# Feasibility of Electric Cars Powered by Renewable Energy

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As concerns grow regarding the ever increasing use of fossil fuels, interest in vehicles powered by alternative energy sources continues to develop. This study investigates the feasibility of charging electric cars in Ontario, Canada with electricity generated from renewable sources. Two main implementation methods are considered and analyzed, including charging electric cars directly from a grid with an enhanced renewable power generation capacity, and charging from small isolated off-grid systems powered entirely by renewable sources. In 2006, Ontario used nearly as much energy in the form of gasoline for personal transportation (118.6 TWh) as it used in the form of grid generated electrical energy (151 TWh). However, the much greater thermodynamic efficiency of electric motors compared to internal combustion engines means that the grid would need to provide approximately 28 TWh of additional renewable energy per year to displace all gasoline used for personal transportation. If the majority of electric vehicles are charged during off-peak hours, this new load could be met by Ontario's existing generation capacity. Alternatively, 28 TWh is equivalent to approximately 5100 2.5 MW wind turbines operating at a capacity factor of 25%. Based on the historical cost of wind energy in Ontario, and the expected average energy demand (16 kWh/day) of the Chevrolet Volt (a new electric vehicle expected in 2010), the cost of charging from grid connected wind farms is estimated to be between $900 and $1086 per car per year. Alternatively, a small off-grid system in Guelph, Ontario powered entirely by solar energy could generate 500 kWh/month, with an installation cost of $56k. A similarly sized system powered by a small wind turbine in Guelph could generate 530 kWh/month, with an installation cost of $44k. These price estimates are considerably higher than the Volt's expected retail price of $35-$40k. Both of these isolated systems can generate enough energy on an annual basis to meet the Volt's energy requirements. However, simulations (carried out using Simulink, a MATLAB tool) have shown that due to the variability of wind, a very large on-site storage capacity would be required to meet the daily energy demand of the vehicle in Guelph. For a site in the city, the required energy storage system capacity is prohibitively high. The most feasible way of charging electric cars using renewable energy is through grid-based large scale renewable power plants.
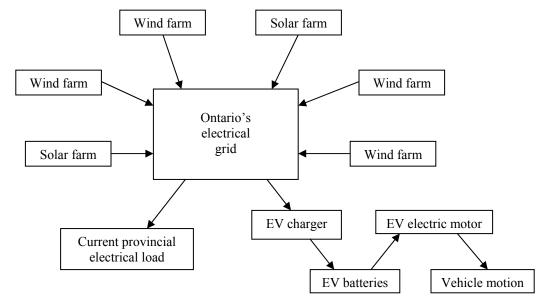
## Nomenclature

| | | |
|---|---|---|
| E | = | Energy |
| P | = | Power |
| T | = | Time |
| ESS | = | Energy Storage System |
| SOC | = | State of Charge |
| EV | = | Electric Vehicle |

## I. Introduction and Overview

The vast majority of vehicles that are driven in Canada today derive their energy from gasoline or diesel through the use of internal combustion engines (Transport Canada, 2008). However, a small but growing number of electric vehicles (EVs) also exist, and are available throughout the country. The availability of EVs is expected to continue to increase in the near future, as automotive companies such as General Motors, Tesla Motors, and ZENN Motor Company strive to provide Canadians with the opportunity to purchase economically competitive electric cars. The question has been raised as to where the energy that will charge these cars will come from. The purpose of this study is to determine the feasibility of charging electric cars with electricity generated from renewable sources in the Canadian province of Ontario. Specifically, wind and solar energy are considered. Ontario, specifically the city of

Guelph, is used as a case study here, but the general method could be applied to other cities, provinces or regions.

Two different approaches are considered for supplying renewable energy to charge electric cars. In both cases, a standard car (the Chevrolet Volt) is used as the vehicle to be charged, in order to maintain consistency. The first approach assumes that the power for charging the car is provided by distributed renewable energy plants located throughout the province, and delivered through the provincial power grid. Figure 1 contains a diagram showing the flow of power from the renewable sources to an EV's battery.

**Figure 1. Flow of energy from renewable sources to charge one or more EVs. Power is generated at distributed facilities and added to the grid. Electric cars charge their batteries from this increased renewable capacity. The energy is eventually converted into vehicular motion by an electric motor.**

The implications of a large number of electric cars charging in this manner are investigated. Assuming that all gasoline powered cars in Ontario are replaced by electric cars, the total increase in energy demand from the grid over one year is estimated, taking into account the much higher thermodynamic efficiency of an electric motor when compared to that of an internal combustion engine (Çengel and Boles, 2002). Based on the magnitude of this load increase, the total new renewable power generating capacity on the grid required to charge all cars is estimated.

