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The Business Case for Matching Renewable Energy Production with Vehicle Charging

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Abstract

Plug-in vehicles, both hybrid electric and battery-only, are now available to the car-buying public with new models coming to dealer showrooms in 2012 and beyond. The paper describes a new business opportunity called renewable energy to electric vehicle (RE2EV), whereby consumers are offered a premium green charging option for their new plug-in vehicle. RE2EV envisions a new opportunity for load serving entities (LSE) in wholesale power markets coordinating vehicle charging with renewable energy production. Plug-in vehicle owners will likely pay a premium for this service, while at the same time allowing the LSE to leverage the inherent nature of vehicle load and grid-connected storage to assist with the integration of variable renewable forms of energy like wind and solar using vehicle to grid systems. The technical potential of using energy storage to manage the variability of wind and solar is well understood. However, the ability to increase the revenue for wind and solar energy in wholesale markets using storage is location specific and largely depends on wholesale power markets' structures and rules. The premium that consumers would be willing to pay for RE2EV in combination with increasing the value of renewable energy resources delivered in wholesale markets creates a potentially attractive margin for an innovative LSE. Meter roaming is identified as a key innovation needed to maximize the RE2EV potential. Enabling information technologies are being developed and one limited demonstration of RE2EV is currently underway.

Keywords: PHEV (plug in hybrid electric vehicles); V2G (vehicle to grid); energy storage; charging; smart grid

1 Introduction

For the first time in over a decade, major automobile manufacturers have begun selling all electric and plug-in electric hybrid vehicles to the car-buying public. Nissan began selling the all electric Leaf in select Japanese and North American markets in December of 2010. GM also began selling its much anticipated plug-in hybrid Volt in the US in mid-December of 2010. According to Hybridcars.com's December Dashboard 17,813 plug-in cars were sold in the US in 2011.

In addition to these early pug-in vehicle offerings from Nissan and GM, virtually every other major automobile manufacturer will be introducing plug-in cars as part of their product offerings in the near future. For example, Ford Motor Company announced that it will begin selling an all electric version of the Focus in the spring of 2012. In

April of 2010, Toyota began taking reservations for a plug-in version of its industry leading Prius hybrid electric vehicle for delivery in the spring of 2012.

In the US 138 billion gallons or gasoline are consumed each year in the nation's fleet of light vehicles and trucks. Electricity as a fuel source for light vehicles would reduce the transportation sector's dependence on a single primary energy source—petroleum. The petroleum displacement realized from the introduction of plug-in cars will depend on the pace of consumer adoption. Plug-in cars may also offer benefits from decreased emissions of harmful pollutants, including CO_2 a key greenhouse gas contributing to global climate change. However, the emissions benefits of displacing gasoline purchased at the pump with electricity from the grid are determined by the type of fuels used to produce the electricity for vehicle charging.

Early adopters of plug-in vehicles are likely motivated by the benefits of displacing gasoline purchased at the pump with electricity from the grid. Charging a vehicle with renewable energy would further enhance the environmental benefits of owning a plug-in vehicle. Americans support greater use of wind and solar as indicated in a March 2011 CNN poll, which found that over 80% of survey respondents reported that the US should rely more on wind and solar for the country's future energy needs. It is likely that many plug-in vehicle owners would be interested in having the option to charge their vehicles from renewable forms of power production.

As sales of plug-in cars increase in the coming years, a new opportunity emerges to develop renewable energy projects specifically to fuel an emerging fleet of plug-in cars. Existing regulations and business models can accommodate linking renewable energy projects with vehicle charging on the "customer side" of the meter. However, new business models will be needed to develop a wholesale energy business matching renewable energy production with vehicle charging.

This paper describes a business model based on the value of matching renewable energy production with vehicle charging; this model is called renewable energy to electric vehicle (RE2EV).

2 Survey of Existing Models

A number of studies have analyzed the grid impacts associated with charging an emerging fleet of all electric and hybrid electric plug-in vehicles [1] [2] [3]. These studies found that a large fleet of plug-in cars could be charged without the need to build additional power plants or transmission and distribution infrastructure.

