Large-scale Solar PV Investment Models, Tools and Analysis: The Ontario Case

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***Abstract* – In this paper, an optimization model and techniques to facilitate a prospective investor to arrive at an optimal plan for investment in large-scale solar photovoltaic (PV) generation projects are proposed and discussed. The optimal set of decisions includes the location, sizing and time of investment that yields the highest profit. The mathematical model considers various relevant issues associated with PV projects such as location-specific solar radiation levels, detailed investment costs representation, and an approximate representation of the transmission system. A detailed case study considering the investment in PV projects in Ontario, Canada, is presented and discussed, demonstrating the practical application and usefulness of the proposed methodology and tools.**

***Index Terms* – Power system planning, renewable energy generation, solar photovoltaic, investment tools.**

I. Nomenclature

A. Indices

i, j	Zone
k	Year

B. Parameters

a	Discount rate [%]
$EC_{k,i}$	Equipment cost [$/kW]
$LC_{k,i}$	Land cost [$/kW]
$TC_{k,i}$	Transport cost [$/kW]
$LbC_{k,i}$	Labor cost [$/kW]
$OM_{k,i}$	Operation and maintenance cost [$/kWh]
CF_i^{PV}	Solar PV capacity factor [%]
CF_i^{conv}	Conventional generation capacity factor [%]
$Cap_{k,i}^{conv}$	Conventional generation capacity available [MW]
$PD_{k,i}^{eff}$	Effective zonal peak demand [MW]
$P_{k,ij}^{MAX}$	Transmission line capacity [MW]
$B_{k,ij}$	Element of B-matrix [p.u.]
ρ	Price of energy sold to grid/utility [$/kWh]
$ABud_k$	Annual budget [$]
$TBud$	Total budget [$]
$Po_{i,m}^{PV}$	Monthly average power from solar PV module [kW]
P_r^{PV}	Rated power of a typical solar PV module [kW]
DB	Dead-band imposed on initial investment [years]
N	Investment period [years]
L	Plant useful life [years]
A	Solar PV module area [m^2]
I_i	Zonal solar radiation in zone [kWh/m^2-day]
T_i	Zonal ambient temperature [°C]
η_i	Solar PV system conversion efficiency [%]
η_o	Solar PV module efficiency [%]
η_{inv}	Inverter efficiency [%]
$n_{d,m}$	Number of daylight hours available per month [hrs]
n_m	Number of hours per month [hrs]

C. Variables

Ω	Net present value of investor profit [$]
$NC_{k,i}^{PV}$	New solar PV capacity [MW]
$Cap_{k,i}^{PV}$	Total solar PV capacity [MW]
$P_{k,ij}$	Transmission line power flow [MW]
$\delta_{k,i}$	Zone power angle [rad]
$P_{k,i}^{conv}$	Power dispatched from conventional generation [MW]
$P_{k,i}^{PV}$	Power dispatched from solar PV generation [MW]
$E_{k,i}^{conv}$	Energy available from conventional generation [MWh]
$E_{k,i}^{PV}$	Energy available from solar PV generation [MWh]

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II. Introduction

The depleting oil reserves, uncertainty and political issues concerning nuclear generation, combined with the environmental concerns associated with coal and natural gas-fired generation, is encouraging researchers, practitioners and policy makers to look for alternative and sustainable sources of energy. Among them, wind and solar generation have become preeminent in recent years. In this context, the ease of installation, declining cost of technology and supportive government policies have been the catalysts for the fast growth of solar photo-voltaic (PV) generation in the world. Thus, in just a short duration of 6 years, from 2004 to 2009, the total global grid-connected solar PV capacity has increased at an average rate of 60%, annually, to a total of about 21 GW [1]. As of 2009, in the province of Ontario, Canada, out of a total renewable energy generation capacity of 1,422 MW, solar PV generation capacity accounts for 525 MW [2]. The current world's largest solar PV power plant with an installed capacity of 80 MW was completed in Sarnia, Ontario, Canada, in October 2010 [3].

Grid-connected solar PV systems provide a quiet, low maintenance, pollution-free, safe, reliable and independent alternative to conventional generation sources. Major breakthroughs in solar cell manufacturing technologies have enabled it to compete with conventional generation technologies in the large-scale as well. According to the European PV Technology Platform Group, solar PV is expected to reach grid parity in most of Europe by 2019 [4].

In an attempt to attract investments in renewable energy and help phase-out coal generation in Ontario by 2014 to meet emission reduction targets, the Green Energy and Green Economy Act of Ontario was passed in May 2009 [5]. Ontario's Feed-in Tariff (FIT) was established as North America's first comprehensive guaranteed pricing structure for renewable energy production. The FIT offers lucrative prices under long-term contracts for energy generated from biomass, biogas, landfill gas, on-shore and off-shore wind, hydro power and solar PV. The FIT price schedule for larger projects, allows the highest rates to investments in solar PV systems up to 10 MW [6]. This program opens up opportunities for new investments in the renewable energy sector in Ontario. It also stimulates the development of new tools and techniques to determine optimal paths of integration of renewable energy resources into the existing power system.