Alternatively, an EV could be charged from an isolated off-grid system powered by renewable energy. One possible set up of such a system, and the flow of energy through it, are shown in figure 2. Energy is derived from a renewable source, such as solar or wind. If a wind turbine is used, a generator will convert the energy into electricity (if solar power is used, a generator is not needed). On-site power electronics (such as a transformer, a rectifier, and an inverter) and are used to convert the power into a form that is reliable and useable by the vehicle.
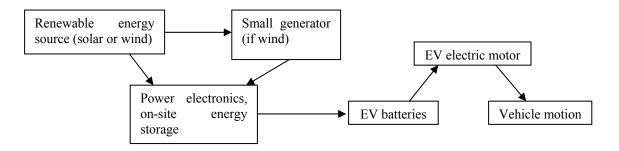
**Figure 2. Flow of energy from renewable source to charge a single EV from an off-grid system. Electrical power is generated by a small renewable power source. On-site power electronics and energy storage condition the power such that it can be used to charge the EV's battery.**

The potential scale of such a system could vary. It could be located on the car owner's property and designed to provide power to a single vehicle, or it could be in a central location in a neighbourhood and designed to provide power to a larger number of vehicles. Two main system configurations are investigated: one where the car's energy needs are met entirely by solar energy and another where the car's energy needs are met entirely by wind energy. Size and cost estimates of both system configurations are made. Another key consideration for such systems is how the energy will be stored when the vehicle is not on-site. This is necessary to enable the system to collect energy at times when the car is not present for later use. Methods considered include batteries, hydrogen, and pumped water storage. Once the system scale, energy source, and on-site storage method are determined, a preliminary system design is completed using currently available components. Based on the preliminary design, the off-grid charging system is simulated using Simulink (a MATLAB tool) to predict its ability to meet the energy demand of the vehicle. Conclusions are given regarding the system's capabilities. As well, more general conclusions are drawn regarding the feasibility of powering electric cars with renewable energy.

## II. Electric Cars

The following description of the history and development of electric cars is based on McNicol and Rand (1984), unless otherwise noted. Electric cars first appeared in the late nineteenth century, and for a time, they were produced in greater numbers than vehicles powered by internal combustion engines. However, as advances were made in internal combustion engine technology, battery powered cars fell out of favour. From a practical point of view, batteries could not and still cannot compete with gasoline as a power source for vehicles for many reasons. Gasoline has much greater energy and power densities than even modern batteries. Electric vehicles require large batteries, which can weigh up to several hundred kilograms, and even then, the range provided by the batteries is much lower than the range of a conventional car powered by fossil fuels. Gasoline stores energy well, while a charged battery will slowly discharge itself over time if left alone. Batteries have durability issues; their life cycles are limited and they must be replaced after a limited number of charging cycles. These are only some of the advantages of gasoline over batteries. A more detailed discussion can be found in McNicol and Rand (1984).

It was not until relatively recently, starting in the 1970s, that interest in electric cars was renewed. Reasons for this renewed interest included concerns regarding the environmental effects of internal combustion engines, the long term supply of fossil fuels, and the increasing cost of gasoline and diesel. General Motors released the first modern production electric vehicle from a major automaker, the GM EV1, in 1996 (Motor Trend, 2004). However, driving range limitations, lengthy charging times, and high production and development costs resulted in the EV1 being discontinued in 1999 (Motor Trend, 2004). Other electric vehicles released in the same time period but discontinued shortly later include an electric Ford Ranger, the Toyota RAV4 EV, and the Honda EV+. Currently available electric vehicles include the Tesla Roadster (Tesla Motors, 2008), and the Zero Emission, No Noise (ZENN) neighbourhood electric vehicle (ZENN Motor Company, 2008). Several major automotive manufacturers plan on introducing new electric vehicles in the near future, notably General Motors with the Chevrolet Volt (GM, 2008), and Toyota with the next generation Prius (Motor Trend, 2008). Recent developments, such as volatile and high oil prices and continually improving battery technology, have potentially increased the viability of electric vehicles to the point where they are competitive with similarly priced conventionally powered vehicles. It seems likely that electric vehicles will be on the roads in great numbers in the near future.

## III. Ontario's Energy Use

The feasibility of charging large numbers of electric vehicles directly using Ontario's existing power grid and generation infrastructure is investigated. Consumption of different forms of energy in Ontario in 2006 is shown in Figure 3, and summarized in Table 2 (NRC, 2007; IESO, 2007). 118.6 TWh of energy was used in Ontario in 2006 in the form of gasoline for personal transportation (NRC, 2007). Assuming that this chemical energy was converted to useful work at an average efficiency of 20%, which is a common estimation of the efficiency of an internal combustion engine (Johnson, 2008), 24TWh of work was actually done for vehicle propulsion. Electric motors have a much greater efficiency than internal combustion engines, since they are not limited by the Carnot efficiency (Çengel and Boles, 2002). To estimate the required increase in electrical generation required to replace this 24 TWh of work, the total efficiency of the electrical distribution system must be considered along with the efficiency of the vehicle's charger. This is referred to as the generator to wheel efficiency, and can be approximated as the product of the efficiencies of each step in the flow of energy, which are included in table 1. An ideal case of 100% efficiency is assumed for the charger. The overall efficiency is calculated using optimal efficiency values.

