Final Report

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Building Hydrogen Economy One Block at a Time

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Building Hydrogen Economy One Block at the Time

PROJECT REPORT

To: Leonard Transportation Center

California State University San Bernardino

(230681—GT10119)

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Contents

Appendix A

Executive Summary

Hydrogen economy is a long-term solution to the dependence on oil, global warming, and clean air concerns associated with the transportation sector. Over the past several years, CSULA has invested considerable effort and funds into bringing a Sustainable Hydrogen Fueling Facility on campus. Through multiple funding sources, CSULA was awarded $4 M toward the construction of a hydrogen station on campus utilizing the latest technologies and providing the capacity of 60kg/day, sufficient to fuel 15 vehicles or a bus and 5 more vehicles. The station will be utilizing a Hydrogenics electrolyzer, boost and delivery compressors capable of dispensing up to 10,000 psi (700bar), 60 kg of hydrogen storage, water purification, and equipment cooling system. One of the key elements in operating the fueling facility is to determine a fair retail price for hydrogen. National Renewable Energy Laboratory has developed “H2A” station analysis software, which predicts the cost of hydrogen production by utilizing hundreds of variables. The "H2A" model combines the economic/financial aspects with the technical parameters. The research student worked with the “H2A” software and the PI to evaluate various model outcomes. The financial support for the student was provided by NSF's Research Experience for Undergraduates program. As a long-term goal, the station's presence on campus and active research on its performance will enable CSULA to design and offer a unique hi-tech curriculum addressing workforce development in the new "green" economy and ensuring our graduates an advantage in securing high-wage employment. The findings of the project were presented at the 2010 Jack R. Widmeyer Transportation Research Conference at CSU San Bernardino.

Project Outcomes

The PI worked with the student Keith Bacosa who was a mechanical engineering student at CSULA. His work period was ten weeks in summer 2009 and was supported by NSF Research Experience for Undergraduates funding. In addition, Keith worked on writing a conference article summarizing his research in fall 2010 and spring 2011. The abstract had been accepted, however the reviewers provided challenging comments and Keith was not able to complete the necessary work due to his upcoming graduation and withdrew the paper. However, the PI believes that it was still an excellent learning experience for the student, as he currently considering graduate studies and is aware of expectations and challenges to be faced.

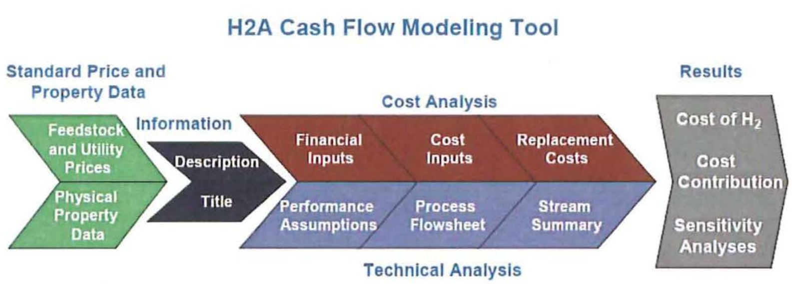

Figure 1. H2A Production Analysis Tool (http://hydrogendoedev.nrel.gov)

NREL has developed the "H2A" station analysis tool, which determines the cost of hydrogen production by utilizing hundreds of variables blending technical parameters with economic aspects. The conceptual description of the "H2A" model is found in Figure 1, where the upper line of the variables corresponds to the economic/financial aspects and the bottom to the technical parameters.

Price of hydrogen for CSULA hydrogen station using inputs from construction and equipment bids was calculated as $36.30 per kg H2. However, since the station was funded by various agencies, the real price of hydrogen is lower. Also the model shows that increased production rates will lower the price. The CSULA hydrogen production capacity of 60 kg H2 per day and the need to recuperate pricing of the equipment are significant factors that lead to hydrogen production being costly. If the production rate is increased, there is evidence that the end price of hydrogen could be greatly reduced. By doubling the production capacity, the analysis shows that the price of hydrogen per kg is reduced by almost $10 or 27%, even with increases to capital costs factored in.

I. After Tax Real Internal Rate of Return

The After Tax Real Internal Rate of Return is defined as the rate of return calculated after all taxes are accounted for, minus the inflation rate. The rate of return describes the rate at which profit will be returned to the investor based on the original capital investment. Businesses are able to use a rate of return calculation to help them determine the price that they must sell their goods at in order for them to make the desired profits. Since the purpose of the hydrogen station at Cal State LA is not for profit, the 0.1% lowest rate of return allowable by the model for hydrogen price estimate was used. The effect of the rate of return on the price of hydrogen per kilogram, which behaves linearly, is shown in Figure 2.

