A Feasibility Study of a Wind/Hydrogen System for Martha's Vineyard, Massachusetts

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by

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ABSTRACT

The use of wind generated hydrogen for public transportation systems opens up a large number of potential future applications for wind-driven renewable energy systems. In this paper the results of a technical and economic feasibility study for incorporating hydrogen-powered buses into the existing public transportation system on Martha's Vineyard, Massachusetts, is presented. This analysis was carried out at the University of Massachusetts using a specially developed system simulation model. The proposed wind-hydrogen system is designed to supply gaseous hydrogen to a varying number of hydrogen-powered buses from a grid connected wind turbine- electrolyzer system. In addition to a detailed description of the model system and its components, the parametric results of its use applied to an existing public bus system on Martha's Vineyard are presented. For example, it was found that a 1.5 MW wind turbine combined with a 72 kW electrolyzer for the one bus system, or 252 kW electrolyzer for a three bus system could produce hydrogen at a cost of between 3.33 – 3.55 $/kg, or 0.333 – 0.355 $/mile. By subsidizing the system with the sale of both excess electricity and renewable energy production credits, the pay back period of the system was found to 5.7 years for the one bus system and 12.0 years for a three-bus system. The paper also presents a number of recommendations for future work on the Martha's Vineyard application as well as wind-hydrogen transportation systems in general.

1.0 INTRODUCTION BACKGROUND

1.1 Overview

Recent European work (see Zoulias, et al, 2004) has reviewed the market potential for the introduction of hydrogen technologies in stand alone power systems (SAPS). Their work specifically concentrated on non-grid connected systems that included local renewable energy source inputs. As shown in Figure 1, this study concluded that the main future potential market will be the transportation industry.

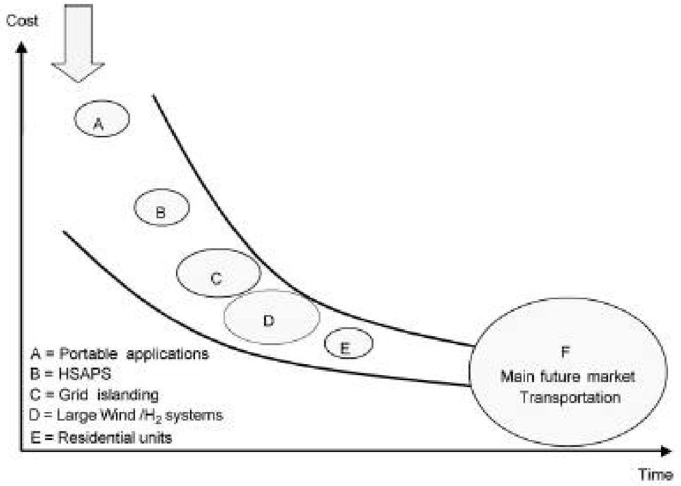


Fig. 1 Projected European Route for Hydrogen Applications

The use of renewable energy to power transportation is not a new idea (e.g., see Pohl, 1995). It is only in last two hundred years that fossil fuels have become the preferred method of powering transportation. This transition has left us with an unsustainable, environmental unfriendly transportation system.

Hydrogen can be used in a variety of energy conversion technologies. Internal combustion engines, turbines, and fuel cells can convert hydrogen into useful power for transportation. The exhaust from these energy conversion technologies consists primarily of water vapor. Using hydrogen to power transportation, however, will only be clean if hydrogen is produced using a clean method. Producing hydrogen by electrolyzing water with electricity generated by a non-fossil fuel primary energy source, such as wind or solar power, would make hydrogen a clean, renewable replacement for fossil fuels.

1.2 Existing Wind/Hydrogen Systems

Wind/hydrogen systems are a developing technology. Wind power has matured greatly over the last twenty years, and the cost of electricity from wind turbines is becoming more competitive with other source. The conventional way of generating hydrogen from wind turbines is to use electrolyzers to convert the generated electricity to hydrogen. Since conventional electrolyzers have been designed to operate with steady power input, the performance of electrolyzers with varying power, as is the nature of renewable energy sources, is a subject of current research.

Despite the infancy of wind/hydrogen systems, a number of demonstration project have been carried out. These projects both show the technical feasibility of wind/hydrogen systems and identify areas where further research is needed. A few of the existing demonstration projects are outlined below and are summarized in Table 1.

System Name	**Size**	**Installation date**	**Notes**
Wellgas (Sweden)	**1 household, approx 30,000 kWh/year**	**Approx. 1986**	**Stand alone system. Powered vehicle as well**
ENEA's Casiccia Research Centre (Italy)	**14 kW turbine 2.25 kW electrolyzer**	**2000**	**Test bed for intermittent electrolyzer operation**
Hydrogen Research Institute (Canada)	**10 kW turbine 1 kW PV array 5 kW electrolyzer**	**2000**	**Uses hydrogen as energy storage for times of low wind and low sun.**
Utsira (Norway)	**Two 600 kW turbines 50 kW electrolyzer**	**2004**	**Stand alone, introduced summer 2004**
NREL DERTF (USA)	**10 kW turbine 5 kW electrolyzer**	**2004**	**Test bed for wind/hydrogen component interactions**

Table 1 Summary of Existing Wind/Hydrogen Systems

Poul la Cour was the first known person to generate hydrogen using wind power (www.windpower.org). Around the turn of the 20th century, la Cour was both the first person build wind turbines specifically to produce electricity and the first to generate hydrogen using electrolysis with the electricity from a wind turbine. The hydrogen generated by la Cour's wind turbines powered the gaslights in the school at which he taught.

In the mid-1980s, a project titled the Welgas-Härnösand in Sweden used a wind turbine and electrolyzer to supply all the energy for a single family. The house was retrofit with hydrogen and electric powered appliances and a hydrogen powered car supplied transportation. The system utilized metal-hydride storage both in the car and for home hydrogen use. This project claims to be the first to incorporate these technologies (Tegström, 1988).

A wind/hydrogen system is operating at ENEA’s Casiccia Research Centre in Italy. This project has used two different wind turbines: a North Wind L-916 modified to run at variable speeds, and a 5.2 kW Riva Calzoni M7S wind turbine. The North Wind L-916 is rated at 14 kW at 11.5 m/s, and is currently being used. Two electrolyzers have been used for this project. The first was a 10 kW HYSOLAR electrolyzer, which was used to evaluate the effects of intermittent operation on electrolyzers. Intermittent operation due to a fluctuating power supply reduced the electrolyzer efficiency reduced by about 2% (Dutton, 2000). A von Hoerner System GmbH electrolyzer, rated at 2.25 kW nominal power, was installed in the final system. Research at ENEA is focused on the interaction between wind turbines and electrolyzers, so the hydrogen is dumped.

The Hydrogen Research Institute (HRI) at the University of Québec, Trois Rivierès uses a 10 kW Bergey Excel wind turbine coupled with a 1 kW PV array to supply power to a demonstration house. When more power is generated by the renewable energy system than is needed by the house, the excess energy is used to power a 5 kW Stuart Energy Systems electrolyzer (Agbossou, 2001). A 5 kW Ballard MK5-E fuel cell generates power using the stored hydrogen when the wind and solar power are inadequate.

A most interesting installation is on Norwegian island municipality of Utsira (Glöckner, 2002). Norsk Hydro, a Norwegian power company, and ENERCON, a German wind turbine manufacturer, are installing a wind/hydrogen system in this small town (250 inhabitants) to provide all the power for at least 10 households. The system consists of 2 600 kW wind turbines coupled with a 50 kW electrolyzer. The system will work much like the one at HRI, generating hydrogen with the excess power from the wind turbines. The hydrogen will then be used to supply power to the households when the wind is not adequate, as well as fuel for the local boat fleet. Initially, power is being generated with a hydrogen run generator, but eventually a fuel cell will be added to the system. This project shows the technical feasibility of large-scale wind/hydrogen systems for real world applications.