Assuming a generator to wheel efficiency of 85%, the generation of approximately 28 TWh of electrical energy could displace the 118.6 TWh of chemical energy used from gasoline. It should be kept in mind that this is an ideal estimate and the actual efficiency would be lower in reality. Adding this to the total electrical energy consumed in Ontario in 2006, which was 151 TWh, it is estimated that 179 TWh of energy would needed to meet current electricity needs while also displacing all gasoline used for personal transportation. Depending on how Ontario's electrical load can be most efficiently met, some power may be

**Table 1 – Approximate efficiencies of each major electrical component from generator to wheel. These are rough estimations only. Taken from Ryff (1994).**

| Step | Approximated Efficiency |
|---|---|
| Transformer | 92%-99% |
| Transmission | 95% |
| Transformer | 92%-99% |
| Charger | 100% |
| Electric Motor | 92% |
| **Overall Generator to Wheel** | **85%** |

imported or exported from the province. However, since the vast majority of power consumed in Ontario is also generated here, imports and exports are assumed negligible for this analysis.

A power plant's capacity factor is defined as the ratio of its actual energy output over a period of time to the energy output of the power plant if it were running at its full rated capacity for the entire time period. In the case discussed here, Ontario's capacity factor over the full year based on currently installed generation would increase from 55% to 65%, representing an increase in load of 18%. Due to practical constraints, the province's maximum capacity factor is lower than 100%. The actual magnitude of the highest possible capacity factor at any given time would depend on the availability of each specific power plant at that time (for example, a specific plant may be shut down for maintenance). The determination of this peak capacity factor, which would vary with time and load ramp rate, is a very complex problem and as such is beyond the scope of this paper. Based on these calculations, it is seen that the increased load due to charging electric cars would not be negligible. Annual energy demand would increase significantly if all gasoline powered vehicles were replaced by electric cars. However, from an energy point of view, Ontario's existing grid does have the capacity to meet this increased demand.

Although on an annual energy basis, the generation capacity exists to meet the projected need, charging cars directly from the grid will also increase the instantaneous power demand. 28 TWh of electricity generated per year is equivalent to an average power of 3.2 GW or 3,200 MW. The actual charging load would vary greatly depending on factors such as the time of day, time of year, and weather. The makeup of Ontario's existing installed electrical generating capacity is shown in Figure 4. The record peak energy demand for the province is 27,005 MW, which occurred on August 1, 2006 (IESO). Combining this actual peak demand with the estimated average demand due to charging vehicles, the estimated total peak power demand is 30,205 MW. Although this is lower than the total installed capacity, it should be kept in mind that at any given time, a large fraction of Ontario's generating capacity may not be available due to maintenance or other issues (IESO, 2008). As well, this estimate is based on the average charging load as opposed to the expected maximum charging load, the magnitude of which could be investigated in future studies.
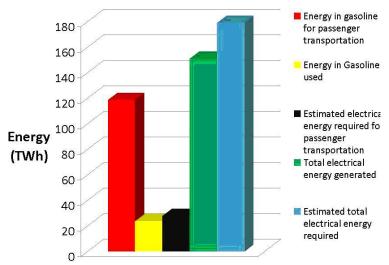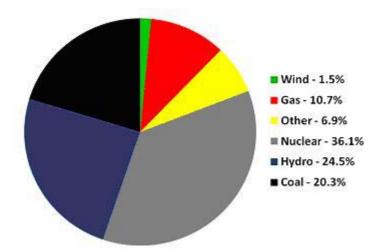


**Figure 3. Energy use in Ontario, 2006. Energy used in the form of gasoline is on the same order of magnitude as the total electrical energy generated. Data taken from IESO (2008).**

**Figure 4. Ontario's installed electrical generating capacity. October 2008. Total capacity is approximately 31,600 MW. Data taken from IESO (2008).**

**Table 2 – Energy use in Ontario in 2006** (NRC, 2007, and IESO, 2008)

| Form of Energy | Magnitude of Energy (TWh) |
|---|---|
| Gasoline for passenger transportation | 118.6 |
| Energy in gasoline used | 24 |
| Estimated electrical energy required for passenger transportation | 28 |
| Total electrical energy generated | 151 |
| Estimated total electrical energy required | 179 |

