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Recipient: EVermont, Inc.

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Project Title:

*EVermont Renewable Hydrogen Production and Fueling
System*

Distribution: Unlimited

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Executive Summary

Transportation is essential to society, yet current transportation-related technologies contribute to many of our health and environmental threats, and the fuels used are finite in nature. The sustainability of transportation depends on the technologies that provide mobility and the fuels that power those technologies. One step toward sustainable transportation may be hydrogen produced from clean renewable resources.

For environmental, economic and energy security reasons, the United States needs to move from being a society that derives over 96% of its transportation energy from one finite fuel, to a being a nation with a more diverse transportation energy portfolio. Renewable forms of energy need to be part of that portfolio. One fuel in that portfolio could be hydrogen. However, for hydrogen to deliver on its promise of being clean and sustainable, how the fuel is made,, and what technologies are developed for its use, are critical issues. There are two parts to delivering a hydrogen economy – infrastructure providing the fuel and the technology to use the fuel. And given the complexities of these choices and issues, an educated populace is essential to achieving sustainable transportation energy.

The objectives of the EVermont Renewable Hydrogen Production and Fueling System project were (1) to develop advanced PEM electrolysis fueling technology, (2) to build and test a validation system in Vermont -- a cold northern climate of rural settlement patterns -- which uses renewable electricity from wind and is capable of providing hydrogen fuel to vehicles, and (3) to procure, operate and maintain a hydrogen fueled vehicle for testing and validation of the station.

All elements of these objectives were achieved. This project documents the measures necessary to design and operate a self-contained hydrogen generation station for vehicle fueling in a cold northern climate. Prior to this project, forecourt hydrogen stations were limited to warm southern climates. While the basic principles of electrolysis remain the same regardless of location, many design issues had to be overcome to create a station that functions reliably in all weather conditions, from below -20°C to over 30°C. It is essential to have operational transparency throughout the country, in all climatic regimes, for hydrogen to merit consideration as a transportation fuel. Further, through the vehicle deployed in this project, it has been demonstrated that hydrogen as a compressed gas motor fuel can displace gasoline and replace it with a renewable form of energy that produces no carbon emissions and uses technology that is extremely cost-effective. Through this project, many publics were engaged on the issue of transportation/energy/sustainability/environment and were offered a vision of a possible future – de-centralized clean sustainable transportation energy from renewable sources of energy.

This completed project documents and provides the technical justification for policies that would benefit the public through a cleaner and healthier environment, more secure energy future and more sustainable economic investments. Successful forecourt hydrogen production – and utilization of that hydrogen as a motor fuel – enables a public policy of having small centrally fueled fleets of vehicles convert (either through regulation or through incentives) to this model of operation. This would be a logical next step as part of an overall plan to see

Project Objectives:

- *Develop advanced PEM electrolysis fueling station technology*
- *Build and test a validation system in Vermont that utilizes renewable electricity and is capable of providing hydrogen fuel to vehicles*
- *Procure a hydrogen fueled vehicle for testing and validation of the station/system*

hydrogen advance as a transportation fuel. By moving small fleets to using hydrogen as a motor fuel, a public policy of creating a technology 'bridge' to a 'hydrogen economy' would be advanced. For hydrogen to be successful in future on a broad scale, the twin issues of vehicle technology and infrastructure to fuel those vehicles must be addressed simultaneously. Modeling a policy that would move small fleets to replicate this project would 'seed' infrastructure development based on this 'bridge technology' (using hydrogen as a motor fuel). And seeding infrastructure development would not only provide essential near-term infrastructure, but provide experience, bring clarity to policy development, and help drive technology costs down.

As hydrogen is being considered as a transportation fuel, the success experienced by this project suggests that forecourt production is a viable means of providing this fuel in rural areas. While centralized production and distribution of hydrogen for transportation may be an option in concentrated urban areas, forecourt production may be most appropriate option for rural areas. In these areas, for the near-term, there will not be high concentrations of hydrogen powered vehicles, as compared to urban areas. Therefore, it may not be economical to build/extend a centralized production distribution system in rural areas. However, for consumers to have confidence in new vehicle technology, they are not going to want to give up functionality. To give consumers greater confidence, infrastructure will be required in these low density areas. In addition, locally produced hydrogen would allow for the fuel to be created from local renewable resources and avoid being transported from distant centralized production facilities, which may offer further appeal to rural consumers.

The EVERmont Renewable Hydrogen Production and Fueling System has become the northern terminus of an evolving "East Coast Hydrogen Highway". While the "East Coast Hydrogen Highway" is more of a concept than a functioning system at this point, through this project, the public can begin to envision it, and policy-makers can identify existing investments which can represent the "kernel" of such a network.

Strategically locating the next few stations would allow near-term hydrogen powered vehicles to travel between New York City and Burlington, Vermont. Doing so would communicate to the public the functionality and transparency of hydrogen as a transportation fuel, and the universality of the vehicle technology.

Throughout this project, publics have been engaged. This public engagement has occurred on many levels – at public energy fairs, civic events (e.g. Fourth of July parades), and school sponsored educational opportunities. Of particular note is one school-age educational event: the Vermont Agency of Natural Resources' "Science on the Green." Science on the Green is an annual event, where schools from all over

ANR's Science on the Green 2007

The Agency of Natural Resources conducts an annual event named 'Science on the Green' where over four hundred students in 2006 (the first year of the program) were exposed to contemporary environmental and health protection science issues and challenges. In 2007 this number increased to over six

Vermont are invited to the Agency's headquarters in Waterbury Vermont and Agency staff present the environmental challenges facing contemporary society. The vision presented by the EVermont Renewable Hydrogen Production and Fueling System project was very well received and allowed the issues of sustainable transportation to be presented to Vermont school-age children in a positive, tangible and meaningful way.

The EVermont Renewable Hydrogen Production and Fueling System project is intended to remain in operation and serve the following functions: (1) to continue the demonstration of decentralized, sustainably generated transportation energy, (2) to support further hydrogen motor fuel and fuel cell demonstration projects, (3) to serve as a living laboratory for engineers and scientists working in the field of renewable and sustainable energy, and (4) to present a vision to school-age children and the general public of one element of a system that could meet our transportation needs in the future.

Actual Accomplishments vs. Goals

Project Objective	Actual Accomplishment
1) Develop advanced PEM electrolysis fueling station technology	A PEM electrolysis station was designed and built for cold weather operation. Many design and engineering challenges were presented in achieving functionality of this technology; all challenges were identified and met. Subsequent facilities will benefit from lessons learned in this project. Confirmation was made of laboratory results indicating advancements in PEM electrolysis that produce a lighter, less expensive, more efficient cell-stack design through field operations.
2) Build and test a validation system in Vermont that utilizes renewable electricity and is capable of providing hydrogen fuel to vehicles	A twelve kilogram per hydrogen generation station was constructed and operated. The station continues in operation. Energy to power the station is associated with a wind turbine operated by the City of Burlington, Electric Department. The hourly output of the turbine is well-matched to the energy demand of the H2 generation station. The wind turbine and the H2 generation station are grid interconnected with the renewable energy credits (RECs) assigned to EVermont. This arrangement is preferential to the two units being tied directly together; rather than through the grid. The use of RECs and the grid allow each system to operate on demand and make best use of the available resources. While, in this project, the turbine is located adjacent to the H2 generation site, in future projects this may not be so, nor may it be

	desirable. It may not be optimal to locate the H2 generation/dispensing infrastructure next to the optimum location of a wind turbine.
3) Procure a hydrogen fueled vehicle for testing and validation of the station/system	An H2 Hybrid was acquired from Quantum Technologies. This vehicle is a Toyota Prius converted to internally combust hydrogen rather than gasoline. The vehicle demonstrated that modifying a vehicle to use hydrogen as a motor fuel was a very cost-effective technology for displacing gasoline (especially as compared to the cost of fuel-cell technology), documenting how this technology could serve as a 'technology bridge' to fuel cells.