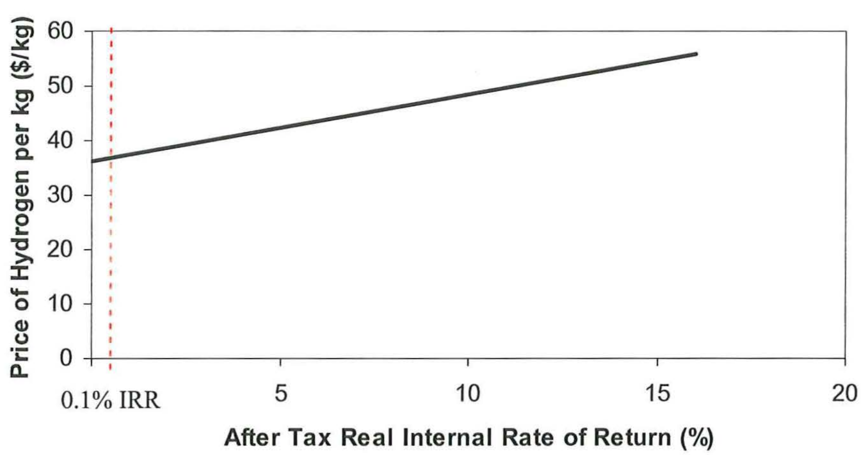

Figure 2. Price of Hydrogen per kg vs. After Tax IRR

II. Plant Design Capacity

The plant design capacity refers to the amount of hydrogen (mass) that can be produced by the hydrogen station each day. Because of economies of scale, the plant design capacity can have a strong effect on the price of hydrogen . The hydrogen station planned for CSULA has a production capacity of 60 kg H_2 per day. The price of hydrogen has an exponentially decreasing relationship with plant production capacity.

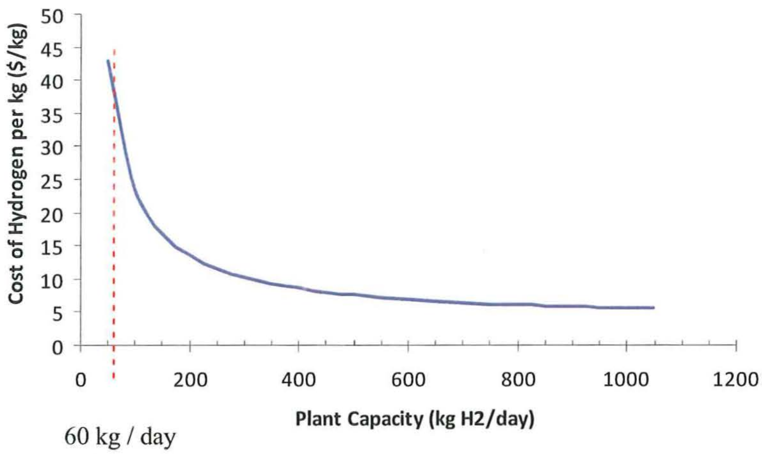

Figure 3. Price of Hydrogen per kg vs. Daily Hydrogen Production Capacity

III. Facility Lifetime

The analysis period is the entire lifetime of the plant. It begins when the plant first starts producing hydrogen until the plant is decommissioned. CSULA is under the contract to operate the facility for three years, however in the general case the longer the planned life expectancy of the facility the lower price of hydrogen.

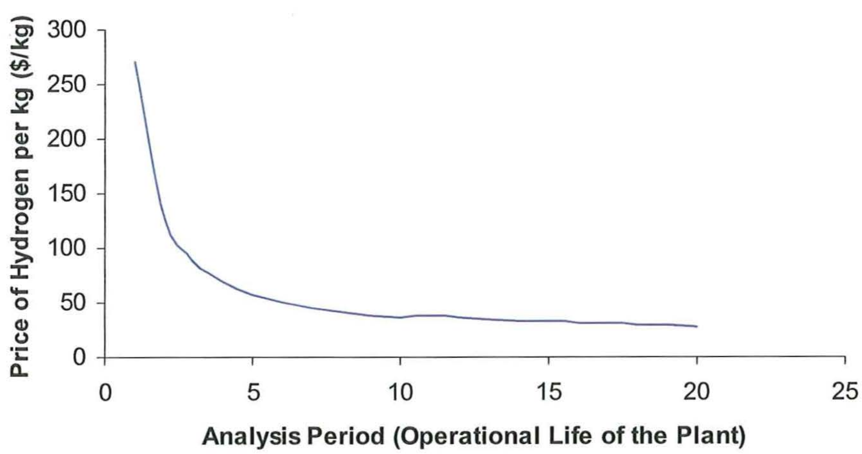

Figure 4. Price of Hydrogen per kg vs. Analysis Period

The price of hydrogen has an exponentially decreasing relationship with the period of operation. For this graph it is assumed that the plant life would be 10 years which means the major components (the electrolyzers) would have to be replaced or refurbished after this period. This new cost created a small kink in the graph which meant the price of hydrogen actually raised a little bit if operated beyond the ten year period as shown in Figure 4.

