Assessment of Renewable Energy Technologies for Charging Electric Vehicles in Canada

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Abstract

Electric vehicle charging by renewable energy can help reduce greenhouse gas emissions. This paper presents a data-intensive techno-economic model to estimate the cost of charging an electric vehicle with a battery capacity of 16 kWh for an average travel distance of 65 km from small-scale renewable electricity in various jurisdictions in Canada. Six scenarios were developed that encompass scale of operation, charging time, and type of renewable energy system. The costs of charging an electric vehicle from an off-grid wind energy system at a charging time of 8 hours is 56.8-58.5 cents/km in Montreal, Quebec, and 58.5-60.0 cents/km in Ottawa, Ontario. However, on integration with a small-scale hydro, the charging costs are 9.4-11.2 cents/km in Montreal, 9.5-11.1 cents/km in Ottawa and 10.2-12.2 cents/km in Vancouver, British Columbia. The results show that electric vehicle charging from small-scale hydro energy integration is cost competitive compared charging from conventional grid electricity in all the chosen jurisdictions. Furthermore, when the electric vehicle charging time decreases from 8 to 4 hours, the cost of charging increases by 83% and 11% from wind and hydro energy systems, respectively.

Keywords: Renewable energy; electric vehicle; techno-economics; GHG mitigation; wind power; small-hydro power.

Nomenclature

A	Turbine rotor swept area
AC	Alternating current
B	Battery bank size, kWh
BC	British Columbia
CNGV	Compressed natural gas vehicle
CO_2-eq	Carbon dioxide equivalent
C_p	Power coefficient of the turbine
C_{pr}	Total project cost of a small-scale hydro plant, in pounds
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CV	Conventional vehicle
D	Number of days without adequate wind energy
DC	Direct current
DOD	Depth of discharge, %
E	Energy requirement per day, kWh
EPA	Environmental Protection Agency
EV	Electric vehicle
FCV	Fuel Cell Vehicle

GHG	Greenhouse gas
H	Head of the hydro plant, m
Mt	Megatons
NHTSA	National Highway Traffic Safety Administration
ON	Ontario
P	Power output of the wind turbine, kW
PHEV	Plug-in hybrid electric vehicle
P_r	Power requirement, kW
QC	Quebec
USA	United States of America
USD	US dollar
V	Velocity of wind, m/sec
η_c	Charging efficiency
η_d	Discharging efficiency
ρ	density of air, kg/m^3

1. Introduction

The fuel consumption transportation industry contributes around 27% to the world's total energy consumption and accounts for 33.7% of greenhouse gas (GHG) emissions [1]. Of the total 6,526 million metric tons of GHG emissions in the United States for the year 2012, around 28% were attributed to the transportation sector [2]. While the total GHG emissions in the US have increased around 4.7% from 1990 to 2012, the increase in the GHG emissions in the transportation sector is significant and has increased around 18.3% for the same time period [2]. In August 2012, the U.S. Environmental Protection Agency (EPA) and the Department of Transportation's National Highway Traffic Safety Administration (NHTSA) issued rules to reduce GHG emissions and improve the fuel economy of light-duty vehicles for the years 2017 through 2025 [3]. As per the NHTSA's Rule, a light duty vehicle must reduce GHG emissions to 163 grams/mile by 2025, which is equivalent to a fuel efficiency of 54.5 miles per gallon [3].The EPA anticipates that increased market penetration of alternative fuel vehicles such as electric vehicles (EV), plug-in hybrid electric vehicles (PHEV), fuel cell vehicles (FCV), and compressed natural gas vehicles (CNGV) can help reach the expected standard [3].

Canada's national GHG emissions in 2010 were estimated at a value of 692 Mt CO_2-eq from all sources [4]. Of these total GHG emissions for the same year, 166 Mt CO_2-eq were attributed to the transportation sector. Passenger transport including cars, trucks, and motorcycles contributed to 88 Mt CO_2-eq of GHG emissions, which is close to 13% of Canada's total GHG emissions [4]. By 2025, the Government of Canada plans to curtail GHGs from new cars and light trucks by up to 50% compared to 2008 models [5]. The GHG emissions regulation in the Canadian passenger transport sector is aligned with the United States of America's (USA) emissions regulations [5].

In order to mitigate release of GHG emissions, Canada aims to have about 500,000 EVs by 2018 [6]. An additional 1.5 TWh of electrical energy will be required to charge these vehicles, over and above the 99 TWh required to meet normal load growth in electricity demand in Canada [6]. As of 2011, only 1% of the total electricity demand was from the transportation sector [7]. Ontario, one of the largest provinces in Canada, envisions having 5% of all vehicles electrically powered by 2020 and has stated a target of 20% of new passenger vehicle purchases to be EVs by 2020 [6]. Moreover, the Québec (another province in Canada) government has set a goal of 1.2 million EVs on Québec's roads by 2020; this figure represents 18% of the total number of light vehicles currently on the road [6]. Undoubtedly, there is an interest in the implementation of safe and environmentally friendly and more efficient transportation systems. PHEVs offer a high promise in satisfying our needs for sustainable future development and are also cost effective [8].

Due to significant modernization and industrial growth, alternative technologies that show promise for decreasing energy use are being sought vigorously. The environmental concerns associated with GHG emissions have increased the interest in development and implementation of renewable energy systems. With anticipated market penetration of EVs in Canada, their integration with renewable energy systems such as wind, hydro, and solar has some potential to address environmental concerns. A number of studies push for the implementation of renewable technologies and evaluate system performance or the ability of EVs to accommodate the renewable capacity. While the environmental advantages of EV use and the system performance of an integrated renewable energy system are known and well understood, there are limited studies in the literature that evaluate and appropriately quantify the economic competitiveness of such systems, especially from a Canadian perspective.

For instance, Richardson [9] has done a detailed review of various aspects of EVs and renewable resource integration and concluded that EVs have the potential to reduce GHG emissions in the transportation and power industries. A smart grid concept has been successfully demonstrated by Tesla Motors Inc., USA with an EV supercharging station that uses canopies covered with solar panels to produce electricity to charge EVs [10]. The expansion of EVs with a focus on using wind power to abate GHG emissions has been discussed in the Netherlands [11]. Hedegaard et al. [12] analyzed the possibility of a large-scale operation of PHEVs in five northern European countries (Germany, Norway, Sweden, Denmark, and Finland). It was concluded that without any economic support for renewable energy technologies, coal-based electricity is likely to be used for EV charging [12]. The integration of PHEVs with wind were investigated, and the results show a 4.7% reduction of emissions compared to systems with CVs [13]. Short et al. [14] demonstrated that large-scale integration of wind energy with PHEVs can result in increase of wind capacity by 243 GW upon conversion of a vehicle fleet to 50% PHEVs.

The authors in [15] identified the cost savings resulting from wind penetration in PHEV charging by applying a mixed integer linear programming model. They showed savings of 5-15% with 20% wind penetration with a system integrating wind power [15]. Further studies showed that in Inner Mongolia, China, there is a potential for an 8% increase in wind power use upon integration with EV charging and resulting in significant savings in fuel cost [16]. Simulation studies on the integration of PHEVs with wind supply and demand response were done for an Illinois power system with the aim of reducing the operating costs associated with the system [17]. The UK grid system was tested in a simulation model with 1000 EVs with wind generation systems, with the results showing tremendous potential for flexible charging and tariffs [18]. Ekman [19] presented a correlation between power consumption, wind energy production, and EV charging patterns and found that smart grid EVs are likely to use surplus wind energy. In New Zealand, the linking of EVs and wind power has been illustrated with respect to a reduction in market integration costs, production, and transmission [20]. It was concluded that if made flexible, greater wind penetration reduces the cost of recharging EVs [20].

In a Portuguese case study, Camus et al. investigated the impact of EV penetration with hydro [21]. The study shows that for the year 2020, the cost to recharge 2 million EVs is 20 cents/kWh at peak hours, which could be reduced to 5.6 cents/kWh at off-peak hours [21]. The study results show enormous reductions of 3%, 10%, and 14% for primary energy consumption, CO_2 emissions, and fossil fuel resources, respectively [21]. However, the literature on the integration of wind energy systems with EVs is much more comprehensive than that of other renewable resources [9]. That said, as EVs become economically competitive than conventional vehicles and rise in numbers in Canada, there will be an additional demand for electricity for charging. An ideal scenario is likely to be the one in which the electricity demand is met by a renewable energy system. Moreover, there is scarcity of research on the assessment of renewable technologies for EV charging in North America and specifically in different jurisdictions of Canada. These assessments are very limited in terms of associated costs of EV charging from small-scale renewable energy systems in Canada.

