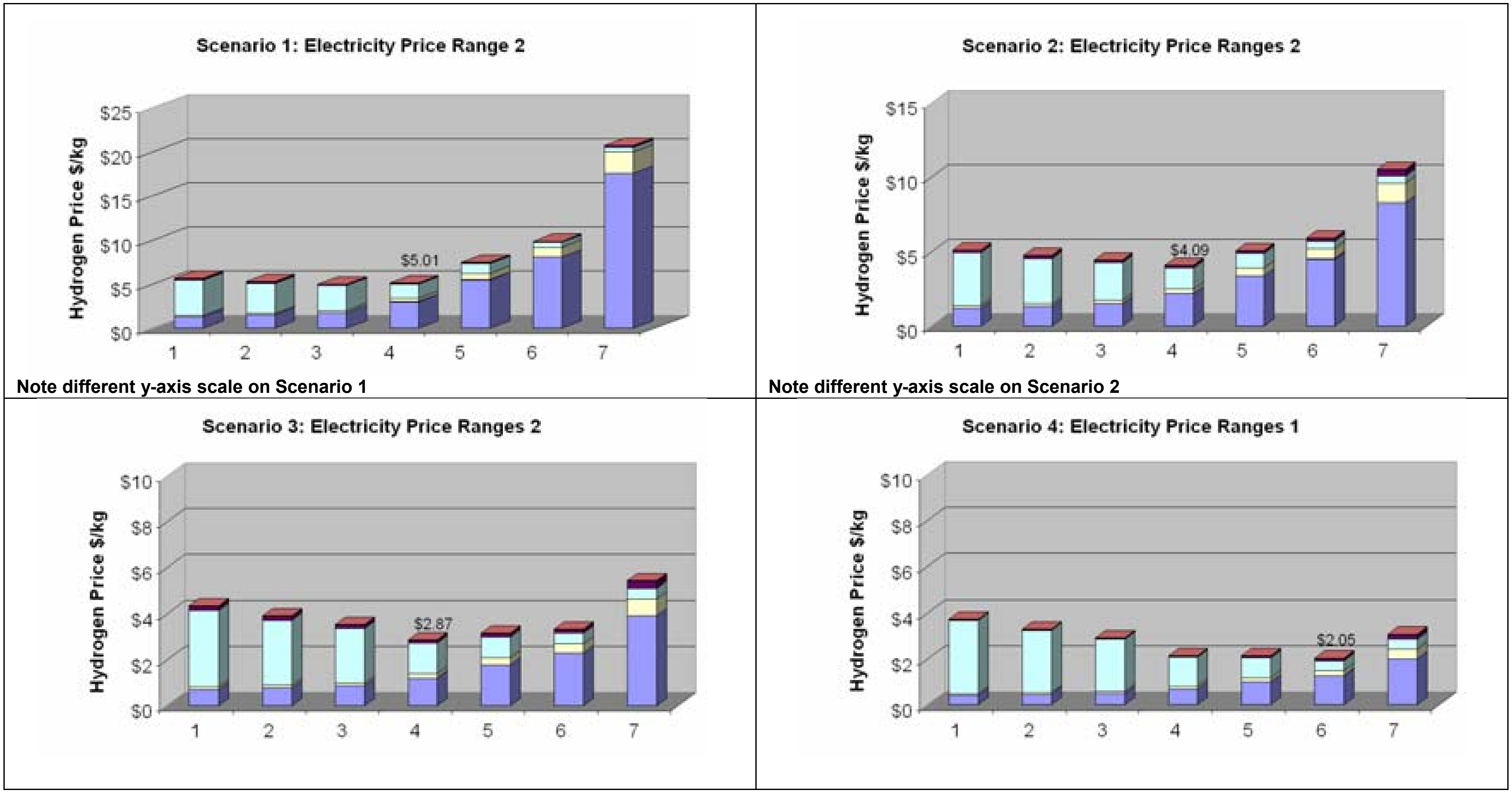


Figure 6: Assumptions, Legend and Cost Contribution Charts for Electricity Price Range 2 Case

d. Stage 4 - Real Time Cases

The final analysis stage uses the HOPE model to determine if using off-peak electricity results in a lower hydrogen price using electricity prices that vary over the entire year, not just 24 hours. Until this point in the analysis, hypothetical 24-hour electricity price structures were used to determine if off-peak electricity could result in lower priced hydrogen. However, it should be determined if using off-peak electricity with actual real time electricity prices yields the same result: that using off-peak electricity results in lower hydrogen prices. Two sources of real time market electricity prices were considered from the New York Independent System Operator (NYISO) website and the Independent System Operator New England (ISO New England) website. Due to the ease in collecting the ISO New England data, it was chosen as the source for real time electricity pricing in this analysis, but the NYISO data could be considered in future Cases. From ISO New England's website, the "Combined Day-Ahead and Preliminary Real Time Report" was downloaded for each day, and the Real Time Location Marginal Price (LMP) was used to calculate the price of electricity. The Real Time LMP is a sum of the Real Time Energy Component, the Real Time Congestion Component and the Real Time Marginal Cost Component. These data are available for all pricing nodes from ISO New England. It should be noted that the use of these data need to be vetted with industry for their applicability for this particular use, however, even if the prices are not exactly applicable to this analysis, their hourly and seasonal variations give a different view of electric pricing structures than the hypothetical 24 hour electricity price ranges. In addition, this model is meant for easy re-runs of data, so as additional sources of data are found and vetted, the results can be re-evaluated.

