



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 kW h 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 h 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 h, the cost of charging increases by 83% and 11% from wind and hydro energy systems, respectively.

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1. Introduction

The fuel consumption transportation industry contributes around 27% to the world's total energy consumption and accounts for 33.7% of GHG (greenhouse gas) emissions [1]. Of the total 6526 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. EPA (environmental protection agency) and the Department of Transportation's NHTSA (National Highway Traffic Safety Administration) 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 g/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 EV (electric vehicles), PHEV (plug-in hybrid electric vehicles), FCV (fuel cell vehicles), and

CNGV (compressed natural gas vehicles) can help reach the expected standard [3].

Canada's national GHG emissions in 2010 were estimated at a value of 692 Mt CO₂-eq from all sources [4]. Of these total GHG emissions for the same year, 166 Mt CO₂-eq were attributed to the transportation sector. Passenger transport including cars, trucks, and motorcycles contributed to 88 Mt CO₂-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

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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
C _{pr}	total project cost of a small-scale hydro plant, in pounds
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

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 Ref. [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, CO₂ 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

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