EVS26
Los Angeles, California, May 6 - 9, 2012

PEV Charging in a Smart Grid Framework: Policy Drivers to Manage Load-Shaping and Environmental Impacts

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Abstract

Recently announced Smart Metering Infrastructure (SMI) initiatives by the Canadian utility, BC Hydro, provide a smart grid framework that includes smart meters and in-home, time of use (TOU) energy displays. SMI provides near real-time information and control over existing electrical loads, and enables the integration of alternative energy resources such as wind, tidal and solar power. With the advent of original equipment manufacturer (OEM) Plug-in Electric Vehicles (PEVs), SMI provides the opportunity to reduce overall Greenhouse Gas (GHG) emissions by linking the electricity generation and transport sectors. This paper provides insight into how provincial government and utility policies can contribute to user savings through the intelligent inclusion of PEVs to the electricity demand mix.

Keywords - emissions, EV, load management, policy, smart grid

1 Introduction

Major automakers began to introduce plug-in electric vehicles (PEV) in early markets at a pre-commercial scale in 2011 and will begin to deploy globally at a commercial scale by 2015. Governments and significant electric utilities around the world are preparing for widespread PEV deployment by evaluating the opportunities these vehicles may present for jurisdictions particularly with respect to the potential impacts on energy systems. Numerous jurisdictions are developing and implementing PEV-related incentive programs and policies [16]. This analysis focuses on PEV deployment challenges and solutions in British Columbia (BC).

PEVs represent an important opportunity for reducing the environmental impacts resulting from transportation sector greenhouse gas (GHG) emissions by decreasing the reliance on a limited fuel resource. However, as an additional and unplanned transient load on electrical distribution networks, PEVs also pose challenges to providing reliable service. To evaluate the ability of existing electrical grids to provide consistent service, more analysis is needed to quantify the additional, hourly, PEV load for different levels of market penetration and charging levels. Once this additional load is better understood, it will be possible to evaluate the necessary upgrades to the existing grid to allow for increased capacity and utility control to defer and manage load.

Smart grid technologies and energy systems management provide new opportunities for increasing the reliability of electricity systems, through utility managed energy demand, and deployed distributed generation. Furthermore, the smart grid provision of customer access to near real time charging data has the potential to promote energy electrical grid conservation and GHG reduction. As a result, smart grid technologies and management systems will play a significant role minimizing impacts and realizing benefits from PEVs within the transportation sector.

This paper predicts the GHG emissions associated with different time of use (TOU) PEV charging scenarios in BC. Previous studies have considered the GHG emissions associated with electricity usage [3], [9], [12], [13], specifically PEV charging, as an aggregate average of all electricity used in BC (53 CO_2 equivalent /GWh [1].) However, this approach does not accurately re-

flect the electricity fuel mix actually experienced by BC end users. For example, depending upon TOU, the electricity could be derived from clean, low carbon intensity BC Hydro based generation or high intensity coal-fired Alberta generation. Consequently, there is a variable environmental impact associated with when PEVs are charged.
To accurately gauge the potential impacts of different levels of PEV market penetration and different TOU charging scenarios on the existing electrical grid, the marginal load is calculated over the study period 2010-2030.
This 20-year study period reflects both the increasing market share of PEVs and allows for future proofing of the analysis; it is possible to model SMI and PEV technologies not yet available in the market.
Section 2 presents a background to PEVs, PEV charge point infrastructure and the smart grid framework in BC. Section 3 presents the analysis framework, including BC electricity load profiles, and analysis assumptions and limitations. Section 4 presents and discusses the analysis results. Section 5 concludes the paper; Section 6 outlines future research work.

2 Background

2.1 Plug-in Electric Vehicles

For the purposes of this analysis, Plug-in Electric Vehicles (PEVs) are considered to be any vehicle that requires connection to an electricity grid, in this case the BC Hydro electricity distribution network, to charge an onboard energy storage system. This includes both extended range Battery Electric Vehicles (BEVs) and Plug-in Hybrid Electric Vehicles (PHEVs). Most commonly, energy storage systems are realized through high capacity battery packs comprised of Nickel Metal Hydride (NiMH) or Lithium-ion (Li-ion) cells. These packs vary in size depending on the desired electric-only range of the PEV. Particularly for larger batteries, the charge rate is a critical concern that must be addressed both in the design of the vehicle and the development of a charging infrastructure network.
With the advent of OEM PEVs, in regions with renewable or *clean* electricity, there are considerable opportunities for GHG savings when the electricity generation and transport sectors are linked. These benefits are additional to the localized air quality savings resulting from replacing conventional vehicles with PEVs. Nevertheless, the GHG emission reductions come at the cost of an additional marginal load to the existing grid. Without some degree of *smart* intervention on PEV charging, it is expected that charging will likely take place during peak loading times, after work, during dinnertime (17:00-18:00).
In BC, the legacy hydro-electric dam infrastructure is already nearing full capacity [1]. BC Hydro demand forecasting has shown that electricity loading is expected to increase beyond the existing network capacity. To mitigate the forecasted additional load due to province-wide growth, as one measure, BC Hydro has launched extensive demand side management (DSM) public outreach programs that focus on improved energy efficiency and conservation in all provincial sectors that use electricity. The addition of a transportation load, if left unchecked, could seriously compromise electricity distribution reliability. These impacts to reliability come both in terms of PEV marginal peak loads triggering brownouts and blackouts, and potentially in terms of transformer resizing and early failures, and additional energy capacity requirements at high PEV penetration levels.

