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ENVIRONMENTAL BENEFITS OF USING WIND GENERATION TO POWER PLUG-IN HYBRID ELECTRIC VEHICLES

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SUMMARY

As alternatives to conventional vehicles, Plug-in Hybrid Electric Vehicles (PHEVs) running off electricity stored in batteries could decrease oil consumption and reduce carbon emissions. By using electricity derived from clean energy sources, even greater environmental benefits are obtainable. This study examines the potential benefits arising from the widespread adoption of PHEVs in light of Alberta's growing interest in wind power. It also investigates PHEVs' capacity to mitigate natural fluctuations in wind power generation.

Index Terms: PHEV, wind energy, emissions.

I. INTRODUCTION

Rising concerns about volatile oil prices and greenhouse gas emissions (GHGs) have strengthened the search for cleaner, more efficient energy resources. PHEVs are one promising solution — they use less gasoline and produce fewer emissions. They also benefit electrical grids by providing regulation and spinning reserve, using their batteries as a distributed storage network accessible to system operators.[1, 2, 3] This ability allows PHEVs to mitigate imbalances in electricity supplies arising from wind-based generation.

As the share of wind generation increases in power systems, the need to match the system's load to the intermittent nature of wind becomes more acute. Through the controlled charging and discharging of PHEV batteries, grid operators can overcome this difficulty.[4]

Building on previous work by the authors,[5] this study investigates the environmental impact of large-scale PHEV adoption in Alberta. Given the dominance of thermal generators and the growing integration of wind-powered generators in the province, we examine how electricity from wind can further improve PHEVs' environmental impact by lowering GHG emissions associated with power generation. The energy required for charging PHEVs is calculated and compared to the expected growth in Alberta's wind power capacity between 2008 and 2025, which could exceed 11 GW.[6] PHEVs are considered as a controllable storage system that can absorb the power generated by wind farms. The results are presented in terms of the environmental benefits of such a scheme and PHEVs' capability to assist in integrating more wind generation in the province. This study only considers the emission reductions associated with PHEVs versus conventional vehicles.

Section II contains a brief overview of PHEVs, an outline of how they store energy and an overview of wind generation. Section III sets out the environmental benefits of PHEVs for Alberta's power systems. Section IV details PHEVs' ability to absorb energy generated by wind farms. Section V sums up our findings.

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1 R. Sioshansi and P. Denholm, "Emissions Impacts and Benefits of Plug-in Hybrid Electric Vehicles and Vehicle-to-Grid Services," Environmental Science and Technology, vol. 43, no. 4, pp. 1199 - 1204, 2009.

2 W. Kempton and J. Tomic, "Vehicle-to-Grid Power Fundamentals: Calculating Capacity and Net Revenue," Journal of Power Sources, vol. 144, no. 1, pp.268 - 79, Sep. 2005.

3 H. Lund and W. Kempton, "Integration of Renewable Energy into the Transport and Electricity Sectors through V2G," Energy Policy, vol. 36, no. 9, pp.3578 - 87, Sep. 2008.

4 J. Short and P. Denholm, "A Preliminary Assessment of Plug-in Hybrid Electric Vehicles on Wind Energy Markets," National Renewable Energy Laboratory (NREL), U.S. Department of Energy, Washington, DC, Tech. Rep., Apr. 2006.

5 M. Hajian, H. Zareipour, and W. D. Rosehart, "Environmental Benefits Of Plug-In Hybrid Electric Vehicles: The Case Of Alberta," 2009 IEEE Power and Energy Society General Meeting, PES '09, p. 6 pp, 2009.