Uncontrolled vehicle charging, however, can lead to an increase in the peak demand for power adding additional strain on segments of the power system that are at or near capacity. As plug-in cars gain greater market share, the timing of vehicle charging becomes increasingly important to avoid increasing the peak demand for power. Fortuitously, smart grid technology is being deployed concurrently with the mass marketing of plug-in vehicles. The US Department of Energy has funded several projects to explore the use of smart grid technology to manage the timing of vehicle charging.

Smart meters allow for two-way flows of information between utility companies and their customers. Smart grid technology can play a critical role in managing vehicle charging in response to power system conditions, and perhaps facilitate the delivery of so called vehicle to grid (V2G) services.

2.1 Net metering approach

We are already seeing early adopters of plug-in vehicles investing in renewable energy systems at their homes using existing net metering regulations to fuel their electric vehicles. In addition, some electric vehicle supply equipment (EVSE) vendors and renewable energy system developers have integrated renewable energy systems at vehicle charging stations. A number of charging stations integrating a solar photovoltaic array have been constructed in various locations.

Figure 1: Solar-Powered Charging Station

These examples are on the "customer side" of the meter, which primarily use photovoltaic (PV) technology. Given that most states allow net metering, this is the most direct route to linking renewable energy production with vehicle charging. The PV system output spins a meter backwards feeding power onto the local grid when the demand for vehicle charging is less than the system output, thus creating a credit for vehicle charging later when no electricity is being produced from solar.

Alternatively, Central Vermont Public Service, the electric utility serving central Vermont, built a solar-powered vehicle charging station with stationary batteries to store the solar-generated electricity for vehicle charging during the evening hours and on cloudy days. This approach more closely links solar power production with vehicle charging relative to a strictly net metering approach without stationary battery storage.

Several analysts have evaluated the economics of using solar for vehicle charging using a net metered approach [4] [5]. Letendre (2009) calculates that solar-generated electricity is less expensive compared to gasoline as a fuel for light vehicles and explores both single home and group net metering scenarios. Hoff (2009) analyzed what he refers to as a solar sustained vehicle (SSV); at the point of electric vehicle sale, the buyer is offered the option to bundle the cost of a home PV system with the cost of the vehicle. Projections of a SSV in New York State found that the consumer would benefit from dramatic fuel cost reductions for the next 30 years. These concepts are behind the partnership between Ford Motor Company and SunPower Corporation (a leading PV module manufacturer), which was announced in August of 2011.

2.2 V2G for renewables integration

Some analysts have studied how a fleet of plug-in cars can offer the storage capacity needed for large-scale renewable penetration on the grid [6] [7] [8] [9] [10]. These studies conclude that the storage capacity inherent in a fleet of plug-in cars can be utilized to effectively manage the intermittent nature of renewable forms of energy including wind and solar. This is made possible through the deployment of vehicle to grid (V2G) systems, which serve to regulate the rate of charge and control the bi-directional flow of power to and from the vehicle and the electric grid.

Letendre, Perez, & Herig (2002) evaluate the use of battery-powered vehicles providing buffer storage for grid-connected PV installations, assuming a V2G infrastructure. They explore the use of batteries in electric vehicles to provide firm capacity for distributed PV systems, concluding that between 0.75. and 1 MWh of energy storage could provide the buffer storage necessary to provide firm capacity for 1 MW of installed PV in California.

Kempton and Tomic (2005) found that a V2G capable fleet could stabilize large-scale wind power at one-half US electricity production with 3% of the vehicle fleet dedicated to regulation for wind, plus 8–38% of the fleet providing operating reserves or storage for wind.

Short and Denholm (2006) used the Wind Deployment System (WinDS) model to assess the role that plug-in hybrid cars with different all electric ranges could serve to address the intermittent nature of wind. Their analysis found that larger batteries (e.g., longer all electric range) resulted in more than doubling installed wind capacity, as well as decreasing electric-sector carbon emissions, even considering the increased electric load resulting from replacing 40% of the nation's light duty vehicle fleet gasoline use with electricity.