2.2 Charge Point Infrastructure

In North America, the Society of Automotive Engineers (SAE) J1772 standard defines three *levels* of Electric Vehicle Service Equipment (EVSE) charging rates or levels [18] that correspond to specific power, infrastructure, and vehicle design requirements. Table 1 summarizes the levels of charging associated with PEVs. Until recent OEM PEV deployments, non-commercial PEVs, such as the aftermarket Toyota Prius HEVs Hymotion conversion, have formed the total PEV share of the transportation sector. These conversions have utilized Level 1 charging which can be realized using standard household electrical outlets. As shown in Table 1, Level 1 charging is associated with a long charge time and low peak load. Because the number of conversion vehicles has been minimal, they have not represented a significant sector of the transportation sector. As such, these PEV conversions have not represented a significant mechanism for reducing GHG emission by replacing conventional vehicles, or a substantial marginal load to the existing BC electrical distribution network.

Table 1: PEV Charge Level Summary

	Voltage (V)	Current (A)	Power (kW)	Time nominal charge 10kW battery
Level 1	120	16	1.8	5 h
Level 2	208/240	30	6.2 - 7.2	2.4 h
Level 3	400	125	50.0	12 min

As an increasing number of OEMs release PEVs with larger battery capacities, there is a greater need for faster charging options both in residential and public locations. Level 2 charging can still be supported in residential applications through use of existing high voltage outlets used to power dryers or dishwashers. However, the significantly shorter charge time results in a greater peak draw to the grid, which has impacts on electricity supply and reliability. This peak draw is dramatically increased for Level 3 DC Fast Charging, which is capable of charging a large capacity battery on the order of minutes, as shown in Table 1. To date, Level 3 charging has not being considered for residential applications because of the high infrastructure cost and voltage requirements. This paper focuses on residential and at work charging opportunities; Level 3 is not considered further in this analysis.

An increase in PEV market penetration will result in a greater need for charging *on-the-go*, in public and office locations. At a minimum, these charging stations must have a method of providing information to the customer concerning the amount and cost of energy consumed. However, to ensure reliable service, an improved solution would integrate these charge points into a *smart grid* that facilitates communication between end user and utility. The utility would then have the ability to defer PEV charging if it cannot guarantee service; the user would have the ability to make near-realtime decisions to improve their charging practices.

BC is currently undertaking PEV charge point pilot programs that focus on so-called *'grid aware'* charging infrastructure to facilitate smart communications between end user and main electrical utility, BC Hydro.

A review of market available charging station technology has indicated that there is no solution yet that meets all criteria; the development of the charge point market will be to monitored as the deployment of OEM PEVs increases.

2.3 Smart Grid Framework in BC

Smart Grid refers to the addition of detailed monitoring, reporting and real time control to existing distribution networks. Electric loading conditions are monitored by way of sensors; this information is then communicated to the utility and end user. The near-realtime communications facilitated by the smart grid framework provide end users with the ability to modify their behaviour based upon utility control signals such as electricity cost, personal energy consumption and neighbourhood network loading.

Important features of the smart grid include enhanced utility connectivity to the end users through near-realtime monitoring and control and improved reliability of service. Overall system efficiency and service to large transient loads is improved through the dynamic reallocation and deferral of resources. The more robust, smart grid also protects against blackouts and brownouts. Emphasis is also placed upon increased usage of renewable resources, such as wind, tidal, solar or hydro power.

Smart grids support the growing trend of home automation by encouraging the use of *smart* appliances that can be wirelessly controlled and regularly monitored for energy usage. This paper focuses on a particular application of home automation: smart garage charging of PEVs. It then expands this analysis beyond the residential sector to include *at work* applications.

BC Hydro is a net importer of GHG-intensive electricity at night during its low loading hours (LLHs). Consequently, the GHG emission reductions resulting from replacing conventional vehicles with PEVs is reduced when charging occurs overnight, as opposed to during daytime high loading hours (HLHs). Therefore, one of the most important considerations for both peak load management and GHG reduction is when PEV charging will take place. However, under traditional BC import/export electricity flows, these goals are conflicting.

If end users are allowed to decide when to charge without external influence or additional information, it is likely that they will start to charge their PEVs in the early evening, 17:00-18:00, during the already peak loading period. This behaviour trend is expected to become increasingly apparent as PEV market penetration progresses past the early adopter stage. In addition to the increasingly *peaky* marginal load associated with more PEVs, particularly with an increase in Level 2 over Level 1 charging, studies indicate that many early adopters are more cognizant of the environmental implications of charging during peak times and are more likely to adapt their behaviour than mainstream adopters [6], [9], [11], [12]. Furthermore, this additional *peakiness* will become more pronounced as an increasing number of PEV require Level 2 over Level 1 charging.

An increase in load when the distribution network is already most taxed could have significant implications for reliable electricity distribution. Reliability of service is cited as one the key components of a modern smart grid [7]. If the utility cannot guarantee that PEV charging be offset from peak loading times, it may be necessary to resize the substation transformers [2], or to switch from simpler primary distribution networks to more robust secondary networks. These infrastructure upgrades would then have an impact on electricity rates and environmental costs.

Nevertheless, BC is in a unique position with respect to environmental opportunities and centralized smart electric grid control. BC Hydro services approximately 94% of provincial users; 87% of their generating capacity is renewable hydroelectric [1]. This scenario is in direct contrast to many other jurisdictions that rely on coal-fired or nuclear electricity generation [3], [6], [11], [14], [15]. However, it should be noted that BC imports much of its overnight power from Alberta's coal-fired generators. Since the intention of utility and government policy makers is to shift PEV charging from early evening to overnight, the environmental implications are significant. Therefore, the hourly electricity fuel mix and loading, in addition to time of year, are considered in this analysis.

At this stage in technology development, it is not clear how BC will define its smart grid. It is unlikely that utilities will take real time control over residential applications of customers PEV charging. Instead, it will be the role of utility demand side management (DSM) and provincial policy makers to educate and entice the customer to charge during non-peak hours. Such enticements could include preferential electricity rates to promote an electrical *valley-filling* approach [2].

A first step to realizing a smart grid framework in BC and other jurisdictions is the addition of smart meters to the existing electrical distribution network. Smart meters facilitate two-way communication between utility and customer for near real time feedback on energy usage and, potentially in the future, TOU pricing. Smart meters support the reliability paradigm associated with smart grids through automatic outage detection and advanced meter tampering alarms.

