

OPTIMIZATION OF HYDROGEN FILLING STATION

by

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ABSTRACT

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After experiencing the price hikes in the fuel and electricity, renewable energy is considered as one of the most attractive alternatives for future utility industry. Also, Hydrogen via renewable energy is of interest due to the environmental concern when compared with traditional fossil fuels. The Energy Bill of 2005 has included an authorization of \$3.7 billion for hydrogen and fuel cell research and development. Further, hydrogen fuel cell vehicles (FCVs) are currently in the pre-production stage of development and the infrastructure needs to support them.

Hence to overcome issues like price hike, exhaustion of crude oil and to gain appreciation for research, this thesis proposes the development of an intelligent

hydrogen filling station to monitor, control, and protect the price hike by using renewable energy & T-O-U electricity tariff as the generation facilities.

The proposed filling station will provide hydrogen for FCVs and act as a smart coordinator between the renewable energy and the utility supply.

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CHAPTER 1

MOTIVATION

1.1 Introduction

In the present time the use of oil and natural gases has been increasing rapidly and is used in almost all the fields, for example automobile, power generation, etc. If the use of the oil is going to be increased at the present rate then it is expected that the sources of oil on earth would exhaust approximately in less than hundred years.

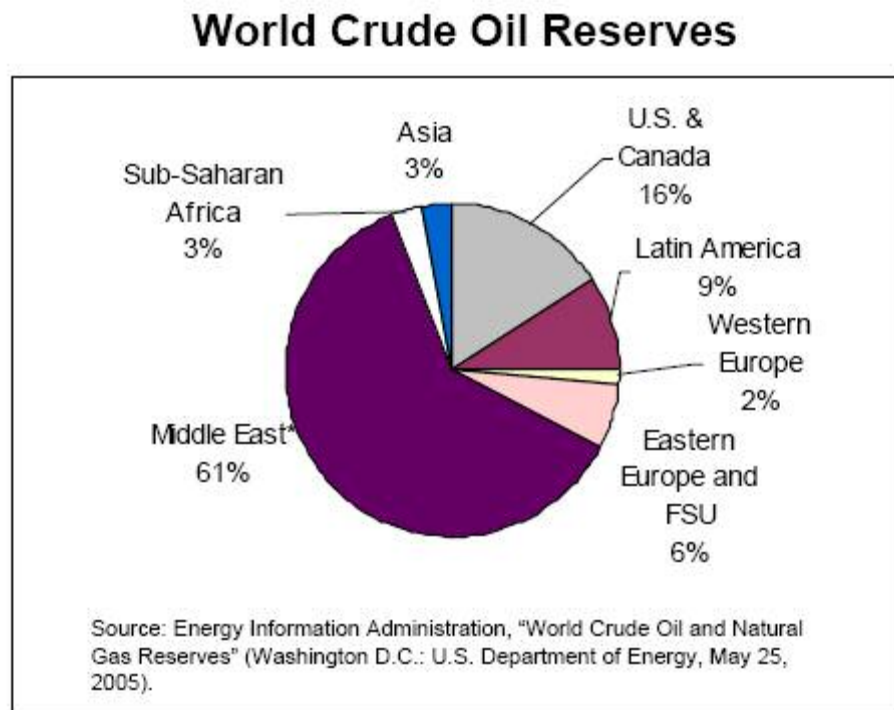


Figure1. World crude oil & natural gas reserves, May 2005

Fig. 1 shows the world reserves of crude oil & natural gases. The Energy Information Administration (EIA), in conjunction with the Oil and Gas Journal and World Oil publications, estimates world proved crude oil reserves to be around 1016.8 billion barrels. As can be seen from the graph, most of these reserves are located in the Middle East with 675.6 billion barrels, or 61 percent of the world total, and Eastern Europe and the Former U.S.S.R. with 58.9 bb, or 6 percent of total world reserves. At 2003 consumption levels, EIA predicts that the remaining reserves will be exhausted in 40.5 years.

1.2 Appreciation for Research

Additional 2000 MW of renewable energy are mandated to be installed in Texas system by 2009 as per Texas Senate Bill 7. Furthermore, the Energy Bill signed by President Bush includes an authorization of \$3.7 billion for hydrogen and fuel cell research and development. And the bill includes a fuel cell tax credit up to \$1,000 per kilowatt on the purchase of fuel cells used in residential or commercial applications. This makes the market potential on the research of hydrogen fuel significant.

The Bill goals on enabling a commitment by automakers no later than year 2015 to offer safe, affordable, and technically viable hydrogen fuel cell vehicles in the mass consumer market; that will lead to infrastructure by 2020 that will provide

- (a) Safe and convenient refueling;
- (b) Widespread availability of hydrogen from various energy sources;

Production tax credit (PTC) for renewable energy was included in the Energy Bill. Passage of the PTC reflected recognition of the important role that renewable energy can and should play in our nation's energy system. Generally, the credit is a business credit that applies to electricity generated from renewable for sale at "wholesale" (i.e., to a utility or other electricity supplier which then sells the electricity to customers at "retail"). It applies to electricity produced during the first 10 years of the plant's operation. The company that owns the plant subtracts the value of the credit from the business taxes that it would otherwise pay.

An incentive similar to the PTC is made available to public utilities (which do not pay taxes and therefore cannot benefit from a tax credit). The incentive is called the Renewable Energy Production Incentive (REPI) and it consists of a direct payment to a public utility installing a renewable plant that is equal to the PTC.

1.3 Factors behind the increase in Gasoline prices: US Oil Price Control Policy

During the rapid increase in crude oil prices from 1973 to 1981, US imposed price controls on domestically produced oil in an attempt to lessen the impact of the 1973-81 price increase. The obvious result of the price controls was that U.S. consumers of crude oil paid about 50 percent more for imports than domestic production. Put another way U.S producers received less than world market price. In the short term the recession induced by the 1973-1981 crude oil price rise was less because U.S. consumers faced lower prices. However, it had other effects as well. In the absence of price controls U.S. exploration and production would certainly have been

significantly greater. The higher prices faced by consumers would have resulted in the discovery of an alternate fuel. As a consequence, the United States would have been less dependent on imports especially from the Middle East.

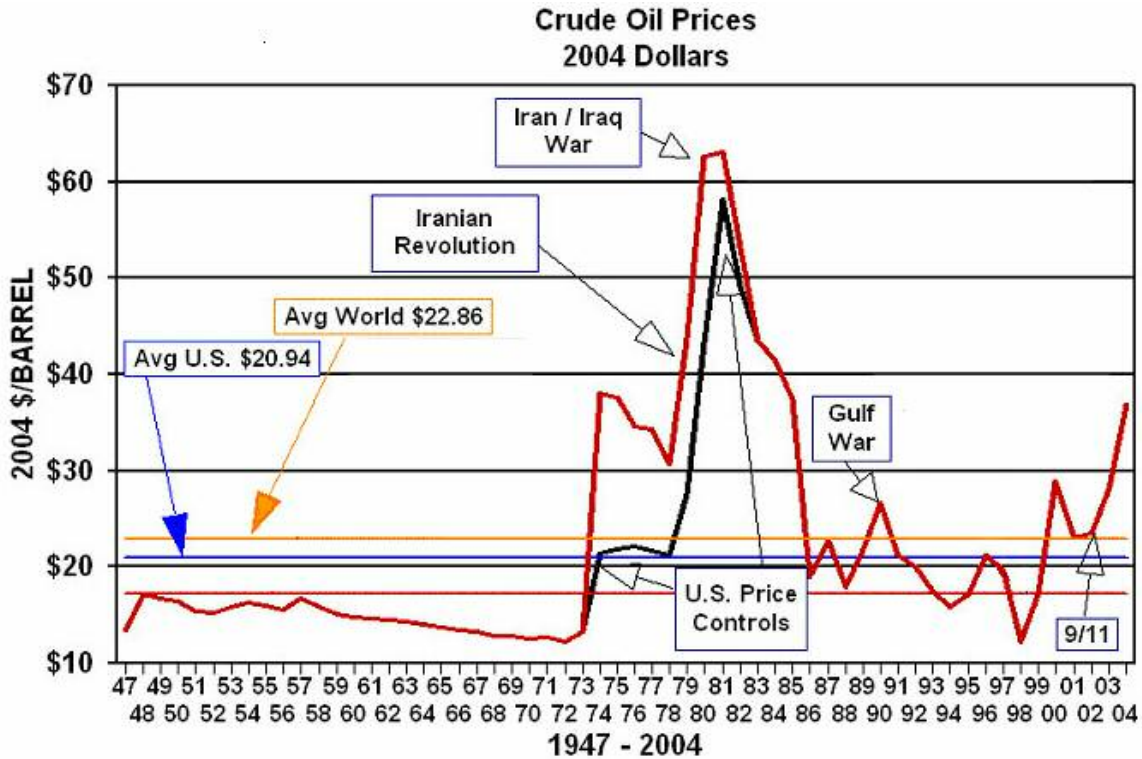


Figure 2. Crude Oil Prices

Hence no new refinery was built in the past 30 years. Also more than half of the old refineries still operate as they were running in the 1980s without any significant improvement. The increase in the usage has drastically raised the price of crude oil. U.S. retail gasoline prices started increasing, with the average price of regular gasoline rising from \$1.78 per gallon on January 3rd, 2005 to as high as \$3.07 per gallon on September 5th, 2005. Gas was going as high as \$3.29 a gallon in Southern California. In 2005 US almost lost the price control and the price kept on increasing steadily.

The dependency on the oil can only be reduced by using an alternate fuel. From the discussions above the market potential of hydrogen as a fuel is very significant. Also, Hydrogen fuel cell vehicles (FCVs) are currently in the pre-production stage of development and the infrastructure needs to support them.

Hence, the thesis proposes the development of a Hydrogen filling station. The proposed hydrogen filling station will provide hydrogen for FCVs and act as a smart coordinator between the renewable energy and the utility supply.

CHAPTER 2

HYDROGEN FILLING STATION

2.1 Introduction

From the previous chapter we understand the need for Hydrogen as a fuel. Hence in this chapter we discuss about the hydrogen infrastructure, production paths, need of T-O-U tariff & design description.

2.2 Hydrogen Infrastructure

Transportation of hydrogen has three special focus depending upon past, present or future infrastructures i.e. (a) a system for transporting natural gas/hydrogen mixtures utilizing an existing natural gas supply infrastructure, (b) a system for pure hydrogen transport utilizing an existing hydrogen gas supply infrastructure, and (c) a system for pure hydrogen transport via a new infrastructure.

2.2.1 Pipeline transportation

2.2.1.1 Existing hydrogen pipelines

Presently, the aggregated length of pipelines for hydrogen transport that are known to be either in service, under construction, or under planning reaches approximately 1,930 km.