Summary of Project Activities

The award for the EVERmont Renewable Hydrogen Production and Fueling System project was granted September 22, 2004, and the project was completed on December 31, 2007.

2004 Q4

Highlights--

- Award granted
- Met with owner of prospective site
- Negotiated and signed subcontracts
- Worked on task 1 – project planning
- Held kickoff meeting
- Negotiated quotes from major suppliers

Details--

The DOE award for this project was granted on September 22, 2004.

On November 16, 2004 representatives from EVERmont, Proton Energy Systems (Proton) and Northern Power Systems (Northern) met with staff members from the Burlington, VT, Department of Public Works (DPW) to discuss the possibility of installing the hydrogen refueling station there. DPW requested that EVERmont write a proposal to present to them; the proposal was to be delivered in January 2005 with a tentative lease date of March 1, 2005. All parties mutually agreed that if the installation goes there, the EVERmont project must coordinate closely with the design and construction of a CNG filling station also slated to be installed on that site under a DOT program.

On December 16, 2004 the subcontracts were signed between EVERmont and Proton, and between EVERmont and Northern. At the same time a preliminary kick-off meeting was held via

conference call to involve all the parties and to present the preliminary project work plan and some early site layout drawings.

During November and December Proton and Northern worked on a project work plan. Proton continued its work on improving the design of its electrolyzer for outside, cold-weather use, and Northern negotiated a reasonable quote from Air Products and Chemicals, Inc., who will be supplying the compression, storage and dispensing components of the system.

2005 Q1

Highlights--

- Ordered compression, storage and dispensing system
- Received quotes for hydrogen vehicles
- Base electrolyzer fabrication completed
- Performed system and cost modeling
- Reached agreement in principle to terms for lease with DPW
- Selected a different site within the same parcel at DPW
- BED agreed in principle to donate wind energy RECs to project
- Preliminary drawings completed
- Held Preliminary Design Review

Details—

Compression, storage and dispensing system:

Northern released a purchase order in early January to Air Products and Chemicals, Inc. for the compression and storage components, as these had the longest lead times of any part of the system.

By early February Northern and Proton determined that no hydride vehicles were going to be available for this project (see vehicle discussion below). An additional P.O. was released to Air Products at that time for the high-pressure hydrogen dispenser.

At the end of Q1, the compressor refurbishing was finished; the frame for the compressor and controls was complete; the 12kg hydrogen storage pack was ready; and other smaller components were on order. The Air Products components are expected to be ready for shipping by the end of Q2.

Hydrogen Vehicle:

PES learned early in Q1 that the original proposed vehicle, a converted Prius with hydride storage built by Texaco-Ovonic Hydrogen Systems, was not going to be available for this project. This prompted a new set of bids for compressed hydrogen vehicles, including:

- Quantum – converted ICE Prius for purchase
- Electric Transportation Applications – converted Ford F-150 for lease

After examining the budget and the needs of the program, the Quantum vehicle was selected.

Electrolyzer fabrication and modeling:

The base electrolyzer fabrication was completed and the system underwent testing. The testing did uncover some issues, but none were insurmountable. Durability tests began. Once testing was complete, cold weather customization and controls was added to the unit. The electrolyzer was on schedule for delivery at the end of May 2005.

Northern and Proton created a proprietary cost and performance model in Excel to estimate electricity usage and cost based on system settings, run times and electricity rates. This model were used to determine the most appropriate run times for hydrogen generation, and also the most appropriate electric rate.

EVERmont and NPS presented a formal proposal to Burlington DPW for use of their land for the hydrogen fueling station. DPW accepted the proposal in principle, and a formal agreement would be negotiated in Q2.

Site Selection:

Burlington DPW's CNG fueling project is progressing more slowly than expected, so NPS and DPW decided to choose a site for the hydrogen station that is not collocated with the CNG station, thus eliminating the immediate need for coordination between the two sites. The new site is located on the northern boundary of DPW's property, along North Road directly across from BED. The new site is larger, flatter, has a better view of BED's wind turbine, and greatly reduces the distance between the storage and the dispenser.

Wind Renewable Energy Credits:

Burlington Electric Department agreed in principle to donate wind RECs to the project in exchange for being named as a partner in the project. It is projected that a year of operation, BED's 50kW wind turbine will produce an equivalent amount of power that the hydrogen station will consume.

Preliminary Design Review:

A Preliminary Design Review meeting was held at Proton's headquarters in Wallingford, CT, on March 25, 2005. Proton created a project specification document for review at the meeting, and many minor points were clarified during the meeting. This review resulted in decisions on major remaining purchases, including the low-pressure buffer tank and the cooler/heater for maintaining electrolyzer temperature.

The review also brought up several issues, including:

- Automated communications with Air Products equipment for monitoring purposes will not be possible. Air Products is unwilling to give direct access to internal data electronically, so the automated data monitoring system will be limited to electricity usage and hydrogen generation. Other aspects of operation will be monitored remotely by Air Products, or manually locally, and data will be available periodically.
- Fills will be slow under 10°F, and not allowed under -10°F due to low-temperature limitations on the storage tanks.

- Proton created preliminary drawings for the site and revised these drawings after the meeting to reflect the new proposed site.

2005 Q2

Highlights--

- Proton received compression, storage and dispensing system
- Proton ordered and received the buffer tank and cooler
- Northern ordered and received a Toyota Prius that will be converted to hydrogen over the next two quarters
- Proton completed pad layout drawings
- Northern contracted with a civil engineer to create civil site drawings, assist with permitting and oversee construction
- Northern purchased and configured an industrial computer to monitor the hydrogen production

Details--

Component procurement and fabrication:

A representative of Proton attended the factory acceptance test for the Air Products compression, storage and dispensing system. Hydrogen compression was observed up to 6250 psi, and dispensing hydrogen into a receiving tank at 5000 psi was also observed. All equipment functioned properly at the factory.

Proton received the compression system, storage tanks and dispenser at their facility in Wallingford, CT on June 24, 2005. The components were placed on a staging pad in the same arrangement as they would be on the final site.

The base electrolyzer was nearly ready to be turned over to the Proton design team for cold-weather customization at the end of June. The controls cabinet assembly was 80% complete by the end of Q2. A 200 psi buffer tank and the thermal control system (cooler) were delivered in June, and Proton engineers worked on integrating them into the system.

