Optimal Transition to Plug-in Hybrid Electric Vehicles in Ontario-Canada Considering the Electricity Grid Limitations

Amirhossein Hajimiragha, *Student Member, IEEE,* Claudio A. Cañizares, *Fellow, IEEE,*
Michael W. Fowler, and Ali Elkamel

***Abstract*—This paper analyses the feasibility of optimally utilizing Ontario's grid potential for charging Plug-in Hybrid Electric Vehicles (PHEVs) during off-peak periods. Based on a simplified zonal model of Ontario's electricity transmission network and a zonal pattern of base-load generation capacity from 2009 to 2025, an optimization model is developed to find the optimal as well as maximum penetrations of PHEVs into Ontario's transport sector. The results of this study demonstrate that the present and projected electricity grid in Ontario can be optimally exploited for charging almost 6% of the total vehicles in Ontario or 12.5% of the vehicles in Toronto's transport sector by 2025; this corresponds to approximately 500,000 PHEVs that can be charged from the grid without any additional transmission or power generation investments beyond those currently planned.**

***Index Terms*—Plug-in Hybrid Electric Vehicle, transportation, electricity grid, planning, optimization, Ontario.**

I. INTRODUCTION

ENERGYutilities are presented with the challenges of increased energy demand and the need to immediately address environmental concerns such as climate change. Due to population and economic growth, the global demand for energy is expected to increase by 50% over the next 25 years [1], [2]. This large increase in demand along with the dwindling supply of fossil fuels has raised concerns over the security of the energy supply.

The transport sector is one of the largest and fastest growing contributors to energy demand, urban air pollution and greenhouse gases, which are major issues for the sector in view of the challenges associated with the supply of oil and expected higher gasoline prices, as well as tighter emission requirements. In the case of Canada's transport sector, it represents almost 35% of the total energy demand and is the second highest source of greenhouse gas emissions [3], [4]. Therefore, the subject of alternative fuels for meeting the future energy demand of the transport sector has gained much attention due to the present energy and environmental concerns.

Hybrid Electric Vehicle (HEV) technology presents an option for significant reductions in gasoline consumption as well as smog precursor and greenhouse gas emissions. This is achieved through the possibility of downsizing the engine and the ability to recover a substantial amount of the vehicle's kinetic energy in the battery storage system through regenerative braking [5]–[7]. However, HEVs still suffer from their dependence on a single hydrocarbon fuel source and range limitations. The emerging Plug-in Hybrid Electric Vehicle (PHEV) is somewhat similar to a conventional HEV, but features a much larger onboard battery and a plug-in charger; this helps it to achieve a large All-Electric-Range (AER) capability for the initial portion of a driving trip. The main advantage of PHEV technology is that the vehicle is not dependent on a single fuel source; thus, it can travel the first 30 km or more on battery power alone, without running the internal combustion engine. This allows the completion of daily trips on battery power alone, and thus substantially reduces gasoline consumption as well as cold-start emissions [7]–[10]. However, at the present state of technological development, there are still some concerns regarding the viability of PHEVs; in particular energy storage costs, range and durability are the major challenges that must be overcome [11].

Present and future electrical infrastructures are designed to meet the highest expected demand, which occurs only a few hundred hours per year. Hence, the grid is in general underutilized and thus could generate and deliver a substantial amount of energy to charge the batteries in PHEVs. Nevertheless, the introduction of PHEVs in the transport sector must consider their interaction with existing and planned electrical energy resources. Thus, if electricity is produced from high polluting sources, the environmental advantages of PHEVs are limited [12]. In the case of Ontario, as per the Integrated Power System Plan (IPSP) [13], most of the electricity generation by 2025 will be environmentally friendly, as coal plants are planned to be phased out in 2014. Furthermore, the development of renewable energy resources is a particular concern in the IPSP; for example, the target value of total renewable energy in 2025 is 15,700 MW, which is about 40% of total capacity, of which about 4,700 MW is wind power [14].

Manuscript received February 27, 2009; revised May 4, 2009; accepted for publication June 8, 2009.

This work was supported in part by the Ontario Center of Excellence (OCE), Bruce Power and the Natural Sciences and Engineering Research Council (NSERC) of Canada.

A. Hajimiragha, and C. Cañizares are with the Power and Energy Systems Group, Department of Electrical and Computer Engineering, University of Waterloo, Waterloo, ON N2L 3G1, Canada (phone: 519-888-4567 ext. 35355; fax: 519-746-3077; e-mail: ahajimir@uwaterloo.ca; ccanizar@uwaterloo.ca).

M. Fowler, and A. Elkamel are with the Department of Chemical Engineering, University of Waterloo, Waterloo, ON N2L 3G1, Canada (e-mail: mfowler@cape.uwaterloo.ca; aelkamel@uwaterloo.ca).

However, the intermittent behaviour of wind and solar, and their consequent low capacity factors make the development of these resources a challenging task and thus they are often the subject of criticism. In this context, the integration of PHEVs into Ontario's transport sector will provide energy storage capacity for Ontario's grid, thus facilitating the integration of intermittent energy resources such as wind and solar.

In the past, energy infrastructure projects have typically been planned and operated separately, but the present trend is to move towards an integrated view, because of the common technical and economic interactions between different types of energy infrastructure [15]–[18]. PHEV technology is a prime example of the integration of the transport sector with power systems to improve the efficiency of both. In this case, the integration of the energy demand for electrical power with the energy demand for transportation fuel is of particular interest. With this in mind, appropriate quantitative tools and planning models for the transition to PHEVs should be developed in order to maximize its environmental benefits and to minimize its corresponding costs.

In view of the technical and environmental advantages of PHEVs, the possible impacts on the grid as a result of the PHEV load should be analyzed in detail. For example, in [19], both PHEV charging and discharging is studied in six geographic regions in the United States to examine the grid impacts for different PHEV penetration levels up to a maximum level of 50%; this study disregards the environmental impacts as well as different types of vehicles, and it assumes a unique average value for the energy requirements of all PHEVs. Based on different charging scenarios, the authors in [20] evaluate various PHEV-charging impacts on utility system operations within the Xcel Energy Colorado service territory; environmental issues are also studied, evaluating different types of emissions considering the time of charging and the marginal power plant. In [21], the impact of PHEVs on both generation supply and emission for the Virginia-Carolinas electric grid in 2018 is evaluated for different charging levels and timing, based on a gradual ramp up of PHEV market share to 25% in 2018; this analysis is also extended to all regions of the U.S., finding the marginal power plants in different regions for different charging patterns. In [22], the percentage of the U.S. light-duty vehicle that could potentially be supplied by U.S. electricity infrastructure without additional investments in generation, transmission and distribution capacities is estimated in 2007; the impact on overall emissions of criteria gases and greenhouse gases is also studied. Smart demand management of power systems integrated with PHEVs is studied in [23] for an urban area with a relatively small number of PHEVs; a smart agent-based demand management scheme is proposed based on nonlinear pricing to assure proper distribution of the available energy to PHEV customers. The issue of PHEV charging strategies and their impacts on generation expansion planning is studied in [24]; this study identifies the future required generation infrastructure based on an assumed high penetration of PHEVs.

The current paper discusses the transition to grid-charged vehicles in Ontario, Canada. Motivated by the notion of efficient utilization of the existing infrastructure and the concept of integrated energy systems, an optimization planning model that takes into account both electricity and transport sectors as one integrated system is presented and discussed. Considering the future development of both power generation and electricity transmission capacities in Ontario between 2009 and 2025 based on Ontario's IPSP [13], this paper aims to find the maximum level of PHEV's penetration into Ontario's transport sector within this constrained planning framework, taking into account the environmental benefits of PHEVs. Specifically, this paper intends to determine the maximum percentage of cars on the road in different zones of Ontario that could be recharged from the grid during off-peak electricity price time intervals. The main goal of the present research is to determine how Ontario's electricity network can be optimally exploited during the base load periods for charging the PHEVs, without jeopardizing the reliability of the system through stressing the system at peak demand periods or developing a new and separate infrastructure to cover the electricity requirement of PHEVs.