After testing smart meters in pilot projects, in January 2011, BC Hydro announced its *Smart Meter Infrastructure (SMI) Program*. Under the SMI Program, 1.8 million Itron Open Way smart meters will be deployed in BC by December 2012. Announcements regarding the addition of in-house displays, that would communicate with the smart meters are also expected in 2012. Through the SMI Program, it will be possible to provide end users with hourly information regarding their home energy usage, and more specifically, PEV charging. Itron's meters operate on a Zig Bee mesh network and provide hourly resolution by transmitting energy consumption data for a few seconds per hour to the nearest smart meter in the network. This data is then daisy-chained until it reaches a collector, located on a BC Hydro powerline; all the collected data is then transmitted to BC Hydro. BC Hydro asserts that 80% of projected Smart Metering Infrastructure (SMI) energy savings will result from improved electricity transmission efficiency; the remaining 20% will result from user behaviour modifications [1].

3 Analysis Framework

This paper predicts the marginal loading and GHG emissions associated with the different time of use (TOU) PEV charging scenarios as facilitated by SMI, topology shown in Fig. 1. As mentioned, previous studies have considered the GHGs associated with electricity usage as an aggregate average of all electricity used in BC (53 tonnes CO2 equivalent/GWh) [1], [3], [9], [11], [12], [13], [14], [15]. However, this approach does not accurately reflect the temporally varying electricity fuel mix experienced by BC users or link results to actual SMI capabilities. BC Hydro is a net importer of electricity, some of which is from GHG-intensive coal and natural gas-fired generation. Consequently, BC's GHG intensity varies hourly. Using SMI and in-home displays, this as yet unquantified variable environmental impact due to PEV charging could be used to inform user behaviour.

Figure 1: BC Hydro SMI Topology [1]

As an efficient energy management system, SMI enables monitoring of the electrical grid for GHG emission and energy load impacts associated with TOU charging for different PEV market penetrations charging scenarios [1]. An optimal power flow (OPF) model of a simplified BC electrical grid with interconnects to neighbouring jurisdictions will be developed in future work and scenarios re-run for PEV variable market penetrations [2]. In the current model, however, BC loads aggregate to a single node. The study period 2010-2030 is used to reflect both the projected increase in PEV market share as a percentage of total vehicles in BC and as an absolute number, as shown in Fig. 2. In addition, it facilitates future proofing of the research by modelling SMI and PEV technologies not yet market available.

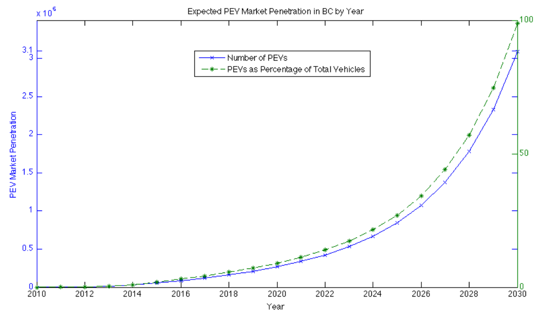

Figure 2: PEV Market Penetration 2010-2030 [16]

To establish baseline use cases, as shown in Fig. 3, three electrical loading days in BC are examined . Using standard BC Hydro assumptions concerning hourly electricity imports/exports, the baseline GHG emissions are calculated [1]. To calculate the marginal loading and GHG emissions associated with PEV charging, system variables including PEV market penetration and SMI control signal functionality are incrementally added to the baseline use case.

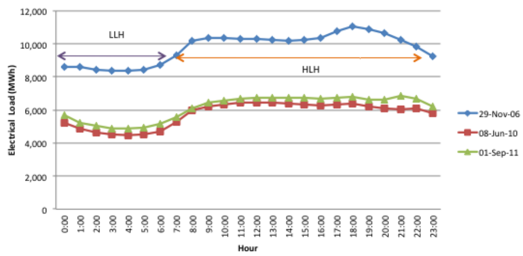

Figure 3: Three Sample Loading Days

Future analysis will consider an agent-based modelling (ABM) approach to simulate more in-depth end user behaviour by modelling consumer changes with respect to government and utility policy drivers. Behavioural impacts of interest include examining the implications of user awareness, facilitated by SMI, of the GHG emissions associated with TOU charging, as well as the effect user loading has on regional electricity distribution networks.

Other policy drivers to be considered include preferential TOU electricity pricing, tax incentives and rebates, and public awareness campaigns. Previous studies generally do not consider these ancillary drivers. Instead they focus on the distribution level technical impacts, and highlight the need for this type of research [12], [13]. Now that SMI and OEM PEVs have reached the deployment phase, it is increasingly important to address the ramifications of existing and proposed PEV policies.

3.1 Daily Electricity Load Profile

For planning purposes, BC Hydro separates daily load profiles into two regions: *low loading hours* (LLHs), 0:00 to 7:00; and *high loading hours* (HHLs), 8:00 to 23:00, as illustrated in Fig. 3. BC Hydro is a net importer of electricity during its overnight, LLHs [1]. From a peak loading perspective, promoting *valley-filling* during the LLHs will likely be preferential to BC Hydro. Nevertheless, to accurately calculate the true ability of PEVs to help meet Provincial GHG reduction targets [16], the TOU carbon intensity of electricity must be considered.

3.1.1 Load Data

Three sample daily load profiles were chosen from historic BC Hydro data to represent the existing BC Hydro baseline load. The marginal loads of different levels of PEV market penetration were then added to the baseline loading profiles to calculate the aggregate effect. November 29, 2006 was chosen as the highest loading day, with the largest ever recorded peak 11,039 MW, recorded at 18:00. This peak caused brownout conditions throughout the most densely populated regions of BC, south Vancouver Island and Vancouver-area. June 8, 2010 was chosen as a sample summer day with a cooling load; September 1, 2011 was chosen to represent a mild autumn or spring day.