Hourly real time pricing data for 950 nodes were downloaded from NE ISO from May 1, 2004 to April 30, 2005 and entered into a Microsoft Access database. Queries were then run to determine the NE ISO nodes that had the highest average electricity price, and the lowest average electricity price for the entire time period. The node with the highest average electricity price was network node 4616, which had an average electricity price of \$0.055/kWh, a max electricity price of \$0.79/kWh and a minimum electricity price of \$0.00002/kWh. The node with the lowest average electricity price was network node 4010 with an average price of \$ 0.048/kWh, a maximum price of \$0.61/kWh and a minimum price of \$0.00002/kWh. The electricity price distribution for these two nodes can be seen in Figures 11 and 12

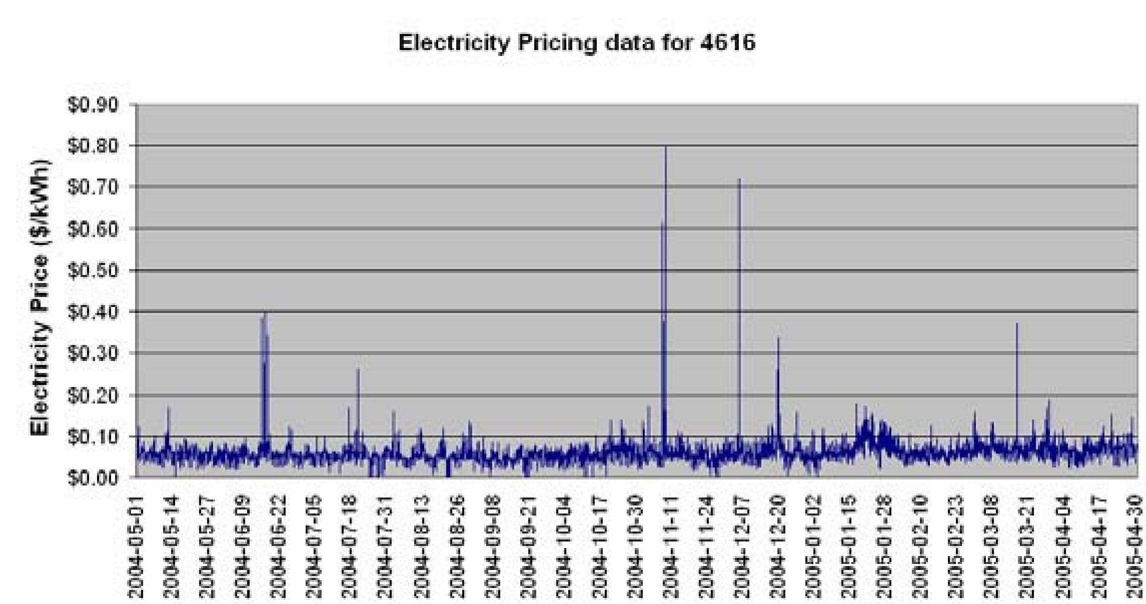


Figure 7: Hourly real time electricity prices for ISO-NE Node 4616

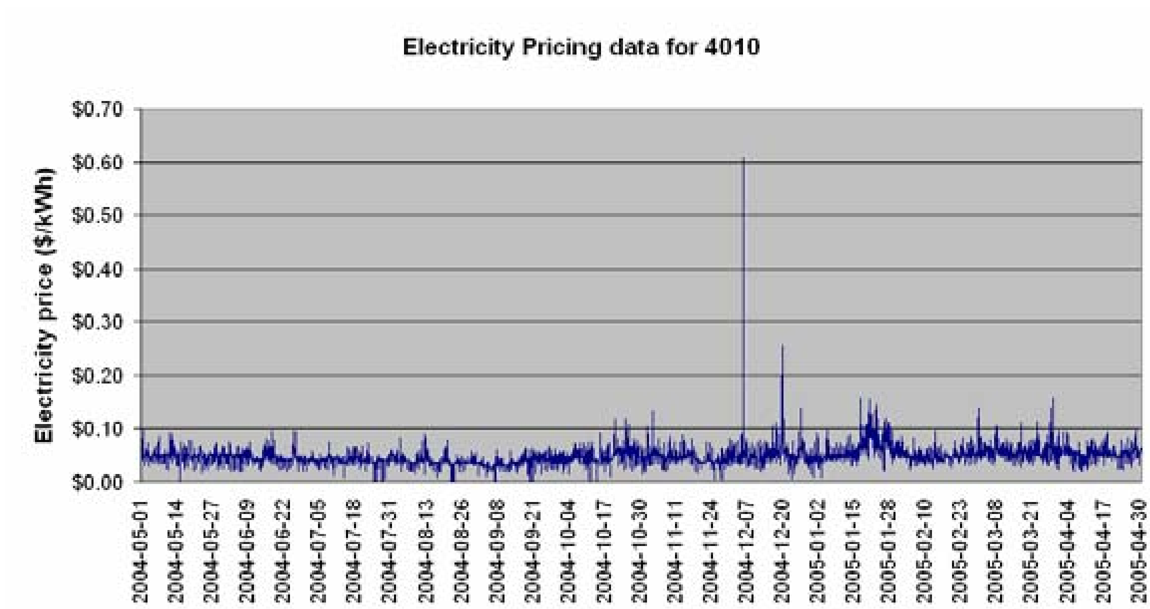
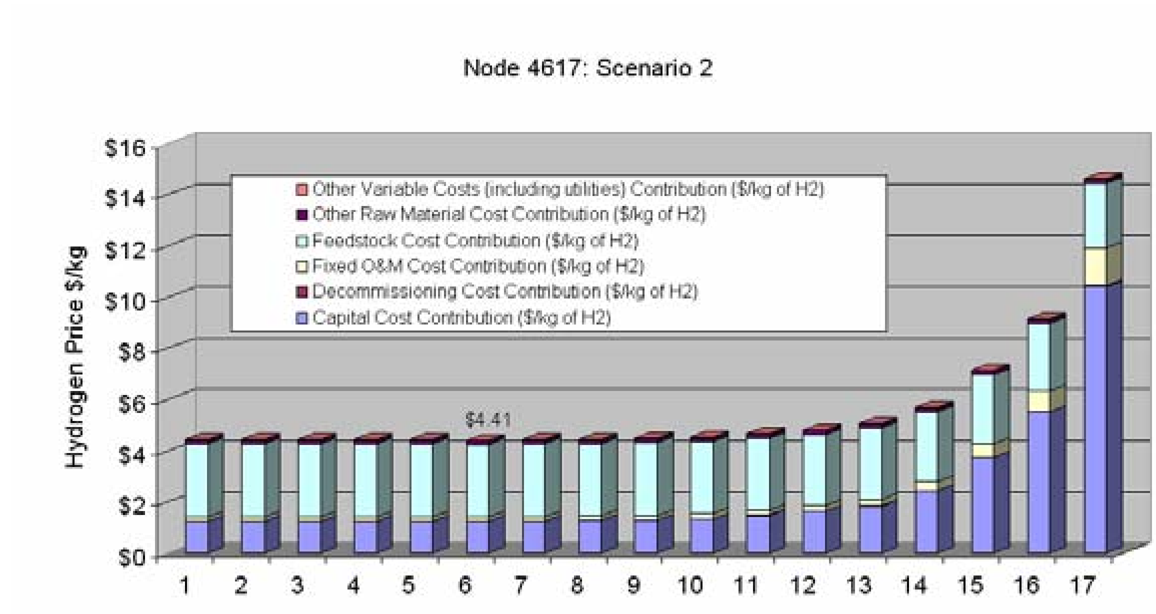