More recently, Tuffner & Kintner-Meyer (2011) found that grid friendly charging of electric vehicles could facilitate the integration of large quantities of wind onto the Northwest Power Pool (NWPP) grid. They explored the concept they refer to as V2GHalf, which involves modulating the rate of vehicle charging to meet the balancing requirements for new wind farms in the NWPP territory. They found that if 13% of the existing light-duty vehicle stock (about 2.1 million vehicles) were PHEVs with a 33-mile electric range and using V2GHalf charging strategies at home and at work, all of the additional balancing requirements of 3.7 GW of wind could be provided by the electric vehicles.

These studies demonstrate the technical potential of using plug-in cars to facilitate the integration of wind and solar into the electric power system. However, these studies did not explore the mechanisms by which a load serving entity (LSE) meeting new electric vehicle load would operate given the wholesale power market structures in place across the country to meet this technical potential.

It is likely that plug-in vehicle owners will value using renewable energy for vehicle charging. In addition, the value of renewable energy in wholesale power markets can be increased by regulating the rate of vehicle charging and using the storage capacity of an emerging fleet of plug-in cars to meet balancing requirements. The RE2EV concept presented here seeks to exploits this opportunities, while meeting a growing market of environmentally-conscious consumers seeking a clean transportation solution.

3 Wholesale Power Markets

The nation's electric power industry is characterized by numerous industry participants functioning under a variety of business/regulatory structures. As a result of a several decade process to deregulate the generation of electric power, most of the country's electricity is transacted through wholesale power markets managed by independent system operators (ISO), also referred to as Regional Transmission Organizations (See Figure 2). Collectively we refer to these organizations as system operators.

Today, system operators (ISOs/RTOs) serve two-thirds of electric consumers in the US. These independent organizations are charged with providing open access to the nation's transmission system to facilitate greater competition. System operators manage the flow of power and provide a variety of essential services, including the operation of wholesale markets for energy, capacity (in some cases) and ancillary services.

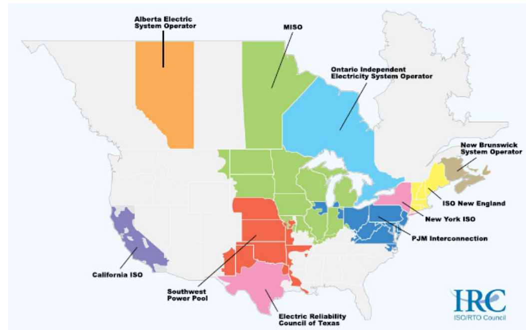

Figure 2: ISO/RTO Map North America

Wholesale power markets create a mechanism for power generating companies to transact with load serving entities (LSEs), which can be retail electric providers, municipally owned utilities and cooperatives. Much of the purchase and sale of electricity between these parties takes the form of a bilateral contract—an obligation on the part of power generating companies to deliver power and on LSE's to purchase that power at an agreed rate over a specified time period.

System operators also operate day-ahead and real-time energy and ancillary services markets. These markets allow power generating companies to sell power not committed through bilateral contracts and LSEs serving loads to buy power beyond what they have procured through bilateral contracts. In practice, market participants can use these various approaches to hedge and manage price risks.

While each system operator has slightly different protocols for day-ahead scheduling, they generally involve qualified market participants providing hourly load and generation schedules. Non-committed generation resources include bid prices, which are used by the system operators to determine market clearing prices for energy, typically based on the last bid that meets the anticipated day-ahead load forecast for each hour.

3.1 Renewable Energy Development in Wholesale Energy Markets

Wind power represents the vast majority of new renewable energy projects being developed in the US today. In 2011, the American Wind Energy

Association estimates that 6,810 MW of new wind capacity was brought online, bringing the total installed wind capacity in the US to 46,919 MW. As discussed earlier, solar photovoltaic (PV) technology historically has been deployed on the customer side of the meter. However, MW-scale PV plants have been installed in several locations in the southwest. The Solar Energy Industry Association estimates that there are currently 809 MW of utility-scale PV projects completed, 3,119 MW under construction, with an additional 19,221 MW under development.

Investment in solar and wind are being driven largely by state renewable energy portfolio standards (RPS), which require utility companies to purchase a percentage of their energy from renewable energy sources. While wind has been the more cost-effective technology to meet RPS requirements, dramatic cost reductions for PV in recent years and solar carve-outs within RPS programs are driving the market for solar technologies. Currently there are 24 states plus the District of Columbia that have RPS policies in place. Together these states account for more than half of the electricity sales in the United States.

