

# Wind to Wheels Hydrogen Project

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A great deal of research funding is being devoted to the use of hydrogen for transportation fuel, particularly in the development of fuel cell vehicles. When this research bears fruit in the form of consumer-ready vehicles, will the fueling infrastructure be ready? Will the required fueling systems work in cold climates as well as they do in warm areas? Will we be sure that production of hydrogen as the energy carrier of choice for our transit system is the most energy efficient and environmentally friendly option? Will consumers understand this fuel and how to handle it?

Those are questions addressed by the EVermont Wind to Wheels Hydrogen Project: Sustainable Transportation. The hydrogen fueling infrastructure consists of three primary subcomponents: a hydrogen generator (electrolyzer), a compression and storage system, and a dispenser. The generated fuel is then used to provide transportation as a motor fuel.

EVermont Inc., started in 1993 by then-governor Howard Dean, is a public-private partnership of entities interested in documenting and advancing the performance of advanced technology vehicles that are sustainable and less burdensome on the environment, especially in areas of cold climates, hilly terrain and with rural settlement patterns.

EVermont has developed a demonstration wind powered hydrogen fuel producing filling system that uses electrolysis, compression to 5000 psi and a hydrogen burning vehicle that functions reliably in cold climates. And that fuel is then used to meet transportation needs in a hybrid electric vehicle whose internal combustion engine has been converted to operate on hydrogen Sponsored by the DOE EERE Hydrogen, Fuel Cells & Infrastructure Technologies (HFC&IT) Program, the purpose of the project is to test the viability of sustainably produced hydrogen for use as a transportation fuel in a cold climate with hilly terrain and rural settlement patterns. Specifically, the project addresses the challenge of building a renewable transportation energy capable system. The prime energy for this project comes from an agreement with a wind turbine operator.

**Keywords:** Hydrogen, Sustainability, Internal Combustion Engines, Electrolysis, Wind Energy, Demonstration Project

## 1. BACKGROUND AND DESIGN OVERVIEW

The Transportation Sector is responsible for an estimated 28% of national energy consumption [1], 43% of the conventional air pollution regulated under the federal Clean Air Act [2], and 33% of national Greenhouse Gas emissions [3]: in other words, the activity of transportation, which is essential to society, is central to major energy and environmental issues facing our nation. Compounding this, one fuel, petroleum, constitutes in excess of 96% of transportation energy.

Petroleum derived motor fuel is finite in nature. It requires large-scale intrusive resource extraction procedures that make the crude resource available to industrial chemical processing facilities. These centralized facilities produce a highly refined product that is stored, transported, stored again, and then distributed at the wholesale and retail level. At every step in this process and distribution network there are emissions to the environment that represent a threat to human health and the environment. The scale of this operation is global in nature.

For sustainability in the transportation sector, a carbon-free, clean and renewable fuel is needed. A fuel with these characteristics can be hydrogen, but only if certain choices are made. Hydrogen is abundant. Unlike petroleum, hydrogen is a secondary form of energy, an energy carrier, rather than a primary form of energy as petroleum is. As such, how hydrogen

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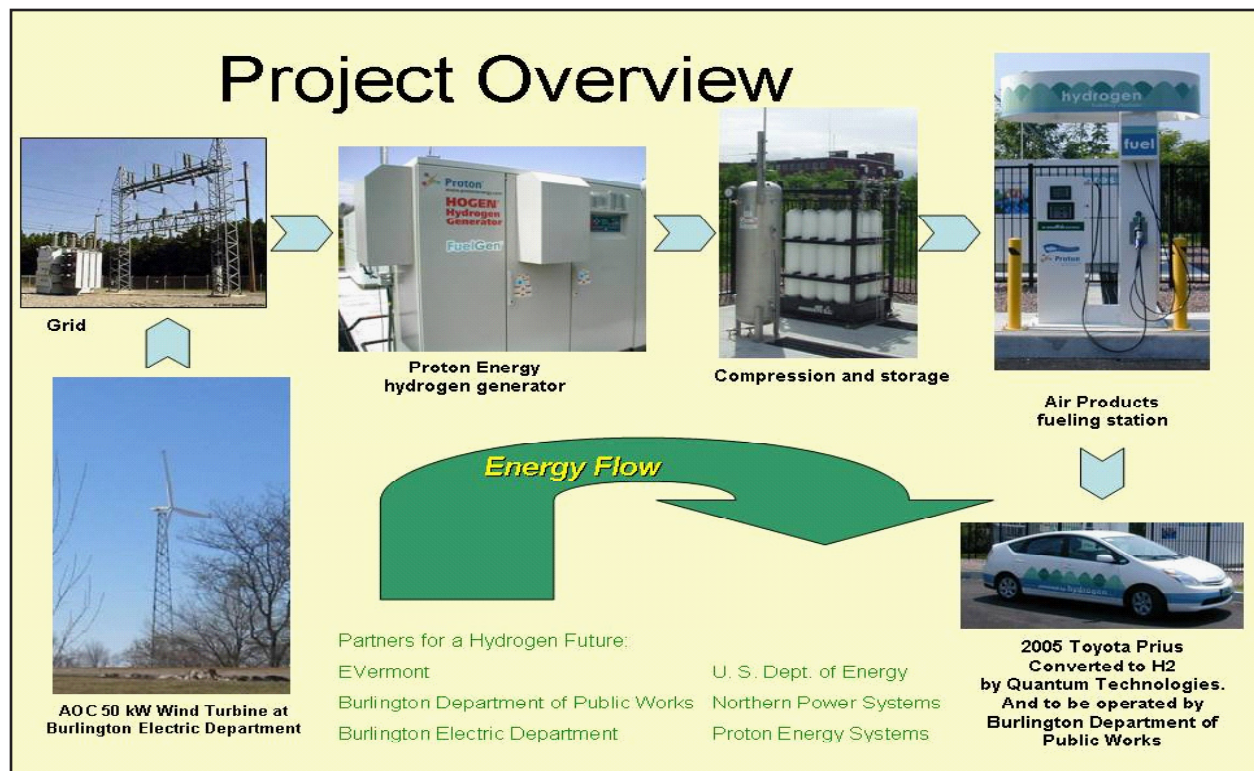