Figure 8: Hourly real time electricity prices for ISO-NE Node 4616

The hourly (8760) electricity prices for the two nodes were entered into the HOPE model. Appropriate Price Points for the data were entered into the model, and the system was optimized and the resulting hydrogen prices were found. For both systems, only Scenario 2 was run in order to get an understanding of whether or not using off-peak electricity results in lower hydrogen prices. Additional Runs for other Scenarios could be run in the future to develop an understanding of how technology improvements modify the results.

Figure 13 shows the results of the HOPE model for ISO NE Node 4616. This model shows that reducing the Price Point from the high value of $0.80/kWh to $0.30/kWh makes the largest reduction in cost. This lowest hydrogen cost Run is shown as the yellow column of data on the chart in Figure 13. The reason this is the lowest cost Run is a result of the number of storage tanks needed for the system. As the Price Point decreases from $0.80/kWh to $0.30/kWh, only 17 hours in the day are eliminated from hydrogen production. After the electricity Price Point is $0.30/kWh (Run 6) the price of hydrogen gradually starts increasing as the storage needs of the system increase, even as the number of electrolyzers and compressors stays relatively constant. At Run 13, the hydrogen price jumps $0.25/kg while the number of electrolyzers and capacity factor stay relatively constant from Run 12. From Run 13 to 14, the price of hydrogen jumps an additional $0.64/kg, while again the number of electrolyzers stays basically constant and the capacity factor decreases 1%. The change in cost is due to the increased amount of storage needed from 35 tanks at Run 12, to 45 tanks at Run 13, and 75 tanks at Run 14. Upon detailed analysis of the electricity pricing data, it was found that there is a period in January when electricity prices are consistently high. During that time, hydrogen production is low, so hydrogen storage is being depleted during this time, and large hydrogen stores are needed before that time to be able to meet the demand of the system. Figure 14 shows the hydrogen storage depletion during Run 14 in the month of January.



		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Hours operating	hours	8760	8757	8754	8754	8753	8743	8736	8729	8714	8695	8672	8646	8599	8484	8262
Electrolyzers	#	1.48	1.48	1.48	1.48	1.48	1.48	1.48	1.48	1.49	1.49	1.49	1.50	1.51	1.53	1.57
Electricity price point	$/kWh	0.80	0.70	0.60	0.50	0.40	0.30	0.20	0.17	0.15	0.14	0.13	0.12	0.11	0.10	0.09
Tanks needed	#	13.82	13.82	13.82	13.82	13.82	14.62	15.62	16.20	16.88	19.46	26.96	34.67	44.95	74.91	135.84
Tanks charged initially	#	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
Electrolysis capacity factor	%	97%	97%	97%	97%	97%	97%	97%	97%	96%	96%	96%	96%	95%	94%	91%
Average Electricity Price	$/kWh	0.059	0.059	0.059	0.059	0.059	0.058	0.058	0.058	0.058	0.058	0.057	0.057	0.057	0.056	0.055
Compressors	#	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.01	1.01	1.01	1.02	1.03	1.06
H2 Cost	$/kg	$4.45	$4.45	$4.45	$4.45	$4.45	$4.41	$4.44	$4.45	$4.48	$4.54	$4.65	$4.81	$5.06	$5.70	$7.14
Capital Cost Contribution	$/kg	$1.20	$1.20	$1.20	$1.20	$1.20	$1.21	$1.23	$1.24	$1.27	$1.32	$1.46	$1.61	$1.82	$2.42	$3.72
Electricity Feedstock Cost Contribution	$/kg	$2.89	$2.89	$2.89	$2.89	$2.89	$2.85	$2.85	$2.85	$2.85	$2.85	$2.80	$2.80	$2.80	$2.75	$2.70