Wind and solar are viewed as variable energy resources (VER), in that the output from these sources varies with the availability of the wind and sun. A number of analyses have been conducted, particularly for wind, to better understand the impacts of integrating VER within the context of existing wholesale power market structures. Studies have shown that when the generation from multiple wind farms is aggregated, the relative variability will decrease. By its very nature the electric power system is designed to manage the variability in loads and thus has employed a fleet of generation technologies that serve different functions, from base load power plants to units that are designed for fast ramping to meet peak demand for electricity. At relatively low penetration rates of less than 20% of load, VER can be integrated onto the system with little additional cost [11].

It should be noted that system operators do not have a long history of experience with integrating VER onto the grid. A recent report by the ISO/RTO Council—an organization made up of member system operators—describes potential market structure changes needed to more effectively integrate VER onto their systems (RTO Council). The report states: "…ISOs and RTOs are working toward meeting these challenges by developing and implementing tools such as forecasting methodologies and services such as incorporating VERs into the bidding process and dispatch process and developing additional product offerings in the ancillary services markets witch will help integrate these resources effectively and efficiently into both system operations and wholesale markets." [12]

4 Matching Vehicle Charging with Renewable Energy Production

We propose a new model whereby a LSE is formed specifically to serve load associated with vehicle charging. The LSE would enter into bilateral contracts for renewable energy production with owners of wind and solar generation assets. The LSE would extract a margin based on customers' willingness to pay a premium for renewable energy vehicle charging, while developing systems to regulate the rate of charge and deploy the vehicles' storage capacity to increase the value of the wind and solar power in wholesale markets. This is made possible only with the development of a vehicle to grid (V2G) infrastructure. We call this new business model renewable energy to electric vehicle (RE2EV).

Green Mountain Energy—a retail energy provider—offers its customers a product it calls "Pollution Free^{SM} EV" in select locations in Texas. They guarantee customers purchasing qualified plug-in cars that subscribe to the program that their vehicle will be charged with 100% wind power. Green Mountain Energy is partnering with eVgo, which is an initiative of NRG Energy to build-out a vehicle charging infrastructure. Customers subscribing to the program are given the opportunity to enrol in eVgo's Complete Charging Plan, which combines "Pollution Free^{SM} EV" with a home charging dock and related equipment, and access to a networked charging infrastructure.

The Green Mountain Energy model is different from the RE2EV model being proposed here. Customers pay a premium to support renewable energy production; there is no attempt to coordinate end-use loads with the timing of renewable energy production. The RE2EV model being proposed here seeks to create real-time coordination between renewable energy utility-scale system production and plug-in vehicle charging. This creates a new market for renewable energy projects specifically to meet the new load associated with plug-in vehicle charging, through offering a premium green charging product to plug-in vehicle owners.

4.1 RE2EV Value Proposition

The RE2EV business model rests on capturing the margin associated with plug-in vehicle owners' willingness to pay a premium for a green charging product and maximizing the revenue to renewable energy sources deployed within existing wholesale power market frameworks.

It is well established that electricity is significantly less expensive as a fuel for light vehicles when compared to gasoline. Even relatively expensive forms of renewably-generated electricity compete favourably with gasoline as a fuel. Figure 3 illustrates the gasoline equivalent cost of fuel for electricity under a range of levelized cost of energy (LCOE) assumptions. These calculations assume 4 miles/kWh efficiency of the electric vehicle compared to gasoline-only vehicle getting 35 miles per gallon. Both wind and solar-generated power are less expansive than gasoline as a fuel for light vehicles, with the national average price of gasoline at $3.56 per gallon at the time this article was produced.