Conclusions

With the CSULA Sustainable Hydrogen Facility coming online in 2011, the project has allowed to evaluate multiple price forming parameters in operating a hydrogen facility. In order to recuperate in 3 years the equipment funds ($1.4 M) invested in the station (additional 2.6 M for construction) the price for hydrogen would have been $36 /kg. The model has shown that prices would be falling below $20 /kg if long term operations and high production/sale are achieved. Funded by public and private funds, the fueling facility will dispense Hydrogen at prices which are relatively competitive to those of gasoline.

Considering the minority composition of the CSULA student body and the investments into hydrogen technologies in Southern California, the hydrogen facility provides advantage to benefit students and local communities.

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(230681—GT10119)
Author: Keith Bacosa

Introduction

Hydrogen production to support the use of hydrogen fuel cell powered transportation is one of CSULA's goals. CSULA has released a call for proposals that contractors have already responded to for building a hydrogen station. A quote made by General Physics already outlined the details for the equipment needed and the CARB proposal prepared by CSULA gave us information on the expected cost of all the equipment needed to build a hydrogen refueling station.

Using the information we find on the CARB proposal and General Physics quote, we are able to use the H2A program to see what the price of hydrogen will be to the consumer. The H2A Forecourt Electrolysis program is an excel sheet written by the Department of Energy that allows users to input information about their own hydrogen refueling station and returns many results important for analysis of planned hydrogen refueling stations such as the price of hydrogen per kg produced and emissions information.

Objective

In our study we will use the H2A program to model the hydrogen station planned for CSULA and see what the price of producing hydrogen would be. We will also do a "what if" analysis to try and isolate variables that greatly affect the price of hydrogen and make suggestions for ways to lower the cost.

Research Activities

The diagram below shows the general layout of the H2A Cash Flow Modeling Tool and the major components of the program. The major sections are color coded and separated by the function they perform in the program. **We are interested in studying the dark green section of the program that is circled in red in the diagram** (financial inputs, cost inputs and replacement costs) **to see how it will affect the results of the price of hydrogen**(blue section).

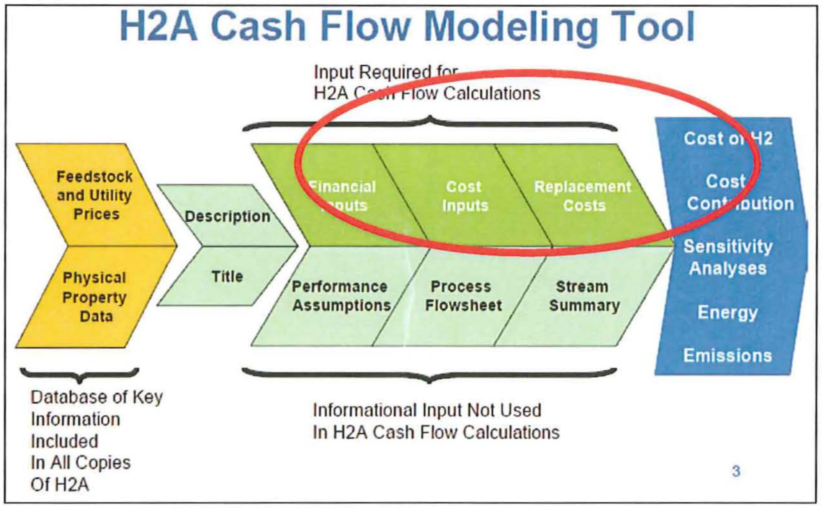

Figure 1: H2A Cash Flow Diagram
http://www.hydrogen.energy.gov/pdfs/review08/an_6_steward.pdf, august 2009

The tabs that are associated with the dark green sections of the flow chart are the Input_Sheet_Template, Replacement Costs, Capital Costs, and Refueling Station Tabs. Each of these tabs leads to an excel sheet that asks for many different values related to costs of building the hydrogen station.

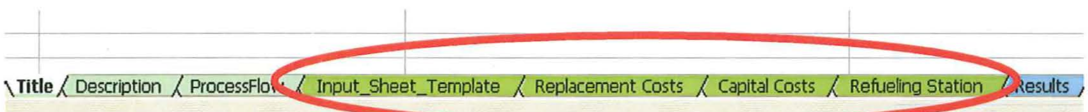

Figure 2: Tabs related to cash flow diagram

The required input boxes are colored orange and these will be the inputs that will change the final price of hydrogen per kilogram produced.