The operating entities of these pipelines are mainly large industrial gas producers such as Air Liquide, Air Products & Chemicals, etc., or organizations such as Los Alamos National Laboratory or NASA who use large amounts of hydrogen for specific purposes.

2.2.1.2 Existing natural gas lines

With little or no changes, the majority of existing steel natural gas lines can be used to transport mixtures of natural gas and hydrogen. It is also possible, to use pure hydrogen in certain existing natural gas lines. This depends on the carbon levels in the pipe metal. Newer gas pipelines have low carbon content and are therefore suitable for transporting hydrogen. Gas pipelines, in addition to being used for transportation, can also be used to store great quantities of hydrogen. By regulating the pressure in the pipes, it is possible to use the large volume that a pipeline offers as storage during certain situations.

2.2.2 *Roadway transportation*

Hydrogen can be shipped with tank trucks in compressed state. Several companies currently deliver these types of tank trucks.

2.2.3 *Ocean transportation*

Hydrogen can be transported as a liquid in tank ships. The advantage is that liquid hydrogen is lightweight but the disadvantage is that better insulation is required

to keep the hydrogen cooled down (-253°C) over long distances.

2.2.4 Air transportation

There are several advantages in transporting liquid hydrogen by air rather than by ship. Liquid hydrogen is lightweight and the delivery time is much shorter, and evaporation is therefore not a big problem.

2.2.5 Fuel forms of Hydrogen

Compressed hydrogen is a simpler, less expensive, and more energy-efficient method of storage than other methods and is well suited for the range of the majority of urban drivers in the U.S. Liquid hydrogen is even more compact, but is complicated and not energy efficient. Typically, 11 to 12 kilowatt-hours of electricity are needed to produce 1 kilogram of liquid hydrogen. This high energy penalty can be a key factor. Hence in our design we use compressed hydrogen.

2.2.6 Central Production vs. On-site Production

Hydrogen can be produced at large central production plants or it can be generated on-site at the local fueling station.

The cost of hydrogen production can be minimized by building large central plants. However, the cost of transporting hydrogen from the central production plant to the fueling station can be excessive. The three major hydrogen transportation modes are:

- 1) Compressed hydrogen in tube trailers.
- 2) Liquid hydrogen in cryogenic (super cold) tanker trucks.

3) Hydrogen pipelines

Compressed hydrogen transportation is expensive as only little compressed hydrogen can be transported via on-road transport. Unfortunately, these moderate pressures lead to large fuel tanks and/or limited driving range because the density of simple hydrogen molecules (H_2) is lower than the density of conventional fossil fuels such as gasoline (C_8H_{18}) or natural gas (CH_4), both of which are more complex molecules. As a result, industrial hydrogen is rarely transported more than a 200 miles by tube trailer.

Once hydrogen is liquefied to $20^\circ K$ ($-253^\circ C$ or $-487^\circ F$), it can be transported thousands of miles in tanker trucks at very low cost. However, liquefying hydrogen is energy-intensive and hence highly expensive.

Transporting gaseous hydrogen by pipeline is the least expensive option, provided that there is enough demand to justify building the pipeline system. Herein lies the dilemma for the introduction of hydrogen-powered cars: there will not be enough cars initially to justify building a national or even regional hydrogen pipeline system.

In either case the on-site generation option eliminates the need to build large central hydrogen production plants and the need to build a transportation infrastructure before there are large numbers of hydrogen-powered cars on the road, and also it eliminates the high cost of transporting hydrogen.

2.3 Hydrogen production paths

There are many technologies that can be used to produce hydrogen. Hydrogen has to be extracted from one of the sources: fossil fuels, nuclear, renewable & water. The term renewable has been defined to include solar, wind, biomass, geothermal. All the energy we use, including hydrogen, must be produced from one of these three primary energy resources.

On earth, hydrogen is found combined with other elements. For example, in water hydrogen is combined with oxygen. In fossil fuels, it is combined with carbon as in petroleum, natural gas or coal. There are several methods for extracting hydrogen. Steam reforming is a well-established technology that allows hydrogen production from hydrocarbons and water. Steam-methane reformation produces about 95% of the hydrogen used in the United States. ($\text{CH}_4 + \text{H}_2\text{O} + \text{heat} = \text{CO} + 3\text{H}_2$)

Another way to make hydrogen is by electrolysis—splitting water into its basic elements—hydrogen and oxygen. Renewable energy can be used to power electrolyzers to produce the hydrogen from water. Using renewable energy provides a sustainable system that is independent of petroleum products and is nonpolluting. Some of the renewable sources that can be used to power electrolyzers are wind, hydro, solar and tidal energy. After the hydrogen is produced in an electrolyzer, it can be used in the fuel cell. Electrolysis involves passing an electric current through water to separate the atoms ($2\text{H}_2\text{O} + \text{electricity} = 2\text{H}_2 + \text{O}_2$). Hydrogen collects at the negatively charged cathode and oxygen at the positive anode. Hydrogen produced by electrolysis is extremely pure. Water is abundant and renewable, and technological advances in

renewable electricity could make electrolysis a more attractive option to produce hydrogen in the future.

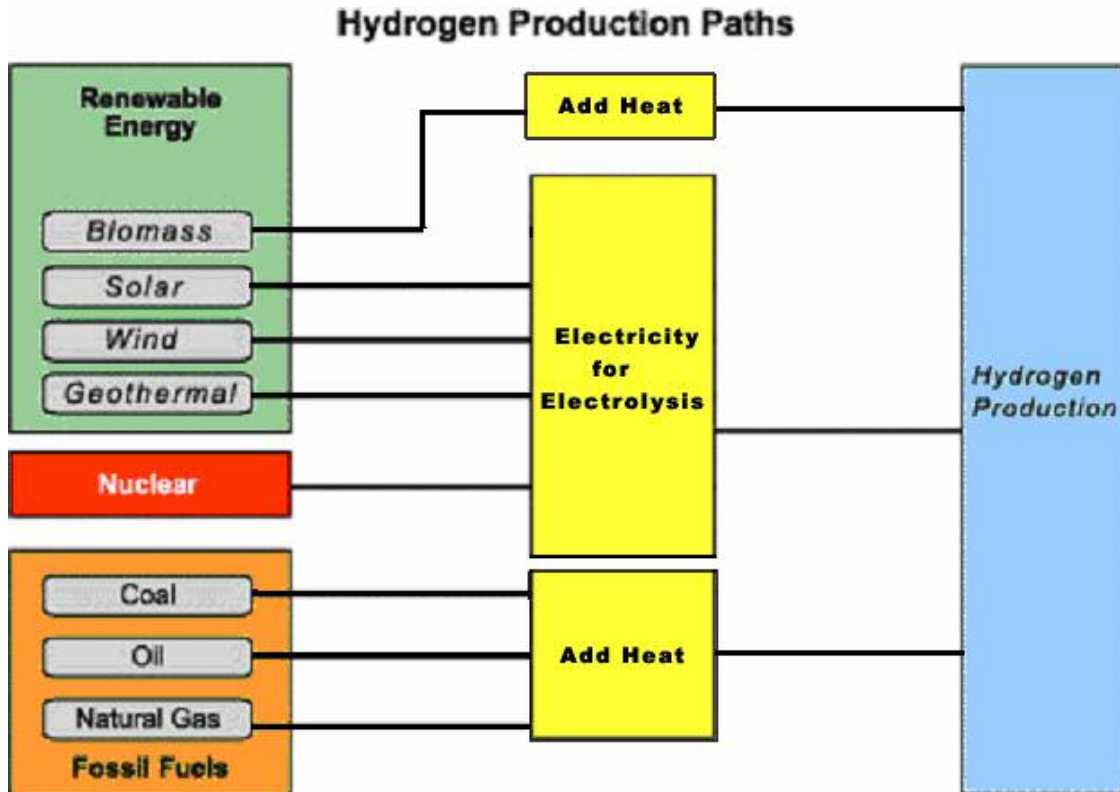


Figure 3. Hydrogen production paths

There are also several experimental methods of producing hydrogen.

In biomass gasification, wood chips and agricultural wastes are super-heated until they turn into hydrogen and carbon monoxide.

In coal gasification, the coal is subjected to high temperature and pressure, using steam and measured amounts of oxygen. This leads to the production of carbon dioxide and hydrogen.

Scientists have also discovered that some algae and bacteria produce hydrogen by splitting water molecule using sunlight as their energy source (photo biological). Experiments are underway to find ways to induce these microbes to produce hydrogen efficiently.

The practical status of various hydrogen production processes are as follows:

Table 1: IEEE Power & Energy, Vol. 2, No. 6, Nov-Dec, 2004 "Hydrogen: Automotive Fuel of the Future" by FSEC's Ali T-Raissi and David Block

Process	Practical Status of Technology
Steam methane reforming (SMR)	Mature
Coal gasification (TEXACO)	Mature
Biomass gasification	R&D
Photo biological	Early R&D
Grid electrolysis of water	Mature
Solar/Wind electrolysis of water	R&D to mature

Thus the current feasible technology which is ready to mature is Solar & Wind energies for electrolysis of water and our design is based on this process.

2.4 Time-of-use electricity billing

When power prices are high or supplies are short, reducing peak loads becomes a top priority for utilities. Billing customers for energy based on the time of day has

proven to be a viable means for reducing peak loads. The demand for power is not constant; there are certain hours of each day when demand "peaks" at levels considerably higher than the remainder of the day. Flat-rate electric tariffs shield most customers from fluctuations in energy costs. Utilities, however, are not insulated from these fluctuations.