The remainder of the paper is structured as follows: In Section II, appropriate models for the proposed Ontario-centered studies are briefly described, including a simplified transmission network and planned generation capacity contributing to base-load energy in each zone; the required electricity system data is also discussed in this section. Different aspects of PHEVs in the context of Ontario such as different penetration trends, energy and power requirements, and environmental issues are discussed in Section III. The proposed optimization model is described in Section IV. The results obtained from the proposed models and data are presented and discussed in Section V. Finally, Section VI summarizes the main conclusions and contributions of the present study.

II. Ontario Electricity System Model

A. Electricity Network Model

The Ontario's Independent Electricity System Operator (IESO) represents the Ontario network with 10 zones [25]. This same representation is used in this work to develop the 10-bus simplified model of Ontario's network shown in Fig. 1, which considers the main grid load and generation centers and transmission corridors. This model is mostly a 500 kV network, with a 230 kV interconnection between NE and NW. Hence, the parameters used to model this network are based on typical values of 500 and 230 kV networks, considering the approximate distances between zones and transmission capacities, as per general information provided by the IESO [25]. Based on the existing and planned projects provided by the Ontario Power Authority (OPA) [13], [26], the transmission capacity enhancements presented in Table I are assumed for the simplified model used in this study.

B. Electricity Generation Model

Based on the Ontario IPSP and a variety of information provided by the OPA and the IESO [13], [14], [26]–[31], a zonal pattern of generation capacity between 2008 and 2025 that is contributing to base-load energy in Ontario was developed. This pattern shown in Fig. 2 specifies the total

Fig. 1. Simplified model of Ontario's grid.

TABLE I
ESTIMATED TRANSMISSION CORRIDOR ENHANCEMENTS FOR SIMPLIFIED GRID MODEL

Year	Corridor	Current MW	Planned MW
2012	Bruce-SW	2560	4560
2012	SW-Toronto	3212	5212
2013	NE-NW	350	550
2015	Bruce-West	1940	2440
2017	Toronto-Essa	2000	2500
2017	Essa-NE	1900	2400

effective generation capacity which is available in each zone to supply base-load. The mix of base-load generation resources in Ontario considered in this model includes nuclear, wind, hydro (only those units with limited dispatch capability and small scale units less than 10 MW), Combined Heat and Power (CHP), Conservation and Demand Management (CDM), and coal. It is important to mention that the contribution of gas-fired generation to base-load energy has been disregarded in this study, based on the Ontario government's 2006 Supply Mix Directive indicating that natural gas should be used only at peak-load times and in high-efficiency and high-value applications [13], [32]. Also, the new nuclear units which are planned to be in service in 2018 are assumed to be in the Toronto zone.

C. Base-load Electricity Demand Model

Based on the zonal peak demand forecast from 2007 to 2015 [33], approximate values of annual peak demand growth rate were determined and are reflected in Table II. It is assumed here that these values apply to all future years up to 2025.

As per [28], [29], the average base and peak-load values in Ontario from 2007 to 2025 will increase by 21% and 24%, respectively. On average, these load increases translate into 1.11% and 1.26% of respective base and peak-load annual growth rates for all of Ontario. Based on the data in Table II, the base-load growth rate in the whole of Ontario was decomposed into individual zones. The resulting annual zonal growth rates along with Ontario's average base-load demand in 2007, as per [34], were used to obtain the annual expected base-load demand in different zones of Ontario during the planning years. Since Ontario's IESO defines the off-peak time intervals to be between 12 am and 7 am, all system studies, including the calculation of base-load demands, were performed during this time period when PHEVs could take advantage of the low electricity price and demand in the system, thus reducing costs and not affecting significantly system reliability through increased load during high demand periods. As a conservative assumption, the model utilizes the larger winter base-load demands for generating the base-load data during the planning study, as per Fig. 3, which shows that larger base-load demands occur during winter time in almost all zones of Ontario.

Comparing the total effective generation capacity in Ontario with the expected base-load shows that there is a capacity deficit to supply base load power from 2016 to 2021. This is mainly due to retirement of coal plants and refurbishments of both Bruce B and Pickering B nuclear units. The possible supply alternatives for covering this power deficit include power imports from neighbouring grids, contributions from further conservation, renewable and CHP resources in excess of planned levels, and contributions from intermediate-load resources such as combined cycle gas turbines [28]. Since there are strong tie lines with New York and Michigan, and an Ontario-Quebec HVDC interconnection is scheduled to be operational by 2010 [14], the base-load deficit is assumed here to be supplied by power imports, as discussed in more detail below.

D. Imports/Exports in Ontario

Since there is surplus capacity during the base-load periods in the Bruce and Niagara zones, the possibility of power exports to Michigan and New York through the West and Niagara zones, respectively, has been considered. Furthermore, a maximum of 1500 MW of power imports from New York and Quebec from 2015-2022 is assumed for the East zone. Power imports in both NE and NW from Quebec and Manitoba/Minnesota, respectively, are also considered in this study; thus, a maximum of 500 MW of imports in both NE and NW are assumed from 2015-2022. Also, a maximum of 250 MW imported power in NW is assumed in other years within the planning period.

E. Base-load Electricity Price

Study on off-peak electricity prices in Ontario shows in general a declining trend. For example, the average Hourly Ontario Energy Price (HOEP) in Winter time during the time period from 12 am to 7 am has decreased from 49.23 $CAD/MWh in 2006 to 34.14 $CAD/MWh in 2008. However, considering the expected price increase between 2016 and

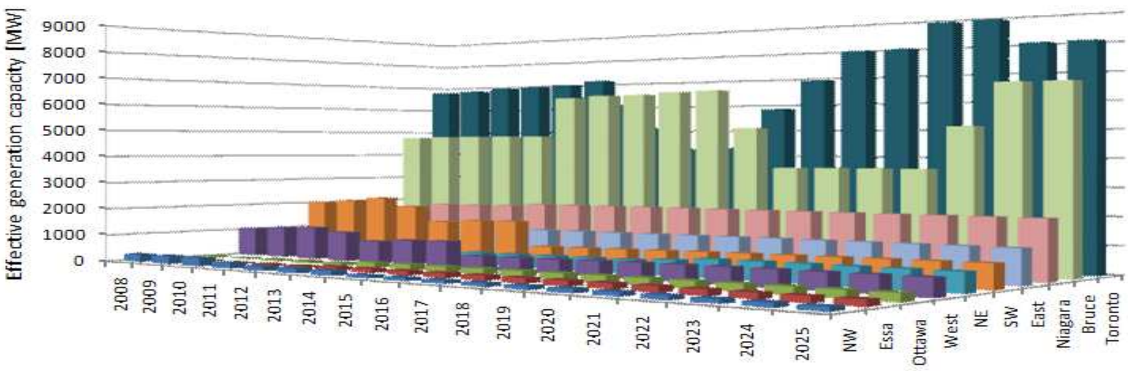


Fig. 2. Zonal effective generation capacity in Ontario contributing to base load energy.

TABLE II
ESTIMATED PERCENT OF ZONAL ANNUAL PEAK-DEMAND GROWTH RATE IN ONTARIO

Zone	Bruce	West	SW	Niagara	Toronto	East	Ottawa	Essa	NE	NW
Annual growth rate [%]	0.78	1.14	1.28	0.41	0.77	0.71	1.42	1.17	-0.33	0.10

2021 due to relatively limited base-load generation capacity and a potential increase on base-load prices due to increased demand associated with PHEVs, the average HOEP in 2008 is assumed here to be the expected electricity price for all the planning period.

