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Article

Multi-Period Optimization Model for Electricity Generation Planning Considering Plug-in Hybrid Electric Vehicle Penetration

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Abstract: One of the main challenges for widespread penetration of plug-in hybrid electric vehicles (PHEVs) is their impact on the electricity grid. The energy sector must anticipate and prepare for this extra demand and implement long-term planning for electricity production. In this paper, the additional electricity demand on the Ontario electricity grid from charging PHEVs is incorporated into an electricity production planning model. A case study pertaining to Ontario energy planning is considered to optimize the value of the cost of the electricity over sixteen years (2014–2030). The objective function consists of the fuel costs, fixed and variable operating and maintenance costs, capital costs for new power plants, and the retrofit costs of existing power plants. Five different case studies are performed with different PHEVs penetration rates, types of new power plants, and CO_2 emission constraints. Among all the cases studied, the one requiring the most new capacity, (~8748 MW), is assuming the base case with 6% reduction in CO_2 in year 2018 and high PHEV penetration. The next highest one is the base case, plus considering doubled NG prices, PHEV medium penetration rate and no CO_2 emissions reduction target with an increase of 34.78% in the total installed capacity in 2030. Furthermore, optimization results indicate that by not utilizing coal power stations the CO_2 emissions are the lowest: ~500 tonnes compared to ~900 tonnes when coal is permitted.

Keywords: plug-in hybrid electric vehicles; mixed integer programing; forecasting; optimization; energy planning; power plants; carbon management

1. Introduction

Plug-in hybrid electric vehicles (PHEVs) combine the combustion engine of conventional vehicles and the electric motor of electric vehicles. PHEVs have greater fuel efficiency because they consume less fuel than conventional vehicles in which gasoline is the only energy source. PHEVs' batteries can be recharged by connecting them to the electrical grid. This makes PHEVs "fuel flexible vehicles" because they can use both gasoline and electricity for propulsion (Figure 1) [1,2]. In Figure 1, CVs symbolize conventional vehicles, HEVs represent hybrid electric vehicles, PHEV-20 and PHEV-60 are PHEVs that could travel 20 and 60 miles on electric engines, respectively.

As indicated in Table 1, in addition to the significant benefits of adopting PHEVs, one of the main challenges of PHEVs' widespread market penetration would be their impact on the electricity grid. Moreover, the amount of electricity required for charging PHEVs increases correspondingly with the extent of PHEV penetration, so the energy sector must anticipate and prepare for this extra demand and implement long-term planning for electricity production.

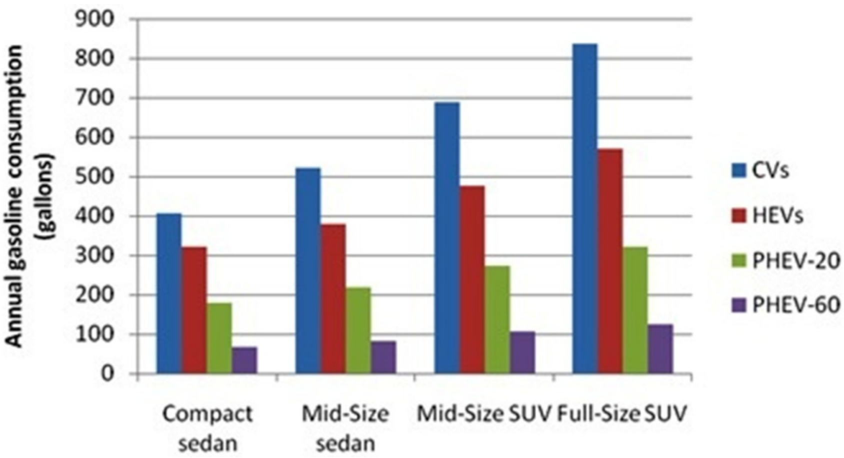

Figure 1. Fuel consumption of CVs, HEVs, PHEVs.

Table 1. PHEVs' benefits and challenges.

Benefits	Challenges
Flexibility of fuel	Battery cost
GHGs emissions reduction	Shifted emissions to power plants
Gasoline consumption reduction	Load demand increase
Improved fuel economy	

A number of studies have considered PHEV penetration in the transportation sector. For example, the rate of EV/PHEV market penetration and its effect on carbon emissions were forecasted by [3]. Factors such as battery learning curves, geographic distribution of daily travel distances and an optimal power generation planning model for charging electric vehicles were used to determine the rate. The forecast showed that in Japan only a quarter of the vehicle share in 2050 will be EV/PHEVs. This market share forecast is sensitive to battery development and the initial prices of vehicles. In addition, carbon emission reduction rates are also predicted in the forecast as a result of EV/PHEV penetration.

Regional growth patterns of light-duty passenger vehicles were explored in three developed areas in China [4]. In addition, several scenarios for the penetration of HEVs, PHEVs and EVs were developed for the 2010–2030 time period. Factors such as petroleum consumption, fossil fuel use and carbon emissions were employed to evaluate various technologies that could be implemented. It was found that HEV penetration reduced carbon emissions more in intensive coal electricity producing regions, while PHEVs and EVs were better suited for regions with cleaner electricity production methods.

In our previous study [5], we considered PHEVs' penetration and its impact on Ontario's electricity grid. For this purpose, long-term regression models, both linear and non-linear, of electricity load demands were forecasted for the years 2012–2030. In these forecasting models various variables were considered in the climate, economic, and demographic sectors. The number of PHEV's was calculated based on different penetration levels. The PHEVs' charging electricity demands for different PHEV penetration scenarios was estimated. The effect on base and peak load demands was analysed. Moreover emission reduction as a result of PHEVs penetration was determined. Finally, additional electricity load demands considering PHEVs penetration were identified for energy planning purposes.

A resource dispatch and emissions model was developed with respect to electric grid demand changes due to the penetration of electric vehicles for a western US grid [6]. Results from the model were compared to historical data to validate the model. The impact of EV penetration on the western grid was found based on correlations between historical dispatch and system load data. Findings from this study showed that dispatch planning can be assisted using the model, charging scenarios affect the emissions intensity and type, and ideal charging profiles can be found using hourly model resolution of changes in emission intensity.

Current progress in PHEV technology, economic constraints, market trends, research requirements and challenges ahead for the integration of PHEVs into the electric grid were assessed in [7]. Policies required for the implementation of vehicle-to-grid operation and the advantages of PHEVs for consumers and power producers were also explored. A PHEV can be charged from a utility and a vehicle-to-grid capable vehicle can reverse the direction of electricity flow back to the grid.

Waraich *et al.* [8] introduced an iterative approach that integrates PEV electricity demand and a power system simulation to expose inadequacies in the energy system due to increased PEV electricity demand. The main goal of this study was to understand the potential impact of PEV charging on the electrical grid. An agent-based traffic demand model along with an interconnected multiple energy carrier system was used to trend electricity demand and production. It was found that charging patterns are very sensitive to electricity pricing.

Richardson *et al.* [9] reviewed the current literature on different types of EVs, the electric grid and renewable energy integration. Main ideas such as key methods and assumptions from the literature were discussed and the economic, environmental and grid impact of electric vehicles were assessed.

The capability of EVs to integrate intermittent and renewable energy sources (especially wind power) were reviewed in various papers. The literature indicates that EVs might reduce the amount of excess electrical energy produced under specific conditions.

A comprehensive survey of various research problems and their solutions with respect to PHEV integration into a smart grid was demonstrated [10]. Many aspects of PHEV-to-grid integration have been addressed recently, such as charging and control strategies for PHEVs, vehicle-to-grid technology, and application domains. Mathematical models were formulated based on artificial intelligence methods, intelligent methods and agent based computing methodologies to resolve these problems.

The effects of PHEV penetration on the fuel consumption of coal, natural gas and oil, and on pollutant levels were explored [11]. Specifically, this study focused on the New York Metropolitan Area considering two battery charging scenarios on a normal summer and winter day. Network constraints were incorporated into an economic dispatch model in addition to battery charging pattern models based on commuter transportation. Findings show that the network-constrained economic dispatch penetration of PHEVs was much more realistic than unconstrained scenarios, and that fuel consumption was on the margins. In addition, regulated PHEV charging produced lower night-time emissions than unregulated charging. It was found that models combining network constraints and economic dispatch can optimize the performance of PHEV penetration in energy systems.

Falvo *et al.* [12] created a design of sustainable urban mobility systems through integrated metro-lines with surface PEVs. This study is a review of the planning criteria of urban mobility systems in large cities with respect to transportation power systems. A case study was applied in terms of power system architecture and business models which identified energy savings, environmental sustainability objectives and cost savings. The integration of the metro transit system and electric vehicles connected by a smart grid would minimize the economic and environmental impact while optimizing the performance of both systems.

An investigation into the systems and processes required to implement vehicle-to-grid technology is presented in [13]. Vehicle-to-grid uses the high power capacity, low utilization and low capital cost of vehicle power along with long operating life and low operating costs of power generators to complement one another. Business models and strategies are suggested to optimize the electricity utilization, power production and electricity costs in a vehicle-to-grid energy system. In addition, vehicle-to-grid can provide storage for intermittent renewable energy sources, especially wind power.

Mullan *et al.* [14] reviewed the most common variants of the vehicle-to-grid theme using a case study of Western Australia, which is an energy-isolated geographic location with no hydroelectric storage capabilities that cannot import or export electricity. There is already an underutilization of generation and transmission capacity in this region. The study concludes that vehicle-to-grid technology operations in Western Australia would require too much infrastructure investment and can carry a significant implementation risk. However, it was found that simply charging electric vehicles can be added to the planned electricity demand without extra capital investment.

Goransson *et al.* [15] investigated the costs and benefits of integrating electric vehicles in a power grid supplied by a quarter wind power and the remainder thermal energy electricity generation. Four different PHEV integration methods with varying impacts on the total electric load were examined. It was found that a controlled PHEV charging system will reduce carbon emissions up to 4.7%, while an uncontrolled charging system will lead to an increase in emissions. Reductions in emissions can be mostly attributed to a decrease in thermal power plant start-up and partial load operation conditions.