Hydrogen Vehicle:

A 2005 Toyota Prius was purchased in May 2005. Quantum Technologies Worldwide, Inc. (Quantum) was selected to convert this vehicle to run on hydrogen fuel. As per Quantum's request, the vehicle was driven by EVERmont and Northern for about 3000 miles to work through any warranty or lemon law issues. There were no issues with the vehicle during that time period. Gasoline mileage was tracked, and was generally in the range of 42-49 mpg for most of the road conditions encountered. The vehicle was scheduled for delivery to Quantum in August and the conversion was scheduled to be complete by December 2005.

Project site:

On April 21, 2005 final site selection was made. DPW agreed that the site is appropriate, and that decision was presented to the DPW Commission in an informational meeting on May 4, 2005. Information on the project was presented to local and state fire officials and Burlington Electric Department in separate meetings on May 18, 2005. Proton incorporated the fire marshal's input into the preliminary site drawings. Northern and EVERmont also presented

project information to the Transportation, Energy and Utilities Committee of the Burlington City Council, who were quite enthusiastic of the project.

A civil engineering firm was hired to create site drawings assist with permitting and oversee construction. Proton finished the preliminary site drawings. Northern, together with the City of Burlington and the civil engineer worked to ensure that the final site layout will allow the system to function properly and look attractive, while remaining as low-cost as possible. Civil site plans were scheduled to be completed by the end of July, 2005. A NEPA application for categorical exclusion was also submitted during this timeframe. All permits and the categorical exclusion were planned for August, 2005, so site construction could begin the end of August and equipment installation is scheduled for September. However, this scheduled turned out to be too optimistic.

Data Monitoring System:

An industrial PC was procured. Northern's SmartView™ software and other appropriate software and drivers to allow communication with the electrolyzer and other devices on site were installed. Initial attempts at communication indicated some minor problems, but these were overcome.

2005 Q3

Highlights--

- Applied for and received NEPA Categorical Exclusion
- Completed civil engineering drawings
- Applied for and received local permit for construction
- Held Final Design Review (FDR)
- Assembled and commissioned fueling station for testing at Proton
- Shipped base vehicle to Quantum Technologies for conversion to hydrogen
- Developed HMI and data collection system for the electrolyzer

Details—

Component procurement and fabrication:

The base electrolyzer unit was completed and the cold-weather customization and controls cabinet were completed and assembled. The completed custom unit was placed on the testing pad in Wallingford, CT, along with the cooler, hydrogen compressor, dispenser, high-pressure storage tanks and low-pressure buffer tank. With the exception of the dispenser, all components were laid out according the design for final installation in Burlington, VT.

On August 11, 2005, Proton and Northern held a Final Design Review. All aspects of the design were discussed, and it was concluded that the design was on track.

Hydrogen Vehicle:

In August, the base vehicle was shipped to Quantum Technologies in California for conversion to hydrogen. Delivery was confirmed and verified by representatives from both Northern and

Proton in late August. At that time the vehicle return delivery date was estimated to be the end of November.

Project site and permitting:

The civil engineer completed plans in August, considerably later than originally planned. The plans were presented to the Burlington Development Review Board on September 20, 2005, and the project was approved. The permit became valid on October 20, 2005. Construction on the site was scheduled to begin October 24, with final installation of equipment in November.

NEPA documentation was submitted to DOE in early August, and the site received a categorical exclusion in September.

The site owner, DPW, and the immediate neighbor, BED, both raised major concerns about insurance costs in July, and it appeared that it might be prohibitively expensive to insure the site. The underwriters for the City of Burlington viewed the site as a major risk and planned to apply surcharges to both entities. On September 19, 2005, Northern and Proton connected their insurance agent with the broker for the City of Burlington. This conversation resulted in the composition of a letter explaining how the site is compliant with safety regulations and why it is safe. Upon submitting this letter to the underwriters it was determined that there would not be a surcharge, and the issue was resolved.

Data Monitoring System:

Northern finished developing the data collection portion of the data monitoring system and developed an HMI for viewing data at the site. The system is known as SmartView™

2005 Q4

Highlights--

- Received permit to construct site
- Hired site contractor
- Completed 90% of site construction
- Shifted equipment into winter test mode

Details—

Component fabrication:

Delays in permitting and site construction at the final site in Vermont allowed for further testing of the equipment as set-up in Wallingford, CT. During these tests issues with the software governing the system startup were identified, requiring correction. When started manually the modified electrolyzer worked perfectly; but when it was programmed to start upon system power being turned on, it did not always start generating hydrogen correctly. This was determined to be a software control issue, not an overall system issue, and corrected.

Proton decided on a different approach for starting the electrolyzer automatically. Instead of automatically generating hydrogen as needed when power is applied, the system will only generate hydrogen when commanded by the PLC.

To validate the cold-weather functionality of the control system, Proton removed the cell stacks from the system – thereby removing the danger of damaging them by freezing – but left the control and heating system on for the winter. Though the conditions are not as harsh as those in Vermont, this approach provided valuable data in preparation for the upcoming 2006/2007 winter and model performance through a Vermont winter without the risk of damaging the cell-stacks.

The latest scheduling had the system being installed in Burlington, Vermont by May 2006.

Hydrogen Vehicle:

The hydrogen vehicle was originally scheduled for shipping to Vermont during Q4 2005. Quantum gave verbal notice to Proton that the revised vehicle ship date would be in May 2006.

Project site and permitting:

The zoning permit for the hydrogen fueling station became valid on October 20, 2005. Construction on the site began in November, and by the end of the quarter all of the major concrete was poured. The remaining work (paving the turnaround, etc.) is not critical to the function of the station and was rescheduled to be completed in the spring as weather permits.

The delays in the civil planning, and permitting pushed the construction of the site to early winter. This in turn delayed the installation of the hydrogen generation/storage/dispensing equipment on site until spring 2006.

The construction cost came in considerably higher than anticipated due to increased material costs and scheduling the work later into the year. These increased costs did not increase the overall budget from DOE's standpoint but it did increase Northern's cost share.

DPW and EVermont determined that a lease could be complex legally, so it was decided to use a memorandum of agreement (MOA) instead to form the terms of their relationship.

Data Monitoring System:

Northern's installed its SmartView™ system in the controls cabinet attached to the electrolyzer. This system will monitor the electrolyzer and also the PLC that controls the heaters and the overall operation of the hydrogen production (note that the compression, storage and dispensing system has a separate proprietary data storage system). Several minor revisions were made to the system in late December.

The overall data acquisition plan was set and included:

- Automated monitoring of hydrogen production, temperatures of components (for cold-weather analysis), and possibly electricity consumption (TBD)
- Semi-automated logging (monthly reports) of electricity production (wind turbine) and consumption (if not collected automatically)
- Semi-manual logging (manually recording stored data) of hydrogen dispensing

- Manual logging of vehicle mileage and road/weather/driving conditions

2006 Q1

Highlights--

- Tested internal re-circulating heaters over the winter
- Planning remaining construction for spring

Details--

Component fabrication:

The project was on hold for most of Q1 2006. Even though the winter was significantly milder than usual for Vermont, conditions were too harsh to complete fall construction and install the station.

