Large-Scale Solar PV Investment Planning Studies

by

Wajid Muneer

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

In the pursuit of a cleaner and sustainable environment, solar photovoltaic (PV) power has been established as the fastest growing alternative energy source in the world. This extremely fast growth is brought about, mainly, by government policies and support mechanisms world-wide. Solar PV technology that was once limited to specialized applications and considered very expensive, with low efficiency, is becoming more efficient and affordable. Solar PV promises to be a major contributor of the future global energy mix due to its minimal running costs, zero emissions and steadily declining module and inverter costs.

With the expanding practice of managing decentralized power systems around the world, the role of private investors is increasing. Thus, the perspective of all stakeholders in the power system, including private investors, has to be considered in the optimal planning of the grid. An abundance of literature is available to address the central planning authority's perspective; however, optimal planning from an investor's perspective is not widely available. Therefore, this thesis focuses on private investors' perspective.

An optimization model and techniques to facilitate a prospective investor to arrive at an optimal investment plan in large-scale solar PV generation projects are proposed and discussed in this thesis. 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 large-scale solar PV projects in Ontario, Canada, is presented and discussed, demonstrating the practical application and usefulness of the proposed methodology and tools.

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Dedication

To my loving family.

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List of Abbreviations

PV	Photovoltaic
IEA	International Energy Agency
PVPS	Photovoltaic Power Systems Program
PVGCS	Photovoltaic Grid Connected System
FIT	Feed-in Tariff
RESOP	Renewable Energy Standard Offer Program
IESO	Independent Electricity System Operator
OPA	Ontario Power Authority
OPG	Ontario Power Generation
RPS	Renewable Portfolio Standard
LCC	Life Cycle Cost
ALCC	Annualized Life Cycle Cost
PBP	Pay Back Period
NPV	Net Present Value
NPW	Net Present Worth
OECD	Organization for Economic Cooperation and Development
TGC	Tradable Green Certificate
IRR	Internal Rate of Return
ROI	Return On Investment
ELI	Energy Location Information
PWI	Positional Weight Information
SRUF	Solar Resource Unavailability Frequency
SRAUD	Solar Resource Average Unavailability Duration
SPP	Small Power Producer
LDC	Local Distribution Company
DG	Distributed Generation
GAMS	General Algebraic Modeling System
PPA	Power Purchase Agreement
CSP	Concentrated Solar Power
SEGS	Solar Energy Generating System
CIGS	Copper Indium Gallium Selenide
CdTe	Cadmium Telluride
BOS	Balance Of System
MPPT	Maximum Power Point Tracking
MILP	Mixed Integer Linear Programming
NASA	National Aeronautics and Space Administration

SSE	Surface Meteorology and Solar Energy
SW	South West
NE	North East
NW	North West
CDM	Conservation and Demand Management
IPSP	Integrated Power System Plan
LMV	Land Market Value

Nomenclature

Indices

i,j	Zone
k	Year

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 [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]

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]
σ	Standard deviation of NPV [$ or p.u.]
μ	Mean of NPV [$ or p.u.]

Chapter 1
Introduction

1.1 Motivation

The depleting oil reserves, uncertainty and political issues concerning nuclear generation, and the environmental concerns associated with coal and natural gas-fired generation are 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.

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. Evolution of the price of PV modules as per International Energy Agency Photovoltaic Power Systems Program (IEA PVPS) indicates that the price of PV modules has reduced by 30 – 60% of its value in the last 10 years [1]. Figure 1-1 shows the reduction in PV module prices in Canada from 1999 to 2009. Figure 1-2 shows the cumulative installed solar PV capacity growth as per the IEA PVPS. It is observed that in a short duration of 6 years, from 2004 to 2009, the total global grid-connected solar PV capacity increased at an average annual rate of 60%, to a total capacity of about 21 GW [3].