There has been some reported works in the literature on system-wide analysis, planning and operational effects of distributed generation (DG) on power systems. For example, the analysis and mitigation of the adverse effects of solar PV sources on the utility grid is discussed in [7] and [8]. However, development of decision making tools for a solar PV investor, not concerned with system-wide operation or planning are not generally available in the current technical literature. Therefore, this paper focuses on developing optimal plan decision tools for solar PV investments from the perspective of investors. The proposed and general mathematical model considers the future generation, demand, transmission parameters, solar PV and conventional generation capacity factors, carefully evaluated with adequate accuracy for a planning problem of this nature.

It is important to highlight the fact that the primary purpose of this paper is to present an investor-oriented solar PV planning model, with the results meant to aid private investors in their decision making. Generally, in the prevalent decentralized power systems, private investors do not own or operate the transmission network and are hence not solely responsible for its performance, security or reliability; therefore, the traditional centralized planning aspects such as minimization of overall system losses and overall system security are not considered here. This is in line with the current investment trends in power systems with the influx of private investments, driven by various incentives and support policy mechanisms offered by governments. However, the model presented here does incorporate transmission constraints, power angle constraints and power flow equations in the planning framework, thus representing somewhat system security issues, making the results viable from a systems' point of view. Therefore, this model can be considered as the first stage of a two stage planning framework for a decentralized power system, as discussed in [9].

It was concluded in [10] that solar PV systems become much more economically competitive with conventional generation sources when they are installed on a large-scale. Hence, the focus of this work is restricted to large-scale solar PV systems (5 MW and above). The model is demonstrated in the case of a prospective investor in Ontario's booming green energy sector.

The structure of the rest of this paper is as follows: Section III provides a brief background review of the relevant economic criteria and technical literature. Section IV presents the proposed investor-centric generation planning model to determine the optimal investment decisions in solar PV. Section V discusses the Ontario case study, which includes development of cost components, the transmission system model, and evaluation of solar PV capacity factors. In Section VI the results obtained from the Ontario case model are presented and analyzed, including a probabilistic study to consider relevant parameter uncertainties. Finally, the main conclusions and contributions of the paper are highlighted in Section VII.

III. Background

Solar PV systems are generally characterized by high fixed costs and low operation costs [11]. Unlike certain conventional generation sources that have substantial operational costs such as thermal units, which cannot be ignored in their investment planning programs, solar PV investment planning models are not significantly affected by their operating costs. The following economic criteria have been proposed in the literature for the evaluation of solar PV investments [12]: least cost energy; net present value (NPV) or life-cycle cost (LCC); annualized life-cycle cost (ALCC) or cost annuity; payback period (PBP); and return on investment (ROI). Least cost energy is a reasonable criterion, but it is only useful when solar energy is the only available resource. NPV is the discounted sum of the revenue from selling the gross generated energy net of all costs associated with the energy delivery system. ALCC is the average yearly flow of money; the actual flow varies with year, but the sum over the period can be converted to a series of equal payments. PBP is a non-life cycle criteria and simply calculates the time needed to recover the investment made. ROI is the market discount rate that results in zero NPV.

From a literature review, it can be observed that the most appropriate economic criteria for solar PV investment analysis is the NPV analysis [9],[10],[13]-[15], as it incorporates the entire life-cycle of the projects and the time value of money. Thus, NPVs are calculated for all the proposed projects, and the project with the highest NPV is selected.

In [10], the viability of solar PV systems is examined and a sensitivity analysis is carried out to estimate their comparative viability with conventional diesel-powered units based on region specific parameters; an LCC analysis using a cost annuity method is applied. Cost comparisons reveal that PV systems have the lowest cost when the daily energy demand is low. It also concludes that the break-even point occurs at high energy demand, as the cost of solar PV systems decrease and diesel cost increases.

A technical and economic assessment of utility interactive solar PV systems for South East Queensland is reported in [14]. A simple PBP and LCC analysis of NPV is carried out, given the cost parameters, tariff structure and grid interconnection policy of the region.

Long-term effects of FIT, carbon taxes and cap-and-trade on renewable energy investments by small power producers (SPPs) and/or local distribution company (LDC) are presented in [15]. It is concluded that government incentives such as FIT are necessary to attract investments in solar PV, and that either a carbon tax or cap-and-trade mechanism to the FIT would result in reduction of both emissions and energy cost.

Finally, in [9], a coordination scheme for approval of DG investment proposals is presented. This scheme relies on an iterative process satisfying both the objective of the LDC (maximizing DG participation and penetration) and the SPP (maximizing profit based on sizing, siting and production schedule).