III. PHEVs IN ONTARIO

A. Light-duty vehicles

Light-duty vehicles are referred to as vehicles with a gross weight below 4.5 tonnes. According to the Canadian Vehicle Survey [35], in a 2005 base, the light-duty vehicle fleet consists of passenger vehicles with a 58% share, and light trucks including SUVs, vans and pickup trucks with 8%, 16%, and 18% shares, respectively. These shares were considered to be valid for Ontario. Therefore, the passenger vehicles were classified into 6 types of light-duty vehicles, i.e., compact and mid-size sedan (each with 29% share), and mid-size and full-size SUVs (each with 4% share), vans (16% share) and pickup trucks (18% share).

In order to find Ontario's grid potential for charging the PHEVs and performing other system related studies, it is first necessary to determine the number of light-duty vehicles during the 2009-2025 period, which in turn requires the zonal population levels during the planning period. Therefore, the population of cities and towns of more than 10,000 inhabitants were used to find the population of each zone, considering the geographical location of the zones. The population of each zone was then scaled up such that the sum of zonal populations would equal the 12,861,940 population estimate for Ontario on January 1, 2008 as per [36]. The annual base-load growth rate for each zone was also used to find the zonal population in the study period. The total projected population of Ontario in 2025 estimated in this way (15,663,374) is very similar to what is reported in [37], confirming the adequacy of the assumptions used here.

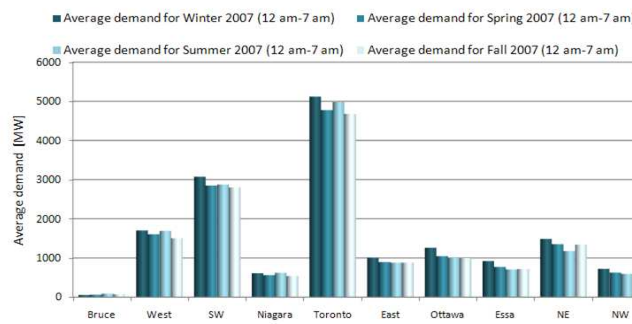


Fig. 3. Average demands by season during the time period of 12 am to 7 am based on 2007 data. Similar patterns can be observed for other years.

According to [35], the per capita number of vehicles in Ontario (in a 2005 base) was almost 0.55; this value was considered to be valid during the planning period in this paper. Based on the zonal population and the per capita number of cars, the total number of the 6 types of light-duty vehicles in the 2009-2025 period can be estimated. The number of light-duty vehicles estimated this way is depicted in Fig. 4 for each year and zone considered in the study; notice the increase of light-duty vehicles from 7,155,108 in 2009 to 8,614,856 in 2025.

B. Transition to Grid-charged Vehicles

The transition to PHEVs in Ontario for the study years is assumed to be as shown in Fig. 5, where K=100 represents a 100% PHEV penetration into the transport sector. These curves specify the level of PHEV penetrations to be realized each

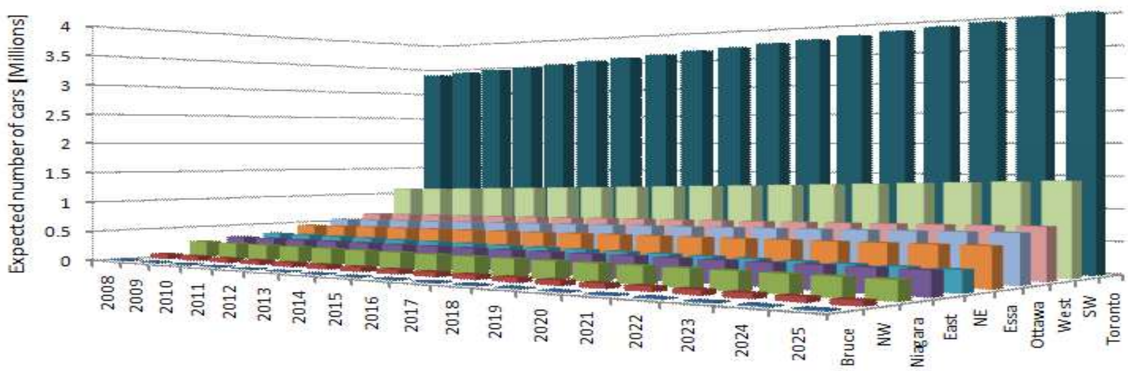


Fig. 4. Expected number of light-duty vehicles in Ontario during the planning period.

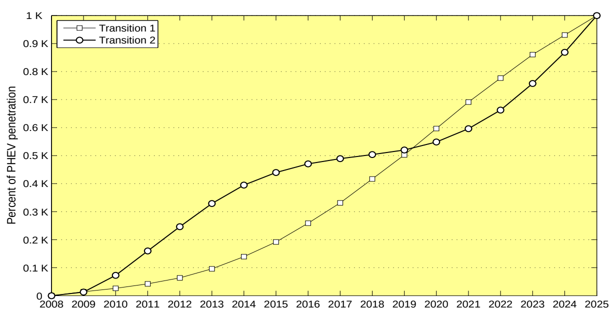


Fig. 5. Assumed PHEVs transitions in Ontario.

year, i.e., the percent of the total light-duty vehicles on the road to be charged from the grid to meet the target value in 2025.

Transition 1 in Fig. 5 assumes a sluggish penetration of PHEV, in particular from 2009 to 2015, with a faster slope thereafter to reach the target value in 2025. Sluggish penetration in the first years provides sufficient time for the development of required PHEV infrastructure, technology and market acceptance. However, the major part of PHEV penetration would occur in the time period of 2015-2022 when Ontario's network is short of base-load capacity. Transition 2 assumes a fast penetration of PHEV during the time periods of 2009-2015 and 2022-2025, with a relatively limited penetration between 2015 and 2022. This transition is appealing as it considers the scarcity of base-load resources between 2015 and 2022; however, it requires a fast development of PHEV infrastructure, with about 45% of the 2025 target level of penetration being realized before 2015.

C. Charging demands

In order to evaluate the PHEVs charging demands on Ontario's grid, the following assumptions were made:

- A 30 km all electric average daily trip (referred to as PHEV30 hereafter). This covers at least 60% of the average daily trip range per light-duty vehicle in Ontario [35]. In other words, the electric share of Vehicle Miles Travelled (VMT) is 60%, and the rest is driven by gasoline.
- A 70% maximum allowable depth of discharge. Due to cycle life considerations [11], [38], [39], at most 70% of the battery's energy is assumed to be used in charge depleting mode.
- A 1.4 kW connection power level (120 V/15 A). This is the capacity of the plug to which the battery is connected and is based on the assumption that little change will take place in the standard Ontario household infrastructure. Note that the continuous rating of a plug circuit is less than its peak capacity [19], [21].
- An 85% charging efficiency.

It should also be pointed out that this study is mainly concerned with generation and transmission system issues, and does not consider distribution system issues. Nevertheless, keeping in mind that only *off-peak* demand and *base-load* generation conditions during the time period of 12 am to 7 am are considered, the total demand levels should not be close to on-peak conditions; consequently, technical problems such as overloading of distribution feeders and transformers or potential unbalanced conditions should not be expected to be a major concern. However, these issues need to be studied further in more detail.

Based on the previous assumptions and the required specific energy [6], [39], [40], the battery charging requirements for different types of PHEV30 vehicles shown in Table III were calculated; full-size SUVs, vans, and pickup trucks are approximately assigned the same energy requirements. Observe that the charging times fit in the assumed 8 hours (12 am - 7 am) off-peak time periods. Note that according to the IESO's notation, 12 am - 11 pm represents a full 24-hour time period, with the first and last hours corresponding to 12 am and 11 pm, respectively. It is also to be pointed out that a wide distribution of PHEV vehicle models and technologies are expected to be introduced; the classifications used in this work simply make use of representative vehicle types.