A generation planning optimization model for power plant portfolios was developed to estimate the costs and benefits from EVs for future power systems [16]. In the formulated models, the charging and discharging of EVs were integrated with the rest of the power system. A large difference was found in the power system cost for EVs with smart charging systems compared to dumb EVs. Some findings from this study were that the price of electricity for electric vehicles was reasonable. In addition, the power system will benefit from a smart timing charging system for EVs and lower power plant portfolio costs.

PHEV and EV penetration through 2030 was analysed for five northern European countries (Denmark, Finland, Germany, Norway and Sweden [17]). Shares of private passenger EVs were assumed to increase 2.5%, 15%, 34%, 53% in 2015, 2020, 2025 and 2030, respectively. Results illustrate that a smart grid connection to the PHEVs and EVs will propagate wind energy investments and reduce reliance on new coal or natural gas power plants. If renewable sources do not complement PHEV and EV penetration, fossil fuel-sourced electricity will likely increase substantially. EVs will bring carbon emission reductions and total cost increases, although this result varies from country to country and is sensitive to fuel and carbon pricing.

A review of the existing literature on power systems integrated with electric vehicles and economic dispatches of PHEV in the electricity market was published [18]. In addition, the joint scheduling problem considering renewable and intermittent energy sources and risk management of PHEV-penetrated power grids are discussed. Due to government incentives, rapid development of PHEVs in the market has occurred recently. If PHEVs are randomly connected to the power grid in large quantities, this will bring great challenges to power system operations.

Soares *et al.* [19] developed a linear programming optimization tool for the modeling of electric power system expansion in northeastern Brazil, with a particular focus on the variable output of future wind farm production capacity. Disparity between the supply and demand of electricity was expected due to power generation variations. As a result, PHEVs were considered in this study to assist in the moderation of power supply fluctuations. From this study, it was found that increasing the fleet of PHEVs (from 0.5 million to 1.5 million) over the next two decades would be able to regulate power loads generated from wind farms. Advantages of simultaneously optimizing power generation and transportation sectors as part of a "smart grid" were also explored.

A group of models based on light-duty PEVs fleets for national level planning studies of the transportation and energy sections was developed [20]. Three case studies were performed over a 40 year period for the U.S. transportation and energy sectors based on the models. The results of the case studies indicate that penetration of PEVs along with investments in renewable energy sources can reduce total energy and transportation cost by 5%. Emissions and gasoline consumption can also be reduced, although 800 TWh of extra annual electricity production will be required. It was noted that optimization of the entire electric vehicle fleet is unlikely to occur in a free market economy such as now exists in the U.S., and that these optimization results should rather be viewed as targets.

More recently, Brouwer *et al.* [21] evaluated the performance of four types of CHP plants to PEVs compared to using electricity from the grid. Simulation of CHP plant performance was achieved by integrating the composition of a future power system, the demand for heat and electricity, and specifications of EVs and CHP plants. It was found that combined deployment of CHP plants and EVs offered no significant added benefits. Timing of electricity supply and demand as well as abatement costs were not improved.

An integrated optimization model was employed to find the most economic and environmentally sustainable plans for future smart electricity systems with intermittent renewable energy sources and electric vehicle penetration was demonstrated [22]. Two goals of this model were to find the ideal power generation and capacity combination to meet future electricity demands, and to obtain a detailed model of hourly operations of power plants and controllable electric devices. This model was applied to a case study in the Tokyo area in Japan with a time horizon of 2030. Results found the paths towards the ideal energy generation combinations based on fossil fuels, hydroelectric power, nuclear and renewable energy.

A mixed integer linear programming model for capacity expansion, plant dispatch and PHEV charging was introduced recently [23]. The cost savings from controlling PHEV charging and the trade-off between a controlled charging program or increased power system generation capacity was also explored. It was found that by controlling PHEV charging, the integration costs of PHEV into the power system were cut in half. In addition, wind generation intense systems and system that require capacity expansion benefit greatly from controlled charging.

The main contributions of this paper are:

- Study the effect of PHEVs penetration on energy planning for long term (in the literature, most existing investigations considered only short periods of time such as 24 h).
- Employing more comprehensive data and modeling techniques for predicting PHEVs penetration and load demands.
- Developing a multi-period optimization model based on the current and projected infrastructure of Ontario encompassing all generating companies (in the literature, multi-period energy planning in Ontario has been done using OPG data only).
- Defining new and realistic charging scenarios on an hourly basis. The results can contribute significantly to the establishment of an Ontario government policy to encourage consumers to save energy.
- Developing an optimization model to address optimal planning of the Ontario power generating sector in consideration of different PHEV penetration levels.
- The developed optimization model can be used on a larger scale *i.e.*, for all Canadian provinces and territories, as well as for other parts of the world.

In this paper, a mixed integer multi-period mathematical programing model is presented which assumes PHEVs are commercially produced from a given year. The model is an extension of our previous work on multi-period modeling of power generation [24]. The time dependent decision variables that comprise the model include energy demand, fuel prices, construction lead time, and variability in operational and maintenance costs. Besides, only new light-duty vehicles are considered as potentially new PHEVs since they have more potential to be PHEVs. Battery capacity is another issue, especially for charging patterns. Deeper battery charging and discharging cycles than conventional hybrids are required for PHEVs. Since battery life is influenced by the number of full cycles. PHEVs battery life may be shorter than in traditional HEVs which do not deplete their batteries as much as PHEVs. In addition, design issues and trade-offs against battery life, capacity, heat dissipation, weight, costs, and safety are batteries limitations. In this paper 80% safety factor and 82% of charger efficiency are assumed. To calculate the demand from charging, identification of types of PHEVs that will penetrate the transportation sector is essential. As a case study is considered based on the average commuting distance in Ontario (12.9 km). In this case PHEV-20 is the main PHEV that would penetrate the light-duty vehicles sector. However, this restriction can be easily waived. Another assumption is that no PHEVs are retired during the period under study.

2. Optimization Methodology for Multi-Period Energy Planning

The methodology that is used to find the optimal solution of energy planning of power plants electricity generation consists of six different steps as indicated in Figure 2. The details of each step are provided in subsequent subsections.

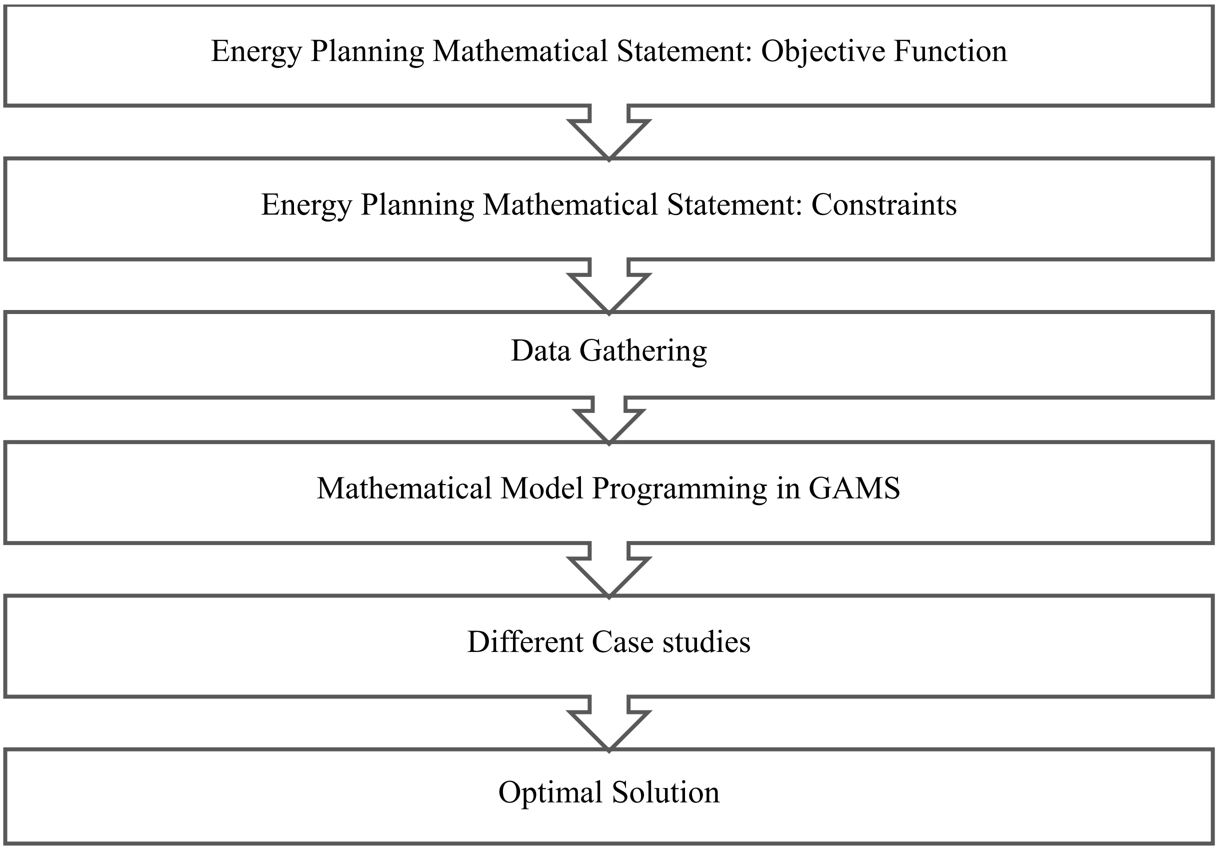

Figure 2. General optimization methodology.

2.1. Objective Function

As a first challenge after calculating the difference between load demand and generated power, a mathematical programming model is formulated for the existing electricity fleet for load demand satisfaction. The model is a mixed integer linear program (MILP) which identifies discrete decision variables for fuel switching of each power plant. The binary variables of existence or nonexistence of different types of new power plants are also defined. As a final step, CO_2 emission targets are considered.