Fig. 3 depicts the baseline loading. Note that each follows the same basic loading curve shape, and that the overall daily load profiles are near linear offsets of each other. In particular, note the approximately 3,500 MW offset between November 29, 2006 and June 8, 2010; the approximately 3,000 MW offset between November 29, 2006 and September 1, 2011 due to the winter peak load.

3.1.2 Intertie Data

Near real time data exists on the BC-Alberta and BC-USA intertie electricity flows [1]. However, not all electricity that flows into BC interties due to hourly electricity trades is used by BC end users. At this time, the realtime electricity mix experienced by BC users is not specifically tracked. Under the BC-USA free trade agreement, the interties are open to trading from a variety of different companies, not just the BC Hydro affiliated company, Powerex [17]. Fig 4 maps out the BC-Alberta and BC-USA interties.

To meet the Province of BC GHG reduction target of net zero GHG emissions from power plants by 2016, BC Hydro is currently in the process of devising a methodology to track the hourly electricity mixes based upon historic import/export energy purchases compared with domestic energy usage. Many jurisdictions that BC ultimately imports from do not have mechanisms in place to track the GHG emissions associated with their electricity generation. Therefore, in the absence of reliable realtime data about hourly electricity mix and associated GHG emissions, the BC Hydro endorsed approach of assuming that BC is a net importer during LLH and a net exporter of electricity during HLH is used.

To define the boundary conditions associated with Alberta versus USA intertie imports, two different GHG simulations are run. The first case assumes all the LLHs marginal load is met by Alberta generation; the second case assumes the marginal load is met by USA imports. During HLHs, it is assumed that the PEV marginal load is met by BC domestic generation.

The impact of the marginal load on import and export electricity trades and, consequently, on the price of electricity experienced by the end user, is not considered in this analysis. Future analysis will refine the TOU electricity mix models and address basic pricing impacts due to the marginal load increase. Regional dependence upon charging and the impact on particular transformers will also be considered in future work.

3.2 Model Description

Previous analyses have focused on PEV charging use cases that address extreme, boundary conditions [9], [11], [12]. This analysis considers the energy loading of three sample daily baseline energy load profiles: winter, summer, and interim [9]. Building upon existing hour-by-hour BC energy loading data, including time of day electricity mix information, this analysis then uses probabilistic analysis to determine the additional hourly loading from different levels of PEV market penetration.

For each PEV, daily parameters are obtained from statistically sampling the parameters listed in Table 2. If a charging event is triggered, the charge time is calculated according to Equation 1; the hourly parameters involved in this calculation are described in Table 3, assuming a uniform distribution.

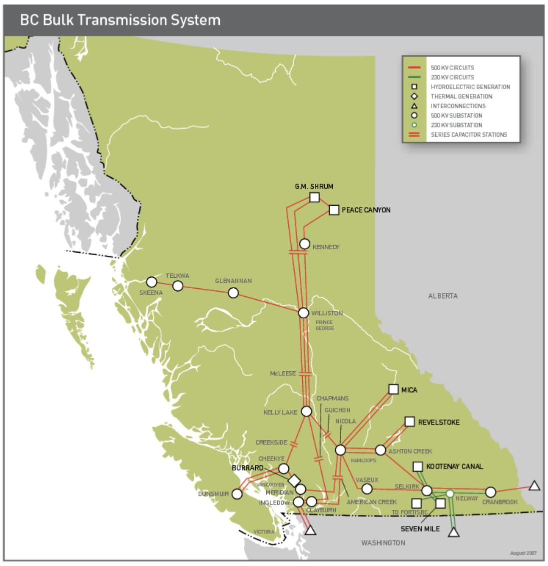

Figure 4: BC Interties [17]

Table 2: PEV Daily Parameters

Parameter	Description
Vehicle Name	The name of a compliant PEV.
Battery Capacity	The battery size associated with *Vehicle Name* (5.2 - 53 kWh) .
Work Start	Work start time (7:00-9:30).
Work End	Length of the work day in hours (6 - 9.5 hours), to be added to *Work Start* to calculate begin of home-bound driving commute.
Work Access	Availability of at work charging.
Charge After Work	Whether PEV will charge immediately after work.
Charge At Night	Whether PEV will charge at night.

$$\text{Charge Time} = \frac{\text{Charge Demand}}{\text{Charge Rate}} * \text{Charge Efficiency} \tag{1}$$

The battery size is determined by PEV type, and charge level can be either Level 1 or 2, with a power load as described by Table 1 are assigned. This analysis considers the different loading effects associated with whether Level 1 or 2 charging is available *at work* and *at home*. This analysis does not directly make assumptions with respect to drive time of commutes and the associated battery state of charge (SOC) depletion. Instead, PEV battery SOC is pseudorandomly calculated at each hourly time step, assuming a uniform distribution. The variability of battery SOC emulates the effect of driving events. Battery SOC only contributes to PEV marginal load when a charging event is initiated. At the beginning of a charging event, the battery SOC at that time is used as a reference point to calculate the time required to charge the battery to completion. Then, for subsequent time steps during the charging event, battery SOC is recalculated to reflect the effect of charging. Table 3 lists PEV parameters calculated hourly. Daily and hourly parameters are pseudorandomly determined except where otherwise noted.

Table 3: PEV Hourly Parameters

Parameter	Description
Battery SOC	Current battery SOC. During charging event, calculated according to initial SOC and time charged. In between charging events, pseudorandomly calculated to reflect variable driving events that would deplete battery SOC.
Charge Demand	The amount of energy required to fully charge battery based upon *Battery Capacity* and *Battery SOC*.
Charge Mode	Type of charging available (Level 1 or 2).
Charge Rate	Hourly rate of charging based upon selected *Charge Mode*.
Charge Efficiency	Efficiency with which vehicle will be charged.
Charge Time	The length of time in hours a PEV battery requires to restore to full charge. Reset if calculated *Charge Time* is longer than available charging access.