Figure 9: System variables and hydrogen pricing results for ISO-NE Node 4616

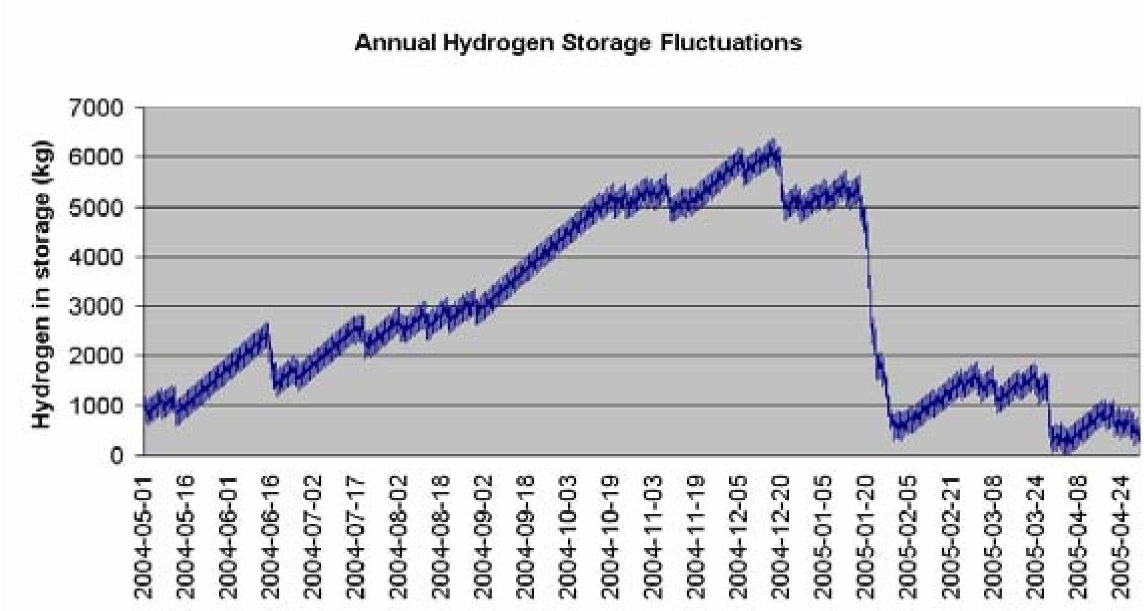
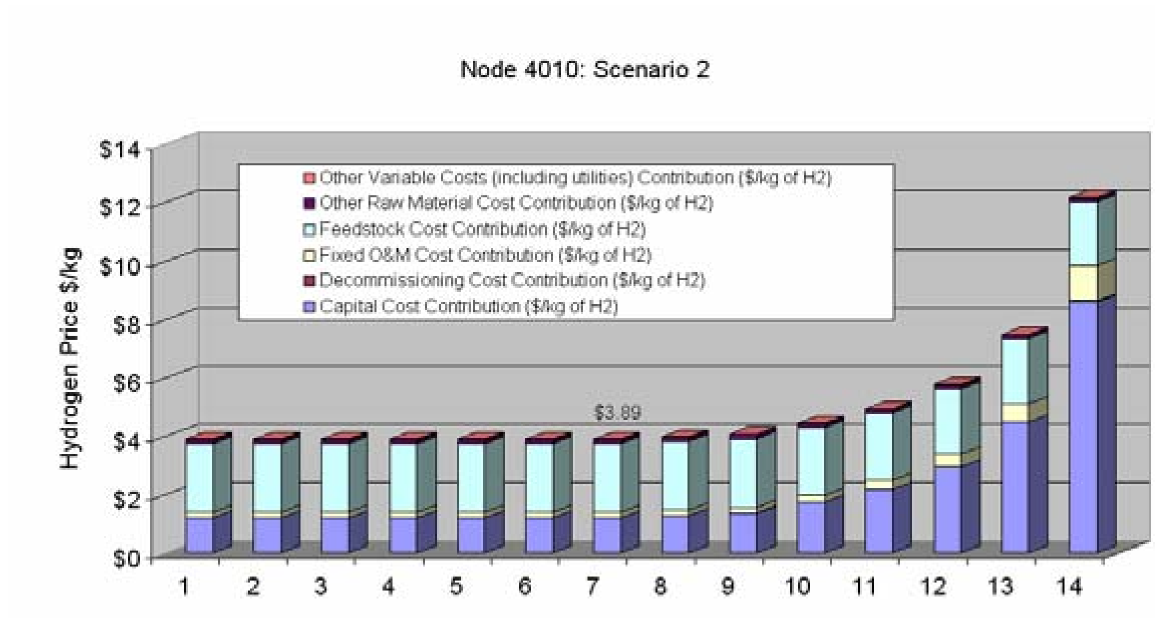


Figure 10: Annual storage requirements for ISO-NE Node 4616 during Run 14

The results for the second Case of real time data for ISO NE Node 4010 can be seen in Figure 15. In this Case the cost of hydrogen is $3.89/kg until the reaches $0.15/kWh (Run 7). Then the price of hydrogen starts rising. At the Price Point of $0.15/kWh only 17 hours out of the year are eliminated for hydrogen production. After this point the storage requirements begin rising, as in the Node 4616 analysis.

An interesting result of these two analyses is that if utilities could disrupt power to the electrolysis units during peak electricity demands, which are assumed to be correlated to when electricity prices are high, it would not adversely affect the price of hydrogen. However, it appears as though if more hours then just peak shaving were eliminated, the storage requirements would be detrimental to using off-peak electricity to produce hydrogen due to seasonal peaks in electricity prices. This is partially due to the assumptions made with this version of the HOPE model, which work well for 24-hour electricity price ranges, but need to be improved for 8760 price ranges. Additional work needs to be done to determine if modifications could be made to the model to better account for the storage needs during peak periods. For example, could a second electricity Price Point be used when storage levels decrease? What if the demand were allowed to not be met 5% of the time and it is assumed hydrogen is purchased during those times to meet the demand? What if a maximum storage size is set, and the model could calculate when the demand could not be met? All these questions need to be considered for inclusion by future versions of the HOPE model.



		1	2	3	4	5	6	7	8	9	10	11	12	13	14
Hours operating	Hours	8760	8759	8759	8759	8759	8757	8754	8741	8730	8683	8622	8495	8229	7474
Electrolyzers	#	1.48	1.48	1.48	1.48	1.48	1.48	1.48	1.48	1.48	1.49	1.50	1.52	1.57	1.73
Electricity price point	$/kWh	0.61	0.60	0.50	0.40	0.30	0.20	0.15	0.13	0.12	0.10	0.09	0.08	0.07	0.06
Tanks needed	#	13.82	13.82	13.82	13.82	13.82	13.82	13.82	17.36	22.59	41.48	62.90	102.08	173.87	342.66
Tanks charged initially	#	10	10	10	10	10	10	10	10	10	10	10	10	10	10
Electrolysis capacity factor	%	97%	97%	97%	97%	97%	97%	97%	97%	97%	96%	95%	94%	91%	83%
Average Electricity Price	$/kWh	0.048	0.048	0.048	0.048	0.048	0.048	0.048	0.048	0.048	0.047	0.047	0.046	0.045	0.044
Compressors	#	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.01	1.02	1.03	1.06	1.17
H2 Cost	$/kg	$3.89	$3.89	$3.89	$3.89	$3.89	$3.89	$3.89	$3.96	$4.07	$4.45	$4.94	$5.78	$7.49	$12.19
Capital Cost Contribution	$/kg	$1.20	$1.20	$1.20	$1.20	$1.20	$1.20	$1.20	$1.27	$1.36	$1.74	$2.16	$2.95	$4.48	$8.62
Electricity Feedstock Cost Contribution	$/kg	$2.36	$2.36	$2.36	$2.36	$2.36	$2.36	$2.36	$2.36	$2.36	$2.31	$2.31	$2.26	$2.21	$2.16

Figure 11: System variables and hydrogen pricing results for ISO-NE Node 4010

8. Model Capabilities

In addition to the capabilities already outlined in the four stages of the analysis, the HOPE model could be used for other analysis exercises. In addition, future enhancements could be envisioned that would make the model more user friendly, and give additional functionality.

a. Current capabilities

As outlined in the four hydrogen stages, the HOPE model has the current capabilities:

- It can determine the best off-peak pricing structure for the production of hydrogen using both 24-hour and 8760-hour data.
- It can determine how the hydrogen production system configuration needs to change with different electricity price distributions
- It can determine if off-peak electricity can lead to a lower hydrogen price.
- It can evaluate how system improvements change the hydrogen production system configuration and the optimum off peak pricing structure.