The objective function of the energy planning optimization model is to minimize the present value of the cost of electricity over a sixteen year period (2014–2030). The overall costs consist of the fuel costs, fixed and variable operating and maintenance costs, the capital costs for new power plants, and the retrofit costs of existing power plants (associated with fuel switching from coal to natural gas for coal-fired stations). The total discounted present value is minimized by considering the electricity demand as an effect of PHEV penetration, as well as, in the last stage of this work, satisfying CO_2 emission target. The mathematical model of the previously mentioned objective function is written as:

$$\begin{aligned} minf(i,j,n,N,H,W) &= \sum_{i\in FF}\sum_{j} F_{ij}^{FF} Opr_{ij} F_{ij} F_{FF}^{D} + \sum_{N\in NUCLEAR} F_{N}^{NUCLEAR} Opr_{N} F_{N}^{D} \\ &+ \sum_{H\in HYDRO} F_{H}^{HYDRO} Opr_{H} F_{H}^{D} + \sum_{W\in WIND} F_{W}^{WIND} Opr_{W} F_{W}^{D} \\ &+ \sum_{i\in CMAX,C}\sum_{j} Rcost\left(\frac{F^{CMAX}}{Optime}\right)(AF)\left(F_{i,ng}^{C}\right) \\ &+ \sum_{n\in NEWMAX} Cap_{n}\left(\frac{F_{n}^{NEWMAX}}{Optime}\right)(AF)\left(F_{n}^{D}\right) \\ &+ \sum_{n\in NEWGEN} \left(Opr_{n} + (P_{n} Hr_{n})\right)\left(F_{n}^{NEWGEN}\right) \end{aligned} \tag{1}$$

where i is the index of all fossil fuel generators, j is the fuel used, Opr are the associated operating and maintenance costs for each Power Plant ($). $\mathrm{Cap_n}$ is the capital cost for new power plants. n, N, H, and W are indices representing all of the new possible nuclear, hydro and wind power plants. F^{FF}, $F^{NUCLEAR}$, F^{HYDRO} and F^{WIND} are electricity generated (MWh) by the fossil fuel, nuclear, hydro, and wind power plants in Ontario. F_{FF}^{D}, F_{N}^{D}, F_{W}^{D}, F_{H}^{D} and F_{n}^{D} are binary variables (0–1) for the existence or not existence, operation or not of unit related to identified indices at the time. F^{CMAX} is the set of the maximum power generation of all the current coal generation plants, and F^{C} is the set of the adjusted power generation of the current coal plants. Optime is a maximum operation time in a year which is 8760 h. AF is the annual factor. F^{NEWMAX} is the set of the maximum power generation possible for the possible new power plants, and F^{D} is the decision variable to build a new power generation plant. P is the index of the price of the fuel used at each plant; Hr is the heat rate (efficiency of each type of fuel) at each new possible power plant, and F^{NEWGEN} is the amount of Power generated at each new power plant.

This function is minimized through the constraints laid out by the equations that follow: total electricity generated, fuel selection and plant shutdown, fuel switching constraints, non-fossil plant constraints, and constraints on the amount of power that can be produced by the new plants, upper bound on the amount of electricity that can be produced by a new plant in that year, lower bound on the amount a current plant can produce, and selection of new plants.

The structure of the programming code is as follows; first the sets for all of the power plants are listed, and then the scalars are listed. The maximum possible generation for all of the power plants is input, along with the same variable for the possible power plants. Actual generation for all of the power plants is listed, along with two different operational costs for all of the fossil fuel power plants (one for coal, the other natural gas). The capital costs and operating costs are stated for the new possible power plant. Variables for the optimal amount of electricity generated by each power plant, electricity generation for the possible new power plants, adjusted generation based on fuel switching (for fossil fuel plants) are initialized, along with binary variables for fuel selection at each plant and decision variables for the possible new power plants.

2.2. Constraints

The constraints comprise requirements on total electricity generated, fuel switching, logical constraints that set certain plants to be natural gas, total electricity generation for each plant, capacity constraints, new plant capacity constraints, upper bounds on generation for new plants, lower bounds for generation of current plants, and a cap on additional new plants that can be created. These constraints are outlined below:

$$\sum_{i}\sum_{j} F_{ij}^{P} \leq \sum_{i}\sum_{j} F_{ij}^{PMAX} F_{ij}^{DP} \tag{2}$$

F_{ij}^{MAX} is the maximum power generation of plant p, and F_{ij}^{DP} is a binary decision variable to keep the current power generation plant in operation. This is enforced for all power generation plants, including the possible new plants. This set of constraints states that the output of a power plant must be less than its maximum possible output multiplied by either a 1 or 0 (1, if the plant is in, or 0 if no electricity will be produced):

$$\sum_{n} F_{n}^{NEW} \leq \sum_{n} F_{n}^{NEWMAX}(ACF) \tag{3}$$

F_{n}^{NEW} represents the output from a new possible power plant (n), F_{n}^{NEWMAX} represents the maximum possible power generated at each new possible power plant, and ACF is the annual capacity factor for new stations (e.g., an ACF of 75%, means that all new stations, for the first year of the code, must operate at less than 75% capacity):

$$\sum_{i}\sum_{j} F_{ij}^{FF} \geq \sum_{i}\sum_{j} F_{ij}^{FFMAX}(LOWER) F_{ij}^{DFF} \tag{4}$$

F_{ij}^{FF} represents the electricity produced at fossil fuel stations, F_{ij}^{FFMAX} is the maximum amount of electricity produced at each fossil fuel station, LOWER is the annual capacity factor lower bound, and F_{ij}^{DEF} is the decision variable to keep a current fossil fuel plant in operation. From a practical perspective, all operational plants should operate at over 1% capacity, if not the plant would be shut down. The total generated power should be equal to or greater than the electricity demand, *i.e.*:

$$\begin{aligned} D^{T} \leq & \sum_{i \in FF}\sum_{j} F_{ij}^{FF} F_{ij} F_{FF}^{D} + \sum_{N \in NUCLEAR} F_{N}^{NUCLEAR} F_{N}^{D} + \sum_{H \in HYDRO} F_{H}^{HYDRO} F_{H}^{D} \\ & + \sum_{W \in WIND} F_{W}^{WIND} F_{W}^{D} + \sum_{i \in CMAX,C}\sum_{j} F^{CMAX}\left(F_{i,ng}^{C}\right) \\ & + \sum_{n \in NEWMAX} F_{n}^{NEWMAX}(F_{n}^{D}) \end{aligned} \tag{5}$$

2.3. Data Gathering

The following data are gathered from Ontario Power Generation [25] and IESO [26]

- Installed capacity of power plants
- Net electricity generation
- Capacity factor of power plants

- Operating cost
- Retrofit cost
- New power plants economic evaluation

2.4. Mathematical Model Programming in GAMS

The optimization model (Equation (1) subject to constraints (2)–(5) is a MILP. It is implemented in the Generalized Algebraic Modeling System (GAMS) and is solved using the CPLEX solver. Sets of the different types of power plants, such as fossil fuel, hydro, nuclear, wind power plants, are defined. Then all the equations including the objective function and constraints are coded. All the variables, parameters, scalars are defined. Variables are continuous and binary variables. Parameters are all the data that were mentioned in the previous section and which have been gathered from IESO and OPG.

The operating costs of each fossil fuel plant using both coal and natural gas, which allows the model to choose between coal and natural gas for each power plant, thus allowing for complete control over which fuel is used in each plant. The model contains also the capital costs and operating costs associated with each of the possible new power stations. This makes for the most control in the event the model decides a new power plant should be built, as the model will be able to make the best possible choice for the remaining power needing to be generated.

3. Case Studies, Results and Discussion

This section outlines the results for five different case studies (Table 2). The different cases include CO_2 emission constraints, PHEVs penetration, and ceasing the use of coal by the end of 2014.

Table 2. Case studies considered.

Case Study	PHEVs Adoption Rate	Type of Potential Power plants	CO_2 Limit
A: Base Case	Medium Penetration	All type of power plants except Coal power stations	No
B: Base case with increased NG prices	Medium Penetration	All type of power plants including NG double price	No
C: Base case with Coal	Low Penetration	All type of Power plants	No
D: Base case with 6% reduction in year 2018 CO_2	High Penetration	All type of power plants except Nuclear power stations	Yes
E: Base case without considering current load deficit	Medium Penetration	All type of power plants except Coal power stations	No

In the event of a surplus of power in the power grid, the model identifies which plants are ineffectual and recommend their closure, while in the event of a deficit of power in the grid, the program recommends new plants to be built to meet the demand. The results represent the lowest electricity cost option, which should always be considered in solving problems of this magnitude.

3.1. Case Study A (Base Case) & B (Base Case with Increased NG Prices)

The base case considers PHEVs are penetrated with a medium rate in Ontario. Therefore, load demand would be increased by vehicles' electricity charging amount. All coal power plants have been phased out according to the Environmental Protection Act (EPA) engaged in the year 2014 [25]. In Case B the penetration is still with a medium rate but the price of natural gas is doubled starting in year 2020.

3.1.1. New Power Generating Stations

In the base case (Case A), depicted in Table 3, new NGCC stations make up 68% of the total new installed capacity. In Case B with increased NG prices, when the natural gas price is doubled (Table 4), the fleet relies on more coal technologies making up 30% of the total new installed capacity. In the early years, NG is used because of shorter construction time; however there are NG power plants later because of coal and nuclear capital expenditure constraints.

Table 3. New power generating stations and their construction time for Case A.

<table>
<tr><th colspan="2" rowspan="2">New Capacity (MW)</th><th colspan="17">Years (20..)</th></tr>
<tr><th>14</th><th>15</th><th>16</th><th>17</th><th>18</th><th>19</th><th>20</th><th>21</th><th>22</th><th>23</th><th>24</th><th>25</th><th>26</th><th>27</th><th>28</th><th>29</th><th>30</th></tr>
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Table 4. Detailed fleet structure for Case B.