6 AESO Long-Term Transmission System Plan, 2009. [Online]. Available: http://www.aeso.ca/downloads/AESO_LTTSP_Final_July_2009.pdf

II. BACKGROUND

A. Plug-in Hybrid Electric Vehicles

In a PHEV, grid electricity stored in a battery pack is the main power source. In charge depleting/charge sustaining mode (CD/CS) design, the vehicle uses electricity (CD mode) until the battery reaches a certain charging level. At this point, the combustion engine starts up (CS mode). Please note that when considering PHEVs, this study refers to the Chevrolet Volt, the first commercially available PHEV. The Volt features a 16 kW lithium-ion battery pack, 56-km all-electric range, 0.225 kwh/km electricity consumption in CD mode and fuel efficiency around 3.9 L/100 km in CS mode.[7]

B. Controlled Charging of PHEVs

The widespread adoption of PHEVs would require a lot of electricity, creating operational issues for Alberta's electrical grid if this increased demand is uncontrolled (e.g., during evenings when most PHEVs would be parked and plugged in). However, if the power required to recharge PHEVs is controlled and shifted to off-peak periods, a large number of PHEVs could be supplied without as much need to expand generation and transmission infrastructure.[8] With a "smart charging system"[9] in place, when a PHEV is plugged in, the system operator has control over its charging and the PHEV's battery can even be discharged to provide power back to the grid. In such a case, PHEV owners could realize some benefits in return for supplying power to the grid.[10, 11] Although a smart charging system requires an initial investment in communication infrastructure and incentive plans to encourage owners to participate, it would bring with it several advantages. One is the possibility of employing PHEVs to balance out variations in power output from wind farms. Pairing PHEVs' needs with wind generation can also produce significant environmental benefits.

C. Wind Generation

In the last five years, the world's total installed capacity in wind power has tripled, rising from 47,600 MW in 2004 to 152,000 MW in 2009.[12] However, due to wind's intermittent nature, regulating the amount of power available to consumers on the grid has proven difficult. Alberta's electricity system currently has an installed capacity of 12,500 MW — 47.56 percent from coal, 40.56 percent from gas, 6.96 percent from hydro and 5.03 percent from wind.

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[7] Chevrolet. (2010) Chevrolet Voltage. [Online]. http://www.chevroletvoltage.com/

[8] M. Kintner-Meyer, K. Schneider, and R. Pratt, "Impact Assessment Of Plug-In Hybrid Electric Vehicles On Electric Utilities And Regional U.S Power Grids, Part I: Technical Analysis," Pacific Northwest Laboratory, Nov. 2007.

[9] W. Kempton and S. Letendre, "Electric Vehicles As A New Power Source For Electric Utilities," Transportation Research, Part D (Transport and Environment),vol. 2D, no. 3, pp. 157 - 75, Sep. 1997.

[10] W. Kempton and J. Tomic, "Vehicle-To-Grid Power Fundamentals: Calculating Capacity And Net Revenue," Journal of Power Sources, vol. 144, no. 1, pp.268 - 79, Sep. 2005.

[11] W. Kempton and J. Tomic, "Vehicle-To-Grid Power Implementation: From Stabilizing The Grid To Supporting Large-Scale Renewable Energy," Journal of Power Sources, vol. 144, no. 1, pp. 280 - 94, Jun. 2005

[12] World Wind Energy Association, 2009. [Online]. Available: http://www.wwindea.org/home/index.php

Increased interest in wind power could add over 11 GW more, presenting the Alberta Electric System Operator (AESO) with a considerable challenge due to the limited flexibility of its thermal-dominated system. By using PHEVs as a distributed storage system amenable to controlled charging, AESO would be able to smooth out variations in the available power supply arising from wind's irregular nature. This would permit more wind power to be incorporated into the system and dramatically increase the environmental benefits of PHEVs by ensuring they run off clean electricity.

III. METHODOLOGY

In this study, we focus on the issue of charging PHEVs and link it to wind energy production in Alberta between 2008 and 2025. Our system models were developed based on data from AESO for three different load profiles from 2008 (low, medium and high) for all four seasons. Our forecast of the system's load to 2025 was determined using Appendix C of AESO's Long-Term Transmission System Plan. Our forecast of new generation capacity was based on the AESO effective reserve margin (ERM). The ERM is calculated as the ratio of the sum of the installed thermal generation capacity, 20 percent of the installed wind and irrigation hydro capacity, 33 percent of the legacy hydro and 50 percent of new hydro capacity to the annual peak load. AESO maintains an ERM of 10 percent for Alberta and new capacity is added using this criterion. New capacity includes developments under construction and the expected wind farms. This study assumes that the new generating infrastructure Alberta requires includes supercritical pulverized coal generators located in the north and combined-cycle gas generators in the Calgary area. The assumption of coal in the north is based on the availability of coal resources in this part of the province.