IV. Mathematical Model

In this section the proposed optimization model, including the objective function and constraints, are presented and discussed in detail. All variables and parameters throughout this section are properly defined in Section I. The proposed optimization model is linear and most of the decision variables are continuous, while the investment selection variables are binary. This results in a Mixed Integer Linear Programming (MILP) model that was solved in GAMS using the CPLEX solver [16].

A. Objective Function

The objective is to maximize the NPV of the investor's profit (Ω). Based on the annual cash flow over the useful life of the new investments, Ω is calculated for a discount rate a, as follows:

$$Maximize\ \Omega = \sum_k \frac{\sum_i (Revenue_{k,i} - Cost_{k,i})}{(1+a)^k} \qquad (1)$$

where, $Cost_{k,i}$ denotes the total annualized project cost in year k and zone i, which includes annualized values of equipment cost $EC_{k,i}$, transportation/freight cost $TC_{k,i}$, land cost $LC_{k,i}$ and labor cost $LbC_{k,i}$ associated with new investments $NC_{k,i}^{PV}$. It also includes operation and maintenance cost $OM_{k,i}$ associated with inverter replacements and periodic maintenance checks. Thus:

$$Cost_{k,i} = (EC_{k,i} + TC_{k,i} + LC_{k,i} + LbC_{k,i}) NC_{k,i}^{PV} + OM_{k,i} E_{k,i}^{PV} \qquad (2)$$

Note that the variable $NC_{k,i}^{PV}$ is discrete with 5 MW steps.

In (1), the annual revenue generated by new investments is calculated based on the amount of energy $E_{k,i}^{PV}$ injected into the grid and the negotiated contract price ρ:

$$Revenue_{k,i} = \rho E_{k,i}^{PV} \qquad (3)$$

The aforementioned cost components and revenue stream are annualized considering the total plant life L.

B. Constraints

1) Demand-supply Balance: The effective power demand of each zone is met by existing conventional generation and new solar PV generation while considering the transmission network representation through the following dc power flow model:

$$P_{k,i}^{conv} + P_{k,i}^{PV} - PD_{k,i}^{eff} + \sum_j P_{k,ij} = 0 \qquad (4)$$

2) Line Flow Limits: The power transferred between the zones depends on the impedance of the transmission lines. This transfer must not exceed the maximum power transfer limit of each of the transmission lines; thus:

$$P_{k,ij} = -B_{k,ij}(\delta_{k,i} - \delta_{k,j}) \qquad (5)$$

$$P_{k,ij} \le P_{k,ij}^{MAX} \qquad (6)$$

3) Power Angle Limits: The power angles are constrained to be within a range to ensure system stability (±30° limits were used here):

$$\delta_{min} \le \delta_{k,i} \le \delta_{max} \qquad (7)$$

4) Energy Generation From Conventional Sources: Zonal capacity factors of conventional generation CF_i^{conv} can be evaluated using the system's historical data of generator outputs and available capacity. Based on these capacity factors, the annual energy available from conventional generation sources $E_{k,i}^{conv}$ is constrained as follows:

$$E_{k,i}^{conv} \le 8760\, Cap_{k,i}^{conv} CF_i^{conv} \qquad (8)$$

$$E_{k,i}^{conv} = 8760\, P_{k,i}^{conv} \qquad (9)$$

5) Energy Generation From Solar PV Sources: Zonal capacity factors of solar PV generation CF_i^{PV} can be determined from solar energy data, as discussed in the next section for the case of Ontario [12]. Based on these capacity factors the annual energy available from the solar PV generation sources $E_{k,i}^{PV}$ is constrained as follows:

$$E_{k,i}^{PV} \le 8760\, Cap_{k,i}^{PV} CF_i^{PV} \qquad (10)$$

$$E_{k,i}^{PV} = 8760\, P_{k,i}^{PV} \qquad (11)$$

6) Dynamic Constraint on Solar PV Capacity Addition: This constraint ensures that the solar PV capacity for the next year is the cumulative sum of the new capacity installed and the capacity of the previous year. This cumulative sum is taken only for the investment period as follows:

$$Cap_{k+1,i}^{PV} = Cap_{k,i}^{PV} + NC_{k,i}^{PV} \quad \forall\, k = 1, 2, \dots, (N-1) \qquad (12)$$

7) Constraint on Initial Year Investment: This constraint ensures that there are no investments made during the first few years. Thus, the following constraint is included to account for budgeting delays, policy changes and other similar temporary effects (DB was assumed here to be 2 years):

$$Cap_{k,i}^{PV} = 0 \qquad \forall\, k = 1, 2, \dots, DB \qquad (13)$$

8) Constraint on Terminal Year Investment: The solar PV capacity remains unchanged beyond the plan period, thereby implying that there are no new investments beyond year N; thus:

TABLE I
PERCENTAGE ANNUAL GROWTH RATES FOR ZONAL LABOR COSTS IN ONTARIO FROM 2010 ONWARDS

Zone	Annual Growth Rate [%]	Zone	Annual Growth Rate [%]
Bruce	3.67	East	4.49
West	2.37	Ottawa	1.95
SW	2.73	Essa	2.44
Niagara	3.31	NE	5.24
Toronto	0.90	NW	3.27

$$Cap_{k+1,i}^{PV} \leq Cap_{k,i}^{PV} \qquad \forall\, k = N \tag{14}$$

9) Decommissioning of Solar PV Units: After a useful life of L years, each solar PV installation is considered to be phased out of operation (L is assumed here to be 25 years); hence:

$$Cap_{k+L+1,i}^{PV} = Cap_{k+L,i}^{PV} - NC_{k,i}^{PV} \quad \forall\, k = 1, 2, \ldots, (N-1) \tag{15}$$

10) Annual Budget Limit: This constraint ensures that the annual cost of new solar PV installations is constrained by an annual budget limit (a limit of \$100 M was assumed here); thus:

$$\sum_i CC_{k,i}^{PV} NC_{k,i}^{PV} \leq ABud_k \tag{16}$$

11) Total Budget Limit: This constraint ensures that the total cost of new solar PV installations over the entire plan period is constrained by a total budget limit (a limit of \$500 M was assumed here); hence:

$$\sum_k \sum_i \left(CC_{k,i}^{PV} NC_{k,i}^{PV} + OM_{k,i} E_{k,i}^{PV} \right) \leq TBud \tag{17}$$

C. Solar PV Power Model

Zonal solar PV capacity factors CF_i^{PV} can be evaluated based on zonal solar radiation and zonal ambient temperature data as discussed in the next section. The monthly solar radiation I_i and ambient temperature T_i can thus be obtained and used to find the system conversion efficiency η_i, given by [8]:

$$\eta_i = \left[1 - 0.0042 \left(\frac{I_i}{18} + T_i - 20 \right) \right] \eta_o \eta_{inv} \tag{18}$$

Consequently, the power output from the solar PV module is given as:

$$Po_{i,m}^{PV} = A\, I_i\, \eta_i \tag{19}$$

Equations (18) and (19) can be used to evaluate the energy available per unit area per month for a particular type of solar module [17]. The energy produced is determined based on the number of daylight hours available [18]. Therefore, the capacity factors are evaluated using the rating of the solar PV module as follows:

$$CF_i^{PV} = \frac{\sum_m \left(Po_{i,m}^{PV} n_{d,m} \right)}{P_r^{PV} \sum_m n_m} \tag{20}$$

TABLE II
ANNUAL GROWTH RATES FOR COST COMPONENTS

	Module Cost	Inverter Cost	Land Cost	Transportation Cost
Annual Growth Rate [%]	-1	-0.8	2.56	2.8

TABLE III
REMAINING INPUT PARAMETERS

Item	Value
Annual Maintenance Cost, $OM_{k,i}$ [\$/kWh]	0.01
Discount Rate, a [%]	8
Net Inflation Rate [%]	4
Useful Life, L [years]	25
Energy Price, FIT [\$/kWh]	0.42
Annual Budget, $ABud$ [\$/year]	100,000,000
Total Budget, $TBud$ [\$]	500,000,000
Investment Period, N [years]	2010 – 2018

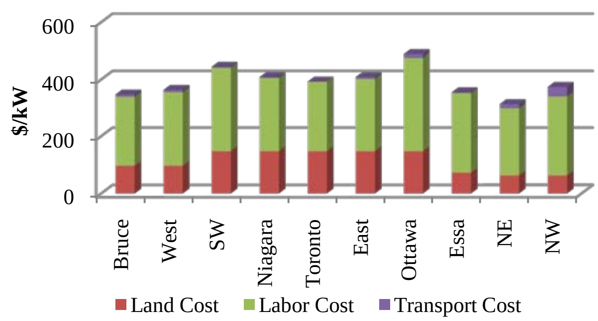

Fig. 1. Capital cost components for the year 2010.

V. ONTARIO CASE STUDY PARAMETERS

A. Cost Model Parameters

The cost of installing a solar PV power plant can be split into four main components: the equipment cost, land cost, transportation cost, and labor cost [19]. These costs are dependent on a variety of parameters, as discussed next.

1) Equipment Cost: This cost reflects the cost of modules, inverters and balance of system. The per unit equipment cost $EC_{k,i}$ is determined based on the number of modules and inverters required per unit of power produced, and is independent of the zone in which the plant is installed. The effect of technology change and the consequent expected reduction in module and inverter costs over the next 30 years [20], based on the trend over the last 10 years, was also taken into consideration here.

2) Land Cost: This cost reflects the cost of land required for the installation. The per unit land cost $LC_{k,i}$ was determined using proportional land market prices [21], which are associated with the "dominant" type of land in each zone. Also, the increase in land prices observed from 2005-2009 was extrapolated to obtain the land cost trends in the future [22].