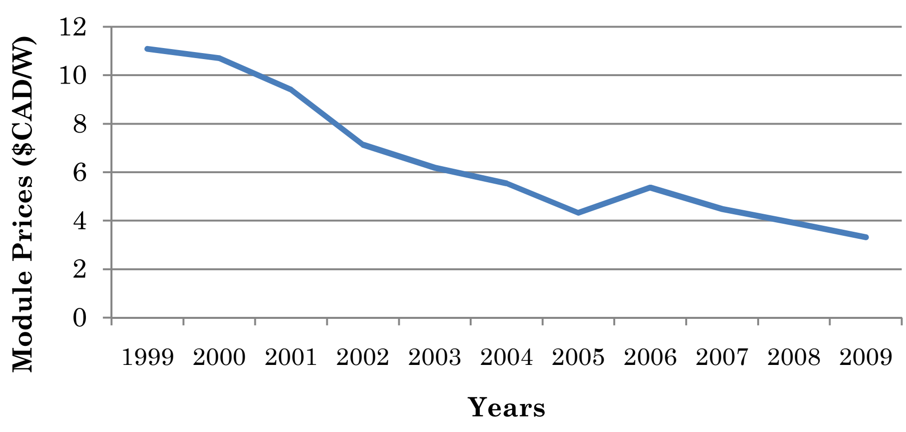

Figure 1-1 PV modules prices in Canada [2].

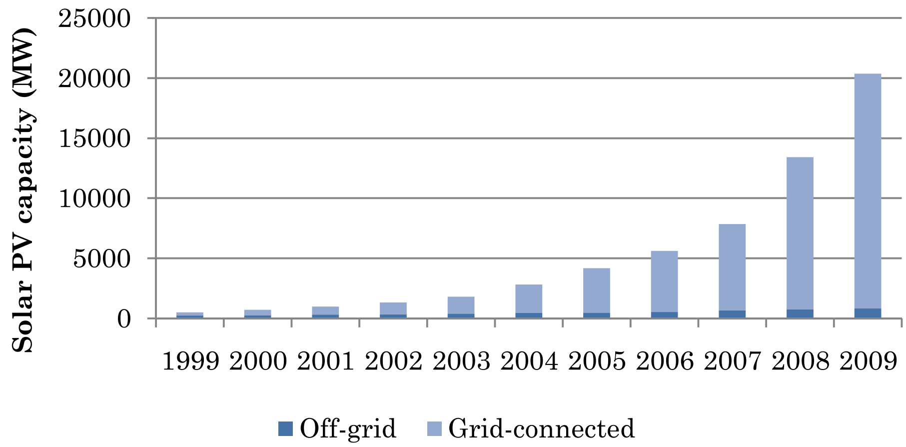

Figure 1-2 Cumulative installed solar PV power capacity as per the IEA-PVPS [1].

In 2009, an estimated 7 GW of solar PV power capacity was installed world-wide (6.2 GW in the countries that report to IEA-PVPS). An impressive addition of 43.6% of new solar PV power capacity in 2009 is observed in Figure 1-2. 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 [4]. The world's largest solar PV power plant with an installed capacity of 80 MW was completed and started commercial operation in Sarnia, Ontario, in October 2010 [5].

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. Hence, an expected global shift toward grid-connected PV power world-wide is observed (Figure 1-3); according to IEA, 99% of the total solar PV capacity added during 2009 was grid-connected. The European PV Technology Platform Group ambitiously forecasts solar PV to reach grid parity in most of Europe by 2019 [6]. At the beginning of 2009, the total large-scale or MW-scale PV system installed capacity reported by the IEA had reached about 3 GW [7]. A report submitted by IEA-PVPS Task 8 (Figure 1-4) participants predicts that during the middle of the 21st century PV systems of even greater installed capacity ranging in GW could be realized [7]. Thus large-scale PV systems are a promising option to meet future global electricity demand.