In the United States, NREL is opening a new test facility, the Distributed Energy Resources Test Facility (DERTF), which will examine wind/hydrogen and solar/hydrogen systems. Part of the research focus at DERTF will be to optimize wind turbine controls for hydrogen production (Hock, 2004).

1.3 Existing Hydrogen Transportation Systems

A number of hydrogen powered transportation projects have been implemented. Starting in the mid-1990s, Europe and North America began demonstration hydrogen-powered transportation projects. Recently, the scale and scope of these projects has increased dramatically. An overview of some of these projects follows:

1) The Euro-Québec Hydro-Hydrogen Pilot Project put three hydrogen-powered buses into service in Europe; two of the buses were converted HICE buses, one was a hybrid hydrogen bus (Wurster, 1995). The Montréal Urban Hythane Bus Project installed two hythane buses into service on regular urban bus routes in Montréal (Wurster, 1995). Hythane is a mixture of hydrogen and natural gas that can be used in natural gas engines with reduced emissions. Chicago and Vancouver, B.C, both tested hydrogen fuel cell passenger buses for two years (Wurster, 1995). These buses, produced by Ballard used compressed hydrogen stored on the roof.

2) The Munich airport has been a continual test bed for hydrogen transportation projects (Wurster, 1995). The airport's fleet of service vehicles has slowly been converted to run on hydrogen. The hydrogen is generated on-site by excess electricity from a cogeneration plant, and solar PV arrays.

3) The Clean Urban Transport for Europe (CUTE) project is installing 30 Ballard FC buses in 10 European cities (Hugosson, 2003). The different cities have been chosen to test the durability of FC buses in a variety of climates and driving conditions. The hydrogen to run the buses is being produced using different technologies, from stream reformation of natural gas to renewable energy electrolysis.

4) In California, the California Fuel Cell Partnership plans to run up to 20 hydrogen buses in the East Bay Area and Palm Desert (www.fuelcellpartnership.org) . The buses will be a combination of hybrid and FC buses. The SunLine Transit Agency in Palm Desert has been testing a hybrid bus for the last few years (Chandler, 2003).

5) The Ecological City Transport System (ECTOS) project put three FC buses in service in Reykjavik, Iceland during the summer of 2003. Iceland was the first country to open a hydrogen filling station to the public and has made a pledge to eliminate fossil fuel use (Andersen, 2003).

One of the obstacles that hydrogen transportation projects have to overcome is the onboard storage of hydrogen. All three of the primary options for the storage of hydrogen (compressed gas, cryogenic liquid, and metal-hydride) have been tested. The current trend is toward using compressed hydrogen gas. Hydrogen storage is not as big of a problem for public buses as it is for smaller vehicles because the extra space is not a limiting factor. The limited range of hydrogen powered buses, as compared to conventional fuel powered ones, however, could be a problem.

There are three main types of power plants for hydrogen-powered buses: fuel cell, hydrogen internal combustion (HICE), and hybrid. Fuel cells have become one of the most commonly implemented technologies. Fuel cell buses tend to be the most expensive hydrogen-powered bus option, but manufacturer participation in projects has made them popular. Demonstration HICE buses have been tested, but no production models are currently available. Most HICE buses are converted from either diesel or natural gas powered buses. Natural gas buses can be run on hydrogen, natural gas, or a mixture, which is an advantage if the hydrogen supply is not reliable.

Hybrid hydrogen buses use a fuel cell in combination with another form of energy storage, such as batteries, to power the bus. The advantage to these buses is that they can utilize energy saving techniques like regenerative braking to improve their fuel economy. Hybrid hydrogen buses are less expensive than fuel cell buses, but more expensive than hydrogen ICE buses. Thor Industries and ISE Research have developed a bus line incorporating this technology (Chandler, 2003).

2.0 WIND/HYDROGEN TRANSPORTATION SYSTEMS: GENERAL OVERVIEW

In general, a wind/hydrogen transportation system consist of these main components:

- Wind turbine
- Electrolyzer
- Hydrogen storage/delivery

The layout of a typical system is shown in Figure 2. A summary overview of the basic components follows.

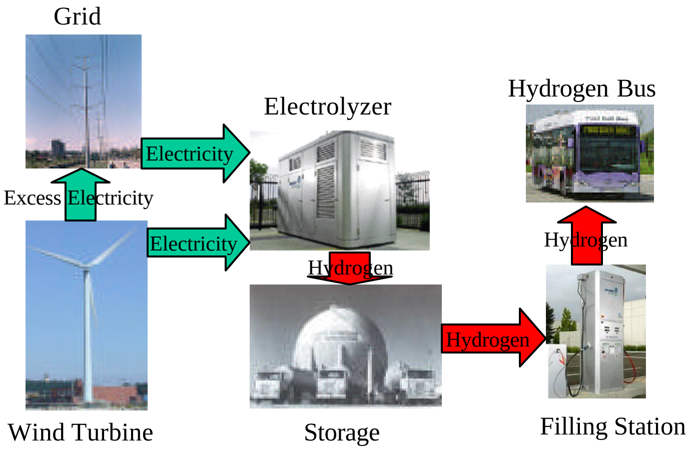


Fig. 2 Overview of Wind/Hydrogen/Bus System

2.1 Wind Turbine

The wind turbine in a wind/hydrogen system is the primary energy source. The optimum size and number of wind turbines for a system depends on the wind resource, fuel demand, and economics. A range of turbines is available on the market, from under 10 kW to around 4 MW. Utility grade turbines with a size range of 660 kW to 3.6 MW were considered for this project.

Wind/hydrogen systems may be grid connected. This configuration has the advantage of allowing power to be imported in times of low wind and to be exported, possibly sold, in times of high wind. The sizing of the wind turbine, as well as storage, is greatly affected by whether the system is grid tied. An off grid system needs a dump load to deal with excess electricity and a back up power supply, or large enough source of energy storage, to deal with low wind periods. The wind turbine in a grid tied system supplies less expensive, clean electricity to the system resulting in lower cost of hydrogen and a more sustainable system. An additional benefit in a grid tied system is the displacement of previous electrical loads in the local sub-grid. The local sub-grid includes any electrical loads that are on the client's side of the electrical meter. By locating the wind turbine on the client's side of the electrical meter, electricity that was previously imported from the grid to power auxiliary load (such as offices) can be supplied by the turbine. The economic benefits of this depend on the cost of grid electricity and the amount of electricity used by the client. Utility grade wind turbines are designed to supply power to a power grid. Research into optimizing wind turbines for wind/hybrid systems is just beginning (Hock, 2004).

The turbine in an off grid system must be large enough to supply sufficient power, with adequate energy storage, throughout the year. In a grid tied system, there is no minimum size (the system will operate using only grid electricity if necessary). The maximum size and number of wind turbines depends on the site, grid capacity, and public opinion, to name a few of the variables.

2.2 Hydrogen Electrolyzer

The electrolyzer in a wind/hydrogen system converts electric power and water into hydrogen. The primary criterion in choosing an electrolyzer for a wind/hydrogen system is that it can efficiently supply the required amount of hydrogen. Other important features of an electrolyzer for an isolated wind/hydrogen system include: ability to handle fluctuating power input, performance under no-power conditions and output pressure. For a grid-connected system, performance under no-power conditions is less important. Reliability and ease of operation are also important.

High-pressure electrolyzers, those that output high-pressure hydrogen, can reduce the energy required to compress to hydrogen to storage pressure. ELT Elektrolyse Technik, Stuart Energy, and Norsk Hydro all produce electrolyzer high-pressure electrolyzers of the capacity necessary for a wind/hydrogen system. The performance of electrolyzers can be classified by their efficiency. Manufacturers usually supply a rating in terms of kWh/kg-H_2. This number can be easily converted into efficiency by noting that hydrogen contains 33.325 kWh/kg (www.eere.energy.gov)˙ Table 2 lists the efficiencies and operating pressure of several commercially available electrolyzers.