However, there are other uses for the model. An additional set of Cases was run to help show some additional capabilities of the HOPE model. The purpose was to determine how hydrogen price varies with average electricity cost and capacity factor for a specific Case for each Scenario in Table 1. Such an analysis could be run with a known demand curve and a known electricity pricing structure for any utility node. The results of this type of analysis would provide graphs and equations to help calculate how best to operate an electrolysis hydrogen production system for a given location. In addition, they help analysts understand under what conditions locations can meet the DOE hydrogen cost targets of \$2 - \$3/kg of hydrogen with forecourt electrolysis.

This analysis considered a system running 24 hours per day (97% capacity factor), 18 hours per day from 3 p.m. until 8 a.m. (73% capacity factor), and 12 hours per day from 6 p.m. to 5 a.m. (49% capacity factor). Note that the time periods above are of importance, because of how the demand curve correlates to the hours when electricity is available. The results presented here are only applicable if the electricity is available in the timeframe listed above. If this timeframe were to shift, the results would also change. For example, the 73% capacity factor has the system using electricity to produce hydrogen during the two peak periods of fuel demand, at 8:00 a.m. and 6:00 p.m. If the hours were shifted so that electricity was not being used from 8:00 a.m. to 11:00 a.m. and 6:00 p.m. to 9:00 p.m., the resulting systems would change as hydrogen would not be produced during the peak periods, and storage demands would increase.

The hydrogen/electricity optimization routine in the HOPE model was used to determine the equipment needed for each capacity factor and time of day listed above, and then the H2A model was used to determine the cost of the hydrogen produced for the different average electricity prices at different capacity factors. This was a manual process, as opposed to the process seen in Figure 2.

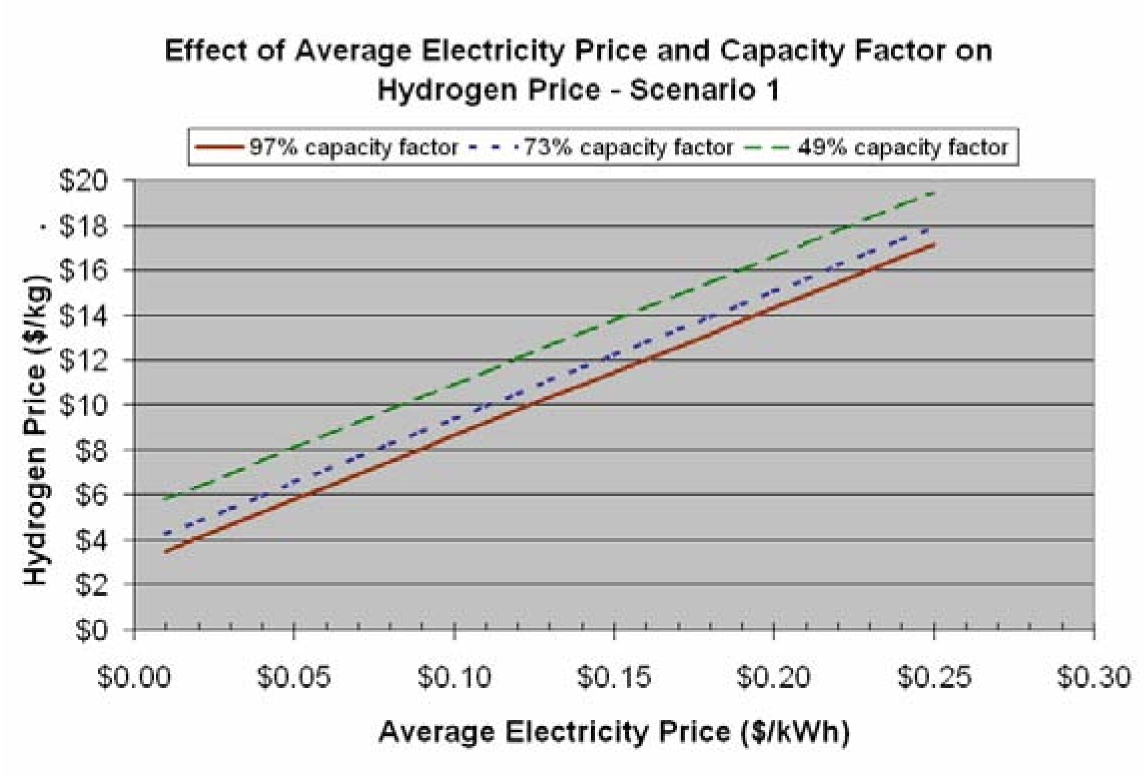
The hydrogen/electricity optimization ensured that each system produced enough hydrogen to meet the forecourt demand, seen in Figure 1, by calculating the capacity factor, plant design capacity, electrolyzer size, number of compressors and number of storage tanks using the electricity availability timeframes listed above. The capacity factors result from the timeframes listed above: a 24 hour a day system has a 97% capacity factor because it is assumed that each electrolyzer only operates 97% of the time, but the system runs 24 hours a day. The 18 hour a day system has a 73% capacity factor because the system runs 18 hours a day at a 97% capacity factor, or 18 hours a day/24 hours a day * 97% capacity factor.

The equipment sizes and plant design capacities for each capacity factor are in Table 4; these values were entered into the H2A model for each Scenario. In addition, the capital cost and electricity requirement for the equipment was varied by Scenario as seen in Table 1. For each Scenario the average electricity price was varied from $0.01/kWh to $0.25/kWh in the H2A model.