TABLE III
CHARGING REQUIREMENTS FOR DIFFERENT TYPES OF PHEV30

Vehicle type	Specific energy requirement [kWh/km]	Required useable energy [kWh]	Required battery size [kWh]	Total energy demand [kWh]	Charging time [hour]
Compact sedan	0.16	4.8	6.86	5.65	4.03
Mid-size sedan	0.19	5.7	8.14	6.71	4.79
Mid-size SUV	0.24	7.2	10.29	8.47	6.05
Full-size SUV	0.29	8.7	12.43	10.24	7.13
Van	0.29	8.7	12.43	10.24	7.13
Pickup truck	0.29	8.7	12.43	10.24	7.13

An average hourly power consumption for each type of vehicle was considered in this study from 12 am to 7 am, assuming that the charger system's controller is capable of providing a smooth charging current and consequently make a uniform charging demand during the whole time period. Based on these averages, total power requirements of PHEV30 vehicles were calculated for the different zones and years of the planning period for both assumed transition curves, based on a 100% penetration level by 2025; these results are used to define the zonal demand constraints in the optimization model described in Section IV. It should be mentioned that this methodology yields approximately 8.4 GW of power requirement for a 100% penetration of PHEVs into Ontario's transport sector by 2025, i.e., about 26% for the estimated peak demand in that year.

D. Environmental Credit

PHEVs result in reductions of GHG emission in populated areas; however, in order to cover the PHEVs charging demands, extra power must be generated by generation facilities. The latter may not necessarily be renewable sources of energy, thus increasing the GHG emission in the power generation area. Consequently, the net emission reduction is directly influenced by the share of fossil fuel in the marginal generation mix. Although high penetration of PHEVs may not necessarily result in GHG emission reductions in all regions, it would help to shift the GHG emissions from millions of tailpipes in highly populated areas to a limited number of central generation power plants, thus facilitating more efficient control and management of GHG emissions. This can be considered as an "environmental credit" for PHEVs, even in regions where coal-fired power plants are the marginal generation resource. Studies show that PHEVs result in lower GHG emissions compared to conventional gasoline vehicles even for regions with high CO_2 levels from electric generation [12], [20], [21].

Fossil fuel-based resources considered in the mix of Ontario's base-load generation in this study include coal and CHP plants. Considering that coal plants in Ontario are planned to be phased out by the end of 2014 [13], the maximum contributions of coal plants to the total base-load energy in Ontario has been determined in this study to be 17% in 2008-2010, 14% in 2011, 9% in 2012-2014, and none after 2014; thus, the contribution of coal plants to CO_2 emissions is not very significant in the proposed model for the study period. Natural gas-fuelled power plants also emit CO_2 but at a substantially lower rate per unit of output energy compared to coal plants, and CHP plants emit an even lower amount of CO_2 due to their high efficiencies [41]–[43].

In view of all these considerations, a CO_2 credit was assigned to each PHEV added to Ontario's transport sector; these credits are thus considered in the objective function of the developed optimization model. Note that this is a credit or benefit assumed in the model, and thus it does not necessarily represent an actual CO_2 emission credit to be traded at the obtained value. This value was generated by the model with the objective of a maximum utilization of the grid, with all its relevant constraints, for PHEV charging. It is worth mentioning that based on a 140 gr/km CO_2 production of a gasoline vehicle, which is a typical value for new cars, the annual amount of CO_2 cut by one PHEV30 in a populated area in Ontario is almost equal to 1.5 ton.

IV. OPTIMIZATION MODEL

In order to find the maximum level of extra load in the form of PHEVs that can be added to Ontario's electricity network between 2009 and 2025, a multi-interval DC optimal power flow (OPF) model with loss factor considerations was developed, based on the proposed zonal model of Ontario's electricity system during base-load time intervals. Considering a piecewise linearization of power losses, the resulting optimization model is a Mixed Integer Linear Programming (MILP) problem. This section describes in detail the proposed optimization model.

A. Objective Function

The model's objective is to minimize the total cost. Thus, the following objective function consists of electricity generation and imported/exported power costs and revenue components from 12 am to 7 am, as well as the environmental credit components that are assigned to each PHEV added to Ontario's transport sector:

$$\sum_{y\in Y}\sum_{i\in Z}\{(Pg_{iy}+Pim_{iy}-Pex_{iy}).HOEP_y\times 8\times 365 \\ -\lambda_i.Nphev_{iy}.EC\} \quad (1)$$

where:

Y={2009, ..., 2025} is the set of indices of planning years.

Z={1, ..., 10} is the set of zones or buses in the simplified network.

Pg_{iy}, Pim_{iy} and Pex_{iy} are zonal generation power, imported power, and exported power, respectively, in Zone i and Year y.

λ_i is the PHEV penetration level in Zone i by the end of the planning years, i.e., 2025.

$HOEP_y$ is the average Hourly Ontario Energy Price in Year y.

$Nphev_{iy}$ is the maximum number of PHEVs in Zone i and Year y based on a 100% penetration level.

EC is the annual environmental credit assigned to each PHEV.

B. Constraints

1) Transmission System: The transmission system model in this paper is appropriate for long-term planning studies, which are mainly concerned about generation, transmission and demand of active power [44], [45]. In these studies, reactive power and related voltage issues are usually indirectly represented in the transmission system constraints by further limiting the amount of active power that can be transferred between relevant areas, as discussed in Section IV-B4. Therefore, the power losses in Line (i,j) of the electricity network can be approximately calculated as:

$$Ploss_{ij} \cong g_{ij}(\delta_i - \delta_j)^2 \tag{2}$$

where g_{ij} is the conductance of the line between buses i and j, and δ denotes the corresponding bus voltage angles. Following the method proposed in [46], a linear approximation of power losses in Year y can be obtained using L piecewise linear blocks as follows:

$$\delta_{ijy} = |\delta_{iy} - \delta_{jy}| \tag{3}$$

$$\delta_{ijy} = \sum_{l=1}^{L} \delta_{ijy}(l) \tag{4}$$

$$Ploss_{ijy} = g_{ijy} \sum_{l=1}^{L} \alpha_{ijy}(l)\delta_{ijy}(l) \tag{5}$$

where $\alpha_{ijy}(l)$ and $\delta_{ijy}(l)$ denote the slope and value of the lth block of voltage angle, respectively. Assuming that each angle block has a constant maximum length $\Delta\delta_y$, the slope of the blocks of angles for all lines (i,j) can be calculated as:

$$\begin{gathered}\alpha_{ijy}(l) = (2l-1)\Delta\delta_y \\ \forall (i,j) \in \Omega \wedge y \in Y\end{gathered} \tag{6}$$

where Ω is the set of indices of transmission lines. Consequently, each block of voltage angle is bounded between zero and $\Delta\delta_y$, as follows:

$$\begin{gathered}0 \le \delta_{ijy}(l) \le \Delta\delta_y \\ \forall (i,j) \in \Omega \wedge y \in Y \wedge l \in L_1\end{gathered} \tag{7}$$

where L_1 is the set of total voltage angle blocks; L_1=$\{1, ..., L\}$.

