OPTIMIZATION OF HYDROGEN FILLING STATION

by

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ABSTRACT

OPTIMIZATION OF HYDROGEN FILLING STATION

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Due to the price hike of the fossil fuel and the concern of the global warming, the hydrogen economy can be envisioned to address those problems. After the Energy Bill was announced in 2005, a transition of national energy system from hydrocarbon to hydrogen had been recognized. However, safe and convenient refueling and widespread availability of hydrogen from various energy sources are the prerequisite for the development of hydrogen economy.

This research focuses on the hydrogen filling station with on-site hydrogen production by electrolysis of water. The virtual wind farm and on-site installed photovoltaic (PV) supply the main and renewable energy for electrolyzers in the station. The utility electricity is served as an auxiliary energy resource to compensate the intermittence of wind and solar. Since the market clearing price (MCP) can change dramatically in the deregulated power market, the station can participate in the power market with a hydrogen storage tank as energy storage devices. Based on the forecasting of wind power with artificial neural network (ANN) model and MCP with the

statistical model, this research proposes an optimization algorithm for the hydrogen production schedule and the strategy of power trading to optimize the production costs of the station.

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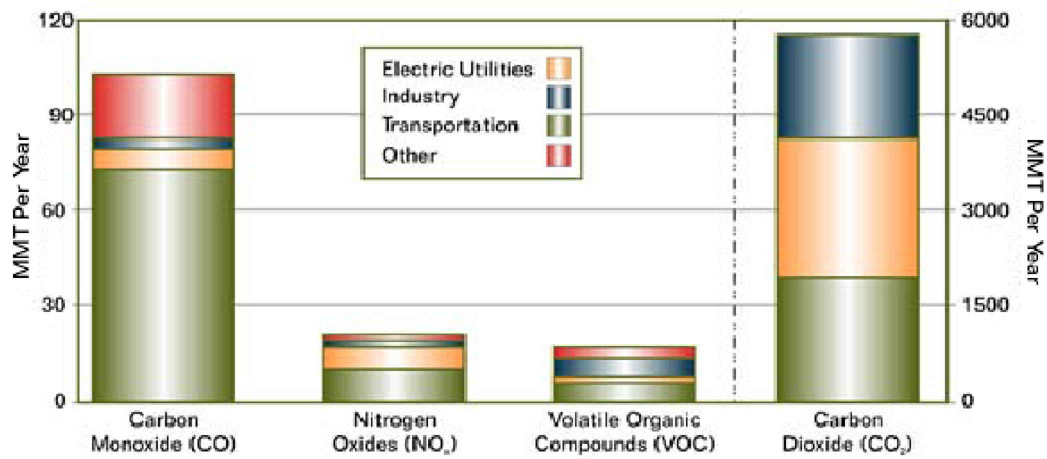
CHAPTER 1

INTRODUCTION

1.1 Hydrogen Economic

Energy is the life-blood of the human being. Clean forms of energy are especially needed to support sustainable economic growth while mitigating impacts on air quality and the potential effects of greenhouse gas emissions.

Air quality is a national concern. It is estimated that about 50 percent of Americans live in areas where level one or higher air pollutants do harm to public health. As shown in Figure 1, vehicles are the major contributor to the air problem in USA [1].



Source: Oak Ridge National Laboratory, *Transportation Energy Data Book: Edition 25*, (2006), ORNL-6974, http://cta.ornl.gov/data/tedb25/Edition25_Full_Doc.pdf.

Figure 1.1 Air pollutants in USA

On the other hand, America, as a nation, is also confronted to the challenge to reduce its growing reliance on foreign energy supplies. The United States consumes more than 20 million barrels of oil each day, half of which is imported, and it is expected to rise to 60 percent by 2025 [2]. America's transportation sector relies almost exclusively on refined petroleum products, accounting for over two-thirds of the oil crudes.

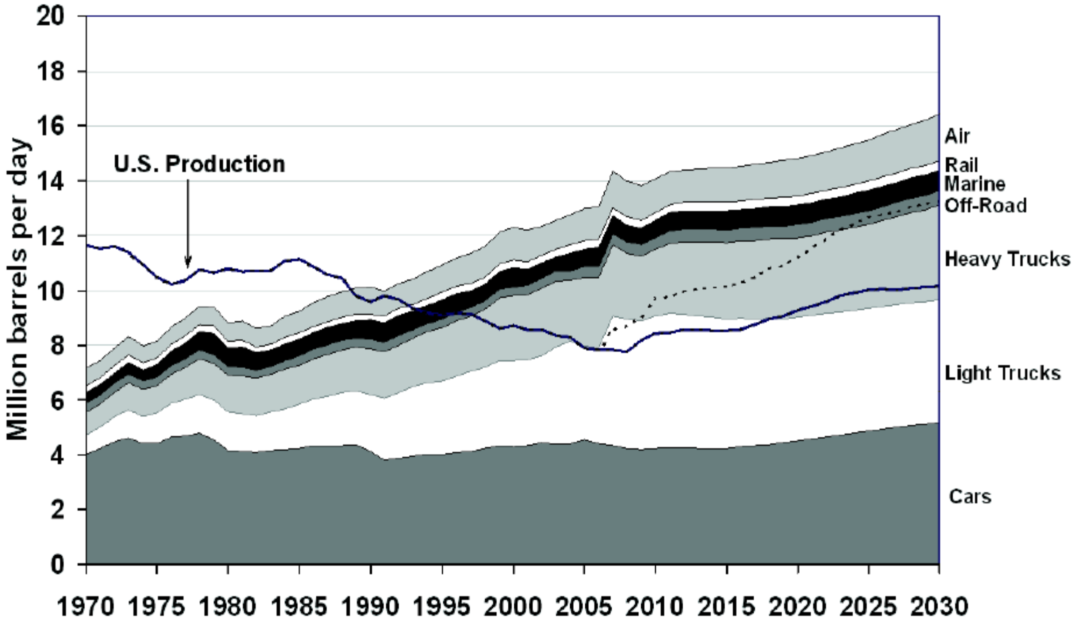


Figure 1.2 Oil Consumption and Production in USA

As shown in Figure 1.2, there is a projected gap growth between U.S. oil production and transportation oil needs [3]. The immense increase of light duty vehicles accounts for most of the growth.

To address these concerns, the U.S. Department of Energy recognizes the need to develop renewable energy supplies. The Investment Tax Credits (ITC) and Production Tax Credit (PTC) for renewable energy reflect the recognition of the importance of renewable energy in the nation's energy system. The Emergency Economic Stabilization Act of 2008 signed by former President Bush includes a fuel cell tax credit up to $3,000 per kilowatt or 30 percent of the capital cost on the purchase of fuel cells used in residential or commercial applications [4]. PTC is a business credit that applies to electricity generated from renewable for sale at "wholesale". It provides companies that own the plant 2.1 cent per kilowatt-hour (kWh) benefit for the first ten years of a renewable energy facility's operation [5]. Thus the company subtracts the value of the credit from the business taxes that it would otherwise pay. The American Recovery and

Reinvestment Act of 2009 signed into law by President Obama on February 2009, extended PTC and ITC, which have been critical to the growth of the renewable energy sector.

Among diverse renewable energy, hydrogen is regarded as one of the most promising energy alternatives. As former President Bush acknowledged in his state of the Union 2003 address, hydrogen has the potential to play important role in America's future energy system [6]. Hydrogen can be produced almost entirely from diverse domestic sources of fossil, renewable and nuclear energy. Furthermore, hydrogen can benefit the environment because it can be produced and used in ways that improve health-related air quality and reduce greenhouse gas emissions.

In January 2003, the administration announced a 5-year, $1.2 billion Hydrogen Fuel Initiative to perform research and development of hydrogen fuel cells to substitute gasoline engines. Led by the Department of Energy (DOE), the initiative's goal is to develop the technologies by 2015 that will enable U.S. industry to make hydrogen-powered cars available to consumers by 2020 [7]. In 2006, President Bush announced the Advanced Energy Initiative (AEI). The AEI reinforces the Hydrogen Fuel Initiative. And currently the U.S. government spends about $400 million annually on hydrogen fuel cell related research and development [8].

A transition from hydrocarbon economy to hydrogen economy has already begun.

1.2 Hydrogen Vehicle

On September of 2009, the US house just passed a $2.85 billion bill over 2010 to 2014 for the US Department of Energy (DOE) to support the research of vehicle technology [9]. In the last century, gasoline internal combustion engine vehicle has played the major role in the transportation system. No matter how the technology is improved, there is still no significant improvement on the reduction of air pollution and the oil consumption. In response, hybrid electric vehicles, which combine batteries and electric motors with regular engines, hit on the roads just several years ago. Recently, many hybrid vehicles are available to the consumers, aiming at reducing fuel consumption and air pollution. Another type is the battery only electric vehicle, which can be a zero-emission alternative in the future. However, it has a disadvantage of short driving distance between charges and requires advance in battery technology.

Hydrogen vehicles are those that use hydrogen in internal combustion engines or hydrogen fuel cells to generate electricity to power the car cleanly and efficiently. Compared with other promising vehicle and fuel combinations, the hydrogen vehicle scenario is the only one that can cut greenhouse gas pollution in the transportation sector to 80 percent below 1990 levels. And hydrogen vehicle has the potential to cut urban air pollution towards zero by the end of the century, followed by the battery only electric vehicle [10].

The price tag of the hydrogen vehicle may seem daunting in the consumer market at first. However, with the improvement of technology of Hydrogen fuel cell, manufacturing scale-up, and cumulative experience, the price of hydrogen fuel cell vehicle is expected to drop dramatically to get almost even with that of gasoline vehicles by 2025. Figure 1.3 is the H_2 FCV Vehicle Price curve based on model by Greene, Leiby and Bowman (2007) [11].

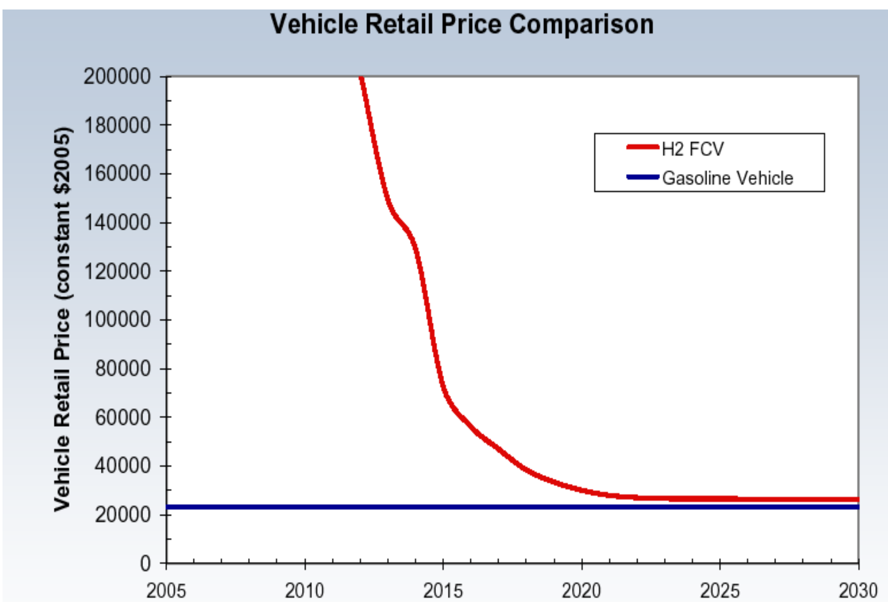


Figure 1.3 Hydrogen FCV Retail Price

Thus, hydrogen fuel cell vehicles will become dominant in the mix of vehicles over time.

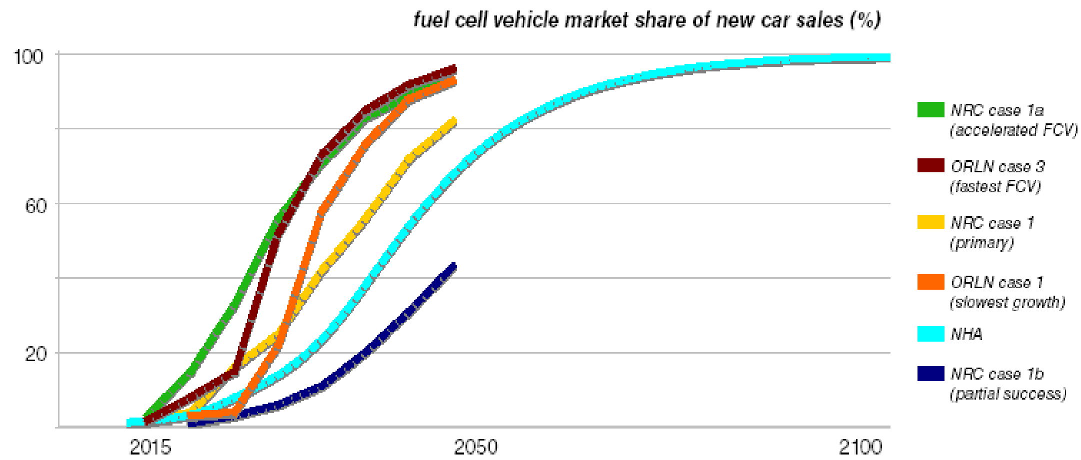


Figure 1.4 Share of Future Fuel Cell Vehicle Market

Figure 1.4 shows future fuel cell vehicle market share forecasted by two research agency. The National Research Council (NRC) study assumed the FCV market penetration reaching 65 percent market share by 2050, while the Oak Ridge National Laboratory l (ORNL) assumes the most aggressive penetration as high as 95 percent [10].

1.3 Hydrogen Filling Station

Once Hydrogen fuel cell vehicles become more common and important part of a cleaner and more sustainable transportation future. It is essential to develop nationwide hydrogen filling stations to enable high level public acceptance. Safe and convenient refueling and widespread availability of hydrogen from various energy sources are the prerequisite for the development of hydrogen economy. However, this will not happen overnight.

As of fall 2007, there were only 60 active stations in the United States, with many others under construction or in the process of obtaining permits. Clusters of multiple stations are located in the Greater Los Angeles, Greater San Francisco Bay, and Detroit metropolitan areas [12]. Majority of these hydrogen fueling stations were built for fleet applications and facilities. They exist either standalone or as a complementary part with current gas stations.

Opinions vary widely on the required minimum number of fueling locations needed to sustain a mass market fuel cell vehicle introduction. Figure 1.5 shows a proposed scheme of hydrogen fueling stations along major interstates [13].

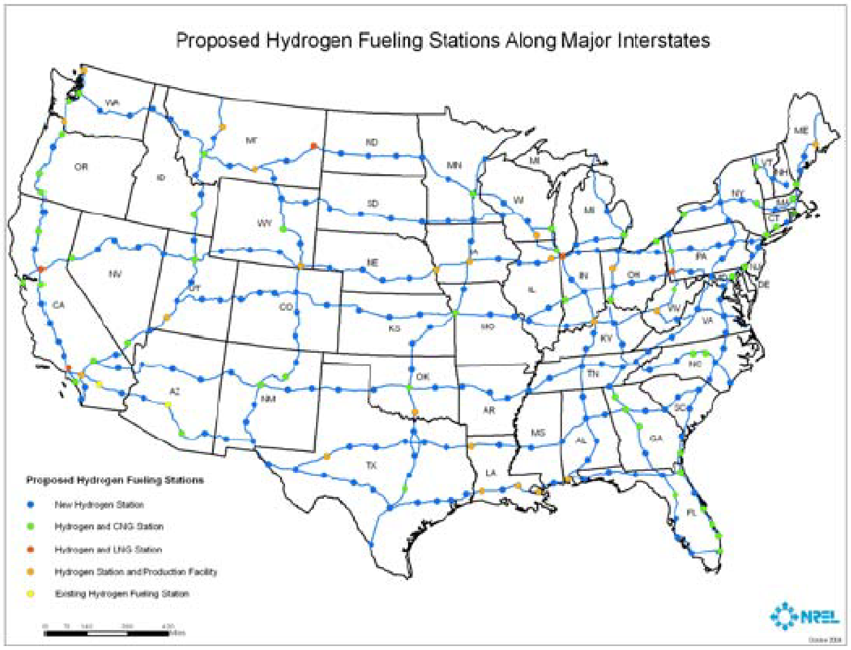


Figure 1.5 Proposed Schemes of National Hydrogen Filling Stations

1.4 Contribution

This research investigates the pros and cons of hydrogen production paths in centralized and distributed manners. Then on-site (distributed) production by electrolysis of water is selected in the hydrogen filling station since it is the most suitable approach at the initial stage of hydrogen economy. The on-site installed photovoltaic (PV) and “virtual wind farm” produce renewable and main energy for electrolyzers. The utility electricity is served as an auxiliary energy resource to address the intermittent nature of wind power and PV output.