3) Transportation Cost: This cost $TC_{k,i}$ reflects the cost of

TABLE IV
DEMAND FORECAST BASIS [30]

	Bruce	West	SW	Niagara	Toronto	East	Ottawa	Essa	NE	NW
Effective Peak Demand in 2009 [MW]	57.64	1656.44	2853.12	513.49	5473.43	935.51	1219.7	906.8	1162.44	478.91
Demand Growth Rate [%]	0.78	1.14	1.28	0.41	0.77	0.71	1.42	1.17	-0.33	0.1

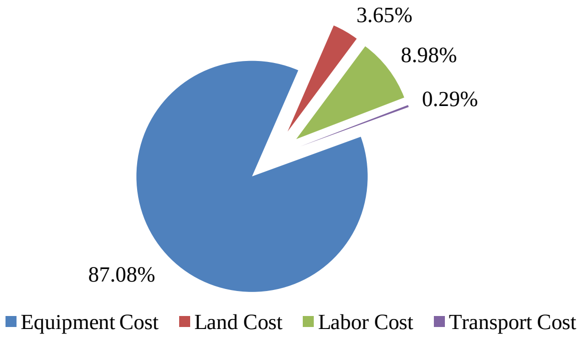

Fig. 2. Percentage distribution of solar PV capital cost in Bruce in 2010.

transporting the equipment from the supply center (assumed to be Toronto here) to the construction site. In this work, the mode of transportation is considered to be trucking. In addition to the distances from the supply centers to the zones, the transportation cost also depends on the unit cost of freight [23], and the weight of the equipment [17], [24]. The increase in trucking costs in Ontario [25] since 2003 was considered and used to determine future transportation costs.

4) Labor Cost: This cost reflects the cost of labor at each zone and is determined using the median income of the zone [26], after calculating the number of labor required per unit capacity of solar PV plant [27]. The increase in the median income was forecasted based on the census data of Ontario for the period from 2000 to 2005 [26], and is shown in Table I.

5) Total Capital Cost: The solar PV cost model developed realistically reflects the trends in these components in different zones in Ontario. The actual cost components obtained for 2010 are shown in Fig. 1. Figure 2 shows the respective percentage distribution for Zone 1 (Bruce). Observe that the equipment cost component, which is independent of location, is the most significant, followed by the cost of land and labor; transportation costs are only a fraction of the total capital cost. Future cost components were also forecasted using a variety of reliable resources [20]-[27], and are presented in Table II. The annual maintenance cost associated with periodic check-up and repair of modules and inverter replacements were also considered [28], as shown in Table III, along with other parameters considered in this work.

B. Ontario Power System Model

In this work, a ten zone equivalent model for Ontario's transmission network has been used, as depicted in Fig. 3. The IESO also considers this model to forecast and assess the reliability of existing and committed resources and transmission facilities in the Ontario electricity market [29]. In this work, the model is estimated from information available from various resources [29]-[32]. The model developed

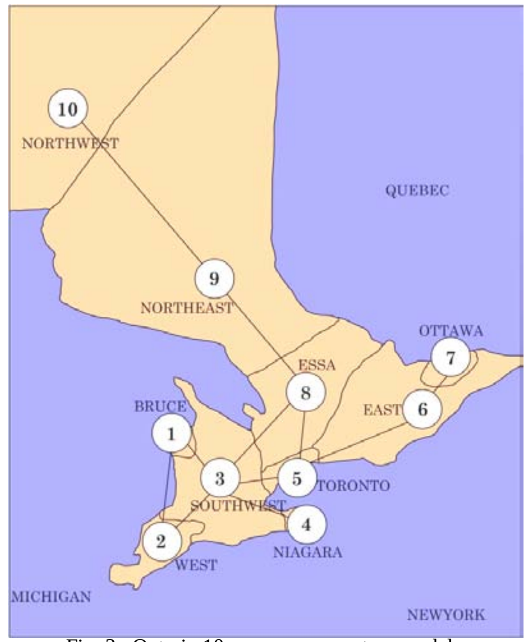

Fig. 3. Ontario 10-zone power system model.

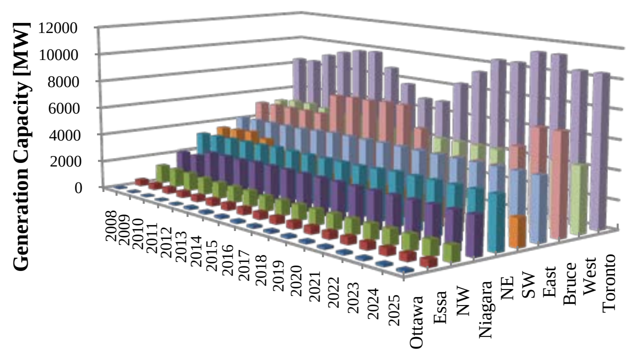

Fig. 4. Zonal generation plan in Ontario.

represents the system in a detail that is adequate for planning studies.