Electrolyzer	Operating Pressure	Efficiency
ELT Elektrolyse Technik (www.elektrolyze.com)	30 bar (435 psi)	65-70%
Norsk Hydro (www.hydro.com)	30 bar (435 psi)	73%
Stuart Energy (www.stuartenergy.com)	25 bar (363 psi)	60%

Table 2 Operating Pressure and Efficiency of Commercial Electrolyzers

2.3 Hydrogen Storage/Delivery

Economics and safety will serve as the main criteria for selecting the appropriate storage technology. The three primary methods for storing hydrogen are compressed gas, liquid, and metal hydride. Metal hydride storage is competitive with the other technologies on small scales, but offers no economy of scale. Liquid hydrogen storage is good for long-term storage, but the extra energy required to liquefy the hydrogen and maintain storage conditions often makes it uneconomical. Containers for storing cryogenic liquids, or dewars, are relatively inexpensive. A liquefier is very expensive, however, and consumes a lot of power. Compressed gas storage has been found to be the most economic option for storing large quantities of hydrogen (Amos, 1999). On-board storage of hydrogen is generally as a compressed gas.

3.0 SCOPE OF WORK

Ideal sites for wind/hydrogen-bus systems combine good wind resource, a heavily used and adequately sized public transportation system, and a public that is willing to try novel technologies. The wind resource needs to be good enough to supply power to the system for less than grid electric prices. A grid-connected system has the option to import power, but the cost of producing hydrogen can be prohibitally expensive if the average cost of electricity is too high.

The existing public transportation system needs to have adequate maintenance facilities. Installing a wind/hydrogen-bus system requires adding separate fueling stations and maintenance facilities to the bus system. Staff must be trained to maintain and fuel the buses. A small transit system will have a difficult time making these upgrades. Public exposure to hydrogen-powered transportation ensures future support. For this reason, it is important that the first systems be installed in locations with a high ridership and a clientele that is willing to try a novel technology. Many of the existing systems have been installed in urban areas, which ensures these criteria are met.

With this background, the overall purpose of this project was to assess the feasibility of a wind/hydrogen-bus system on Martha's Vineyard. Thus, the project explored design options for a wind/hydrogen-bus system on Martha's Vineyard. Specifically, the project aimed to accomplish the following objectives:

- Determine design issues for a wind/hydrogen-bus system.
- Determine the economic and technical feasibility of a wind/hydrogen system.

The design issues of a wind/hydrogen system were investigated using:

- A literature review of existing wind/hydrogen and hydrogen bus systems.
- An evaluation of existing technology.
- An assessment of data pertaining to Martha's Vineyard's wind resource, existing power system, energy demand, and general site characteristics.

As will be described in the next sections, the economic and technical feasibility of the wind/hydrogen system was determined using a system model specifically designed for this project. The model allows for a variety of configurations and control schemes in order to determine the optimal system design.

4.0 ANALYTICAL MODEL

A system model, called WindH2, determines the economic and technical feasibility of a grid connected wind/hydrogen-bus system. System variables include the number and size of wind turbines, the size of electrolyzer, the amount of hydrogen storage, the number and type of buses, the daily transportation load (either in miles/day or gal/day), and the control algorithm. For each time step wind speed data are used to calculate the power from the wind turbine, the electricity exported or imported, the cost of exporting or importing electricity, the hydrogen produced, and the state-of-charge of the hydrogen storage. After the model completes processing the time series data, the cost of hydrogen (both in $/kg and $/mile), cost of electricity from the wind turbine, total cost of the system with and without interest, total electricity imported and exported, and the simple payback period are output. An operational flow chart of WindH2 is shown in Figure 3. More details of this computational code are included in the project report of Geer (2004).

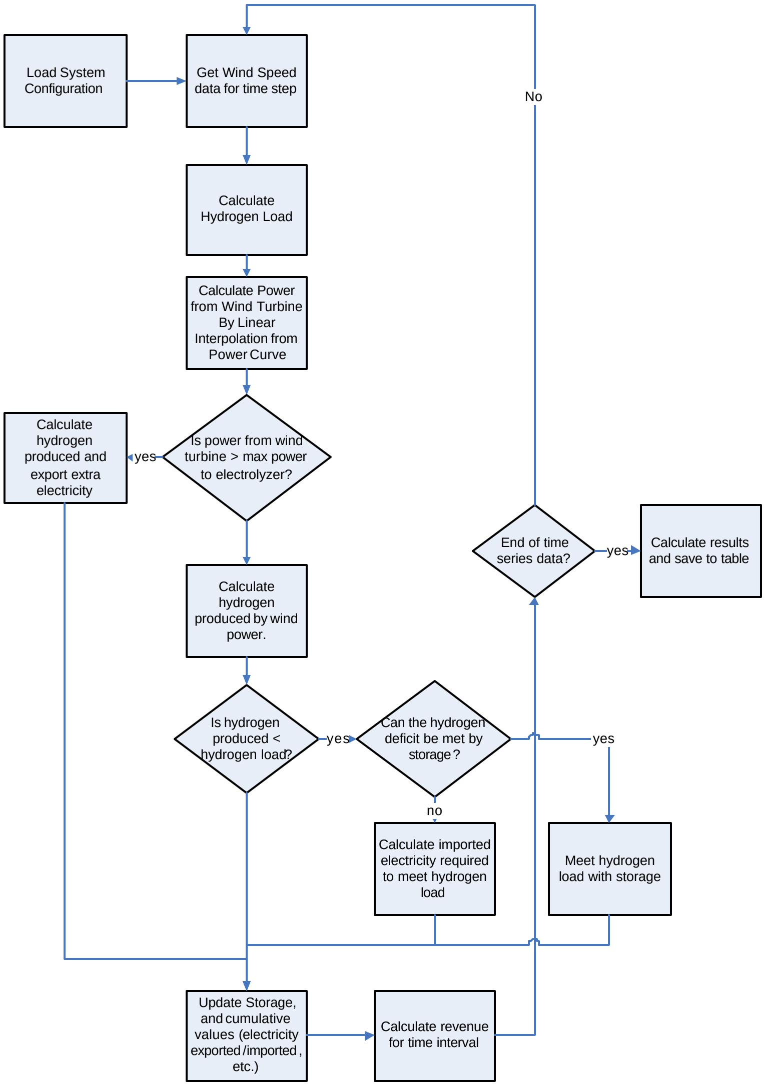
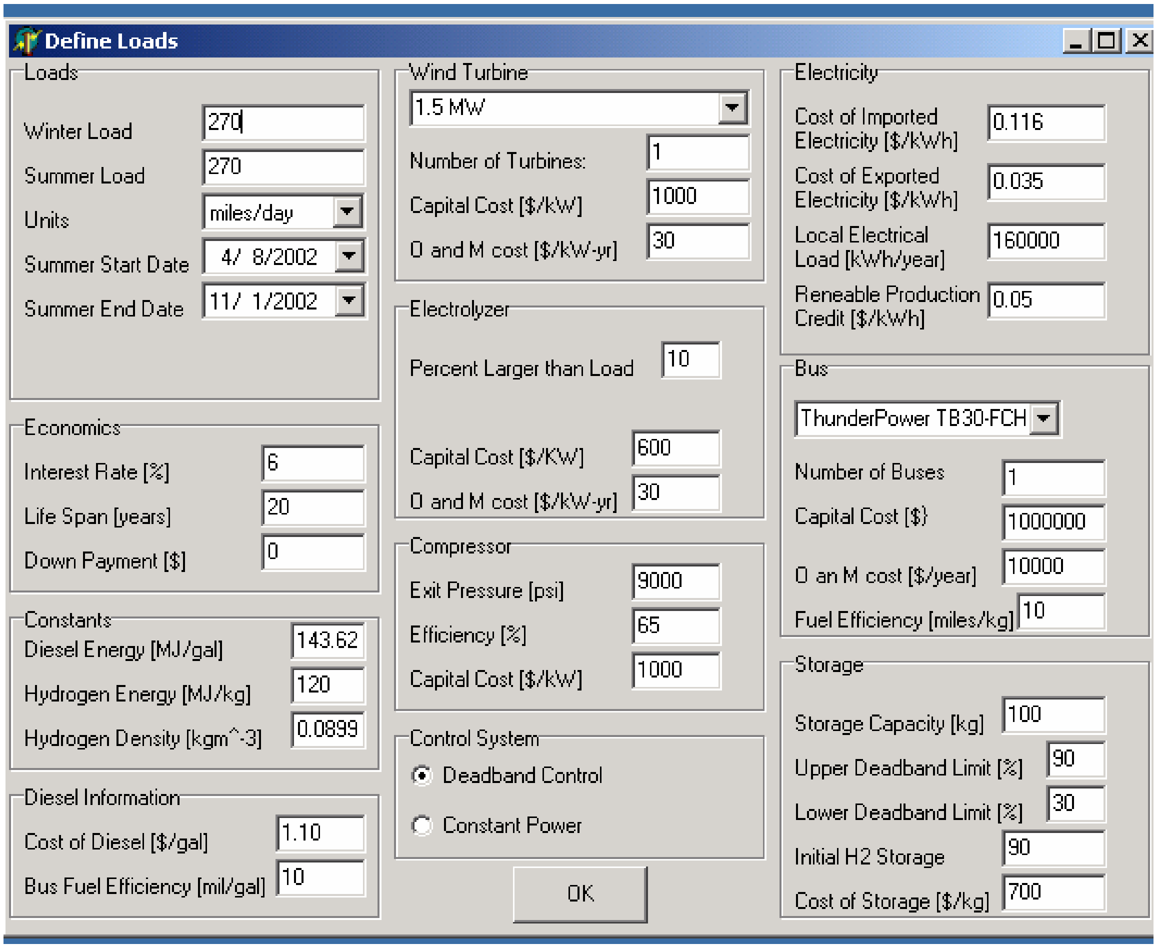