Table 6: System Assumptions for Initial Analysis

Capacity Factor	**97%**	**73%**	**49%**
Plant Design Capacity (kg/day)	1540	2060	3090
Number of Electrolyzers	1.48	1.97	2.95
Number of 85 kg high pressure tanks	13.82	15.29	18.23
Number of 2000kg/day compressor systems	1.00	1.33	2.00

Results for Scenario 1 can be seen in Figure 3. The chart and equations can be used to determine what average electricity price is needed to produce hydrogen at a given cost at different capacity factors. For example, for $3/kg hydrogen, a 97% capacity factor system would need electricity prices to be just above $0.001/kWh electricity, while a system with a 73% capacity factor, or a 49% capacity factor could not produce hydrogen for this low of a price at any electricity price. This can be seen both by the lines on the graph, and by using the equations of the lines. The x in the equation is the electricity price in $/kWh, and the y in the equation is the hydrogen selling price in $/kg. To find the minimum hydrogen cost if the electricity were free for the 73% and 49% capacity factors, set x to 0, and then y, the hydrogen price, equals the intercept of the equations. At an electricity price of 0, where x equals the electricity price, the intercept (3.7088 at 73% and 5.2318 at 49%) is higher than $3.00/kg of hydrogen.

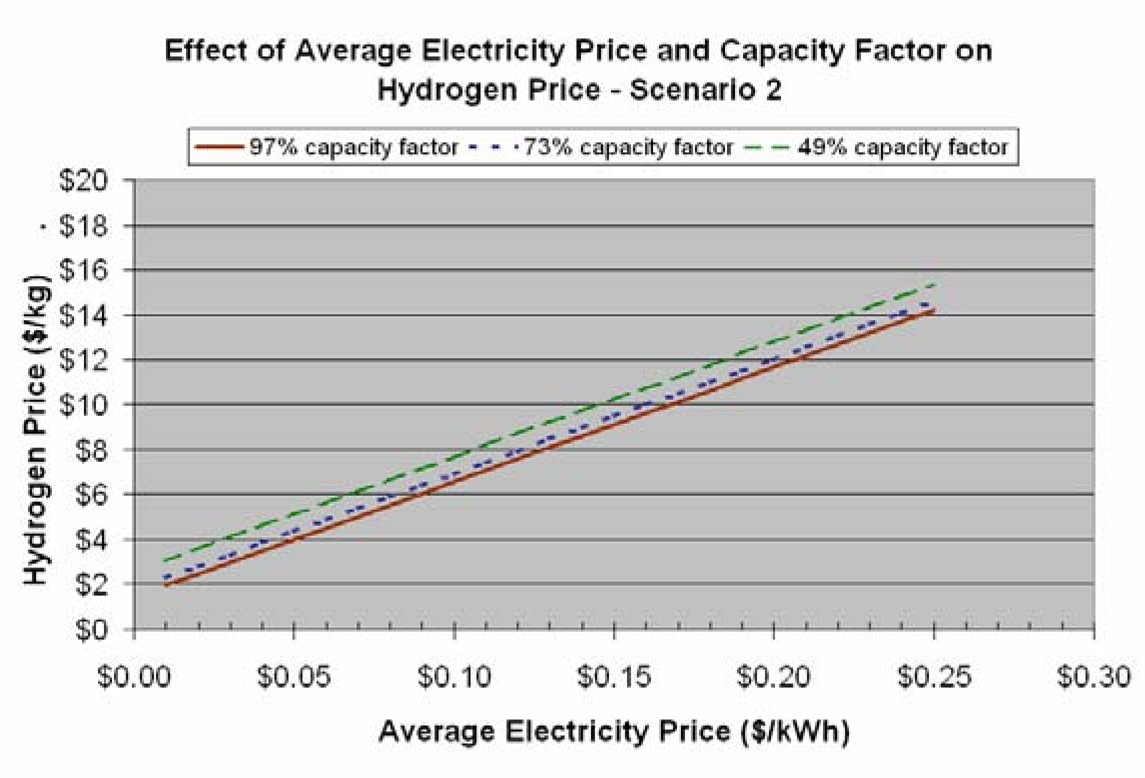


The equations for the three lines shown on the graph are as follows:

Capacity Factor	97%	73%	49%
Equation where x is electricity price in $/kWh and y is hydrogen price in $/kg	y = 56.842x + 2.9412	y = 56.842x + 3.7088	y = 56.843x + 5.2318

Figure 12: Average electricity price at various capacity factors versus hydrogen price for Scenario 1

Results for Scenario 2 can be seen in Figure 4. For Scenario 2 to produce $3/kg hydrogen, the average electricity price would need to be below $0.031/kWh, $0.023/kWh, and $0.001/kWh for 97%, 73%, and 49% capacity factors, respectively. The equation and chart can also be used to determine what price hydrogen could be sold at if an average electricity rate is know for a certain capacity factor. For Scenario 2, if you could get $0.025/kWh average electricity prices from 3 p.m. until 8 a.m., the price of your hydrogen could be calculated using the Scenario 2 equation under 73% capacity factor. With x being your electricity price, you would calculate the hydrogen price (y) by multiplying 51.208*0.025 and adding 1.8028, giving you $2.31/kg of hydrogen.