Figure 1: Overview of sustainable transportation energy generation and use

is produced determines its attributes of cleanliness and sustainability. Further to hydrogen providing transportation energy is the issue of the vehicle technology which the hydrogen will power.

A “Hydrogen Economy” has been envisioned by many (e.g., [4]). To be realized, a hydrogen economy has to overcome two major hurdles at once; it not only requires vehicles that operate on hydrogen, it also requires the infrastructure to produce and deliver the hydrogen and support this new technology.

Additionally, as new and different technologies and fuels are brought to consumers, consumers need to become familiar and comfortable with new and different re-fueling dispensers and automotive technicians need to be trained in proper procedures for handling the fuel and servicing the vehicles that operate on this fuel.

Fuel cell vehicles are thought to be the vehicle technology of the future. While much progress has been made advancing this technology, the reality is that it may be decades away from being a ‘consumer product’. If fuel cell vehicles were available today, there is no infrastructure to support them.

If fuel cell vehicles will not be available for decades, and they will need a whole new infrastructure to support them, how is it justified to begin to build this infrastructure when its use is uncertain, or is sufficiently far into the future? The EVermont facility provides a “technology bridge”: A technology that justifies the investment in infrastructure, by using that infrastructure available today to make incremental progress toward the ultimate goal. That incremental progress is not only a matter of science and engineering, but of education and outreach to student populations and the general population.

## 2. FUEL GENERATION, STORAGE AND DISPENSING

Sponsored by the DOE EERE Hydrogen, Fuel Cells & Infrastructure Technologies (HFC&IT) Program, EVermont has developed and built a unique wind to wheels energy conversion unit that addresses the dual challenges of building energy for sustainability in the transportation sector. It looks at energy use through the lens of local, decentralized production and use, based upon a renewable form of energy and non-toxic, non-polluting processes.