The objective of this paper is to develop scenarios for EV charging by assessing renewable resources in North America focused on different Canadian provinces. Data-intensive techno-economic models were developed to estimate the costs of charging an EV from renewable energy resources (mainly hydro and wind power) in given jurisdictions in Canada. This was done for an appropriate size of the renewable system derived from fundamental engineering principles. Furthermore, a comparative assessment of the cost of charging was completed to judge the competitiveness and feasibility of small-scale renewable energy systems with grid electricity for different scenarios. A sensitivity analysis was also done to observe the impact of the various input parameters. Lastly, a brief discussion on the challenges in implementation of renewable energy systems for EV charging, and GHG mitigation potential by replacing conventional gasoline vehicles with EVs, from an operational perspective, is completed for different jurisdictions in Canada.

2. Scope of Work – EV charging scenarios

Based on characteristics of the provinces, associated infrastructure and available resources, scenarios were developed to determine places or conditions for EV charging in given jurisdictions in Canada. Tables 1a and 1bshow the total electricity generation from renewable energy and vehicle information in different Canadian, respectively. Solar energy contributes little to electricity production compared to other renewable sources, namely hydro and wind energy. The contribution of solar power to electricity generation is very low in all provinces. Ontario contributes the largest share of solar energy, 0.1% of the total electricity production. Therefore, considering the low contribution, a solar-powered energy system is not included in this study. However, wind and hydro energy may prove to be potential sources of electricity for charging EVs. Hydro-powered electricity generation is highest in Quebec, followed by Ontario and British Columbia. Ontario leads in the wind energy sector, followed by Quebec. Table 1 also indicates the EV market penetration in different Canadian provinces. Based on the ratio of conventional vehicles (CVs) to EVs, Quebec, Ontario, and British Columbia have the highest penetration of EVs in Canada.

Table 2 shows six scenarios for the assessment of renewable energy technologies for EV charging. Based on the current renewable electricity distribution and number of EVs in the market, each scenario was developed for three different cities, Montreal (QC), Ottawa (ON), and Vancouver (BC). However, scenarios 1, 2 and 3 are not applicable to Vancouver due to the low contribution of wind power to the electricity generation in British Columbia.

The number of charging points indicates the scale of operation. For instance, a home would have a single charging point. Public spaces (a workplace, shopping mall, or highway) would have multiple charging points.The number of charging points in a shopping mall ranges from 15 to 20 and from 3 to 5 in a work place parking lot [22]. Each scenario is evaluated for charging times varying from four to eight hours. An EV charging time of eight hours is considered as the base case for each of the scenarios in this study.

3. Techno-economic assessment

3.1. System boundary and modelling methodology

Figure 1 represents the methodology developed for calculating the costs associated with electricity production from renewable energy sources for the purpose of charging EVs. The functional unit chosen is $/km. Scenarios were developed to represent the scale of operation in a given jurisdiction in Canada. The key underlying assumption in the present assessment is that there will be a single charging point for each EV in the market. The effect of the key assumptions/input parameters of the model is investigated with the help of sensitivity analyses and has been discussed later in the paper. Hydro and wind energy systems are not only different with regards to the origin of the energy source but also due to availability of energy at a given point of time; hydro energy is available at any time compared to intermittent wind energy especially in urban areas. Therefore, such systems require energy storage systems for a sufficient period of time to fulfil the electricity demands of the EV charging station. In order to appropriately size the wind energy system, the number of turbines was estimated based on the statistical distribution of wind speeds in a given jurisdiction, along with the utilization of capacity factor. Since the daily-hourly wind speed data was not available for a given jurisdiction, eight observations of mean wind speeds at a three hour interval were derived for each month using data reported earlier [27] in a given jurisdiction. The rated power was then calculated based on a wind speed equal to the annual mean speed plus two times the standard deviation of the annual wind speed data. This methodology has also been used by authors in [28].

The effect of driver's behaviour and the charging patterns of each specific EV are not considered in this paper. Charging pattern is defined as the distribution of electricity demand by the EVs in a given time of the day. This may differ on a weekday compared to a weekend or a holiday. Furthermore, the driver behaviour (discharging of the EV batteries) and the power withdrawn from the energy system (charging pattern) may be correlated. That said, this can only be derived from real data. Moreover, there are limited resources in the literature and public domain to obtain this real data for different jurisdictions of Canada. The effect of charging pattern is important to investigate for determining the required infrastructure improvements needed for electrical generation and distribution systems, especially in large scale systems. In order to address this, an average daily power consumption of an EV based on the annual driving distance of a driver in a given jurisdiction in Canada is considered in the paper. Moreover, to improve the reliability of the system presented in this paper, the batteries have been sized for sufficient number of days (three days) without adequate power production by the renewable energy system.

The system boundary is presented in Fig. 2 and shows the scope of the model in terms of the cost calculated for the entire unit operations/components involved, starting from the setup of the renewable energy plant to EV charging at a station. The distance of the charging station and the renewable energy system affects the transmission and distribution costs. The present study assumes that the renewable energy system is located close to the EV charging station. For EV charging stations located far from the renewable energy source, existing transmission and distribution infrastructure is utilized. However, any grid reinforcements for the charging station have been considered and included in the total charging costs.

3.2. Techno-economic model for wind and hydro: methodology and key assumptions

Figures 3 and 4 depict the techno-economic modeling methodology developed for EV charging from wind and hydro. The cost of charging is calculated for a small-scale renewable electricity generation energy system, and any incentive from the government in lieu of installing the charging station or renewable electricity generation system is not considered. Table 3 shows electricity load requirement in a given jurisdiction in Canada along with the key assumptions.

The vehicle chosen for this study is a Chevrolet Volt. The Volt is a PHEV manufactured by General Motors and has the highest sales of all PHEVs and EVs in Canada [29, 30]. Although the vehicle considered is a PHEV, the analysis can be generalized for any other type and specification of EV. The total number of EVs is calculated for a given vehicle to population ratio and number of CVs to EVs ratio, and it is assumed that the EV sales growth matches the CV sales growth [31-33]. The number of charging cycles required per year per EV is calculated by dividing the average km driven by the all-electric range of the vehicle. The charging station electricity requirement is calculated by multiplying the number of charging points and load requirement per EV per day. It is also assumed that 90% of the charge is consumed as the EV is driven [34].

Table 4 presents battery and charging station lifetimes, efficiencies associated with charging and discharging of batteries, and cost numbers for techno-economic modeling for both wind and hydro. A discount rate of 10% and an inflation rate of 1.8% [35] are assumed for techno-economic modeling for both renewable energy systems.

With regard to the assumptions and key input parameters for an off-grid, small-scale wind energy system (as given in Tables 4 and 5), the specifications of the charging station, wind turbine, and wind velocity are significant for techno-economic modeling in different jurisdictions of Canada. As discussed in section 2 of this paper, scenarios 1, 2, and 3 are not applicable for Vancouver. Therefore, the cost of charging from a wind energy system is not calculated for this jurisdiction. The average wind speed for given coordinates of the jurisdiction is calculated from the monthly wind speed data provided by [27] in 2013. Given the low average wind speeds of 4.3 and 4.2 m/sec in Montreal and Ottawa, respectively, a wind turbine was chosen for this study based on its cut-in speed and rated power: a 7.5 kW wind turbine, manufactured by BergeyWindpower, USA, and with model name BWC Excel-R [36]. A power coefficient of 35% and a hub height of 50 m are assumed. All the other specifications of the turbine are listed in Table 5. Due to the unavailability of hourly wind speed data, continuous power delivered by the turbine is defined at two times the standard deviation of the wind speed [28]. Equation (1) [37] given in the appendix is used to calculate the power generated by the wind turbine.

The key input parameters and assumptions for a small-scale hydro power plant are given in Table 6. Based on an assumption that a single small-scale hydro plant will satisfy the electricity requirements for all the EVs in a given jurisdiction, plant sizes are calculated as 8.1 MW, 3.3 MW, and 2.7 MW for Montreal, Ottawa, and Vancouver, respectively. All the cost numbers presented in Tables 5 and 6 are in 2013 US dollars.

4. Results and discussion

4.1. Cost to charge an EV with renewable energy

Two sources of electricity, wind and hydro power, are considered in the paper. Scenarios are developed based on three sizes of charging stations with charging times varying from four to eight hours. The techno-economic model provides the capital cost distribution of the charging infrastructure and the cost of charging an EV in three jurisdictions of Canada. All cost numbers are calculated in USD.