The yields from different modes of generating power are dispatched in the order of ascending offer price, given the deregulated energy market in Alberta. The Generation Stacking Order (GSO) is developed based on the variable costs of different methods of power generation and is calculated from the lowest variable cost. The estimated variable cost of each type of generation is given by AESO in the Long-Term Transmission Plan as part of their Levelized Unit Electricity Costs (LUEC).[13] More detail on the electrical model used in this paper can be found in *Transmission Policy in Alberta and Bill 50, the Electric Statutes Amendment Act, 2009*.[14]

The number of light vehicles in Alberta is estimated to be 2.5 million, with around 50 percent being sedans.[15] Estimates of PHEVs' eventual penetration into this market vary from 10 percent to 50 percent. When considering the possibility of charging PHEVs at home or work, four different charging scenarios are examined:

1) PHEVs are charged during the day,
2) PHEVs are charged at night,
3) PHEVs are charged over all 24 hours,
4) PHEVs are charged during the night without any control over charging.

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[13] AESO Long Term Transmission System Plan – Appendix E, page 255.

[14] J.Church, W.Rosehart and J.MacCormack "Transmission Policy in Alberta and Bill 50," Revised Discussion Paper, School Of Public Policy Workshop, November 2009 [Online] Available: http://policyschool.ucalgary.ca/files/publicpolicy/TransmissionPolicyONLINE.pdf

[15] Canadian Vehicle Survey, 2008. [online]. Available: http://www.statcan.gc.ca/pub/53-223-x/53-223-x2008000-eng.pdf

With a smart charging system in place, PHEVs' ability to recharge is controlled in the first three scenarios. The system operator monitors the output from wind farms at all times. If power is available, PHEVs receive a signal telling them to start charging, ensuring that the demand for power matches the available supply. In the fourth scenario, PHEVs begin charging as soon as they get home. If wind farms are unable to meet demand, other power sources take over. The exact mix of usable generating capacity is determined based on the corresponding GSO as mentioned above.

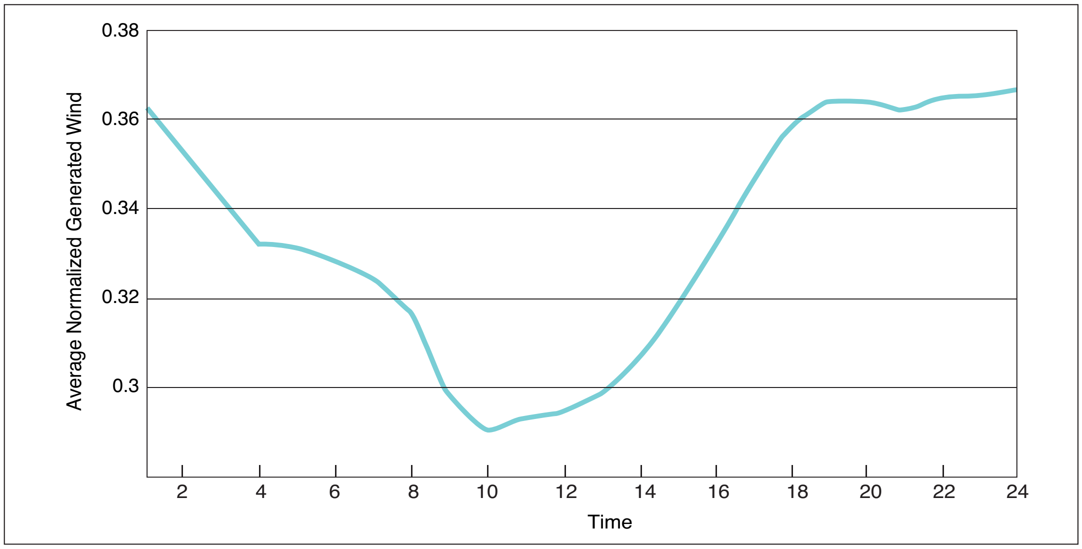
It is assumed that all PHEVs are available for charging when not commuting. According to statistical surveys,[16] commuters' departure time can be modeled via a normal distribution. Based on a normal distribution function, the fraction of the vehicles on roads is assumed to be 15 percent, 35 percent, 35 percent and 15 percent for the hourly commuting blocks from 6:00 to 10:00 in the morning and 16:00 to 20:00 in the evening. An average commuting distance of 40 km for Albertans is based on the Canadian Vehicle Survey 2008.