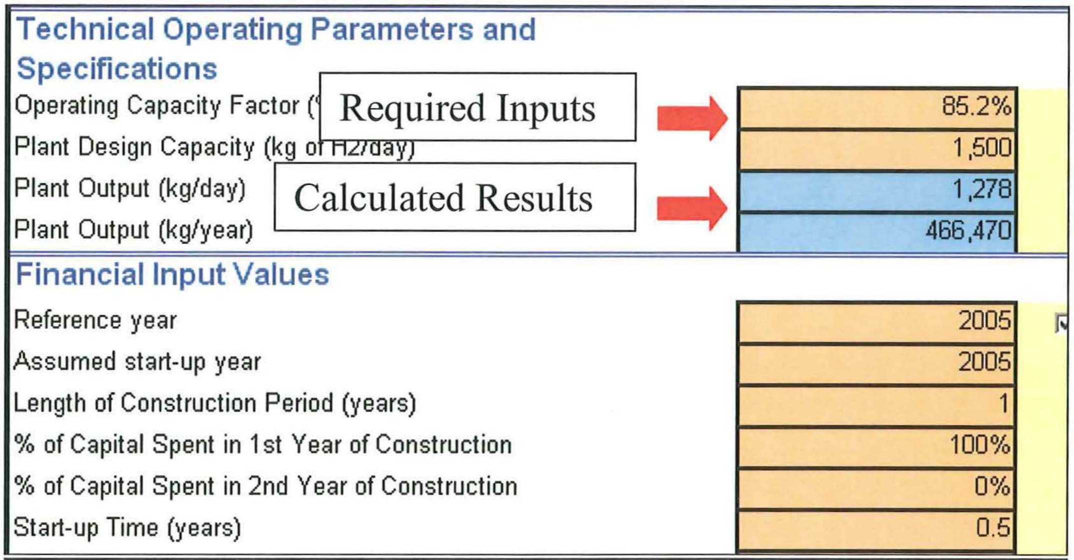

Figure 3: Input and Results Boxes

The following is an attempt to define each of the required inputs for all the tabs that are used in the calculations for hydrogen production.

<u>Input_Sheet_Template Tab</u>

I. Technical Operating Parameters and Specifications

Operating Capacity Factor (%) – the efficiency of the hydrogen plant. For example, a 50 kg per day plant with an operating capacity factor of 80% will produce 40 kg of hydrogen per day on average. The operating capacity factor is standard for the H2A program so we do not have to change it. It is set at 85.2%.

Plant Design Capacity (kg of H2/day) - How many kilograms of hydrogen will be produced by the plant per day

II. Financial Input Values

Reference Year – Bases prices of everything on assumed prices of that year. For example the price of an electrolyzer may not be the same in 2005 as in 2010.

Assumed Start-up Year- Year that plant construction will begin

Length of Construction Period – How long it will take to construct the plant

% of Capital Spent in 1st year of construction – percentage of total construction money used in the first year

% of Capital Spent in 2nd year of construction- percentage of total construction money used in the second year

Start-up Time(years)- the amount of time it takes to get from the initial capital investment till the hydrogen plant is operating (selling hydrogen)

Plant Life- life expectancy of the plant. This would be the life expectancy of a very important and expensive part of the hydrogen production plant.

Analysis Period – period of time considered for the analysis

Depreciation Schedule Length – amount of time it takes for the plant to reach full depreciable cost

Depreciation Type – kind of depreciation schedule used (straight line or MACRS options only)

% of equity financing – The percent of the total cost that is financed by borrowing money that has already been invested in property, stocks, etc.

Interest Rate on Debt – interest rate

Debt Period – how long it will take to pay off the debt if money is borrowed.

% of Fixed Operating Costs During Start Up – % of starting capital that is used for fixed operating costs before the plant begins to sell hydrogen

% of Revenues During Start-up – % of revenues during start up time

% of Variable Operating Costs during Start-up – % of starting capital that is used for variable operating costs before the plant begins to sell hydrogen

Decommissioning Costs (% of depreciable capital investment) – costs of putting the station out of commission at the end of its planned life

Salvage Value (% of total capital investment) – amount of money you can get back at the end of the plants planned life

Inflation Rate – national inflation rate

After Tax Real IRR – the after tax rate of return minus the inflation rate

State Taxes – state taxes

Federal Taxes – federal taxes

Working Capital – Cash in the bank

III. Capital Costs

Indirect Depreciable Capital Costs

Site Preparation – costs related to preparing the site for construction

Engineering and Design – engineering and design of the refueling station
Process Contingency – extra money used to pay for penalties in processing paperwork for the hydrogen station

Project Contingency – extra money used to pay for unexpected costs in building the hydrogen station

Other (Depreciable) Capital – petty cash

One time licensing fees – licensing for site use

Up front permitting costs – property preparation permits

Non-Depreciable Capital Costs

Cost of land ($/acre) – cost of land per acre

Land required (acres) – number of acres required

Other non depreciable capital costs – Other costs in building the hydrogen station that are not depreciable

IV. Fixed Operating Costs

Production facility plant staff – number of full time employees working at the plant

Burdened labor cost, including overhead ($/ man-hr) – Costs of labor including overhead such as accounting, legal fees, supplies, taxes, telephone bills, etc.