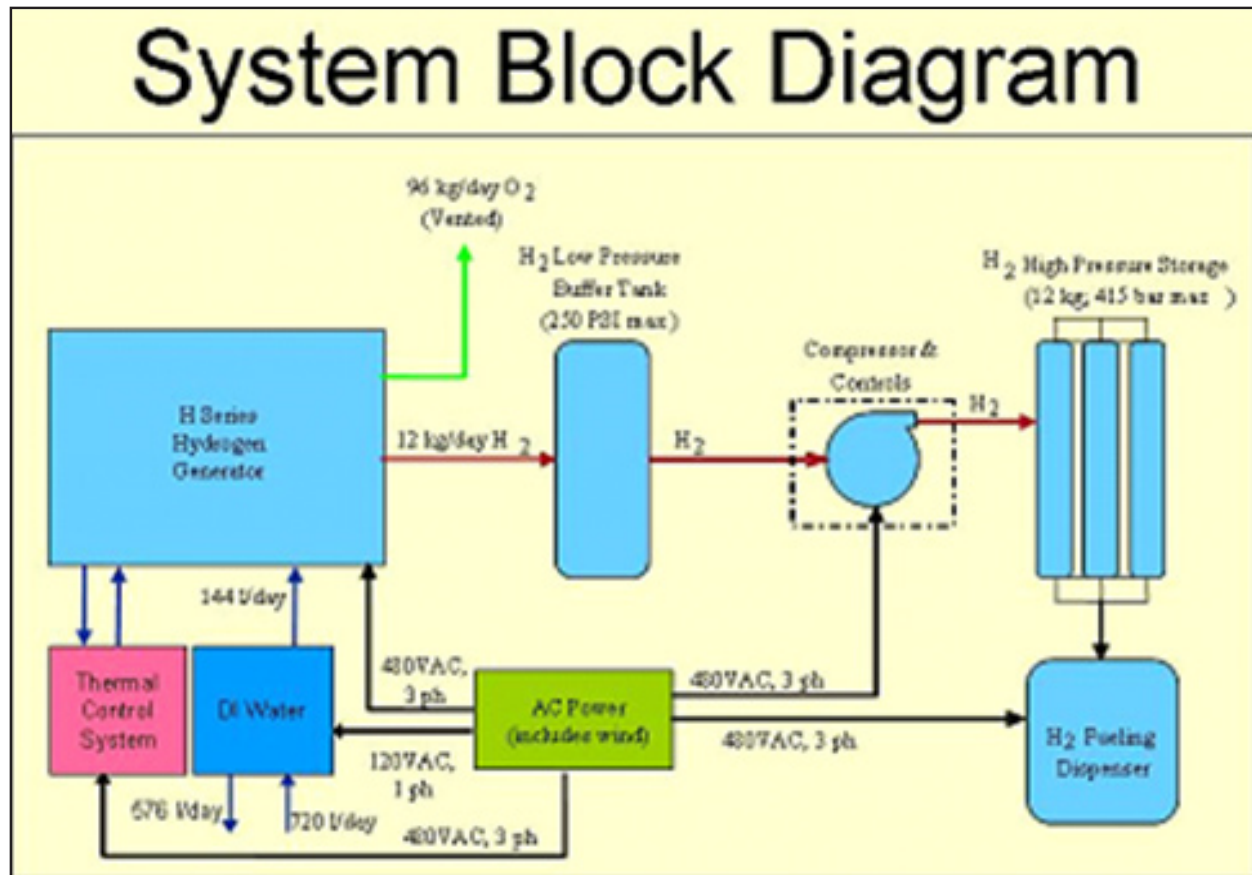


Figure 2: System block diagram; onsite components

Primary energy for the project is from electricity, the generation of which comes from an Atlantic Orient Corporation (AOC) 50 kilowatt wind turbine located adjacent to the site owned and operated by the Burlington Electric Department (City of Burlington Vermont). The energy is fed through the grid and the Renewable Energy Credits (RECs) from this production are assigned to the EVermont Sustainable Transportation Project.

The onsite components of the system are laid out in Figure 2, and consist of four sub-systems; 1) the electrolyzer, 2) compression, 3) storage, and 4) fuel dispensing.

The electrolyzer unit is a Proton Energy Systems HOGEN H Series electrolyzer. (Note: at the start of this project EVermont employed two major contractors, Proton Energy Systems and Northern Power Systems. During the course of this project these two companies merged into one; Distributed Energy Systems. They are referred to as one company, Distributed Energy Systems, through the remainder of this paper.) This

unit is designed to produce 12 kg/day of hydrogen gas. The particular unit used in this project consists of three Proton Exchange Membrane (PEM) fuel stacks, two of which represent conventional PEM fuel cell stack design, and the third an advanced design (see Figure 3.) The advanced PEM electrolyzer has been documented in bench studies to be 5 to 10% more efficient in conversion of electrical energy to hydrogen gas, and at the same time smaller, lighter and requiring less manufacturing costs. Total onsite production of hydrogen is 0.54 kilograms per hour.

Hydrogen generated through the electrolysis process is captured, conditioned for moisture and directed to a buffer tank. Normal operating pressure of the buffer tank ranges between a nominal 150 to 250 psig.

From the buffer tank, the fuel is compressed and stored in twelve high pressure cylinders. These cylinders are arranged in three banks of four, with a control strategy that provides a (relative) "high", "medium", and "low" bank. Maintaining these banks at three different levels is important to fuel management and vehicle refueling,



as the compressor design is to maintain the storage tanks and is not used to fuel the vehicle. Hydrogen gas storage is provided at a nominal 5000 psig (35 MPa).

Fuel storage and dispensing equipment is an Air Products Series 200 Hydrogen fueler. The unit dispenses fuel to a 5000 psig vehicle storage system. It is capable of delivering fuel to a vehicle fitted with California Fuel Cell Partnership (CaFCP) communication protocol for a 'smart fill', or it can deliver fuel to a vehicle in a "NON COMM" mode, based solely on pressure. Normal dispenser display reports the mass of fuel dispensed, and has memory capacity to retain details of each re-fueling event.