4.1.1. Economics of wind-powered EV charging

Table 7 shows the values of the economic parameters for the base case in different scenarios with corresponding observations. As stated above, Vancouver is not included due to its low contribution percentage of wind power to the total renewable electricity generation in British Columbia (see Table 1). The number of wind turbines is calculated by dividing the total power limit of the charging station and effective power delivered by one 7.5 kW turbine. A capacity factor of 30% is assumed to calculate the effective power delivered by the wind turbine [28, 42]. As can be seen in Table 7, the total power limit per day and the number of turbines required for EV charging increases almost linearly from scenario 1 to scenario 3 in the two jurisdictions. These values are higher for Ottawa than Montreal because people in Ontario drive more than people in Quebec [24], which results in a higher load requirement (see Table 3). The annualized cost of the wind turbine, batteries, converter, charging station, and other system components are also formulated in Table 7. Scenario 1 is assumed to have no cost associated with civil works and the grid reinforcement of the charging station. However, the civil works and the grid reinforcement costs are calculated as $1730 and $3460 for scenarios 2 and 3, respectively [39]. Figure 5 shows the capital cost distribution of the various system components of scenarios 1, 2, and 3 in Montreal and Ottawa, respectively. The capital cost of turbines contributes around 85% to the total capital cost of the system in the two jurisdictions.

Table 8 summarizes the cost of charging for scenarios 1, 2, and 3 and with different charging times in Montreal and Ottawa. For Montreal, the cost of charging an EV for scenario 1 with eight hours of charging is estimated to be 58.5 cents per km. This value decreases by 2.1% to -57.2 cents/km and by 2.9% to 56.8 cents/km for scenarios 2 and 3, respectively (see Table 8). One can easily notice that a cost advantage is achieved as the number of charging points increases from one to ten. The cost of charging decreases with an increase in the scale of operation as fixed costs are spread out. While the capital cost of turbines, charging equipment and batteries increases linearly with an increase in the scale of operation, the converter cost does not show this trend. This is mainly because the number of turbines, charging equipment and batteries required for operation rise almost linearly with an increase in the number of charging stations, but the converter, being single equipment, has a lower capital cost at a larger operating scale. The effect of the decreased cost per EV and per km is less pronounced with consideration of civil works and grid reinforcement costs in large-scale operations (five and ten charging point stations).Since these costs contribute less to the total system cost, the cost of charging does not decrease significantly with an increase in scale of operation. For the same reasons, a similar trend is observed with increasing the scale of operation in Ottawa as well. However, the cost of charging in Ottawa is a little more expensive than the cost of charging in Montreal. This might be due to fewer kilometers driven by people in Quebec than in Ontario (see Table 3).

4.1.2. Economics of hydro-powered EV charging

As stated earlier, hydro energy is a significant contributor to the total renewable power generation in Quebec and British Columbia (see Table 1). Table 9 shows the values of the economic parameters for the base case of eight hours of charging time in scenarios 4, 5, and 6 with specific comments. The parameters include the capital cost of the hydro plant and also the amortized capital cost of all the components of the system. Figure 6 illustrates the capital cost distribution of the system for scenarios 4, 5, and 6 in different jurisdictions. Batteries constitute around 58-68% of the total capital cost. The capital cost of the hydro power plant is relatively small as compared to other system components, as this cost spreads out in a given jurisdiction when calculated on a per-vehicle basis.

Table 8 also summarizes the cost of charging for scenarios 4, 5, and 6 with charging times of four, six, and eight hours in Montreal, Ottawa, and Vancouver. The cost of charging an EV at a charging station in Montreal with one, five, and ten charging points is estimated to be11.2, 9.9, and 9.4 cents/km, respectively. For the same reasons as discussed in section 4.1.1, there is a weak economy of scale in this system as well. Moreover, a parallel trend is noticed for the scenarios in other jurisdictions. Interestingly, the cost of charging an EV in Ottawa is almost the same as that in Montreal. It is worth noting that the cost figures for Vancouver are significantly higher than in the other two cities. The reason for this difference is attributable to the ratio of CVs to EVs; there are fewer EVs in Vancouver (see Table 1 and 3). Additionally, people in Vancouver drive less than people in the other jurisdictions studied here [24], resulting in a lower electricity requirement per day. Due to economies of scale in hydro plant construction (see equation (3) [44]), the cost of charging per EV ultimately increases.

4.2. Comparative assessment of cost of charging from wind energy, hydro energy and conventional electricity

Figure 7 shows the cost of charging for the base case of 8 hours of charging time from wind energy, hydro energy, and conventional electricity in Montreal, Ottawa, and Vancouver. The data-intensive techno-economic model developed in this paper shows that charging an EV from hydro-based electricity is considerably cheaper than charging an EV from wind-based electricity in all the three cities (see Fig.7).This is mainly because it costs less to build a hydro power plant than a wind power plant per unit of power generated. Another reason for the lower charging costs with hydro electricity is that a single small-scale hydro plant satisfies the electricity requirement of all the EVs in scenarios 4, 5, and 6, compared to an off-grid small-scale wind plant generating enough power for a particular charging station in scenarios 1, 2, and 3.

Based on residential electricity tariff rates of $67.48, $131.43, and $87.77 per MWh in Montreal, Ottawa, and Vancouver, respectively [46], the cost of charging was calculated; it is illustrated in Fig.7. The cost of charging from wind is not competitive with charging from conventional electricity. However, when EVs are charged from electricity produced from a small-scale hydro plant, costs are competitive.

4.3. Effect of charging time on charging cost

The cost of charging was analyzed for charging times ranging from 4 hours (fast charging) to 8 hours (slow charging) at a level II EV charger. Figures 8 and 9 show the variation of the cost of charging with charging time in wind and hydro scenarios. As the charging time is reduced, charging costs increase significantly. This may be because the infrastructure for fast charging is more costly than that for slow charging, which increases the overall charging cost. The effect of increased charging time on cost is more pronounced in wind energy systems than in hydro energy systems .By increasing the charging time from 4 to 8 hours, the cost of charging from wind and hydro energy systems decreases by around 83% and 11%, respectively. While the increase in the cost of charging station equipment, batteries, converters, etc., remains the same in both wind and hydro scenarios cases, a noticeable difference is observed in the electricity generation costs by wind and hydro energy systems.

By decreasing the charging time from 8to 4 hours, the total number of turbines required to satisfy the load requirements of the charging station increases by around 50% in scenarios 1, 2, and 3. Similarly, the power to be delivered by a hydro plant also increases by around 50% in scenarios 4, 5, and 6. Since the capital cost of wind turbines and hydro plants is around 85% and 10%, respectively (see Figs. 5 and 6), of the overall system costs, there is a greater sensitivity of charging time is in scenarios 1, 2, and 3 than in scenarios 4, 5, and 6.

Overall, this analysis suggests that there is a tradeoff between the charging time and the costs of charging an EV to achieve optimality. This relationship holds for all three provinces at all three charging locations and is evident in Figs.8 and 9. Further decreases in charging time can be achieved by a level III AC charger, level III DC charger, or a super-fast DC charger [39]. Such charging systems require upgradation of the grid and transformer, and this increases costs [39].

4.4. Environmental impact

A conventional vehicle (CV) (with a spark ignition engine and gasoline as fuel) in Canada emits 0.290 kgCO_2-eq of greenhouse gases (GHG) per km [47]. With grid electricity emission factors ranging from 0.006 to 0.797 kgCO_2-e/kWh [48], there is a significant potential to reduce GHGs if CVs are replaced with EVs. A lower emission factor is possible for a province that can contribute renewable resources to the total electricity production. Based on the average distance travelled by a light vehicle in different jurisdictions of Canada (see Tables 1 and 3 for calculation methodology), the GHG mitigation potential from CVs' replacement with EVs ranges from 4306.6 to 5059.4 kgCO_2-eq/year/vehicle. However, if EVs are charged with electricity generated from renewable resources, there is additional GHG mitigation due to lower GHG emissions associated with electricity production from wind and hydro energy systems. The increase in GHG mitigation ranges from 0.6% to 42.3% per vehicle with total GHG mitigation ranging from 4332.4 to 8203.9 kgCO_2-eq/year/vehicle. It is important to reiterate that the GHG mitigation potential is estimated only from an operational standpoint of EV use and not from a life cycle perspective involving all process stages, e.g., manufacturing and construction of renewable energy system (wind and hydro), battery bank and EV batteries, etc.

4.5. Challenges in implementation of small scale renewable energy systems for EV charging in Canada

While EV penetration in the Canadian transportation sector and its integration with renewable energy systems will mitigate GHG emissions, there are several challenges with regards to its implementation. A small scale off-grid wind energy system for EV charging may not be feasible due to inadequate or variable wind speeds, small size of turbines in urban areas, higher capital costs ($/kw) of wind turbines, remoteness of the wind resource from the charging station, and large battery storage requirements and costs. A more economical way of charging EVs can be through large scale wind energy systems which are connected and integrated with the existing grid. This is mainly due to economies of scale in wind turbine costs and cost savings in mitigating the use of battery bank. Moreover, small scale hydro energy system is more feasible and attractive than the wind counterpart mainly due to non-intermittent nature of the former case. However, additional analysis is vital on EV charging patterns and associated energy demand distribution on a daily basis. This is important to characterize and determine any transmission and distribution adjustments required in the existing infrastructure, both in case of hydro and large-scale renewable energy system.