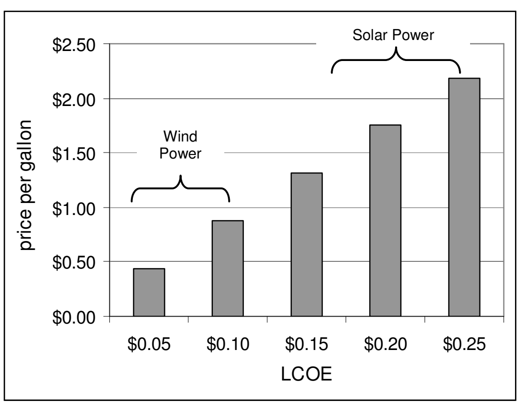

Figure 3: Gasoline Equivalent Price vs. LCOE

Residential and business customers have had the ability to voluntarily purchase renewable energy for homes and facilities for over a decade. Customers in regulated utility markets are often given the opportunity to purchase some portion of their energy from renewables under regulator-approved green pricing programs. A 2010 report by the National Renewable Energy Laboratory (NREL) found that 850 utilities nationally offer green pricing options to their customers [13]. Customers in regions with deregulated markets can choose a retail supplier that offers green power. In addition, many businesses voluntarily purchase renewable energy certificates (RECs) to meet corporate environmental sustainability goals. The Environmental Protection Agency's Green Power Partnership works with organization to encourage the purchase of green power. The EPA's Green Power Partnership program has expanded from 104 partners in May 2003 to 1,203 partners in October 2009. The Partnership members must report the quantity of RECs they purchase annually, which has increased from approximately 83,400 MWh in May 2003 to approximately 13.3 million MWh in December 2009 [14].

There is a growing, robust market for green power, which will very likely carry-over to plug-in vehicle charging. RE2EV would be a premium green charging product offering to customers guaranteeing that most if not all vehicle charging would occur at the precise time when renewable energy is being produced. Vehicle charging represents a very flexible load relative to other end-uses, and thus regulating the timing and rate of charge provides the LSE with greater flexibility, relative to LSEs serving traditional loads. Smart grid technology and an emerging electric vehicle supply equipment (EVSE) infrastructure could be leveraged to provide this premium service to customers.

The US Department of Energy's Green Power Markets listing of utility programs by state shows the premiums for green power can range from less that $0.01 per kWh up to $0.10/kWh [15]. Here in Vermont the regulated utility Central Vermont Public Service offers customers power from cow methane digesters at a $0.04/kWh premium. This gives a rough range of the value that consumers might place on green charging. It could be argued that an even higher premium may be realized based on the premium nature of the RE2EV model.

The value a LSE could create from maximizing the revenue for VER participating in wholesale power markets is more difficult to determine and would be region specific, depending on the wholesale market structure and rules. As noted earlier, many studies have found that plug-in cars providing energy storage can help integrate wind and solar onto the grid. These studies focused on the technical potential. Several studies have tried to quantify the value of bulk storage to wind power projects [16] [17] [18].

A study on wind integration by the NY Independent System Operator found: "The typical diurnal pattern for wind generation peaks late at night and is lowest during the day. The price of energy typically follows the load pattern, with costs lowest at night and highest during the day. The ability to take advantage of the spread between on- and off-peak prices creates value for additional energy storage in New York."

Hirst (2001) analyzed the interactions of wind farms with bulk-power operations and markets and finds that the value of wind can be enhanced through scheduling wind power ahead of time. Furthermore, Hirst discusses the increased cost associated with wind integration from the need to move other generating resources up and down in response to the uncontrollable, unpredictable, and variable wind fluctuations. Pairing energy storage with wind power systems could mitigate these challenges and thus increase the revenue from wind generators.

A more recent study by Ramteen (2011) arrived at a similar conclusion, "…that coupling energy storage with wind generation can increase the selling price of wind and the profits of a wind generator. This increase in the price of wind benefits wind generators and can help to further incent investment in wind capacity." Although the study found that the cost of existing storage technologies cannot yet be justified by the increased value it provides to wind power systems. The RE2EV concept presented here leverages investments in storage for transportation and thus the capital investment need not be justified by the value it delivers solely to enhancing the value of wind power in wholesale power markets.

At mentioned prior, utility-scale solar projects are entering a growth phase. The same benefits that storage brings to wind are relevant to solar as well. One study found that storage paired with PV can increase the use of PV production on an integrated grid [19]. If VER can schedule their output in advance and minimize the variance between scheduled and unscheduled energy in real-time using storage, the value of renewable energy systems can be enhanced.