**Table 3 – Relevant Chevrolet Volt specifications (GM, 2008)**

| | |
|---|---|
| battery chemistry | lithium-ion |
| energy storage system capacity | 16 kWh |
| battery mass | 170 kg |
| charging time (through conventional outlet) | 8 hours |
| charging load | ~2 kW |
| vehicle range on battery alone | 64 km |
| generator fuel | gasoline, E85 |
| engine volume | 1.4 L |
| generator power | 53 kW |
| electric motor power | 120 kW |
| estimated price | $35-$40 k |

Estimating the timing and frequency of when utility users will charge their vehicles is a complicated problem, and outside the scope of this study. Ideally, electric vehicle owners would charge their cars during off-peak hours. Assuming that each car requires 2 kW of power while charging, a simple calculation shows that if 100,000 cars are charging at the same time, the total increase in power demand would be approximately 200 MW. If 500,000 cars are charging at the same time, the power demand would increase by 1 GW. An increase in load of this magnitude could be handled if experienced during off peak hours.

To summarize, it has been shown that the increases in both annual energy demand and instantaneous load related to charging electric vehicles are non-negligible compared to the magnitude of Ontario's existing total generation capacity. The potential increase in instantaneous power demand due to electric vehicle charging is large enough that Ontario's existing generation capacity would not be able to meet it if a large number of vehicles are charging during times of peak load. This is consistent with findings for regions in the United States (Pacific Northwest National Labs, 2006). Determining the specific generation and infrastructure improvements required to handle the increase in annual energy demand and instantaneous load is outside the scope of this study.

## IV. The Chevrolet Volt

In order to define the criteria and constraints of a system capable of charging one or more electric vehicles, it is necessary to define an electric car's general specifications, such as its energy requirements and charging needs. For the purposes of this study, it is assumed that the electric car to be charged will be the Chevrolet Volt, or another car with similar specifications. The Volt will be an extended range electric vehicle (EREV), a new concept from GM. Expected to be released in late 2010, the Volt will be similar to a plug-in, or series, hybrid. The vehicle will have a large enough battery that it is capable of travelling a limited distance entirely on electric power. There are two main ways in which the battery can charge. It can plug into and draw energy from an external source, such as the electrical grid. Alternatively, the Volt is equipped with a small internal combustion engine, powered

by gasoline or ethanol, that can directly charge the battery. This enables the Volt to either travel a limited distance entirely on electrical power, and use no fossil fuels, or travel an extended distance by using its onboard engine and generator. Table 3 summarizes relevant characteristics of the Volt, as made available by General Motors at the time of writing.

## V.  Charging from Grid Based Renewable Energy

It has been estimated that the additional generation of approximately 28 TWh of electricity per year could displace all the energy in gasoline used for personal transportation in Ontario. Assuming that wind power is used to meet the increase in demand, the GE2.5xl 2.5 MW turbine is used as a case study. Using an average capacity factor of 25%, which is a conservative estimate for Canada (Canadian Wind Energy Association, 2008), the energy generated by each turbine is calculated.

Each turbine will generate an average of 5.5 GWh of energy per year. Approximately 5100 turbines would be needed to meet the specified energy demand. Looking at the increase in electrical load another way, each turbine will generate an average of 15 MWh per day. If each car requires 16 kWh of energy per day, each turbine could provide power to over 900 cars. The Ontario Power Authority (OPA), which is responsible for purchasing the electrical power that is supplied to the grid from power producers in Ontario, reports that the cost of  the wind energy it purchased from major producers from 2003 to 2007 ranges from \$77 - \$93 per MWh (OPA, 2008). At this rate, the generation of 28 TWh would cost between \$2.16 billion and \$2.60 billion. Assuming each Volt uses 16 kWh per day, or 5.84 MWh per year, it will cost from \$450 -\$543 to generate enough energy for each vehicle per year. These costs reflect the price paid by the OPA for generating power, and do not include transmission costs or the costs of corresponding improvements in infrastructure. Large grid infrastructure improvements would likely be needed to move this electricity from the wind turbines located in windy rural areas to the predominantly urban electric vehicle charging locations. Assuming transmission costs are roughly double generation costs, it will cost an electric vehicle owner between \$900 and \$1086 to charge their car each year.

## VI.   Off-Grid Charging System

This section examines the feasibility of an off-grid charging system in Guelph, Ontario. Compared to grid-connected large-scale renewable energy plants, such a system has several pros and cons. No grid infrastructure improvements are required for this system to work. It is self contained, isolated, and would enable a higher degree of energy independence. However, since the system would be much smaller than a comparable grid based solution, it would likely cost much to charge a single car more due to economies of scale. This is especially true for a wind-based solution. As turbine size increases, the power coefficient typically increases, resulting in greater power output per unit of swept blade area. The cost per installed Watt of wind power becomes cheaper as turbine size increases (Manwell et al, 2002). For both wind and solar-based solutions, the physical size of such an off-grid system may be prohibitive, since the average car owner may not have access to large plots of land in especially windy or sunny areas.