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<tr><th colspan="2" rowspan="2">New Capacity (MW)</th><th colspan="17">Years (20..)</th></tr>
<tr><th>14</th><th>15</th><th>16</th><th>17</th><th>18</th><th>19</th><th>20</th><th>21</th><th>22</th><th>23</th><th>24</th><th>25</th><th>26</th><th>27</th><th>28</th><th>29</th><th>30</th></tr>
<tr><td>PC</td><td>420</td><td bgcolor="#b0b0b0"></td><td bgcolor="#b0b0b0"></td><td bgcolor="#b0b0b0"></td><td bgcolor="#b0b0b0"></td><td bgcolor="#b0b0b0"></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>PC</td><td>410</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td bgcolor="#b0b0b0"></td><td bgcolor="#b0b0b0"></td><td bgcolor="#b0b0b0"></td><td bgcolor="#b0b0b0"></td><td bgcolor="#b0b0b0"></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>PC</td><td>410</td><td></td><td></td><td></td><td bgcolor="#b0b0b0"></td><td bgcolor="#b0b0b0"></td><td bgcolor="#b0b0b0"></td><td bgcolor="#b0b0b0"></td><td bgcolor="#b0b0b0"></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>PC</td><td>420</td><td></td><td bgcolor="#b0b0b0"></td><td bgcolor="#b0b0b0"></td><td bgcolor="#b0b0b0"></td><td bgcolor="#b0b0b0"></td><td bgcolor="#b0b0b0"></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>IGCC</td><td>440</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td bgcolor="#b0b0b0"></td><td bgcolor="#b0b0b0"></td><td bgcolor="#b0b0b0"></td><td bgcolor="#b0b0b0"></td><td bgcolor="#b0b0b0"></td><td></td><td></td><td></td></tr>
<tr><td>NGCC</td><td>430</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td bgcolor="#b0b0b0"></td><td bgcolor="#b0b0b0"></td><td bgcolor="#b0b0b0"></td><td></td></tr>
<tr><td>NGCC</td><td>500</td><td></td><td></td><td></td><td></td><td bgcolor="#b0b0b0"></td><td bgcolor="#b0b0b0"></td><td bgcolor="#b0b0b0"></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Nuclear</td><td>1010</td><td bgcolor="#b0b0b0"></td><td bgcolor="#b0b0b0"></td><td bgcolor="#b0b0b0"></td><td bgcolor="#b0b0b0"></td><td bgcolor="#b0b0b0"></td><td bgcolor="#b0b0b0"></td><td bgcolor="#b0b0b0"></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Import</td><td>1250</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td bgcolor="#b0b0b0"></td><td bgcolor="#b0b0b0"></td><td></td></tr>
<tr><td>Wind</td><td>1000</td><td bgcolor="#b0b0b0"></td><td bgcolor="#b0b0b0"></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Wind</td><td>1000</td><td></td><td></td><td bgcolor="#b0b0b0"></td><td bgcolor="#b0b0b0"></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
</table>

As shown in Tables 3 and 4, adding new power plants is suggested as soon as possible to satisfy the current load demand deficit. The optimizer suggests building NG power plants because of the coal capital expenditure constraint in the model. The highlighted areas represent periods of construction. The year thereafter is when electricity production commences, except for the import option where power is imported at the beginning of the highlighted area.

3.1.2. Economic and Emission Analysis

As indicated in Figure 3, both cases A and B follow a general trend where a peak is observed during 2014. The base case, where no new or existing coal is available after 2014, has a particularly high cost of electricity during the early years. A large capacity of existing coal power supply has gone offline, forcing the model to purchase a large amount of new supply technologies to prepare the fleet for this urgent lack of generating capacity.

A different capacity expansion strategy is employed in Figure 4 and Figure 5. The total expenditure is higher for the case with the double natural gas price (Case B), since there would be more investment on nuclear power plants. The CO_2 emissions for Cases A and B are ~500 Mt and ~900 Mt, respectively. The same general trend is observed in both curves in Figure 6. In the base case, the overall emissions are reduced dramatically due to the elimination of both new and existing coal power stations.

3.2. Case Study C: Base Case with Coal

Case Study C assumes there would be low PHEV penetration in Ontario from 2014 to 2030. Besides, all the coal power stations are in operation and persist in generating electricity. In addition, CO_2 emission restrictions do not apply in the time frame; however CCS technology is assumed to be available.

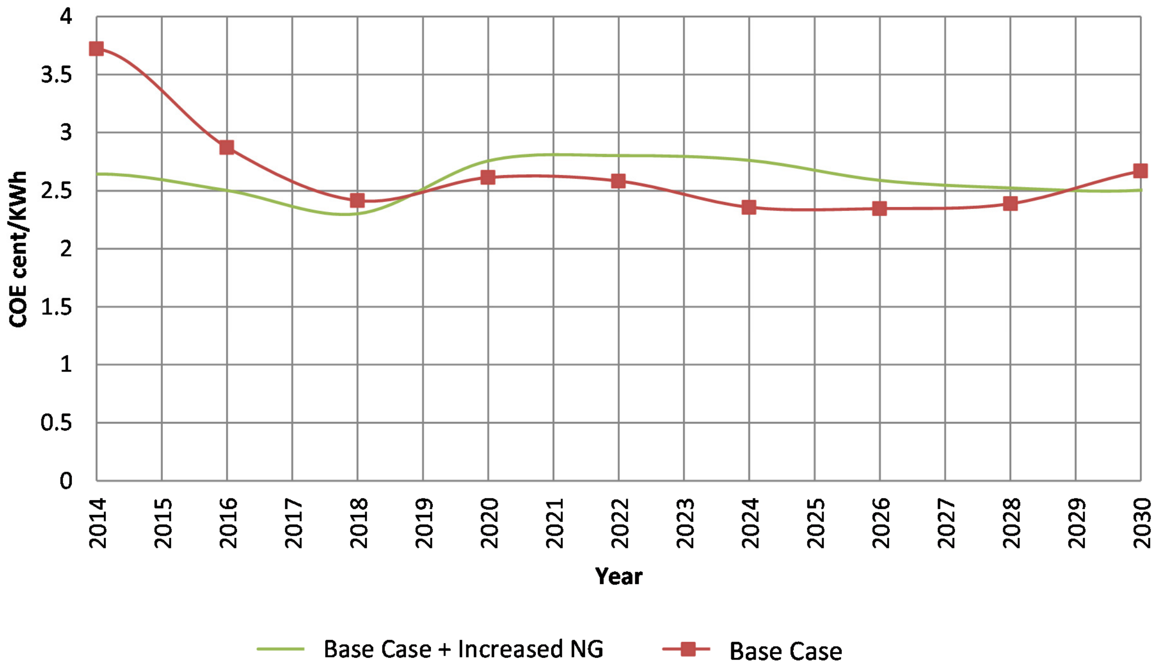

Figure 3. Overall cost of electricity.

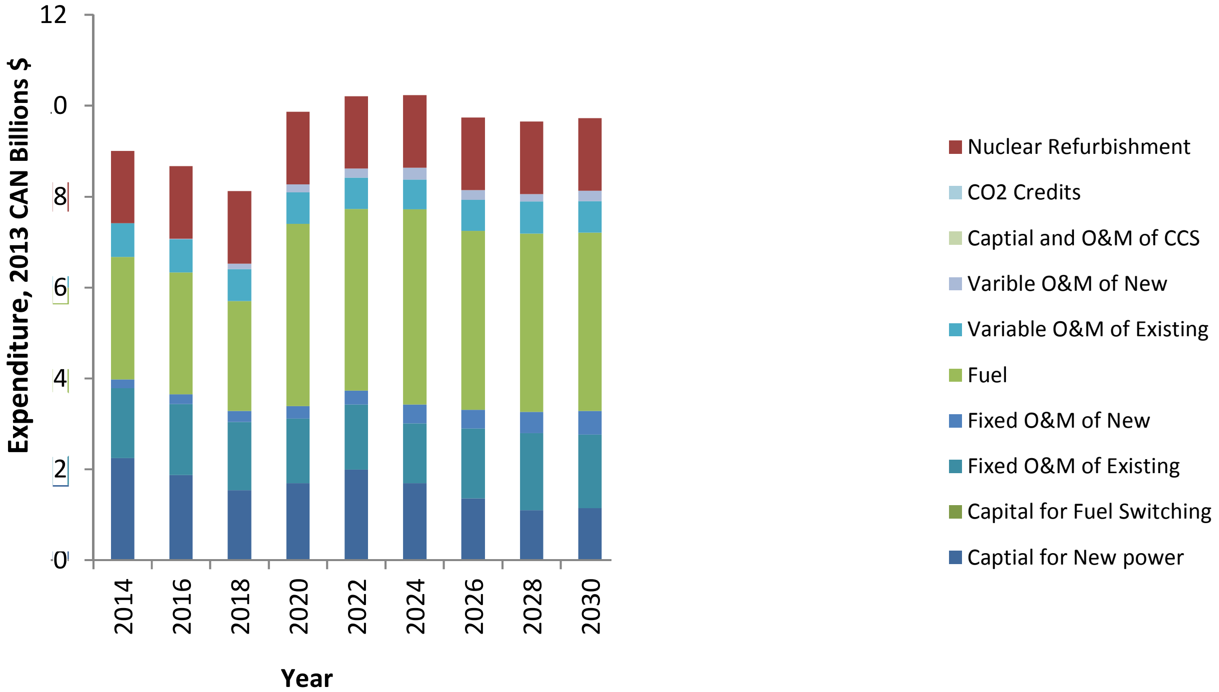

Figure 4. Detailed expenditures for Case B.