In the first scenario, vehicles' charging time starts at 8:00 when the first fraction of PHEVs arrives at work and ends at 18:00 when the last fraction leaves work. In the nighttime charging scenario, vehicles are charged starting at 17:00 with those fractions that are plugged in at home. The charging period ends at 9:00 the following day when the last fraction of vehicles at home starts commuting. In the 24-hour charging scenario, PHEVs can be charged both at home and at work with the exception of the commuting times described in the beginning of this section. In the uncontrolled charging scenario, vehicles start charging at 17:00 with those fractions that are plugged in at home, i.e., 35 percent of PHEVs.

IV. ENVIROMENTAL BENEFITS OF PHEVS

The 2008 profile of wind generation in Alberta is used as a starting point with a total energy production of 1.53 TWh. The average normalized hourly wind profile in 2008 is presented in Figure 1. As the graph shows, wind farms produce the most electrical energy during the evening, when most vehicles are parked.

FIGURE 1. NORMALIZED AVERAGE HOURLY OUTPUT OF WIND FARMS IN ALBERTA.



[16] C. Reschovsky, "Journey to work: 2000," U.S. Census Bureau, Tech. Rep., Mar. 2004. [Online] Available: http://www.census.gov/prod/2004pubs/c2kbr-33.pdf

For this study, PHEVs are modeled to represent varying percentages of the sedan market, which represents approximately 50 percent of light vehicles in Canada.[17] Emissions were calculated based on the percentage of PHEV sedans and the type of generation used in a particular hour. The total generating capacity used in each hour is based on the GSO. During the daytime in Alberta there is relatively low availability of wind energy compared to the evening. Therefore, in the daytime only charging scenario PHEVs utilized a small portion of the total wind-based energy (18 percent for a 10 percent PHEV market share and 36 percent for a 50 percent PHEV market share). During the nighttime charging scenario, wind energy usage is between 32 percent and 63 percent. The percentages increase to 36 percent and 89 percent in the 24-hour charging scenario due to the relatively high availability of PHEVs for charging.

In the uncontrolled charging scenario, PHEVs are all plugged in starting at 20:00 with peak demand reaching 1125 MW, assuming PHEVs capture 50 percent of the light vehicle market. This peak demand contributed to about 10 percent of the province's installed generating capacity in 2008. Note that peak demand is limited by the maximum capacity of available electrical outlets. Larger outlet capacity results in higher peak demand. For example, if owners choose 6.6 kW outlets, which correspond to the rating of high-demand appliances such as washers and dryers, peak demand would be as high as 1970 MW, 17 percent of the province's installed capacity. Since PHEV owners mostly recharge their vehicles at night, a fairly reasonable amount of wind energy, 18 percent to 33 percent, can be absorbed.

Figure 2 illustrates the emissions produced by conventional vehicles versus the extra emissions from PHEVs in the four charging scenarios. The difference between the emissions of conventional vehicles and PHEVs can be interpreted as an overall reduction in emissions arising from cleaner technology used in transportation and generation systems. Generally, emission levels in each scenario are significantly less than in the case of conventional vehicles. This difference will grow as PHEVs become more popular. In addition, due to the higher availability of wind energy during the night, emissions in the uncontrolled charging scenario will remain relatively close to those of the daytime charging scenario. The lowest emission level is achieved in the 24-hour scenario, which allows the system operator to control PHEV demand at all times.

Figure 3 demonstrates the additional emissions resulting from PHEVs not being supplied with wind power under the 24-hour charging scenario up to 2025. The corresponding emissions of conventional vehicles for different penetration levels are similar to the one shown in Figure 2. More wind generation in Alberta's power system will mean fewer emissions due to demand from PHEVs.