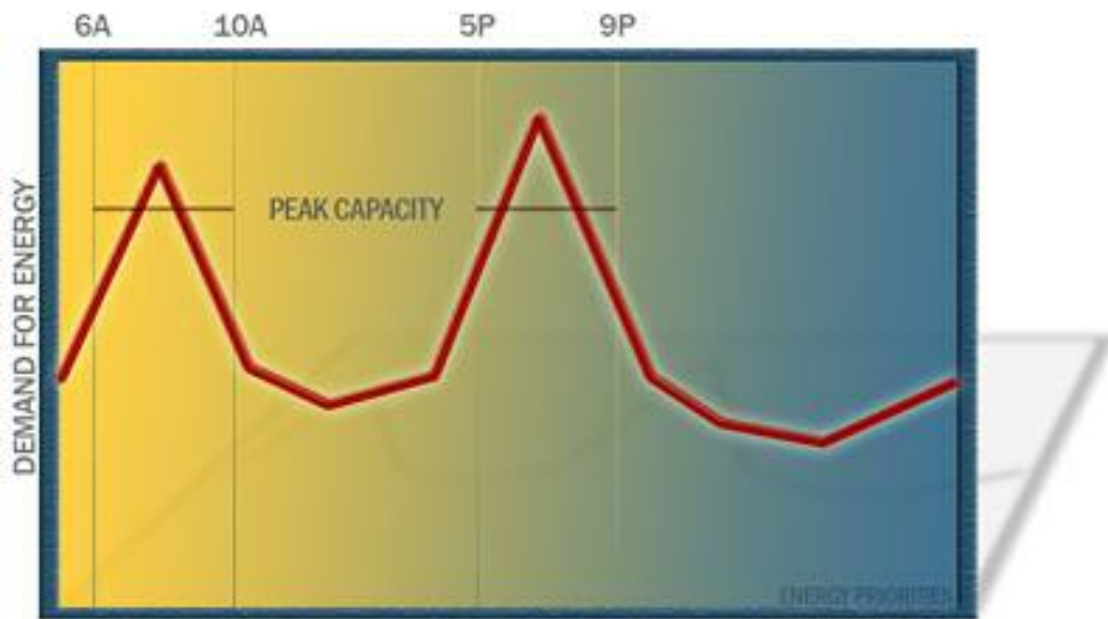


Figure 4. Energy demand fluctuates throughout the day, with morning and evening periods of high usage. (Puget Sound Energy PSE)

During the morning and evening peaks, when power demands which sometimes exceeds the resources available, utilities has to buy more than expected on the spot market at prices several times higher than ever before. Unlike an unregulated business, utilities can't simply pass price increases along to customers without regulatory approval. This can really be financial crisis for the Utilities. Hence they motivate customers to use electricity rates based on time-of-use billing.

Shifting demand from peak morning and evening periods into the mid-day and nighttime hours would reduce peak power demands and alleviate the problem. With only a slight shift in consumer behavior, Utilities could buy much less of its energy at record-high spot-market prices.

Pudget Sound Energy (PSE) proposed the Personal Energy Management program to Washington Utility and Transportation Commission (WUTC) in early 2001 as they required the approval of the state agency in charge of regulating private, investor-owned utilities such as PSE.

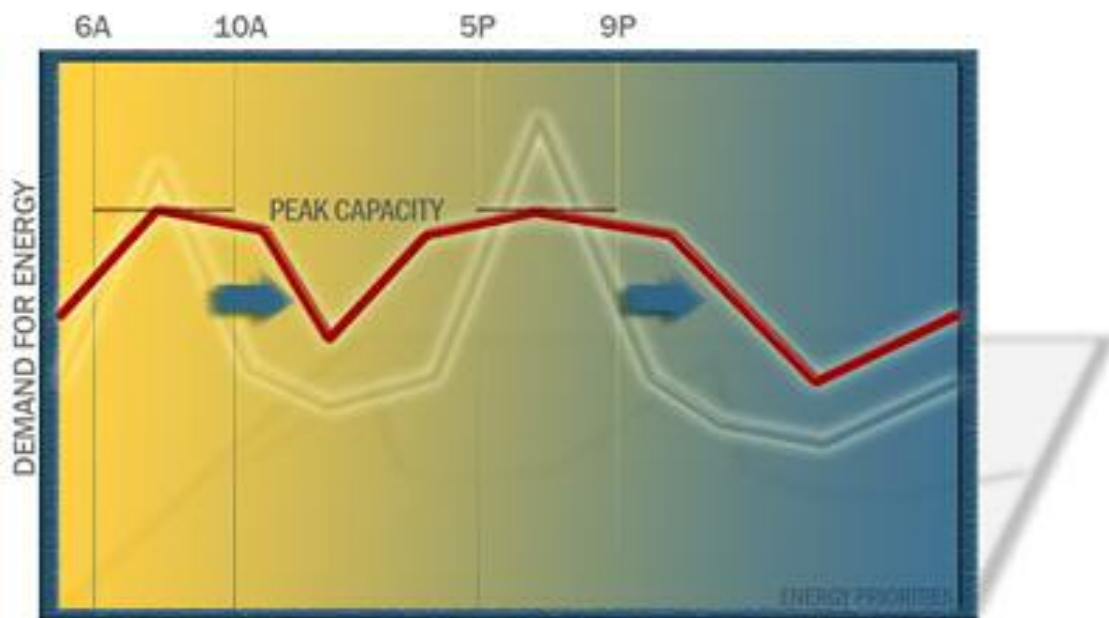


Figure 5. PSE customers responded by shifting about 4% of their loads out of peak and into economy hours. This equated to about a 25,000 kW peak reduction for PSE, and significant savings on last-minute wholesale energy purchases.

The commission's purpose was to ensure the utility provides safe and reliable service to customers at reasonable rates, while allowing PSE the opportunity to earn a fair profit. The program was potentially a long term solution to the supply and cost

crisis. In addition, it could help the utility use its power plants more efficiently, postpone building new power plants and avoid costly expansions of its distribution infrastructure.

The WUTC approved a TOU tariff (electric rates based on time of use) starting May 1, 2001. PSA would apply the new TOU rates by reading each customer's meter four times a day instead of once a month by using electronic meters.

As PSE hoped, customers shifted their loads according to the price incentives. The average customer shifted 13 kilowatt hours out of peak periods and into off-peak periods. It translates to 25,000kilowatts of reduced peak demand.

To motivate consumers to change, electric approved tariff set lower electric rates for off-peak energy use, and higher rates for peak consumption.

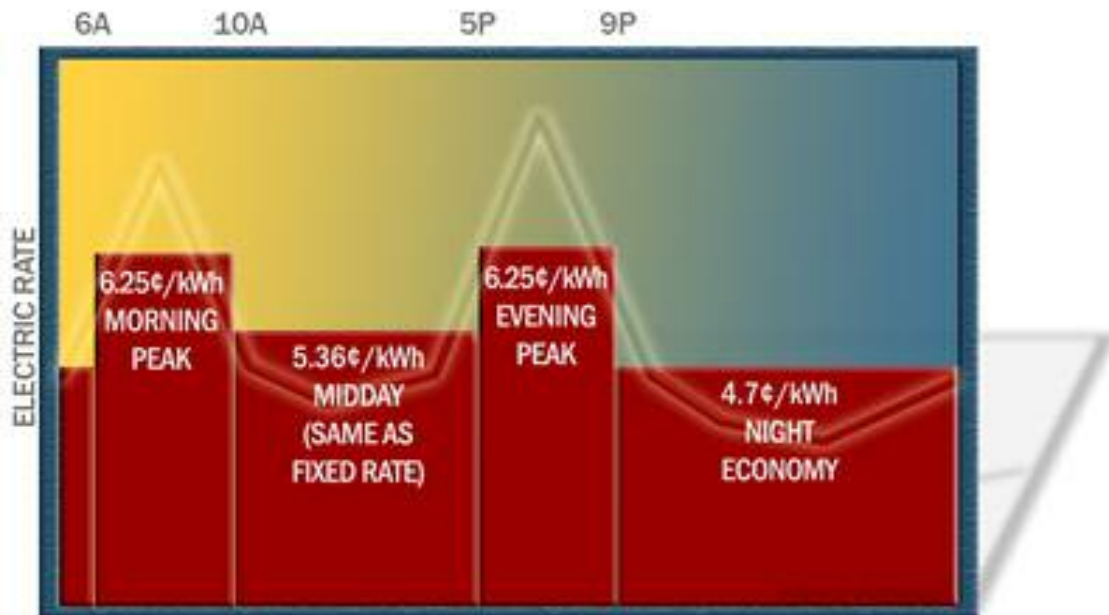


Figure 6. The time-of-use electric tariff approved for PSE charged customers. The goal was to encourage customers to shift certain loads by a few hours.

In our design we take advantage of TOU tariff as wind energy and solar energies are not enough to produce the needed hydrogen. Hence hydrogen will be generated economically and avoid any high demand for the Utility. Thus the Utility can use it's existing power plant more efficiently.

2.5 Design description

A hydrogen filling station mainly consists of electrolyzer, compressor, storage tank and dispenser. The scheme is shown as in Fig. 7.

In this project we have simulated the hydrogen filling station using LabVIEW. The station monitoring system monitors each function of the fuel station. Each process has got its own window. This gives a high level of flexibility to operate the fuel station at the optimum condition. The Fig.8 shows the interface for the various functions of the fuel station.

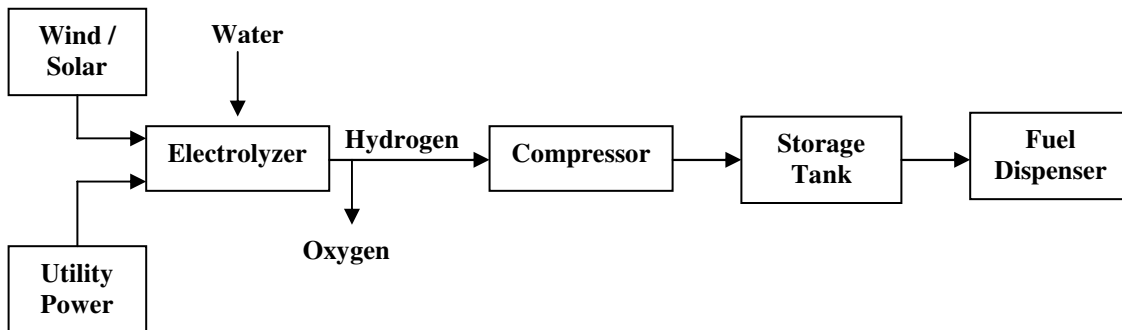


Figure 7. Hydrogen Filling Station scheme

This interface allows the monitoring and control of the electrolyzers, storage and compressors. Additionally this interface also provides real time economic analysis for

the system and gives real time fuel price calculations. Price of raw materials and the value of wind/solar energy, the load, the tank limit etc. can be changed using the settings interface. The interface diagram of initial setting and real time economic analysis is as shown in Fig. 9 and 10.