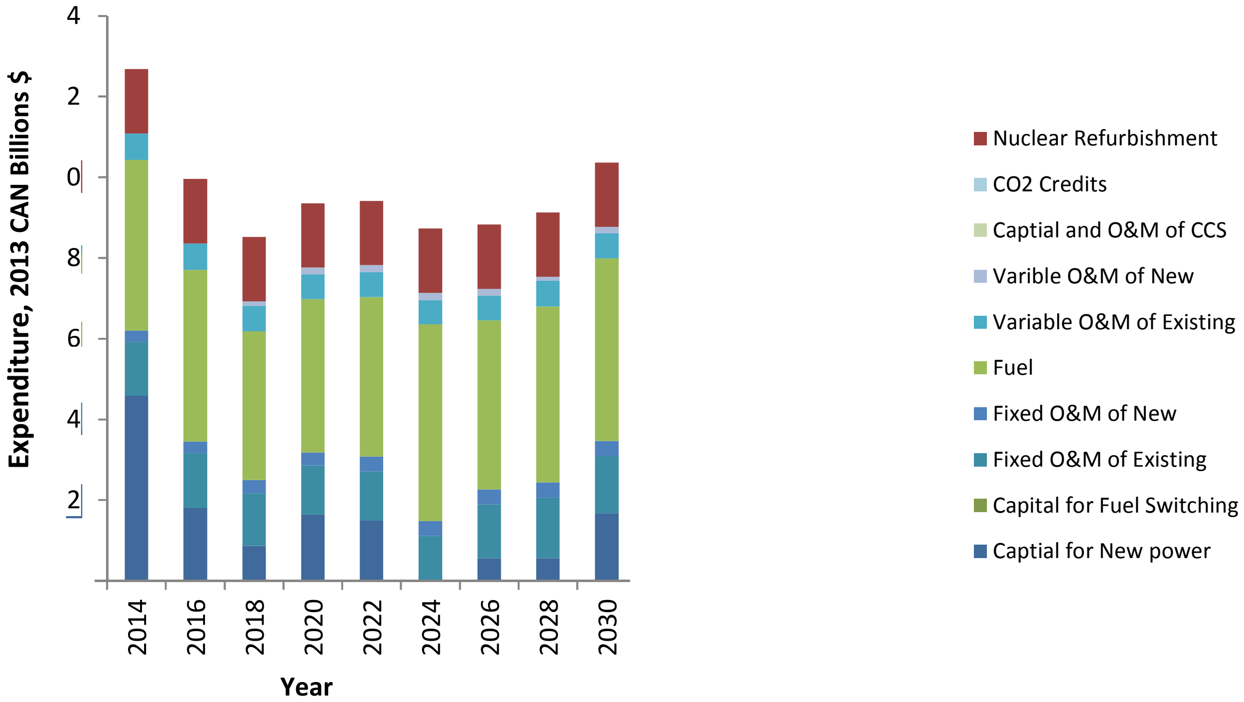

Figure 5. Detailed expenditures for Case A.

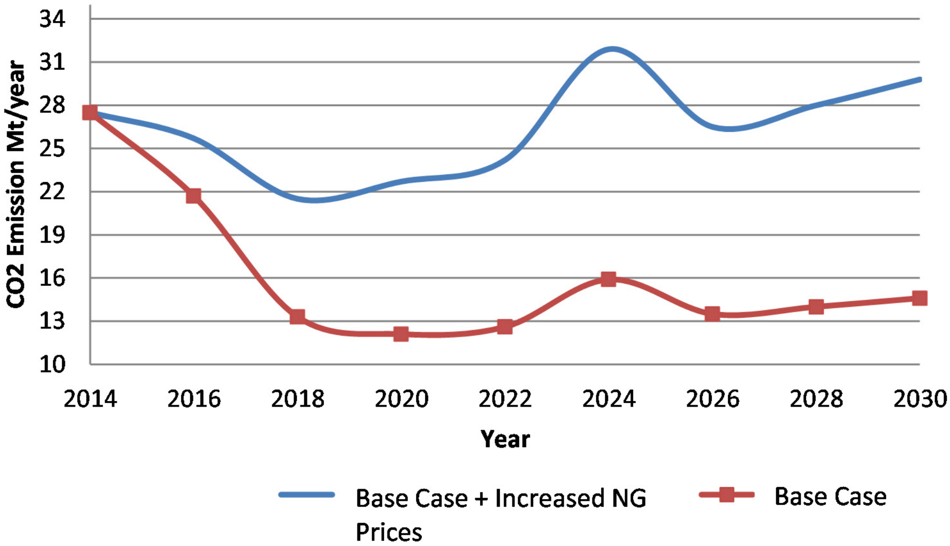

Figure 6. Overall CO_2 emissions for Cases A and B.

3.2.1. New Power Generating Stations

In this case the best possible solution for Ontario power stations to meet the load demand from 2014 to 2030 is determined. As indicated in Table 5, the model recommended a significant increase in electricity obtained through two new PC and two new NGCC generating stations with a total capacity of 3136 MW and 3364 MW, respectively. Figure 7 shows that nuclear, wind and hydro power stayed at about the same power generation levels, which are equal to 12,947, 1948, and 8014, respectively. Therefore, the rate of power allocated for renewable energies does not change. The reason is the more economical capital cost of coal power plants than other sources of electricity. As a result no fuel switching is proposed. Additionally, in case of retrofitting the coal power station to either biomass or NG without employing CCS technology, the emission penetration would be more than coal power plants.

Table 5. New power generating stations and their construction time (base case with coal).

New Capacity (MW)		**Years (20..)**																
		14	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**
PC	2119																	
NGCC	1568																	
NGCC	1568																	
PC	1245																	

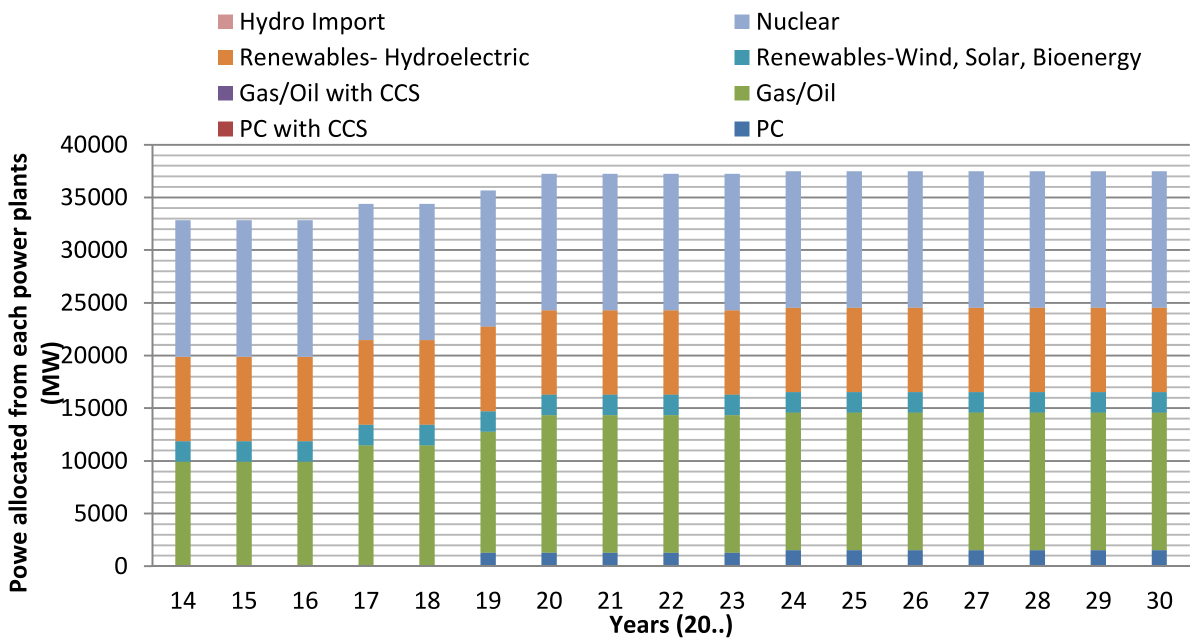

Figure 7. Total allocated capacities of each power plant (mw) from 2014 to 2030 for Case C.

Figure 8 displays the percentage change of power allocated in the four different years 2014, 2021, 2026 and 2030. Power allocated from nuclear decreased from 40% in 2014 to 35% in 2030. Also natural gas and oil power plants generated more of the electricity, from 30% in 2014 to 35% in 2016 and will keep a constant power percentage rate to 2030.

The annual electricity generation by new power plants is shown in Figure 9. After 2018, new power stations, PC and NG, generate a significant amount of energy, however, the proposed solution is not feasible with the current state of Ontario's power plants and the plans of the Government of Ontario and the companies that produce Ontario's electricity due to the phasing out of all the coal stations by the end of 2014.

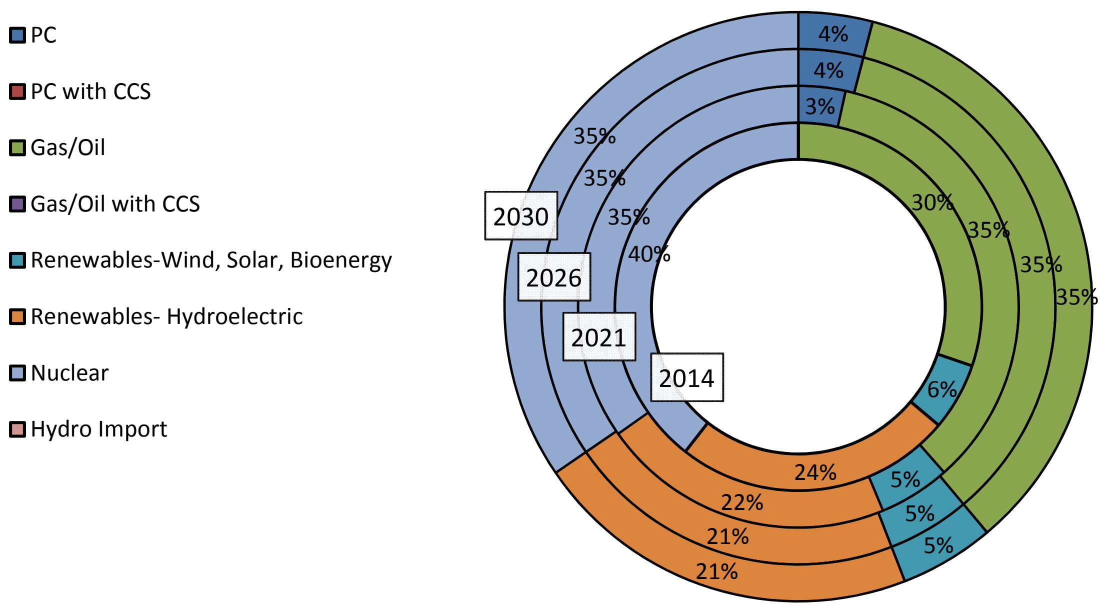

Figure 8. Total power allocated percentage for Case C.