Power industry is undergoing significant change under the environment of deregulation and more renewable energy penetration. The fixed electricity price (wholesale) is replaced by flexible price in the competitive power market. More and more distributed renewable energy, such as wind farms, have been built in recent years. However, the power grid still remains bogged down with mid-20th century technology [14]. Smart grid and other concepts were developed to adapt those changes. The program of “Active Demand” in smart grid was developed to motivate the active participation of customers in power market [15]. The hydrogen filling station with electrolysis inherently is a load for power system. It will be primary load since transportation consumes 28% energy in USA in 2007 [16]. With wind power and PV, the hydrogen filling station can also play an active role in power system.

The research proposed the design of smart hydrogen filling station which actively participates in power market:

1) Acquire Real-time market clearing price (MCP) by communication from the market.

2) Forecast the future MCP.

3) Forecast the generation output of wind power.

4) Optimize the electricity generation schedule to serve the need of customers.

5) Optimize the hydrogen production (electricity consumption) schedule.

With the communication system and forecasting techniques, the hydrogen filling station can serve as smart electricity generation/consumption in power system. The energy cost of the station will be significantly reduced by optimizing the electricity generation/consumption schedule. From the point of view of the power grid, such intelligent station and its energy-storage devices can shape the system load, improve the efficiency of the system, mitigate the congestion, prevent the price spike, and fully utilize the renewable energy.

The electricity generation/consumption schedule is optimized by the trading strategy “Buy Low, Sell High” in power market. An accurate forecasting of wind power and MCP is the prerequisite to “Buy Low, Sell High”. Wind power is forecasted by the artificial neural network (ANN) model in this project [17]. An autoregressive model [18] is utilized for MCP forecasting in this project. Based on the forecasting, the solver of linear programming is applied as the optimization method to make hydrogen production schedule and sell/buy decision for power trading.

1.5 Organization of This Thesis

This chapter has described an introduction which provides background of hydrogen filling station. The rest of this thesis is organized as follows. Chapter 2 discusses the hydrogen production paths. Chapter 3 describes the conceptual design of our hydrogen filling station. Based on forecasting in Chapter 4, the optimization algorithm of linear programming is developed to minimize the electricity cost. The Graphic User Interface (GUI) is implemented in LABVIEW in Chapter 5. Finally, Chapter 6 concludes the thesis.

CHAPTER 2

HYDROGEN ENERGY INFRASTRUCTURE

2.1 Introduction

Hydrogen has two overwhelming benefits. One of them is that it can be derived from diverse domestic energy sources. Another is that the by-products of the conversion are generally benign to human health and the environment.

However, in spite of these benefits, realization of hydrogen economy faces multiple challenges. First, hydrogen, unlike gasoline or natural gas, has no existing large-scale infrastructure, and therefore investment budget to build one is costly. Lacks of commercially available, low-cost hydrogen production, storage and conversion devices are also inhibiting elements for large scale deployment of hydrogen economy. Finally, hydrogen safety is another important issue. To address these problems, an outline of the activities, milestones, and deliverables of the infrastructure being made to pursue the development of hydrogen energy system will be discussed [6]. The key elements of which are shown in Figure 2.1.

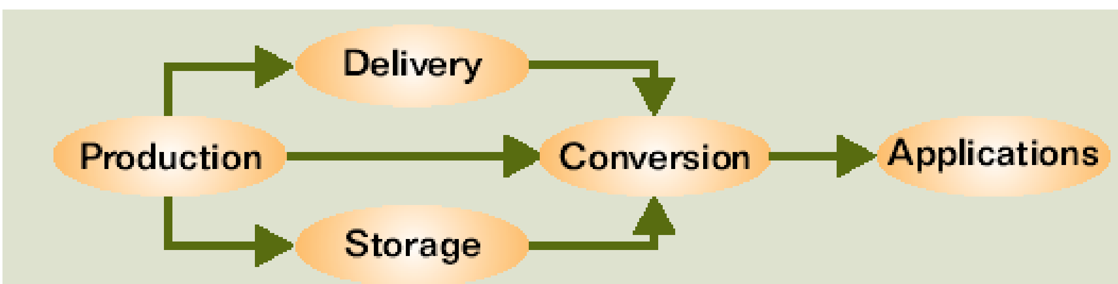


Figure 2.1 Five Elements in Hydrogen Energy System

Hydrogen filling station is the location where one or even more hydrogen energy system elements are fulfilled. To design a hydrogen station, an in-depth study of the infrastructure should be examined first.

2.2 Production

Hydrogen can be produced from a variety of sources, including fossil fuels, renewable energy sources such as wind, solar, or biomass and nuclear power. The process technology includes thermochemical, bilological, electrolytic and photolytic processes.

2.2.1. Production Method

2.2.2.1 Thermochemical Way

Steam methane reforming (SMR) is a catalytic oxidation process that involves reacting natural gas or other light hydrocarbons with steam to produce a mixture of hydrogen and carbon dioxide. The mixture is then separated to produce high-purity hydrogen. This method is the most energy-efficient commercialized technology currently available, and is most cost-effective ($1.00–$5.00/kg of hydrogen) and therefore is dominant method for producing hydrogen on an industrial scale.

Partial oxidation of fossil fuels in large gasifiers involves the reaction of a fuel with a limited supply of oxygen to produce a hydrogen mixture, which is then purified. It can be applied to a wide range of hydrocarbon feedstocks, including natural gas, heavy oils, solid biomass and coal. Its primary by-product is carbon dioxide [6].

A major drawback of these two thermochemical method is that both processes use nonrenewable fossil-fuel as source, more than half of which are already imported into the United States. Besides, the reaction processes also produce carbon dioxide, and the hydrogen product gas can have high levels of impurities.

Solar and nuclear driven high-temperature water splitting cycles are also thermochemical methods to produce hydrogen. They produce near-zero greenhouse gas emissions using water and either sunlight or nuclear energy. However, this technology is currently in the early stage of development and presents many challenges.

2.2.1.2. Electrical Way

Hydrogen can also be produced using electricity in electrolyzers to extract hydrogen from water. Electrolysis uses direct current (DC) electricity to split water into its basic elements of hydrogen and oxygen. Figure 2.2 shows the experimental process of the electrolysis of water [19].

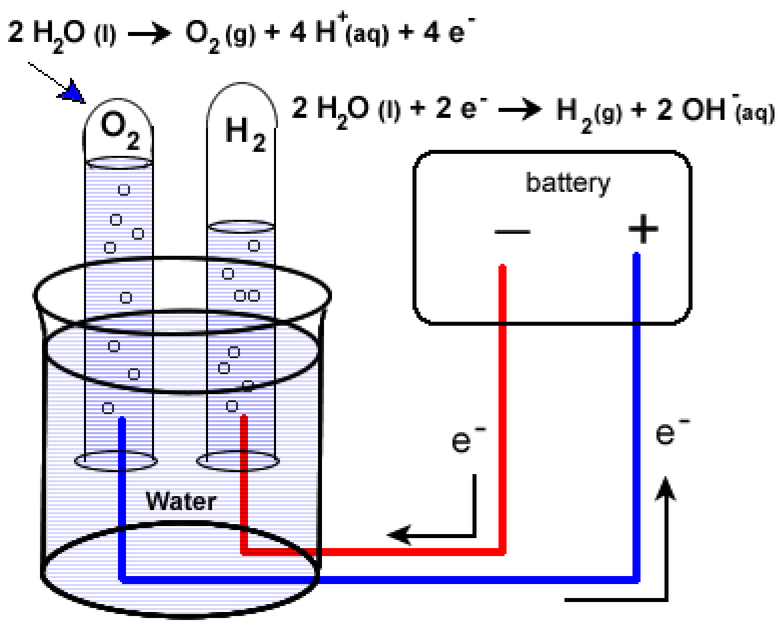


Figure 2.2 Diagram of Electrolysis of Water

There are currently two basic types of low temperature electrolyzers—alkaline and proton exchange membrane. Since this process uses only water as a source, it can produce up to 99.9995% pure hydrogen and oxygen.

This method currently is not as efficient or cost effective as using fossil fuels in steam methane reforming or partial oxidation. Ideally, 39 kWh of electricity and 8.9 liters of water are required to produce 1 kg of hydrogen at 25℃ and 1 atmosphere pressure. Typical commercial electrolyzer system efficiencies are 56%–73% and this corresponds to 70.1–53.4 kWh/kg of hydrogen production [20].

Electrolysis was discovered in 1800 shortly after the invention of electric battery. The electrolyzer industry grew substantially during the 1920s and 1930s. Most of these installations were near hydroelectric plants that supplied an inexpensive source of electricity.

Electrolyzers are mainly used in places where electricity prices are low or those require high hydrogen purity. As the price of natural gas increases, electrolysis becomes a viable option for competition in the hydrogen market. In the future hydrogen economy, an added benefit of electrolytic hydrogen production is that since the electric power industry is almost entirely supported by U.S. energy resources, it offers a more stable and secures energy future than oil or imported natural gas.

2.2.1.3. Other Methods

There are also several experimental methods which hold the promise of producing hydrogen with zero carbon dioxide emissions. They include photolytic processes using solid state technique and biological techniques. But all of these are still in early development phases.

2.2.2. Production Today in USA

The United States hydrogen industry currently produces 9 million tons of hydrogen per year, only a small portion of which are used as an energy carrier, most notably by National Aeronautics and Space Administration(NASA).

Steam methane reforming (SMR) is the most popular method being adopted in United States, accounting for 95 percent.

2.3 Delivery

Delivery is the distribution of hydrogen from production and storage sites. At present, hydrogen produced in centralized locations is delivered via pipeline or stored in tubes, tanks, or cylinders that are loaded onto trucks and rail to be transported to consumers.

The pipeline is employed as an efficient means to transport hydrogen. However, they are limited to areas where large hydrogen refineries and chemical plants are concentrated, such as in Indiana, California, Texas, and Louisiana. At present, the aggregated length of hydrogen specific pipelines reaches approximately 1930 km, and they are mainly operated by large industrial gas producers or organizations that use large amounts of hydrogen. The existing steel natural gas line with lower carbon content is suitable for transporting hydrogen, and therefore can act as hydrogen pipelines with little or even no changes.

Hydrogen distribution via high-pressure cylinders and tube trailer has a range of 100 to 200 miles from the production or distribution facility [6]. When the distance goes up to 1000 miles, hydrogen is usually transported in the form of liquid, stored in super-insulated, cryogenic, over-the-road tanker, railcars, and barges, and finally vaporized for use at the customer site.

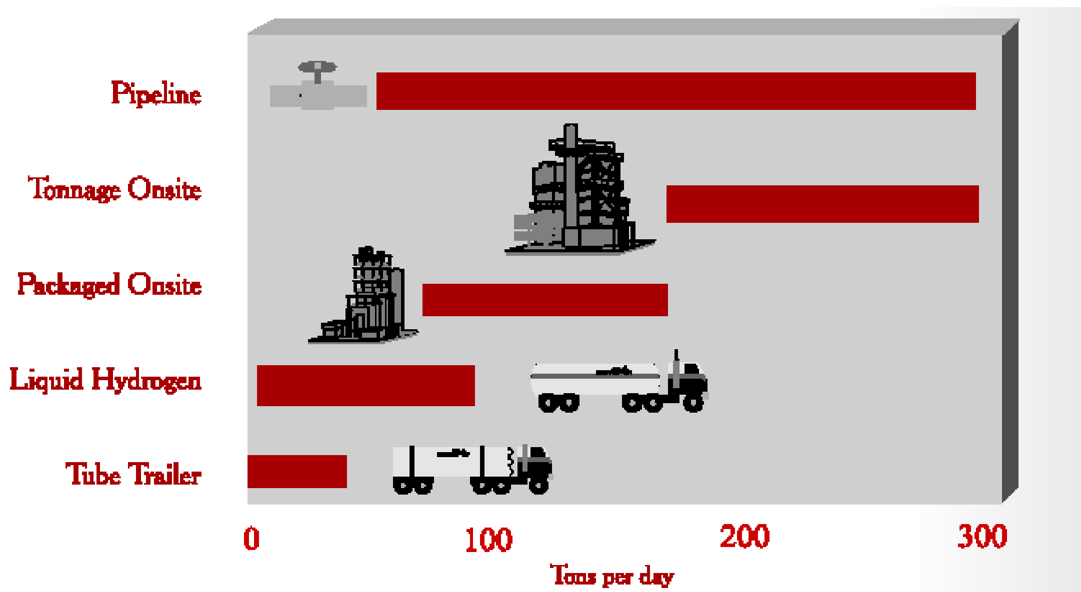


Figure 2.3 Hydrogen Delivery Methods

Figure 2.3 shows the hydrogen delivery methods and the transportation capacity comparison [6].

2.4 Storage

Hydrogen can be stored as gas or liquid or in a chemical compound.

Currently, the most mature technology is to compress hydrogen gas in tanks. The low density of hydrogen is translated to an inefficiency use of space aboard a vehicle, although a higher compression such as 5000psi to 10000 psi can mitigate the inefficiency.

Liquid hydrogen is stored in cryogenic containers and takes up less storage volume than gasoline. However, the liquefaction of hydrogen is an energy-intensive process and loses about one-third of the energy content of hydrogen.

Efforts are being taken on exploring higher-risk storage technologies involving advanced materials such as lightweight metal hybrids and carbon nanotubes.

2.5 Conversion

Hydrogen can be used in engines and fuel cells.

Engines can combust hydrogen in the same manner as gasoline or natural gas. This is a fairly well developed technology- the National Aeronautics and Space Administration use it in the engine of space shuttle and unmanned rocket. Vehicles with hydrogen internal combustion engines are now in the demonstration phase.

Fuel cells use the chemical energy of hydrogen to produce electricity and thermal energy. As electrochemical reaction is more efficient than the combustion way, fuel cells are more efficient than internal combustion engines. Fuel cells are in various stages of development. Fuel cell efficiencies range from 40 to 50 percent at full power and 60 percent at quarter-power, with up to 80 percent efficiency reported for combined heat and power applications. Currently, polymer electrolyte membrane (PEM) fuel cell and alkaline fuel cells (AFC) are being developed and tested for use in transportation applications.

2.6 Applications

Conversion devices are installed into end-use applications and used to power vehicles or to generate electricity for buildings and communities. In our research, we focused on transportation applications.

Transportation applications for hydrogen include buses, trucks, passenger vehicles and trains. Hydrogen-fueled internal-combustion engine vehicles are viewed as a near-term, low-cost option to help develop of hydrogen econoomy. The hydrogen energy infrastructure faces a chick-and-egg dilemma. Large numbers of hydrogen vehicle are required to support the hydrogen infrastructure, while a nationwide availability of fueling is a prerequisite for large-scale production of hydrogen vehicle, and therefore building hydrogen filling station is crucial to the introduction of hydrogen vehicle.

CHAPTER 3

HYDROGEN FILLING STATION DESIGN

3.1 Central VS Onsite

Hydrogen can be produced in centralized facilities or at decentralized locations where it will be dispensed. From centralized facilities, the hydrogen is distributed to the filling station pipeline or by road via rail or truck. When produced onsite, hydrogen can be stored and fed directly into the hydrogen vehicle.

The cost of hydrogen production can be minimized by building large central plants. However, the cost of transporting hydrogen from central production plant to the fueling station can be excessive. As we know, the density of hydrogen is lower than that of conventional fossil fuels such as gasoline (C8H18) or natural gas (CH4). It is more costly and bulky to deliver hydrogen having the same energy content as fossil fuels. Compressed hydrogen transportation by tube trailer as a most suitable option has a limitation of short distance of 200 miles. Furthermore, liquefying hydrogen is energy-intensive and hence very expensive. Although pipeline is the least expensive option, it becomes a viable option only when a national or even regional hydrogen demands are high enough to justify the construction of the pipeline.

Since the on-site hydrogen filling station options eliminates the need to build large central hydrogen production plants, it becomes an attractive option before a fully mature hydrogen-vehicle transportation market is established.

Figure 3.1 shows the main block of a typical on-site hydrogen filling station. It is composed of five parts: production, compression, storage, dispense and an ancillary part [21].

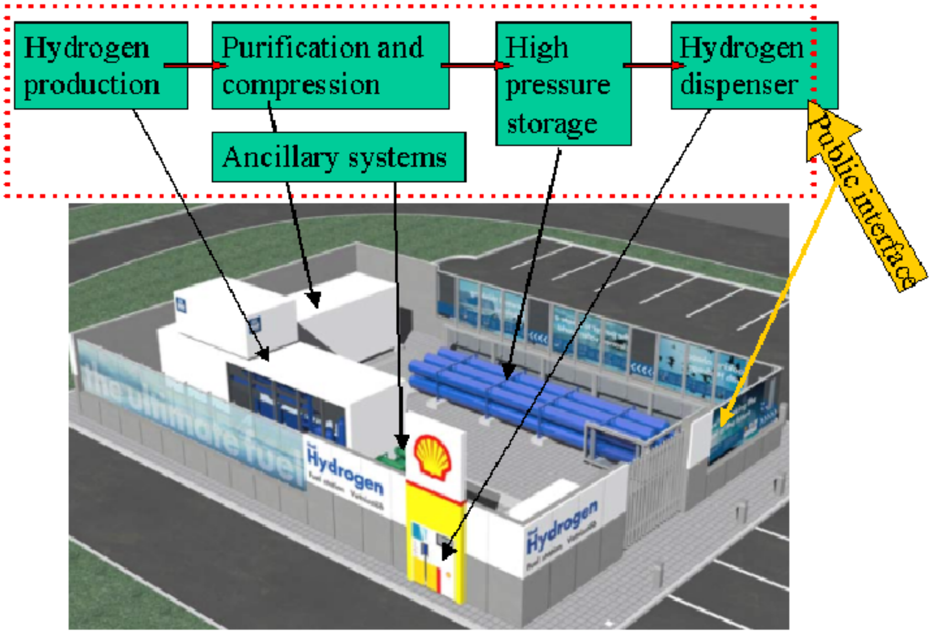


Figure 3.1 Illustrations of Main Blocks of an Onsite Hydrogen Filling Station

3.2 Production Method of Hydrogen Filling Station

The practical status of various hydrogen production processes are listed in Table 3.1 [22].