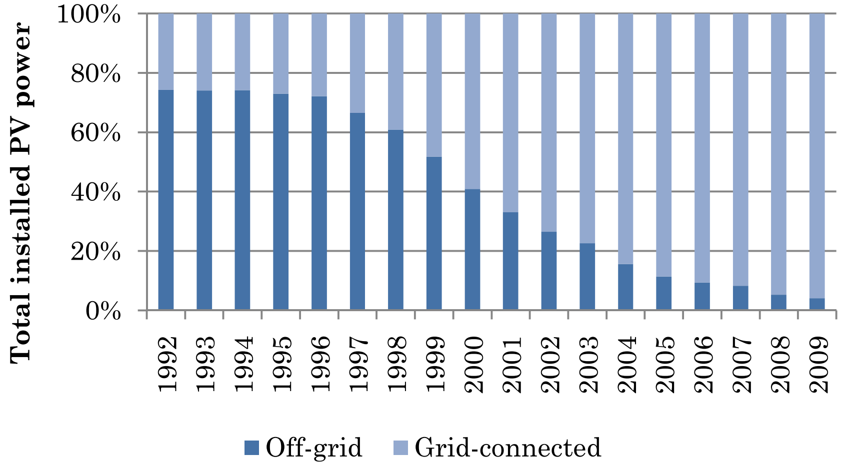

Figure 1-3 Percentages of grid-connected and off-grid PV power capacity as per IEA PVPS [1].

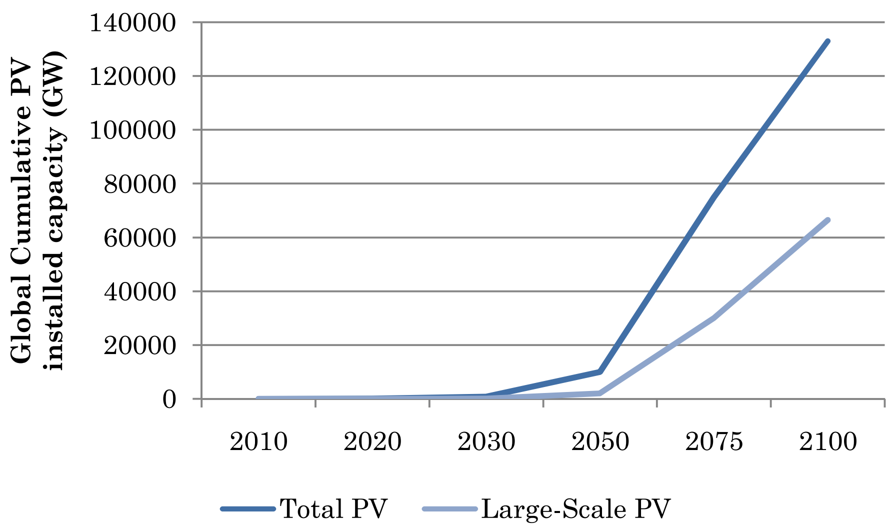

Figure 1-4 Proposed large-scale solar PV roadmap [7].

The rate of deployment of solar PV systems is greatly influenced by the perception of general public and utilities, local, national and international policies, as well as the availability of suitable standards and codes to govern it. Among a variety of support mechanisms put in place in different IEA PVPS participating countries (Table 1-1), it is clearly evident that Feed-in Tariffs (FITs) are the main reason behind the strong growth in PVGCS applications in 2009, particularly in Australia, Austria, Canada and Switzerland [1].

The Government of Ontario, Canada, which has an ambitious target of phasing out coal generation by 2014, passed the Green Energy and Green Economy Act of Ontario in May 2009 [8]. This established North America's first comprehensive guaranteed pricing structure for renewable energy production, referred to as Ontario's FIT. The FIT program replaced the Renewable Energy Standard Offer Program (RESOP) which was in existence since 2007. Ontario Power Authority (OPA) is responsible for the FIT program and offers lucrative prices to investors under long-term contracts for energy generated from biomass, biogas, landfill gas, on-shore & off-shore wind, water power and solar photovoltaic (PV) sources [9]. This program opens up tremendous opportunities for entrepreneurs and investors who are willing to be a part of this green revolution. Such initiatives leads to decentralized operating and planning of the power system, wherein grid-connected solar PV systems are a vital part, reducing the need for transmission and distribution reinforcements and generating power where it is needed. Moreover, with a smooth transition to renewable and clean energy sources, the next generation will inherit a better environment. The FIT contract price schedule for larger projects, revised in August 2010, allows the highest rates to investments in solar PV system up to 10 MW [9]. In order to make the most of this offer, the ground-mounted solar PV system is the only realistic option compared to the roof-top system.