### 3. FUEL USE/VEHICLE

Demonstration of the production of sustainable hydrogen with technologies that exist today is one goal of the project; however, demonstration of sustainable transportation is an over-arching goal. To demonstrate sustainable transportation requires use of the fuel in a daily setting. For this, a Quantum 'H2 Hybrid' vehicle was acquired. This vehicle is a Model Year 2005 Toyota Prius modified to operate on hydrogen gas as its motor fuel. The modifications to the vehicle were designed and completed by Quantum Technologies [5].

The Prius was selected as the base vehicle as it represents an advanced vehicle design with an efficient



Figure 3: Three PEM fuel cell stacks that make up the electrolyzer unit; note the advanced cell in the middle which is smaller yet of equal fuel generation capacity.

drive system. It incorporates many desirable features such as electric motor acceleration assist, engine shutdown at idle, regenerative braking and electric-only operating mode.

The efficiency of the vehicle is important as onboard fuel storage is limited in the vehicle conversion. The design developed by Quantum was to limit the hydrogen fuel tanks to essentially the same location (volume space) that had been occupied by the gasoline fuel storage equipment. This criterion, together with a design of high pressure gas storage (5000 psig) provides a maximum of 1.6 kilograms of fuel onboard

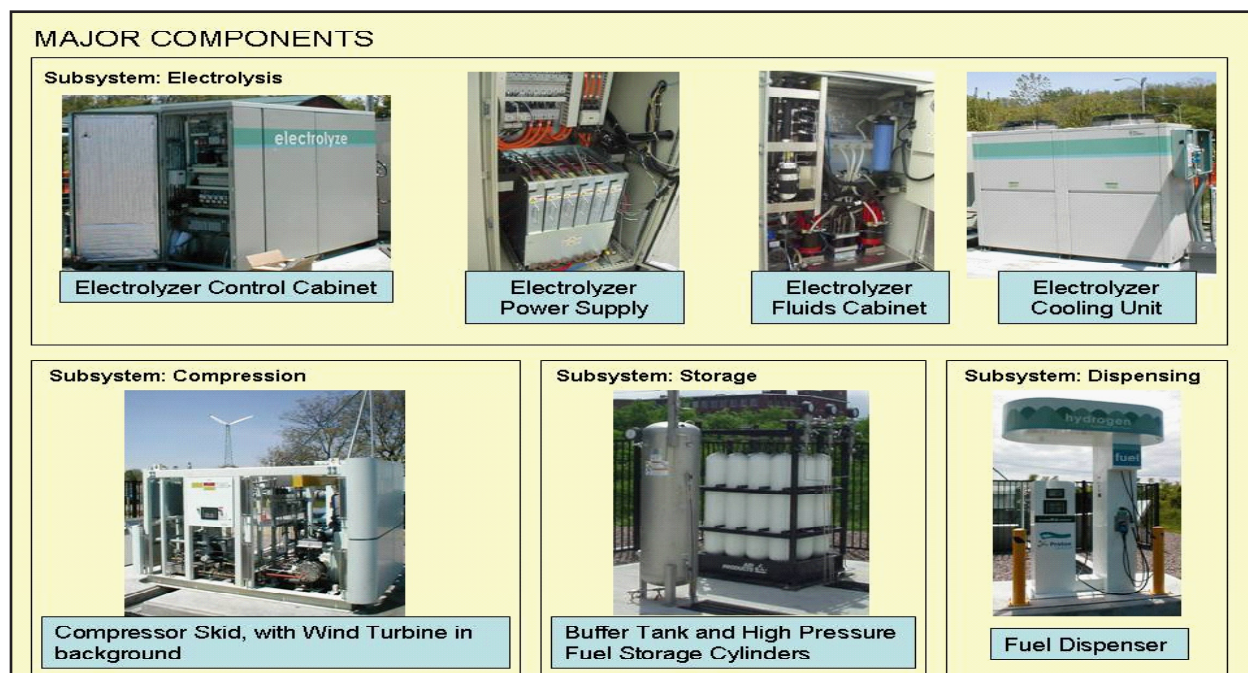


Figure 4: Onsite major components; hydrogen generation, compression, storage and dispensing

the vehicle.

The modifications encompassed removal and replacement of the gasoline fuel storage and delivery components with components to store and deliver hydrogen gas. These components include high pressure gas storage cylinders, valves and piping, fuel injectors designed to deliver hydrogen motor fuel, and combustion controls to properly combust and optimize the combustion of hydrogen fuel. Additionally, as hydrogen gas used as a motor fuel can reduce the power output of an internal combustion engine, the engine was fitted with a turbocharger and intercooler to regain this power loss.