### A.  Energy Sources in Guelph, Ontario

Again, it is assumed that the Chevrolet Volt requires 16 kWh/day, or 480 kWh/month. Wind and solar are both considered as energy sources. A biodiesel generator was also briefly considered to generate the required electricity; however, it was decided that it would be much more efficient, cost effective, and simple to use biodiesel to directly power the vehicle in an onboard internal combustion engine, as is already commonly done.

Guelph's maximum annual average irradiation for a fixed flat plate solar panel is calculated to be 262.9 W/m$^2$ using the solar irradiance model provided by McQuiston et al (2005). A common and popular solar panel is the Sharp NT-185U1, which provides maximum power and efficiency of 185 W and 17.5%, respectively (Sharp, 2008). As a conservative estimate, the average efficiency is assumed to be 10%. The panel has an area of 1.3 m$^2$ and costs \$1200. From the panel's specifications and Guelph's solar resource, the average power production of the panel is 26 W/m$^2$, or 18.7 kWh/m$^2$/month. 26 m$^2$ of solar panels are needed, which can be met by using 20 of the Sharp panels. The estimated cost of the panels alone is roughly \$24,000. Sharp provides a clean power estimator on their website which estimates the total cost of a system based on its location and energy requirements (Sharp, 2008). For a system located at Guelph's latitude (43.54° N) that must provide 16 kWh/day, Sharp estimates a total cost of \$56,000.

From the Ontario Wind Atlas, Guelph has a 10 m wind speed of 3.78 m/s. This makes the city a class 1 resource, which is considered generally unsuitable for wind energy development. A Bergey Excel-R 7.5 kW small turbine is selected (Bergey, 2008). This turbine is optimized for battery charging at low wind speeds, which makes it ideal for this application. The Bergey XL-R's power curve is shown in figure 5.
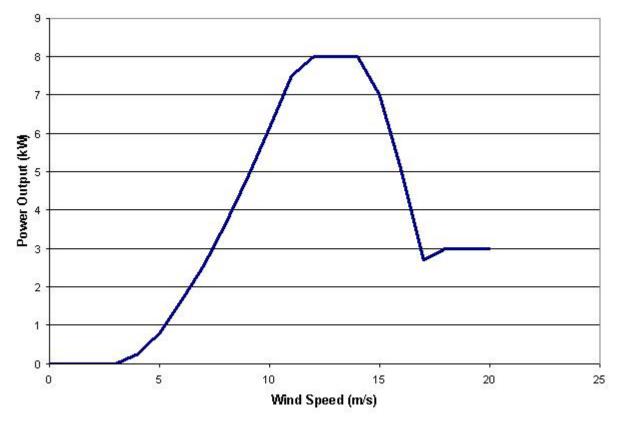
**Figure 5. Bergey XL-R power curve, taken from the brochure on the Bergey website (2008).**

The Bergey design is proven and widely used worldwide. The turbine itself is an upwind three blade design with a rotor diameter of 6.7 m. According to the turbine's specification sheet (Bergey, 2008), with an 18 m tower and Guelph's wind resource, approximately 530 kWh will be generated per month. The turbine and tower cost $23,500 and $10,150, respectively.

Both solar and wind power could provide sufficient energy to charge the vehicle on a daily basis. The following analysis of the off grid charging system will be conducted assuming that the wind is chosen as the energy source. This is mainly due to its lower expected cost. However, a solar array has many advantages over a wind turbine including easier installation and little to no maintenance requirements. Perhaps most importantly, a solar array on the roof of a house is much more likely to meet local zoning regulations than even a short turbine tower.

### B. Scale of Charging System

Two general concepts were considered regarding the scale of the system. It could be designed to charge all vehicles in a residential neighbourhood, which would require users to park their cars and plug them in to the system at a central location, and walk a short distance to their home. Alternatively, the system could be designed to be located right on the owner's property, and to provide power to a single car. It is thought that a system designed to charge a single vehicle would be simpler than a system that must charge multiple vehicles. For this reason, the system will be designed to charge a single vehicle. Higher cost is a major drawback to this scale, since a system designed to charge multiple vehicles would use a larger turbine, taking advantage of economies of scale as previously discussed. A more in depth design of a larger system could be pursued as further work, building on the initial simpler design seen here.