Table 1-1. Solar PV support mechanisms and indicative retail electricity price [1].

	AUS	AUT	CAN	CHE	DNK	DEU	ESP	FRA	ISR	ITA	JPN	KOR	MEX	MYS	NLD	NOR	PRT	SWE	TUR	USA
Enhanced feed-in tariffs	•	•	•	•		•	•	•	•	•	•	•			•		•	•		•
Direct capital subsidies	•	•		•		•		•		•	•	•		•				•		•
Green electricity schemes	•	•	•	•		•	•			•	•									•
PV-specific green electricity schemes	•	•		•																•
Renewable portfolio standards (RPS)	•										•	•						•		•
PV requirement in RPS																				•
Investment funds for PV			•			•	•					•								•
Tax credits			•	•				•			•			•			•			•
Net metering	•	•	•	•	•					•			•	•						•
Net billing			•	•		•					•			•						•
Commercial bank activities	•					•			•		•				•				•	•
Electricity utility activities	•		•	•	•	•	•				•									•
Sustainable building requirements	•		•	•	•	•	•					•					•		•	•

• The support mechanism is applicable in this country.

1.2 Literature Review

The viability of solar PV systems is examined in [10], where a sensitivity analysis is carried out to estimate their comparative viability with conventional diesel-powered units based on region specific parameters. A Life Cycle Cost (LCC) analysis using 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.

In [11], a detailed size and design optimization of solar PV grid-connected systems is carried out using genetic algorithms to determine the optimal number of PV modules, the configuration of the arrays/strings, the PV module tilt angles, number of DC/AC converters, allocation of PV modules among the converters and the dimensions of the actual installation area. The effect of high level of penetration of grid-connected solar PV in the distribution network is analyzed in [12]. This work examines voltage drop, network losses and grid benefits on two different geographic locations with different climates (Lisbon and Helsinki). Three types of network configurations in the two regions are compared on the basis of peak-load shaving, reduction in network loss and voltage profile change occurring from large-scale PV penetration.

A technical and economic assessment of grid-connected solar PV systems for South East Queensland is presented in [13]. Although Australian national guidelines for grid connection are available, every utility imposes its own regulations on the specifications for grid connection along with the metering and tariff structure. The paper deals with the local utility, Energex, which offers three types of tariff for purchase and two for the sale of electricity. Four scenarios are assumed, representing a combination of the tariff structures, metering and PV system configuration (grid-interactive/battery-charging). Simple Pay Back Period (PBP), LCC analysis of Net Present Value (NPV) and sensitivity analysis are carried out, considering the cost parameters, tariff structure and grid interconnection policy of the region. It is concluded that even though small-scale PV is feasible under the prevailing conditions, the electricity tariff for PV needs to be substantially enhanced so that it returns an acceptable PBP to attract private investors. The authors also suggest removing the limit on the energy transfer as well as advocate net metering.

The authors in [14] present easy-to-use charts and tables to enable a PV designer and an investor to assess the profitability of the system. These tools are based on two different economic scenarios corresponding to Japan and Europe/USA, as per discount and inflation rates. The economic incentives offered, by some of the countries in the Organization for Economic Co-operation and Development (OECD), to promote solar PV grid interconnection have also been incorporated. In addition to the two regional scenarios, the analysis is further expanded by considering five and ten year interest-free loan programs. The results are presented in the form of LCC and Present Worth per kW-peak for a 25 year system useful life.

A multi-objective optimization approach is applied in [15] to the optimal allocation and sizing of PV grid-connected systems (PVGCS) in feeders considering both technical and economical aspects. Three different PVGCS candidate locations are studied based on the improvement of voltage profiles, reduction in the power losses and locating PVGCS in each bus of the feeder. Twenty five PV penetration levels in 2 different distribution systems are studied to demonstrate the robustness and applicability of the method. The simulations reveal that PVGCS allocation based on voltage profile improvement yields the best results with least computation burden.