Fig. 3 Flow Chart of System Model

4.1 Model Input Parameters

Before WindH2 begins processing, the user must enter a number of parameters. The window that defines these parameters is shown in Figure 4.



Loads
Winter Load: 270
Summer Load: 270
Units: miles/day
Summer Start Date: 4/ 8/2002
Summer End Date: 11/ 1/2002

Economics
Interest Rate [%]: 6
Life Span [years]: 20
Down Payment [$]: 0

Constants
Diesel Energy [MJ/gal]: 143.62
Hydrogen Energy [MJ/kg]: 120
Hydrogen Density [kgm^-3]: 0.0899

Diesel Information
Cost of Diesel [$/gal]: 1.10
Bus Fuel Efficiency [mil/gal]: 10

Wind Turbine
1.5 MW
Number of Turbines: 1
Capital Cost [$/kW]: 1000
O and M cost [$/kW-yr]: 30

Electrolyzer
Percent Larger than Load: 10
Capital Cost [$/KW]: 600
O and M cost [$/kW-yr]: 30

Compressor
Exit Pressure [psi]: 9000
Efficiency [%]: 65
Capital Cost [$/kW]: 1000

Control System
● Deadband Control
○ Constant Power

Electricity
Cost of Imported Electricity [$/kWh]: 0.116
Cost of Exported Electricity [$/kWh]: 0.035
Local Electrical Load [kWh/year]: 160000
Reneable Production Credit [$/kWh]: 0.05

Bus
ThunderPower TB30-FCH
Number of Buses: 1
Capital Cost [$]: 1000000
O an M cost [$/year]: 10000
Fuel Efficiency [miles/kg]: 10

Storage
Storage Capacity [kg]: 100
Upper Deadband Limit [%]: 90
Lower Deadband Limit [%]: 30
Initial H2 Storage: 90
Cost of Storage [$/kg]: 700

Fig. 4 WindH2 System Input Configuration Screen

4.2 Wind Turbine Model

A variety of wind turbine sizes are available in WINDH2, each rated by their peak power output. Their rated sizes ranged from 0.66 to 3.6 MW. Wind turbine performance is characterized by a power curve, which relates wind speed to power output. When a wind turbine is selected, the power curve, with 1 m/s resolution, is loaded into memory. The power output of the wind turbine is determined by linear interpolation from the power curve, given a wind speed; this value is multiplied by the number of turbines to get the total power produced. Array losses are not considered.

The installed cost of the wind turbine is calculated based on a user definable cost/kW based on the peak production of the turbine. Yearly operation and maintenance cost for the wind turbine is calculated based on a fixed cost per kW.

4.3 Hydrogen Load

The hydrogen load is calculated in one of two ways. If the system load is defined in terms of diesel-gallons/day then the load is calculated by converting the amount of diesel used to the energetic equivalent amount of hydrogen used. If the system load is defined by the number of miles/day, then the fuel economy of the selected hydrogen bus is used to calculate the amount of hydrogen used. WINDH2 is designed to allow for different loads in the winter and summer; the transition dates are user defined. An hourly hydrogen load is calculated based on the daily hydrogen load. The load is distributed equally among the hours of the day.

4.4 Control System

There are two different control algorithms for the system: Dead Band and Constant Power. In Dead Band mode, the operation of the system is dependent on the state-of-charge (SOC) of the hydrogen storage tanks. If the SOC is greater than the user-defined upper limit, then all the power from the wind turbines is exported to the grid. If the SOC is less than the upper-limit, but greater than the lower limit, the power from the wind turbine goes to the electrolyzer-compressor system; any extra power generated by the wind turbine above the rated power of the electrolyzer-compressor system is exported. If the SOC is less than the lower limit, then the power from the wind turbines is augmented by power from the electric grid to meet the hydrogen load.

In the Constant Power mode, the power sent to the electrolyzer-compressor system is constant and enough to meet the hydrogen load. If the wind turbine is not producing enough power, power is imported; if the wind turbine is producing too much power, power is exported. Operation in Constant Power mode requires minimal hydrogen storage, but greater importing of electricity.

4.5 Electrolyzer-Compressor System

Production of hydrogen is determined by the size of the electrolyzer, efficiency of the compressor, and the power input to the electrolyzer-compressor system. WINDH2 uses an electrolyzer model based on one developed at the Institute for Energy Technology, Norway (Ulleberg, 1997). In this model, the I-V curve of an electrolyzer is characterized by the following equation:

$$V = V_{ref} + \frac{r}{A} I + s \log\left(\frac{t}{A} I + 1\right) \qquad (1)$$

Where V_{ref} is the reversible cell voltage, A is the electrode area, r, s and t are constants (based on an operational temperature of 20°C). Figure 5 shows the relation between current and voltage in the electrolyzer.

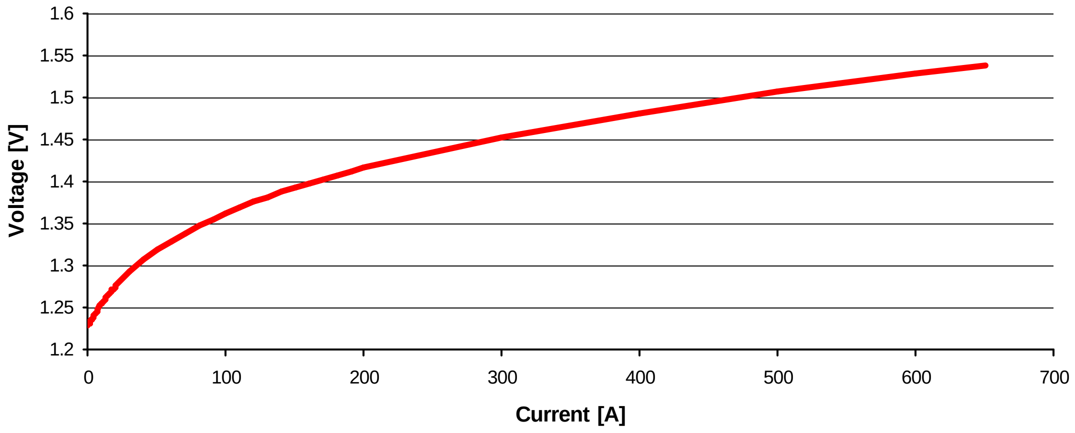


Fig. 5 I-V Curve for Electrolyzer Model

Hydrogen production in an electrolyzer is determined by the current and the Faraday efficiency; the relationship is given in Equation 2**.**

$$\dot{n}_{H_2} = \eta_F \frac{n_c I}{zF} \qquad (2)$$

Where η_F is the Faraday efficiency given in Equation 3, n_c is the number of cells, z is the number of electrons transferred per reaction, and F is the Faraday constant

$$\eta_F = \frac{\left(\frac{I}{A}\right)^2}{F_1 + \left(\frac{I}{A}\right)^2} F_2 \qquad (3)$$

F_1 and F_2 are constants based on the original electrolyzer model.