Table 3.1 Status of Hydrogen Production Technology

Process	Practical Process 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

It can be seen that eletrolysis is a mature method that produces less carbon dioxide compared to the traditional way of SMR and coal gasification. Therefore, electrolysis is adopted as our production method used in the hydrogen filling station.

3.3 Energy Source of Hydrogen Filling Station

In our design, maximum utilizing the renewable energy is our goal. Two natural resource, solar power and wind power, work together to produce renewable and main energy for the electrolyzers, while the intermittence of wind power and PV output can be compensated by grid electricity.

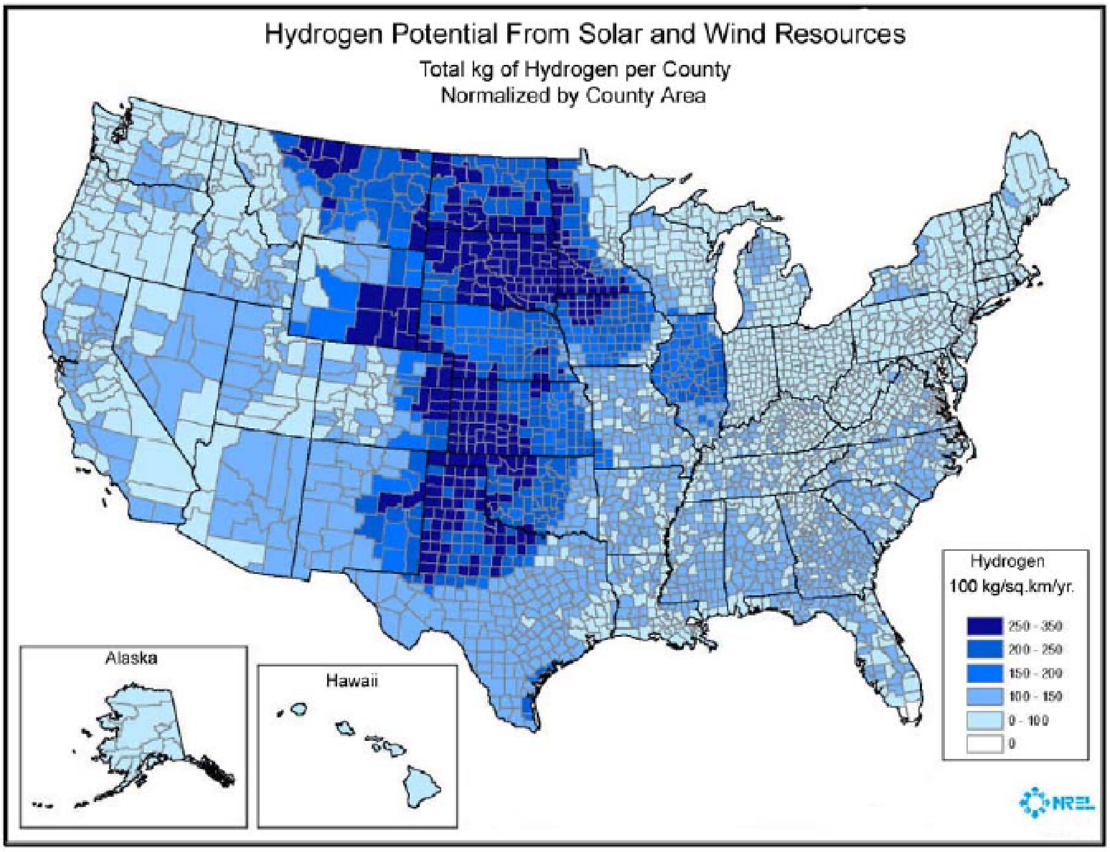


Figure 3.2 Hydrogen potential from solar and wind resources

Figure 3.2 shows the potential for hydrogen production from wind and solar. One can see that the United States has sufficient solar and wind resources to meet transportation demand [23].

3.3.1 Wind Power

3.3.1.1 Introduction of Wind Power

Wind power is the generation of electricity from wind energy which comes from air current flowing across the earth's surface. The wind is caused by the heat energy of the sun and the rotating of the earth.

A wind energy system transforms the kinetic energy of the wind into mechanical or electrical energy that can be harnessed for practical use. Popular uses for mechanical energy include pumping water and the farm windmill.

Wind power is inexhaustible and consumes no fuel for its operation. It works without the emissions associated with electricity production. Wind power does not produce carbon dioxide or any other type of air pollution that is produced by fossil fuel. Wind energy can provide us with cleaner air and a healthier, safer environment.

Wind power is the most mature and cost effective renewable energy technologies available today, costing between 3 and 5 cents per kilowatt-hour, depending upon the wind resource and project financing of the particular project. Since wind is free, the price of wind power is stable, unlike electricity from fossil fuel powered sources which depends on fuels whose prices are costly and may vary considerably. In the power market, the cost of generation is very important. Now, with the advance in wind turbine technologies, the cost of wind energy becomes competitive with traditional power plants.

Furthermore, wind turbines can be built on farms or ranches, thus benefiting the economy in rural areas, where most of the best wind sites are found. Farmers and ranchers can continue to work the land because only a fraction of the land is used for wind turbine. Wind power plant owners pay the rent to the farmer or rancher for the use of the land. However, good wind sites are often located in remote area, far from cities where the electricity is needed, thus requiring substantial infrastructure improvement to deliver the wind power to the load center.

As a clean and sustainable energy source, wind energy is a hot issue in today competitive market. Because wind energy development is consumer and environmentally friendly, requires shorter construction time, is cost competitive, and is quicker to obtain permit, it becomes one of the most competitive sources among different renewable energy technologies [24].

The major challenge to use wind as an energy source is that wind power is"An intermittent power supply" and wind does not always blow when electricity is terribly needed. The figure 3.3 illustrates the intermittent nature of wind power output.

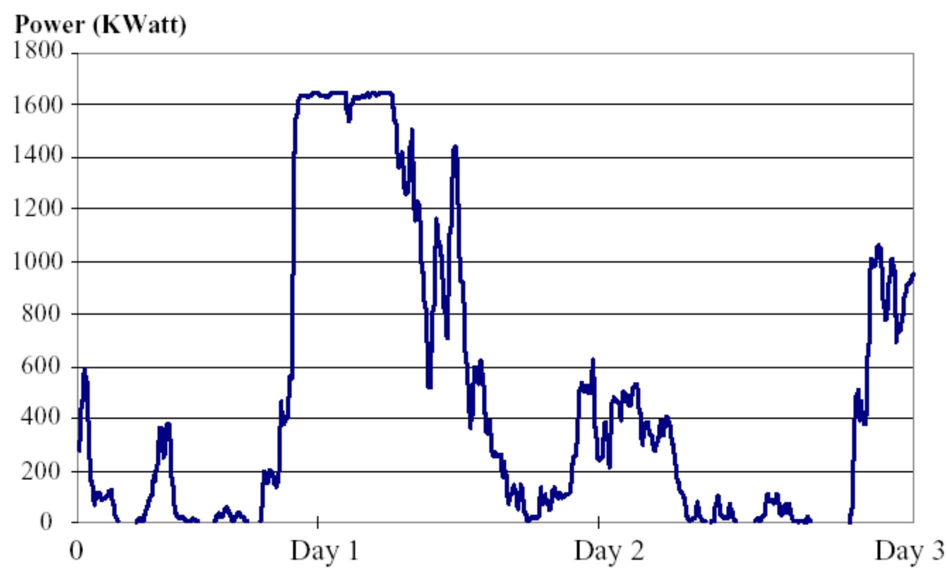


Figure 3.3 Intermittence of Wind Power

3.3.1.2 Wind Power in USA

Figure 3.4 illustrates the total and new wind power installation capacity in Unites States over 1981 to 2008. At the end of 2008, the U.S. surpassed Germany as the country with the largest amount of installed wind power capacity. The American Wind Energy Association has reported that wind projects installed through the end of 2008 were expected to generate 52 million megawatt-hours/year (MWh/yr), representing 1.26% of the nation's electricity in 2008. [25]

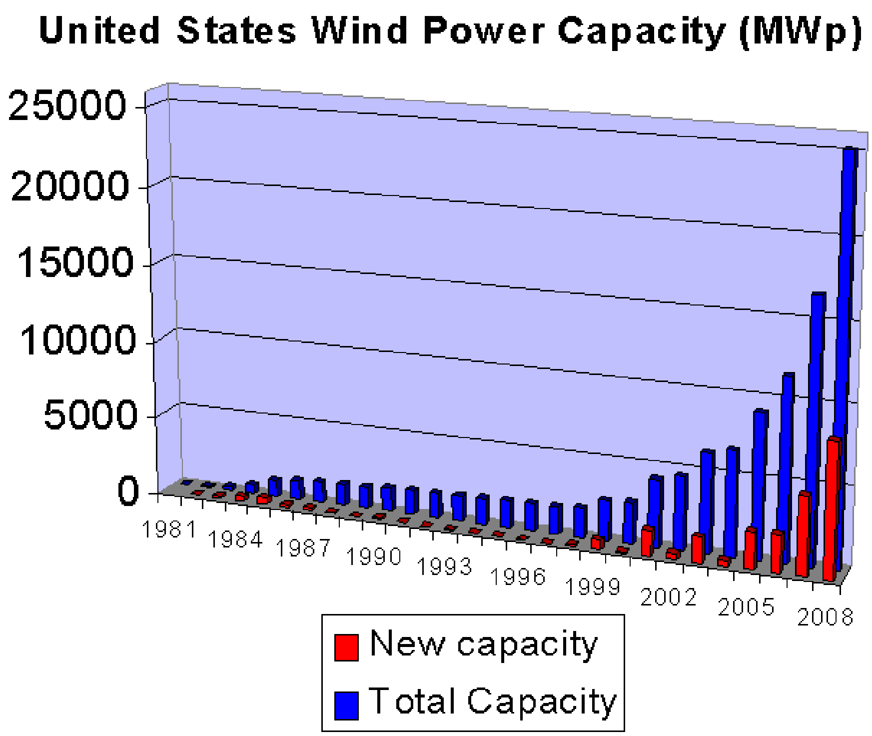


Figure 3.4 Wind Power Capacities in United States

As of the end of the second quarter, 2009, wind power in the United States had reached 29,440 MW megawatts (MW) of installed capacity. Texas, with 7,116 MW of capacity, has the most wind power capacity among any U.S. states [26]. From Figure 3.5, a map of installed wind power capacities in each state can be seen [27].

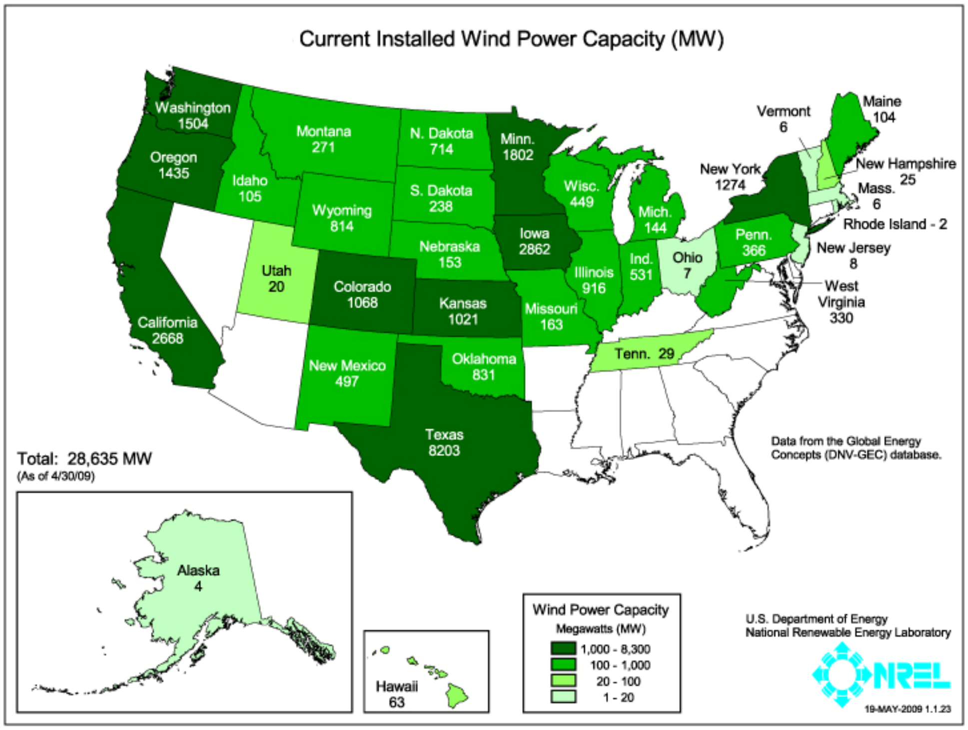


Figure 3.5 Current Installed Wind Power Capacity in United States

The U.S. Department of Energy (DOE) will work towards achieving 20% wind power in the United States by 2030.

3.3.2 Solar Power

3.3.2.1 Introduction of Photovoltaic devices

Photovoltaic devices use semiconductor materials, such as silicon, to convert sunlight including ultra violet radiation directly into electricity. Photons from the sun are absorbed by semi-conductors, with electrons being knocked along electrical wires by the photons until the current (flow of electrons) reaches a device that can be powered by electricity. The principle is illustrated in Figure 3.6 [28].

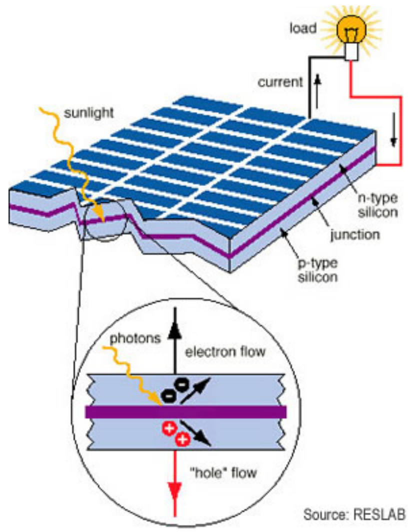


Figure 3.6 Diagram of Photovoltaic Device

They can be used in small cells, panels, and arrays. Photovoltaic systems require little maintenance and have typical lifetimes of about twenty years.

Photovoltaic power capacity is measured as maximum power output under standardized test conditions, and therefore, the actual power output at a particular point in time may be less than or greater than this value.

There are two basic systems available for utilizing the electricity generated by the solar PV, stand-alone or grid connected. In the stand alone system, electricity will be stored and used on demand locally. The output of the solar PV array is connected to charge batteries for running small electrical applications. In grid connected systems the array is directly connected to the electricity grid via an approved inverter and meter. The energy produced by the solar PV array can be used on-site when demand is sufficient, or exported to the grid and sold to utility company.

As a rule of thumb for monocrystalline arrays, an area of 8 to 9 m^2 will be required to produce a power output of 1kW. For the less efficient multicrystalline arrays are used an area of 10 to 12 m^2 for the same output and for the less efficient amorphous arrays an area 20 to 22 m^2 will be required [29].

3.3.2.2 Solar Array in USA

Photovoltaic production has been doubled every 2 years since 2002 and increased by 98% in 2008, making it the world's fastest-growing energy technology. At the end of 2008, the cumulative global PV installations reached 15,200 megawatts. A proposed Topaz Solar Farm with 550 MW is to be built in northwest of California Valley in the US [25].

3.3.3 Power Grid

3.3.3.1 Power Plant Energy Source

Figure 3.7 shows the share of the energy sources in the U.S in 2007. In 2007 the United States generated 4,166,507 Giga watt hours of electricity and coal accounts for 48.5% of the total generation [30].