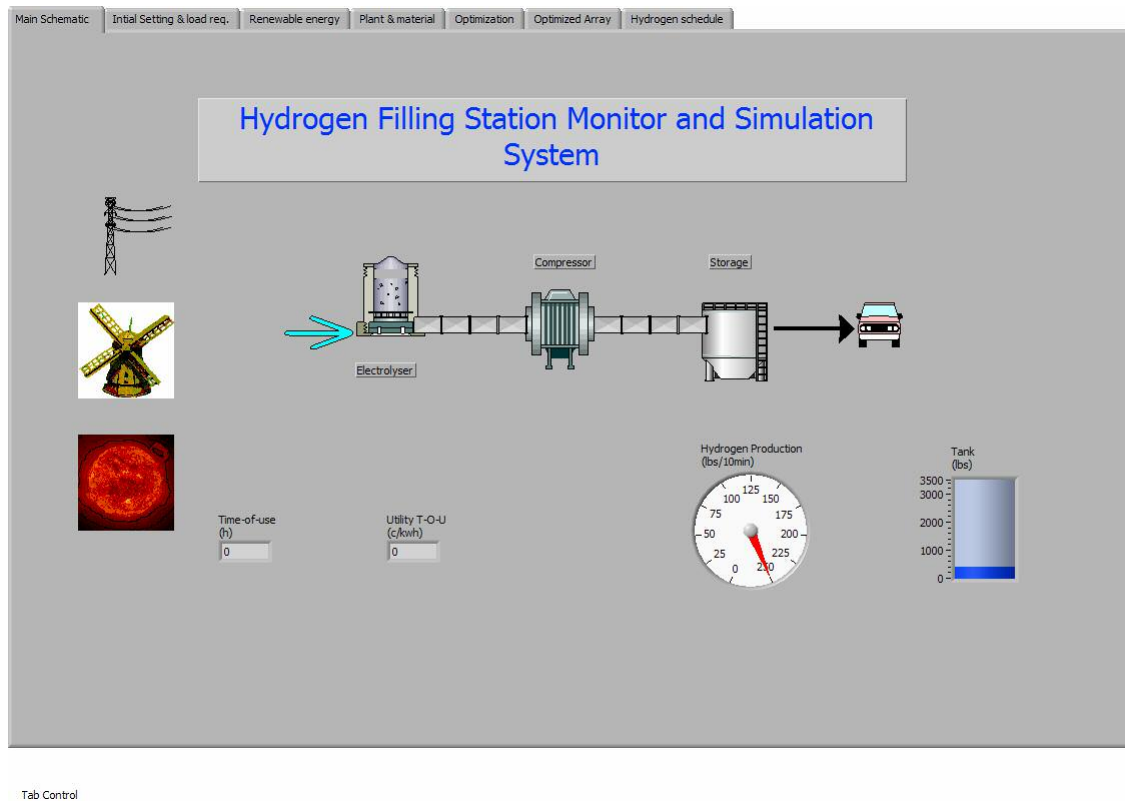


Figure 8. Hydrogen Filling Station Monitoring Interface

2.5.1 Electrolyzer

The energy required to produce hydrogen at atmospheric pressure via electrolysis is 32.9 kWh/kg. A kilogram is about 2.2 lb. For 1 mole (2 g) of hydrogen the energy is about 0.0660 kWh/mole. This power is required to split water into

Main Schematic | Inital Setting & load req. | Renewable energy | Plant & material | Optimization | Optimized Array | Hydrogen schedule

PRODUCTION RATE
(kwh/kg)
46.8

Forecasted load
(lb/10min)
100

Tank upper
limit (lbs)
3500

Tab Control

Main Schematic | Inital Setting & load req. | Renewable energy | Plant & material | Optimization | Optimized Array | Hydrogen schedule

Wind energy in
every 10 min.
(kwh)
250

Solar energy in
every 10 min.
(kwh)
0

Tab Control

Figure 9. Initial Setting Interface (2 nos)

hydrogen and oxygen. For commercial electrolysis, it is 46.8 kW-hr/kg, which corresponds to an energy efficiency of 70%.



$$36\text{g/mol} + \text{electricity} = 2 * (2 * 1\text{g/mol} + 16\text{g/mol})$$

$$\text{Mass fraction of hydrogen in water} = (4\text{g/mol}) / (36\text{g/mol}) = 0.11$$

$$\text{Mass fraction of oxygen in water} = (32\text{g/mole}) / (36\text{g/mole}) = 0.89$$

2.5.2 Compressor

Compressor is used to compress the hydrogen to be stored in the storage tanks. In this project, the pressure of the gas is kept at 5000 psi which can be directly dispensed into the vehicle's storage tank.



Figure 10. Real Time Economic Analysis

Diaphragm compressors are the preferred compression equipment for providing non-contaminating gas compression. The metal diaphragm group of the diaphragm compressor isolates the process gas from the hydraulic fluid and all lubricated parts to ensure purity.

Unlike other types of reciprocating piston compressors in which the primary displacing element, a piston with the lubricant, contacts the gas, the metal diaphragm compressor completely isolates the gas. The motion is transmitted through flexible metal disc called as the diaphragm.

Diaphragm moves into the compression chamber, reducing the volume and thereby increasing the gas pressure. Because the diaphragm isolates the gas from the compressor lubricants, the discharged gas is pure.

2.5.3 Storage tanks

According to the goal of this project, the total capacity of the tanks would be 4000 pounds . This can sufficiently store enough hydrogen (for fueling 151 vehicles at a time) thereby not generating hydrogen during the peak T-O-U tariff.

2.5.4 Dispensers

Dispensers are used to fill the vehicle's storage tank with hydrogen from the station storage tanks. The dispensers must be user friendly and should have the capacity to measure the amount of hydrogen dispensed and also have the ability to carry out transactions using credit cards.

Further from security point of view, they should have surveillance cameras to detect any misuse of the system. Furthermore, the dispensers should have adequate safety arrangements so as to avoid accidents during the refueling process.

CHAPTER 3

SAFETY ANALYSIS

3.1 Introduction

This Chapter gives the safety analysis along with the safety measures of components & eight major failure modes.

3.2 Safety requirements

Like other fuels, hydrogen needs to be carefully handled. As a light gas, hydrogen disperses into air at a high speed. Hence it should be constantly checked and monitored for any leaks during its transfer from one stage or component to another, for example, from electrolyzer to compressor. The pipes should be properly maintained and threaded in their grooves to prevent any leaks. The flammability makes hydrogen difficult to deal with, and special measures must be taken when handling it. Since it is flammable at wide concentrations in air, it should be prevented from the contact with igniting sources. Before introducing hydrogen into any containers, the containers should be purged with inert gas or with nitrogen to prevent hydrogen from forming flammable mixtures with air, oxygen or any other oxidizers. Venting of hydrogen in case of emergency or for cleaning purposes should be done under the specified standards, i.e. the flow rate at which it should be vented. Hydrogen burns with a light blue color flame which is invisible to the naked eyes. As it a clean gas, no smoke is generated when

burning, and its flame is difficult to detect. Hence detectors should be deployed to identify the invisible flame. Due to its flammability, all the electrical equipment should be grounded to prevent any sparks caused by static charge. In case of any fire, the supply of hydrogen to the flame should be slowly cut off other than abruptly shut off. A proper way to fight with fire due to hydrogen is to prevent it from spreading and allow it to burn till the hydrogen supply is slowly cut off. Powered fire extinguisher and water should be kept handy to deal with the fire immediately.

3.3 Safety Measures of Components

In this section safety measures will be explained for each of the main components of our proposed design.

3.3.1 Safety Measures for Electrolyser

Before filling the electrolyzer with the alkaline mixture of water and caustic KOH, the checking for leaks must be done. All the inlet and outlet pipes should be perfectly threaded so that there are no leaks. The body of the electrolyzer is made out of corrosive resistant materials like Titanium which can not become brittle when they come in contact with hydrogen.

3.3.2 Safety Measures for Compressor

The basic diaphragm compressor design provides leak tight and non-contaminating gas compression and transfer. The most possible hazards originating from the compressor are large flow rate and high pressures. A monitoring system,

which monitors the pressure of the gas inside the compressor, is provided for the safe operation of the compressor. According to the design requirements, the hydrogen gas should be compressed to 5000psi. The compressor is equipped with appropriate switches to monitor suction, discharge rates and interstate pressures and temperatures. A safety valve is also provided for the compressor to dispense excess pressure in case of emergency.

3.3.3 Safety Measures for Storage Tank

Because hydrogen in the storage tank is maintained under pressure, the pressure of the storage tank should be continuously monitored for excess pressure. An emergency vent is provided to dispense the gas under over pressure. The material, which the body of the tank is made of, is able to withstand excess pressure of the gas until the pressure valve responds, and is strong enough to act as a shield to protect the gas from the outside temperatures and pressures. The material is also explosion proof. The joints, threads, and valves, which are made from the material, are tight enough to withstand the outside explosion and act as a shield to the gas. The tank is maintained under continuous vigilance for the leaks. The storage system is installed above the ground. It should be kept in mind that storage system can not be installed beneath electric lines. The area within 15 feet of the hydrogen container should be kept free of dry vegetation and any other combustible materials.

3.4 Six Major Failure Modes

The following are the most possible failures which can lead to accidents in our proposed hydrogen fueling station. They are listed by the order of probability.

3.4.1 Leakage of Hydrogen

The main cause for the leaks is the misalignment of valves, deformed seals and gaskets, constructional defects of the components in use. Hence the components used in the system are of superior quality in terms of their constructional materials and self emergency features. All the components should be tested before putting them into use. Not only initial testing but also periodical inspection is required. The control systems should be employed to check proper alignment of valves, seals, gaskets etc. Provision for emergency shut down for gas flow needs to be also provided. To dilute the leaked gas proper ventilation is necessary by using exhaust fans and vents in the walls. The outward opening doors should be lightly fastened so that they can be opened freely in case of emergency. These doors need to be located in exterior walls.

The safety devices used in each of the components in our proposed design to prevent the leakage, are indicated in the figure below:

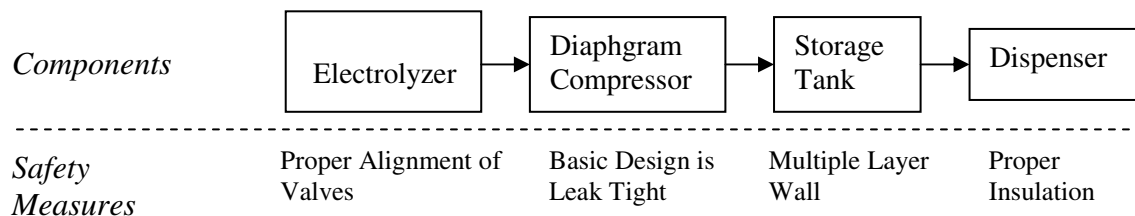


Figure 11. Safety Measures for the Components

The electrolyzer should have controllers to check proper alignment of valves, gaskets and seals. If any malfunctioning is found in the valves, the control system of the electrolyzer will indicate it and the valves are replaced immediately. Automated systems are used to reduce manual errors. The outlet valve from the electrolyzer which is used for the transporting of hydrogen gas to the compressor is periodically checked in order to prevent leaks.