### C. On-site Energy Storage

Storing energy on-site is essential in order for the system to be able to collect energy while the car is not present. When the car returns, the system can charge the vehicle's onboard battery using energy collected and stored during the car's absence. Many storage methods were considered. Battery chemistries considered were lithium-ion, lead

acid, nickel metal hydride, and nickel cadmium. Other storage technologies briefly considered include hydrogen, a flywheel, pumped storage, compressed air, and ultracapacitors. A detailed, thorough analysis of each energy storage technology is beyond the scope of this paper and could be pursued as part of further work. Lead acid batteries are chosen as the energy storage method due to their being a common, well known, proven, and relatively inexpensive technology. However, other energy storage methods show definite potential and may be more suitable to this application in the future. A total energy storage system capacity of 44.4 kWh was chosen as an initial value for the design. This represents 40 of the chosen batteries.

### D. System Configuration

The system configuration as described in the above sections is shown in figure 6. Power is transmitted from the wind to the turbine, and then to the generator, where it is converted into DC electrical energy. A charge controller limits the current flow from the generator to prevent damage to other system components in case of uncontrolled increases in output voltage caused by highly turbulent winds. The DC power centre decides whether to send the power to the battery, or to the vehicle through the inverter. If the wind isn't blowing, the DC power centre controls the power transfer from the battery bank through to the vehicle. The entire system is DC until it power reaches the inverter, which converts the power to AC. Specifications of each system component are shown in Table 4.
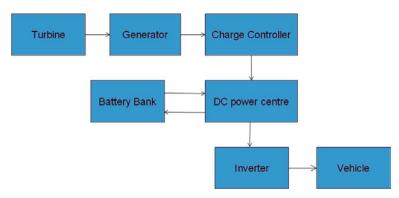


**Figure 6. Proposed configuration for an off-grid, wind/battery hybrid electric car charging system.**

**Table 4. Specifications of system components. A description of each component's purpose is included, as is the cost.**

| Component | Description | Purpose | Price |
|---|---|---|---|
| Turbine / generator | 7.5 kW Bergey Excel-R 240 VDC | Convert kinetic energy in wind to electrical energy | $23,500 |
| Charge regulator | 240 VDC | Limits rate at which current is drawn or added to batteries | Included with turbine |
| Tower | 18 m (60 ft) lattice construction, includes guy wires, anchors, and all associated hardware | Mount turbine higher, to expose it to stronger wind | $10,150 |
| Tower wiring kit | Includes fused disconnect switch, lightning surge arrestor | Transmit electrical power from turbine to base | $1,075 |
| Battery bank | 40 Trojan T-105 6V Deep cycle batteries<br>• 185Ah @ 5 hr<br>• 4.44 kWh capacity | Store energy, enable charging when wind is not blowing, increases reliability of system | $159.00 / battery * 40 batteries = $6369 |
| DC power centre | DC bus and controller for all system inputs and outputs | Controls DC system | $850 |
| Inverter | Pure sine wave, off grid<br>• 2.5 kW, 120V, 60 Hz | Converts DC from battery or turbine to AC, which is required to charge the car | $2,295 |

## VII.   Simulation of Off-grid System

A simulation of the system was created using Simulink, a MATLAB (version 7.0.1) tool used for modeling, simulating, and analyzing dynamic systems. The purpose of the simulation was to verify the system's performance over a long period of operation, specifically, the first half of 2007. The system's ability to meet the energy demand as needed is evaluated, and the energy storage system's SOC is predicted as a function of time. The energy wasted by the system (that is, excess energy that could have been captured by the turbine but was not, since the energy storage system was already fully charged) is also shown as a function of time. The use of a simulation allows the effects of modifying system parameters, such as the battery capacity, to be easily seen and analyzed.

### A. Simulation Inputs

Wind data spanning the first half of 2007 was taken from a weather station at the Guelph Turfgrass Institute (GTI) in Guelph, Ontario (University of Guelph, 2008) and used as input for the simulation. The raw wind data is time averaged over a period of one hour. An entire year or even longer would ideally be simulated, but the required data was not available. The weather station at the GTI measures the wind speed at 10 m. The average wind speed at this height is 3.38 m/s, which is lower than the 3.78 m/s average speed found for Guelph at 10 m in the Ontario Wind Atlas. Wind speeds at the chosen tower height (18 m) were estimated using the power law with a shear coefficient of 1/7.   Even at 18 m, the average wind speed is only estimated to be 3.68 m/s.

The Bergey turbine's power curve (as seen in figure 4) is required for the simulation in order to predict the output power of the generator based on the input raw wind speeds. The initial state of charge of the battery is set at 100%.