To use the electrolyzer model in WINDH2, the hydrogen output was normalized. This is done because functional data, such as the number of cells, the area of the electrodes, and operation temperature is not available for production electrolyzers. What is available is the hydrogen production rate at full power, given in kWh/kg. A value of 53.39 kWh/kg, which corresponds to a 62.4% overall efficiency, was assumed for this model. These numbers correspond to the value for the Stuart Energy high-pressure electrolyzer, which was used because the efficiency included all power conditioning equipment.

The size of the electrolyzers in WINDH2 is determined by the percent larger than the maximum load, or the over sizing. Once the over sizing of the electrolyzer is decided, the maximum power consumption and hydrogen output can then be used to scale the electrolyzer model. The electrolyzer power is scaled to a range 0-1000 and the hydrogen production scaled to 0 to 100%. For example, if the maximum power to an electrolyzer is

100 kW and the maximum hydrogen production is 1.87 kg/hr (assuming 62.4% efficiency), then the power into the model is multiplied by 10 and the percent of hydrogen generated is a percent of 1.87 kg/hr. A plot of scaled hydrogen output to scaled power input is shown in Figure 6.

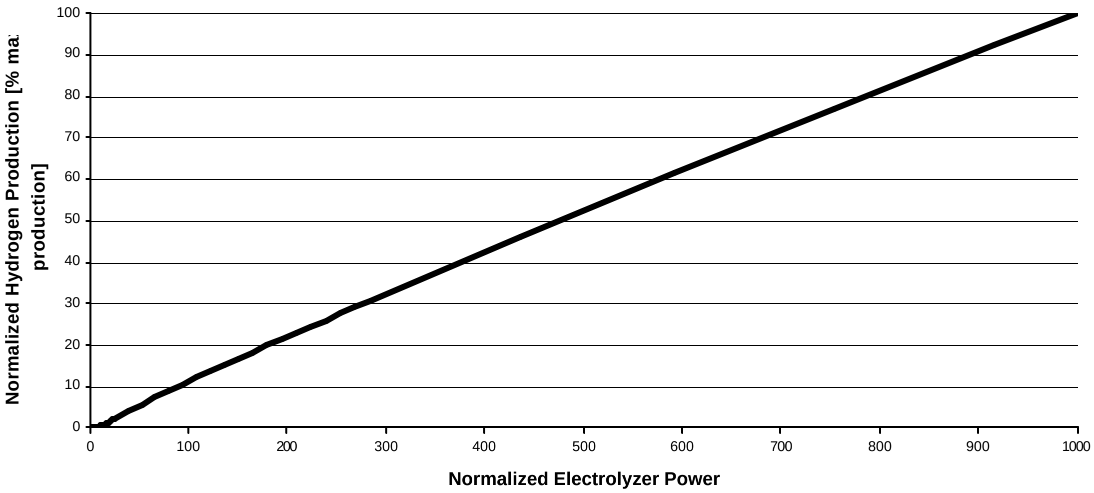


Fig. 6 Normalized Hydrogen Production vs. Normalized Power Input

Compressor losses also need to be considered. The specific work done by the compressor is found by using the following equation based on an isentropic compressor:

$$w_{compressor} = \frac{\frac{kRT_1}{k-1} * \left(\frac{P_2}{P_1}\right)^{\left(\frac{k-1}{k}-1\right)}}{h_{compressor}} \qquad (4)$$

Once the hydrogen production is calculated, the work done by the compressor can be found by multiplying the amount of hydrogen produced by the specific work of the compressor. The sum of the power consumed by the electrolyzer and the power consumed by the compressor must equal the total power input to the electrolyzer-compressor system.

WINDH2 assumes that the compressor is sized to run at 100% load when the electrolyzer is running at 100% load. This corresponds to a compressor size of 0.0618 kW per-kW of electrolyzer.

With scaled equations for hydrogen production rate, the I-V characteristics of the electrolyzer, and the work done by the compressor, the actual hydrogen production can be found from the power input to the electrolyzer-compressor system by using an iterative technique. WINDH2 solves this series of equations and returns the amount of hydrogen produced given an input power with an error threshold of 0.1%, which corresponds to 0.00187 kg/hr-kW.

4.6 Hydrogen Storage

Once the amount of hydrogen being produced is known, the net hydrogen generation is calculated by subtracting the hydrogen load from the hydrogen produced. The net hydrogen produced is the change in hydrogen storage. Storage is assumed to be lossless. If the system is operating in Constant Power mode, the amount of hydrogen produced is always equal to the hydrogen load, so the net hydrogen production is always zero.

4.7 Economics

WINDH2 outputs three main economic indicators: the cost of hydrogen (both in $/kg and $/mile), the payback period of the system, and the cost of energy from the wind turbine. When the system analysis is configured, the capital cost and yearly operation and maintenance cost of various components are entered into the program along with cost of imported and exported electricity, diesel, and the interest rate and term of the loan.

WINDH2 assumes that the wind turbine, electrolyzer and hydrogen filling station are all at the same site. Distribution charges for both electricity and hydrogen are therefore ignored. A levelized yearly payment for various components can be found from the capital cost (CC) of the components and any down payment (DP) using Equation 5, where R is the interest rate, and N is the term of the loan in years.

$$Payment_{Yearly} = \frac{(CC - DP) * R}{1 - (1 + R)^{-N}} \qquad (5)$$

4.7.1 Cost of Energy from Wind Turbine

The cost of energy from the wind turbine is the cost to own and operate the wind turbine divided by the amount of power produced. The cost to run the wind turbine is the yearly payment on the wind turbine, found from the capital cost of the turbine and Equation 5, plus the operation and maintenance costs. This calculation is shown in Equation 6 (with down payment, DP = 0).

$$C_{energy,WT} = \frac{C_{loan,WT} + C_{O\&M,WT}}{P_{Tot,WT}} \qquad (6)$$

4.7.2 Cost of Hydrogen

The cost of hydrogen, in \$/kg, is the cost of owning and operating the electrolyzer, compressor, and storage divided by the amount of hydrogen produced. The yearly cost of owning and running the electrolyzer-compressor system is the sum of the yearly loan payment, $C_{loan,elect}$, of the electrolyzer, compressor, and storage, calculated using Equation 5, the yearly operation and maintenance cost, $C_{O\&M,elect}$, of the electrolyzer, and the cost of power to the electrolyzer-compressor system, $C_{powertoelectrolyzer}$. This calculation is shown in Equation 7.

$$C_{H_2} = \frac{C_{powertoelectrolyzer} + C_{loan,elect} + C_{O\&M,elect}}{m_{H_2}} \quad (7)$$

The cost of power to the electrolyzer-compressor system is the total power to the electrolyzer, $P_{Tot,Elect}$, minus the total imported power, $P_{Tot,Imp}$, multiplied by the cost of power from the wind turbine, C_{wtpow}, plus the total imported power times the cost of imported power, C_{imppow}. This calculation is shown in Equation 8.

$$C_{powertoelectrolyzer} = \left(P_{Tot,Elect} - P_{Tot,\mathrm{Im}p}\right)C_{WTPow} + P_{Tot,\mathrm{Im}p} * C_{impow} \quad (8)$$

The cost of hydrogen can be converted from \$/kg to \$/mile by multiplying by the fuel economy of the selected bus.