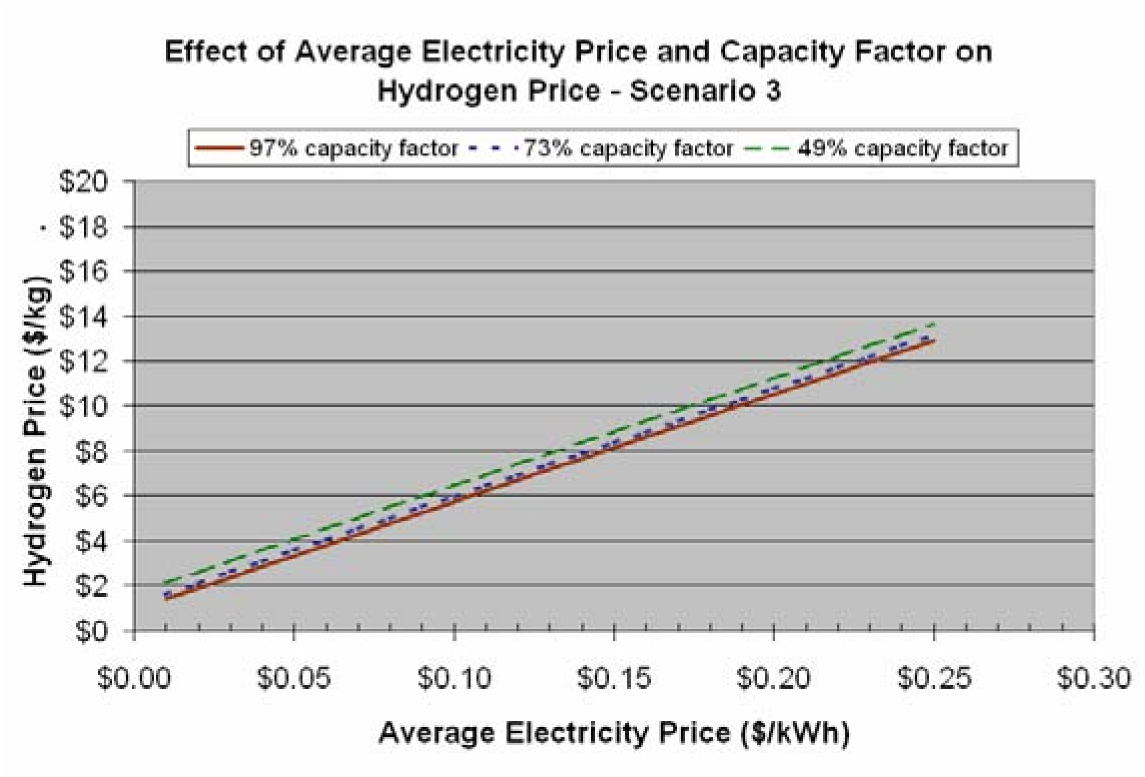
The equations for the three lines shown on the graph are as follows:

Capacity Factor	97%	73%	49%
Equation where x is electricity price in $/kWh and y is hydrogen price in $/kg	y = 51.208x + 1.4276	y = 51.208x + 1.8028	y = 51.208x + 2.5475

Figure 13: Average electricity price at various capacity factors versus hydrogen price for Scenario 2

This analysis can also be used to see if using off-peak electricity can be advantageous economically. For example, in Scenario 2, if a system's average electricity price were over $0.04/kWh at a 97% capacity factor the minimum hydrogen price would be $3.48/kg. If the average electricity price dropped to below $0.032/kWh at a 73% capacity factor the hydrogen produced would actually be less expensive at $3.44/kg.

Results for Scenario 3 can be seen in Figure 5. For Scenario 3 to produce $3/kg hydrogen, a $0.043/kWh, $0.38/kWh, and $0.028/kWh electricity prices would be needed for 97%, 73% and 49% capacity factors, respectively. For this Scenario, even lower hydrogen prices are not out of the question. For $2/kg hydrogen $0.022/kWh, $0.017/kWh, and just under $0.01/kWh electricity would be needed at 97%, 73%, and 49% capacity factors, respectively.

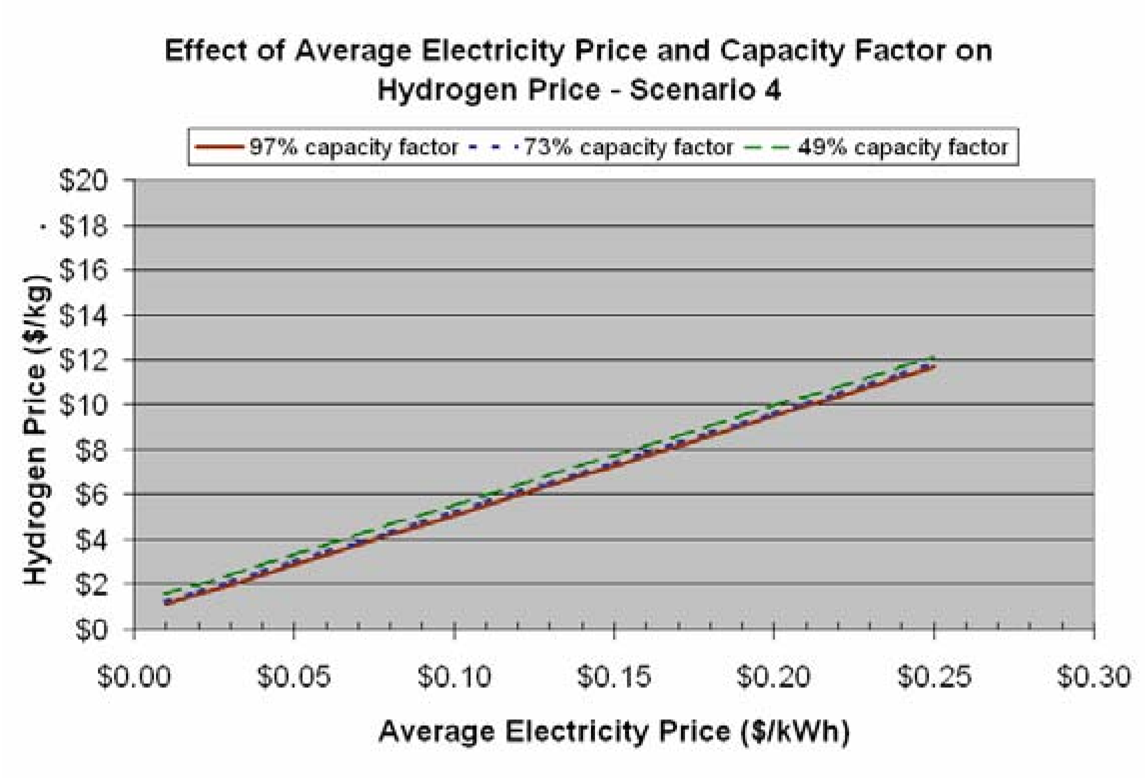


The equations for the three lines shown on the graph are as follows:

Capacity Factor	97%	73%	49%
Equation where x is electricity price in $/kWh and y is hydrogen price in $/kg	y = 47.931x + 0.9391	y = 47.93x + 1.1776	y = 47.93x + 1.6504

Figure 14: Average electricity price at various capacity factors versus hydrogen price for Scenario 3

Results for Scenario 4 can be seen in Figure 6. For Scenario 4 to produce $3/kg hydrogen, $0.053, $0.50/kWh, and $0.43/kWh electricity prices would be needed for 97%, 73%, and 49% capacity factors, respectively. For $2/kg hydrogen Scenario 4 would require $0.030/kWh, $0.027/kWh, and $0.020/kWh electricity at 97%, 73% and 49% capacity factors, respectively. This Scenario displays that even with the most optimistic capital costs and energy requirements if electrolysis is to produce hydrogen at values comparable to $2-3/gallon of gasoline, industrial electricity prices or lower will be required. However, this Scenario also shows that these prices could just be available during off peak hours, and the cost targets could be met.