1) Generation Capability: The proposed planning model requires inputs on zonal generation availability for the future. According to the Integrated Power System Plan (IPSP) of Ontario [32], and information provided by the OPA and IESO, a generation forecast of each zone was obtained for the period 2008-2025, as shown in Fig. 4. The generation forecast in this figure was obtained by combining the information presented in [30] and [31] to give the generation capability contributing to the peak load rather than just the base load. Because of lack of sufficient data from 2025 onwards, approximate zonal generation growth rates were assumed based on historical data. Thus, Bruce has the highest growth rate of 3%, followed by Niagara and Toronto with 2% each. The generation growth

TABLE V
PLANNED TRANSMISSION SYSTEM ENHANCEMENTS [30]

Year	Corridor	Current MW	Planned MW
2012	Bruce – Southwest	2560	4560
2012	Southwest – Toronto	3212	5212
2013	Northeast – Northwest	350	550
2015	Bruce – West	1940	2440
2017	Toronto – Essa	2000	2500
2017	Essa – Northeast	1900	2400

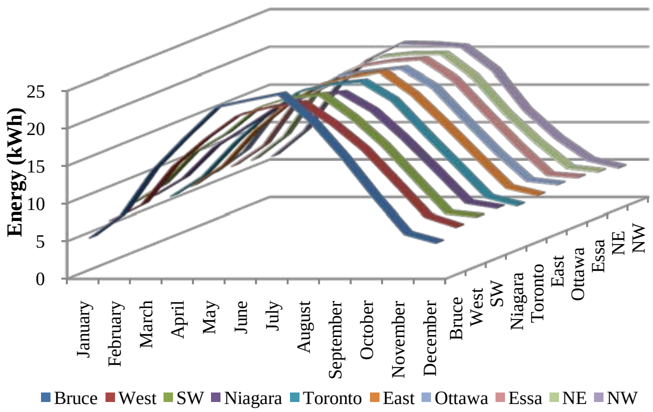

Fig. 5. Solar PV monthly energy yield.

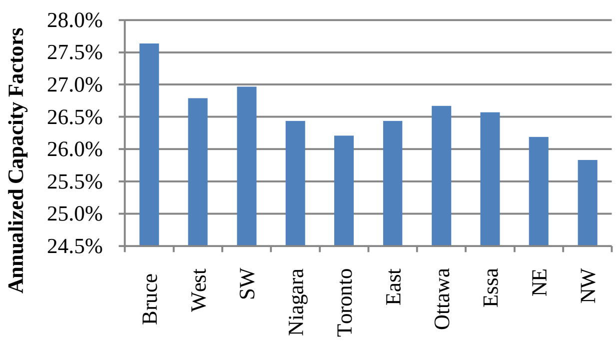

Fig. 6. Zonal solar PV capacity factors.

rate for Essa and Northeast was considered to be 1%, whereas the rest of the zones are not expected to show considerable growth. Zonal capacity factors for conventional generation CF_i^{conv} were evaluated based on two months worth of data from the IESO [33].

2) Effective Peak Demand: The proposed model also requires information on zonal peak demand forecasts. Using the zonal demand forecast from 2007-2015 provided by the IESO, zonal demand growth rates are obtained (see Table IV). In this work, the conservation and demand management plans presented in Ontario's IPSP are also considered and the corresponding reduced peak demand is estimated.

3) Transmission Lines: The simplified transmission system model considered in this work represents Ontario's transmission network, comprising 500 kV and 230 kV lines, with lower voltage lines being neglected. The transmission

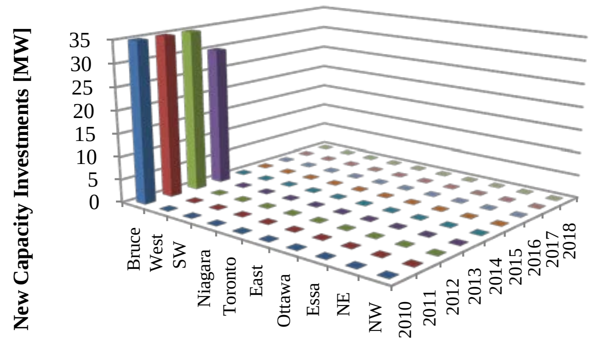

Fig. 7. New capacity investments in Ontario.