4.7.3 Payback Period

The simple payback period for the system is the system capital cost divided by the yearly revenue. The capital cost of the system includes the cost of the wind turbine, electrolyzer, compressor, storage, and bus. The yearly revenue is the sum of the revenue from selling electricity to the grid, any renewable energy production credits, the offset electric cost for the local sub-grid, and the offset diesel costs minus the cost if importing electricity and operation and maintenance costs.

The system revenue is calculated for each time step. The cost of importing electricity is the amount of electricity imported multiplied by the cost of imported electricity defined in the system configuration. The value of exported electricity is calculated in the following way. The yearly electrical load of the local sub-grid is divided into an hourly load. The local sub-grid includes the auxiliary loads, such as office buildings, on the client’s side of the electric metering box. Extra power generated by the wind turbine first goes to offset this load, and is valued at full grid price. If there is still extra power being generated it is exported to the grid and is valued at the price of exported electricity defined in the system configuration. the equation for the revenue from exported and imported electricity is shown in Equation 9.

$$R_{expelect} = (P_{WT} - P_{subgrid}) * C_{exppow} - (P_{imported}) * C_{\mathrm{imppow}} \quad (9)$$

Renewable energy production credits are applied to all the power produced by the wind turbine and represent any state or federal incentives to renewable energy production. The total revenue for the system is given by Equation 10.

$$SPP = \frac{CC_{sys}}{R_{\exp\, elect} + P_{WT} * C_{REPT} + V_{diesel,offset} * C_{diesel} - C_{O\&M}} \qquad (10)$$

5.0 SUMMARY OF ANALYTICAL MODELING STUDY

The objectives of this work were to determine the design issues and the economic and technical feasibility of a wind/hydrogen bus system on Martha's Vineyard. The previous sections summarize a literature review and an evaluation of existing wind/hydrogen and hydrogen bus systems, This section presents a technological and economic evaluation of site specific data using the system model (WINDH2) specifically designed for this project.

5.1 Wind Resource

The wind resource for Martha's Vineyard was determined from a wind resource map of the area and a local meteorological monitoring station. Depending on the location and the height of the wind turbine, the average wind speed on Martha's Vineyard varies between 6.0 and 9.0 m/s (www.awstruewind.com). The distribution of average wind speeds at 70 meters is shown in Figure 7. The average wind speed in the vicinity of the proposed system is between 7.0 and 7.5 m/s. A conservative estimate of 7.0 m/s was assumed for this work.

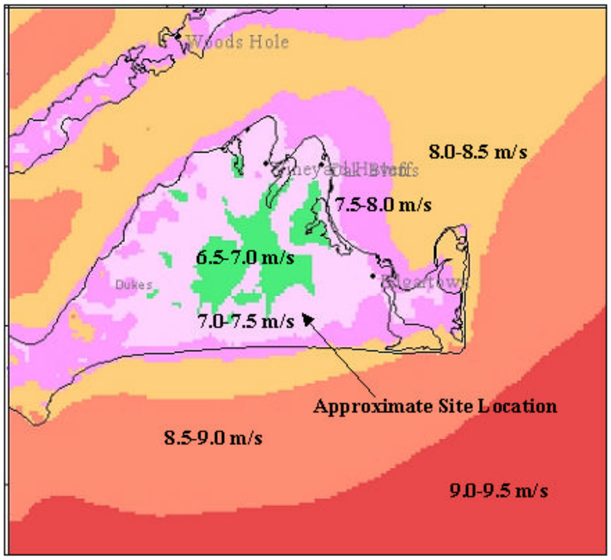


Fig. 7 Map of Vineyard Wind Resource

Long term, 20 minute wind data, at 10 m, have been collected at the Martha's Vineyard Costal Observatory, MVCO, since August of 2001 (www.mvcodata.whoi.edu). These data were used to compile a yearlong sample wind file. Gaps in the MVCO data of two hours or more were filled by copying data from the same time of day one day ahead, if possible, or from the same time and day one year ahead if the data from the next day were also missing. Gaps of less than two hours were filled by linear interpolation. The average wind speed at 10 m was found to be 3.57 m/s. The time series data were then condensed into one-hour averages for input into WINDH2.

5.2 Bus Transportation System and Utility Electricity

Gasoline and diesel are both imported to Martha's Vineyard via barge or ferry. The cost of fuel on the island is among the highest in the nation, often as much as $ 0.25/gallon higher than fuel elsewhere. In 2004, the Vineyard Transit Authority, VTA, paid 0.90 to 1.30 $/gallon for diesel (Gomper, 2004). A value of 1.10 $/gallon was used for this project.

Electricity is imported to Martha's Vineyard via four undersea cables (three 15 MW lines, one 5 MW line). The island also has five 12.5 MW backup diesel generators. Electricity rates are some of the highest in the state. The VTA reports it pays 0.116 $/kWh for grid electricity and uses approximately 160,000 kWh/year (Gomper, 2004).

The bus system on Martha's Vineyard services the whole island. Service runs throughout the year, and varies with the season (peak season being summer). The VTA operates thirty-nine vehicles including seventeen 26-foot long buses and four 37-foot long buses. Diesel use is as high as 700 gallons/day in the summer and drops to as low as 100 gallons/day in winter (Gomper, 2004). The typical fuel economy of the diesel buses was found to be about 10 mpg. To get the full benefit of a hydrogen bus system, the buses should be run all year, so the winter load becomes the limiting factor in scaling the system. A system with 1-3 buses would allow year round operation.

5.3 Hydrogen Load and Storage

The hydrogen load depends on the bus technology and the daily driving distance. Data provide by the VTA indicates that most buses travel between 250 and 270 miles a day. A value of 270 miles-a-day/bus was used for this study.

Three representative buses were used in this study. Characteristics of these buses, including fuel economy, and the amount of hydrogen required per year given a daily driving distance of 270 miles is summarized in Table 3.

Bus Name	**Power Technology**	**Fuel Economy [miles/kg]**	**Amount of H_2 [kg/year]**
XCELLSiS XCS-HY-205 (Eudy, 2001)	**Fuel Cell**	**7.5**	**13100**
Van Hool A-120 HICE (Vandenborre, 1996)	**HICE**	**4.9**	**20000**
ThunderPower TB30-FC (Chandler, 2003)	**Hybrid**	**10**	**10000**

Table 3 Yearly Hydrogen Load for Various Bus Technologies

The minimum requirement for on-site storage was one day's worth of hydrogen without entering the dead-band region. The dead-band is the upper and lower limits of hydrogen storage in which it is either unsafe or uneconomical to operate in. Above the upper dead-band limit (set at 90% for this project), it is unsafe to continue filling the tanks. Below the lower dead-band limit (set at 30% for this project), the pressure in the storage has dropped to a value below which it is economic to operate. Setting the minimum on-site storage to these values ensures an adequate hydrogen supply for daily fueling even if the electrolyzer or wind turbine is down for maintenance.

Given the distance a bus travels per-day, the required amount of storage is found by dividing by the fuel economy of the bus and the storage capacity outside the dead-band region. This value varied depending on the bus. The results are summarized in Table 4.

Type of Bus	**Minimum Storage [kg/bus]**
Fuel Cell	**60**
Internal Combustion	**92**
Hybrid	**45.2**

Table 4 Minimum On-Site Storage Capacities

The cost of compressed hydrogen storage varies with size. For the capacities used in this report, storage costs ranged from 625 to 950 \$/kg (Amos, 1998). A value of 700 \$/kg was used for this analysis.

5.4 Cost of electricity from Wind Turbine

The installed cost of a wind turbine depends on the type and size of the machine, as well as some economic assumptions. The installed cost of new machines was estimated at \$1000/kW. An operation and maintenance cost of 3% of the installed cost of the turbine per was also assumed (Manwell, McGowan, Rogers, 2003). Given the yearly wind profile the cost of electricity from the assumed set of available wind turbines can be calculated. The results are summarized in Table 5.