G&A rate (% of labor cost) – these are general and administrative expenses for the business. Given as a % of the labor costs.

Licensing Permits and Fees ($/year) – Licensing permitting and fees costs per year

Property tax and insurance rate (% of total capital investment) – The percentage of the starting money that goes to paying property taxes and insurance.

Rent ($/year) – cost of rent

Material Costs for Maintenance and Repairs ($/year)- how much materials for maintenance and repairs cost

Production Maintenance and Repairs ($/ year) – maintenance and repairs that are expected for the equipment used to produce hydrogen.

Forecourt Maintenance and Repairs ($/year)- maintenece and repairs expected for the hydrogen refueling station

Other Fees ($/year) – any other yearly fees

Other Fixed O&M Costs ($/year) – other fixed operating and maintenance costs not described by the other inputs

V. Energy Feedstocks, Utilities and Byproducts

Lower Heating value(GJ/Nm3) – the amount of heat released by combusting a specific quantity of fuel starting at 25°C and returning it to 150°C. The LHV assumes the water components are in a vapor state at the end of combustion.

Usage (Nm3/kg H2)- read the unit as specific volume in meters cubed per kilogram of hydrogen at normal conditions.

VI. Other Materials and Byproducts

Usage per kg H2 (gal)- This is the amount of cooling water that must be used per kg of H2 produced

VII. Other Variable Operating Costs

Other variable operating costs (e.g. environmental surcharges) ($/year)- Other variable operating costs not already accounted for

Other Material Costs ($/year)- any other material costs not already accounted for

Waste treatment costs ($/year)- waste treatment costs

Solid waste disposal costs ($/year)- solid waste disposal costs

Total Unplanned Replacement Capital Cost Factor (% of total direct depreciable costs/year) – percentage of the depreciable capital cost of the project that is planned for paying for replacements of parts that fail.

Royalties ($/year)- royalties

Operator Profit ($/year) – profit

Subsidies, Tax Incentives ($/year) – money given to help offset the costs of the project

Replacement Costs Tab

Note: Replacement costs are assumed to be equity financed

Specified Yearly Replacement Costs ($) – these are the anticipated replacement costs of equipment. There are input values for every year for 40 years so equipment with different expected life spans can be replaced on different years.

Capital Costs Tab

Note: Capital and operating costs for compression, storage, and dispensing can be entered on the "Input Sheet Template" or click the link button to automatically calculate optimized storage and dispensing values on the "Refueling Station" sheet.

Major pieces/systems of equipment- major equipment with large cost that will be installed in the hydrogen station

Uninstalled baseline cost – cost of the equipment without installation costs

Installation cost factor- the number used to multiply the baseline cost in order to add the installation costs to it i.e. 1.10

Refueling Station Tab

Note: all inputs in refueling station tab have a default setting provided by the H2A program that can be activated.

I. Forecourt Specific Economic Assumptions

Compressor MACRS Depreciation Schedule Length (years) – depreciation schedule for compressor

Dispenser MACRS Depreciation Schedule (years)- depreciation schedule for dispenser

Remainder of Station MACRS Depreciation Schedule Length (years)- depreciation schedule for all the other components of the refueling station

Compressor Lifetime (years)- compressor life expectancy

Dispenser Lifetime (years)- dispenser life expectancy

II. Refueling Station Design Inputs

Production process outlet pressure (psi)- outlet pressure from the electrolyzer

Dispensing Pressure (psi)- outlet pressure from the hydrogen storage tanks

Hydrogen Temperature at the Station (degrees C)- temperature of H_2 at the station

High Pressure Cascade Storage Vessel

Maximum Pressure (psia)- maximum pressure rating

Minimum Pressure (psia)- minimum pressure rating

Medium Pressure Cascade Storage Vessel

Maximum Pressure (psia)- max pressure rating

Minimum Pressure (psia)- min pressure rating

Low Pressure Cascade Storage Vessel

Maximum Pressure (psia)- max pressure rating

Minimum Pressure (psia)- min pressure rating

Vehicle Tank Maximum Pressure (psia)- max pressure in the hydrogen vehicle's tank

Vehicle fill time (min)- amt of time it takes to fill the hydrogen vehicle up

Vehicle Lingering time (min)- how many minutes the vehicle will stay around once it is refueled with hydrogen

Hoses per dispenser- how many hoses each hydrogen dispenser will have

Vehicle tank capacity (kg)- the capacity of the hydrogen tank in the vehicle

Scaling daily demand profile as % of Chevron peak above average- averaged daily demand of fuel based on data collected by Chevron

Design Maximum Hose Occupied Fraction During Peak Hour- the percentage of how many hoses can be used during peak hours.