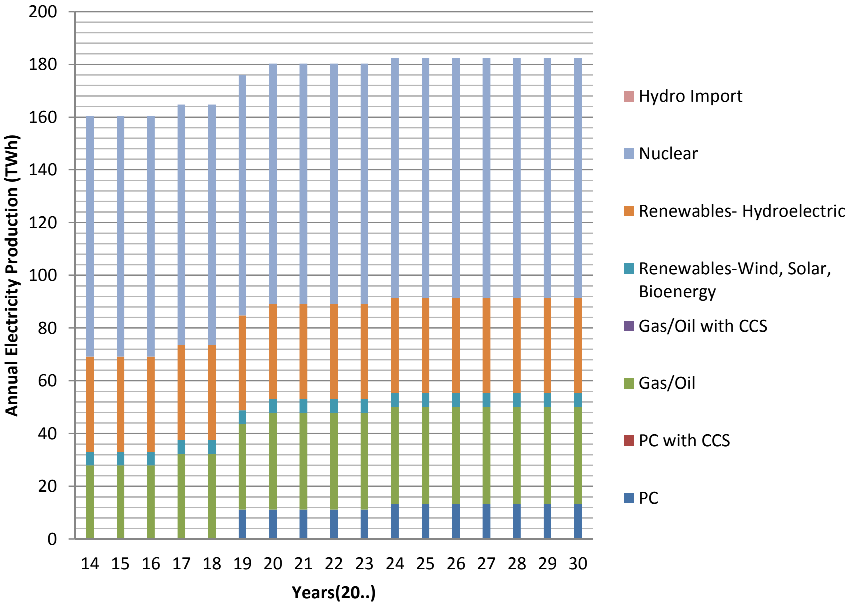

Figure 9. Annual electricity production for Case C.

3.2.2. Economic and Emission Analysis

Figures 10 and 11 show the detailed expenditures of the entire electricity sector and electricity cost of the total investment from 2014 to 2030 for Case C. The expenditures including nuclear refurbishment, CO_2 credits, capital and O&M cost of CCS, variable O&M cost of new and existing power plants, fuel, fixed O&M of new and existing units, capital cost of fuel switching, capital cost of new power plants, are revealed based on 2013 Canadian dollars.

Figure 12 gives the amount of CO_2 created over the years from existing and new power plants, totalling 869 Mt, in the case study where no PHEVs are penetrated. The amount of CO_2 rises between 2019 and 2024 because of the new sources of electricity. As a result of not considering any emission limit in Case C, the model predicted two NG and two coal power plants which cause the CO_2 emission slope to be steeper at the starting point of new electricity generation than the remaining part of the figure.

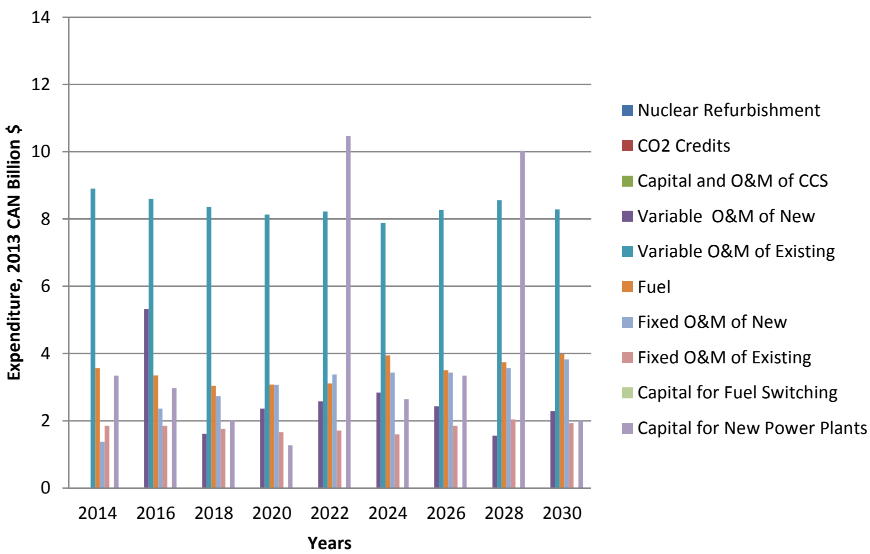

Figure 10. Detail expenditures for Case C.

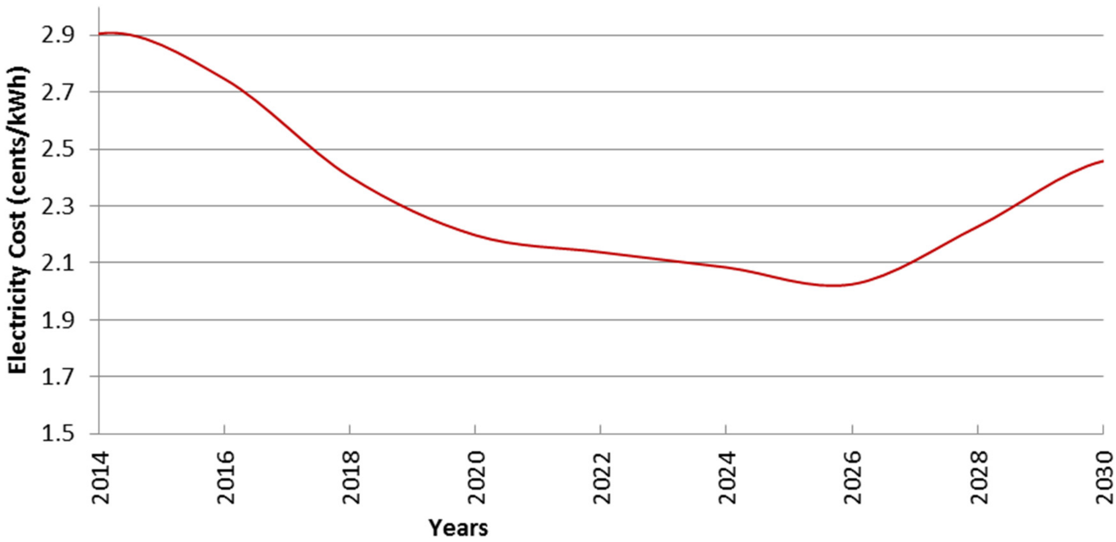

Figure 11. Overall electricity costs for Case C.

3.3. Case Study D: Base Case with 6% Reduction in CO_2 by Year 2018

Case study D considers the impact of PHEVs' high penetration rate under two conditions: (1) no new nuclear power stations; and (2) CO_2 emission reduction of 6% by the year 2018.

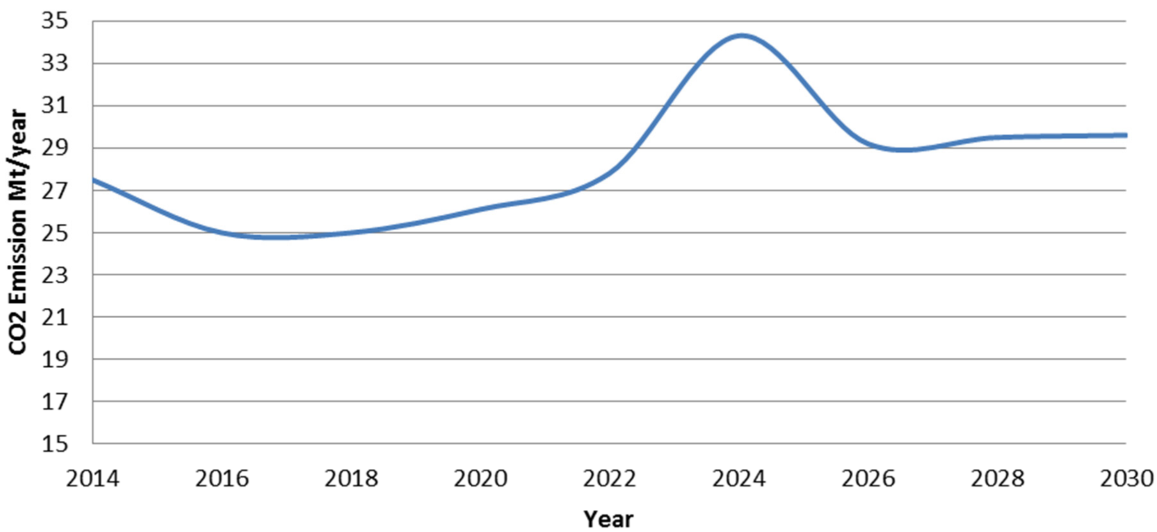

Figure 12. CO_2 emissions for Case C.

3.3.1. New Power Generation Stations

Under a high PHEV adoption rate, no new nuclear stations, and CO_2 emission reduction target of 6%, NGCC is generating electricity with ~4400 MW of new installed capacity (Table 6). New power stations with CCS systems are suggested by the model to guarantee meeting the CO_2 emission targets.

Table 6. New power generating stations and their construction time for Case D.

New Capacity (MW)		Years (20..)																
		14	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**
NGCC	528																	
NGCC	730																	
NGCC	950																	
NGCC	892																	
NGCC	866																	
IGCC+CCS	700																	
IGCC+CCS	400																	
NGCC+CCS	432																	
Import	1250																	
Wind	1000																	
Wind	1000																	

3.3.2. Economic and Emission Analysis

Figures 13 and 14 give the overall expenditures for Case D. The overall average cost of electricity is 2.36 c/kWh as indicated in Figure 15. The similarities between the previous cases and this case are not significant.