This analysis determines the aggregate data for each year in the study period for the associated PEV market penetration. In particular, the marginal load and associated GHGs for each year are added to the baseline load profiles.
As there is a high degree of uncertainty associated with the model inputs, Monte Carlo simulations are used to determine the annually aggregated PEV charging data. Repeated calculation of pseudorandom samples from weighted PEV attribute probabilistic distributions ensures model convergence. This repeated sampling also facilitates sensitivity analysis of model parameters such as: the the availability of *at work* charging and variable charging levels; linear offsets to charging start time; and the ability of the battery to be restored to full SOC by the end of each available charging session. These parameters are analyzed in Sections 4.2- 4.4.

3.3 Model Assumptions

The following high level assumptions were used to define the analysis framework.

1. 20-year study period from 2010-2030.
2. BC Hydro sample baseline daily load profiles taken from three historic days: November 29, 2006, June 8, 2010, and September 1, 2011.
3. This analysis does not consider baseline load growth due to any other source. (Baseline load profiles held constant over study period.)
4. BC is assumed to be a net importer at night over LLHs (23:00-6:00), and a net exporter during HLHs(7:00-22:00). As an importer, two boundary conditions are examined: all imports from Alberta; all imports

from USA. During HLHs, marginal load assumed to be met from domestic generation.

5. Three possible charging scenarios are assumed: *at work*; and either *at home* immediately after work, or overnight. Only one *at home* scenario is selected per PEV instance.

6. This analysis aggregates all PEV charging to a single BC node; the analysis is location independent and is not representative of a specific transformer system. Jurisdictional initiatives to install PEV charge points are not considered.

7. This analysis only includes passenger PEVs identified as compliant by the Province of BC Clean Energy Vehicle Program [16].

8. This analysis focuses on *at work* and *at home* charging scenarios. As a result, only Level 1 and 2 charging is considered. Level 3 is expected to be deployed along public corridors and highways and is therefore not considered further.

Table 4: BC Clean Energy Vehicle Program Compliant PEVs

Manufacturer	Vehicle Name	Battery (kWh)
Fisker	Karma	28.1
Ford Motor	Focus Electric	23.0
Ford Motor	Transit Connect	28.0
General Motors	Chevrolet Volt	16.0
Mitsubishi	iMiEV	16.0
Nissan	LEAF	24.0
Smart Canada/ Mercedes	Smart fortwo Electric Drive	16.5
Smart Canada/ Mercedes	Smart fortwo Electric Drive Cariolet	17.6
Tesla	Roadster	53.0
Toyota	Plug In Hybrid Prius	5.2

4 Results and Discussion

4.1 Simulation Convergence

Following Monte Carlo methodology, the model was tested for convergence by repeatedly simulating until the results matched a single model run for the system with stochastically sampled inputs for the mean case when charging events follow the baseline daily load profile. In this case, the aggregated PEV marginal load approximates a linear offset to the baseline load.
The following sections examine the implications of the availability of *at work* charging, the level of charging available and load shifting to LLHs. Table 5 summarizes the hourly marginal load associated with different levels of PEV market penetration based upon the average PEV charging scenario, when charging events are pseudorandomly distributed. As a point of reference, the baseline loads from the the worst case sample day, November 29, 2006, are included. The marginal load is then presented as a percentage of the historic load. In addition to the average scenario simulated results in Table 5, a worst case upper peak load boundary was also calculated for each year's market penetration, as presented at the bottom of the table (*Worst Case Scenario: Maximum Peak*.
In this scenario, worst case is defined as all PEVs Level 2 charging at once. As a point of reference, this marginal load is compared to the worst ever recorded peak load in BC: 11, 039 MWh on November 29, 2006 at 17:00. As shown in the worst case scenario, the initially slow adoption of PEVs does not result in a significant addition to the baseline load between now and 2020. However, by 2025, all the PEVs charging at 17:00 results in a marginal peak that is 5.50% of the maximum baseline peak; by 2030, PEV charging represents 20.14% of the existing peak. BC Hydro expects up to 40% growth in overall provincial electricity usage over the next 20 years; PEVs will form a large component of incremental electricity usage that will necessitate significant upgrades to BC Hydro electric distribution network.

4.2 At Work Charging

Once simulation convergence was confirmed, the model sensitivity to the availability of *at work* charging and charging start time was tested over the whole study period. Fig. 5 depicts the daily load profile based upon November 29, 2006 for one sample year, 2025 for illustrative purposes.

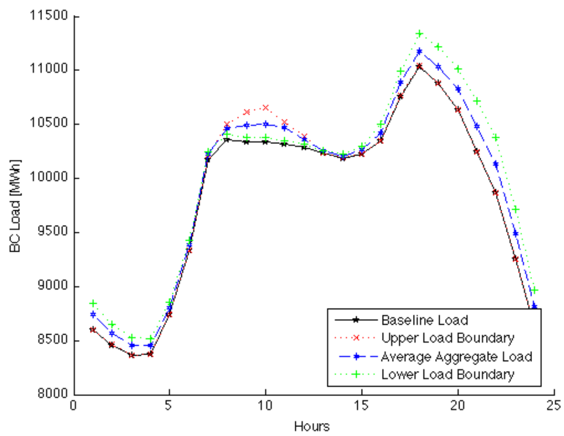

Figure 5: PEV Marginal Load in 2025 At Work Sensitivity Relative to Nov. 29, 2006 Baseload

In 2025, it is estimated that 84,338 PEVs will be deployed in BC [16]. As shown in Fig. 5, this level of PEV market penetration still only represents a slight load increase over the existing baseline load. To determine the effect the availability of *at work* charging has on the overall daily load profile sensitivity, three cases were analyzed.
In the average case, the availability of at work charging was pseudorandomly distributed; the upper boundary represents the case where all PEVs have access to *at work* charging; and the