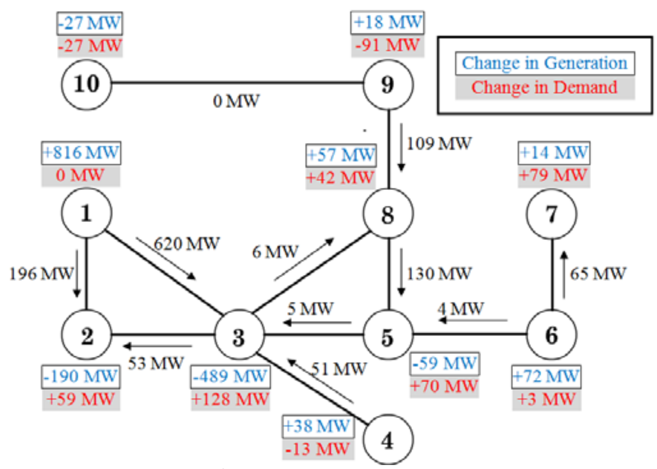

Fig. 8. Transmission line flows, generation and demand changes 2010-2018.

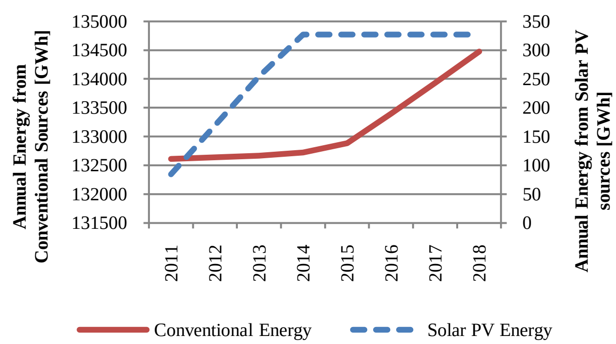

Fig. 9. Energy from solar PV and conventional sources.

line parameters are evaluated from 2008 to 2038 based on the typical values of transmission lines at these voltage levels [34]. The approximate distances between zones, transmission line capacities and line loading limits are also considered, as well as the transmission capacity enhancements planned by the OPA (see Table V). The transmission line capacities so evaluated define the line flow limits.

C. *Zonal Solar PV Capacity Factors In Ontario*

For a typical 140 W solar module of 15% efficiency and dc to ac conversion efficiency of 85% [8], [17], the energy produced per month per solar PV module per zone was computed as discussed in Section IV-C, based on solar radiation and ambient temperature data provided in NASA's

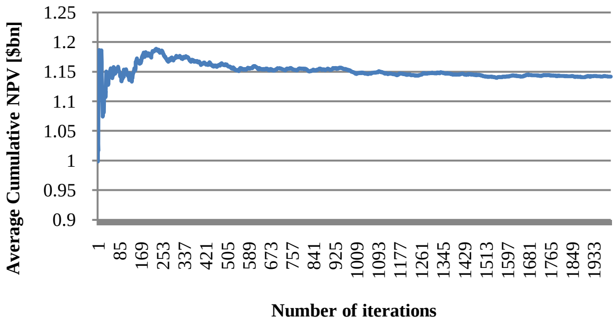

Fig. 10. Cumulative average of NPV in $bn from 2000 iterations.

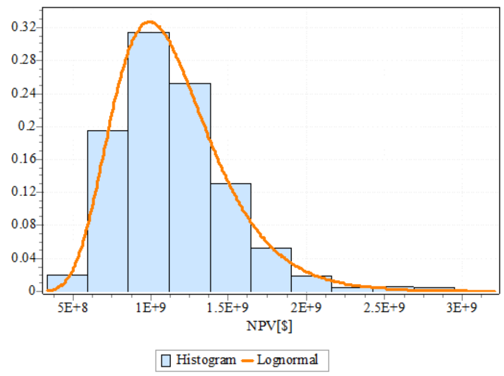

Fig. 11. Histogram and probability distribution function of NPV.

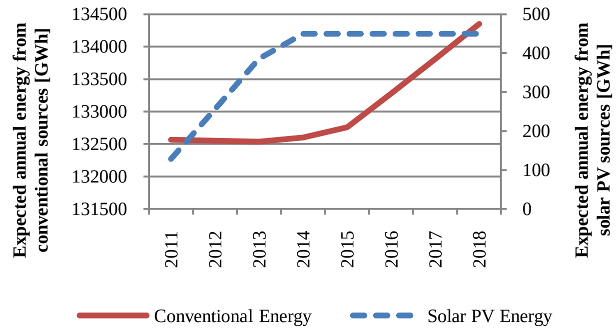

Fig. 12. Energy from solar PV and conventional sources.

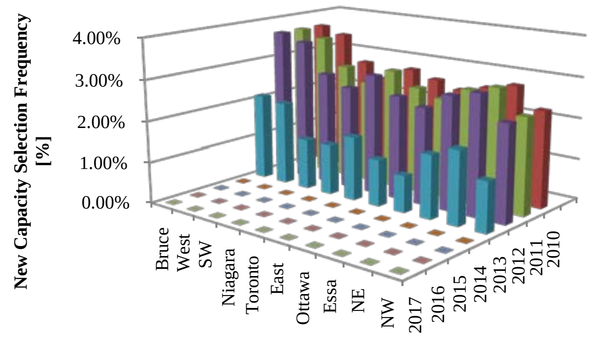

Fig. 13. New capacity decision frequency.