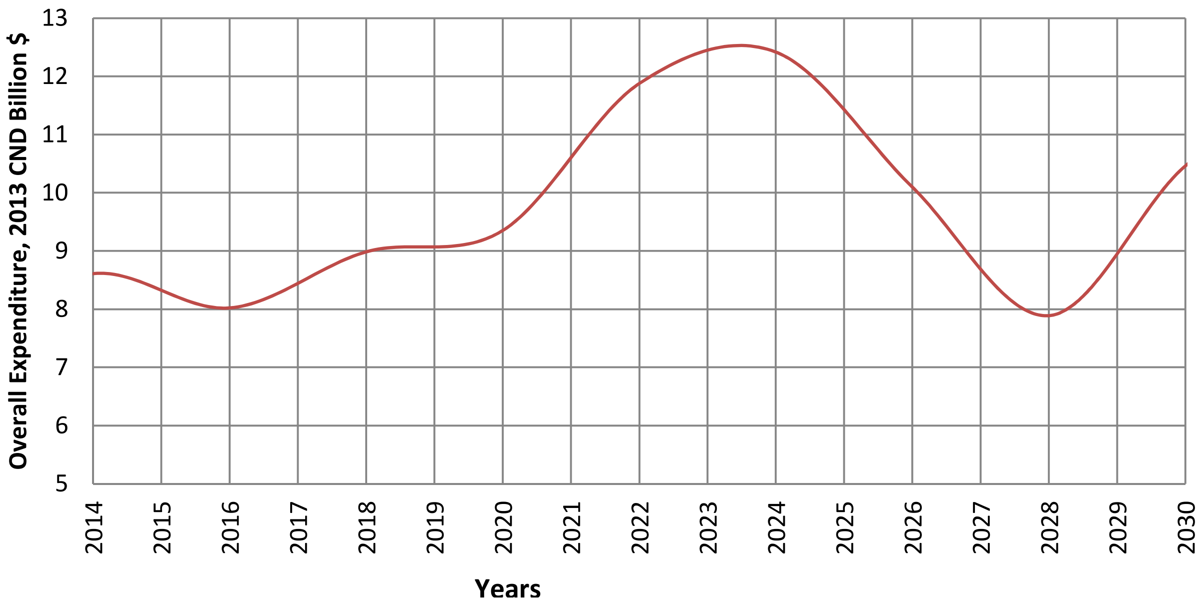

Figure 13. Overall expenditures for Case D.

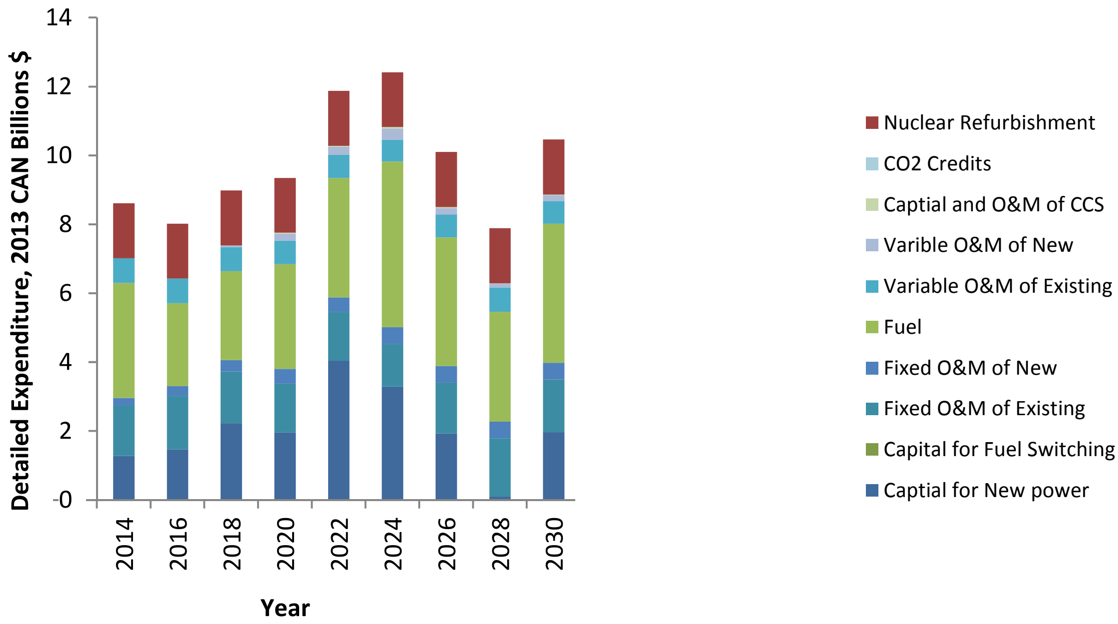

Figure 14. Detailed expenditures for Case D.

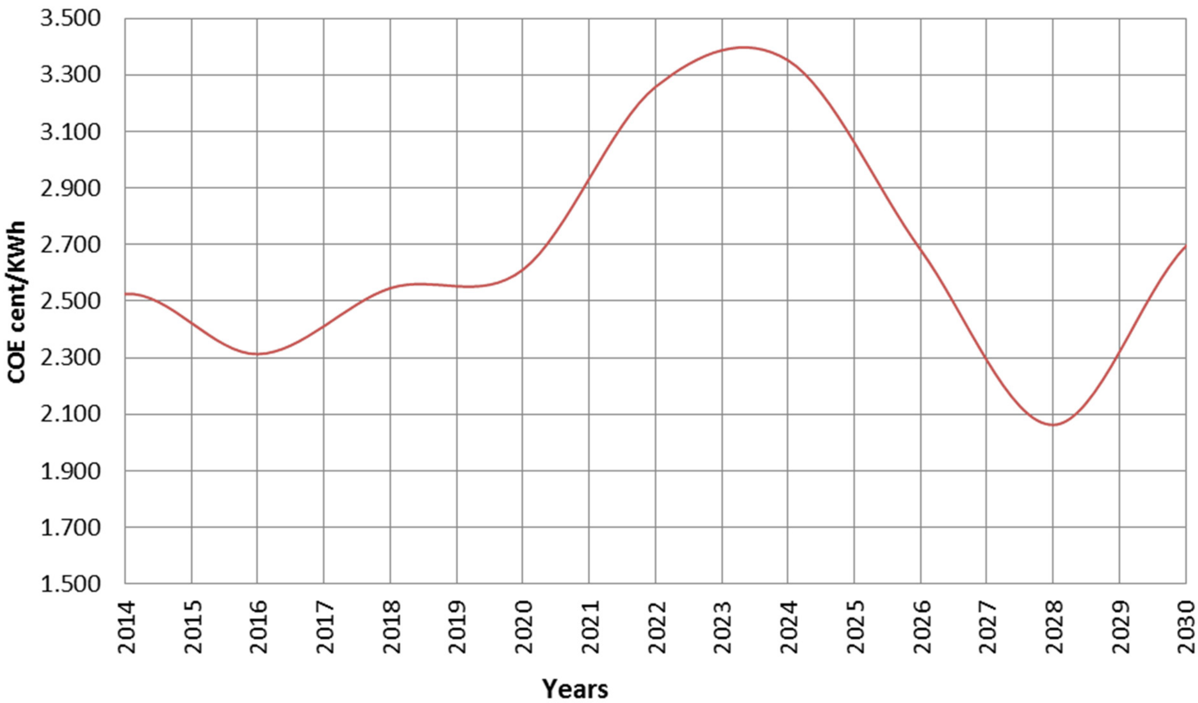

Figure 15. Overall cost of electricity for Case D.

As indicated in Figure 16 the overall CO_2 emissions stay steady after 2020. A total of ~600 Mt of CO_2 emissions is detected in the case with 6% emission reduction by the year 2018. The emission curve shows a minimum in 2018 because of the significant number of PHEVs introduced after 2018.

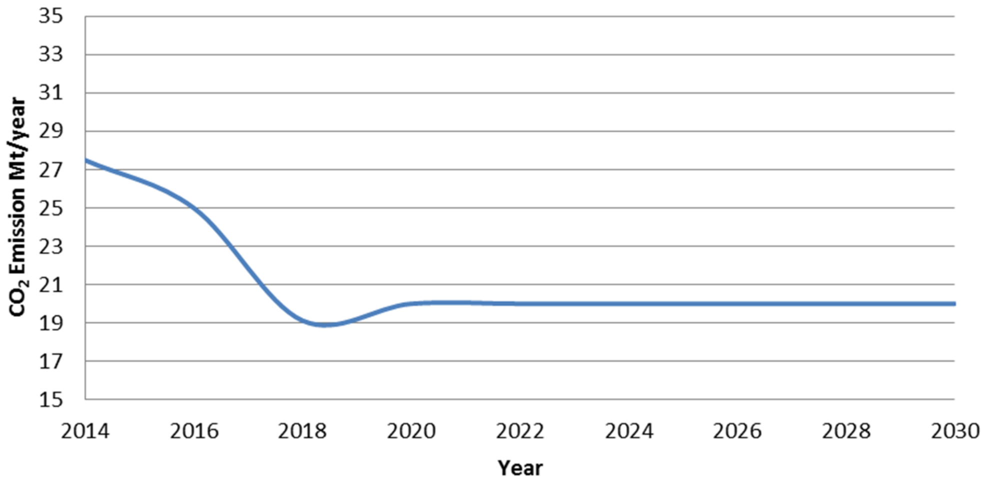

Figure 16. Overall CO_2 emissions for Case D.

3.4. Case Study E: Base Case without Considering Current Load Deficit

Case E does not consider any current load deficit in Ontario. PHEVs' penetration rate is assumed to be medium, and all coal power plants are phased out in 2014.

3.4.1. New Power Generating Stations

Table 7 shows that new NGCC stations and wind stations are added over time, which is due to the addition of more PHEVs over time and all are transferring their electricity load to the grid. NGCC makes up 80% of the total new installed capacity for this case.

Table 7. New power generating stations and their construction time for Case E.

New Capacity (MW)		**Years (20..)**																
		14	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**
NGCC	210																	
NGCC	320																	
NGCC	375																	
Wind	500																	
NGCC	530																	
NGCC	550																	

3.4.2. Economic and Emission Analysis

As indicated in Figure 17, Case E has a lower average cost of electricity. Because of the cheaper capital cost of NG power plants and also almost half of the installed capacity than other cases studied (due to less electricity deficit), the average cost of electricity is the lowest among all the s studied.