4.6. Sensitivity analysis

A sensitivity analysis was conducted to see which input parameters affect the cost of charging an EV from renewable electricity generation scenarios. All the parameters are varied by ±20%. Figure 10 depicts the sensitivity analysis done for scenario 3, wherein the electricity is produced from wind energy to charge an EV at a charging station with ten charging points in Ottawa. This scenario is only a representation of the effect of various input parameters; however, the same trend is observed when the analysis is conducted for a similar scenario in different jurisdictions. The cost increases as the battery capacity is decreased; because the electricity requirement increases, the number of turbines and ultimately the overall cost increase. Since the capital cost of the wind turbines is a major component of the total charging infrastructure cost, any parameter affecting the number or power output of the turbine(s) is expected to affect the overall cost of charging. Evidently, the cost of charging is very sensitive to the capital cost of the turbine. However, a decreasing trend is noticed for all the other parameters selected for the analysis. With an increase in wind velocity, the cost decreases significantly due to an increase in the power output of the wind turbine. The cost of charging is, however, least sensitive to the life of the batteries and the life of the charging station. Increasing the range of the EV decreases the number of charging cycles in a year and ultimately decreases the overall load requirement. The capacity factor has a direct effect on the number of wind turbines required and hence a decreasing trend is observed; that is, the number of wind turbines decreases as the capacity factor is increased.

Figure 11 shows the sensitivity analysis conducted for scenario 6, wherein electricity is produced from a single small-scale hydro plant to charge an EV at a charging station with ten charging points in Vancouver. The charging cost is sensitive to the battery capacity and range of the EV for the same reasons mentioned earlier. The cost is sensitive to the battery life, unlike in the case for wind scenarios. This may be because the capital cost of batteries is a significant portion of the total capital cost in hydro integration, whereas in the case of wind, the high capital costs are from the turbines.

The available head for electricity generation in a hydro plant and the life of the charging station and hydro plant show the least sensitivity on the cost of charging. The total number of EVs in the market also has a significant effect on the cost, and there is a significant economy of scale in terms of the capital cost of the hydro plant with an increase in the size of the plant. Therefore, as the total number of EVs increases, this in effect increases the total load requirement, and the cost of charging per vehicle changes significantly, as shown in Fig.11.

5. Conclusion

This paper provided insight on the cost of integrating renewable energy technologies for charging of EVs in Canada. The cost of charging upon integration of an off-grid, small-scale wind energy system is estimated to be 56.8-58.5 cents per km in Montreal and 58.5-60cents per km in Ottawa for different scales of operations and eight hours of charging time. The economy of scale is weak and the cost of charging is most sensitive to wind velocity, the life of the wind turbine, charging time, and the EV's battery capacity. The integration of EV charging with small-scale hydro energy is more cost competitive than with wind. However, the economy of scale is found to be less significant in the hydro case. In this case, the cost of charging with a charging time of eight hours is estimated as 9.4-11.2 cents per km in Montreal, 9.5-11.1 cents km in Ottawa, and 10.2-12.2 cents per km in Vancouver. The cost is most sensitive to the number of EVs in a jurisdiction, the life of batteries, charging time, and the battery capacity in EV.

With conventional grid electricity as the base case for EV charging, it is more cost competitive to integrate EV charging with a hydro energy system than with a wind energy system. Moreover, considering the significant contribution of passenger vehicles to the overall GHG emissions, it is worth nothing that replacing CVs with EVs and EV charging from renewable resources increases GHG mitigation potential by 0.6%-42.3%, over and above a range of 4306.6 to 5059.4 $kgCO_2$-eq/year/vehicle by replacing CVs with EVs only.

Appendix

$$P=1/2* \rho *A*C_p*V^3 \quad (1)$$

$$B=D*E/(\eta_c*\eta_d*DOD) \quad (2)$$

$$C_{pr} =25,000*(P_r/H^{0.35})^{0.65} \quad (3)$$

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Fig.1: Developed methodology for this study