Table 5: Hourly Marginal Load for Average PEV Charging Scenario by Year

Hour	Year										
	Nov. 29, 2006	2013		2015		2020		2025		2030	
	PEV Market Penetration (number of vehicles)										
	0	1313		5537		26889		84338		308814	
	Baseline Load	Marginal Load									
	MWh	MWh	%	MWh	%	MWh	%	MWh	%	MWh	%
0h	8600	0.6	0.007	2.5	0.029	12.3	0.143	38.5	0.448	141.0	1.639
1h	8460	0.5	0.005	1.9	0.023	9.4	0.112	29.6	0.350	108.4	1.281
2h	8363	0.4	0.005	1.6	0.019	7.9	0.094	24.7	0.296	90.6	1.083
3h	8374	0.3	0.004	1.4	0.017	6.9	0.083	21.7	0.260	79.6	0.950
4h	8738	0.3	0.003	1.2	0.013	5.6	0.065	17.7	0.202	64.8	0.741
5h	9337	0.2	0.002	0.9	0.009	4.2	0.045	13.3	0.142	48.7	0.521
6h	10177	0.2	0.002	0.8	0.008	4.1	0.040	12.7	0.125	46.6	0.458
7h	10357	0.5	0.004	1.9	0.018	9.3	0.090	29.1	0.281	106.7	1.030
8h	10339	0.7	0.007	2.8	0.028	13.8	0.134	43.4	0.419	158.7	1.535
9h	10339	0.7	0.007	3.0	0.029	14.8	0.143	46.4	0.448	169.7	1.642
10h	10323	0.6	0.006	2.7	0.026	13.0	0.126	40.7	0.394	149.0	1.443
11h	10289	0.3	0.003	1.2	0.012	5.9	0.058	18.6	0.2	68.2	0.662
12h	10239	0.1	0.001	0.2	0.002	1.1	0.011	3.5	0.034	12.7	0.124
13h	10190	0.1	0.001	0.3	0.002	1.2	0.012	3.8	0.037	14.0	0.137
14h	10230	0.2	0.002	0.7	0.007	3.2	0.032	10.2	0.099	37.3	0.364
15h	10350	0.3	0.003	1.3	0.013	6.5	0.063	20.3	0.197	74.5	0.720
16h	10762	0.6	0.005	2.4	0.022	11.6	0.108	36.3	0.337	132.9	1.235
17h	11039	0.6	0.006	2.6	0.024	12.6	0.115	39.7	0.359	145.2	1.315
18h	10882	0.6	0.006	2.7	0.025	13.3	0.122	41.6	0.382	152.4	1.400
19h	10635	0.8	0.008	3.5	0.033	16.8	0.158	52.8	0.497	193.4	1.819
20h	10248	1.0	0.010	4.3	0.042	21.0	0.205	66.0	0.643	241.3	2.354
21h	9868	1.1	0.011	4.8	0.048	23.1	0.235	72.6	0.736	265.8	2.694
22h	9252	1.0	0.011	4.4	0.047	21.2	0.229	66.4	0.717	243.0	2.626
23h	8626	0.8	0.010	3.5	0.041	17.0	0.197	53.3	0.618	195.1	2.262
Worst Case Scenario: Maximum Peak											
17h	11039	9.5	0.0856	39.9	0.361	193.6	1.754	607.2	5.501	2223.5	20.142

lower boundary represents the case where there is no access to *at work* charging. From both a peak management and GHG reduction perspective, the *valley filling* approach associated with the upper boundary case is preferable.

The average case follows the historic load profile shape. Nevertheless, as shown in Table 7, the marginal load associated with PEV charging during LLHs is assumed to be met by GHG-intensive import energy. The lower boundary case represents the worst case from both the peak management and GHG reduction perspectives. Without access to *at work* charging, PEVs charge exclusively *at home*, resulting in a large incremental load during peak time (17:00 -18:00) as well as an increased reliance on energy imports because of a shift to LLH charging.

An interesting result of shifting all charging to be *at home* is that a new peak is created from 21:00-22:00 likely due to the length of time required to charge a PEV to completion without topping up the battery SOC during the day. As a result, the increased availability of *at work* PEV charging is critical to promoting optimal load management and GHG emission reductions.

4.3 Charging Levels

The model sensitivity to different types of PEV charging was also analyzed for three cases. In the average case, the availability of Level 1 versus Level 2 charging was evenly distributed, as is planned for by the Province of BC's Clean Energy Vehicle Charging Infrastructure Program [16]. In the lower boundary case, only Level 1 charging was assumed to be available; in the upper boundary case, only Level 2 charging was assumed to be available, thereby resulting in greater *peakiness*.

As shown in Fig. 6, the overall daily load profile was found to be relatively insensitive to type of charging available for the relatively low expected numbers of PEVs. As PEVs become more widely adopted, it is expected that the gap between the availability of Level 1 versus Level 2 charging will increase and that without any mitigating measures, PEV charging will begin to approach the worst case scenario outlined in Table 5. Although currently outside the scope of this analysis, it is anticipated that a greater sensitivity will be observed with the increased introduction of Level 3 DC Fast Chargers. With peak power draws on the order of 50 kW per charging station, Level 3 chargers will represent a significant addition to load profile *peakiness*.

4.4 At Home Charging

The model sensitivity to overnight charging, during LLHs, was also analyzed. This analysis al-

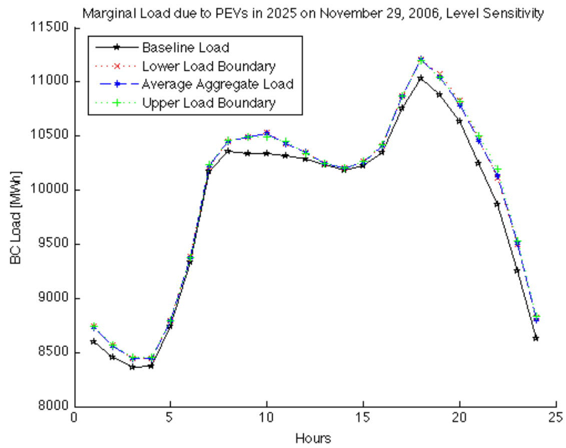

Figure 6: PEV Marginal Load in 2025 on November 29, 2006, Charge Level Sensitivity

lowed for pseudorandomly distributed availability of *at work* charging, but forced overnight charging, as opposed to allowing charging during peak hours (17:00-18:00).