The vehicle's charging schedule is specified as part of the simulation. The system needs to know whether to route power directly from the turbine to the vehicle, from the turbine to the battery, from the battery to the vehicle, or not at all. In reality, there are three possibilities for the vehicle's status at any given time. First, it may be present and needing a charge. It is assumed that this occurs from 11 pm to 7 am daily, since this is expected to be the most common time when the vehicle will be present. Second, it may be present, but not need charging, in which case the battery bank will be charged. It is assumed that this is from 7 am to 8 am daily, when it should already be fully charged, and from 5 pm to 11 pm daily, when the vehicle may or may not be present. The last possible vehicle status is "not present," in which case the system will charge the battery bank. Depending on the wind resource over a short period, there may be circumstances where both the vehicle and battery bank are fully charged. In this case, in actuality, the brake will be applied to the turbine to prevent overcharging and damage to any system components. However, for the purposes of the simulation, this excess power will be measured throughout the simulation period and totalled at the end to determine the total unused but accessible energy.

### B. Description of Simulation Process

The following calculations are completed at each time step. From the input wind speed, the electrical power output of the generator is calculated. The load from the car is either 0 kW or 2 kW, depending on the time. This load is subtracted from the power output of the turbine. At this point, the power will be negative if the power output of the turbine is less than 2 kW and the car is charging at the time. This power signal is added to the battery's state of charge at the previous time step. If the power signal is negative, then the battery's state of charge will decrease, representing a drain caused by the load. If the power signal is positive, then the battery's state of charge will increase, representing a charge on the battery. Simulating the system as described here could potentially result in a "negative" SOC in the battery. If this happens, the simulation will continue to run as normal. However, a negative SOC is unacceptable, since it means that the system is no longer providing enough power. Whether or not the battery's SOC decreased to below zero at any time can be determined by looking at the SOC as a function of time once the simulation is complete. This is the key indication as to whether or not the system can provide enough power. As well, the battery's SOC can only increase to its maximum capacity, which is initially set to 44.4 kWh. Any excess charge is kept track of throughout the simulation in order to calculate the total unused energy at the end. Figure 7 shows the Simulink model as described.
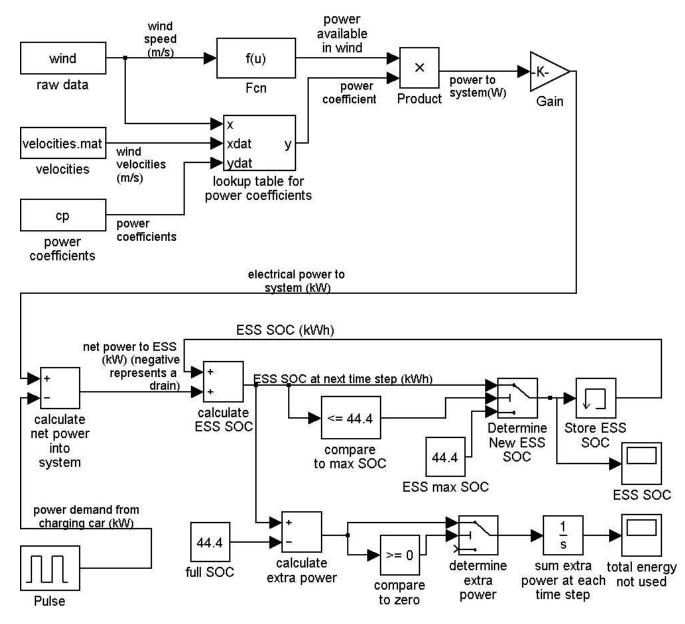
**Figure 7. Simulink model used to simulate the wind/battery hybrid system. System parameters can be modified to predict changes in system performance, if required.**

### C. Results

The simulation was run as described. It was found that the battery's SOC decreased to below zero frequently due to low wind speeds. The SOC is shown as a function of time in figure 8. During the first four months, the SOC occasionally decreases to below 0, indicating that the system cannot charge the vehicle as needed. However, during this time period, the battery still eventually returns to full charge. A great deal more energy could be extracted from the wind during this period than is needed or could be used, as shown in figure 9.
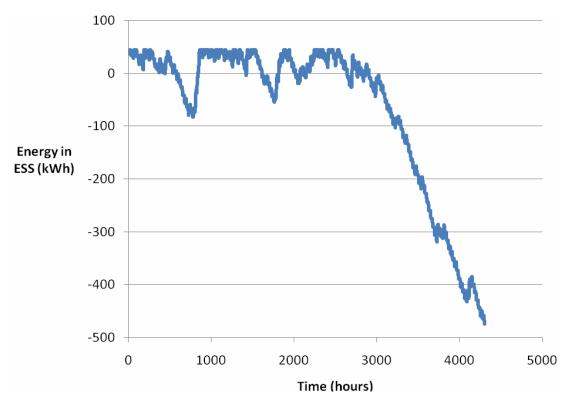
**Figure 8. Variation in the battery's state of charge as a function of time. SOC is on the y-axis, in kWh, while time is on the x-axis, in hours. Site is in Guelph, Ontario, with a battery capacity of 44.4 kWh.**
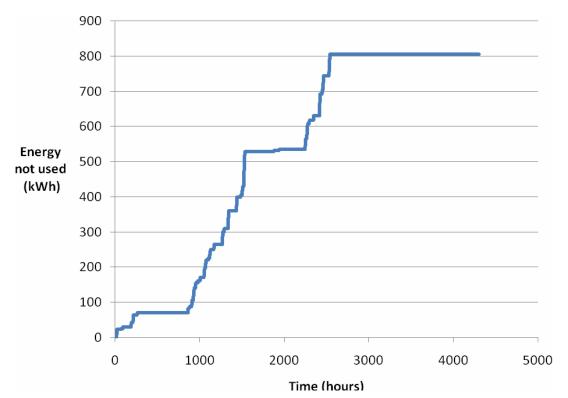