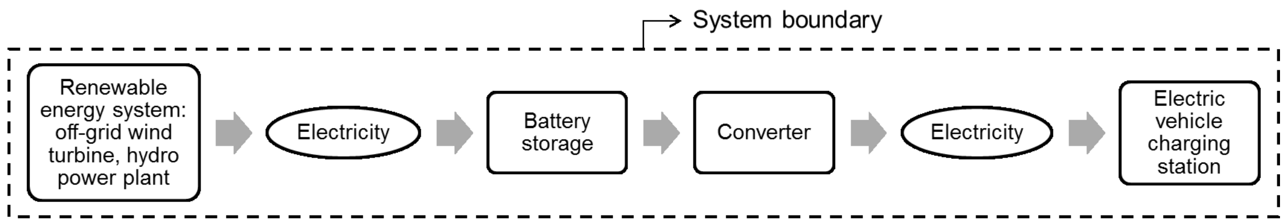

Fig.2: System boundary for this study

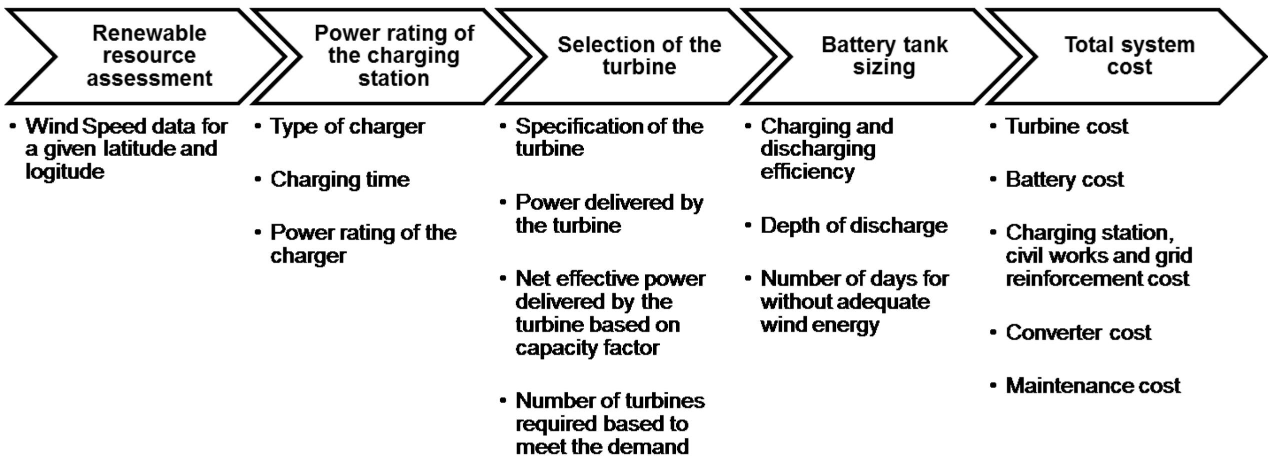

Fig.3: Techno-economic modeling methodology of EV charging from wind

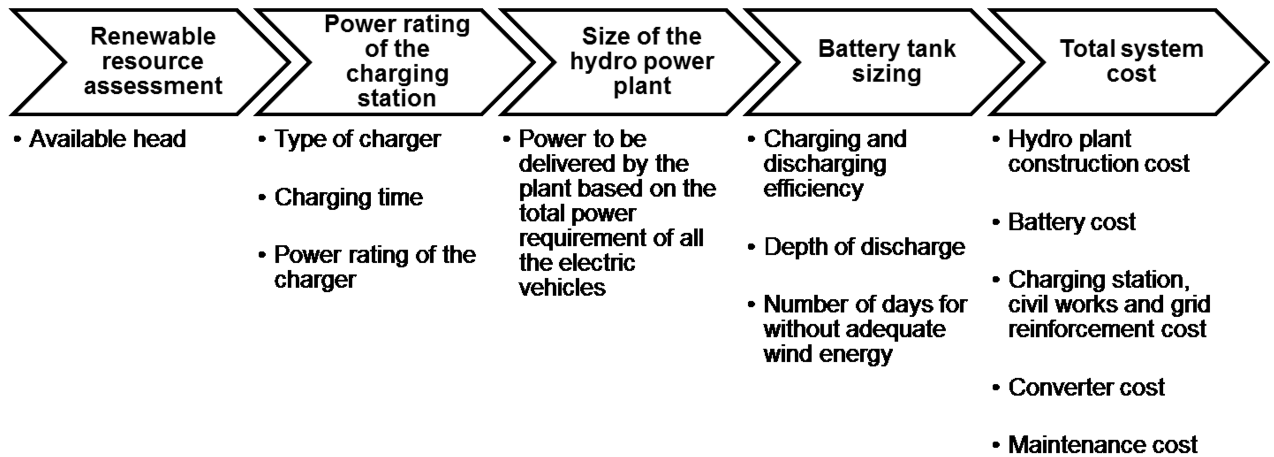

Fig.4: Techno-economic modelling methodology of EV charging from hydro

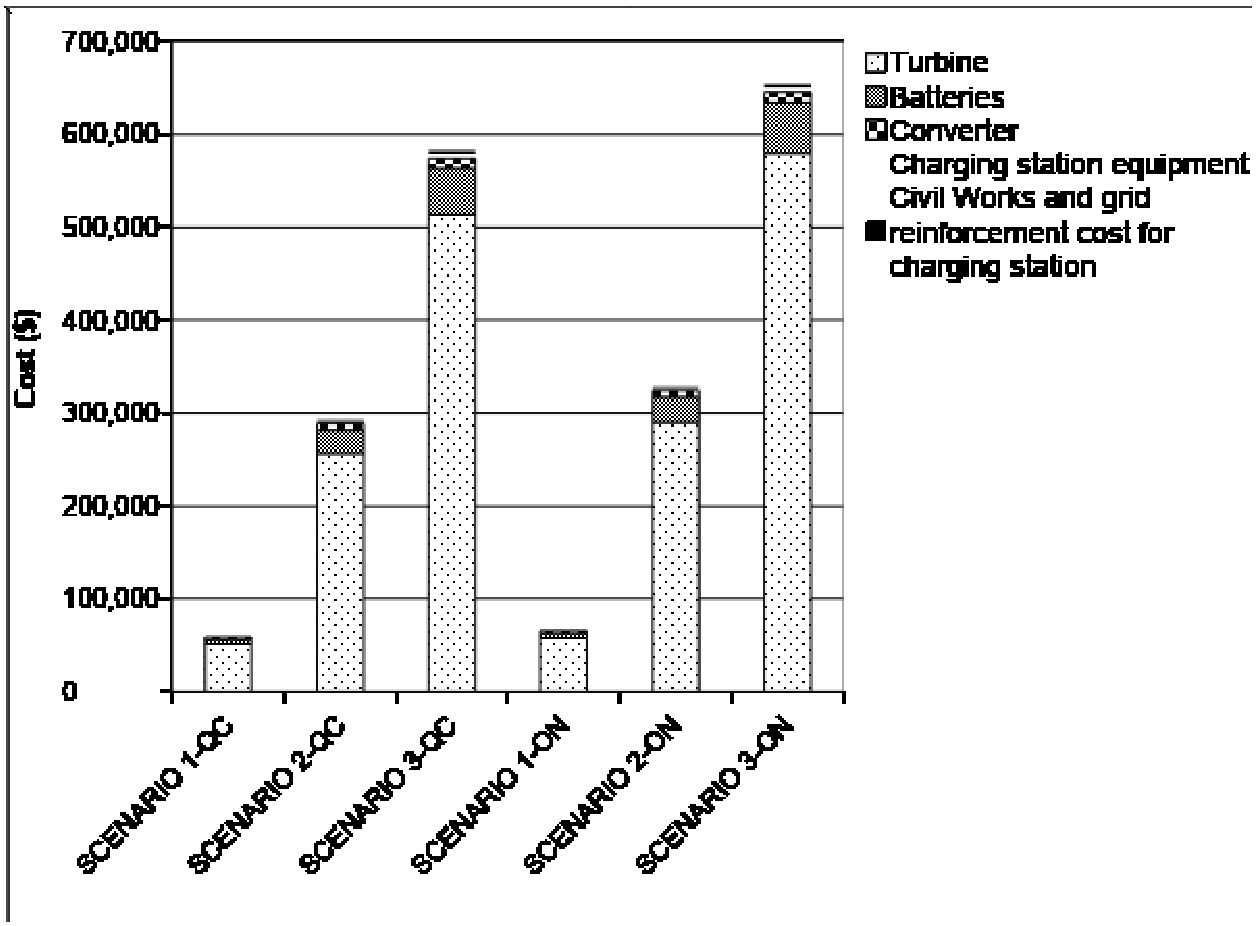

Fig.5: Capital cost distribution for a charging station (eight hours of charging time) with a wind energy system in Montreal, QC and Ottawa, ON. Base year – 2013.

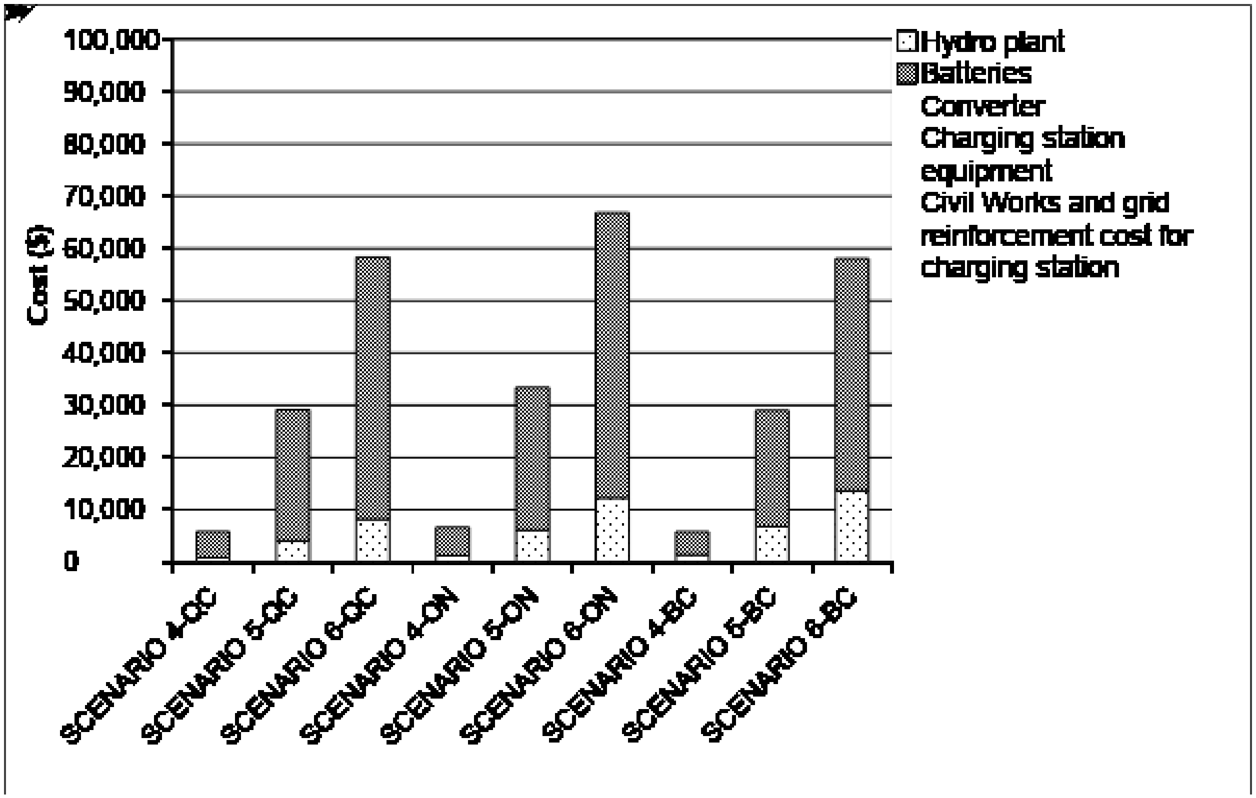

Fig.6: Capital cost distribution for charging station (8 hours of charging time) with a hydro energy system in Ottawa, ON, Montreal, QC and Vancouver, BC. Base year – 2013.