To linearize the absolute value in (3), the two new non-negative variables δ^+_{ijy} and δ^-_{ijy} are defined, together with the following constraints [47]:

$$\begin{gathered}\delta_{ijy} = \delta^+_{ijy} + \delta^-_{ijy} \\ \delta_{iy} - \delta_{jy} = \delta^+_{ijy} - \delta^-_{ijy} \\ \delta^+_{ijy} \ge 0, \delta^-_{ijy} \ge 0 \\ \forall (i,j) \in \Omega \wedge y \in Y\end{gathered} \tag{8}$$

The following constraints are also needed to enforce the adjacency of the angle blocks:

$$\begin{gathered}\mu_{ijy}(l).\Delta\delta_y \le \delta_{ijy}(l) \\ \forall (i,j) \in \Omega \wedge y \in Y \wedge l \in L_2\end{gathered} \tag{9}$$

$$\begin{gathered}\delta_{ijy}(l) \le \mu_{ijy}(l-1).\Delta\delta_y \\ \forall (i,j) \in \Omega \wedge y \in Y \wedge l \in L_3\end{gathered} \tag{10}$$

$$\begin{gathered}\mu_{ijy}(l) \le \mu_{ijy}(l-1) \\ \forall (i,j) \in \Omega \wedge y \in Y \wedge l \in L_4\end{gathered} \tag{11}$$

where $\mu_{ijy}(l)$ is a binary variable which adopts the value of 1 if the value of the lth angle block for the line (i,j) is equal to its maximum value $\Delta\delta_y$; L_2=$\{1, ..., L-1\}$; L_3=$\{2, ..., L\}$; and L_4=$\{2, ..., L-1\}$.

Considering the line losses model just described, the net power injected at Zone i can be represented as:

$$P_{iy} = \sum_{(i,j)\in\Omega} \left[\frac{1}{2} g_{ijy} \sum_{l=1}^{L} \alpha_{ijy}(l)\delta_{ijy}(l) - b_{ijy}(\delta_{iy} - \delta_{jy}) \right] \tag{12}$$

where b_{ijy} is the susceptance of the line (i,j) in Year y. As a result, the zonal power balance constraints can be generally formulated as follows:

$$\begin{gathered}Pg_{iy} - Pl_{iy} + Pim_{iy} - Pex_{iy} \\ - \sum_{(i,j)\in\Omega} \left[\frac{1}{2} g_{ijy} \sum_{l=1}^{L} \alpha_{ijy}(l)\delta_{ijy}(l) - b_{ijy}(\delta_{iy} - \delta_{jy}) \right] = 0 \\ \forall i \in Z \wedge y \in Y\end{gathered} \tag{13}$$

where Pl is the total base-load in each zone and is comprised of the zonal electricity demand (Pe) and the total PHEVs charging power (λPch) as follows:

$$\begin{gathered}Pl_{iy} - Pe_{iy} - \lambda_i Pch_{iy} = 0 \\ \forall i \in Z \wedge y \in Y\end{gathered} \tag{14}$$

Note that Pch is the maximum PHEVs charging power for 100% penetration by 2025 following the transition patterns, as discussed in Section III-C.

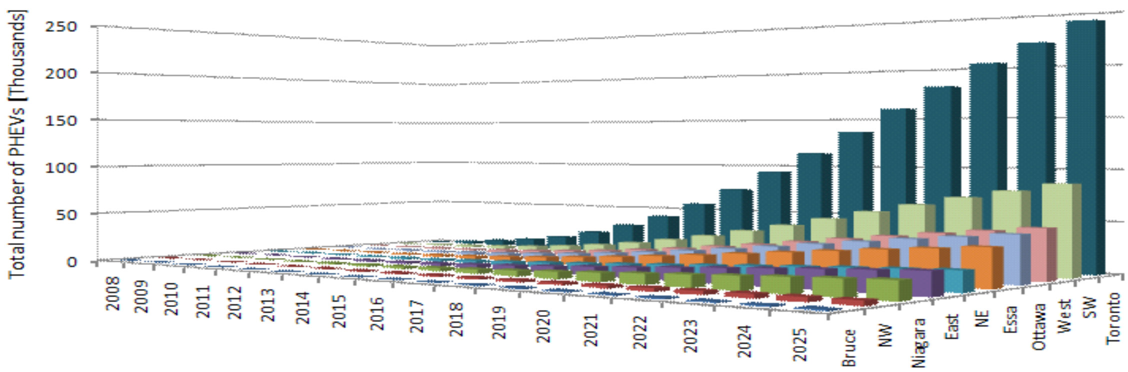
2) Zonal Power Generation Limits: Zonal power generation in each year is confined by minimum and maximum limits $\underline{Pg}_{iy}$ and $\overline{Pg}_{iy}$, respectively. These limits are the minimum and maximum effective generation capacities which are available in each zone during the planning years in the time period of 12 am to 7 am, as discussed in Section II-B, resulting in the following inequality constraints:

$$\begin{gathered}\underline{Pg}_{iy} \le Pg_{iy} \le \overline{Pg}_{iy} \\ \forall i \in Z \wedge y \in Y\end{gathered} \tag{15}$$

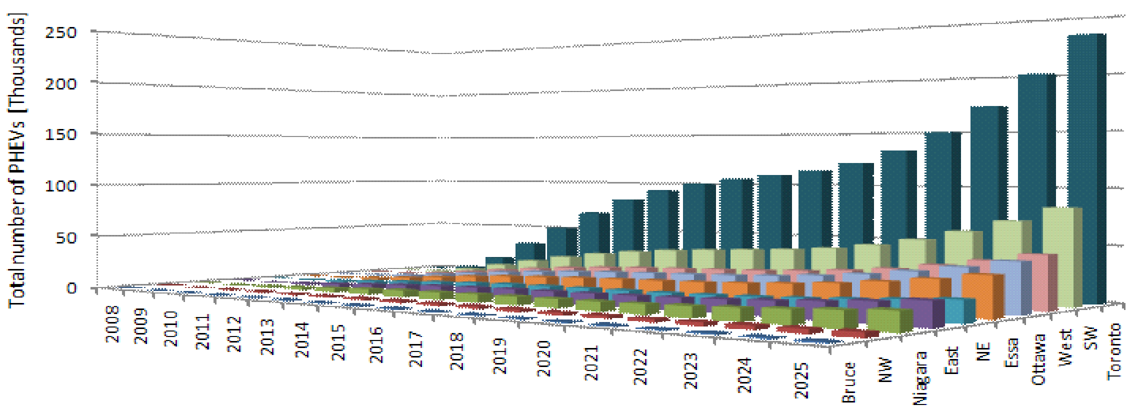
3) Zonal Import/Export Power Limits: These limits are stated as:

$$\begin{gathered}\underline{Pim}_{iy} \le Pim_{iy} \le \overline{Pim}_{iy} \\ \underline{Pex}_{iy} \le Pex_{iy} \le \overline{Pex}_{iy} \\ \forall i \in Z \wedge y \in Y\end{gathered} \tag{16}$$

where $\underline{Pim}_{iy}$ and $\overline{Pim}_{iy}$ are lower and upper bounds of imported power, respectively; and $\underline{Pex}_{iy}$ and $\overline{Pex}_{iy}$ are exported power minimum and maximum limits, respectively. These limits are set based on the arguments presented in Section II-D.



(a) Transition 1



(b) Transition 2

Fig. 6. Maximum number of PHEVs for a uniform penetration across the whole of Ontario.

4) Transmission Capacity Constraints: These constraints are defined as:

$$-b_{ijy}(\delta_{iy}-\delta_{jy})+\frac{1}{2}g_{ijy}\sum_{l=1}^{L}\alpha_{ijy}(l)\delta_{ijy}(l)\le\overline{Pd}_{ijy}$$
$$b_{ijy}(\delta_{iy}-\delta_{jy})+\frac{1}{2}g_{ijy}\sum_{l=1}^{L}\alpha_{ijy}(l)\delta_{ijy}(l)\le\overline{Pr}_{ijy}$$
$$\forall(i,j)\in\Omega\wedge y\in Y \qquad (17)$$

where $\overline{Pd}_{ijy}$ and $\overline{Pr}_{ijy}$ are the maximum capacity of the transmission corridor (i,j) in Year y for direct and reverse power flow, respectively. These limits have been obtained based on thermal and stability considerations; for example, reactive power and related voltage issues are indirectly accounted for in these power limits.