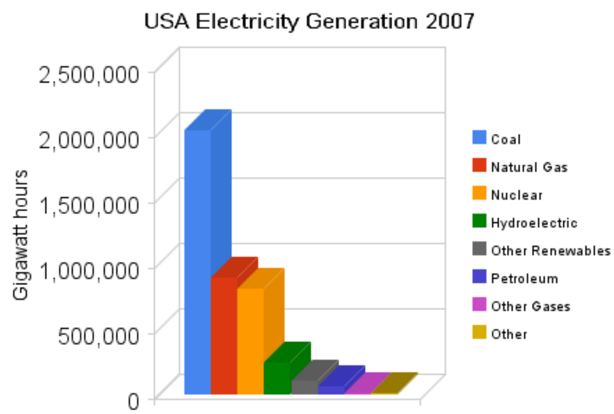


Figure 3.7 Shares of Energy Sources in USA

3.3.3.2 MCPE

MCPE stands for Market Clearing Price for Energy and is the bare bones price that Texas companies generally use to fashion a custom tailored contract when they are buying their energy in large blocks. Essentially MCPE allows a Texas company to use the block purchase of power and then go over that purchase without penalty. The company simply pays the variable market rate at that time. The MCPE is a variable rate that changes every 15 minutes and is historically much lower then a fixed price rate [31].

Figure 3.8 illustrates the MCPE Price on Sep-23-2009 provided by ERCOT [32].

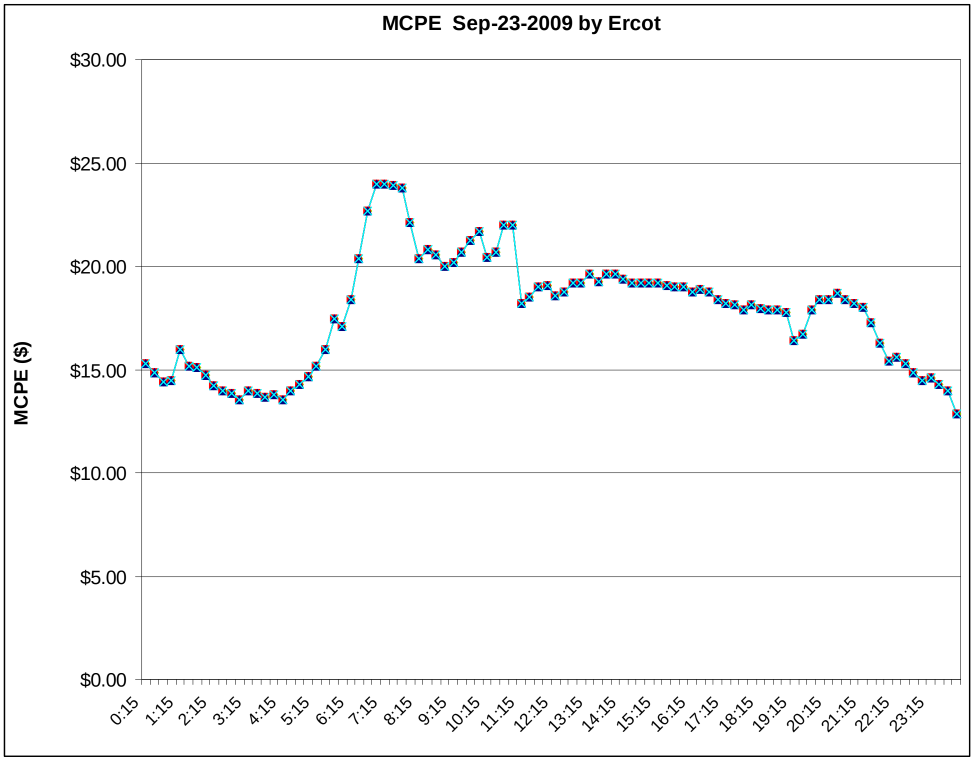


Figure 3.8 MCPE on 09-23-2009 provided by ERCOT

3.4 The Conceptual Design

As mentioned in the previous section, electrolysis of water is the most suitable approach for on-site hydrogen production. This research adopts this concept to establish optimal hydrogen production schedule of a hydrogen filling station. Figure 3.9 shows the conceptual design of the hydrogen filling station.

The photovoltaic is installed in the filling station to harvest solar energy. As for the wind part, it is usually difficult to obtain permit for large scale wind generation installation in the urban area where majority of hydrogen filling stations are located. Even with permission on hand, the station owner has to take risk of the poor wind profile at the station and high investment of wind turbines. In this research a “virtual wind farm” concept is introduced to overcome these problems. The filling station can sign an agreement with wind farm owner to "purchase" the electricity from some of wind generation units to form its "virtual wind farm". The "virtual wind farm" works as if it was in the hydrogen filling station, while wind profile at the station is not necessarily important. The owner of the hydrogen filling station can focus more on the economic aspect of building the station by either building a new one from scratch or transforming an existing gas station to the hydrogen alternative, without worrying about wind profile at the site. Through the remote monitoring system, the filling station will consume the power output from the virtual wind farm plus other sources. Any excess power can be sold back to the system (if the price is right) or stored in the local storage system (hydrogen storage tank).

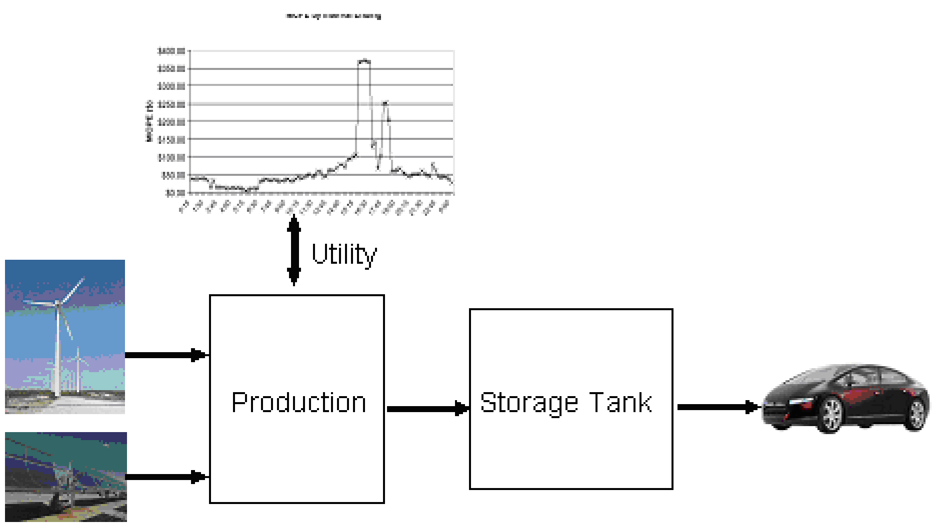


Figure 3.9 Conceptual Design of the Hydrogen Filling Station

CHAPTER 4

OPTIMIZATION OF HYDROGEN FILLING STATION

4.1 Uncertain factors

There are four uncertain factors in the optimization problem: solar array output, hydrogen demand, wind power output, and MCPE price.

4.1.1. PV Output

PV output is decided by the solar radiation which is variable during any time. Figure 4.1 shows the monthly average daily solar radiation in Fort Worth, Texas from the recent thirty year historical data [33].

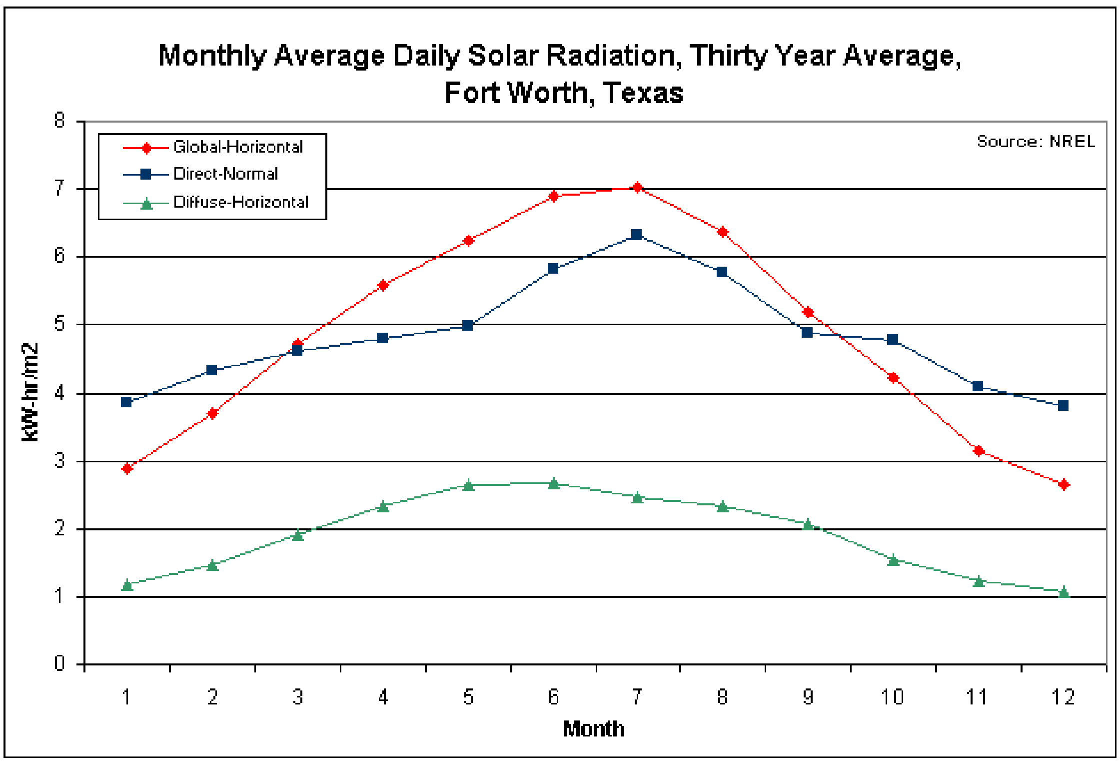


Figure 4.1 Statistical Solar Radiation Data at Fort Worth, Texas

Typical PV output is assumed in our research since the capacity of PV is very small. Accounting the conversion efficiency for single-crystal PV commercial module which ranges from 15% to 20%, the profiles of PV output are shown in Table 4.1. However, the uncertainty of PV output will be considered in the evaluation of the optimization design.

Table 4.1 A Typical PV (50m*50m) Output Profile

Time	Output (kW)	Time	Output (kW)
6:00 AM	94	1:00 PM	284
7:00 AM	188	2:00 PM	284
8:00 AM	284	3:00 PM	284
9:00 AM	284	4:00 PM	284
10:00 AM	284	5:00 PM	284
11:00 AM	284	6:00 PM	188
12:00 PM	284	7:00 PM	94

4.1.2 Wind Power Forecasting

Wind energy forecast is a complex as wind magnitude is influenced by many factors such as temperature, pressure variation, solar radiation, landscape, etc. Since the power generation from the wind turbine is theoretically proportional to a cube of wind speed, the large error in wind speed prediction can lead to a significant error of wind turbine generation, which in turn affects the hydrogen production schedule and power trading decision of the station.

Artificial Neural Network has been used as a general mathematical tool in many applications. For the forecast application, a multi-layer feed forward perceptron (MLP) shown in Figure 4.2 is generally employed. ANN model of this type is well suited for function mapping problem, which is analogous to our forecast problem. The main benefit of ANN over other conventional statistical methods is that it has ability to extract system information by training process. In other words, the model is capable of recognizing the embedded dependency between a set of the inputs and outputs of the system without necessity to express this relationship explicitly, as usually does required in other statistical approaches.

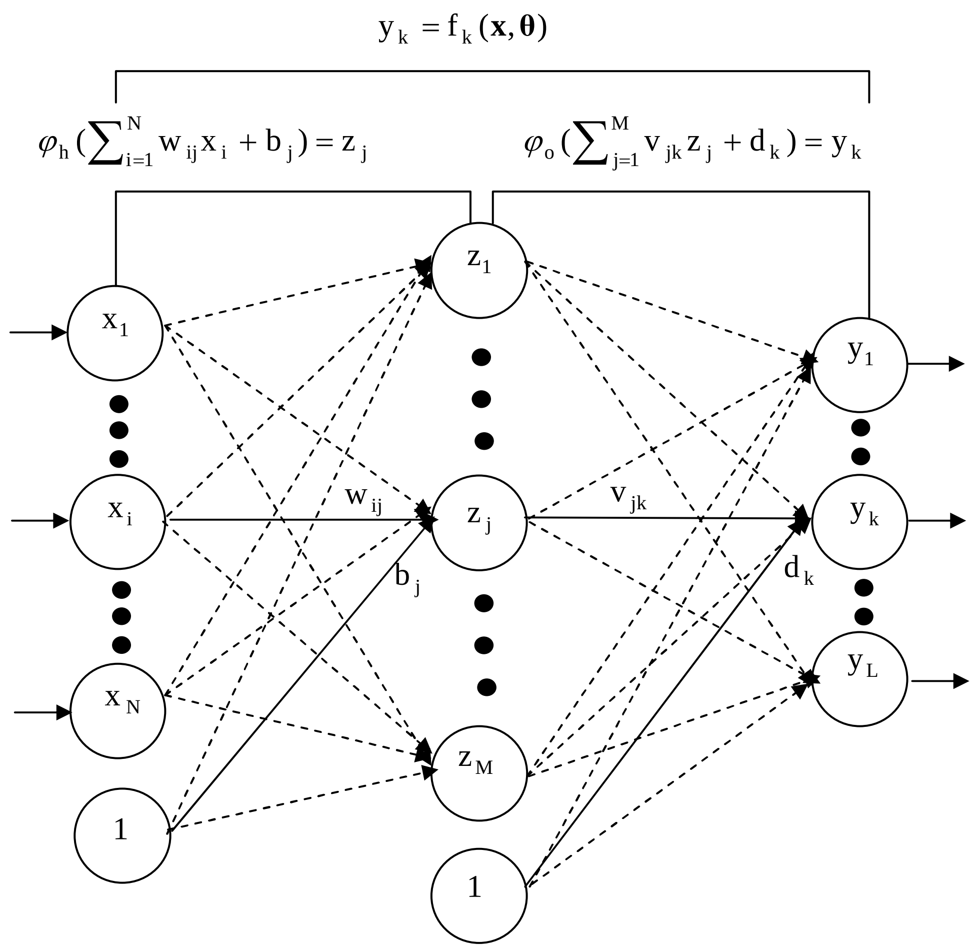


Figure 4.2 Multi-layer Feed Forward networks

This research adapts three-layer-feed-forward ANN networks for wind power forecasting [34]. The historical data of wind speed and wind power output is selected as the input parameters of the model, input neurons. The wind power output is the only one neuron. The hidden neurons are decided by the forward heuristic simulation. The Levenberg-Marquardt method is utilized to train the ANN model after the set up of the network structure.

4.1.3 MCPE Forecasting

The market clearing price for energy (MCPE) is highly flexible under the competitive power market environment after de-regulation. It exhibits extreme volatility (up to 50%) comparing with other commodities (less than 4% for stock market).

Many MCPE forecasting methods have been proposed in the last decades after deregulation. They can be classified in two sets: simulation methods and statistical methods. The detailed physical data of the power system, including load forecasting, unit data, transmission data, has to be modeled in simulation methods. The power flow technique and economic dispatch have to be performed in simulation methods. Simulations method may achieve good forecasting results. However, it is not practical for the owner of hydrogen filling station to build and maintenance such complicated system data. The statistical methods usually explore the historical MCPE and load data, which can be accessed on the ISO's website, to forecast the future MCPE. There are many statistical methods which have been applied to MCPE forecasting: ARMA-type methods, time series models with exogenous variables, autoregressive garch models, regime-switching models, threshold autoregressive models, markov regime-switching models etc [35].

The statistical model of Autoregressive model with exogenous/input variables (ARX) is utilized for MCP forecasting in this research. The system load is used as the input variable.

The model structure of ARX is:

$$\phi(B)\, p_t = \psi_l L_t + d_1 D_{Mon} + d_2 D_{Sat} + d_3 D_{Sun} + \varepsilon_t$$

Where:

p_t is the current price.

B is the backward shift operator.

$\phi(B) = 1 - \phi_1 B - \ldots - \phi_p B^p$

ψ_l is the coefficient of the load forecast L_t.

d_1, d_2, d_3 are three coefficients of the three dummy variables $D_{Mon}, D_{Sat}, D_{Sun}$.

ε_t is the white noise.

According to the forecasting test results in the California Power Exchange (CalPX) market [33], the Mean Daily Errors (MDE) of the ARX model is less than 5%.

4.1.4. Hydrogen Demand

Hydrogen demand is depending on the time, the location of the station, and other issues. Hydrogen demand can be forecasted once the location of the station is selected. However, a typical 1500kg/day hydrogen demand is assumed in this report [36].

Generally, the energy content of a gallon of gasoline and a kilogram of hydrogen are approximately equal on a lower heating value basis. A kilogram of hydrogen is approximately equal to a gallon of gasoline equivalent on an energy content basis, and therefore this hydrogen filling station is assumed to have the capability of serving around 100 vehicles per day, 15 gallon each vehicle supposed.

The profiles of hydrogen demand are shown in Table 4.2. The uncertainty of hydrogen demand will be considered in the evaluation of the optimization design.