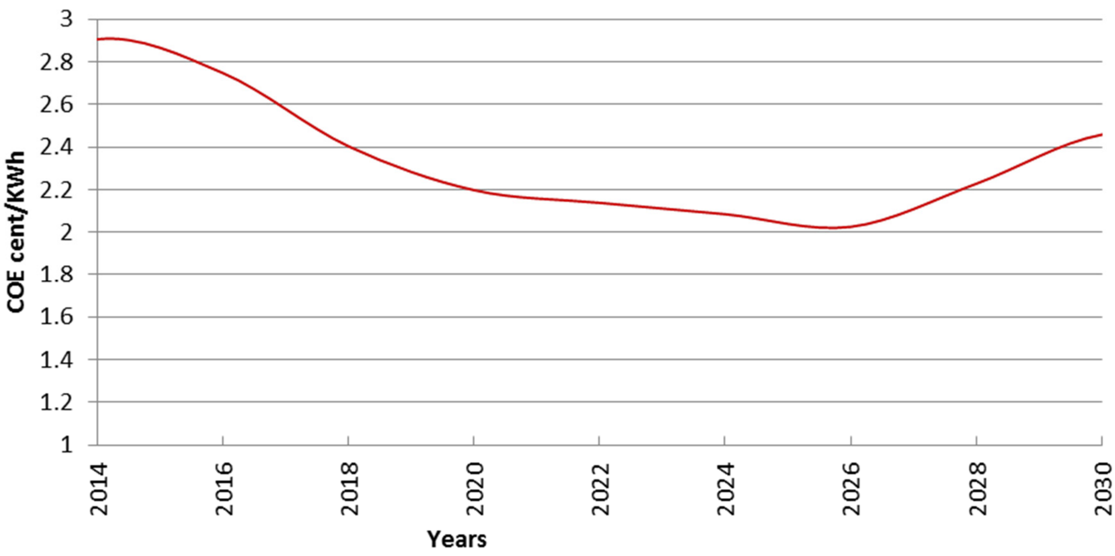

Figure 17. Overall cost of electricity for Case E.

No CO_2 emission reduction constraints are applied in this case. Because of the increasing number of PHEVs as a function of square time, there would be less gasoline consumption by vehicles each year compared to the previous year. Therefore, the amount of CO_2 emissions decreases over time, as is shown in Figure 18. In the next section, a summary that compares all cases is provided.

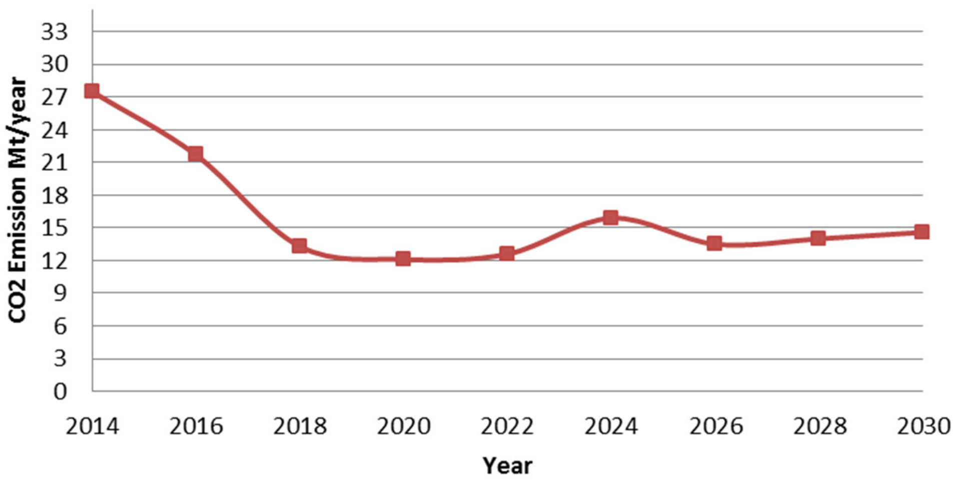

Figure 18. Overall CO_2 emissions for Case E.

3.5. Summary

As indicated in Figure 19, Case E has the lowest average cost of electricity and Case B has the highest one. The total new installed capacity is the highest for case D, 8748 MW, and lowest for Case E, 2400 MW (Table 8). Almost half of electricity generated by the new fleet is from nuclear power stations. Although, the cases studied are different, there are many similarities between them. For example, after optimization of the model, a large amount of electricity is generated from nuclear stations in cases A and B. At the same time, 49% of new power plants are NGCC in Case A (compared to 47% in Case C).

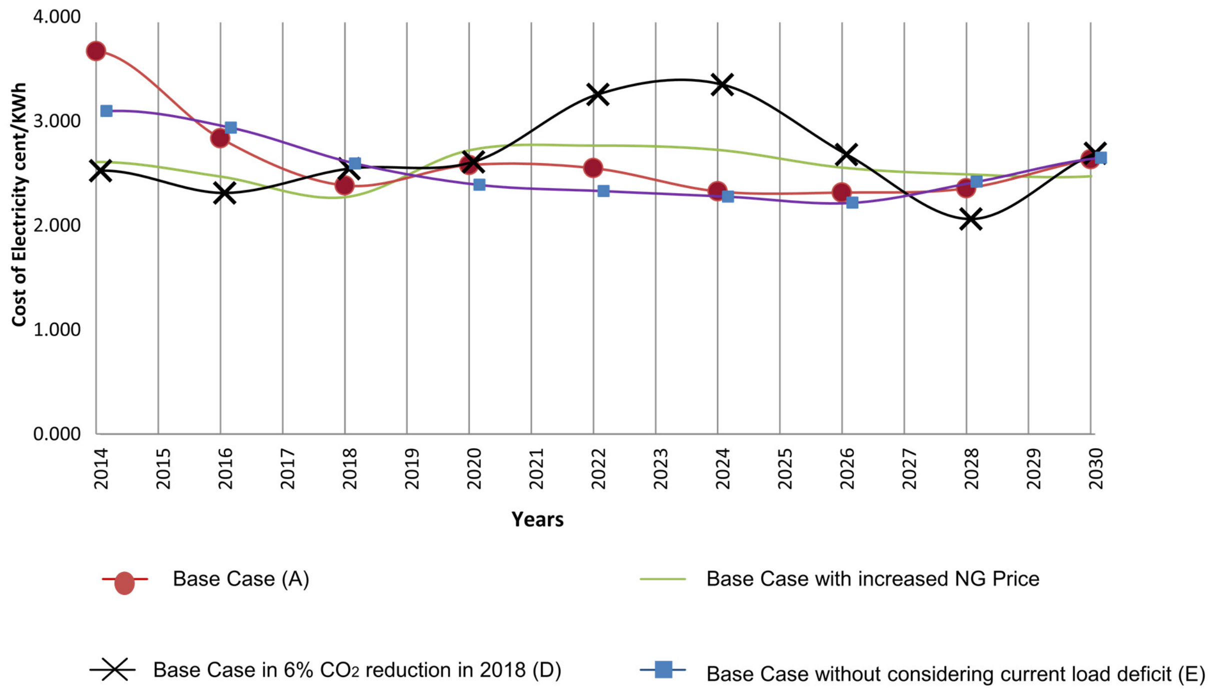

Figure 19. Overall cost of electricity comparison.

Table 8. New power generation, COE comparison.

Case	Total New Installed Cap (MW)	COE ¢/kwh	New Power (MW)	Installed Cap in 2030 Compared to 2013				
				Coal	NGCC	Wind	Hydro	Nuclear
Case A	7270	2.27	NGCC: 2890 Wind: 2000 Nuclear: 1080	2%↓	4%↑	4%↑	0	3%↓
Case B	7270	2.34	Coal: 1660 NGCC: 1370 Wind: 2000 Nuclear: 12010	2%↑	0	4%↑	3%↓	3%↓
Case C	6500	2.20	Coal: 2792 NGCC: 3136	7%↑	4%↑	1%↓	4%↑	6%↓
Case D	8748	2.36	IGCC: 1100 NGCC: 4398 Wind: 2000	1%↑	6%↑	4%↑	4%↑	7%↓
Case E	2400	2.19	NGCC: 1985 Wind: 500	2%↓	5%↑	1%↑	1%↓	3%↓

4. Conclusions

The Ontario energy planning is optimized to minimize the value of the cost of the electricity considering the effect of PHEV charging over sixteen years (2014–2030). Based on our previous work [5], after PHEV penetration in Ontario, peak load demands and base load demands in December 2030 would be increased by ~13% and 4% compared to the 2013 demand. Consequently, supply is less than the peak load demand. The additional electricity demand on the Ontario electricity grid from charging PHEVs is incorporated for electricity production planning purposes and therefore, more power plants are needed if PHEVs are widely adopted. It is noted that this conclusion is based on the cases studied in this paper and associated assumptions. There are however many other factors that can be considered. For instance the grid and through wireless communication can start and stop charging vehicles as per customers' agreements (if they agree to a lower cost of electricity incentive). Furthermore, much more integration of

PEVs might take place; especially at other provinces or countries. Therefore we stress that the conclusions in this paper might differ for other cases.

The mathematical objective function employed in this work consists of the fuel costs, fixed and variable operating and maintenance costs, the capital costs for new power plants, and the retrofit costs of existing power plants (associated with fuel switching from coal to natural gas for coal-fired stations). The mathematical model of objective function and related constraints were implemented in GAMS. Five different case studies are considered with different penetration rates, types of new power plants, and CO_2 emission constraints.

Among all the cases studied, the highest new capacity (~8748 MW) is installed for the base case with 6% reduction in CO_2 by the year 2018, which considers a high adoption rate for PHEVs, and no utilization of any new nuclear power plants, with the carbon dioxide emissions restriction. The next highest ones are the base case and base case with increased NG price with ~7270 MW (an increase of 34.78% in the total installed capacity in 2030), which considers NG price increases to double in 2020 with a medium PHEVs adoption rate. One of the main reasons of having more installed capacity in the base case with 6% reduction in CO_2 in year 2018, is the high PHEV penetration which leads to more electricity consumption. Therefore, more electricity needs to be generated to satisfy load demand over the years. As a result of the highest amount of installed capacity in the case of the base case with 6% reduction in CO_2 in year 2018, the total expenditure and average cost of electricity of this case (148 CND billion, and 2.36 c/kWh) are more than the three other cases. Moreover, the optimization results indicate that by not utilizing coal power stations, the CO_2 emissions are the lowest; ~500 tonnes compared to ~900 tonnes when coal is permitted.

For future work, different types of PHEVs could be considered based on the percentage of people with specific driving distances. For this purpose, different scenarios could be defined. Moreover, the computation time of the model could be improved by utilizing a continuous time index or representative curves. Other work could be decentralizing and integrating the zonal PHEV penetration, and developing an optimization model to address the optimal planning of the Ontario zonal power generating sector. Furthermore, multi-objective functions could be considered for the operating and maintenance costs of various power plants, as well as considering fuel (NG) cost fluctuations.

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Author Contributions

The authors have equally contributed in this study.

Conflicts of Interest

The authors declare no conflict of interest.

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