Maximum Low Pressure Storage Pressure (psi)- max pressure for hydrogen storage at lower pressure to decrease losses

Minimum Low Pressure Storage Pressure (psi)- minimum pressure for low pressure storage tank.

Operating Storage Temperature (degrees C)- Low end of ambient temperature

Cp/Cv ratio- equal to the specific density of the hydrogen

Enter Number of Installed Compressors- number of compressors installed in the system

Enter Number of Compressors in Operation at Any Time- number of compressors in operation simultaneously

Design Refueling Station Compressor Based on Compression Ratio per Stage?- A stage count is the number of times a gas is compressed between coming into the compressor and going out of the compressor

Enter Compression Ratio Per Stage for Refueling Station Compressor- The compression ratio is defined as the outlet pressure from a stage divided by the inlet pressure to the same stage. If a multi stage compressor is used, the compression ratio per stage is defined calculated by the following: 10^((log(Outlet P)-log(inlet P))

Isentropic Compressor Efficiency for Refueling Station Compressor (%)- percentage of the energy that will go into work in compressing the hydrogen and not heat compared to the ideal case (adiabatic conditions)

Compressor Motor Sizing Factor- the percentage increase or decrease from a typical size compressor motor that must be used in the hydrogen station

Hydrogen Lost During Compression (%)- percentage of hydrogen that is lost during compression

III. Refueling Station Scenario Inputs

Hours per day the Refueling Station Is Operating- hours of operation

Surge: % Above the System Average Demand

What if Scenario's

We will investigate the trends that certain inputs graphed against the price of hydrogen will show. So far we have identified 4 inputs that seem to make a big difference in the end price of hydrogen calculated by the program. The values are the following:

- After Tax Real Internal Rate of Return
- Plant Design Capacity
- Analysis Period
- Electrolyzer Capital Cost

Other variables that I have looked into changing did not have as big an effect on the end price of hydrogen as these did. Since these inputs seemingly have the greatest effect on the end price of hydrogen, I will concentrate on changing each one individually and monitoring the trend they have on the price.

I. After Tax Real Internal Rate of Return

The After Tax Real Internal Rate of Return is defined as the rate of return calculated after all taxes are accounted for, minus the inflation rate. The rate of return describes the rate at which profit will be returned to the investor based on the original capital investment. Businesses are able to use a rate of return calculation to help them determine the price that they must sell their goods at in order for them to make the desired profits. Since the purpose of the hydrogen station at Cal State LA is not for profit, we have used the lowest rate of return allowable by the excel sheet for our hydrogen price estimate which is 0.1%. Just to show the effect that the rate of return has on the price of hydrogen per kilogram, I have graphed their relationship below.

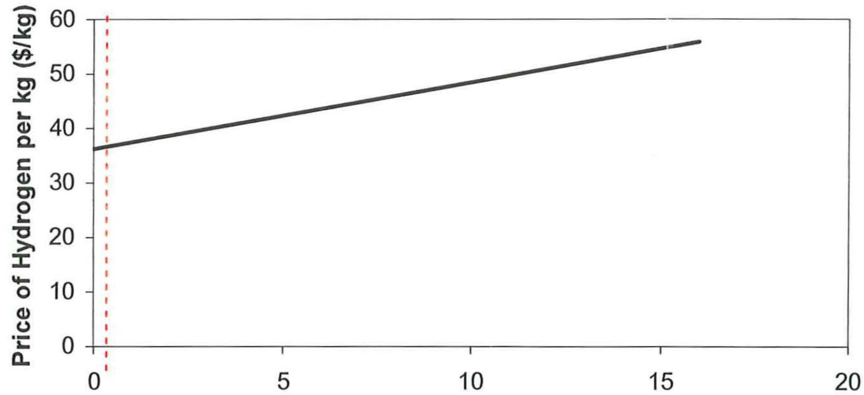

Figure 4: Price of Hydrogen per kg vs. After Tax IRR

We can see from the graph that the desired rate of return has a linear relationship with the price of hydrogen.

II. Plant Design Capacity

The plant design capacity refers to the amount of hydrogen (mass) that can be produced by the hydrogen station each day. Because of economies of scale, the plant design capacity can have a strong effect on the price of hydrogen . The hydrogen station planned for Cal State LA has a production capacity of 60 kg H_2 per day.