[17] Canadian Vehicle Survey, 2008. [online]. Available: http://www.statcan.gc.ca/pub/53-223-x/53-223-x2008000-eng.pdf

FIGURE 2. COMPARING CO_2 EMISSIONS IN DIFFERENT PHEV SCENARIOS AND CONVENTIONAL VEHICLES.

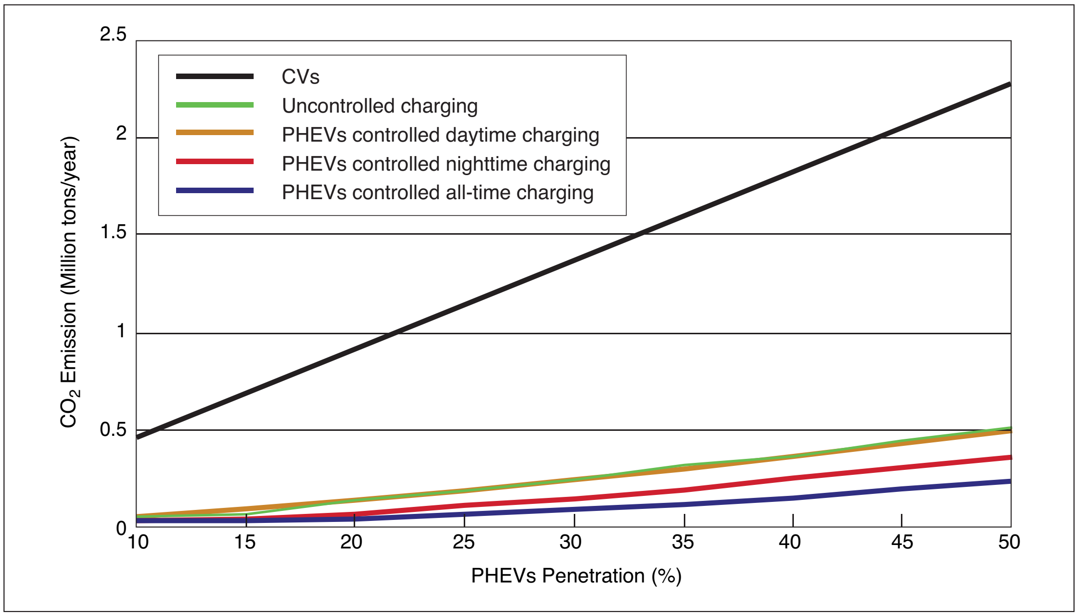
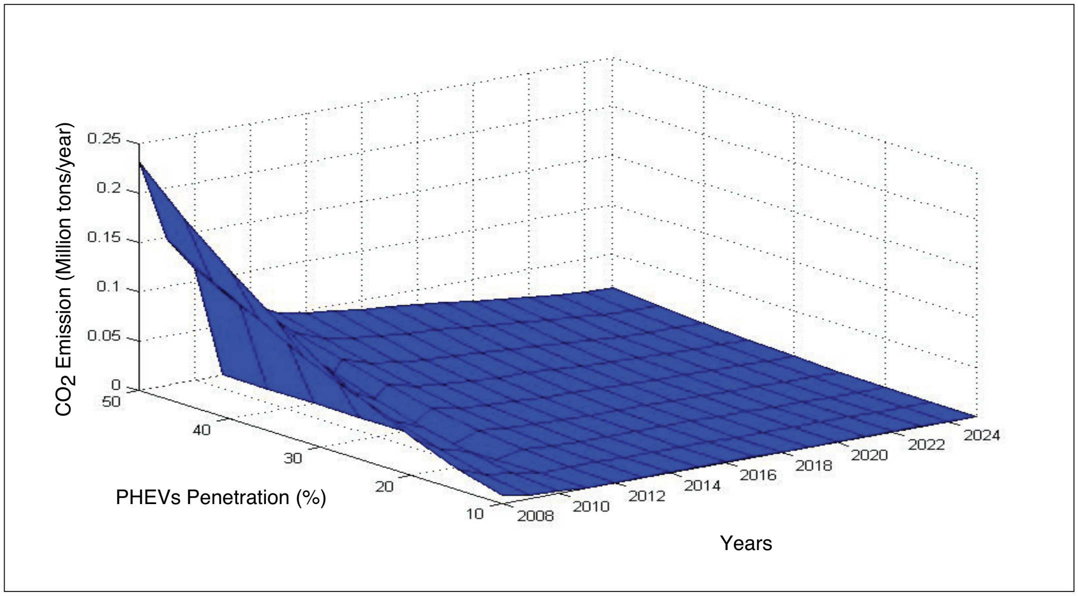