The model sensitivity to only charging at off peak times was analyzed in three cases. As demonstrated in Fig. 7, in the average case, *at home* was pseudorandomly distributed between whether it took place immediately after work or overnight starting at 20:00. The lower boundary case forced *at home* charging to be delayed to starting at 20:00, effectively shifting the peak load to around 22:00. Finally, the upper boundary case assumed all charging takes place immediately after work, adding to the existing peak load at 17:00-18:00. Both boundary cases resulted in shifted versions of very high peak loads. The lower boundary case, resulted in the best load management. However, the average case, where PEV charging is unconstrained *at home*, represented the best trade off between best load management and GHG reductions.

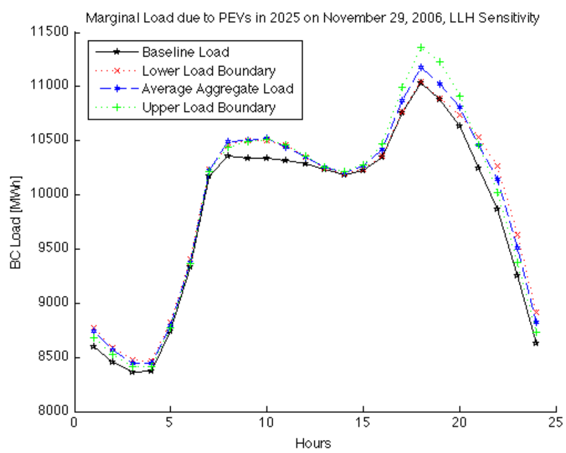

Figure 7: PEV Marginal Load in 2025 on November 29, 2006, At Home Sensitivity

4.5 GHG Emissions

Sensitivity analysis around the PEV marginal load generated with *at work* charging, charge levels, and at deferred *at home* charging, is described in Sections 4.2, 4.3, and 4.4, respectively. Using these marginal load profiles, sensitivity analysis was then completed for marginal GHG emissions, according to the variable life cycle carbon intensities associated with different types of electricity generation included in Table 6.

Table 6: Carbon Intensity by Electricity Generation Type [5] [8] [13] [19]

Generation Type	Carbon Intensity kg CO_2 eq./MWh
Nuclear	1.8
Wind	20
Hydro (Domestic)	35
Gas	540
Coal	975

Fig. 8 provides an example of the expected GHG emissions when the PEV marginal load during LLHs is met by the import electricity generation sources described in Table 6. Recall the BC Hydro assumption that loads during HLHs (8:00 - 23:00) are met by domestic (hydro) generation, while LLHs loads (0:00 - 7:00) are met by import electricity, either through the BC-Alberta or BC-USA interties [1]. As shown in Fig. 8, the worst case GHG emission scenario is when LLH import electricity is met by coal-fired generation. As described in Section 2, this worst case scenario is closest to the actual electricity fuel mix experienced in BC.

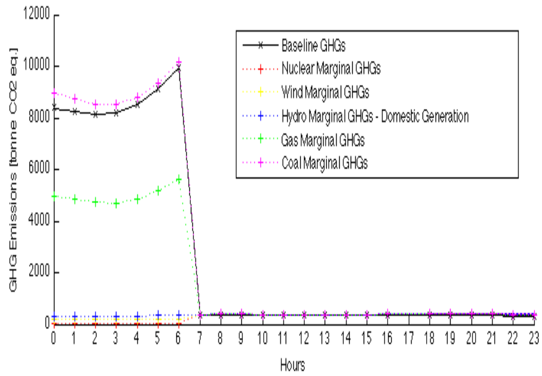

Figure 8: PEV GHG Emissions with Variable Marginal Generation for one day in 2025

Table 7 is based upon two assumptions with regards to the electricity fuel mix currently experienced in BC: all loading during HLHs is met by domestic electricity generation; and all LLHs loading is met by imported coal-fired electricity generation, from either Alberta or California.

To demonstrate the importance of end user TOU charging behaviour, the GHG emissions associated with the PEV charging scenarios outlined

Table 7: Total GHG Emissions for Various Marginal Loading Scenarios

Year	Scenarios		
	Total GHG [tonne CO_2 eq.] for 1 sample day		
	At Work	Charging Levels (Level 1 vs. Level 2)	At Home (LLHs vs. HLHs)
2013	1.1	3.0	3.7
2015	4.4	12.6	15.7
2020	2.2	61.2	76.1
2025	60.2	191.9	238.5
2030	247.1	649.0	830.7

in Sections 4.2- 4.4 are calculated to determine the actual GHG cost of PEV charging. As shown in both Fig. 8 and Table 7, from the perspective of mitigating GHG emissions, the presence of *at work* charging becomes increasingly critical for increasing, sustainable PEV deployment in BC, particularly with respect to meeting provincial government GHG reduction targets [16]. Deferring charging to *at home* overnight during LLHs is shown to have the worst overall GHG impact. As demonstrated in Section 4.3, the availability of Level 2 charging had little impact on overall daily load profiles; accordingly, it has little impact on mitigating potential GHG emissions at low rates of PEV deployment.

4.6 Deployment Challenges

The presented results are based upon assumptions concerning theoretically available technology and pseudorandomized user behaviour. However, significant challenges still exist with respect to the policy implications of smart grid development and the ability to influence end user behaviour to effect best practice, intelligent PEV charging patterns. BC import schedules result in contradicting design goals for load management and GHG emission reduction. The overnight, LLHs are associated with the highest carbon intensity from Alberta and California coal-fired electricity imports.