**Figure 9 – Excess energy in the wind as a function of time. Energy is on the y-axis in KWh, and time is on the x-axis in hours This represents energy that could be extracted from the wind, but isn't, because both the car battery and on-site battery are already full.**

During the last two months of the simulation, the wind speed and power output of the turbine decrease dramatically. The system is consistently unable to meet the power demand. Over the entire six months, the turbine can produce more energy than is needed, but much of it was only available to the system when it was unable to make use of the energy. In this case, this excess energy that the turbine could have produced was essentially wasted. It was found that the battery capacity would have to be increased to 532.8 kWh (12 times larger than initial capacity) in order for the system to be able to meet the vehicle's energy demand over the entire six months. This is a very substantial increase; the price, size, and mass of the required battery would be very high. As well, the required electrical complexity (voltage and current requirements) of such a large system makes it unsuitable for small scale personal use. The main reason the initial system configuration was unsuccessful in Guelph was due to the variability of wind speed; specifically, the low wind speeds experienced during the summer did not provide enough power to the turbine. A wind/hybrid system such as the one described here may work successfully in regions with higher wind speeds.

Other modifications to the system that could make it work are to increase the tower height, or use a turbine with a greater power output. However, again, these options increase the cost and physical size of the system. The magnitude of the tower height or turbine size increases needed for a site in Guelph could be investigated in further study.

## VIII.  Conclusions

Ontario's electrical grid appears to have enough existing extra generation capacity to completely replace all gasoline used for personal transportation. The average annual capacity factor would be increased from 55% to 65%. Meeting this increased power demand relies on the majority of consumers charging their vehicles during off peak hours. Depending on the number of vehicles charging concurrently, the increase in peak power demand may be too great for the grid to handle, with an increase in load of 2 kW per car charging.

Approximately 5100 GE 2.5xl 2.5 MW turbines could generate enough energy over the course of a year to displace all gasoline used for personal transportation in Ontario, assuming a capacity factor of 25%, and taking into account the typically much greater efficiencies of electric motors compared to internal combustion engines. Based on the historical costs of wind farms in the province, it would cost between $900 and $1086 to provide enough energy to each car. An off-grid solar energy based system in Guelph that could provide 500 kWh/month would cost approximately $56,000. A wind energy based system in Guelph that could provide 530 kWh/month would cost approximately $44,200. Multiple system simulations have shown that the required on-site energy storage capacity of this wind system is extremely high. Such a system is possible but unpractical, and prohibitively expensive. The most cost effective way of powering large numbers of electric cars with renewable energy in Ontario is through large wind farms connected to the electrical grid.

## IX.  Considerations / Reservations / Future Work

The feasibility of charging electric cars with electricity generated from renewable sources is a very broad topic. This study raised many interesting and complex questions, including when people are most likely to charge their cars, what the maximum capacity factor of Ontario's existing grid is, what infrastructure improvements are needed to meet this demand, and how this new demand will affect peak load. It has been shown that Ontario's grid has enough existing generation capacity to meet the increased energy demand from charging electric cars. However, depending on the timing of when these cars are charged, the grid may not be able to provide adequate power during peak load. Further investigation into the likely charging cycle patterns and periods of highest charging demand would be essential to determine the necessary infrastructure improvements needed for the province's electrical generation and distribution systems.

An off grid system powered by solar energy, as discussed, could be designed and simulated. The required battery capacity of such a system may vary from the predicted necessary capacity of a wind based system, which would make solar energy more appealing.

One major reason why a small off grid system is not a practical method of charging electric cars with wind energy in Guelph is because the energy storage requirements are very high. An investigation into the potential of other storage technologies, such as hydrogen, may yield promising results in the future. If energy storage can be done efficiently and cheaply, then a system such as described here may be viable. Alternatively, the effectiveness of a system similar to the one described here could be investigated for regions with a greater wind resource. The effect of increasing tower height or using a larger wind turbine could also be studied in the future.

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