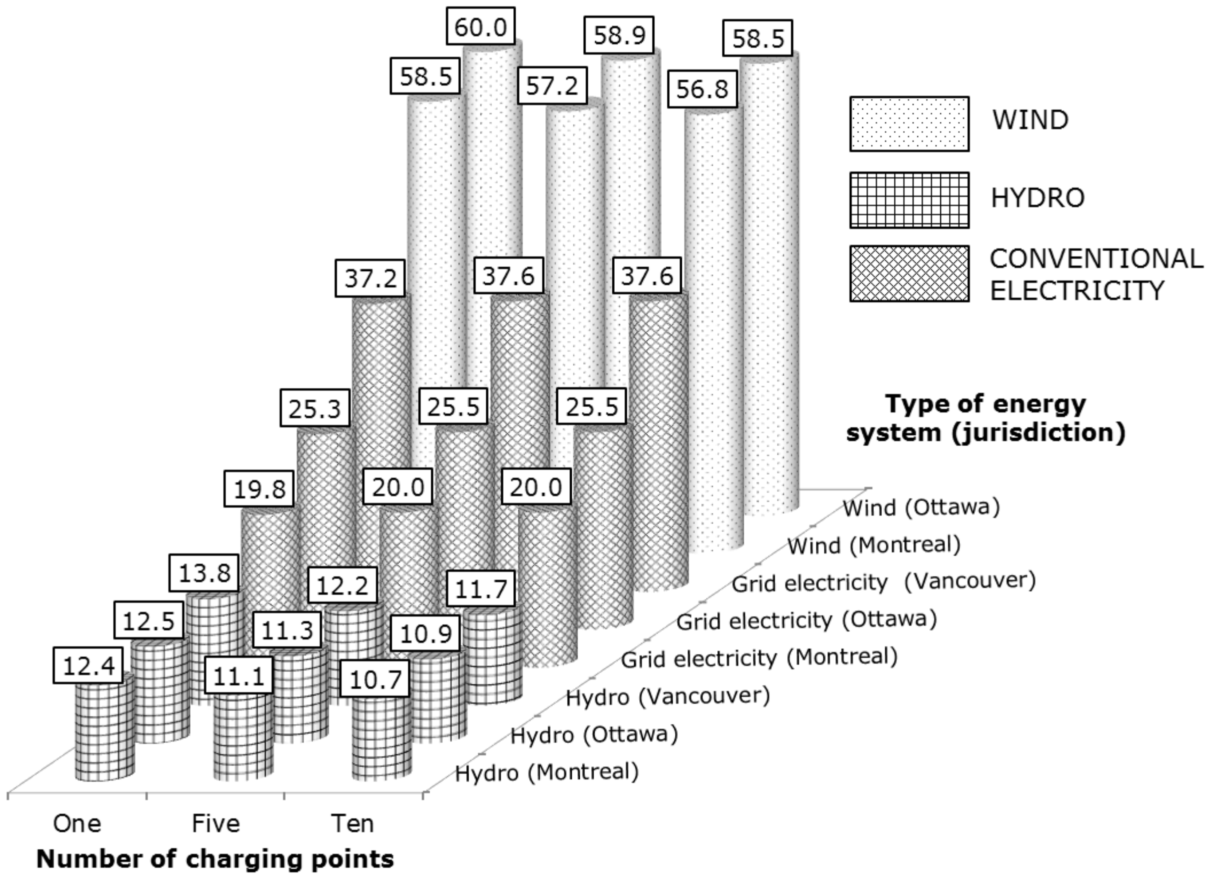

Fig.7: The effect of the number of charging points on charging costs (2013, cents/km) from wind energy systems, hydro energy systems and conventional electricity (base case of 8 hours charging time)

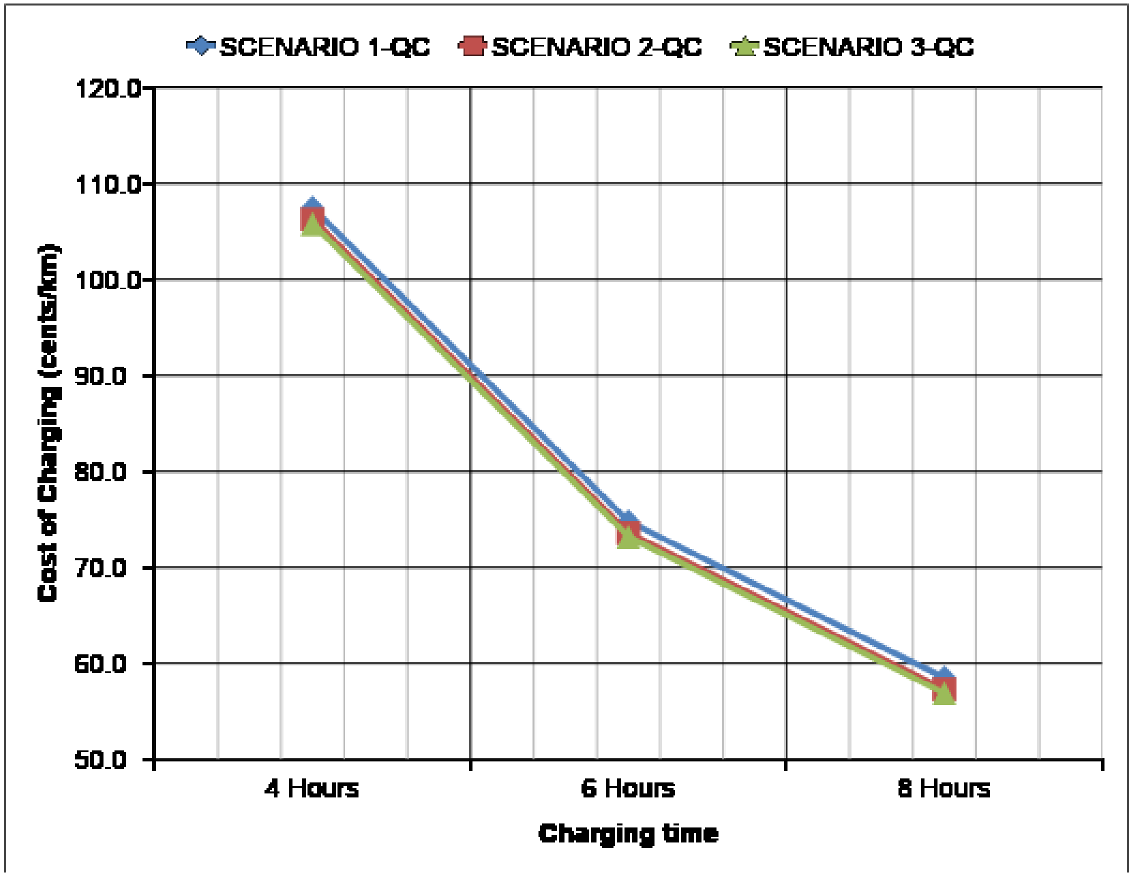

Fig.8: Variation of cost of charging from wind energy systems with charging time in Montreal, QC

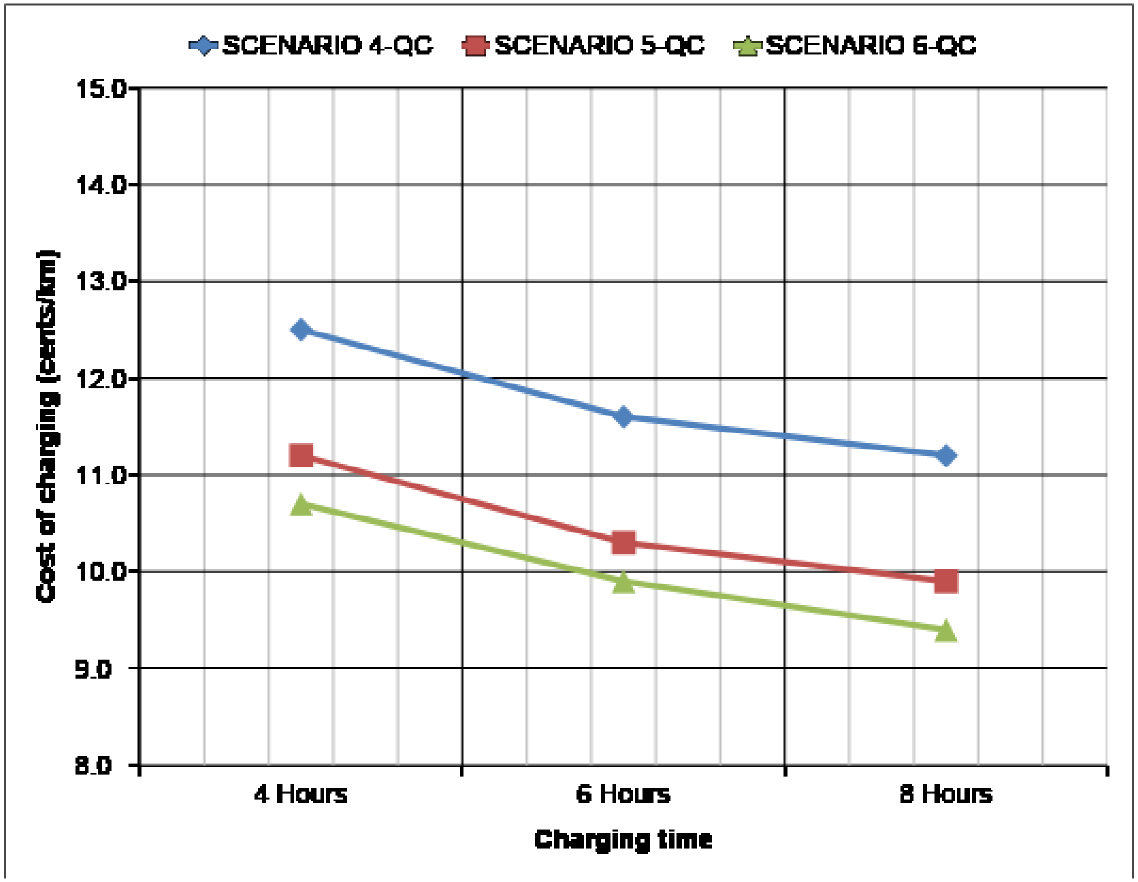

Fig.9: Variation of cost of charging from hydro energy systems with charging time in Montreal, QC