For the project, vehicle use was segmented in to two activities, one being the day-in-day-out use of the vehicle to meet basic transportation needs. The second was to document vehicle performance and fuel economy. This was accomplished by controlled use of the vehicle in standardized settings (e.g. highway travel, urban driving, etc.).

To demonstrate routine use of the vehicle, the H2 Hybrid was placed with the City of Burlington, Vermont Department of Public Works (DPW). After proper training and orientation, the vehicle has been incorporated into routine fleet services, performing all the tasks and duties of fleet service needs.

For vehicle evaluation, EVermont periodically takes the vehicle out of DPW fleet service to complete the desired tests and evaluations.

Funding was awarded to the EVermont project in the fall of 2004. Site selection station design and station permitting proceeded through calendar year 2005, with site permits being received in late fall 2005. Given the onsite of winter conditions, the project schedule was amended to limit site work in Burlington, Vermont to the pouring of the station pad, and to allow for initial qualification of the hydrogen generation system at the Distributed

Energy Systems facility in Wallingford, Connecticut. With Connecticut's milder winter climate this allowed for data collection and system monitoring of the initial qualification to take place under the watchful eyes of the manufacturer and significantly lessened the potential risks to the cell stacks in this new design. (Note: while the system was set-up for complete operation at Distributed Energy's facility, vehicle re-fueling could not be accomplished as the vehicle was being converted by Quantum at the time).



Figure 5: Senator Sanders, I-VT, presides over public dedication of the Hydrogen Station.

#### 4. STATION PERFORMANCE

In the spring of 2006, the station components were

H2 Hybrid Vs. Conventional Prius			
Specification	H2 Hybrid	Conventional Prius	
Horsepower	70 HP @ 4,500 RPM	76 HP @ 5000 RPM	
Torque	82 lb-ft @ 4,000	82 lb-ft @ 4,200	
Fuel Consumption	City: 56-58 M/Kg Highway: 50-52 M/Kg	(Old) City: 60 MPG Highway: 51 MPG	(New) City: 48 MPG Highway: 45 MPG
Fuel Capacity	1.6 Kg @ 5,000 psi	11.9 Gallons	

Table 1: Engine performance specifications, H2 Hybrid vs. Prius

dissembled in Wallingford, Connecticut, transported to Burlington, Vermont, and reassembled. Beta testing of the station began in June 2006. The station was publicly dedicated July 3, 2006. Initial site qualification continued until October 2006.

Operation of the station is monitored via the internet through a system developed by Distributed Energy Systems know as SmartView. SmartView tracks real-time performance, and based on this information provides operator notice of upset or alarm conditions. Further, SmartView is a data management system which provides on-line access to all recorded information to allow trend analysis and observe operation over time. Figure 6 provides an example screen of real-time data and observation over time.

Through SmartView, a continuous data record is compiled of a number of features of station operations. One of interest is the energy consumption of the cell stacks, in particular the comparison of energy consumed by cell stacks one and three as compared to cell stack two (the advanced PEM cell stack design). The parameters tracked are the DC current and voltage supplies to each stack. As reported above, bench testing of the advanced PEM cell stack had documented that it generated the same amount of hydrogen while consuming 5 to 10% less energy. By April 2006, the advanced power supplies had undergone several months of successful testing and had been field deployed for nearly two years. Field

Cell-Stack	EM1	EM2	EM3
<b>H2 Generation, kg/hr.</b>	← 0.54 →		
<b>Current, Amps.</b>	158	158	156
<b>Voltage_1</b>	75	70	75
<b>Voltage_2</b>	76	69	77
<b>Average Volts</b>	75.5	69.5	76
<b>Power, Watts</b>	11,929	10,981	11,856
<b>Delta EM2</b>	8.6%		8.0%

Table 2: Comparison of energy consumption of advanced PEM cell stack to standard stacks

observations of the energy consumption of the three cell stacks confirm the benefits of the advanced design. Table 2 presents observation in routine use confirming the energy advantage of the advanced cell stack design. Based on these observations, cell stack two (EM2), the advanced PEM cell stack, was producing hydrogen gas 8.6 to 8% percent more efficiently than cell stack one and three, respectively.