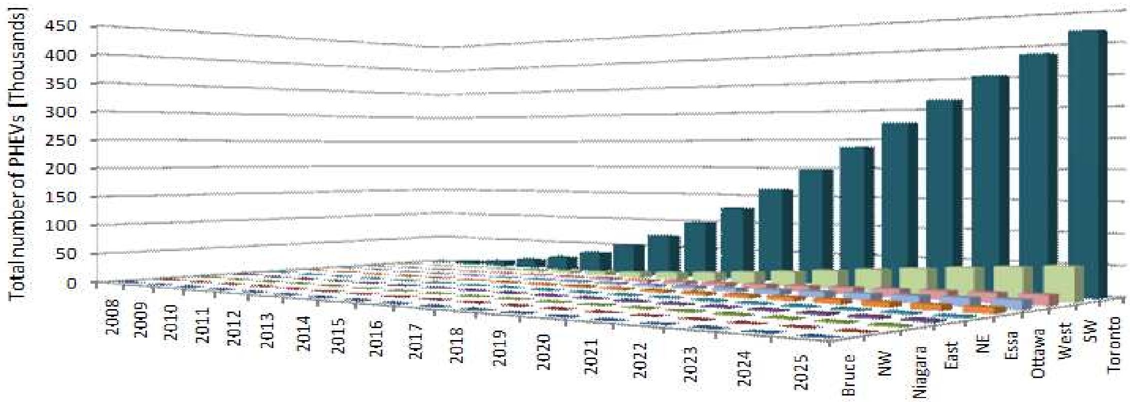
V. Results and Discussion

The optimization model proposed in Section IV was coded in the AMPL mathematical modeling language [48], and then solved using the CPLEX solver [49]. The results of these simulations for different assumed scenarios are presented and discussed in this section.

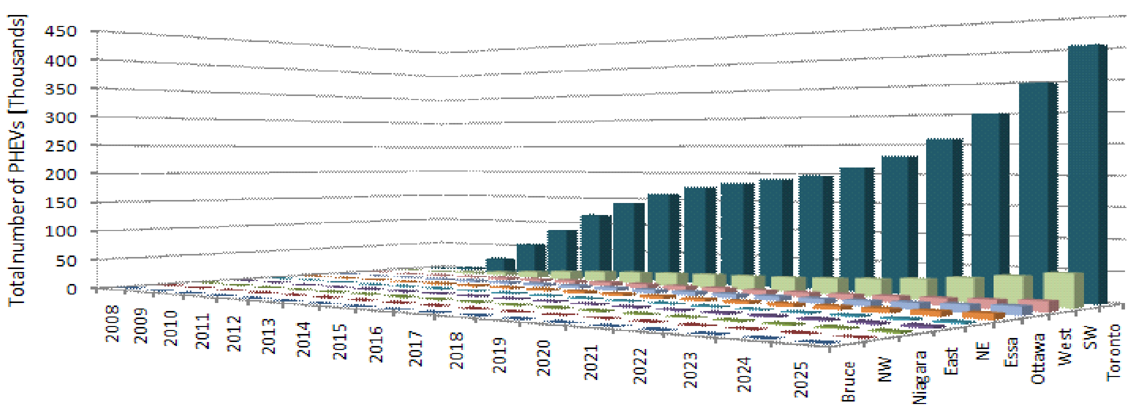
Various values of EC in the 10-110 Canadian dollars (CAD) range were considered, based on typical social cost values of CO_2 emissions [50], [51], and the annual amount of CO_2 cut by one PHEV30 in Ontario. These values affect the penetration levels, as per the objective function (1). It was found that the maximum penetration levels for all performed studies were achieved for EC values larger than 101.18 CAD. Hence, this is the value used in all simulations discussed here.

A. Scenario 1

If a uniform penetration in all 10 zones across the whole Ontario is assumed, the maximum possible PHEVs penetration into Ontario's transport sector is found to be equal to 6.04% for Transition 1, and 5.84% for Transition 2. As shown in Fig. 6, these percentages translate into a penetration of 520,337 and 503,108 PHEVs in Ontario's transport sector by



(a) Transition 1



(b) Transition 2

Fig. 7. Maximum number of PHEVs based on different zonal penetration levels in Ontario.

2025, respectively. These results basically reflect the maximum potential of Ontario's grid for supplying extra load in the form of PHEVs, considering the power system main costs and its limits, which include the security limits of the major transmission corridors.

B. Scenario 2

In this scenario, the maximum penetration level in each zone by 2025 is assumed to be proportional to the maximum number of light-duty vehicles in the corresponding zone. This assumption is based on greater penetration levels in the more populated zones of Ontario such as Toronto due to the environmental advantages of such a distribution. The maximum penetration levels in percentages obtained in this case are depicted in Table IV. Observe in Table IV that more than 10% PHEVs penetration into Toronto's transport sector is feasible in this case; this translates into 416,921 and 402,944 PHEVs in this zone by 2025 for Transitions 1 and 2, respectively. As shown in Fig. 7, the total numbers of PHEVs in Ontario by 2025 for this scenario are found to be 519,715 and 502,372 for Transitions 1 and 2, respectively.

C. Scenario 3

In this scenario, PHEVs are confined to the transport sector of the Toronto zone. If all the PHEVs are supposed to be operated in the Toronto zone, the maximum penetration levels for Transitions 1 and 2 are found to be equal to 12.96% and 12.52%, respectively. As shown in Fig. 8, these penetration levels translate into 517,557 and 499,986 PHEVs in Toronto's transport sector for Transitions 1 and 2, respectively.

D. Discussion and Comparison

The previous results show that the ultimate numbers of PHEVs that can be introduced into Ontario's transport sector by 2025 are not substantially influenced by the assumed

TABLE IV
MAXIMUM PHEVS PENETRATION LEVELS IN % BY 2025 IN DIFFERENT ZONES OF ONTARIO FOR DIFFERENT TRANSITIONS

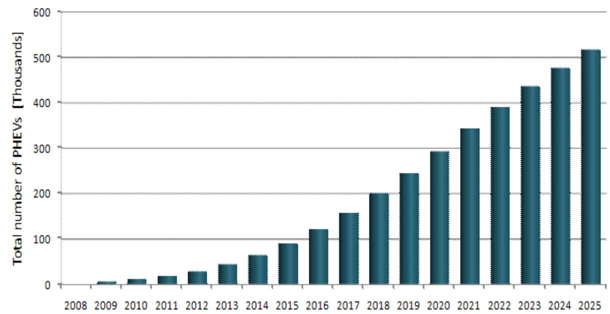
Zone	Bruce	West	SW	Niagara	Toronto	East	Ottawa	Essa	NE	NW
Transition 1	0.05	2.09	3.77	0.73	10.44	0.92	1.94	1.55	0.82	0.19
Transition 2	0.05	2.02	3.65	0.71	10.09	0.89	1.87	1.50	0.79	0.19

scenarios and transitions, since the maximum number of PHEVs by 2025 was found to be 520,337 for Scenario 1 and Transition 1, while the minimum number of PHEVs was found to be 499,986 for Scenario 3 and Transition 2. Observe that the greater number of PHEVs is obtained when these are distributed across all of Ontario; this is to be expected, given the transmission system characteristics and limits.

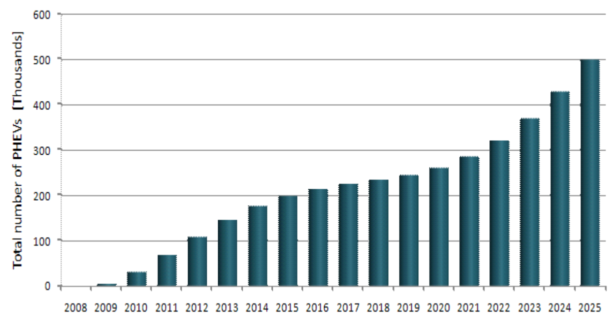
For all the assumed scenarios, somewhat higher penetration levels are achieved for Transition 1; there are lower numbers of PHEVs during the time period of 2009-2018, while there is a greater penetration of PHEVs thereafter up to 2025 when compared to Transition 2. It is worth noting that the differences in the total costs for both transitions and assumed scenarios are quite negligible; thus, there is no significant economical advantage on one particular transition. Therefore, the availability of required PHEV infrastructure in Ontario would be the main deciding factor on determining the most appropriate transition.