The equipment remained in its test configuration at Proton's outdoor fueling station facilities in Wallingford, CT. Over the winter the heaters performed as expected. The only weather-related issue was a frozen section of the cooling system; the freezing was ultimately attributed to an incorrectly mixed antifreeze solution. The project schedule was revised to system installation in Burlington, Vermont scheduled for May 2006.

Hydrogen Vehicle:

Quantum Technologies revised schedule was to have the vehicle ready for shipping by May 1, 2006.

Project site and permitting:

Construction of the site remained on hold for the duration of the winter.

Data Monitoring System:

Northern Power made some minor updates to the SmartView™ HMI in order to meet the needs of Proton during the testing period.

2006 Q2

Highlights--

- Completed MOA between DPW and EVermont
- Finished site construction
- Installed equipment on site
- Received vehicle and successfully tested (initial) fueling

Details--

Northern Power acquired electrical and mechanical permits from the City of Burlington for installation of the site. On May 19, 2006 the system components were delivered to Burlington Vermont, and by Monday the 23rd the equipment was placed in its final location on site. Over the two weeks following, water and electricity were brought to the site; and on June 2 Proton started the equipment and successfully generated hydrogen to 200 psi.

By the middle of June the station was set up to fuel the vehicle, and Internet communications were established to the site. Northern Power made some minor updates to the SmartView™ HMI and also launched the web-based monitoring system for internal use. This system monitors the electrolyzer and associated components; the Air Products equipment is monitored separately.

EVERmont took possession of the H2 Hybrid on May 12, 2006. The vehicle was delivered to the site of the 2006 Tour de Sol (www.tourdesol.org). At this public event the vehicle was shown to several hundred members of the public.

On June 1-2, 2006, the vehicle was invited to Watkins Glenn, NY to participate in the first SCCA sanctioned Green Grand Prix (www.glenspeed.com) and present on the project at the International Motor Racing Research Center (www.racingarchives.org). To facilitate this participation, arrangements were made with the New York State Office of General Services, Clean Car Program (<http://www.ogs.state.ny.us/SupportServices/aboutus/cleanfuels/default.html>) to refuel at their facilities in Albany, New York.

A public dedication of the station was scheduled for July 2006.

2006 Q3

Highlights--

- Held kickoff event
- Completed final local inspections
- Continued testing/using the station

Details--

Initial construction/installation of the hydrogen station installation was completed in the previous Quarter and while the station did begin initial operation, many start-up issues needed to be attended to. Primary problems were associated with “handshaking” between the generation side of the system and the compression/storage/dispensing side. While setting the equipment up in Wallingford, CT to beta test it was valuable, it was speculated that internal control components may have been compromised in the process of disabling, transport and reassembling.

On July 3, a kickoff event was held at the site, with speakers including then-Representative (now Senator) Bernie Sanders, EVERmont chair John Kassel, and Northern Power President Darren Jamison. The station was functional and the vehicle was filled. About 70 people attended the event, which was considered a success.

The start-up problems encountered while frustrating were not surprising as the nature of projects like this is to identify what can't be anticipated and to learn from doing. Much has been

learned from the design, construction and initial operation of the station that has been incorporated in subsequent hydrogen generation and refueling stations.

During this period, Air Products installed a software upgrade (Service Pack 2). This upgrade proved to be troublesome; disabling the recording and display of fuel dispensed. Additional problems with the dispenser prevented complete filling of the vehicle's fuel tank. The problems of refueling the vehicle prevented routine and reliable (certainty of refueling) use of the vehicle.

The vehicle performed well, and drives and operates virtually indistinguishably from the base vehicle.

During the quarter, discussions were held with Quantum Technologies, the developer and supplier of the vehicle, that a component limitation had been identified. In their effort to continue to improve the overall design, they identified that a component of the existing vehicle may fail when the vehicle is fueled below freezing, and advise very strongly that the vehicle not be operated under such conditions until a hardware upgrade is completed. The upgrade is in design and the installation on the vehicle is expected in first quarter 2007.

The project was granted a no-cost extension until the end of 2007.

2006 Q4

Highlights--

- Continued maintenance and tuning on hydrogen system
- Tuned cold-weather settings
- Society of environmental journalists event (http://www.popularmechanics.com/blogs/science_news/4200635.html)
- Project featured in ES&T Online Technology News, December 13, 2006 (http://pubs.acs.org/subscribe/journals/esthag-w/2006/dec/tech/kb_fuel.html)
- Updated monitoring site with new version of software
- Generated approx. 9.4 kg of hydrogen during the quarter
- Accumulated 1,695 miles on the vehicle since modified to operate on hydrogen

Details—

Station:

This quarter began with the site down for maintenance, but the equipment was calibrated on October 18, 2006 and remained operational (production of H₂, see discussion of dispensing below) with few exceptions for the remainder of the quarter. In the initial cold days of the fall some temperature settings were found to be incorrect and were corrected.

As part of a larger upgrade, the web-monitoring site was updated to a newer version of Northern Power's SmartView system, allowing for easier viewing and easier updating. Email alarms were also added for temperature-sensitive components.

The system generated hydrogen for a total of 17.4 hours in Q4, generating approximately 9.4 kg of hydrogen at 0.54 kg/hr. 2511 kWh of electricity were used by the station during this time period for running the generator and compressing hydrogen, maintaining temperature in the DI water cabinet and running controls for the compression and dispensing system (other BOP energy is not included in this number). Approximately 783 kWh of this total were directly attributable to creating hydrogen (45kW x 17.4 hours).

Dispensing subsystem:

The dispensing subsystem has been the most problematic element of the station, inhibiting the use of the vehicle. The nature of the problem is that this subsystem has not reliably provided a complete fill of the vehicle. The nature of the problem has been incomplete fills or the dispenser not dispensing fuel. At this time it was unclear whether the problem was with hardware elements of the dispenser subsystem, software that controls the dispensing process or a combination of hardware and software. A chronology of the problems with fuel dispensing was assembled and provided to Proton who interfaced with Air Products, the storage and dispensing system vendor, to obtain corrective actions.

Vehicle:

Control Tests

On July 18, 2006 testing was conducted to compare the performance of the vehicle modified to operate on hydrogen to its stock (unmodified) equivalent. Acceleration and deceleration testing was conducted on the runway of the E. F. Knapp airport in Berlin, Vermont. In a broad conclusion, vehicle performance was comparable, although the specifics would suggest the unmodified vehicle had slightly better acceleration and gradability; while the modified vehicle had slightly better braking. Following is a summary of performance:

Performance Comparison of Unmodified to Modified Vehicle

In-use

Use of the vehicle has been limited by the dispenser issues identified above, however 329 miles were accumulated during the period 25 October 2006 to 3 January 2007. It can be reported that the vehicle performs well and is judged to be an acceptable product by those who have the opportunity to ride in it or drive it. Performance and operation is virtually indistinguishable from the unmodified vehicle. Two performance parameters of note are that the vehicle has a slightly louder exhaust noise than the unmodified vehicle. This is to be expected, as in the conversion process space that the stock exhaust system occupied was needed for conversion components, resulting in a modified exhaust system that operates at a slightly elevated noise level. This increased noise is not inherent to a hydrogen powered vehicle. And the operator does experience a slight 'turbo lag' in vehicle acceleration. This is not uncommon with turbo equipped vehicles (the turbo may also contribute to the slightly elevated sound level).