Wind Turbine Rated Power [MW]	Capacity Factor	Cost of Electricity [$/kWh]
0.66	0.342	0.0392
0.85	0.335	0.0399
1.5	0.375	0.0357
1.64	0.279	0.0479
1.8	0.341	0.0392
3.6	0.316	0.0424

Table 5 Capacity Factor and Cost of Electricity from Different Turbines

5.5 Cost of Hydrogen

The cost of hydrogen depends on the cost to own and operate the hydrogen production system, the cost of power used, and the amount of hydrogen produced. Since the cost to own and operate the hydrogen production system is assumed to be linearly dependent on the size of system (i.e. there is no economics of scale), it is also directly related to the yearly hydrogen demand. The cost of production electrolyzers is proprietary information, but it has been estimated at between 400 and 1000 $/kW. The average cost is around 600 $/kW (Amos, 1999), which is the value used in this project. Operation and maintenance cost for an electrolyzer is assumed to be 5% of the installed cost per year (Amos, 1999). Compressors cost around 1000 $/kW and have efficiencies of 60-75% (Amos,1998). An efficiency of 65% was used in this project. The cost of storage is 700 $/kg, as was stated above, plus $50,000, which is the estimated cost of a hydrogen filling station.

The amount of hydrogen produced during a year can be found by multiplying the size of the electrolyzer by the capacity factor of the electrolyzer by the number of hours in a year and dividing by the electrolyzer energy use. If the amount of power consumed by the electrolyzer is fixed, the cost of hydrogen is linearly dependent on the cost of power to the electrolyzer. The cost of an energetic equivalent amount of diesel can also be calculated, since diesel has 143.62 MJ/gallon (bioenergy.ornl.gov). This relationship is shown in Figure 8.

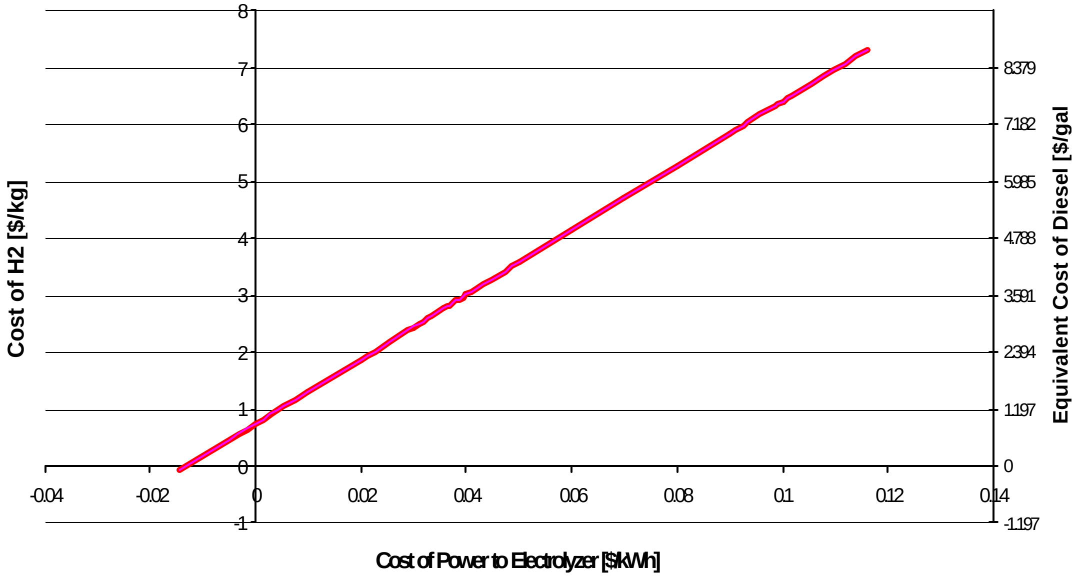


Fig. 8 Ideal Cost of Hydrogen as a Function of Cost of Power to Electrolyzer

The relationship between the cost of hydrogen and the cost of power to the electrolyzer is independent of the size of the system since all of the parameters scale directly with the system size. It should be noted that if the power to the electrolyzer is free, the hydrogen will cost 0.74 $/kg. This is the energetic equivalent of diesel costing 0.886 $/gallon. The percentage of power to the electrolyzer from the wind turbine depends on the size of wind turbine, control strategy and the amount of storage. Table 6 shows the effect of wind turbine size and control strategy for a system with minimal storage.

Turbine Size [MW]	**Percent of Power from Wind Turbine [%]**	
	Constant Power	**Dead Band Control**
0.65	**70.6**	**77.2**
0.85	**76.0**	**83.2**
1.5	**78.9**	**86.6**
1.64	**74.5**	**81.7**
1.8	**74.3**	**81.6**
3.6	**78.4**	**86.2**

Table 6 Effect of Turbine Size and Control Strategy on Percent of Power from Wind Turbine for a System with Minimal Storage.

Using a dead band control strategy clearly increases the amount of power to the electrolyzer from the wind turbine. The lower value of percent of power from wind turbine for the 1.64 and 1.8 MW turbines is due to the mismatch between their power curves and the wind resource (see Geer (2004) for more details).

The effect of bus technology on the cost of hydrogen is a result of varying efficiencies (represented by the fuel economy) and system size requirements (represented by the hydrogen load. The fuel efficiency of the bus used directly affects the cost of hydrogen on a per-mile basis. The size of an ideal hydrogen production system does not directly affect the cost of hydrogen, as has been discussed above, but as the hydrogen production system size increases, the percent of power from the wind turbine decreases and the cost of electricity to the electrolyzer increases.

Oversizing the electrolyzer also increases the cost of the hydrogen production system. In an optimized system, the economic benefit from increasing the percent of power from the turbine must be balanced with the increase in cost of the hydrogen production system. Figure 9 shows the change in cost of hydrogen as with the change in the percent the electrolyzer is over sized. There is a value above zero such that the cost of hydrogen is minimized; this value changes with the number of buses in the system. Another feature that can be deduced from Figure 9 is the increase in cost of hydrogen with the increase in the number of buses. This is due to the reduced percentage of electricity from the wind turbine.

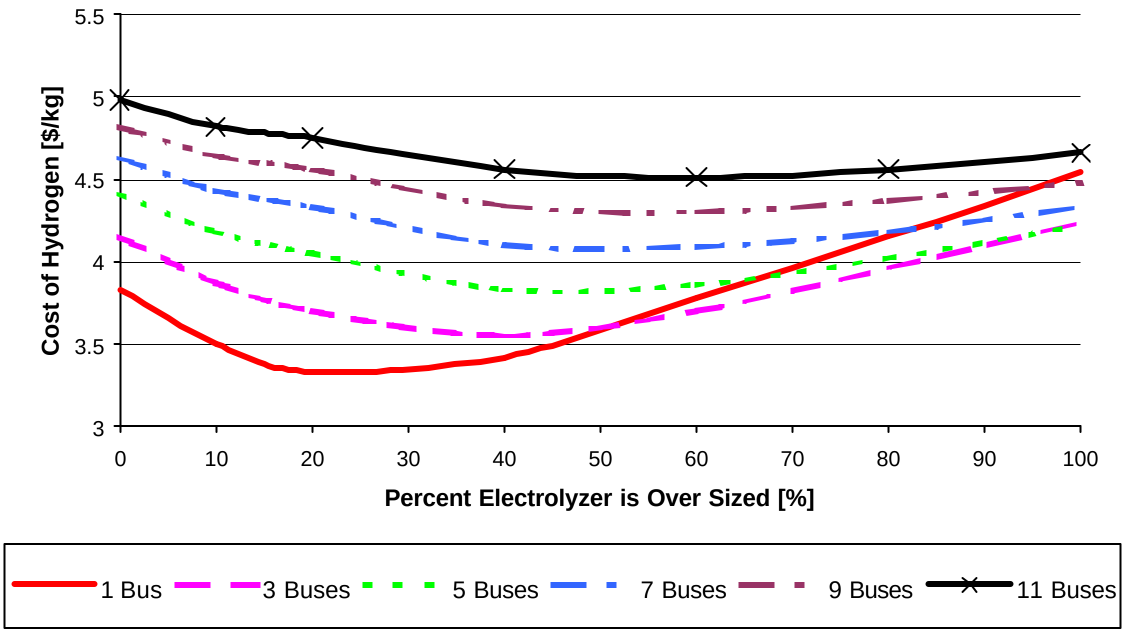


Fig. 9 Change in Cost of Hydrogen by Varying Over Size of Electrolyzer for Systems with Various Numbers of Buses and Minimum Storage