VI. CONCLUSIONS

The feasibility of charging PHEVs in Ontario during off-peak periods using the existing and planned electricity system, as per the IPSP, was studied in this paper. Based on the notion of efficient utilization of the existing infrastructure and the concept of integrated energy systems, an optimization model with environmental considerations was developed for an integrated electricity and transport system in Ontario. This optimization model, which is based on a zonal model of Ontario's transmission network and base-load generation capacity between 2009 and 2025, was used to find the maximum penetration levels of PHEVs into Ontario's transport sector by 2025, assuming different transition patterns. The performed studies demonstrate that about 6% PHEV uniform penetration by 2025 can be optimally realized in Ontario. If PHEV penetrations by 2025 in different zones of Ontario are assumed to be proportional to the maximum number of zonal vehicles, the maximum possible PHEV penetration by 2025 is about 10.5% in Toronto, the most densely populated zone in Ontario. If all the PHEVs are assumed to be confined to the Toronto zone, at least 12.5% of the total light-duty vehicles in this zone can be economically and reliably charged from the grid by 2025. From the different transitions and scenarios studied, it is shown that about 500,000 PHEVs can be introduced into Ontario's transport sector by 2025, without jeopardizing the reliability of the electricity system or the need to develop new or separate infrastructure to cover the electricity requirements of PHEVs. Future work will explore the impact of assumptions such as 30 km vehicle range, drive cycle behaviour and constrained charging periods.



(a) Transition 1



(b) Transition 2

Fig. 8. Maximum number of PHEVs in Toronto's transport sector.

ACKNOWLEDGMENT

The authors would like to thank Professors Jatin Nathwani and Kankar Bhattacharya from the University of Waterloo for their helpful suggestions and comments.

REFERENCES

[1] International Energy Agency, *Key World Energy Statistics*. (2006). [Online]. Available: http://www.iea.org/.

[2] *World Energy Outlook*. [Online]. Available: http://www.worldenergyoutlook.org/.

[3] Transport Canada. [Online]. Available: http://www.tc.gc.ca/environment/menu.htm#climatechange.

[4] Ruby Socorro M. Arico, "Measuring the oil vulnerability of Canadian cities," M.S. thesis, Simon Fraser University, Spring 2007. [Online]. Available: http://ir.lib.sfu.ca/bitstream/1892/4211/1/etd2765.pdf.

[5] D. Hermance, S. Sasaki, "Hybrid electric vehicles take to the streets," *IEEE Spectrum*, vol. 35, no. 11, pp. 48-52, 1998.

[6] M. Duvall, "Comparing the benefits and impacts of hybrid electric vehicle options for compact sedan and sport utility vehicles," Electric Power Research Institute (EPRI), p. 86, 2002.

[7] A. Emadi, Y. Lee, and K. Rajashekara, "Power Electronics and Motor Drives in Electric, Hybrid Electric, and Plug-In Hybrid Electric Vehicles," *IEEE Trans. Ind. Electron.*, vol. 55, no. 6, pp. 2237-2245, June 2008.

[8] L. Sanna, "Driving the solution-The plug-in hybrid vehicle," EPRI Journal, pp. 8-17, 2005.

[9] A. Simpson, "Cost-benefit analysis of plug-in hybrid vehicle technology," In *22nd International Battery, Hybrid and Fuel Cell Electric Vehicle Symposium and Exhibition*, Yokohama, Japan, Oct. 23-28, 2006.

[10] T. Markel, A. Simpson, "Energy storage system considerations for grid-charged hybrid vehicles," in *SAE Future Transportation Technology and IEEE Vehicle Power and Propulsion joint conferences*, Chicago, IL, September 7-9, 2006.

[11] T. Markel and A. Simpson, "Plug-in hybrid electric vehicle energy storage system design," in *Advanced Automotive Battery Conference*, Baltimore, Maryland, May 17-19, 2006.

[12] M. Duvall, E. Knipping, "Environmental assessment of plug-in hybrid electric vehicles," Electric Power Research Institute (EPRI), p. 70, 2007.

[13] Ontario Power Authority, *Ontario's Integrated Power System Plan; Scope and Overview.* (2006, June). [Online]. Available: http://www.powerauthority.on.ca/Storage/24/1922_OPA_-_IPSP_Scope _and_Overview.pdf.

[14] Ontario Power Authority, *Supply-Renewable Resources*. (2007). [Online]. Submission to the Ontario Energy Board (EB-2007-0707, Exhibit D, Tab 5, Schedule 1), Toronto, Ontario, Canada. Available: http://www.powerauthority.on.ca/Storage/69/6444_D-5-1_corrected_080505__mm_.pdf.

[15] B. Bakken, M. Fossum, and M. Belsnes, "Small-scale hybrid plant integrated with municipal energy supply system," in *Proc. of Third International Energy Symposium*, Ossiach, Austria, 2001.

[16] B. Bakken, A. T. Holen, "Energy service systems: Integrated planning case studies," in *Proc. IEEE PES General Meeting*, Denver, CO, 2004.

[17] M. Geidl, G. Andersson, "Optimal power flow of multiple energy carriers," *IEEE Trans. on Power Systems*, vol. 22, no. 1, pp. 145-155, 2007.

[18] A. Hajimiragha, C. A. Cañizares, M. Fowler, M. Geidl, and G. Andersson, "Optimal energy flow of integrated energy systems with hydrogen economy considerations," in *Proc. Bulk, Power Systems Dynamics and Control VII Symposium*, IREP, Charleston, South Carolina, August 2007.

[19] P. Denholm and W. Short, "An evaluation of utility system impacts and benefits of optimally dispatched plug-in hybrid electric vehicles," National Renewable Energy Laboratory, Technical Report NREL/TP-620-40293, Revised October 2006.

[20] K. Parks, P. Denholm, and T. Markel, "Costs and emissions associated with plug-in hybrid electric vehicle charging in the Xcel energy Colorado service territory," National Renewable Energy Laboratory, Technical Report NREL/TP-640-41410, May 2007.

[21] S. W. Hadley, "Evaluating the impact of plug-in hybrid vehicles on regional electricity supplies," in *Proc. Bulk, Power Systems Dynamics and Control VII Symposium*, IREP, Charleston, South Carolina, August 2007.

[22] M. Kinter-Meyer, K. Schneider and R. Pratt, "Impact assessment of plug-in hybrid vehicles on electric utilities and regional US power grids, Part 1: Technical analysis," Pacific Northwest National Laboratory: Richland, WA, 2007.

[23] M. D. Galus, G. Andersson, "Demand management of grid connected plug-in hybrid vehicles," in *IEEE Conference on Global Sustainable Energy Infrastructure (Energy 2030)*, Atlanta, GA, USA, 2008.

[24] X. Yu, "Impacts assessment of PHEV charge profiles on generation expansion using national energy modeling system,"in *IEEE Power and Energy Society 2008 General Meeting*, Pittsburg, Pensylvania, USA, 2008.

[25] Independent Electricity System Operator (IESO), *Ontario Transmission System*. (2006, June). [Online]. Available: http://www.theimo.com/imoweb/pubs/marketReports/OntTxSystem_2006jun.pdf.

[26] Ontario Power Authority, *ElectrON: Planning ONtario's Electricity System*. [Online]. Available: http://www.powerauthority.on.ca/electron/.

[27] Independent Electricity System Operator (IESO), *Monthly Generator Disclosure Report*. [Online]. Available: http://www.ieso.ca/imoweb/marketdata/genDisclosure.asp.