The one (and only) poor operation of the vehicle that was experienced was in November, when rough engine operation was experienced: engine hesitation and engine backfire. Consultation with Quantum resulted in a recommendation to replace spark plugs. This cured the problem and it has not returned.

One other observation that has been made of vehicle operation is with regard to engine lubricant. The lubricant has taken on a 'milky' characteristic; the appearance of an emulsified oil. This has been reported in the literature and is believed to be associated with the fact that combustion of hydrogen fuel produces more water than combustion of gasoline.

The vehicle still awaited a cold-weather upgrade from Quantum Technologies. Additional research by Quantum has lead them to alter their advice to EVermont regarding cold weather (below freezing temperatures) operation of the vehicle. Quantum has advised that the vehicle can be operated at temperatures to -20°C (this is the manufacturer's rated limited of the H2 sensors on-board the vehicle). As to refueling the vehicle, this can be done in temperatures below 1°C provided that the residual pressure in the fuel tank is above 300 psi. Operationally this has been implemented as to not deplete the fuel tanks much below 20%, providing a large margin of safety. Quantum has offered an 'interim' software 'fix' that would prevent tank pressure going below the recommended level until the hardware fix is implemented.

SEJ Conference:

The international conference of the Society of Environmental Journalists (SEJ) was held in Burlington, Vermont October 25 - 29. This event was co-hosted by the University of Vermont and the Vermont Law School. The EVermont Sustainable Transportation project was featured in two elements of conference; a station tour was included as a conference field trip, and the vehicle was included in the Ride-N-Drive. Additionally, the project Director participated on a panel, which included representatives of auto manufacturers, to discuss the development and deployment of advanced technology vehicles. (<http://www.sej.org/confer/index3.htm>)

2007 Q1

Highlights--

- Total miles accumulated on vehicle since conversion to hydrogen motor fuel, 1,826; with 131 miles accumulated this quarter.
- Generated approximately 3.5 kg of hydrogen during the quarter
- Developed budget requirements for long-term operation of the facility and strategy for securing such funding.

Details--

Station -- Generation

The quarter began with the station running routinely and producing fuel for vehicle operations. However, shortly into the Quarter, problems were encountered. A design flaw in the station's control system identified itself. The hydrogen generation sub-system (electrolyzer) was designed to monitor pressure by an Allen-Bradley (A-B) controller and turn off the electrolyzer when certain conditions were met. Important to the protocol of turning off an electrolyzer, is that certain components, i.e. pump, drain valves, vent valves, etc., are required to operate for a short duration past de-powering of the electrolyzer to ensure a safe shutdown as well as to ensure a controlled startup for the next "on" cycle. The logic in the A-B controller added a buffer of time to ensure this controlled shutdown occurred. To increase hydrogen generation reliability, a "three strikes" A-B programming was implemented. In the event of any error, the A-B controller would safely shutdown the cell-stacks, increment a counter and allow another startup if product pressure was not met. When the counter reached three times, no further hydrogen generation would be allowed to occur until the error was cleared on-site.

Ever since the station was installed in Vermont, there has been a slow leak in the product hydrogen line (feed-line from hydrogen generator to buffer tank) between two check valves (one on the buffer tank and one on our electrolyzer). The slow leak was not significant enough to require any immediate attention, or attention of its own; in fact it initially provided a beneficial value by causing limited cycling of the generation system (electrolyzer), having it turn on and off to pressurize the product line. As the temperatures decreased however, the leakage rate increased such that the electrolyzer was turning on and off in ever shorter cycles. When the cycle time for a leak reached the same duration as the buffer time for a controlled shutdown, the system was trying to shutdown at the same time the system was calling to start back up. This event sent an error code and allowed it to restart two more times. After the third error code, the system went into an error state and would not allow restart. Because of difficulties in removing the leaking valve the electrolyzer system was placed in "Bypass" mode on January 11, and remained in this mode through the Quarter.

The system was thoroughly reviewed and it was concluded that to correct the problem, the check valve at the buffer tank needs to be removed, and this work needs to be coordinated with Air Products. By doing so the new configuration would provide for monitoring of the true buffer tank pressure and with updated control logic in the A-B controller the system will not fault as it did, as it would not be able to try and generate hydrogen as it was trying to shutdown.

Station – Fuel Dispensing

During the Quarter, fueling of the vehicle was problematic as the dispensing system did not reliably dispense fuel. Various error messages were encountered in the dispensing process that would abort fills before a fill was complete. "Flow Controller Error" was the most common

experienced error, but others included pressure differentials and very extended fill times (~45 minutes) were experienced. Consultations with Air Products pointed to software problems in the dispenser controls rather than hardware problems.

Station – Overall Operation

During wintertime conditions the water supply line to the DI unit froze. This together with the generation-storage controller issue identified above placed the station in standby mode from January 11, through March 31. During this period of time plans were developed for correction of the controller issue, and rectification of the fuel dispensing issues.

Vehicle Operation:

Vehicle operations were curtailed to the first eleven days of January, as this was the only period of time fuel was available. The vehicle was operated during this period time 131 miles. Because of matters related to fuel dispensing, the specific fuel consumption of the vehicle can only be stated as a range; between 42 to 51 miles per kilogram of hydrogen during a highway driving cycle.

2007 Q2

Highlights--

- The Burlington Department of Public Works (DPW) staffed were trained on the vehicle fueling and operations, and the vehicle was placed in routine service with DPW on May 4, 2007.
- Total miles accumulated on vehicle since conversion to hydrogen motor fuel, 3,276; with 1,450 miles accumulated this quarter.
- Monthly hydrogen production during this quarter was; April – 16.9 kg, May – 24.3 kg, and June – 18.2 kg.
- The station was visited on two occasions by Air Products; one for service (3 April), and the other (7 June) for routine system review.

Details--

Station:

The quarter began with the station off line as there were controller operational issues remaining from the previous quarter. With the station not producing hydrogen, its systems were not being 'exercised'; the winter weather of first quarter 2007 yielded a frozen water supply line. On April 3, 2007, the station was visited by an Air Products field service technician to address the controller issues. The service tech performed a complete and comprehensive site review of the Air Products compression, storage and dispensing subsystems. This review identified a number of minor problems such as loose wires at connectors, and pin connectors not fully seated. Also identified were some hydrogen piping issues that were thought to allow for to rapid a flow, thereby 'confusing' the flow controller. Further, the service tech, working with Air Products internal tech support, identified that installed in the station dispensing controls was a version of 'Service Pack 2' software with known bugs/problems.