## 5. VEHICLE PERFORMANCE

The MY 2005 Prius was converted to H2 Hybrid by Quantum Technologies, as one of a number of identical

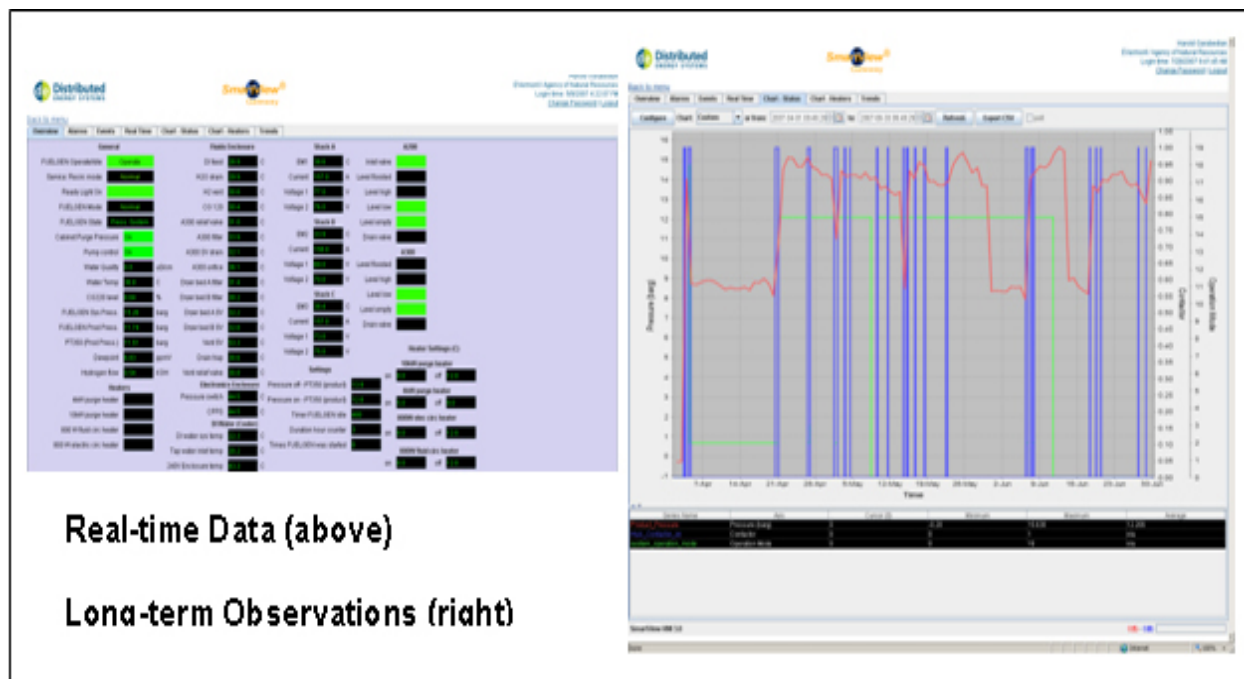


Figure 6: SmartView screen shots; left - real-time data; right - long-term observations



vehicles prepared for other customers. The vehicle was delivered to Quantum in November 2005, converted to hydrogen fuel operations and received back in Vermont in May 2006. To date the vehicle has accumulated over 4,000 miles of operation on hydrogen fuel. These miles represent a variety of experiences from routine fleet operations in an urban setting to high power evaluation on closed track (airport) operation. The vehicle has been well received by the staff of Burlington DPW, the fleet user. The vehicle has performed both very satisfactorily and very well. Only one reportable incident occurred. Rough engine operation was experienced on one occasion. The matter was quickly diagnosed and remedied by replacement of the spark plugs.

As a vehicle in the Burlington DPW fleet, the vehicle is primarily used for travel to meetings and job site inspections. A vehicle operation log is maintained, where all miles traveled and fuel dispensed to the vehicle recorded. Further, the Air Products dispenser has the ability to retain details of fueling events. The dispenser records (and retains) the data and time when fueling was initiated, the initial condition of the vehicle fuel tanks (temperature and pressure), the date and time fueling was completed, the final condition of the vehicle's fuel storage tanks and the mass of fuel dispensed. In the urban driving environment, the vehicle achieves an in-use fuel economy of 39 to 44 miles per kilogram of hydrogen (a kilogram of hydrogen has approximately the same energy content as a gallon of gasoline, so it be considered that the vehicle has a miles per gallon of gasoline equivalent as miles per kilogram of hydrogen). This includes a range of drivers, and



Figure 7: Airport testing of H2 Hybrid vs. Prius

a wide range of driving styles and conditions. When driving style and conditions are controlled for, the vehicle can consistently achieve 50 miles per kilogram of fuel.