Table 4.2 A Typical Hydrogen Demand Profile

Time	Demand (kg)	Time	Demand (kg)
12:00 AM	0	12:00 PM	50
1:00 AM	0	1:00 PM	50
2:00 AM	0	2:00 PM	50
3:00 AM	0	3:00 PM	50
4:00 AM	0	4:00 PM	100
5:00 AM	50	5:00 PM	200
6:00 AM	100	6:00 PM	150
7:00 AM	200	7:00 PM	100
8:00 AM	150	8:00 PM	50
9:00 AM	100	9:00 PM	0
10:00 AM	50	10:00 PM	0
11:00 AM	50	11:00 PM	0

4.2 Optimization Design

The objective functions of the optimization design are:

1) Fully utilize the renewable energy.

2) Minimize the hydrogen production cost.

3) Serve all the customers without interruption.

The constraints are:

1) Size of the hydrogen storage tank.

2) Capacity of the electrolyzers.

According to the objectives and constraints, the formulation of the optimization problem is:

$$Min \quad MCP * PT^T \tag{1}$$

ST: $$PT \geq -WP - PV \tag{2}$$

$$PT \leq Cap\_Electrolyzer - WP - PV \tag{3}$$

$$Hy\_in\_Tank \geq Tank\_\mathrm{Re}s \tag{4}$$

$$Hy\_in\_Tank \leq Tank\_Size \tag{5}$$

The definition of the variables of the formulas is shown in Table 4.3. PT, power trading option, is the optimization variable in the problem. The positive value of PT represents “Buy from market” and the negative value of PT represents “Sell to market” in this research.

Table 4.3 Definition of Variables of the Problem

Parameter	**Meaning**
PT	Power trading (MW)
WP	Wind power output (MW)
PV	PV output (MW)
Cap_Electrolyzer	Capacity of electrolyzers (MW)
Hy_in_Tank	Hydrogen level of tank (kg)
Tank_Res	Minim level of tank (kg)
Tank_Size	Tank size (kg)

All of the objective and constraints are linear, so the linear programming can be applied to solve the optimization problem in this research.

The forecasting and optimization algorithm will be run at the interval of 15 minutes to match the real-time operation of the station since Independent System Operator (ISO) usually post real-time MCP every 15 minutes. The optimization cycle is set as 168 hours (one week) considering the higher forecasting uncertainness for longer time. The optimization algorithm is implemented in MATLAB.

The simulation time is set as one-month (31 days) to evaluate the benefits of the optimization approach. Therefore, the proposed optimization approach will be run 2976 (31 days * 24 hours * 4 quarters) times in the entire operation. The optimization problem is solved based on the next 168 hours (one week) forecasting of wind power and MCP. The following three cases are calculated in this research:

Case1: Power trading when needed (no optimization).

Case2: Optimization based on perfect forecasting results, typical PV output and hydrogen demand.

Case3: Optimization based on uncertain forecasting results, uncertain PV output and hydrogen demand.

In addition, the different uncertainty levels of the four uncertain factors are also considered in this research.

Main parameters of the station are initially assumed in Table 4.4. Only electricity from virtual wind farm and trading in the market are calculated into the electricity cost. The electricity from PV is not included since PV is owned by the station.

Table 4.4 Main Parameters of the Station

Definition	**Value**
Capacity of electrolyzers	3,200 kg/day
Tank size	3,000 kg
Minim level of tank	300 kg

Table 4.4-*Continued*

Hydrogen consumption	1,500 kg/day
PV	50m*50 m
Capacity of wind generators	8 MW
Price of wind power	40 $/MWh
Efficiency of electrolysis	53.44 kWh/kg

4.2.1 Case 1

The typical PV output and hydrogen demand are assumed in case 1. No forecasting is performed since no optimization algorithm is applied in this case. In other words, it is assumed there is no power trading in the market except three conditions:

1) There is not enough hydrogen in tank to meet the demand.

2) There is limited space in the tank to store the hydrogen.

3) The wind power and PV output is higher than the capacity of electrolyzers.

The simulation results are shown in Table 4.5, Figure 4.3, and Figure 4.4. The electricity cost of 1 kg hydrogen is about $2.40.

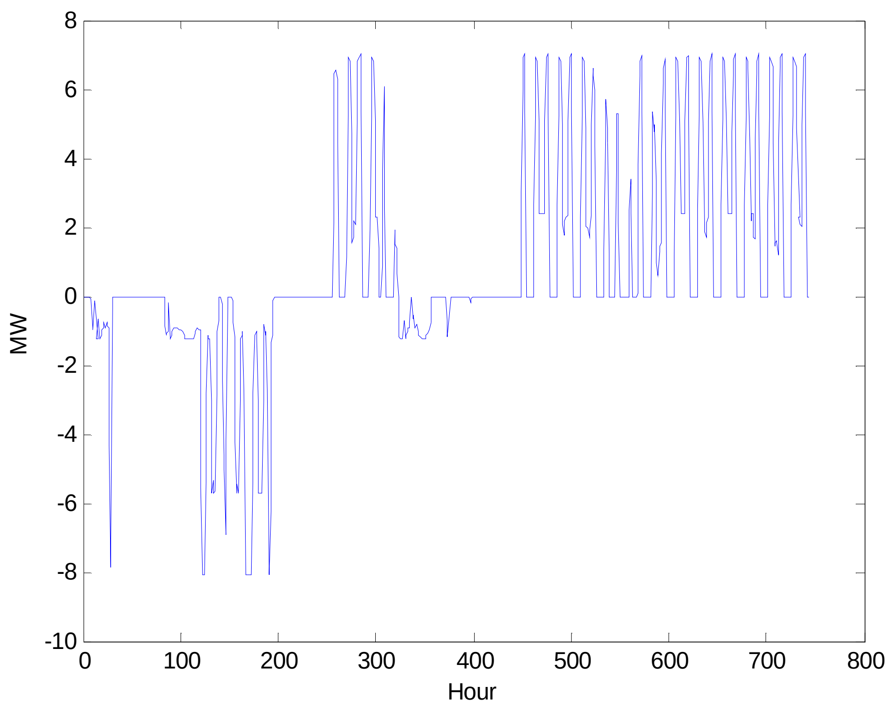


Figure 4.3 Power exchange in power market in case 1

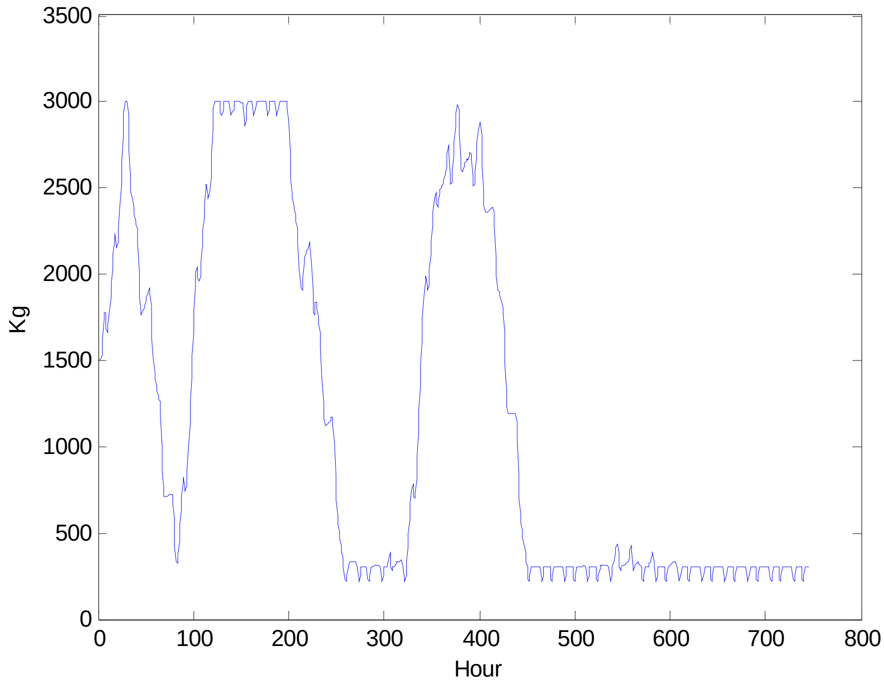


Figure 4.4 Hydrogen level in the Storage Tank in Case 1

4.2.2 Case 2

The perfect forecasting is assumed, i.e., the wind power output and MCPE for next 168 hours are assumed to be known. The typical PV output and hydrogen demand are assumed in this case.

The proposed optimization method is applied in case 2. The simulation results are shown in Table 4.5, Figure 4.5, and Figure 4.6 respectively. As shown in Figure 4.5, the station will sell power to the market when MCPE is higher and purchase power from the market when MCPE is lower.

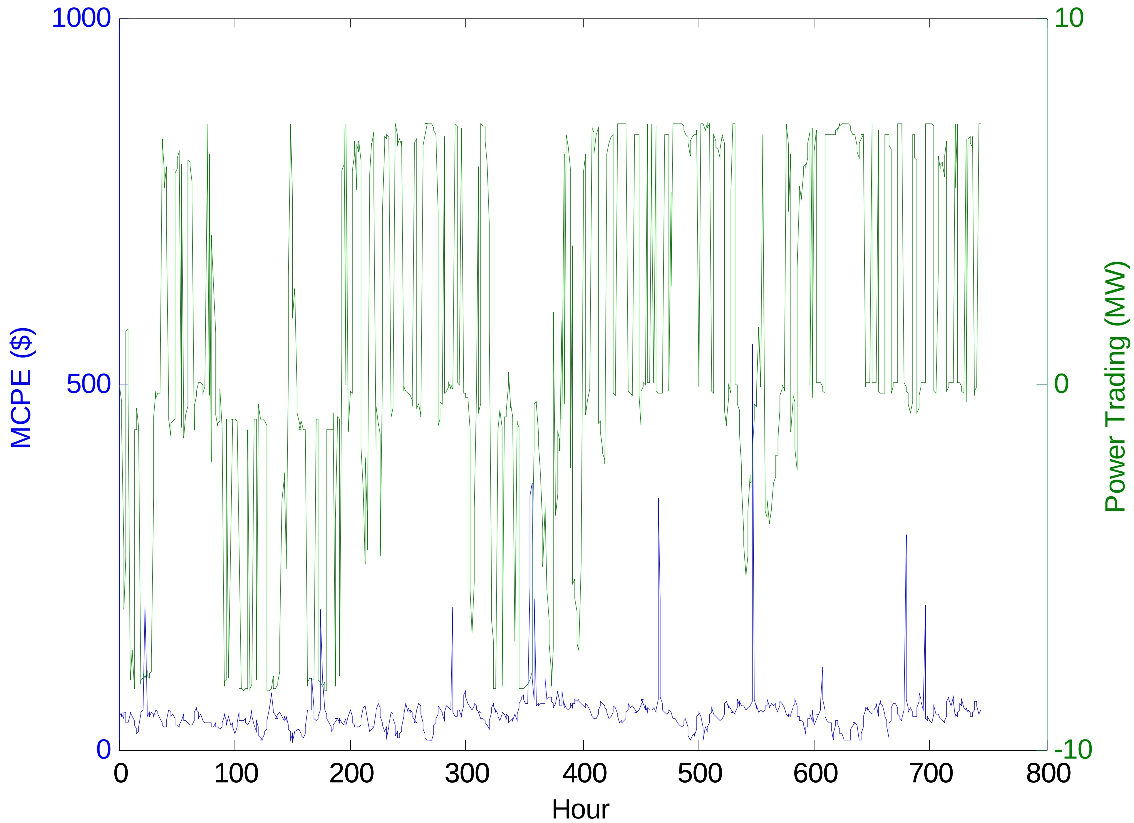


Figure 4.5 Power Exchange in Power Market in Case 2

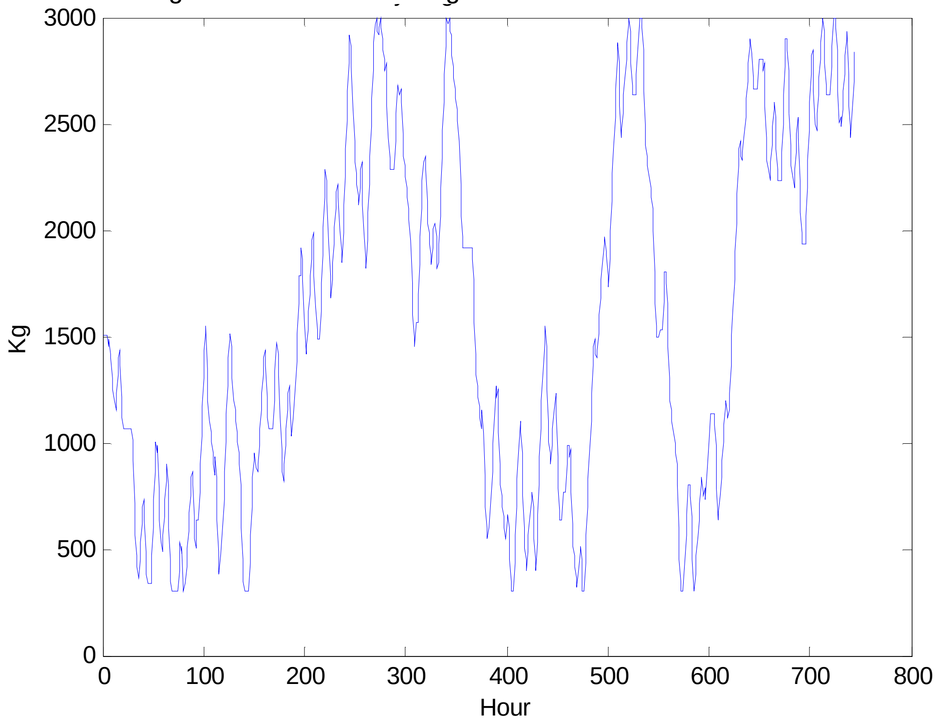


Figure 4.6 Hydrogen Level in the Storage Tank in Case 2

Based on the perfect forecasting, the optimization approach can dramatically decrease the production cost of the station. Comparing with no optimization case (case 1), the electricity cost to produce 1 kg hydrogen is decreased from \$2.40 to \$1.43. The economic improvement is about 40%.

4.2.3 Case 3

Perfect forecasting does not exist in practical situation. Considering the forecasting uncertainties, 20% of noise level is added to the forecasting results of wind power and MCPE in case 3. Also, 20% of noise level is added to typical PV output and hydrogen demand.

The simulation results are shown in Table 4.5, Figure 4.7, and Figure 4.8. Comparing with perfect forecasting, the electricity cost to produce 1 kg hydrogen is increased from \$1.43 to \$1.57. However, the cost of case 3 is still much lower than the cost of case 1.

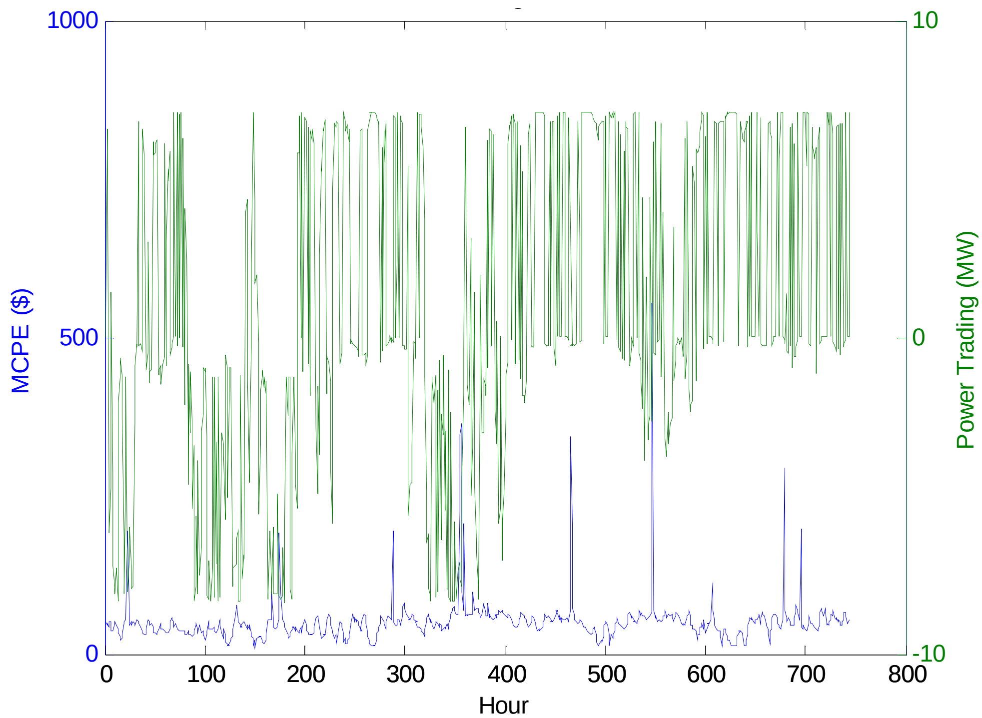


Figure 4.7 Power Exchange in Power Market in case 3

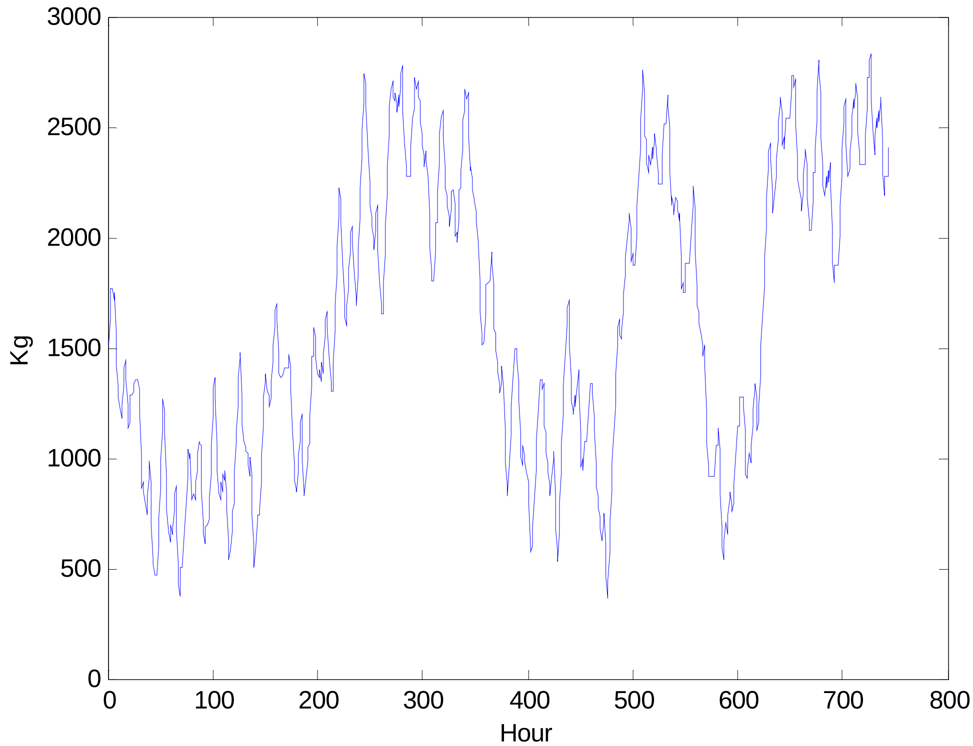


Figure 4.8 Hydrogen Level in the Storage Tank in Case 3

4.2.4 Comparison of Three Cases

Table 4.5 lists the simulation result of three cases.