The failures of gas leakage in storage tank include ruptures due to manufacturing defects in tank, abusive handling, stress fractures and punctures by a sharp object. Massive leakage can occur due to faulty pressure relieves or punctures. Slow leaks can occur due to stress cracks in tank liner, faulty coupling from tank to feed line or fuel connection. The storage tank should be built of multi layer walls to prevent leakage. This type of construction provides more leak tight structure than that with one wall made of stronger material. The dispenser which is an interface between the user and the station should be made leak proof. The possible areas of leakage in this case are through the nozzle. The hose breaks will be employed in the system to ensure that there is no leakage of hydrogen gas while fuel is being filled from the dispenser to the vehicle. In addition to the hose breaks, the pipe from the dispenser is also insulated in order to avoid the leakage of hydrogen gas while fueling.

3.4.2 Excessive pressure inside the components

The pressure inside the components should be constantly checked and monitored. Control systems will be employed to check the pressure and flow rates of the gas. Since the gas inside the components like compressor or the storage tank is

under pressure, if a leak would occur, the rate at which the gas leaks out can be very high, because the gas under pressure escapes more rapidly than that under low pressure. if the component is built indoors, accumulation of the gas should be avoided, and fast venting of the gas can be achieved by the use of exhaust fans and vents in the roof and walls. Automatic venting valves and excess pressure relief valves are employed to decrease delays due to manual operation of valves. To reduce the risks the storage tanks in our design are installed outdoors where the dilution of the gas into the atmosphere reduces the risk of detonation.

The safety devices employed for different components in the system are shown in the diagram below in Fig.12.

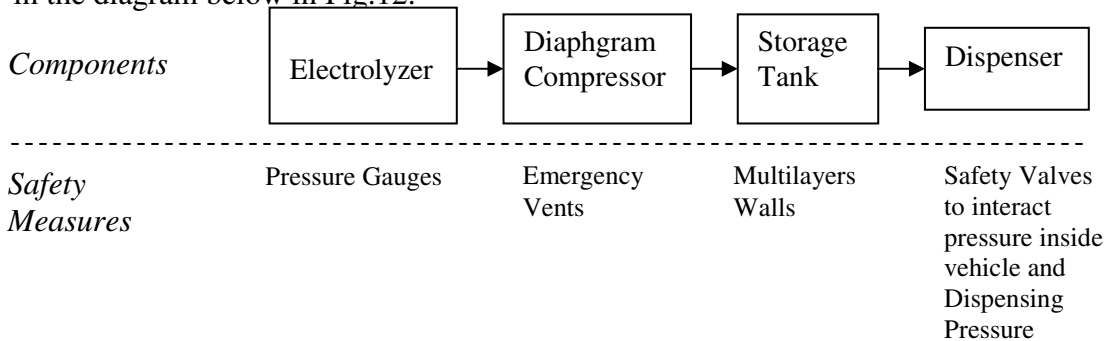


Figure 12. Safety Measures for Excessive Pressure

To make the system from dangers due to high pressure, the electrolyzer should be equipped with pressure gauges to check the pressure of the gas produced inside the electrolyzer. In case the pressure exceeds the limits, either the production should be shut off or the gas be released through the vents installed on the walls of the electrolyzer. The vents has the function to reduce the risk of excess pressure of hydrogen in the electrolyzer. The compressor, where the gas is compressed to the expected pressure, should be equipped with pressure relive devices such as safety valves. Pressure relive

devices and emergency vents are also equipped in the storage tank.

3.4.3 Flammability of Hydrogen

One should first check whether the engine of the vehicle is turned off before the fueling of the gas.

The possible reasons are nozzle / hose breaks, static electricity & friction due to flow. The following are the measures to reduce the risks mentioned above :

- 1) Periodic inspection and preventive maintenance.
- 2) By grounding the electrical equipment including the fuel station so that potential of the vehicle being fueled; the dispenser and the person fueling the vehicle are at same potential.
- 3) By using temperature sensors at regular interval.

Since the dispensing of hydrogen is done at high pressures, fast acting systems should be installed. Automatic valves should be employed at the dispensing unit to reduce the chance of operator error like improper sequencing of the valves.

3.4.4 Detonation of Hydrogen

In case there is a flame detected at a point, it should be extinguished before transforming into detonation. Since hydrogen burns quickly, the time to cut off the gas supply should is very short. Flame detector detects invisible flames at high speed (3-4 milliseconds) by sensing the UV high-energy radiation emitted by fires and explosions at the instant of their ignition & hence should be employed. Also automatic venting

systems, and automatic sprinklers should be employed to prevent any delay or wrong manual inputs. They will take quick responses as soon as they detect gas leak or an invisible flame. Hydrogen needs to be released into atmosphere in case of emergencies when the pressure exceeds the safety limits.

3.4.5 Natural Disasters

Our proposed hydrogen filling station should be constructed with materials which can withstand natural disasters like earthquake, cyclonic effects, tornados, etc. as well as fire accidents.

3.4.6 Lack of Lubrication/Periodic checks

All the components of the station should be checked periodically in order to avoid any malfunctioning. Lack of periodic inspection can cause lack of lubrication, which develops friction generating sparks which might result in damage of the system. Hence all the components of the system should be lubricated properly.

CHAPTER 4
SYSTEM OPTIMIZATION & CALCULATION

4.1 Introduction

This chapter discusses the system optimization . Furthermore, it provides light on the capital cost, the operating cost, the maintenance cost & the total cost of the fueling station.

4.2 Mathematical Model

Using mathematical model to describe the principle of our technical design, the model can be formulated as:

$$\text{Min} \quad f = C_{Cap} + C_{Operation} + C_{Maintenance} - B_{Oxygen}$$

S.T. Safety requirements
 Environmental requirements
 Tank limit

Where C_{Cap} is the capital cost;

$C_{Operation}$ is the operational cost;

$C_{Maintenance}$ is the cost of maintenance;

B_{Oxygen} is the benefit of selling oxygen.

Once the production process is decided and the main items or factors in the constraints are specified, the variables of this model in our proposed design will be the

amount of wind, solar and electricity energy and the load. Capital cost is a constant, maintenance is periodically conducted is too a constant, operation cost is minimized by using free renewable energy & T-O-U electricity tariff. Additional benefit is obtained by selling the oxygen. Thus the model is able to provide an optimal solution where the cost is the minimal while satisfying all the requirements.

4.2.1 Safety Requirements

Like other fuels, hydrogen fuel station has certain safety requirements. This is discussed in previous chapters.

4.2.2 Environmental Requirements

Hydrogen generated has no toxic waste disposal, no air or water pollution, and no global warming. When hydrogen is burned in air, the only byproducts are heat and water.

4.2.3 Tank limit

According to the goal of this project, the total capacity of the tanks would be 4000 pounds. So we can vary the tank limit as along as it is less than or equal to 4000lbs.

4.3 Plant installation & running cost

4.3.1 Capital cost

The capital cost of the electrolytic hydrogen fueling station is assumed to be the total installed capital cost of electrolyzer, compressor, storage tanks, and associated control instruments and safety equipments. The hydrogen production of the hydrogen fueling station is on-site, which means the deliver cost is the dispenser cost.

$$C_{cap} = C_{ele} + C_{com} + C_{sto} + C_{con} + C_{dis} \quad (1)$$

Table 2 summarizes the variables used in calculating the capital cost. Most of the values are provided by industrial companies.¹

Table 2. Variables to Calculate the Capital Cost

Variable		Number	Unit Price	Typical or Estimated
C_{ele}	electrolyzer cost	3 sets	(\$)	450000
C_{com}	compressor cost	2 nos.	(\$)	150000
C_{sto}	storage tank cost	3 nos.	(\$)	75000
C_{con}	control and safety equipment cost	1 no.	(\$)	2000
C_{dis}	dispenser cost	2 nos.	(\$)	50000

Note: Data Source www.stuartenergy.com, www.teledyneenergysystems.com

The life of these capital elements are usually 20 years. So the cost of capital element per day would be $(450,000 + 150,000 + 75,000 + 2000 + 50,000) / (20 * 365) = \99.59

4.3.2 Operating cost

The operating cost is given by:

$$C_{ope} = C_{ene} + C_{wat} - C_{oxy}$$

where: C_{ope} : operating cost, C_{ene} : energy cost, C_{wat} : water cost, C_{oxy} : oxygen sold.

For further economic point of view we sell the oxygen generated. Table 3 summarizes the variables used in calculating the hydrogen unit cost. Most of the values are provided by industrial companies.

Table 3. Variables to Calculate the Hydrogen Unit Cost

Variable	Unit	Typical or Estimated Values
Utility Industrial Price (P_u)	Cents/kWh	T-O-U electricity tariff
Water Price (P_w)	\$/1000gallon	2.80
Oxygen Price (P_o)	\$/kg	0.03
Compressor Energy cost(P_c)	\$	20% of total energy
Hydrogen via commercial electrolysis	kWh/kg	46.8 kWh/kg

Note: 1). Water price: Arlington Water Utilities, Texas

2). Oxygen price: www.scescape.net

$$C_{ene} = \text{Energy cost used for electrolysis} + \text{Compressor energy cost}$$

$$\text{If Energy of wind \& solar} \Rightarrow 46.8 * (\text{H}_2 \text{ in lbs}) / 2.2 \text{ then } C_{ene} = 0$$

$$\text{If Energy of wind \& solar} = 0 \text{ then } C_{ene} = P_u * 46.8 * (\text{H}_2 \text{ in lbs}) / 2.2 + P_c$$

$$\text{If Energy of wind \& solar} < 46.8 * (\text{H}_2 \text{ in lbs}) / 2.2 \text{ then}$$

$$C_{ene} = (46.8 * (\text{H}_2 \text{ in lbs}) / (2.2) - \text{Energy of wind \& solar}) * P_u + P_c$$

Also,

$$C_{oxy} = \text{Oxygen price} * \text{Oxygen production} = P_o * (\text{H}_2 \text{ in lbs}) * 0.89 / (0.11 * 2.2)$$

&

$$C_{wat} = \text{Water price} * \text{Water consumed} = P_w * (\text{H}_2 \text{ in lbs} + \text{O}_2 \text{ in lbs}) / (8.33 * 1000)$$