What is noteworthy is that station held high pressure during its period of inoperation, confirming the system is tight and has no leaks. As the high pressure tanks were full, the vehicle

was filled to demonstrate the dispensing system would operate and fill the vehicle as designed after the service; which it did.

On April 20th, the frozen water line was cleared and the station was back on line.

For the period 23 April thru 2 May, EVERmont worked with Air Products technical support to address the software problems of 'Service Pack 2'; this seems to have been the root of much of the dispensing problems encountered. During this period various upgrades of the software were installed and tested out by fueling the vehicle. The version currently installed in the dispenser controller has been working quite successfully, however a known bug in the program does remain. This bug causes a warning to be displayed on the price panel indicating that there is a compressor malfunction, which is not the case.

With the production of hydrogen and dispensing working at an acceptable reliability level, the vehicle was placed with the Burlington DPW on May 4, 2007 to commence routine service. A training program was developed and delivered to staff for proper refueling and operation of the vehicle. Initial operation of the vehicle and its refueling was limited to key personnel, and as those staff become comfortable with the technology and achieve a level of expertise more staff members will be trained in operations.

For the most part, the station operated normally through-out the remainder of the quarter, however on two occasions (15 May and 6 June) the HoGen unit needed to be manually rebooted, and on one occasion the compressor needed to be reset for no apparent reason.

Vehicle Operations:

As reported above, the vehicle was turned over to Burlington DPW during this quarter. The vehicle has performed flawlessly. Any problems that were encountered can be attributable to 'operator error'. As the vehicle is a conversion vehicle, two aspects of the conversion lend themselves to these operator errors. One is the location of the Comm Port. This is the connection of the communications between the vehicle and the dispenser, providing a ground, and current information as to the amount of fuel onboard, by reporting the temperature and pressure of the fuel tanks. The location of the connector requires an operator to reach below the rear bumper to make the connection. This is very awkward and it is very difficult for the operator to see the connector when trying to make the connection. Further, the materials of the connector are very vulnerable to damage.

The other element of the conversion that leads to operator error is the fuel gage. Quantum elected to convert the battery state-of-charge gage to be the hydrogen fuel gage. In the design the conventional gasoline fuel gage displays a full tank at all times, which can confuse an inexperienced operator into thinking the vehicle has more fuel onboard than it does.

During the quarter the vehicle accumulated 1,450 miles of operation, resulting in a total of 3,276 miles of operation on hydrogen fuel. No vehicle operational problems were encountered. Vehicle operation has been very reliable. And while operators do require a period of time to understand operation of this conversion vehicle, operator satisfaction with overall performance is high.

2007 Q3

Highlights--

- The vehicle continued in routine service at the Burlington Department of Public Works (DPW).
- The Hydrogen Generation/Dispensing station continued routine operation to fuel the vehicle.
- Total miles accumulated on vehicle since conversion to hydrogen motor fuel; 4,022 with 746 miles accumulated this quarter.
- Total Hydrogen production since October 2006; 111.8 kg, with 3.8 kg in July, 13.4 kg in August, and 11.9 kg in September 2007.
- Modified vehicle to make access to the 'Comm Port' more 'user friendly'
- Technical Presentation of the project at the University of Albany, Second Annual New Energy Symposium (www.e2tac.org)
- Paper accepted for presentation at EV-23, Sustainability: *the Future of Transportation* (www.evs23.org). December 2-5, 2007.

Details--

Station:

Station operation for the quarter was quite routine. No major service was required or performed. No major equipment malfunctions were experienced.

A situation was experienced in the quarter of note. On four occasions the HoGen needed to be rebooted. The unit's internal safety checks did shut the station down. Analysis of operational data determined that the situation was the result of a large diurnal temperature cycling during this fall season: specifically, the station would be called to produce hydrogen and that production was generally at the end of the work day, or the evening/overnight period. This is when the daily temperature was falling due the normal diurnal pattern of temperature. The next day as the temperature warmed through the day, the hydrogen (particularly in the buffer tank) would warm and expand. This expansion was sufficient to trigger the upper pressure alarm setting, and cause the production equipment to go into a fail-safe mode so that it would not produce any additional hydrogen that could cause fuel storage pressures to increase further. A software upgrade is being considered to address this condition. As the safety limits are set sufficiently low such that safety would not be compromised if the trigger limit was increased. Consultation with the station designer has confirmed that this is not safety issue, but represents a judgment that the range of diurnal temperature and hence product expansion, would not be of the magnitude that is being experienced under certain conditions in Vermont. Designing for this situation is applicable to all facilities that will be located in northern climates.

Vehicle:

The vehicle operated without incident during the quarter. Operators of the vehicle continue to find vehicle operation very satisfactory. The location of the communication port, the connection between the vehicle and the dispenser, was relocated to be more 'user friendly'.

Agency of Natural Resources "Science on the Green"

The Vermont Agency of Natural Resources annually hosts "Science on the Green". This is an event where schools through-out the state are invited to bring students to the Agency's offices in Waterbury Vermont and all Agency program presents the environmental and health issues that they are working on and students have the opportunity to learn and ask questions about these contemporary issues. The H2 Wind to Wheels Project was presented under the heading of Transportation/Energy/Sustainability. Over 600 school-age children were exposed to the issue and how the project is one way our nation is responding to the issue.

2007 Q4

Highlights--

- The vehicle continued in routine service at the Burlington Department of Public Works (DPW).
- The Hydrogen Generation/Dispensing station continued routine operation to fuel the vehicle.
- Total miles accumulated on vehicle since conversion to hydrogen motor fuel; 4,889 with 867 miles accumulated this quarter.
- Total Hydrogen production since October 2006; 152.3 kg, with 13.9 kg in October, 21.5 kg in November, and 5.13 kg in December 2007.
- Upgraded system control logic to correct identified deficiencies
- Upgraded freeze protection plan for water supply line
- Performed requisite Prevented Maintenance on station
- Re-flashed Quantum ECU on vehicle to provide an added level of safety during cold weather re-fueling
- Presented project at EV-23, Sustainability: *the Future of Transportation* (www.evs23.org). December 2-5, 2007.
- Paper recommended for publication in World Electric Vehicle Journal

Details--

Station:

Overall the Quarter would be characterized as routine operation with two activities of note. In early December the water supply line to the station did freeze. This was not surprising as an upgraded freeze protection plan had been designed, but not yet implemented. The combination of events that lead to the actual freeze occurring was that the heater circuit not being turned on from when it was turned off for summer operation, together with an earlier on-set of freeze threatening weather then expected. The actual freeze was easily identified and quickly remediated. The upgraded freeze protection plan was implemented and there is an extremely high level off confidence that the water supply line is fully protected and will not be subject to freezing again.

The other activity of note is that a deficiency in the control logic of the HoGen system was identified and corrective action taken. The specific condition was that if the safety interlock system of the hydrogen generator detected a condition where any parameter was out of pre-set limits, the system would go into safety mode, as designed. The deficiency was that if it were to go into safety mode, the logic deactivated power to the fluids cabinet where the cell-stacks are

located. This is done to protect the cell-stacks; however the power circuit that was deactivated also provided power to the freeze protection heaters. The software upgrade overcame this deficiency by depowering only the cell-stacks and not the heater circuit. This eliminated the concern of threat to the system if it were to go into safety mode during sub-freezing temperatures weather conditions. Another element of the software upgrade was to correct the problem spoken to in the last Quarterly, were the diurnal temperature swings could cause the product pressure to exceed specified limits and set the HoGen to safety mode. Normal station Preventive Maintenance was performed on the HoGen unit as well.