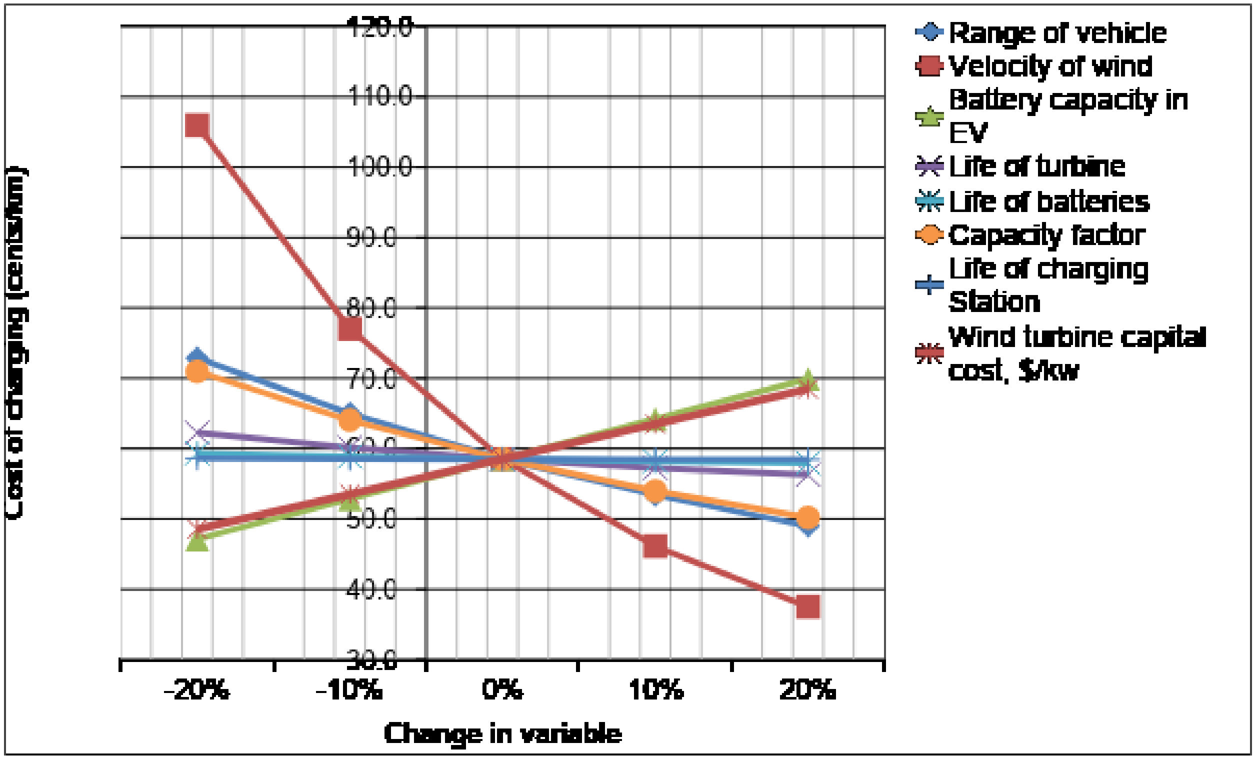

Fig.10: Cost sensitivity analysis for scenario 3 (8 hours of charging time) in Ottawa, ON

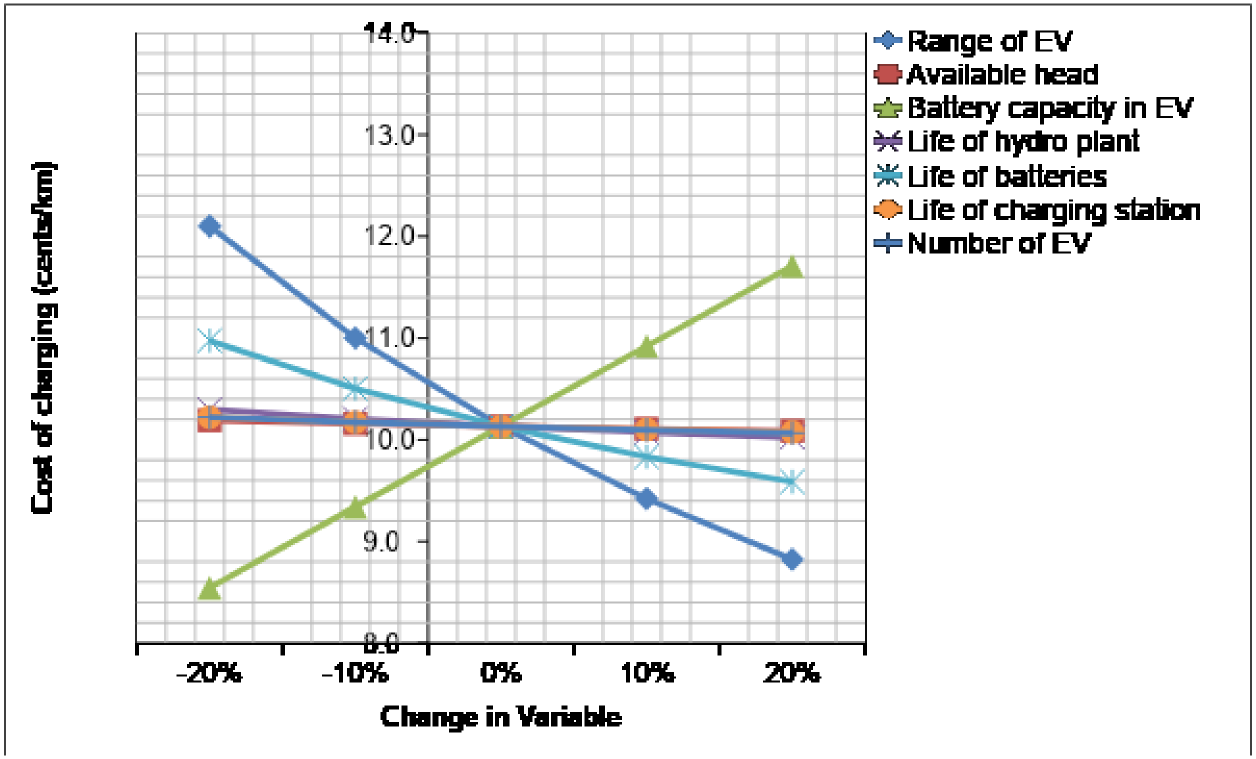

Fig.11: Cost sensitivity analysis for scenario 6 (8 hours of charging time) in Vancouver, BC

Table 1a: Total electricity generation potential from renewable sources in Canada by province and type for charging EVs.

Jurisdiction	Total electricity production in 2011 (TWh)[1]	Percentage of electricity production from renewables in 2011[1]		
		Hydro	Wind	Solar
Quebec	196.7	97.2%	0.3%	0%
Ontario	140.4	24.7%	1.6%	0.1%
British Columbia	66.4	92.1%	0%	0%
Newfoundland and Labrador	40.7	96.7%	0.3%	0%
Prince Edward Island	0.5	0%	100%	0%
Nova Scotia	11.2	9.9%	3.1%	0%
New Brunswick	11.2	34%	5.2%	0%
Manitoba	34.8	98.4%	1.1%	0%
Saskatchewan	23.1	20.1%	3.1%	0%
Alberta	66.0	2.8%	3.3%	0%
Yukon	0.4	90.9%	0.1%	0%

Northwest Territories	0.7	36.8%	0%	0%
Nunavut	0.2	0%	0%	0%

[1] Source: [23]

Table 1b: Vehicle information in different provinces of Canada

Jurisdiction	Average distance travelled by light vehicles in 2009[1] (1000skm)	Ratio of number of CVs to EVs[2]
Quebec	14.7	214
Ontario	16.0	296
British Columbia	13.0	177
Newfoundland and Labrador	15.1	1424[3]
Prince Edward Island	15.1	

Nova Scotia	17.4
New Brunswick	16.1
Manitoba	15.0
Saskatchewan	15.3
Alberta	16.1
Yukon	-
Northwest Territories	-
Nunavut	-

[1] Source:[24]. A light vehicle includes a car, a motorcycle and a light truck [25]. The data for the individual vehicle types is not available. Therefore, the listed data is used for calculations in the present study.

[2] Source: [26]

[3] Combined value for Prince Edward Island, Nova Scotia, New Brunswick, Manitoba, Saskatchewan, Alberta, Yukon, Northwest Territories, and Nunavut

Table 2: Developed scenarios for charging EVs from renewable energy in Canada[1].

Scenario	Electricity Source	Number of charging points	Charging time (hours)
1	Wind[2]	1	4, 6, 8

2	Wind[2]	5	4, 6, 8
3	Wind[2]	10	4, 6, 8
4	Hydro[3]	1	4, 6, 8
5	Hydro[3]	5	4, 6, 8
6	Hydro[3]	10	4, 6, 8

[1] Charging time of 8 hours is considered as the base case in this study.