Table 4.5 Simulation Results of Case 1, Case 2 and Case 3

Definition	**Case 1**	**Case 2**	**Case 3**
Hydrogen produced (kg)	45,301	47,833	47,406
Total Electricity (MWh)	2420.9	2,556	2,533
Electricity from PV (MWh)	105.5	105.5	105.5
Electricity from wind power (MWh)	1726.5	1,727	1,727
Electricity exchange with grid (MWh)	588.8	724.2	701.3
Electricity purchased from grid (MWh)	986.9	1,827	1,830
Electricity sold to grid (MWh)	398.1	1,103	1,129
Total Electricity Cost ($)	108,830	68,196	74,389
Electricity cost per kg hydrogen ($)	2.40	1.43	1.57

4.3 Uncertainties Analysis

The simulation is performed under different level of forecasting uncertainties on power production, real time pricing, and hydrogen demand to fully evaluate their impacts on the optimization approach. The simulation results are shown in Table 4.6 and Figure 4.9. As one can see, the electricity cost of 1kg hydrogen increases when the uncertainty level increases. However, it is still lower than the cost of no optimization case under very poor wind power and MCP forecasting and high uncertain on PV production and hydrogen demand.

Table 4.6 Simulation Results under Different Uncertainty Levels

Uncertainty Level	20%	30%	40%	50%
Electricity cost per kg hydrogen	$1.57	$1.64	$1.70	$1.80

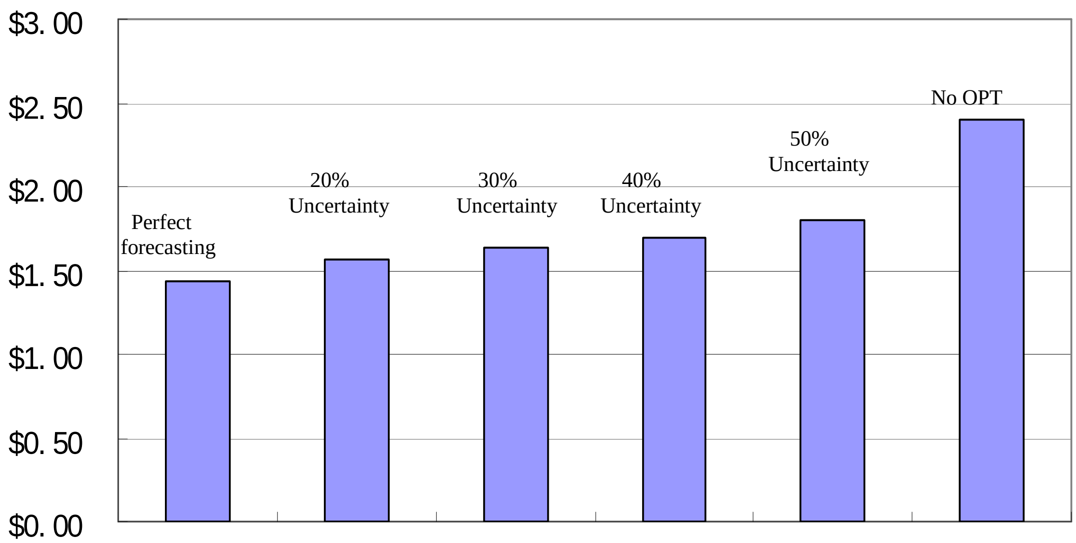


Figure 4.9 Electricity Cost of 1kg Hydrogen under Different Uncertain Levels

CHAPTER 5

SIMULATION IMPLEMENT IN LABVIEW

The Graphic User Interface (GUI) is developed in LabVIEW. With the GUI, the owner or the operator of hydrogen filling station has access to view the real-time operation process, view the statistical data and curves, and simulate the system.

5.1 Real-time Operation Interface

The real-time operation interface is shown in Figure 5.1. The wind farm and the power grid serve as two energy sources from outside of the hydrogen filling station. In the hydrogen filling station, there are six components. Solar array, which is mounted on the roof of the hydrogen filling station, provides the energy during the day time. The power meter stands for power electronic devices, converting AC from wind farm or power grid to DC and coupling the different input sources to the electrolyzer. In this diagram, it is simplified as a power meter to show how much power is totally used by the electrolyzer. Electrolyzer is the place where the electrolysis of water takes place and oxygen and hydrogen is produced. The hydrogen is then sent to the compressor to be compressed and finally fuel the customer by the dispenser.

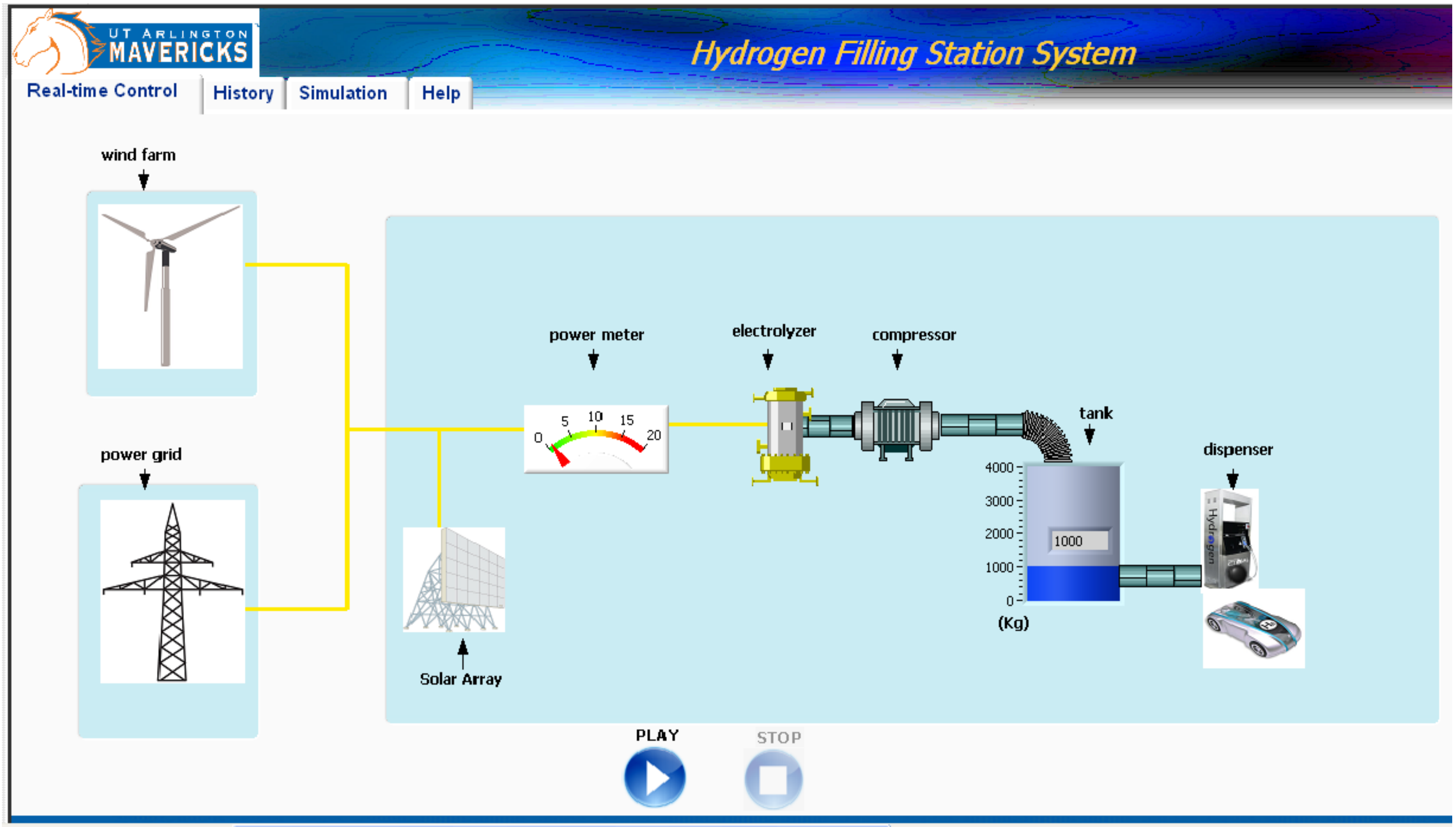


Figure 5.1 Real-time Control Interface

There are two typical scenarios in the real-time operation.

At night time, the wind output is usually high and the MCPE price is relatively low. Therefore, both the wind power and grid power are utilized to maximize the production of the hydrogen. Figure 5.2 is a snapshot of this scenario of "buy low".

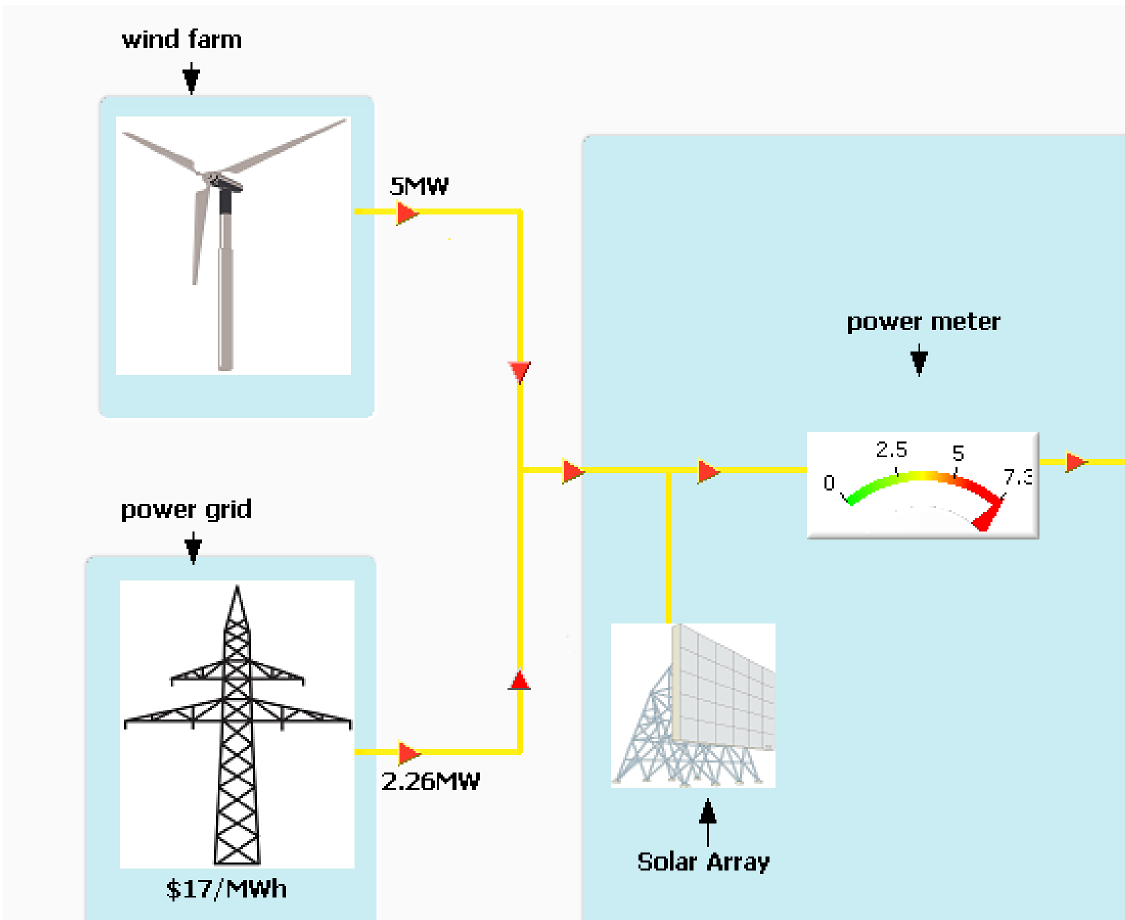


Figure 5.2 Scenario of "Buy Low"

At day time, the solar array has an output and the power grid price is relatively high. When the hydrogen in the tank is plenty enough to satisfy the demand of the customers, there is no need to generate more hydrogen and the wind power or solar power are sold to the power grid when the MCPE is relatively low. Figure 5.3 is a snapshot of this scenario "sell high".

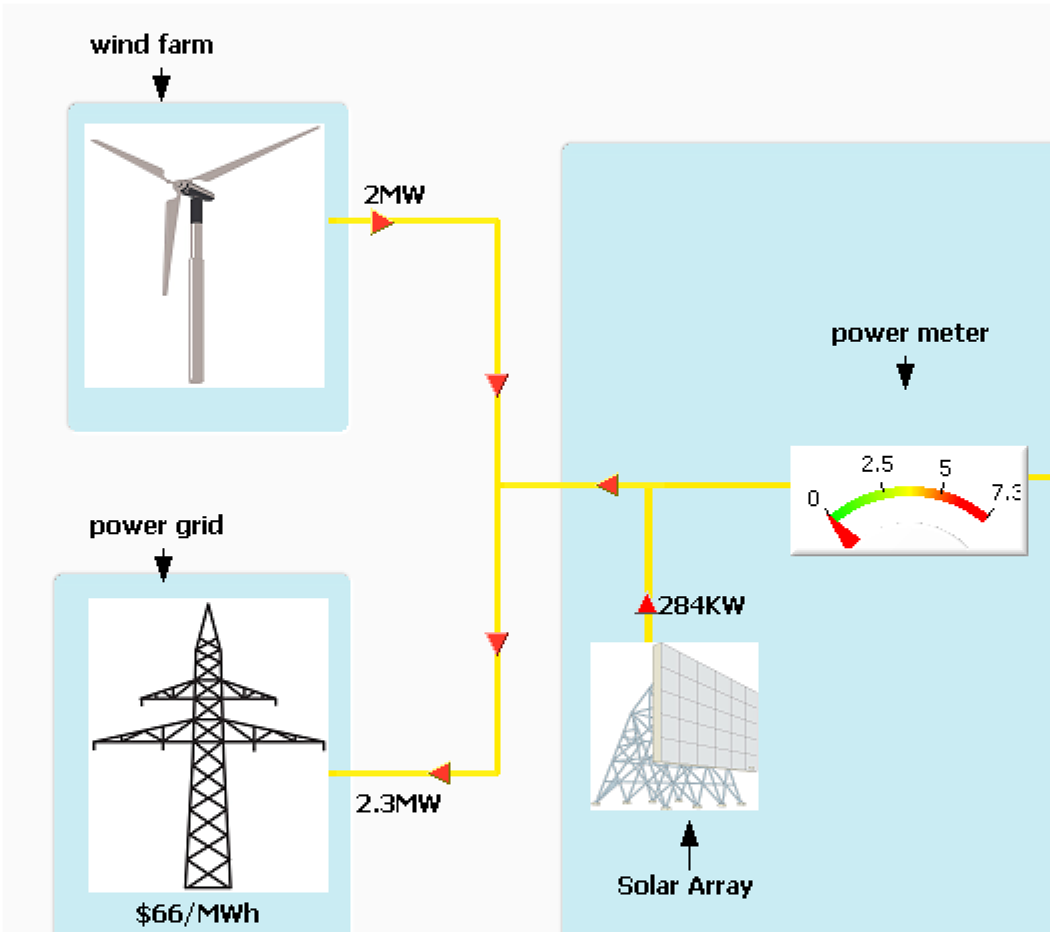


Figure 5.3 Scenario of “Sell high”

5.2 Simulation Interface

The optimization simulation module of the GUI is shown in Figure 5.4.