Surface meteorology and Solar Energy (SSE) database [35]; this analysis yielded the results depicted in Fig. 5. The zonal solar PV capacity factors are obtained considering the total energy produced and the number of daylight hours as per (20), and is shown in Fig. 6.

VI. Results and Analysis

The proposed solar PV investment model, which is an MILP model, was solved using the CPLEX solver in GAMS with a 0.1% optimality gap tolerance. Both the results of deterministic and probabilistic (to consider parameter uncertainties) analyses are shown and discussed next.

A. Deterministic Case Study

The deterministic optimal investment plan for solar PV projects in Ontario is shown in Fig. 7 which indicates that Zone 1 “Bruce” is the ideal zone to invest in solar PV to yield the maximum returns. Four investment projects of sizes 3 x 35 MW + 30 MW respectively, are selected for the Bruce region (Zone 1) over the first four years of the plan period. Figure 8 shows the changes in transmission line flows, generation and demand over the investment period 2010-2018, arising from solar PV investments. Note that the tie-line linking Zone 1 to Zone 3 is the most affected transmission corridor, which can be attributed to the 135 MW of new solar PV capacity being commissioned in Zone 1, besides the increase of over 800 MW conventional generation and a slight decrease in demand.

The energy injected into the system annually during the plan period from new solar PV units is compared with that from conventional sources in Fig. 9. Observe that although the conventional energy sources continue to serve the largest share of the demand, the contribution of solar energy increases during the investment period and attains a steady-state share after 2013. The NPV of all projects selected for investment is $725 million, which represents an annual ROI on investments of 37% (note that the current best average annual rate of return in emerging markets is about 10%).

B. Probabilistic Case Study

In order to account for the uncertainty in various model parameters, a Monte Carlo simulation approach can be used to determine the expected investment plans and associated decisions. The Monte Carlo simulation approach is based on the assumption that the uncertain parameters have an associated probability distribution function. The main parameters that may most directly influence the NPV and the associated investment decisions, are, discount rate, budget limits, negotiated contract price and solar PV investment costs. On the other hand, solar PV capacity factors, conventional generation capacity, effective demand and the transmission system have an indirect effect. Of the parameters directly influencing the NPV, the budget limits are considered to be at the discretion of the investor, and the negotiated contract price can be assumed to remain constant over the entire useful life of the project, as per Ontario’s FIT program; the solar PV investment costs were evaluated based on historical data and are hence expected to steadily maintain their trends in the future. The existing transmission system, demand and generation capacity along with future expansions plans were carefully accounted for and hence are not expected to differ greatly from their assumed values over the investment horizon considered here. Therefore, to represent the risks associated with the investments and related profits over a period of time, discount rate can be considered as an uncertain parameter. Furthermore, even though zonal solar PV capacity factors were evaluated based on 22 years of historical data, their future values may also be considered uncertain due to their inherent variability.

Based on the aforementioned arguments, the discount rate and zonal solar PV capacity factors were considered to be the two most uncertain parameters in the proposed investment model. Thus, the discount rate is assumed here to be normally distributed with a mean of 8% in line with the current financial situation, and a standard deviation of 2% representing a variability of 25% around the mean to account for investment risks. The zonal solar PV capacity factors are assumed to be normally distributed around their base values, shown in Fig. 6, with a standard deviation of 10% to account for their unpredictability.

The average cumulative NPV of the investment plan is plotted over 2000 iterations of Monte Carlo simulations in Fig. 10, resulting in an expected NPV of $1,142 million, which is significantly higher than the values obtained from the deterministic analysis. It should be highlighted that the estimated NPV converges in about 500 Monte Carlo simulations. Figure 11 shows the resulting histogram of the NPV of the probabilistic investment plan, resulting in a lognormal distribution (σ=0.30657, μ=20.808). The expected energy injected from new solar PV capacity addition depicted in Fig. 12 is somewhat higher than that obtained for the deterministic case. Observe in Fig.13 that the new investments are still concentrated in the first four years of the plan period. However, the new solar PV investment decisions are shown in terms of their likelihood of being selected; for example, the Bruce region (Zone 1) has the comparatively highest likelihood of investment.

VII. CONCLUSIONS

In this paper, an optimal planning model for investment in large-scale solar PV generation from the perspective of an individual investor has been presented. The model was tested using the Ontario case, based on realistic estimates for solar radiation patterns, conventional generation and transmission capacities, demand growth, and revenues for a 30 year investment plan, taking into account a very detailed and realistic representation of solar PV unit costs. The test results show the usefulness and practicality of the model for determining optimal investment plans on solar PV and validate the related investment decisions currently being made in Ontario.

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IX. BIOGRAPHIES

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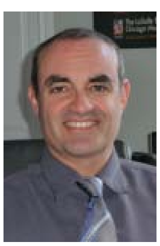

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