4.3.3 Maintenance cost

The maintenance cost includes periodic electrolyser, compressor, control system check fee. The daily maintenance cost is assumed to be a percentage of capital cost:

$$C_{mai} = \eta_{mai} \times C_{cap}$$

where: C_{mai} : maintenance cost, η_{mai} : percentage of capital cost

The maximum maintenance cost is usually 20% of the capital cost. Hence,

$$C_{mai} = 0.2 * C_{cap}$$

4.3.4 Total cost

The total cost to produce electrolytic hydrogen is the sum of the daily capital cost, the daily operating cost and the daily maintenance cost:

$$C_{total} = C_{cap} + C_{ope} + C_{mai}$$

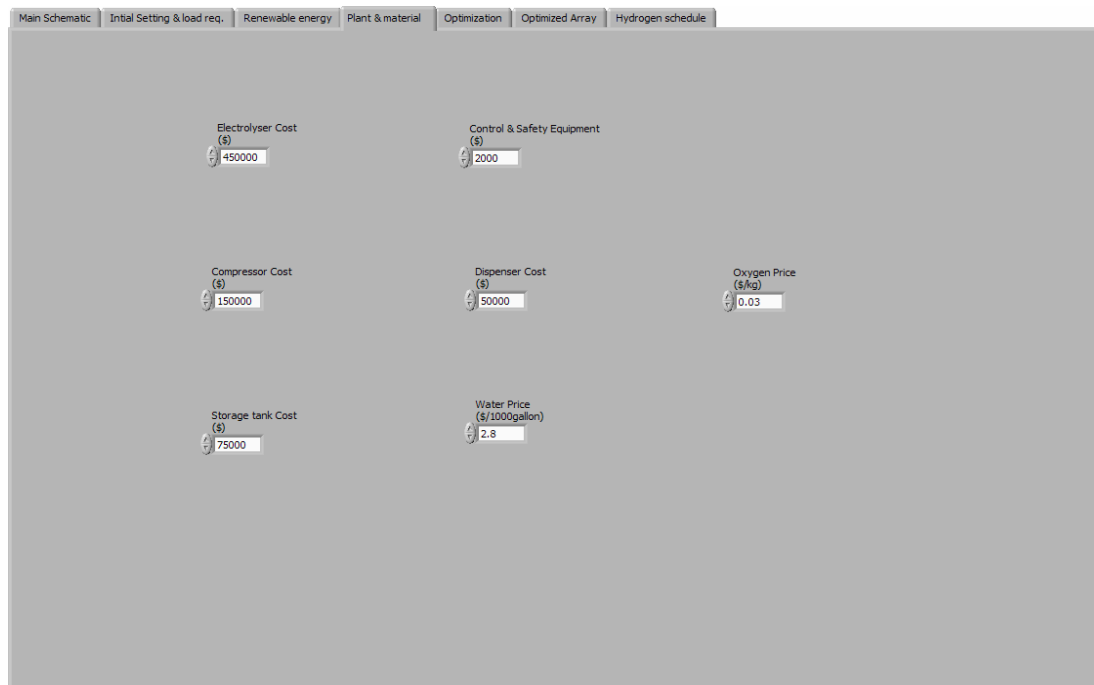
This is the total daily cost.

4.3.5 Hydrogen equivalent cost

Hydrogen has the highest energy content per unit weight of any known fuel- 120.7 kJ/g. The major advantage apart from the ecological consideration is that it stores approximately 3.4 times the energy per unit mass as gasoline. Thus a standard 15 gallon automobile gasoline tank weighs 90 pounds of gasoline and the corresponding hydrogen tank would be 60 gallons, but would weigh only 26.47 pounds. Gasoline and Hydrogen are different chemical elements having different energies.

$$1 \text{ gallon of gasoline} \equiv 6 \text{ pounds of gasoline} \equiv (6/3.4) \text{ pounds of hydrogen}$$

i.e. 1 gallon of gasoline is equivalent to 1.7647 pounds of hydrogen for same energy fuel output. Hence by finding the cost of production of hydrogen for 1.7647 pounds, we actually calculate the equivalent cost of the fuel in terms of same energy output of one gallon of gasoline. Thus, 1.7647 pounds of Hydrogen will cost $(C_{total} * 1.7647) / (\text{Hydrogen production in lbs})$ which will be the equivalent cost in terms of same energy of one gallon of gasoline.



Tab Control

Figure 13. Installed plant & Material cost interface

4.4 Renewable energy

4.4.1 Solar energy

The conversion efficiency for single-crystal PV commercial modules ranges between 15-20%. Based on El Paso, Texas monthly average daily solar radiation we get the solar energy distribution for every 10 minutes for the average fueling station having surface area of 2500m² (50m*50m) as shown in figure 14.

Table 4: El Paso, Texas monthly average daily solar radiation

Month	Solar Radiation (KW/m2/day)	Surface area (2500m2)	Solar power (KW/day)	PV output @ 17% (KW/day)	PV KWh for 12 hrs	PV KWh for 12hrs at 10 min. interval
Jan	3.46	2500	8650	1470.5	122.5416667	20.42361111
Feb	4.53	2500	11325	1925.25	160.4375	26.73958333
Mar	5.85	2500	14625	2486.25	207.1875	34.53125
Apr	7.09	2500	17725	3013.25	251.1041667	41.85069444
May	7.83	2500	19575	3327.75	277.3125	46.21875
Jun	8.02	2500	20050	3408.5	284.0416667	47.34027778
Jul	7.36	2500	18400	3128	260.6666667	43.44444444
Aug	6.75	2500	16875	2868.75	239.0625	39.84375
Sep	5.86	2500	14650	2490.5	207.5416667	34.59027778
Oct	4.93	2500	12325	2095.25	174.6041667	29.10069444
Nov	3.79	2500	9475	1610.75	134.2291667	22.37152778
Dec	3.2	2500	8000	1360	113.3333333	18.88888889
average	5.7225	2500	14306.25	2432.0625	202.671875	33.77864583

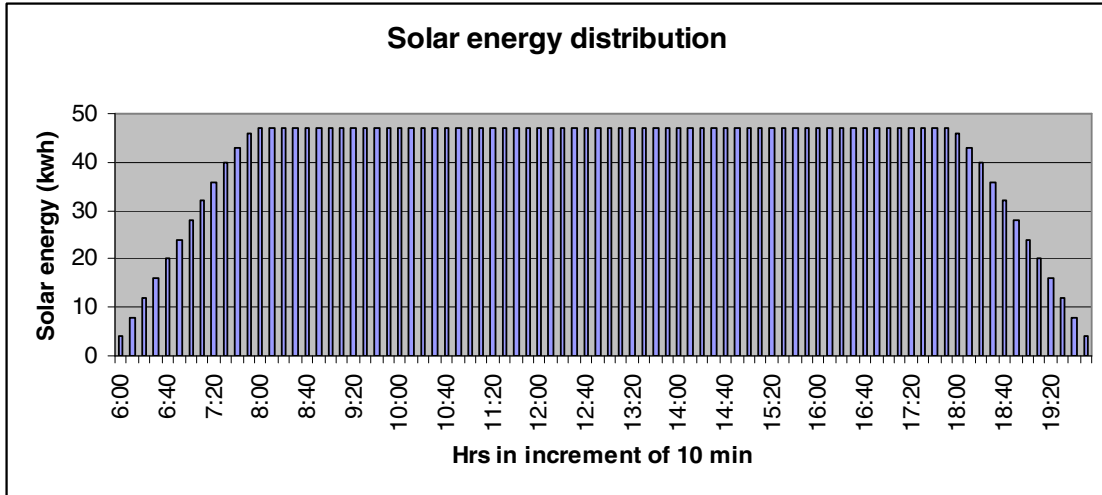


Figure 14. Sample solar energy distribution for 24 hrs for the month of June

4.4.2 Wind energy

We use wind plant of 1.65MW. If we assume the wind speed to be constant throughout the day we can get the energy of 1500kWh. Thus for every 10 minutes we will have 250kWh of wind energy.

4.5 System Optimization

Our goal is to use all the available renewable energy for the generation of hydrogen. Also, to use the cheapest electricity T-O-U tariff i.e. between 9pm to 6am & 10am to 5pm. Thus practically no hydrogen should be generated by using expensive T-O-U tariff from 6am to 10am & 5pm to 9pm (unless the tank pressure is lower than preset value).

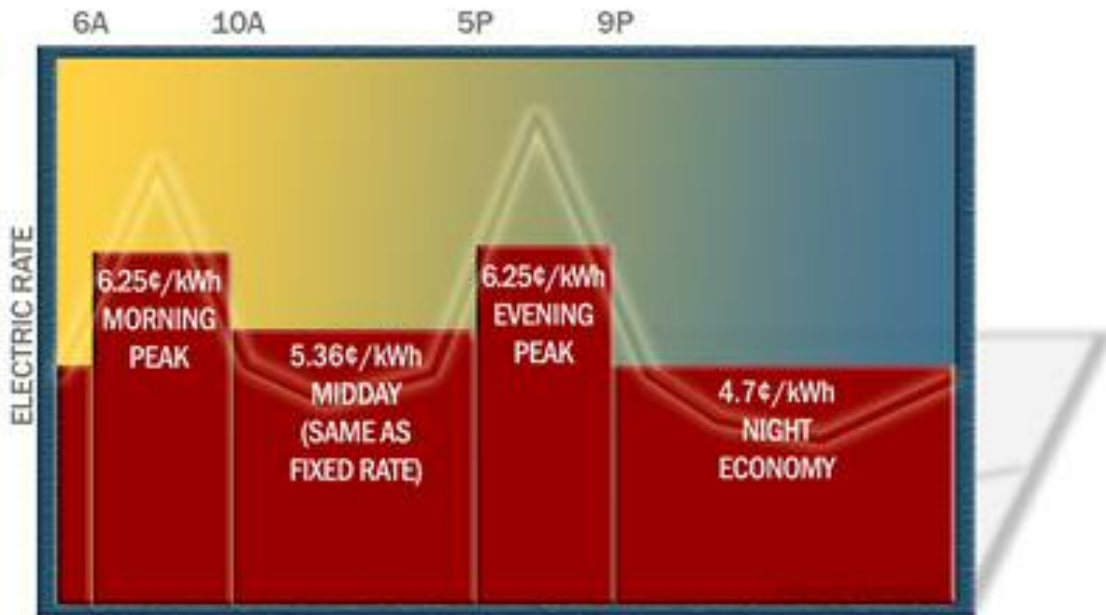


Figure 15. Time-of-use Electric Tariff

Thus, Hydrogen generation schedule can be as follows:

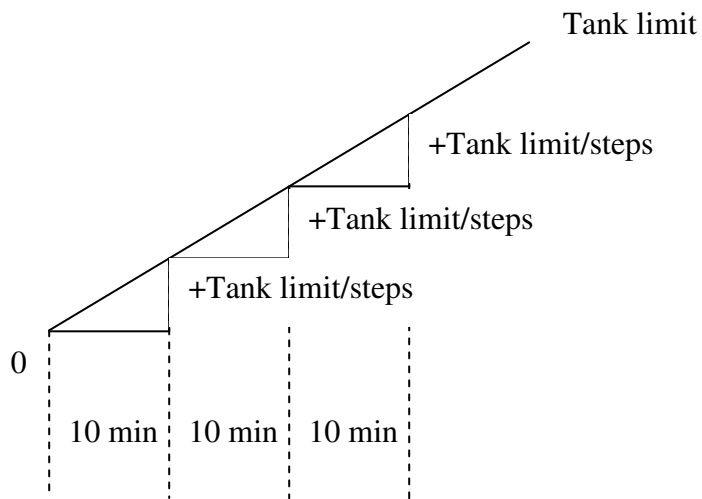


Figure 16. Hydrogen schedule between 9pm to 6am

Between 9pm to 6am hydrogen should be schedule +Tank limit/steps for every 10 minutes (Tank limit/steps more than actual or forecasted load) so that the tank fills to limit lbs by 6am.