In order to consider the performance of the H2 Hybrid to that of a standard Toyota Prius, the two vehicles were evaluated side-by-side on a closed course under controlled conditions. Both vehicles were run through a battery of tests to quantify acceleration, top speed, braking and gradability. Figure 8 presents a summary of these tests in comparative format, the conclusion of which is that performance of the two vehicles are nearly indistinguishable: any differences that might

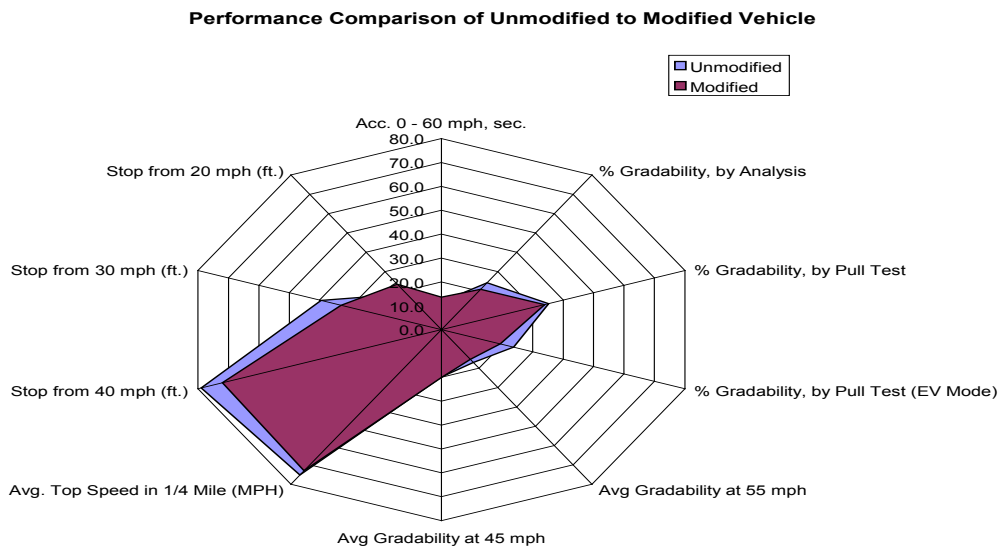


Figure 8: Comparison of measured performance of H2 Hybrid (Modified) and Prius (Unmodified)

be concluded from the data are within the variability expected from the test methods used.

Modern vehicles are fitted with many sensors that constantly monitor engine operating parameters and feed this information to the vehicle's engine control unit (ECU). In the H2 Hybrid, the communication of this information occurs over a central bus (CAN – Controller Area Network) and can be accessed through the vehicle's Data Link Connector (DLC). A method of collecting time-series (engineering estimate) of fuel consumption from the CAN bus has been used to better understand vehicle fuel consumption. The methodology relies primarily of the vehicle's mass air flow meter. This sensor provides a signal of the mass of air taken in by the engine and can be related to an estimate of fuel consumption via the stoichiometric equation for hydrogen. Based on the stoichiometric equation for hydrogen combustion 34 pounds of air is required for each pound of fuel (34:1, mass air/fuel ratio). Because of hydrogen's wide range of flammability, hydrogen fueled engines can operate on air/fuel ratios anywhere from stoichiometric (34:1) to as high as 180:1.[6] However, specifically where an engine is tuned to operate within this wide range will affect its power output and emissions of Nitrogen Oxides ( $\text{NO}_x$ ). A compromise to minimize power loss and minimize  $\text{NO}_x$  emissions formation is to operate the engine at two times stoichiometric (68:1 air/fuel ratio) [7]. An example of the data that can be made available from the approach are provided in Figure 9. Therefore

by tapping the vehicle's onboard sensors an engineering estimate of time-series fuel consumption data can be generated.

## 6. PRIMARY ENERGY GENERATION

Primary energy for the project comes from a wind turbine owned and operated by the City of Burlington, Burlington Electric Department (BED). The unit is an Atlantic Orient Corporation (AOC) 50. The unit has a maximum

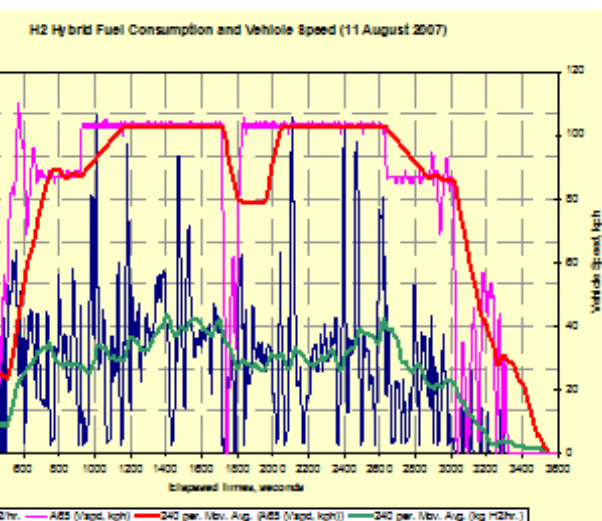


Figure 9: Time series fuel consumption and vehicle speed data

peak generation capacity of 66 kW, and nominal rating of 50 kW; producing 480 volts of three-phase power. The unit sits atop an 82 foot tower and has a rotor diameter of 49 feet.