User can define the parameters for a hydrogen filling station. With the wind power and MCPE forecasting results as the input files, the program will optimize the schedule of the hydrogen production and power trading options for a period of 31 days. Finally, a summary is provided in the forms of lists and pictures.

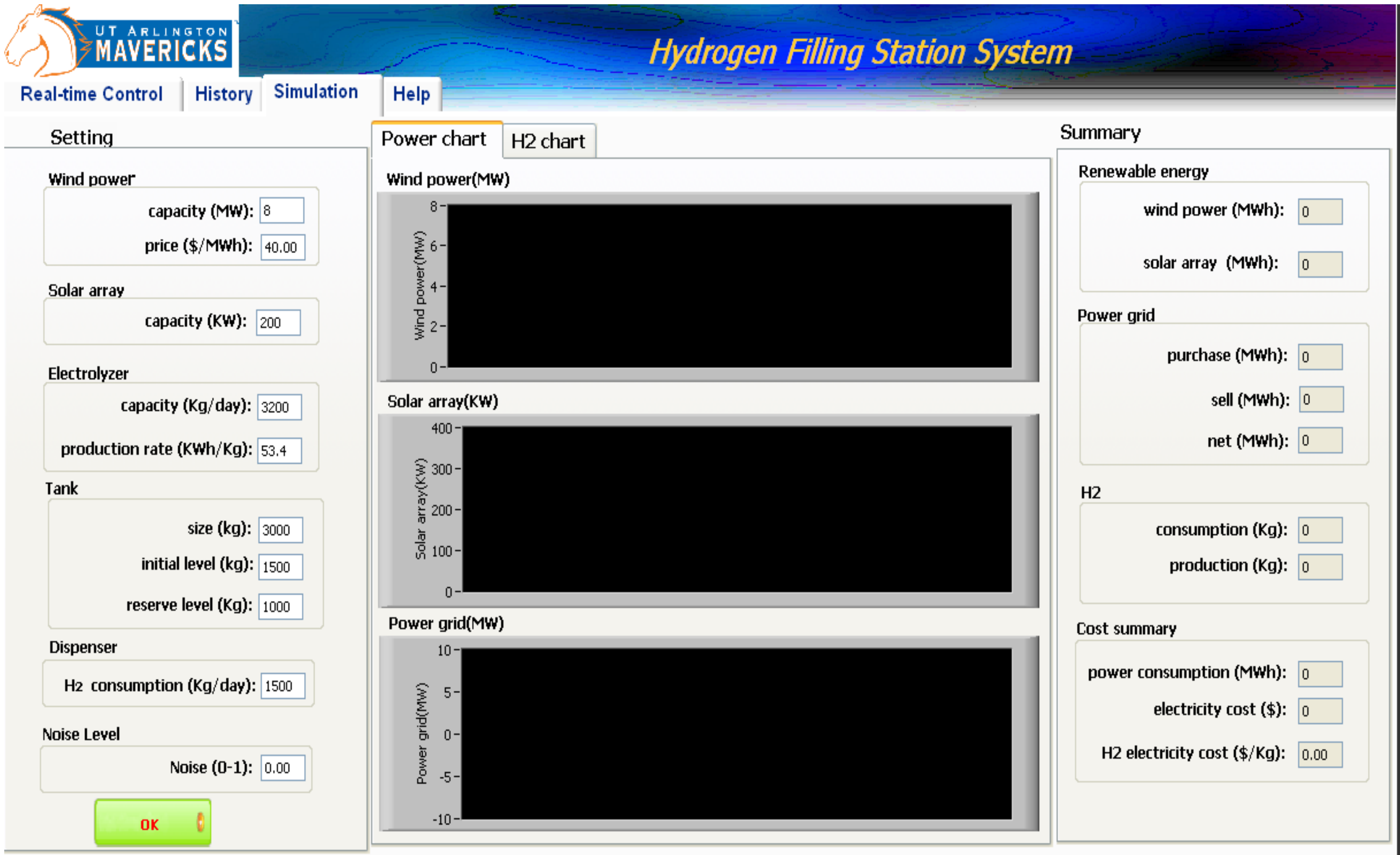


Figure 5.4 Simulation Interface

Figure 5.5 shows the parameter setting for the simulation.

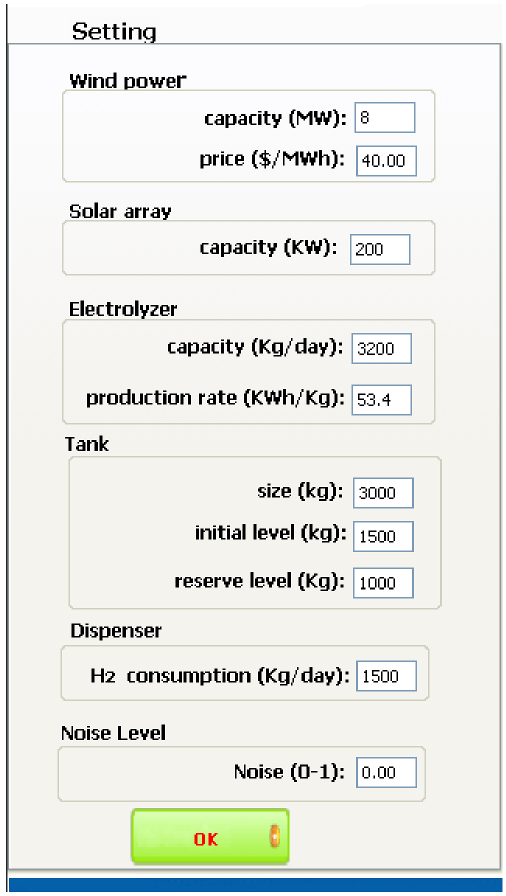


Figure 5.5 Parameter Setting

Figures 5.6 to 5.11 show the simulation result by inputting the parameters in the Figure 5.5. These include wind power generation curve, solar array power generation curve, power grid generation curve, hydrogen consumption curve, hydrogen generation curve and tank level curve in the period of 31 days.

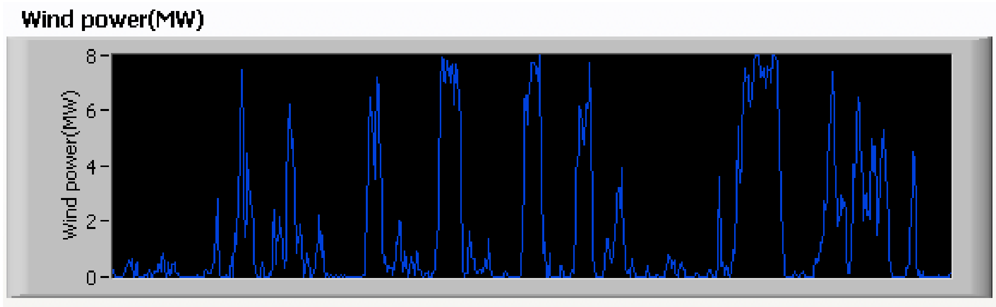


Figure 5.6 Wind Power Generation Curve

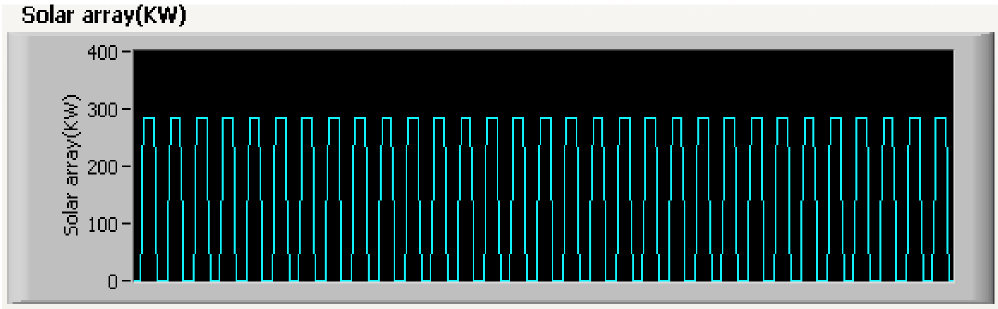


Figure 5.7 Solar Array Power Generation Curve

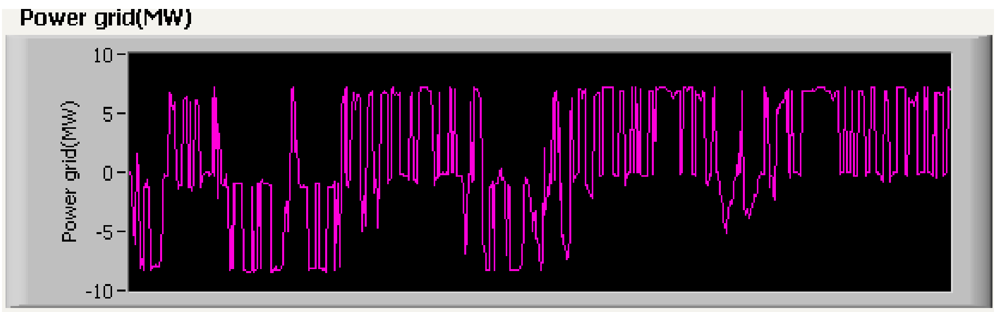


Figure 5.8 Power Grid Generation Curve

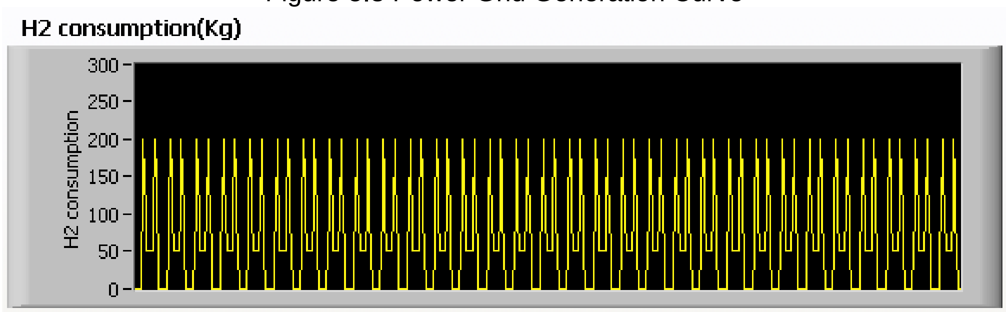


Figure 5.9 Hydrogen Consumption Curve

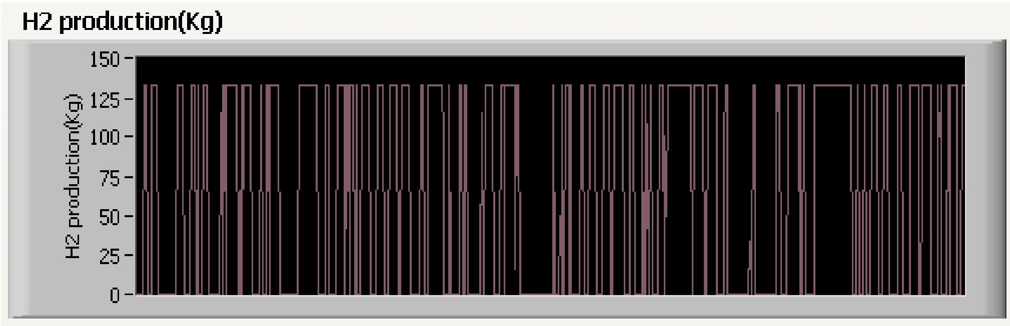


Figure 5.10 Hydrogen Production Curve

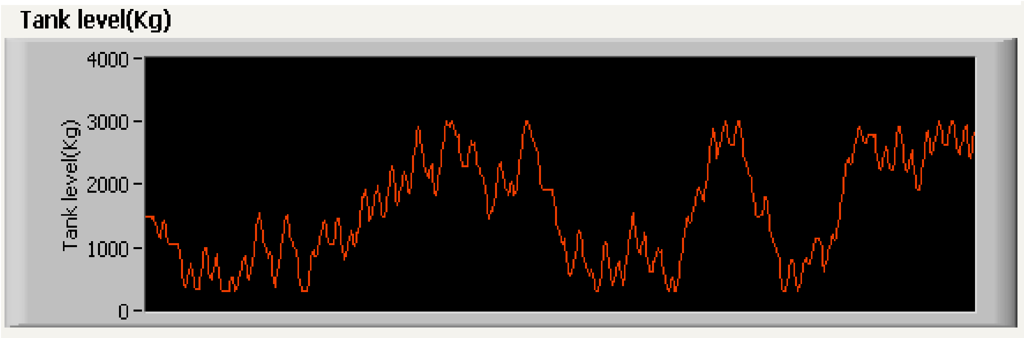


Figure 5.11 Tank level Curve

Figure 5.12 summarizes the total output of renewable energy, the sell and purchase of electricity to or from power market, the hydrogen consumption and production, and finally concludes the cost of hydrogen without equipment cost considered.

The designer can examine critical parameters such as storage tank size and the capability of the electrolyzer to help evaluate the hydrogen filling station.

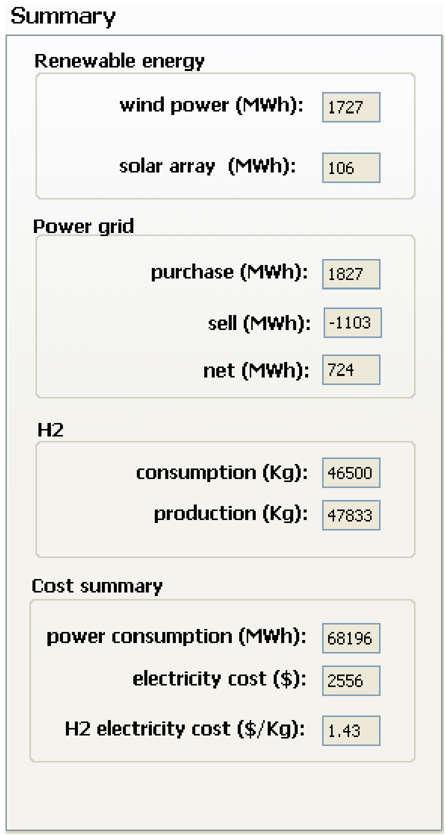


Figure 5.12 Summary of the System

5.3 Historical Interface

The historical data are shown in Figure 5.13. With the historical wind generation records, solar index, and electricity price, the operator of the hydrogen filling station can review the historical data for the latest one day, one month, or even one year.

The historical system can only work in a real system, so the output is currently unavailable.

5.4 Help Manual

To make this application user friendly, a help page gives description about each module. Figure 5.14 is the snapshot of the help page

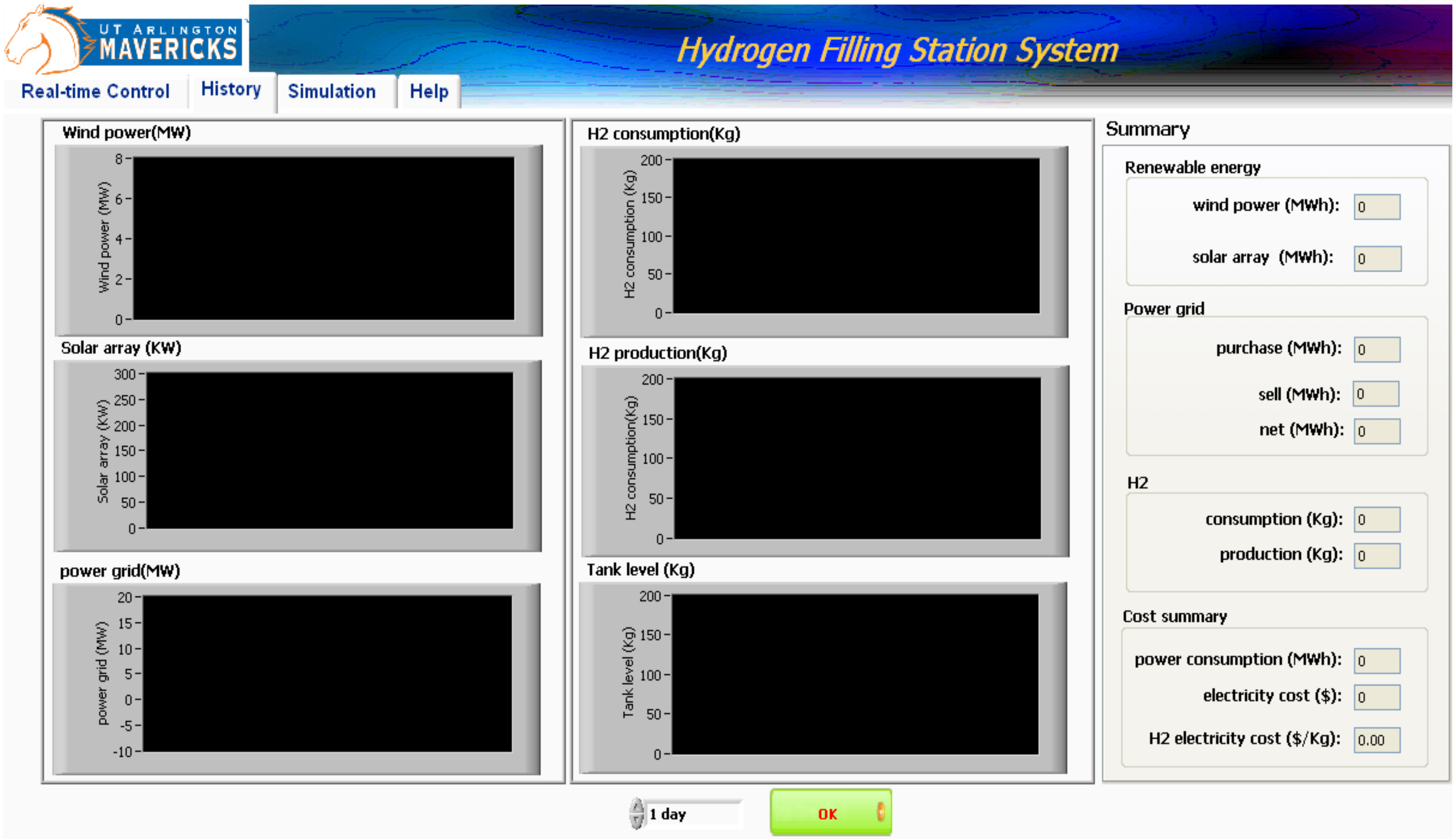


Figure 5.13 Historical Data Interface

.