Vehicle:

During the Quarter the Engine Control Unit (ECU) developed by Quantum which provides the necessary communications for the vehicle to properly combust hydrogen was returned to Quantum for re-flashing (software upgrade). Quantum requested the ECU be re-flashed. The modifications to the ECU control the amount of fuel that can be removed from the fuel tank. Previous to the re-flash, the fuel tanks could be completely emptied (0 psi). With the upgraded software, the ECU will ensure that there will always be remaining pressure in the tank (>0 psi). This is intended to provide a 'buffer' to the in-rush of fuel when the fuel is being re-fueled. Having some residual fuel in the tank is desirable when re-fueling the vehicle, particularly in cold weather, as it will limit the temperature rise of the fuel and lessen the stress on the tanks. As a practical matter, the tanks are never completely emptied, so it has no affect on routine use of the vehicle, but does provide a level of safety that previously was not there.

The operator reports that the relocated Comm Port is far more convenient than the previous arrangement, has reduced re-fueling time and is a joy to use.

Products Developed and Technology Transfer

Publications:

- EVS-23; Sustainability: the Future of Transportation. Anaheim, CA December 2-5, 2007.
- World Electric Vehicle Journal, paper invited for consideration January 2008.

Web sites:

- www.evermont.org. Includes this project among the other projects of EVermont.
- <https://smartview.nps-gateway.com/Login.asp>. Access to real-time and logged data of HoGen operation (access to data is password protected).

Patents:

- "Cold Weather Hydrogen Generation System and Method of Operation". Application Number 11/461478. Can be viewed at: <http://www.freepatentsonline.com/y2008/0029389.html>.

Attachment 1 – EVS 23 Paper

EVS 23 – Sustainability: The Future of Transportation Anaheim, CA December 2-5, 2007

Session 3 C: Energy

“Wind to Wheels Hydrogen Project: Sustainable Transportation”

Harold Garabedian, Vermont Agency of Natural Resources/EVermont

Greg Wight, Norwich University/EVermont

Ken Dreier, Distributed Energy Systems

Nick Borland, Distributed Energy Systems

Attachment 2 – EVS 23 Presentation

EVS 23 – Sustainability: The Future of Transportation Anaheim, CA December 2-5, 2007

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Abstract

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 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.

Figure 1: Overview of Sustainable Transportation Energy Generation and Use.

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.

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 feed 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

Figure 2: System Block Diagram; Onsite Components.

(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 and are referred to one company, Distributed Energy Systems, through the remainder of this paper) HOGEN H Series electrolyzer. 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 one which represents 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).

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.

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.

MAJOR COMPONENTS

Subsystem: Electrolysis

Electrolyzer Control Cabinet

Electrolyzer Power Supply

Electrolyzer Fluids Cabinet

Electrolyzer Cooling Unit

Subsystem: Compression

Compressor Skid, with Wind Turbine in background

Subsystem: Storage

Buffer Tank and High Pressure Fuel Storage Cylinders

Subsystem: Dispensing

Fuel Dispenser

Figure 4: Onsite Major Components; Hydrogen Generation, Compression, Storage and Dispensing.

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].

Table 1: Engine Performance Specifications, H2 Hybrid vs. Prius.

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	

The Prius was selected as the base vehicle as it represents an advanced vehicle design with an efficient 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 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 is segmented in to two activities, one being the day-in-day-out use of the vehicle to meet basic transportation needs. The second is to document vehicle performance and fuel economy. This is 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.

4. Station Performance

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 Distributed Energy Systems' facility in Wallingford, CT. 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.

In the spring of 2006, the station components were disassembled in Wallingford, CT, 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 known 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.

Figure 6: SmartView Screen Shots; Left - Real-Time Data; Right - Long-Term Observations.

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 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 2 (EM2), the advanced PEM cell stack was producing hydrogen gas 8.6 to 8% percent more efficiently than cell stack one and 3, respectively.

Table 2: Comparison of Energy Consumption of Advanced PEM Cell Stack to Standard Stacks.

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

5. Vehicle Performance

The MY 2005 Prius was converted to H2 Hybrid by Quantum Technologies, as one of a number of identical 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 (August 2007) 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

Figure 7: Airport Testing of H2 Hybrid vs. Prius.

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 an miles per gallon of gasoline equivalent as miles per kilogram of hydrogen). This includes a range of drivers, and 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 be concluded from the data are within the variability expected from the test methods used.

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

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

Figure 9. Time Series Fuel Consumption and Vehicle Speed Data.

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 (NO_x). A compromise to minimize power loss and minimize NO_x emissions formation is to operate the engine at two times stoichiometry (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 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.

Figure 10. BED's AOC 50 Wind Turbine.

7. Conclusions, Recommendations and Future Directions

7.1 Conclusions

The EVermont/Distributed Energy Systems Hydrogen generation and vehicle fueling station in Burlington, VT 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) 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; thereby maximizing their contributions to the overall system. If the system was not grid-connected 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 would 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 would 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:

- 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
- Efficiency of conversion of electricity to low pressure hydrogen and costs, including water supply, heating, cooling, maintenance.
- Efficiency of compression from low to high pressure and cost.
- Efficiency of the vehicle filling process, documentation of losses

- Efficiency from tank to wheels and costs particularly as compared to fossil fuel powered internal combustion engine vehicles.
- 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.

8. References

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9. Authors

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Prof. Wight holds the BSME, from the Massachusetts Institute of Technology and the MSME, from the U. of Florida. He has worked as an environmental/mechanical engineer for the US Air Force, the Connecticut Department of Environmental Protection, and Norwich University.
He serves as technical advisor to EVermont

Harold Garabedian is the Deputy Director of the Vermont Agency of Natural Resources Air Quality Program and serves as the Director of Research for EVermont. Mr. Garabedian holds the BSME, from the University of Massachusetts - Amherst. His career in the field of air quality management has focused on energy generation and use in its many forms.

Nick Borland is a Software Engineer at Distributed Energy Systems. Mr. Borland’s expertise is with data acquisition and system controls. He holds a Masters degree from the Massachusetts Institute of Technology, where he focused on incorporating environmental computer models into traditional product design models and he also holds Bachelors in Physics from Oberlin College.

Ken Dreier is a Mechanical Project Engineer at Distributed Energy Systems in Wallingford, CT. Mr. Dreier’s are of expertise is with electrolysis based hydrogen fueling stations and PEM electrolyzer systems integration. He holds a MOT degree from Georgia Tech and a BSME from University of Illinois at Urbana-Champaign.