The wind turbine, while adjacent to the hydrogen generation station was pre-existing. Power from the turbine is feed to the grid and through formal agreements the renewable energy credits (RECs) are assigned to EVermont for the generation of hydrogen.

Data as to wind energy generation and station energy consumption is logged on a fifteen minute basis. These data allow the comparison of electrical energy generation from the wind turbine to electric energy consumption from the production of hydrogen.

## 7. CONCLUSIONS, RECOMMENDATIONS AND FUTURE DIRECTIONS

### 7.1 Conclusions

The EVermont/Distributed Energy Systems Hydrogen generation and vehicle fueling station in Burlington, Vermont works! It produces transportation-grade hydrogen fuel from the local resources of water and wind, providing a transportation fuel free of any carbon whatsoever. It is the nation's first hydrogen station to use this renewable scheme as a system, and one of the first hydrogen generation/fueling stations of any type in a cold climate, representing current state of the art in PEM Electrolysis systems for hydrogen generation.

The energy management concept – to make use of a variable and uncontrollable-rate source of energy (wind)



Figure 10: BED's AOC 50 wind turbine



and store the energy in a constant energy delivery carrier gas (hydrogen) that allows for rapid vehicle fueling and relatively easy storage and delivery of the fuel – is a forward-looking one. The use of renewable Energy Credits (RECs) is a novel and effective means of de-coupling the generation of electricity with the production of hydrogen, thereby allowing for optimization of the design and operation of each subsystem and maximizing their contributions to the overall system. If the system was not grid-connected, matching demand to production would be problematic, and optimization of these subsystems would be far more complicated, and would incur greater costs to achieve the same, or possibly lesser, benefits.

### 7.2 Recommendations

Demonstrating forecourt energy production is important in moving forward on the promise of the “Hydrogen Economy”. Having the fuel produced locally with renewable resources will be important to the development of a hydrogen infrastructure in more rural areas. Demonstrating that technologies are available today to produce hydrogen for transportation and demonstrating that current vehicle technology can be adapted to use hydrogen as a transportation allows policies to be considered that would ‘seed’ the infrastructure that will be needed for wide-scale hydrogen use and represent a ‘bridge’ to the future. An example would be a policy of having small commercial and/or municipal fleets modeled on this project. Such a policy would put sustainable transportation in practice today, while gaining important experience with hydrogen as a transportation fuel and building infrastructure for tomorrow.

### 7.3 Future Directions

Initial considerations indicate that forecourt hydrogen production and its use as a motor fuel in a hybrid electric vehicle has a greater system efficiency than current transportation energy and utilization. However, the efficiency of the process – from wind to wheels – has not been well documented, and could undoubtedly be improved with advancements in designs, equipment, and energy management.

EVERmont has been awarded, with researchers at the University of Vermont, US DOT funds for Research in Hydrogen for Sustainable Transportation. EVERmont’s contribution would be a thorough systems analysis of the hydrogen generation and fueling station with an eye toward documenting and proposing improvements to efficiency of conversion of wind energy to hydrogen for vehicle propulsion.

Specifically, an analysis of the energy utilization and its

efficiency at each step of the process will be performed: wind generation of electricity; use of electricity to electrolyze water and produce hydrogen (at 200 psi); compression of the hydrogen to 5000 psi; fueling of a vehicle; and operation of the vehicle on hydrogen.

It is likely that low temperatures will significantly affect the efficiencies, so a field verification of the entire system will be completed in both warm and cold conditions.

A portion of this work will be performed by a team of senior undergraduate Mechanical and Electrical Engineering students at Norwich University as their Capstone Design Project. Under the guidance of Gregory Wight (Norwich University) and Harold Garabedian (VTANR/EVERmont), the team of students will organize the detailed approach and design any necessary data acquisition equipment/systems. As needed, monitoring devices will be acquired and installed. Data currently logged by Distributed Energy for the Hydrogen Fueling Station and data for the wind generator from Burlington Electric Department will be utilized. These data and engineering studies will allow determination of:

- o Efficiency of conversion of wind energy to electricity, documentation of annual average amount, and projection to larger or multiple units or more efficient wind turbines
- o Efficiency of conversion of electricity to low pressure hydrogen and costs, including water supply, heating, cooling, maintenance
- o Efficiency of compression from low to high pressure and cost
- o Efficiency of the vehicle filling process, documentation of losses
- o Efficiency from tank to wheels and costs particularly as compared to fossil fuel powered internal combustion engine vehicles
- o Overall wind-to-wheels efficiency

The differences between efficiencies in warm weather and cold will be evaluated over the course of a nine month study. Projection models will be developed and comparisons to overall efficiencies and Greenhouse Gas emissions of fossil-fueled automobiles drawn.

Suggestions will be made as to the upgrades of greatest potential.

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