A major challenge to the integration of a smart grid for PEVs is *at home*, smart garage applications. BC Hydro has indicated that they are opposed to deploying additional smart meters in residential buildings to solely monitor the charging of PEVs. Motivations for this decision include the ability of customers to circumvent using the dedicated PEV plug, especially for Level 1 charging, and a desire to maintain customer privacy by not further entering their home. Therefore, for residential charge points to have *smart* capabilities, it is necessary for the customer to have charging and rate pricing knowledge without being directly monitored by the utility.

A potential solution is to install charging stations that also provide intelligence in the form of communications ability and data storage. To encourage PEV charging TOU away from peak periods, the charging stations should be able to download hour-by-hour rates in advance on a per day or per hour basis. Metering would then take place for the entire house, but the charging station would store the customer's data. Similarly, another solution would have the system intelligence reside on the PEV, and charge by way of a *'dumb'* charging station.

Unlike other *smart* home appliances, PEVs also have the ability to charge in *on-the-go* and *at work* scenarios. Through incentive programs, such as the BC Provincial Clean Energy Vehicle Program announced November 2011, all levels of government have indicated their support of widespread charging infrastructure throughout BC. Targeted opportunities for installing this charging infrastructure include *at work*, retail, public spaces and highway corridors.

These non-residential charging stations will likely employ *smart* charging stations capable of, at a minimum, communicating locally with the customer. As these charging stations are expected to experience heavier loading then their residential counterparts, controlled TOU PEV charging will be of greater importance. This requirement is especially true for DC fast chargers, which involve a significant peak draw from the electrical grid. Furthermore, from the perspective of data collection and monitoring energy consumption, storing information in a central location is also of great importance.

Each of these proposed methods has limitations resulting from approaching charging as a case-by-case action with different methods of payment and charging. Isolating individual charging events is ultimately shortsighted to the overall goal of a smart, integrated charging network. Expected future challenges include reliability and consistency of service, which poses a major barrier to widespread consumer adoption. From the perspective of utility and government policy makers, it is challenging to monitor energy loading in real time and collect long term PEV data across a wide array of charging stations.

To facilitate the collection of data at all charge points for the customer, utility and government policy makers, a potential solution could be that all data be stored on the PEV and then uploaded to a central database at regular intervals. The first PEVs deployed in BC will represent a large cross sample of different OEMs. To ensure interoperability between vehicles and charge points, a standard methodology will need to be defined whereby all vehicles identify themselves and charge using the same mechanism.

Standardization of the communication and smart grid charging of PEVs will be of particular importance in BC smart charging pilot programs. Currently, market available charging stations use different communication protocols, ranging from wifi, to ZigBee, to Ethernet, with different degrees of functionality and different degrees of security such as https or 128-bit AES [16].

To ensure that widescale charge point deployment projects are able to address the broader issue of smart grid implementation, consideration should be placed as to how public charging stations from different manufacturers will communicate to the utility, the end user and each other. As the communication protocol used by SMI, ZigBee protocol is emerging as the standard for smart appliance, and by extension, PEV charging, communications [20].

5 Conclusion

This paper provides a first analysis of the potential impacts PEV adoption have on the existing BC Hydro electricity distribution network by considering the hourly implications of PEV charging. Providing service to 94% of BC users, this network is considered representative of provincial electricity usage [1]. The marginal load associated with increasing PEV market penetration over the 20-year study period (2010-2030) is aggregated with the BC Hydro historic baseline load profiles on three sample days: November 29, 2006, which includes the highest ever recorded peak load of 11, 039 MWh at 17:00; June 8, 2010, a summer day; and September 1, 2011, a mild fall or spring day.

Monte Carlo simulations test the sensitivity of the historic daily load profiles to the availability of at work charging, and charge start time. Analysis confirms that at home peak charging (17:00-18:00) is not a sustainable option, so PEV charging must be shifted off-peak. This analysis then tests the sensitivity of promoting a *valley filling* approach of at home, overnight charging during LLHs. The availability of Level 1 versus Level 2 charging has only slight impacts on the overall BC daily load profile for relatively low PEV market penetration. This result, however, is expected to change with increased PEV adoption and the introduction of Level 3 DC Fast Charging.

The key finding is that if only overnight charging is employed, much of the potential GHG emission savings in BC associated with switching from a conventional vehicle to a PEV are lost.

Furthermore, for the PEV market penetrations expected as soon as in the next 5 years, shifting charging to LLHs results in an equally undesirable peak around 22:00. As a result, the increased availability of *at work* charging emerges as the best trade-off between peak power loading and GHG emission reduction.

6 Future Work

Future analysis will continue to refine the real-time import/export electricity mix and associated GHG emissions experienced by BC end users. This information will be key to meeting Province of BC mandated BC Hydro GHG reduction targets by reducing reliance on the carbon tax and *cap and trade* policies. Knowledge of the real-time GHG emissions associated with imported electricity will also serve to inform BC electricity trader, Powerex. Finally, providing this energy loading and GHG emission information to the end user by way of an in home display will promote informed, responsible energy consumption and optimal GHG emission reductions.

BC implementations of smart grid charging for PEVs are likely to take a hands off approach to limiting customer access to electricity. As a result, public education and incentives will need to play a dominant role in load management; additional modelling will provide statistical predictions of this behaviour.

From this user analysis, the next step will be to correlate the behaviour models to government and utility (BC Hydro) incentives. Then, using the specifications for SMI, original equipment manufacturer (OEM) PEVs, and their corresponding market shares, it will be possible to model how to influence user behaviour to shift to optimal PEV charging in terms of both daily load profiles and GHG reductions.

Acknowledgments

The authors would like to acknowledge the continued support of their project stakeholders, the Province of British Columbia, and BC Hydro.

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