FIGURE 3. CO_2 EMISSIONS OF PHEVS IN THE 24-HOUR CHARGING SCENARIO TILL 2025.



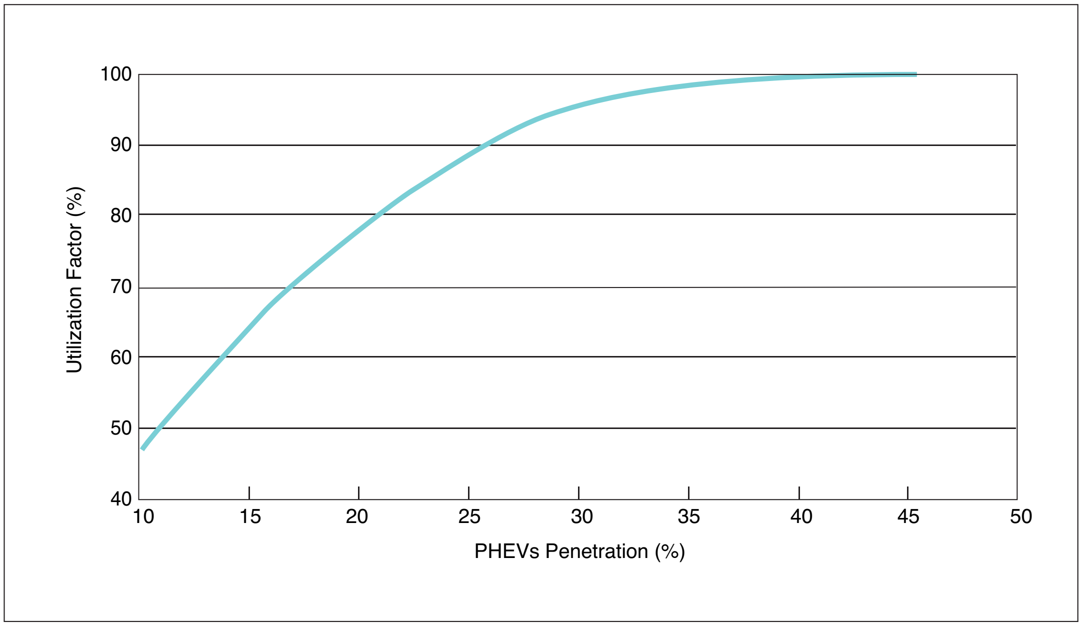
IV. PHEVS' ABILITY TO UTILIZE WIND ENERGY

PHEVs can be used as a controllable storage network to aid in incorporating more wind generation in power systems. Due to a relatively high amount of wind generation in the province, it is impractical to rely solely on PHEVs to soak up all the excess energy. However, a portion of wind generation could be devoted to charging PHEVs. If PHEVs comprise 20 percent of sedans in Alberta and travel 40 km a day, annual demand for energy would amount to 0.82 TWh. This is approximately half the wind energy produced in Alberta in 2008.

However in some instances the available wind energy might be too high or too low to meet PHEVs' energy requirements. Therefore, wind power can't be exclusively relied upon for charging PHEVs and the cars themselves can't always absorb the excess capacity produced by wind farms.