Between 6am to 10am the tank level can come down thus not using high tariff of T-O-U and just using renewable electricity for generation of hydrogen.

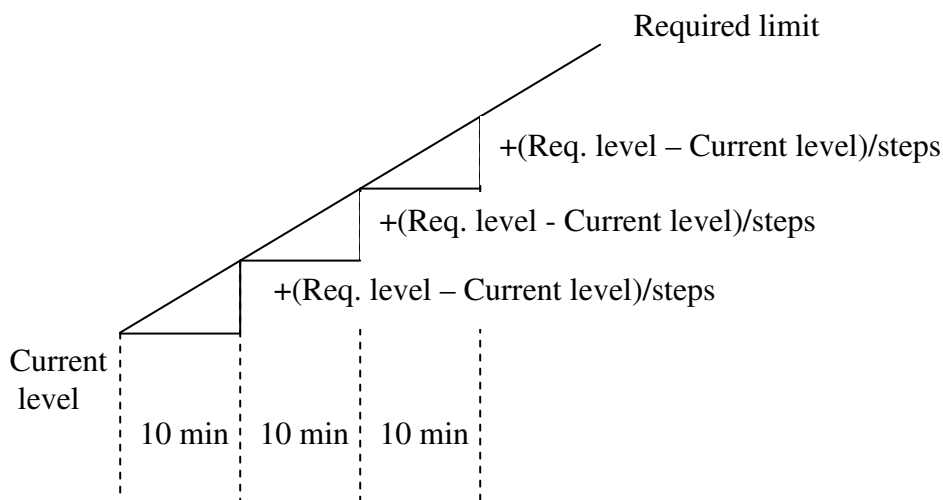


Figure 17. Hydrogen schedule between 10am to 5pm

Again, between 10am to 5pm hydrogen should be schedule $+(\text{Req. level} - \text{Current level})/\text{steps}$ for every 10 minutes ($(\text{Req. level} - \text{Current level})/\text{steps}$ more than actual or forecasted load) so that the tank fills to the required level lbs by 5pm.

Again, between 5pm to 9pm the tank level can come down to lower value thus not using high tariff of T-O-U and just using renewable electricity for generation of hydrogen.

Thus, we get total optimization by using all the renewable energy for the generation of hydrogen, by using T-O-U tariff's lower rate incase if the renewable energy is not enough for generation of hydrogen and by selling the generated Oxygen.

CHAPTER 5

SIMULATION IN LABVIEW

5.1 Introduction

This chapter provides the software simulation/analysis in the Lab VIEW.

5.2 Implementation of Lab VIEW Monitor/Simulation System

This thesis adapts the *Lab VIEW Program*, called Virtual Instruments, or VIs, to conduct both the simulation analysis and real time monitoring. Lab View program is a graphic interface editor, which can be applied in many industrial fields. In this project, Lab VIEW program is applied to develop both the real time monitor and simulation for optimization.

The functions of the real time monitor system are:

- 1) To monitor each function of the fuel station.
- 2) To record the operation data, like energy consumption from wind, solar, hydrogen production, tank level etc.
- 3) To provide real time economic analysis & give real time fuel price calculation.

The objective of the simulation system is to evaluate the feasibility of the proposed algorithm to obtain an optimal design. The simulation system can conduct better interactive interface to make the users to directly capture the concept for the

whole fueling system. Each function has its own window. Unit price of raw materials, the values of wind & solar energies, the load, the tank limit etc. can be changed using the setting interface. The function of the designed simulation system is to simulate the system performance before building the station. Hydrogen selling price, which is an important index for the evaluation of the design, will be provided according to the system operation condition and parameters by the simulation system.

5.3 Simulation and Analysis

Lab VIEW Program is called Virtual Instruments or VIs. It is a graphic interface editor, which can be applied in many industrial fields. In this project, Lab VIEW program is applied to develop both the real time monitor system and the simulation system, whose interface is shown in Fig. 18.

conditions, which were generated by the developed Hydrogen filing Station Monitor/Simulation Systems. Figures 19 & 20 show negative hydrogen price at certain time interval negative hydrogen price (because of the benefit of selling the oxygen) when only the wind & solar energies are used to generate hydrogen. Hence it is clear that the higher the oxygen selling price the lower will be the hydrogen price.

Assume the hydrogen demand increases 1.5 times the regular consumption between 12 to 13 hrs and 2 times the regular consumption between 19 to 20 hrs. Hence as per the simulation since more hydrogen is generated between 12 to 13 hrs the hydrogen selling price increases too. Also since no hydrogen is generated using peak T-O-U tariff between 19 to 20 hrs the price still remains negative owing to generation by only renewable energy.

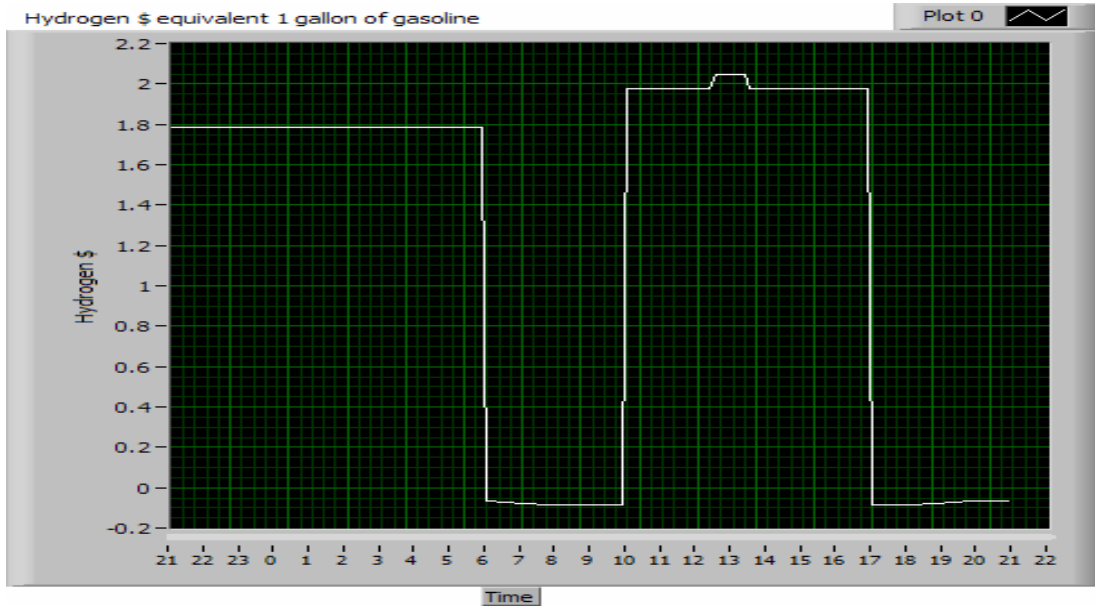


Figure 19. Hydrogen selling price (\$) with tank limit of 3500 lbs & with renewable and T-O-U electricity as the input

We also see some gradual slopes between time 6am to 8am & 6pm to 8pm when the cost of Hydrogen is negative. This is because the solar energy starts building up at 6am and start decaying from 6pm.

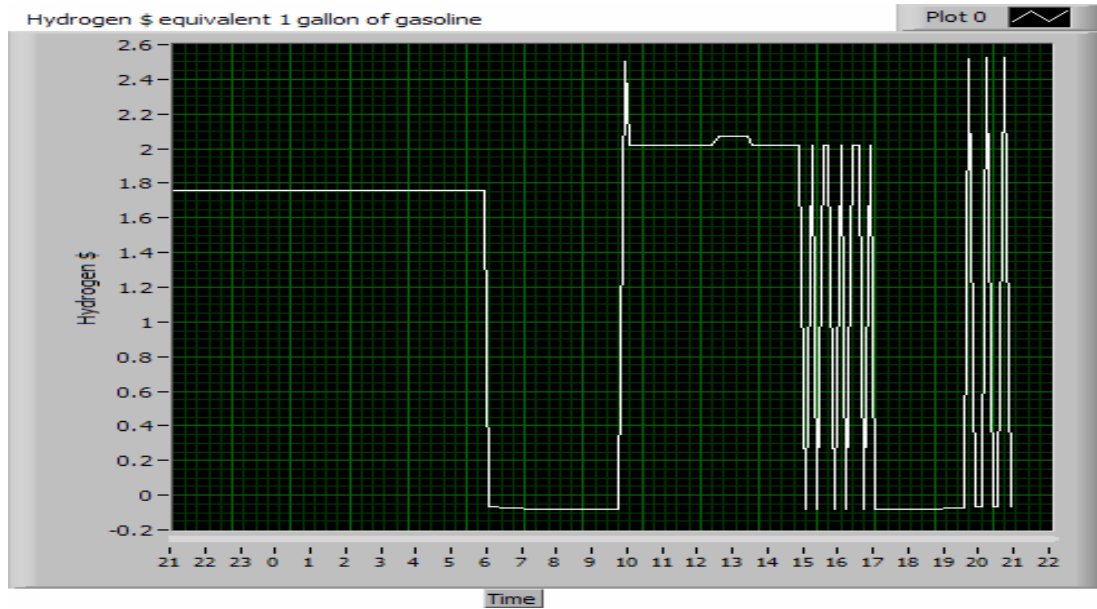


Figure 20. Hydrogen selling price (\$) with tank limit of 2000 lbs & with renewable and T-O-U electricity as the input

In the fig. 20 we see a spike increase in the price at 9:50am. This is caused by generation during peak T-O-U electricity as the need to fill the tank. Further we see similar spikes between time units 19:30 to 20:50. This varies from \$2.50 to negative \$0.06. \$2.50 is because the tank needs to fill using peak T-O-U electricity & renewable energy. The negative \$0.06 is because the generation uses only using renewable energy. Further, we also see small spikes ranging from \$2 to negative \$0.08. This is because when the tank is on its limit, its stops the generation and as soon as it falls below the limit it again generates using non-peak T-O-U tariff. Thus optimization result are better for 3500lbs limit tank as no hydrogen is generated using peak T-O-U electricity.