The equations for the three lines shown on the graph are as follows:

Capacity Factor	97%	73%	49%
Equation where x is electricity price in $/kWh and y is hydrogen price in $/kg	y = 44.048x + 0.6668	y = 44.048x + 0.8161	y = 44.048x + 1.1115

Figure 15: Average electricity price at various capacity factors versus hydrogen price for Scenario 4

These results show that there is *potential* to produce hydrogen at the forecourt at the DOE cost target of $2-$3/kg using electricity 24 hours a day, or using off-peak electricity, if data for the site were consistent with the demand curve and electricity price ranges above. The potential increases if electricity prices are low enough and/or if some process improvements are realized. In the near term, Scenario 1, electricity prices would need to be available at essentially zero cost 24 hours a day to meet the cost target. However, Scenarios 2-4 show that if process improvements in the system are recognized, hydrogen may be produced below $3/kg if electricity is used 24 hours a day and is available in the $0.03-$0.05/kWh range. With off-peak electricity and electrolyzer capacity factors of 49% electricity prices ranging from $0.01/kWh - $0.04/kWh result in hydrogen at $3/kg in Scenarios 2-4. However, the low cost electricity must be available from 6 p.m. – 5 a.m. Validation from industry should be obtained to determine where very low electricity prices are available off peak, and the times that those prices are available, in order to further understand the potential of hydrogen production from off-peak electricity.

b. Future Enhancements

Several future enhancements could be included to make HOPE a more user-friendly model. The current version is useful to the developer, but would be difficult for others to use. A user interface front end could be added to aid in the entry of demand curves, electricity price ranges, and H2A parameters. In addition, currently graphs need to be manually generated. In future versions certain graphs could be automated.

Additional work needs to be done to determine if modifications could be made to the model to better account for the storage needs during the seasonal peak periods that occur in 8760 data. For example, could a second electricity Price Point be used when storage levels decrease to a certain point? What if the demand were allowed to not be met 5% of the time and it is assumed hydrogen is purchased during those times to meet the demand? What if a maximum storage size is set, and the model could calculate when the demand could not be met?

An analysis also needs to be completed to determine the effect of different demand profiles on the cost of hydrogen produced using off peak power. Does the scenario work better with a station in a residential area, or a business area, or on a highway? More realistic demand curves are needed for this type of analysis.

9. Conclusions

The goal of this report is to provide information on the HOPE model, and to use the model to understand if hydrogen can be produced economically at the forecourt using off-peak electricity. The HOPE model was developed to find the optimized hydrogen production system configuration for any electricity pricing structure. The optimized system was considered to be the system that resulted in the lowest price of hydrogen.

The HOPE model was used to run four different analysis stages that help to understand the effects of using off-peak electricity on a forecourt electrolysis system. In the first stage an analysis was run using electricity prices from \$0.01/kWh to \$0.24/kWh where the prices were varied each hour by one cent; three Cases were run where the electricity price was varied from high to low, low to high, and randomly. This analysis showed that regardless of when hydrogen is produced during the day, the number of hours electricity is available determines the size of the electrolyzer and the size of the compressor. Likewise, the design capacity of the plant, plant output, capacity factors, and average electricity are the same for the same electricity Price Point across all three Cases. The differences in the systems come about in the storage requirement. Thus the storage requirement was deemed to be a critical parameter for this analysis.

Three simple electricity pricing Cases were run in the second stage of the analysis where the electricity price range for the Cases was set to $0.04/kWh during 21 hours out of the day, and during the other three hours of the day, the price was varied from $0.08/kWh to $0.09/kWh to $0.10/kWh. Two runs were made for each Case, one where the electricity Price Point was the high price, and one where it was the low price of $0.04/kWh. Using off-peak electricity was only advantageous when the peak price was $0.10/kWh, not at the lower peak prices. This analysis shows the importance of the size of the peak when using off-peak electricity. As a rule of thumb it was assumed that if the peak price of a system is large enough, off-peak electricity should be used.

In the third stage, the HOPE model was used with hypothetical 24-hour pricing structures that varied electricity prices during the day from $0.01/kWh - $0.20/kWh. Two pricing structures were tested, and the results of both Cases show that for the Scenarios run, and the pricing structures and demand curve used, using off-peak electricity resulted in lower prices. In addition, as the system costs reduced and efficiencies improved from Scenario to Scenario, lower cost electricity can be used at a lower capacity factor to produce cheaper hydrogen.

Finally, in the fourth stage, the results of the analysis using hypothetical data in 24 hour increments was challenged by the addition of an analysis using real time data from ISO New England. The hourly (8760) electricity prices for two nodes were entered into the HOPE model. Appropriate Price Points for the data were entered, the system was optimized, and the resulting hydrogen prices were found. It was found that eliminating high peak prices lowered (or did not increase) the price of hydrogen, which demonstrates that if utilities could disrupt power to the electrolysis units during peak electricity demands, it would not adversely affect the price of hydrogen. However, as capacity factors even slightly decrease beyond peak shaving it appears as though increased storage requirements would be detrimental to using true off-peak electricity to produce hydrogen due to seasonal peaks in electricity prices. This finding should be verified with future versions of the HOPE model after storage functionality is enhanced.

The HOPE model provides the following capabilities for any given pricing structure and demand curve:

- Determines the best off-peak pricing structure for the production of hydrogen using both 24 hour and 8760 hour data
- Determines how hydrogen production system configurations change with different electricity price distributions
- Determines if off-peak electricity can lead to a lower hydrogen price
- Evaluates how system improvements change the hydrogen production system and the optimum off peak pricing structure

- Provides data to help calculate how best to run an electrolysis hydrogen production system

In short, the HOPE model can help answer the question for any site: does using off-peak electricity for electrolysis lead to lower hydrogen prices? In addition, the HOPE model can help clarify under what conditions forecourt electrolysis at different locations can meet the DOE hydrogen cost targets of $2 - $3/kg.

10. Appendix A - Bibliography

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