For this analysis, the wind profile is modeled by scaling the normalized 2008 hourly wind profile by a reduced installed wind-generation capacity of 260 MW. The amount of wind energy PHEVs exclusively can use, under this assumption, is shown in Figure 4. At this level, PHEVs can use about 76 percent of the total wind energy produced. If PHEVs become more popular, they will be able to use more wind power. However, due to the intermittent nature of wind, the amount used will not grow in a linear fashion. Rather, it will decline as PHEV power requirements outstrip increases in wind-fueled generating capacity.

FIGURE 4. THE PERCENTAGE OF WIND POWER USED BY PHEVS.



V. ECONOMIC ANALYSIS OF CARBON REDUCTION WITH PHEVS

On sticker price alone, PHEVs are more expensive than comparable conventional vehicles. However, consumers could still save money over the long term by relying on electricity rather than gasoline for fuel. Governments could also lower PHEV purchase prices via tax breaks and financial incentives to encourage quicker uptake.

The capital cost of a PHEV (the Chevy Volt) is expected to be $41,545 in Canada while the cost of a comparable conventional vehicle in Canada (the Chevy Malibu) is $23,995. With a lifespan of 14 years, and a five percent annual depreciation rate, the annual premium for a PHEV will be $1,773. However, this doesn't take fuel savings into account. Albertans' average daily commute amounts to 40 km, which translates into 3.285 MWhr annual energy demand by a PHEV. The average electricity price in Alberta over the last five years is $67.28/MWhr resulting in an annual electricity cost of $222 for a PHEV. The fuel economy of a Chevy Malibu is 7.9 litres/100 km while the average price of gasoline in Alberta was $0.93/liter in

2010. The annual gasoline cost of a comparable conventional sedan is $1073. Therefore, by switching from a conventional vehicle to a PHEV, Albertans could save an additional $851 annually from reduced fuel costs. In total, the relative cost of a PHEV over a conventional sedan can be estimated at $922. The incremental cost of an onboard charger and grid interface is around $200 per vehicle.[18] Spreading the incremental costs out over the expected lifetime of a PHEV amounts to $942 per year with smart charging.

According to Figure 2, the amount of CO_2 reduction achievable by adopting PHEVs could be estimated at approximately 0.74 million tons per vehicle and 0.54 million tons per vehicle for the controlled 24-hour and uncontrolled scenario, respectively. Therefore, the average CO_2 reduction cost using this framework will range from $1265/tons under the controlled 24-hour charging scenario to $1721/tons under the uncontrolled charging scenario. These figures are calculated based on dividing the relative cost to purchase and operate the PHEV vehicles with the reduction of the CO_2 emissions between PHEV and conventional sedans. The PHEV emissions include CO_2 from non-wind electrical generation. This analysis does not include the cost of battery replacement.

VI. CONCLUSION

This paper has attempted to investigate PHEVs as a potential investment in light of Alberta's growing wind power capacity, increasingly volatile oil prices and growing pressure to cut CO_2 emissions. Grid operators' ability to control PHEV recharging could help the province to further reduce its emissions and encourage greater use of wind power. In this study, wind generation and PHEVs are paired together. The reason this study focused on pairing PHEVs and wind generation is because the easy controllability of PHEV charging provides a mechanism to mitigate variations in wind power. We also presented a cost analysis to show the cost of carbon reduction associated with PHEVs. The cost analysis implies that the reduction in CO_2 emissions attained by pairing wind generation with PHEVs does not justify the expense if PHEVs were to be adopted solely because of government incentives aimed at emission reduction. The expense is mainly attributable to the higher purchase price of PHEVs compared to similar conventional vehicles. On the other hand, with automakers' increasing interest in PHEVs, it is likely that the cost of PHEVs will become more competitive with conventional vehicles. Lower capital costs would also encourage more people to buy PHEVs, bringing up the need to control the resulting rise in demand for power. Therefore, policies such as developing smart charging infrastructure to efficiently control that demand or placing extra tariffs on charging during peak times must be created.

ACKNOWLEDGMENT

The authors would like to sincerely thank Mr. John MacCormack for helping us improve the paper by providing data and valuable feedback.

[18] T. B. Gage, Development and Evaluation of a Plug-in HEV with Vehicle-to-Grid Power Flow, Tech. rep., AC Propulsion, Inc., 2003

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