The value that RE2EV can bring will be location dependent, based largely on the wholesale market structures and rules. Additional research is needed to indentify specific market rules that can create barriers to efficient RE2EV implementation and more detailed analyses of the increased value RE2EV can create for REV systems.

4.1.1 Meter Roaming

The more hours in a given day that a plug-in vehicle is connected to a smart EVSE infrastructure that the LSE can access, the greater value RE2EV creates for the customer and VER. Today's metering infrastructure needs to evolve similar to the evolution of the cell phone infrastructure, allowing LSEs to access a networked charging infrastructure to deliver their services. Here we refer to this as meter roaming.

Today the accounting for electric power delivery and consumption occurs through stationary power meters. RE2EV would require that plug-in vehicle owners be able to establish a separate metered account for their vehicle, using an on-board utility-grade meter. Electricity metering for the vehicle is decoupled with a customer's household energy metering. Consumers could choose to select an energy supplier for vehicle charging that is potentially different than the retail provider for their home energy needs.

The EVSE infrastructure is in its early stages of development dominated by third-party developers, including the ChargePoint Network and the eVgo Network. The revenue and business models for EVSE access are similarly in the early stage of development. A model that allows LSEs to deliver power through third-party owned EVSE infrastructure with appropriate compensation for access would help to accelerate the RE2EV business opportunity.

A European-based study suggests a similar business model to RE2EV termed Electric Recharge Grid Operators (ERGO) [20]. The ERGO business model creates a market for coordinated production and consumption of renewable energy leveraging large open access EVSE networks likes those being developed in Israel and Denmark by Project Better Place.

Single ownership of the EVSE infrastructure reduces the barriers to meter roaming, but could create market power issues.

A full analysis of current trends in EVSE deployment models, payment mechanism, and the necessary changes to accommodate RE2EV is beyond the scope of this paper. It is important, however, to emphasize the advantages of an open-access EVSE infrastructure to realizing the full potential of RE2EV. Customers gain value from a premium green charging product, while supporting the development of new renewable energy projects specifically focused on meeting the demand for electricity for vehicle charging.

4.1.2 Early RE2EV Commercial Developments

Earlier this year, General Motors announced a pilot program with Google to use their OnStar vehicle communication system to communicate with the system operator PJM. PJM will provide information to vehicle owners through OnStar on the percentage of renewables being produced on their system in real time. The demonstration will allow Google to control the charge timing of 17 Volts to periods when the percentage of renewables on the system is highest. This is an early step toward the RE2EV concept, which envisions tightly linking renewable energy production with vehicle charging. Ironically, this demonstration is using the amount of renewables on PJM's system along the mid-Atlantic region to determine the timing of charging of Google vehicles located on the west coast in California.

A recent smart grid start up called GridMobility has developed a suite of technologies and software solutions to deliver renewable demand response (RDR) services. GridMobility is developing the type of solutions that could soon make RE2EV a reality. The company's web site states, "GridMobility has developed patent-pending technology enabling the ability to report electricity generation sources in real-time empowering electricity consumers to actively manage their power consumption." [21]

5 Conclusions

The transportation sector is entirely dependent on a single primary fuel source—petroleum. A growing consensus has formed that electrification is the best, nearest-term strategy to reduce the nation's dependence on petroleum for the transportation sector. An increasing number of plug-in vehicle options are emerging in the market place; GM with its hybrid Volt and Nissan with its all electric Leaf were first to market in the US. The number of plug-in cars for the car-buying public to select from is set to expand in the coming years.

The RE2EV business model envisions the formation of an LSE dedicated to coordinating vehicle charging with renewable energy production. A potentially significant margin could be extracted based on customers' willingness to pay a premium for RE2EV services and the increased market value of wind and solar energy from the use of V2G systems. The LSE would enter into bilateral contracts with wind and solar generation resource owners at fixed rates, while regulating the rate of vehicle charging and accessing the stored energy through V2G systems to increase the value of the energy delivered in wholesale markets for power.