[2] Vehicle is charged anytime during the day at a station using electricity generated by a small-scale off-grid wind energy system.

[3] Vehicle is charged anytime during the day at a station using electricity generated by a small-scale hydro power plant

Table 3: Electricity requirement calculation in each jurisdiction

Parameters	Applicable scenarios	Value in the given jurisdiction			Sources/comments
		Quebec	Ontario	British Columbia	
City chosenin the jurisdictions	ALL	Montreal	Ottawa	Vancouver	
Ratio of CVs to EVs	ALL	177	214	296	Refer to Table 1
Vehicles/1000 people in the given city	ALL	553	536	529	[38]
Total number of EVs	ALL	5894	2180	1079	[31-33]
Battery capacity of EV, kWh	ALL	16	16	16	[29]
Range of EV, km	ALL	65	65	65	[29]
Average distance driven per year, thousand km	ALL	14.7	16.0	13.0	Refer to Table 1
Number of charging cycles required per year per EV	ALL	226	246	200	
Load requirement of a charging station, kWh/day/EV	1,4	11.0	12.0	9.7	
Load requirement of a charging station, kWh/day/EV	2,6	55.0	59.9	48.7	

Load requirement of a charging station, kWh/day/EV	3,5	110.1	119.8	97.4

Table 4: Key assumptions and input parameters for techno-economic modelling for both wind and hydro. All costs are in 2013 US dollars.

Parameters	Value	Sources/comments
Inflation rate	1.8%	Based on an annual average inflation rate for the period of 2010-2013 in Canada. Obtained from Statistics Canada [35]
Discount rate	10%	
Charging station		
Life of charging station, years	10	[39]
Life of civil works of charging station, years	20	Assumed to be the same life time of civil work provided in [36]
Type	Level II AC charger, 230 V 16 A single phase	[39]

Charging time of one EV for the electricity requirement per day, hours	8	Time to charge a 20 kWh EV by a 3.6 kW level II charger is 5.6 hours [39]
Charging station material cost, $/kW	384.8	[39]
Maintenance cost	10%	10% of the capital cost [39]
<u>Battery bank, converter</u>		
Life of batteries, years	10	[40]
Life of converter, years	10	[36, 40]
Charging efficiency	90%	[28]
Discharging efficiency	95%	[28]
Depth of discharge (DOD)	80%	[28]
Battery storage cost, $/kWh	103.9	[40]
Converter cost, $	2636.5	[40]

Table 5: Key assumptions and input parameters for techno-economic modelling for wind. All costs are in 2013 US dollars.

Parameters	Value in the jurisdiction		Sources/comments
	Montreal	Ottawa	
Power limit of one charging point based on the energy requirement of EV per day, kW	1.38	1.50	The value is for the base case of eight hours of charging time. To put this into perspective, time to charge a 20 kWh EV by a 3.6 kW level II charger is 5.6 hours [39]
Turbine			
Life of wind turbine, years	20	20	[36, 40]
Coordinates of the jurisdiction chosen	45.5^o N, 73.6^o W	45.4^o N, 75.7^o W	[41]
Average wind speed, m/sec	4.3	4.2	[27]. Applicable in 2013.
Standard deviation of wind speed data, m/sec	0.69	0.69	Calculated from data provided by [27]
Size of turbine, kW	7.5	7.5	[36]
Cut-in wind speed of turbine, m/sec	3.6	3.6	[36]
Swept area by the turbine, m^2	38.5	38.5	[36]

Turbine height, m	50	50	Because wind speed data are available at 50 m[27], that figure is used for the turbine hub height
Capacity factor	30%	30%	[28, 42]
Power generated by the turbine, kW	1.50	1.45	Continuous power is calculated at annual mean speed plus two times the standard deviation of the wind speed [28] by Equation (1) [37] given in the appendix
Capital cost of turbine, $/kW	2239.3	2239.3	[28]. Includes installation, controller, and rectifier costs
Maintenance cost	2%	2%	2% of capital cost [36]

Table 6: Key assumptions and input parameters for techno-economic modelling for hydro

Parameters	Value in the given jurisdiction			Sources/comments
	Montreal	Ottawa	Vancouver	

Life of hydro power plant, years	10	10	10	[43].
Power limit of one charging point based on the energy requirement per day, kW	1.38	1.50	2.46	Refer to Table 4.
Hydropower plant sizing				
Total electricity demand, kW	8109.9	3265.0	2654.5	Based on the electricity requirement of all the EVs in the given jurisdiction and equal to the number of charging points and EVs (see Table 3 for total number of EVs).
Available head, meters	16.2	16.2	16.2	[43]
Maintenance cost	2%	2%	2%	Maintenance cost is low for small-scale hydro plants [44]. 2% of capital cost is assumed in the study

Table 7: Cost of different parameters in wind energy scenarios for the base case (eight hours of charging time). All costs are in 2013 US dollars.

Parameters	**Montreal**			**Ottawa**			**Sources/comments**
	Scenario 1	**Scenario 2**	**Scenario 3**	**Scenario 1**	**Scenario 2**	**Scenario 3**	
Total power limit of the charging station, kW	1.38	6.88	13.76	1.50	7.49	14.98	Value is based on the energy requirement per day
Number of turbines required	3	15	31	4	17	35	
Annualized Cost *(All values are for one charging station with one, five, or ten charging points in the given jurisdiction)*							
Wind turbine, $/annum[1]	6031.6	30157.9	60315.8	6812.0	34060.0	68120.0	

Batteries, $/annum[1]	816.2	4080.9	8161.8	888.4	4442.0	8884.1	See Equation (2) [28, 45] for battery bank sizing. D (number of days without adequate wind energy) is assumed to be 3 in this paper
Converter, $/annum[1]	429.1	1127.0	1708.2	429.1	1127.0	1708.2	Cost values are scaled using an assumed capacity factor of 0.6
Charging station equipment, $/annum[1]	86.2	430.9	861.8	93.8	469.0	938.0	
Civil works and grid reinforcement of charging station,	0.0	203.3	406.5	0.0	203.3	406.5	[39]

$/annum[1]							
Total maintenance, $/annum	1233.0	6074.4	12081.7	1379.4	6806.6	13546.2	Refer to Table 5

[1]Amortized value over the lifetime

Table 8: Cost of charging an EV from wind and hydro energy in different jurisdictions. Base year for costs is 2013.

Scenario	Cost of charging for charging times of 4 hours, 6 hours, 8 hours, respectively(cents/km)		
	Montreal	Ottawa	Vancouver
1	107.5, 74.8, 58.5	110.8, 77, 60.1	-
2	106.3, 73.6, 57.3	109.7, 75.9, 58.9	-
3	105.8, 73.2, 56.9	109.3, 75.5, 58.6	-
4	12.5, 11.6, 11.2	12.6, 11.6, 11.1	13.8, 12.7, 12.2
5	11.2, 10.3, 9.9	11.3, 10.4, 9.9	12.3, 11.2, 10.7
6	10.7, 9.9, 9.4	10.9, 10, 9.5	11.8, 10.7, 10.2

Table 9: Cost of different parameters in hydro energy scenarios for the base case (eight hours of charging time). All costs are in 2013 US dollars.

Parameters	Montreal			Ottawa			Vancouver		
	Scenario 4	Scenario 5	Scenario 6	Scenario 4	Scenario 5	Scenario 6	Scenario 4	Scenario 5	Scenario 6
Capital cost of hydro plant, $/annum[1,2]	499,771.0	499,771.0	499,771.0	276,655.0	276,655.0	276,655.0	153,097.2	153,097.2	153,097.2
	Source/comments: The value is based on total power requirement of all EVs in the given jurisdiction. Total capital cost (calculated by using Eq. (3) [44] of the appendix)								
Hydro plant, $/annum[1]	84.8	424.0	847.9	126.9	634.5	1269.1	141.9	709.4	1418.9
	Sources/comments: Calculated by dividing the total cost by the projected number of EVs (refer Table 3)								
Batteries, $/annum[1,3]	816.2	4080.9	8161.8	888.4	4442.0	8884.1	722.3	3611.4	7222.8
Converter, $/annum[1,3]	429.1	1127.0	1708.2	429.1	1127.0	1708.2	429.1	1127.0	1708.2
Charging station equipment,	86.2	430.9	861.8	93.8	469.0	938.0	76.3	381.3	762.6

$/annum[1,3]									
Civil Works and grid reinforcement of charging station, $/annum[1,3]	0.0	203.3	406.5	0.0	203.3	406.5	0.0	203.3	406.5
Total Maintenance, $/annum[4]	216.4	949.8	1822.1	235.1	1022.8	1962.9	205.8	868.7	1652.8

[1]Amortized over the lifetime of the hydro plant

[2]A factor of 1.64 is used to convert Pounds to $

[3]Refer wind techno-economic model

[4]Refer to Table 6