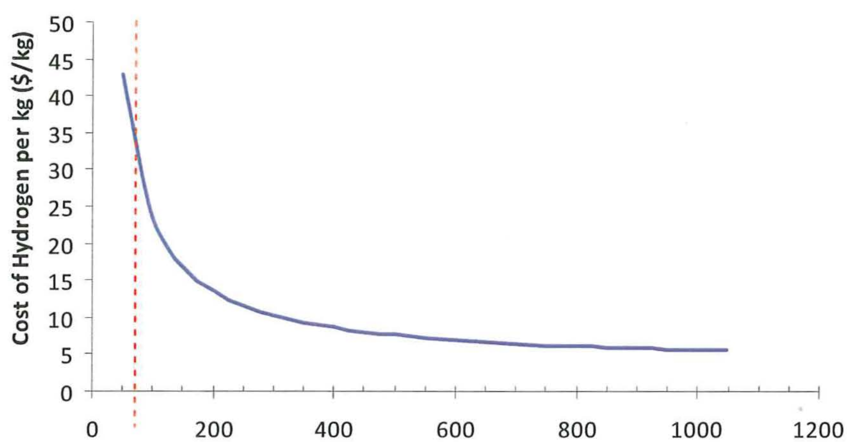

Figure 5: Price of Hydrogen per kg vs. Daily Hydrogen Production Capacity

The price of hydrogen has an exponentially decreasing relationship with plant production capacity.

III. Analysis Period

The analysis period is the entire lifetime of the plant. It begins when the plant first starts producing hydrogen until the plant is decommissioned. We do not know what the planned life expectancy of our hydrogen station is at the moment, however we can look at how the planned life expectancy of the plant will affect the price of hydrogen.

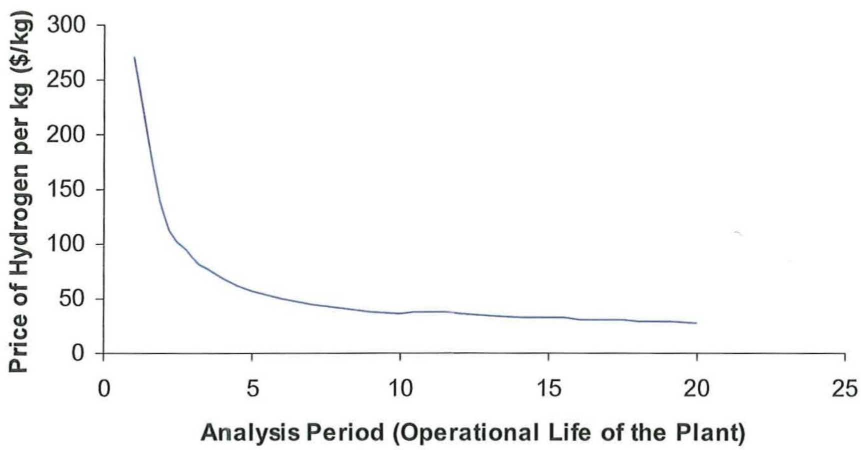

Figure 6 : Price of Hydrogen per kg vs. Analysis Period

The price of hydrogen has an exponentially decreasing relationship with the analysis period as well. For this graph we assumed that the plant life would be 10 years which means the major components (the electrolyzers) would have to be replaced or refurbished. This new cost created a small kink in the graph which meant the price of hydrogen actually raised a little bit if we went past that point as you can see below.

Table 1: Price of Hydrogen per kg vs. Analysis Period

Analysis Period (Years)	$ / kg H_2
1	270.39
2	127.42
3	87.41
4	68.54
5	57.54
6	50.35
7	45.27
8	41.51
9	38.61
10	36.3
11	37.95
12	36.1
13	34.54

Slight Price increase

IV. Electrolyzer Capital Cost

Because the price of hydrogen was affected by the cost of the elctrolyzer replacement/refurbishment (which was assumed to be about 30% of the price of the brand new electrolyzer system) I decided to look into seeing the trend that the price of the electrolyzer system has on the price of hydrogen produced per kg. Knowing relationship that price of the electrolyzer has with the end price of hydrogen will be important because increasing plant capacity means an increase in the capital cost of our electrolyzer system.

Will it be worth it to increase the plants production capacity at the cost of more expensive electrolyzer and hydrogen storage systems?