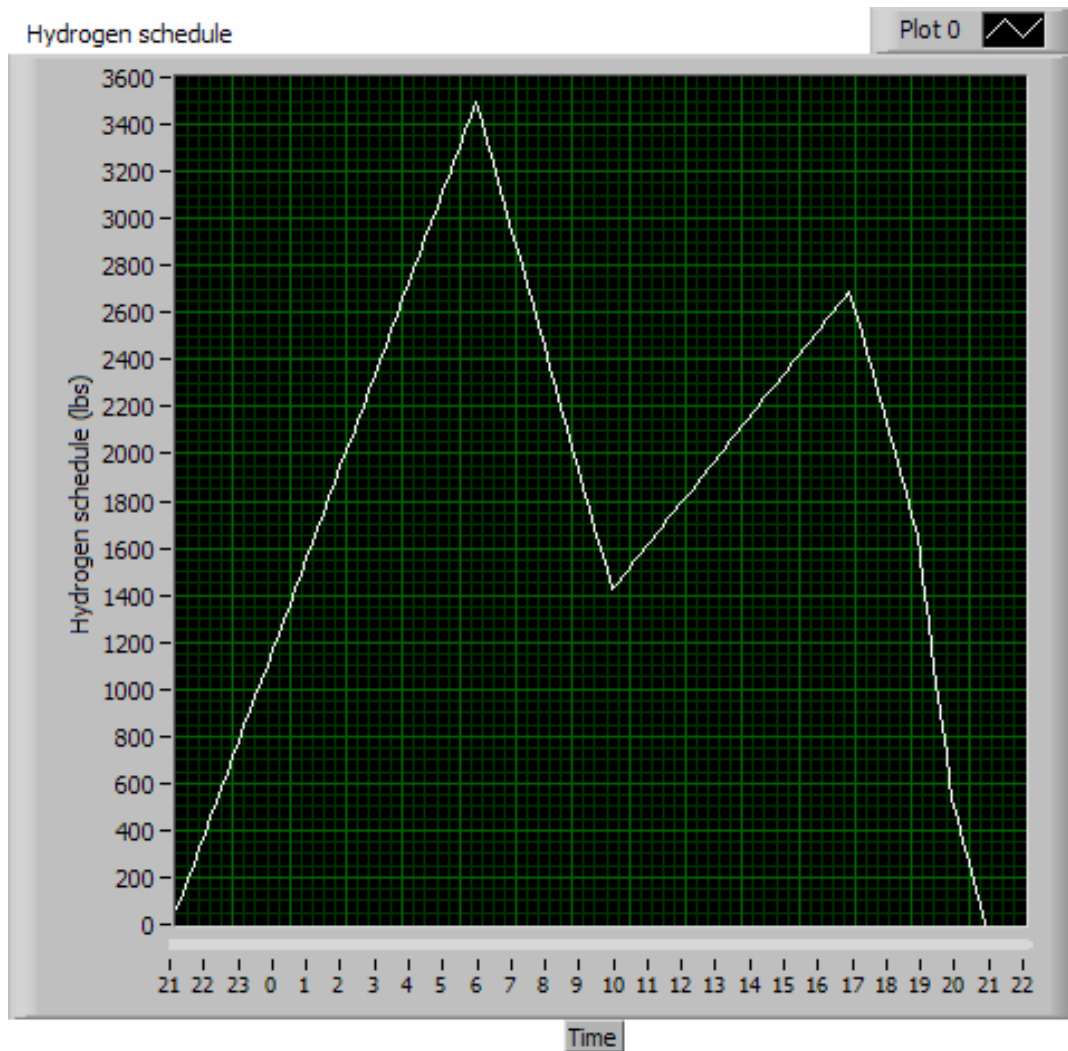


Figure 21. Hydrogen schedule (lbs) with tank limit of 3500 lbs & with renewable and T-O-U electricity as the input

Based on the forecasted/actual hydrogen demands, the hydrogen schedule is generated. In fig. 21 we see a small deflection between the time 7pm to 8 pm. This is because between the time 7pm to 8pm the consumption of hydrogen increases by two times. Hence the slight dip.

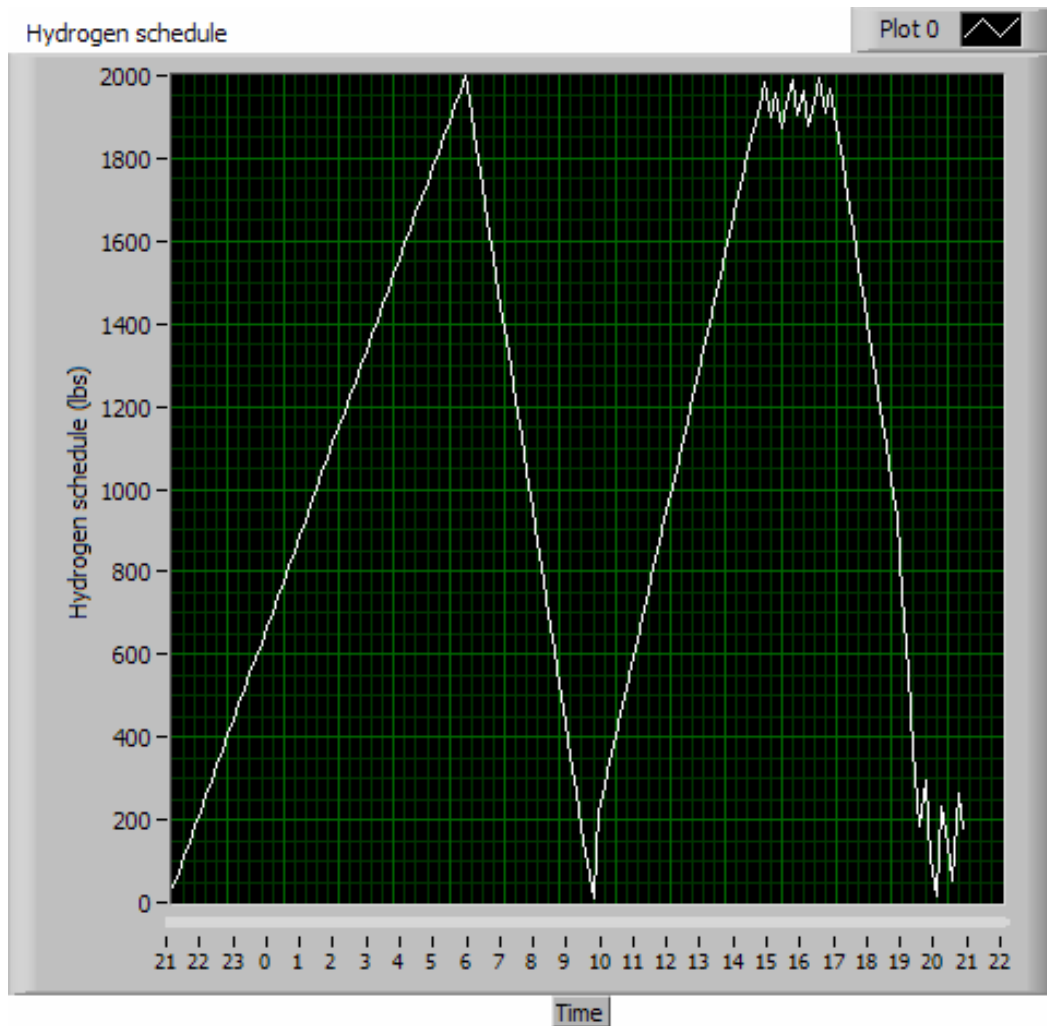


Figure 22. Hydrogen schedule (\$) with tank limit of 2000 lbs & with renewable and T-O-U electricity as the input

In fig. 22, we see a sudden increase at 9:50am. This is caused by default generation of 300lbs when the tank approaches a level less than one lbs. Also we see some surges between time 15 to 17 hrs. This is because the tank limit is 2000lbs and as soon as the tank limit is reached the generation is stopped. Again it starts to generate hydrogen as soon as the tank limit falls below the 2000lbs limit. Further we see some spikes between 19:30 to 20:50 hrs. Between 19:30 & 20:00 hrs the demand is 200lbs.

Since the tank does not have 200lbs, by default 300lbs is generated using peak T-O-U tariff. Between 20:00 & 20:50 hrs the demand is 100lbs. Again since the tank does not have 100lbs, by default 300lbs is generated using peak T-O-U tariff. In all possible cases the generation by renewable energy is never stopped. Thus we have the optimization of hydrogen filling station.

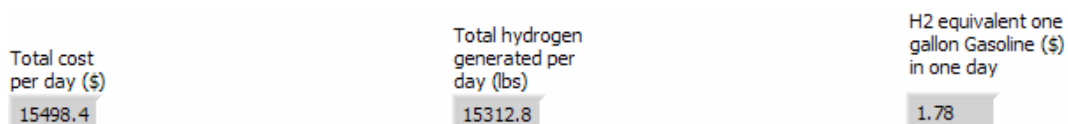


Figure 23. Hydrogen equivalent one gallon gasoline price for the whole day with tank limit of 3500lbs.

Fig. 23 shows the hydrogen prices when both renewable and T-O-U electricity are used for the generation of hydrogen. It is clear that in all possible tank limit cases the hydrogen price for a complete day is less than two dollars for the same equivalent to one gallon of gasoline.

CHAPTER 6

CONCLUSION

6.1 Conclusion

This thesis adapts the Lab View Program, called Virtual Instruments, or VIs, to conduct both the simulation analysis and real time monitoring. After setting up the parameters for the simulated system, running the simulation program, the users will get an on-line training to have a basic idea of how the designed hydrogen filling station works.

By converting hydrogen to energy using engines or fuel cells we will definitively have more advantage ranging from the economical point to the ecological point without worrying about the resources that will be exhausted in the near future. The hydrogen filling station at some time will replace the traditional gasoline station and act as a smart coordinator between the renewable energy and the utility supply.

A new hydrogen fuel station model was presented. The results obtained with the proposed model are very reasonable and economical. The model has a simple formulation, with easy understanding and implementation. By the graphical comparisons of the hydrogen selling price under varying tank limit, hydrogen selling price under varying load, hydrogen selling price under varying wind/solar the author tells us that in all possible comparisons hydrogen price still remains lower than the

gasoline price. Due the simplicity, the author believes that this method may be used for new hydrogen station modeling.

6.2 Future researches

Future research will include the demand charges. Efficient future electrolysis and high PV efficiency will further reduce the cost of hydrogen produced. Further, wind energy and the potential demand should be forecasted using artificial neural network.

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BIOGRAPHICAL INFORMATION

Vishal Bhan received B.E. in electrical engineering from the prestigious school – VJTI (Victoria Jubilee Technical Institute), Bombay University (India) in 1997. His research interest is in power systems.