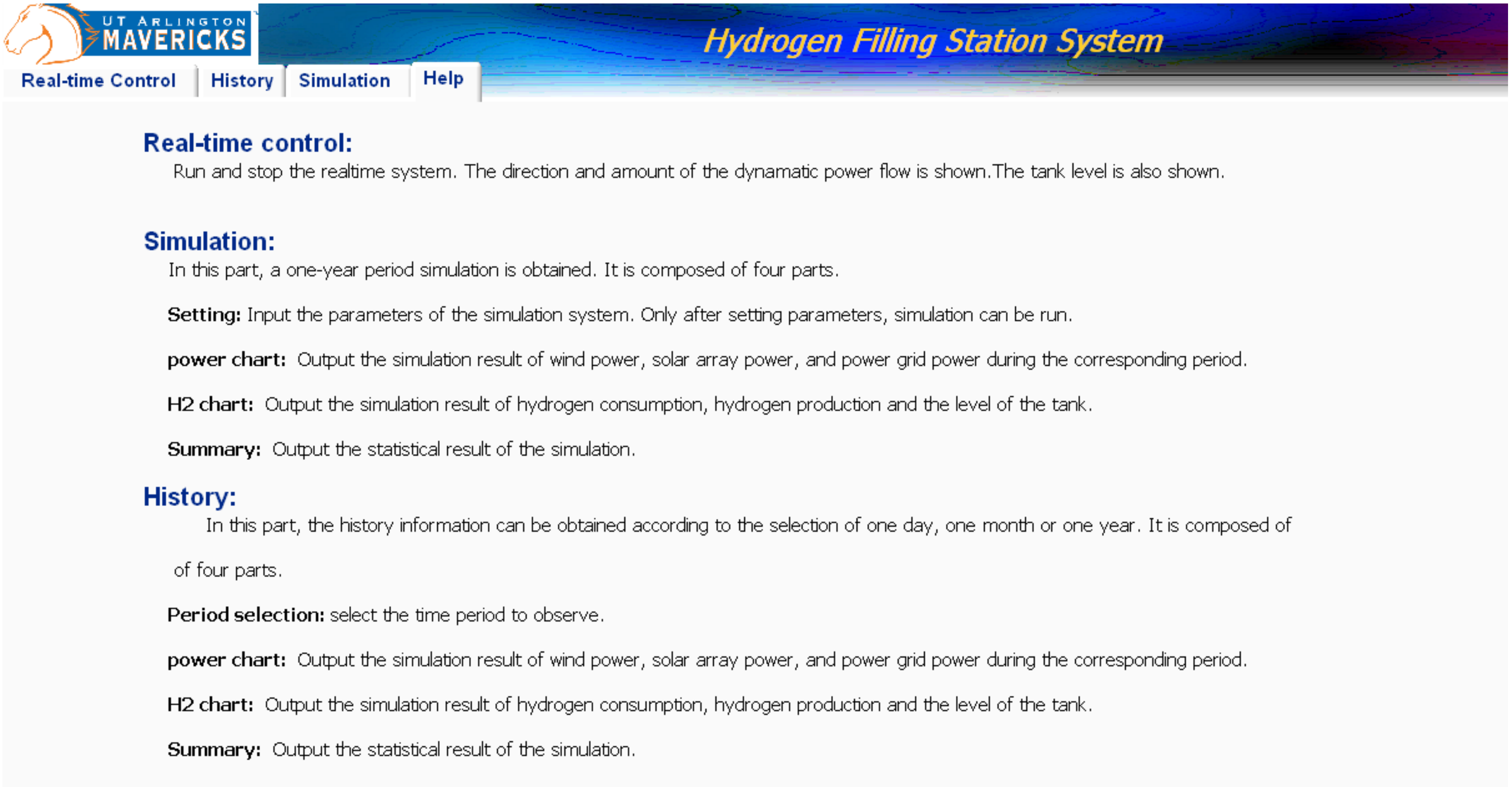


Figure 5.14 Help Page

CHAPTER 6

CONCLUSION

6.1 Conclusion

This research investigates hydrogen production paths and then explores the approach of on-site hydrogen production by electrolysis of water for the hydrogen filling station. The on-site installed PV and “virtual wind farm” produce renewable and main energy for electrolyzers. The power trading in power market is served as an auxiliary energy resource of electrolyzers and decease the electricity cost by the strategy of “Buy Low, Sell High”.

This research proposed an optimized production schedule of hydrogen filling station. The ANN model and ARX model are utilized for wind power and MCP forecasting individually. Based on the forecasting, the solver of linear programming is applied to make optimized production schedule and power trading decisions.

The electricity cost for 1 kg hydrogen production can be dramatically reduced from \$2.40/kg to \$1.43/kg by applying the optimization algorithm under the perfect forecasting and given PV output and hydrogen demand. The electricity cost of 1 kg hydrogen is \$1.57/kg under 20% uncertainty level of forecasting, PV output and hydrogen demand. The optimization approach still shows prominent benefits even under poor forecasting and high uncertainties.

Furthermore, this research applied Lab View Program to conduct both the simulation analysis and real time monitoring. The user can have a basic idea of the how the designed hydrogen filling station works.

By electrolysis of water into hydrogen, then making hydrogen available to everybody, we can mitigate the national dependence of foreign energy, while also improving the air quality on our land.

6.2 Future work

There is still work to fulfill in the future.

First, the pros and cons of an on-site battery storage system should be studied. On-site battery storage system will provide more operation flexibility with the potential to reduce electricity cost even further. However, the installation, operation, and maintenance cost can be the major obstacles for this development. The cost benefits of battery storage should be studied in the future research of the hydrogen filling station.

Second, a system which is composed of a full size mechanical and electronic devices to simulate the process of hydrogen consumption, wind output, solar array output can be set up before introducing this optimization application to the real world. With the hardware environment available, this application can communicate with ERCOT to obtain the real-time power grid price and work exactly the same way in a real hydrogen filling station.

Finally, current work is based on the assumption that hydrogen demand has the same pattern everyday. With more study into the hydrogen vehicle market, a more accurate pattern can be derived at a specific location and hence improves the optimization results.

APPENDIX A

MATLAB PROGRAMMING CODE

```
%%%%read the annual electricity price
MCPE_North = xlsread('MCPE_2007(North)');
Nan_ind = isnan(MCPE_North);
% %delete the Nan or insert apre-set price ($30)
MCPE_North(find(Nan_ind)) = 30*ones(length(find(Nan_ind)),1);
% MCPE_North_vec = MCPE_North(~Nan_ind);
MCPE_North_vec = reshape(MCPE_North',prod(size(MCPE_North)),1);
length(MCPE_North_vec);
mean_price = mean(MCPE_North_vec);
max_price = max(MCPE_North_vec);
min_price = min(MCPE_North_vec);
hrs = length(MCPE_North_vec)/4;
El_Price = zeros(hrs,1);
for i=1:hrs
    El_Price(i) = sum(MCPE_North_vec(i*4-3:i*4))/4;
end


windpower_output = xlsread('windpower_output');%1.5MW
windpower_output_vec = reshape(windpower_output',prod(size(windpower_output)),1);
if hrs~=length(windpower_output_vec)/6
    err = 1
else
    WP_output = zeros(hrs,1);
    for i=1:hrs
        WP_output(i)=sum(windpower_output_vec(i*6-5:i*6))/6;
```

```
    end
end

PV_output =
[0,0,0,0,0,0,94,188,284,284,284,284,284,284,284,284,284,284,188,94,0,0,0,0]'*.001;
Conv_matrix = zeros(365*24,24);
for i=1:365
    Conv_matrix(i*24-23:i*24,:)=eye(24);
end
PV_output = Conv_matrix* PV_output;

Cap_Windpower = 4*2;%MW
WP_output = WP_output*Cap_Windpower/1.5;%change to 4*2.3MW

HE_Rate = .05344;%Mwh/kg
Cap_Electrolyzer = 3200*.05344/24;%MW
Hy_Consumption =
[0,0,0,0,0,50,100,200,150,100,50,50,50,50,50,50,100,200,150,100,50,0,0,0]';

WP_price = 40; %$40/MWh

Tank_Size =3000;%kg
Tank_Ini = Tank_Size*.5;
Tank_Res = Tank_Size*.1; %more than 2hrs of highest comsumption
```

```
Tank =[Tank_Size, Tank_Ini, Tank_Res];


Operation_days = 31;

Opt_days = 7;

Opt_Time = Opt_days*24;


D2M = zeros (Opt_Time+Operation_days*24,24);

for n_i=1:Opt_Time/24+Operation_days

   D2M(n_i*24-23:n_i*24,:) = eye(24);

end

Hy_Consumption = D2M*Hy_Consumption;


%%%%add noise

sd_hy_cons=0;

Hy_Consumption_fc = Hy_Consumption

+Hy_Consumption.*randn(size(Hy_Consumption))*sd_hy_cons;

sd_WP =sd_hy_cons;

WP_output_fc = WP_output +WP_output.*randn(size(WP_output))*sd_WP;

sd_PV=sd_hy_cons;

PV_output_fc = PV_output +PV_output.*randn(size(PV_output))*sd_PV;

sd_El_price =sd_hy_cons;

El_Price_fc = El_Price +El_Price.*randn(size(El_Price))*sd_El_price;


%%%%Decrease Tank_Size & Increase Tank_Res to meet the constraint of tank

%%%%when the forecasting is not perfect
```

```
if sd_hy_cons~=0
   Tank_Size = Tank_Size-200;
   Tank_Res = Tank_Res+250;
end


%%%% Opt day by day
net_Grid = zeros(Operation_days*24,1);
Tank_Ini_Eachday = Tank_Ini;
Tank_Ini_day_vec = zeros(Operation_days+1,1);
Tank_Ini_day_vec(1) = Tank_Ini_Eachday;
for n_i = 0:Operation_days-1
        Start_time = n_i*24+1;
        End_time = Start_time+Opt_Time-1;
        lb = -WP_output_fc(Start_time:End_time)-PV_output_fc(Start_time:End_time);
        ub = Cap_Electrolyzer*ones(End_time-Start_time+1,1) + lb;
        Cul_Mat = triu(ones(End_time-Start_time+1,End_time-Start_time+1))';
        A = [Cul_Mat; -Cul_Mat];
        b_1=HE_Rate*((Tank_Size-Tank_Ini_Eachday)*ones(End_time-
        Start_time+1,1)+Cul_Mat*Hy_Consumption_fc(Start_time:End_time))...
        -Cul_Mat*(WP_output_fc(Start_time:End_time)+PV_output_fc(Start_time:End_time));
        b_2=-HE_Rate*((Tank_Res-Tank_Ini_Eachday)*ones(End_time-
        Start_time+1,1)+Cul_Mat*Hy_Consumption_fc(Start_time:End_time))...
        +Cul_Mat*(WP_output_fc(Start_time:End_time)+PV_output_fc(Start_time:End_time));
        b=[b_1;b_2];
        f = El_Price_fc(Start_time:End_time);
```

```
        [x,fval,exitflag,output,lambda] = linprog(f,A,b,[],[],lb,ub);
        net_Grid(Start_time:Start_time+23) = x(1:24);
        exitflag; %% 1 means success

        %%%check net_Grid for upper and lower limit
        lb = -WP_output(Start_time:End_time)-PV_output(Start_time:End_time);
        ub = Cap_Electrolyzer*ones(End_time-Start_time+1,1) + lb;
        for n_j=1:24
            if net_Grid(Start_time+n_j-1)<lb(n_j)
                net_Grid(Start_time+n_j-1) = lb(n_j);
            elseif net_Grid(Start_time+n_j-1)>ub(n_j)
                net_Grid(Start_time+n_j-1) = ub(n_j);
            end
        end

    Hy_Prod_tmp =
    (PV_output(Start_time:Start_time+23)+WP_output(Start_time:Start_time+23)+net_Grid(Start_ti
    me:Start_time+23))/HE_Rate;
    Tank_Ini_Eachday = Tank_Ini_Eachday+sum(Hy_Prod_tmp-
    Hy_Consumption(Start_time:Start_time+23));
    Tank_Ini_day_vec(n_i+2) = Tank_Ini_Eachday;

    end

    %%%check net_Grid for upper and lower limit
```

```
lb = -WP_output(1:Operation_days*24)-PV_output(1:Operation_days*24);
ub = Cap_Electrolyzer*ones(Operation_days*24,1) + lb;
for n_i =1:Operation_days*24
    if net_Grid(n_i)<lb(n_i)
        disp 'err'
    elseif net_Grid(n_i)>ub(n_i)
        disp 'err'
    end
end

%%%check the tank level
Hy_Electrolyzer =
(PV_output(1:Operation_days*24)+WP_output(1:Operation_days*24)+net_Grid(1:Operation_da
ys*24))/HE_Rate;
Cul_Mat = triu(ones(Operation_days*24,Operation_days*24))';
Hy_in_tank = Tank_Ini + Cul_Mat*(Hy_Electrolyzer(1:Operation_days*24) -
Hy_Consumption(1:Operation_days*24));
if sd_hy_cons~=0
    if find(Hy_in_tank>Tank_Size+200)
        disp 'Hy_in_tank>Tank_Size'
    end
    if find(Hy_in_tank<Tank_Res-250)
        disp 'Hy_in_tank<Tank_Res'
    end
end
```

```
% plot(net_Grid); hold on;
% plot(lb,'r'); hold on;
% plot(ub,'g')

Hy_Electrolyzer =
(PV_output(1:Operation_days*24)+WP_output(1:Operation_days*24)+net_Grid(1:Operation_da
ys*24))/HE_Rate;
Cul_Mat = triu(ones(Operation_days*24,Operation_days*24))';
Hy_in_tank = Tank_Ini + Cul_Mat*(Hy_Electrolyzer(1:Operation_days*24) -
Hy_Consumption(1:Operation_days*24));
Hy_prod_total = sum(Hy_Electrolyzer)
PV_output_total = sum(PV_output(1:Operation_days*24))
WP_output_total = sum(WP_output(1:Operation_days*24))
net_Grid_total = sum(net_Grid(1:Operation_days*24))
total_elec = WP_output_total+PV_output_total+net_Grid_total
from_Grid_id = find(net_Grid>0);
from_Grid_total =  sum(net_Grid(from_Grid_id))
to_Grid_id = find(net_Grid<0);
to_Grid_total =  sum(net_Grid(to_Grid_id))

Elec_cost_total =
El_Price(1:Operation_days*24)'*net_Grid+WP_price*sum(WP_output(1:Operation_days*24))
unit_cost= Elec_cost_total/Hy_prod_total
Hy_cons_total = sum(Hy_Consumption(1:Operation_days*24))
```

```
% plot(El_Price);hold on; plot(net_Grid,'r') %%compare price with net_Grid

x=[1:Operation_days*24];

[AX,H1,H2] = plotyy(x,El_Price(x),x,net_Grid);

set(get(AX(1),'Ylabel'),'String','MCPE ($)')

set(get(AX(2),'Ylabel'),'String','Power Trading (MW)')

xlabel('Hour')

title('Power Trading vs MCPE')


 % plot(Hy_in_tank)

% xlabel('Hour')

% ylabel('Kg')

% title('Hydrogen Level in Tank')

%

Toc
```

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