[28] Ontario Power Authority, *Nuclear Resources for Base-Load*. (2007). [Online]. Submission to the Ontario Energy Board (EB-2007-0707, Exhibit D, Tab 6, Schedule 1), Toronto, Ontario, Canada. Available: http://www.powerauthority.on.ca/Storage/53/4873_D-6-1_corrected_071019.pdf.

[29] Ontario Power Authority, *Determining Resource Requirements*. (2007). [Online]. Submission to the Ontario Energy Board (EB-2007-0707, Exhibit D, Tab 3, Schedule 1), Toronto, Ontario, Canada. Available: http://www.powerauthority.on.ca/Storage/53/4867_D-3-1_corrected_071019.pdf.

[30] Ontario Power Authority, *Calculation of Capacity Contribution of Wind and Hydro*. (2007). [Online]. Submission to the Ontario Energy Board (EB-2007-0707, Exhibit D, Tab 5, Schedule 1, Attachment 4), Toronto, Ontario, Canada. Available: http://www.powerauthority.on.ca/Storage/53/4871_D-5-1_Att_4_corrected_071019.pdf.

[31] Ontario Power Authority, *Ontario's Integrated Power System Plan, Discussion Paper 7: Integrating the Elements-A Preliminary Plan*. Submission to the Ontario Energy Board (EB-2007-0707, Exhibit C-11-1), Toronto, Ontario, Canada, 2007.

[32] Ministry of Energy and Infrastructure, Ontario, Canada. [Online]. Available: http://www.energy.gov.on.ca/english/pdf/electricity/1870_IPSP-June132006.pdf.

[33] Independent Electricity System Operator (IESO), *10 Year Outlook: Ontario Demand Forecast*. (2005, July). [Online]. Available: http://www.ontla.on.ca/library/repository/ser/259652/200601-201512.pdf.

[34] Independent Electricity System Operator (IESO), *Market data*. [Online]. Available: http://www.ieso.ca/imoweb/marketdata/marketData.asp.

[35] Natural Resources Canada, *Canadian Vehicle Survey, Summary Report*. (2007, May). [Online]. Available: http://www.oee.nrcan.gc.ca/Publications/statistics/cvs05/pdf/cvs05.pdf.

[36] Statistics Canada. [Online]. Available: http://www.statcan.ca/Daily/English/080327/d080327d.htm.

[37] Ministry of Finance, Ontario, Canada. [Online]. Available: http://www.fin.gov.on.ca/english/economy/demographics/projections/2007/demog07t1.html.

[38] C. Rosenkranz, "Deep cycle batteries for plug-in hybrid application," in *Plug-In Hybrid Vehicle Workshop at the 20th International Electric Vehicle Symposium*, Long Beach, CA, 2003.

[39] M. Duvall, "Advanced batteries for electric-drive vehicles," Electric Power Research Institute (EPRI), Palo Alto, CA, May 2004.

[40] M. Duvall, "Electricity as an alternative fuel: rethinking off-peak charging," in *Plug-in HEV Workshop*, Electric Power Research Institute (EPRI), Palo Alto, CA, 2003.

[41] R. A. Geyer, *A Global Warming Forum: Scientific, Economic, and Legal Overview*: CRC Press, 1993.

[42] R. E. H. Sims, H. H. Rogner, and K. Gregory, "Carbon emission and mitigation cost comparisons between fossil fuel, nuclear and renewable energy resources for electricity generation," *Energy Policy*, vol. 31, no. 13, pp. 1315-1326, 2003.

[43] R. E. Uhrig, *Greenhouse Gas Emissions: Gasoline, Hybrid-electric, and Hydrogen-fuelled Vehicles*. Encyclopaedia of Energy Engineering and Technology: CRC press, 2007.

[44] A. J. Wood and B. F. Wollenberg, *Power Generation, Operation, and Control*, 2nd ed. New York: Wiley, 1996.

[45] K. Y. Lee and M. A. El-Sharkawi, Eds., *Modern Heuristic Optimization Techniques: Theory and Applications to Power Systems*. New York: Wiley-IEEE Press, 2008, pp. 285-335.

[46] A. L. Motto, F. D. Galiana, A. J. Conejo, and J. M. Arroyo, "Network-constrained multiperiod auction for a pool-based electricity market," *IEEE Trans. on Power Systems*, vol. 17, no. 3, pp. 646-653, 2002.

[47] U. Diwekar, *Introduction to Applied Optimization*, MA: Kluwer Academic Publishers, 2003.

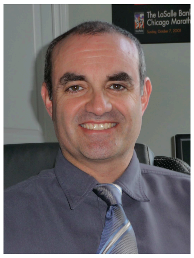
[48] R. Fourer, D. M. Gay, B. W. Kernighan, *AMPL: A Modeling Language for Mathematical Programming*, 2nd edition, Pacific Grove, CA: Duxbury Press, 2002.

[49] ILOG CPLEX Version 11.2 Users Guide, ILOG, 2008.

[50] D. Pearce, "The social cost of carbon and its policy implications," *Oxford Review of Economic Policy*, vol. 19, no. 3, pp. 362-384, 2003.

[51] G. W. Yohe, R. D. Lasco, Q. K. Ahmad, N. W. Arnell, S. J. Cohen, C. Hope, A. C. Janetos and R. T. Perez, 2007: Perspectives on climate change and sustainability. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden and C. E. Hanson, Eds., Cambridge University Press, Cambridge, UK, 811-841.

Amirhossein Hajimiragha (S'09) received his BSc (1995) from K. N. Toosi University of Technology, Tehran, Iran, and MSc (2005) from Royal Institute of Technology (KTH), Stockholm, Sweden, both in Electrical Engineering. During 1996-2003 he worked in Niroo Research Institute (NRI), Tehran-Iran in different research and managerial positions. Currently, he is pursuing his PhD degree in Electrical Engineering at the University of Waterloo. His research interests are in the field of integrated energy systems.



Claudio A. Cañizares (S'86-M'91-SM'00-F'07) received the Electrical Engineer degree from Escuela Politecnica Nacional (EPN), Quito-Ecuador, in 1984 where he held different teaching and administrative positions from 1983 to 1993. His MSc (1988) and PhD (1991) degrees in Electrical Engineering are from University of Wisconsin-Madison. He has been with the E&CE Department, University of Waterloo since 1993, where he has held various academic and administrative positions and is currently a full Professor and the Associate Director of the Waterloo Institute for Sustainable Energy (WISE). His research activities concentrate in the study of stability, modeling, simulation, control and computational issues in power systems within the context of competitive electricity markets. Dr. Cañizares has been the recipient of various IEEE-PES Working Group awards, and holds and has held several leadership appointments in IEEE-PES technical committees and subcommittees.

Michael W. Fowler received his B.Eng. in Fuels and Materials Engineering from Royal Military College of Canada (RMC) in 1986, MASc in Engineering Chemistry from Queen's University in 1988. Following a career as Military Engineer in the Canadian Forces and working as an Environmental Management Consultant he completed a PhD at RMC in 2003. He is currently an Associate Professor in the Department of Chemical Engineering at the University of Waterloo with research interest in fuel cell system design and reliability, fuel cell materials durability and green power systems.

Ali Elkamel holds a BS (1987) in Chemical Engineering and a BS (1987) in Mathematics from Colorado School of Mines, an MS (1989) in Chemical Engineering from the University of Colorado-Boulder, and a PhD (1993) in Chemical Engineering from Purdue University. He is currently a Professor in the Department of Chemical Engineering at the University of Waterloo. Prior to joining the University of Waterloo, he served at Purdue University (Indiana), P&G (Italy), Kuwait University, and the University of Wisconsin-Madison. His research has focused on the applications of systems engineering and optimization techniques to pollution problems and sustainable development. He has contributed more than 200 publications in refereed journals and international conference proceedings.