Attachment 2 – EVS 23 Presentation

EVS 23 – Sustainability: The Future of Transportation Anaheim, CA December 2-5, 2007

Session 3 C: Energy

“Wind to Wheels Hydrogen Project: Sustainable Transportation”

Harold Garabedian, Vermont Agency of Natural Resources/EVermont

Greg Wight, Norwich University/EVermont

Ken Dreier, Distributed Energy Systems

Nick Borland, Distributed Energy Systems

EVS 23

December 2 - 5, 2007

**SUSTAINABILITY:
THE FUTURE OF TRANSPORTATION**
ANAHEIM, CALIFORNIA USA

Speaker Name: Harold Garabedian

Greg Wight, Ken Dreier, Nick Borland

Speaker Title: Deputy Director -APCD

Company Name: Vermont ANR/EVermont

Norwich Univ./EVermont

Distributed Energy Systems

HOSTED BY:

EDTA[®]

Electric Drive Transportation Association

In partnership with the World Electric
Vehicle Association (WEVA)

Title: *Wind to Wheels*

1. Project Objectives
2. Fuel Generation, Storage and Dispensing
3. Fuel Use/Vehicle
4. Station Performance
5. Vehicle Performance
6. Primary Energy Generation
7. Future Direction, Conclusions and Recommendations

Project Objectives

- Develop advanced PEM electrolysis fueling station technology
- Build and test a validation system in Vermont that utilizes renewable electricity and is capable of providing hydrogen fuel to vehicles
- Procure a hydrogen fueled vehicle for testing and validation of the station/system

Project Design

Grid

AOC 50 kW Wind Turbine at
Burlington Electric Department

Proton Energy
hydrogen generator

Compression and storage

Air Products
fueling station

2005 Toyota Prius
Converted to H2
by Quantum Technologies.
And to be operated by
Burlington Department of
Public Works

Partners for a Hydrogen Future

EVERmont

Burlington Department of Public Works

Burlington Electric Department

U. S. Dept. of Energy

Northern Power Systems

Proton Energy Systems

Generation Storage & Dispensing

SUSTAINABILITY: THE FUTURE OF TRANSPORTATION

Major Components

Subsystem: Electrolysis

**Electrolyzer
Control Cabinet**

**Electrolyzer
Power
Supply**

**Electrolyzer
Fluids
Cabinet**

**Electrolyzer
Cooling Unit**

Subsystem: Compression

**Compressor Skid, with Wind
Turbine in background**

Subsystem: Storage

**Buffer Tank and High
Pressure Fuel Storage
Cylinders**

Subsystem: Dispensing

**Fuel
Dispenser**

Fuel Use/Vehicle

- Designed and converted by Quantum Technologies (*H₂Hybrid*)
- *H₂Hybrid* Characteristics:
 - ▶ Energy efficient drivetrain
 - ▶ SULEV emissions with fuel based HCs, CO and CO₂ eliminated
 - ▶ 'Bridge technology' to fuel cell vehicles
 - ▶ 'Seed' demand for hydrogen and infrastructure

Fuel Use/Vehicle

The *H₂Hybrid* includes:

- ▶ **Electronic multi-point hydrogen injection system using Quantum's hydrogen injector and engine controller**
- ▶ **Turbocharger and intercooler for increased performance and efficiency**
- ▶ **Quantum compact lightweight compressed hydrogen fuel storage module**
- ▶ **Hydrogen fuel delivery system comprising of stainless steel tubing produced with Quantum CNG fuel line equipment**
- ▶ **FMVSS crashworthiness tested**

Fuel Use/Vehicle

Onboard Hydrogen Storage System Layout

Fuel Use/Vehicle

***H₂Hybrid* Engine Modifications**

Base engine modifications include the addition of hydrogen fuel injection and associated controls, a turbocharger and an intercooler.

Fuel Use/Vehicle

H₂Hybrid Vs. Prius

Specification	<i>H₂Hybrid</i>	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	

Station Performance

Energy In

|40 - 45 kWh|

(136,480 -- 153,540 BTUs)

Energy Out

H₂

|0.54 – 0.58 kg|

(62,640 – 67,280 BTUs)

$$\eta_e = 44 - 46\% \text{ LHV}$$

Station Performance

Cell-Stack	EM1	EM2	EM3
H2 Generation, kg/hr	←----- 0.54 -----→		
Current, Amps	158	158	156
Avg. Voltage	75.5	69.5	76
Power, Watts	11,929	10,981	11,856
Delta EM2	8.6%	--	8.0%

Vehicle Performance

Operation monitored in;

- Routine use
- Controlled On-Road driving
- Performance Evaluation

Vehicle Performance

Prius and H₂ Hybrid tested side-by-side

Primary Energy Generation

- AOC 50 Wind Turbine operated by Burlington Electric Department
- Electricity generation credits allocated to EVermont Hydrogen station
- Grid connection allows for site optimization of each technology

Future Direction

- Efficiency Evaluation Underway --
DOT grant; team of Norwich University
Mechanical Engineering students
 - Efficiency, wind to electricity
 - Efficiency, electricity to low pressure H₂
 - Efficiency of compression to 5000 psi
 - Efficiency, delivery to vehicle
 - Efficiency tank to wheels for *H₂ Hybrid*
 - Overall efficiency
- Continued Station Operation – Platform
for H₂ education and vehicle
demonstration

Conclusions/Recommendations

- A system can be put together using available technology to provide sustainable transportation energy
- Policies facilitating small fleets based on the design of this program are technically justifiable
- Deployment of this system would 'seed' H2 infrastructure and provide a 'bridge' to the H2 economy
- Efforts need to continue to make these technologies more efficient, more affordable, and readily deployable

THANK YOU

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... and thanks to all our partners.

Attachment 3 – Project Brochures

'Wind to Wheels'

The Vermont Sustainable
Transportation
Demonstration Project

Project Objectives

To Demonstrate a
Sustainable Approach
to Transportation by:

- Developing advance PEM electrolysis fueling station technology
- Building and testing a validation system in Vermont that utilizes renewable electricity and is capable of providing hydrogen fuel to vehicles, and
- Procure a hydrogen fueled vehicle for testing and validation of this systems approach to transportation energy.

**EVermont Hydrogen Generation/Refueling Station,
Burlington Vermont
Adjacent to 545 Pine Street, Burlington VT 05041**

**N 44° 27.7922
W 73° 12.9829**

**Electrolyzer – Distributed
Energy Systems HOGEN;
12 kgH2/day capacity**

**Dispenser -- Air Products
350 bar H2 dispensing;
CaFCP communication fill**

**Wind turbine --
AOC 50; 50 kW capacity**

**Vehicle --
Quantum Technologies H2 Hybrid**

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Partners for sustainable transportation

**EVERmont Hydrogen Refueling Station,
Burlington Vermont
Adjacent to 545 Pine Street, Burlington VT 05041**

**N 44° 27.7922
W 73° 12.9829**

Proton HOGEN Electrolyzer

Rated: 12 kgH₂/day capacity

Air Products Corp. Dispenser

350 bar H₂ dispensing

CaFCP communication fill

**Wind turbine
AOC 50**

**50 kW rated output
66 kW maximum
164,000 kWh annually**

**For additional information,
please contact :
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