Given the potential benefits of increasing the number of hours that the fleet of plug-in cars managed by the LSE is connected to the grid, meter roaming is a key innovation for RE2EV. Access to a third-party EVSE infrastructure with appropriate access fees would allow the LSE to serve vehicle load across a wide geographic area, thus appealing to a broader array of customers. This would be less critical if RE2EV was first deployed with fleets, which tend to have regular use patterns by time of day and location.

Additional research is needed within specific system operator service territories to quantify the increased value that RE2EV service providers could achieve for wind and solar energy delivered within the wholesale market. This is dependent on existing market structures and rules. The ability to bid in the day-ahead market has been identified as a market rule for VER that serves to increase the revenue to renewable energy generators.

RE2EV enabling technology is being developed by smart grid start-ups like GridMobility and GM is using its OnStar communication system to demonstrate an early, rudimentary model of RE2EV.

Acknowledgments

List acknowledgments here if appropriate.

References

[1] S. Hadley & A. Tsvetkova, *Potential impacts of plug-in hybrid electric vehicles on regional power generation*, Oak Ridge National Laboratory: ORNL/TM-2007/150, 2008.

[2] S. Letendre et al., *Plug-in hybrid vehicles and the Vermont Grid: A scoping study*, a University of Vermont Transportation Research Center Report, 2008.

[3] M. Kintner-Meyer, et al., *Impacts assessment of plug-in hybrid vehicles on electric utilities and regional U.S. power grids part 1: Technical analysis*: Pacific Northwest National Laboratory, PNNL 2007.

[4] S. Letendre, *Solar electricity as a fuel for light vehicles*, Proceedings of the American Solar Energy Society, 2009.

[5] T. Hoff, *Solar sustained vehicles (SSV): A consumer's solution to protection in an age of oil dependence, economic uncertainty, and global warming*, Proceedings of the American Solar Energy Society, 2009.

[6] F. Tuffner & M. Kinter-Meyer, *Using electric vehicles to meet the balancing requirements associated with wind power*, Pacific Northwest National Laboratory, PNNL 20501, 2011.

[7] H. Lund & W. Kempton, *Integration of renewable energy into the transport and electricity sectors through V2G*, Energy Policy, 36 (2008), 3578-3587.

[8] W. Short & P. Denholm, *A preliminary assessment of plug-in hybrid electric vehicles on wind energy markets*, National Renewable Energy Laboratory, Technical Report, NREL/TP-620-39729, 2006.

[9] W. Kempton & J. Tomic, *Vehicle-to-grid power implementation: From stabilizing the grid to supporting large-scale renewable energy*, Energy Policy, 144 (2005) 280-294.

[10] S. Letendre, et al., *Battery-powered electric drive vehicles providing buffer storage for PV capacity value*, Proceedings of the American Solar Energy Society, 2002.

[11] M. Milligan et al., *Wind power myths debunked*, IEEE Power & Energy Magazine, November/December 2009.

[12] ISO/RTO Council, *Variable energy resources, system operations and wholesale markets*, IRC Briefing, 2011.

[13] L. Bird et al., *Voluntary green power forecast through 2015*, National Renewable Energy Laboratory, Technical Report, NREL/TP-6A2-48158, 2010.

[14] US EPA Green Power Partnership, http://www.epa.gov/greenpower/, accessed on 2012-02-25.

[15] US Department of Energy Green Power Network, http://apps3.eere.energy.gov/greenpower/markets/pricing.shtml?page=1, accessed on 2012-02-25.

[16] R. Gonzalas et al., *Integration if wind into system dispatch*, New York ISO White Paper,

[17] E. Hirst, *Interactions of wind farms with bulk-power operations and markets*, Project for Sustainable FERC Energy Policy, 2001.

[18] S. Ramteen, *Increasing the value of wind with energy storage*, The Energy Journal, 32, 2, (20011).

[19] P. Denholm & R. Margolis, Evaluating the limits of solar photovoltaics (PV) in electric power systems utilizing energy storage and other enabling technologies, Energy Policy, 35 (2007) 4424-4433.

[20] P. Anderson et al., *Integrating private transport into renewable energy policy: The strategy of creating intelligent recharging grids for electric vehicles*, Energy Policy 37 (2009) 2481–2486.

[21] GridMobiliy, http://www.gridmobility.com/solutions/, accessed on 2012-02-25.

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