5.6 Summary of Modeling Results

Using the previously discussed site, wind turbine, hydrogen production/storage, and transportation system input parameters, a number of WINDH2 simulations were run with various sizes of wind turbines and electrolyzers, amounts of storage, bus technologies, and control systems. Three economic indicators were returned: the cost of electricity from the wind turbine, the cost of hydrogen, and the payback period for the systems. Table 7 summarizes the assumptions that were made for all systems. Table 8 shows various sized feasible systems with the lowest cost of hydrogen and payback period. The three systems with the lowest cost of hydrogen, reasonable payback periods and either 1 or 3 buses were considered feasible.

Interest Rate	**6 %**
Loan Term	**20 Years**
Down Payment	**$0**
Cost of Diesel	**1.1 $/gal**
Wind Turbine Installed Cost	**1000 $/kW**
Wind Turbine Yearly O&M Cost	**30 $/kW**
Electrolyzer Installed Cost	**600 $/kW**
Electrolyzer Yearly O&M Cost	**18 $/kW**
Cost of Imported Electricity	**0.116 $/kWh**
Value of Export Electricity	**0.035 $/kWh**
Value of Renewable Energy Production Credit	**0.035 $/kWh**

Table 7 Assumptions for Evaluating Feasible Systems

Turbine Size	Bus Tech.	Number of Buses	Size of Electro. [kW]	Electro. Over Size [%]	Cost of Hydrogen [$/kg]	Cost of Hydrogen [$/mile]	Payback Period [years]
1.5 MW	Hybrid	1	72	20	3.33	0.33	5.8
1.5 MW	Hybrid	1	84	40	3.42	0.34	5.8
1.5 MW	HICE	1	172	40	3.46	0.71	5.3
3.6 MW	HICE	1	147	20	3.8	0.78	4.9
1.5 MW	Hybrid	3	252	40	3.55	0.36	12.1
1.5 MW	Hybrid	3	216	20	3.7	0.37	12.4
1.5 MW	Hybrid	3	288	60	3.7	0.37	12.1
3.6 MW	HICE	3	515	40	4.02	0.82	7.4

Table 8 Overview of Feasible Systems

The cost of electricity from the wind turbine is an indicator of the match between the wind regime and the wind turbine. The 1.5 MW wind turbine had the lowest cost of electricity in the wind regime at 0.036 $/kWh. Lower cost of electricity and higher percentage of power from the wind turbine make the 1.5 MW wind turbine the most economical choice for this project; this was shown in Table 8 where most of the feasible systems use a 1.5 MW turbine.

The cost of hydrogen was calculated both in terms of cost-per-kilogram and cost-per-mile. The cost-per-kilogram of hydrogen is an indicator of whether it is beneficial to produce hydrogen on-site with renewable energy instead of having hydrogen delivered. The lowest cost of hydrogen was 3.33 $/kg, the cost of delivered hydrogen is on the order of 5-7 $/kg, indicating that it is less expensive to produce hydrogen locally with wind power.

The lowest cost-per-mile was 0.333 $/mile; the cost of fueling a diesel transit bus is on the order of 0.09 to 0.13 $/mile. Comparing the cost-per-mile of hydrogen versus fossil fuels directly does not account for a number of external factors such as reduced emissions and the price volatility of fossil fuels. Putting a dollar amount on the health hazard of fossil fuel emissions is a difficult task, and will not be attempted here. The volatility of fossil fuel costs has a much more measurable effect. An increase in oil costs of 250% to 300% would make hydrogen directly competitive with diesel. With oil prices expected to increase by as much as 150% this summer and the world oil production peak approaching, a 250% increase in the next decade may not be far fetched. Price fluctuations are difficult to plan for and can result in bus fares having to be raised and other budget problems. Using locally generated hydrogen to fuel a bus ensures long-range price stability.

The payback period of the wind/hydrogen-bus system compares the cost of the system to the yearly revenue generated. Since the cost of hydrogen is more than the cost of diesel, the system is only able to have a payback period because it is subsidized by both the sale of electricity to the grid and the sale of renewable energy production credits. The subsidized nature of the payback period makes it less of an important economic indicator of system performance. The lowest payback period was found to be 4.8 years, the lowest payback period of a feasible system was 5.7 years. The payback periods for the systems are significantly less than the expected life of the system (20 years).

The sensitivity of the system payback period as well as the cost of hydrogen was calculated by modifying the input parameters. The payback period was found to be strongly related to the cost of renewable energy production credits and the cost of bus technology. Realistic estimate of increases in the value of renewable energy production credits could reduce the payback period by 30% by the end of 2004. A reduction in the cost of bus technology by 25% would reduce the payback period by 10%. The infancy of hydrogen bus technology makes such a price reduction very likely in the next ten years. Combined, these two effects could lead to a reduction in the payback period of around 37%.

6.0 CONCLUSIONS/ RECOMMENDATIONS

An assessment of the meteorological data and an evaluation of the existing bus system indicates that Martha's Vineyard is a good site for a wind/hydrogen-bus system with 1 – 3 buses. The wind resource in the vicinity of the proposed site is sufficient to produced inexpensive electricity from a wind turbine. The bus system is large enough to have the trained staff and repair facilities necessary to incorporate a new technology. The popularity of public transportation on Martha's Vineyard, both by locals and by the large tourist population in the summer, insures that the hydrogen buses will be seen by a large number of people.

An evaluation of the economics of operating a wind/hydrogen-bus system lead us to recommend implementing such a system only if as part of a collaborative effort in which the costs are shared. In such a situation the following configurations are recommended:

For a one bus system: A 1.5 MW wind turbine, 72 kW electrolyzer, hybrid powered bus, 45 kg of hydrogen storage, and a Dead Band control strategy. This configuration yields the lowest cost of hydrogen both per-mile, at $0.333 and per-kilogram at $3.33 and a payback period of 5.7 years.

For a three bus system: A 1.5 MW wind turbine, 252 kW electrolyzer, hybrid powered bus, 135 kg of hydrogen storage, and a Dead Band control strategy. This configuration yields a cost of hydrogen per-mile of $0.355 and per-kilogram of $3.55 and a payback period of 12.0 years. Using three buses on Martha's Vineyard would still allow the buses to run year round.

It is unlikely that the cost of imported electricity will decrease in the future unless Martha's Vineyard begins generating their own electricity from an inexpensive and abundant resource, like wind power. By running some or all of the buses on hydrogen, the local pollution could be reduced and residents could be proud to know that their public buses were fueled by a local, renewable resource. A wind/hydrogen-bus demonstration project would be the first step toward a clean, reliable energy source for Martha's Vineyard.

The next stage of this project is to build industrial, governmental, and public support for the concept. Industrial support is necessary both to assist in more advanced modeling of the system and to help fund the project. All of the existing hydrogen-bus systems have been installed with the help of industry, and until the technology involved matures, this will continue to be a requirement. Governmental support is necessary both for permitting and funding. The permitting process for installing a novel technology can often be one of the biggest stumbling blocks, especially if the government is opposed to the projects. Financial support in the form of grants to support the development of renewable powered transportation will improve the economics dramatically. Public support is necessary to ensure that the project is received well.

7.0 ACKNOWLEDGEMENTS

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