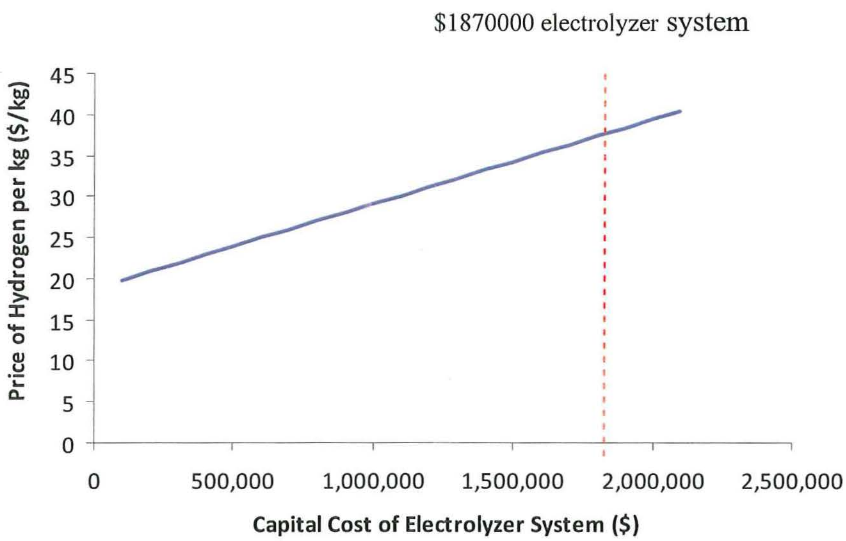

Figure 7: Price of Hydrogen per kg vs. Capital Cost of the Electrolyzer System

The price of hydrogen has a linear relationship with the price of the electrolyzer system. We have assumed Cal State LA's electrolyzer system to be $1,700,000 based on the CARB proposal with an installation factor of 1.1 which brought the system up to $1,870,000.

Since the price of hydrogen drops exponentially with the increase in plant capacity and only rises linearly with the increase in the cost of the electrolyzer system, there may be an overall price decrease if we increase the production capacity of our plant.

In order to investigate this hypothesis I went ahead and tabulated the price of hydrogen vs the production capacity including what I assumed would be the cost of the entire system if the production capacity was increased. Since the price of the electrolyzers was $800,000 for the 60 kg/day system, I assumed a capital cost increase of $1,000,000 for every 60 kg/day increase in production capacity. The extra $200,000 was added on to the cost of the electrolyzers to account for any other costs in increasing production capacity such as storage tanks, pumps, valves, hoses etc. The results show that even with this price increase, it would still be cost effective to increase production capacity. This would be assuming we had the traffic to consume the given amount of hydrogen of course.

Table 2: Price of hydrogen vs. Production Capacity Including Increase in Capital Cost

Hydrogen Production Per Day (kg/day)	*Price of Hydrogen Per kg ($/kg)
60	$36.30
120	$26.44
180	$22.28
240	$20.42
300	$19.31
360	$18.42
420	$17.91
480	$17.41
540	$17.13
600	$16.90

Cal State LA's Planned Hydrogen Station

Here are the same results in a graphical form:

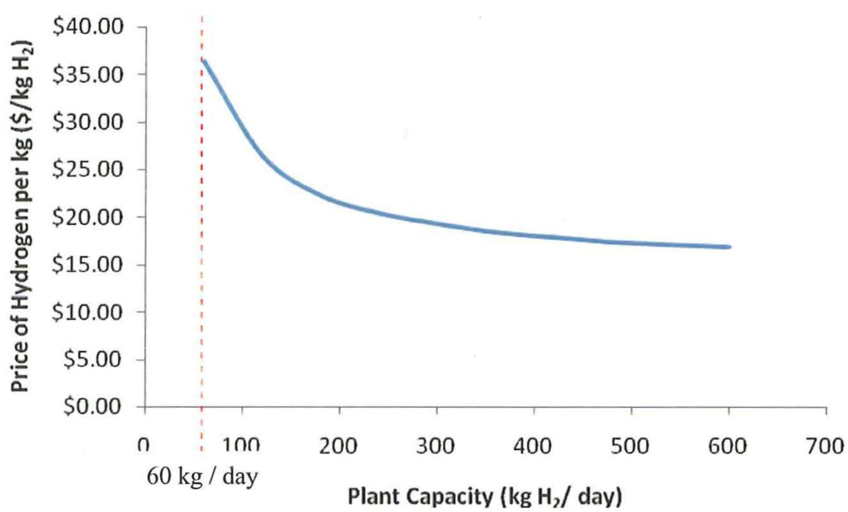

Figure 8: Price of Hydrogen vs. Production Capacity Including Increase in Capital Cost

Conclusion

Price of hydrogen for CSULA hydrogen station using inputs from CARB proposal:

$36.30 per kg H_2

This hydrogen production capacity (60 kg H_2 per day) is a big contributing factor that makes producing hydrogen very costly. If we are able to increase the production rate, there is evidence that we could greatly reduce the end price of hydrogen. By doubling the production capacity, our results show that we could reduce the price of hydrogen per kg by almost $10, even with increases to capital costs factored in.

Price of hydrogen for CSULA hydrogen station if production capacity is doubled:

$26.44 per kg H_2

This is a 27% decrease in the end price of hydrogen.

References

General Physics Quote, General_Physics_Quotes.pdf, California State University Hydrogen Fueling Station Phase 1, 6/10/08