Economic policies such as FITs and Tradable Green Certificates (TGCs) to enhance the solar PV electricity generation in western European countries is analyzed in detail in [16]. A comparative economic analysis based on PBP, NPV and Internal Rate of Return (IRR) indices for a 10 kW-peak building integrated PV residential system considering net metering and other investment subsidies is performed. This study reveals that, in some situations, these support policies can be inconvenient for the owner and, in many cases, the same support policy implementation results in totally different results in different countries. The authors propose that this analysis could help, firstly, the member states to assess the impact of these policies, and secondly, potential PV investors to identify the most profitable scenario.

A framework of a planning model for PV generation integration in China is presented in [17] considering economic feasibility, environmental impact and security. The author proposes various indices to be considered in the planning process, such as, energy location information (ELI), and positional weight information (PWI), and briefly defines the concepts of solar resource unavailability frequency (SRUF) and solar resource average unavailability duration (SRAUD) to present a conceptual framework for a planning model.

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 [18]. It is concluded that government incentives such as FIT are necessary to attract investments in solar PV, and that adding either a carbon tax or cap-and-trade mechanism to the FIT would result in reduction of both emissions and energy cost.

Finally, in [19], a coordination scheme for approval of DG investment proposals is presented. This scheme relies on an iterative process satisfying both the objectives of the LDC, which is to maximize DG participation and penetration, and the SPP, which is to maximize profit based on sizing, siting and production schedule.

1.3 Objectives

The presented literature review shows that the development of decision making tools for an investor in large-scale (≥ 5 MW) solar PV, not concerned with system-wide operation or planning, are not generally available in the current technical literature. It is important to highlight the fact that the primary purpose of this work is to present an investor-oriented solar PV planning model and the results are 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 many power systems with the influx of private investments, driven by various incentives and support policy mechanisms offered by governments. However, the model presented here incorporates transmission constraints, power angle constraints and power flow equations in the planning framework, thus making the results viable from a systems' point of view as well. Thus, this model can be considered as the first stage of a two stage planning framework for a decentralized power system, as discussed in [19].

In order to make an enlightened decision, the investor needs to be aware of several parameters which affect the output of grid-connected solar PV plants. Therefore, the main objectives of this thesis are:

- Develop an optimal planning model to determine long-term investment decisions in large-scale solar PV projects from an investor's perspective.
- Properly incorporate the existent generation and transmission plans, as well as adequately model the grid in the proposed methodology.
- Account in the analysis, the differences in the solar PV potential of each region, along with a detailed study of the solar PV cost components; considering each individual component in each region and projecting future cost trends based on past data.
- Consider in the model the local policy and regulatory framework for PV deployment, such as FIT, TGCs, direct capital subsidies, income tax credits, net metering, etc.
- Perform uncertainty analyses to analyze the effect of variability in the input parameters using a Monte Carlo simulation approach.
- Demonstrate the applicability of the proposed model to study the case of a prospective investor in Ontario's booming solar PV sector.

1.4 Thesis Content

The structure of the thesis is as follows: Chapter 2 provides a brief background of the technical considerations and relevant economic evaluation criteria of solar PV systems, optimal power flow modeling in GAMS, and Monte Carlo simulations. Chapter 3 presents the proposed investor-centric generation planning model to determine the optimal investment decisions in solar PV. Chapter 4 discusses the Ontario case study, which includes development of cost components, the transmission system model, and evaluation of solar PV and conventional generation capacity factors. Chapter 5 presents the analysis of the results obtained from the Ontario case, including a probabilistic study to consider relevant parameter uncertainties. Finally, the main conclusions, and contributions of this thesis and possible future work are highlighted in Chapter 6.

Chapter 2
Background

2.1 Solar Energy Basics

The sun is a non-intermittent and almost inexhaustible source of energy. The total amount of solar energy absorbed by the earth in one hour is comparable to the total global energy consumption in one year [20]. This large amount of solar energy incident on the earth remains unharnessed, mainly because of one major reason: the technology needed to make this energy usable in a more conventional manner is still not economically viable. Solar energy can be harnessed to generate electricity mainly by two different technologies:

- **Photovoltaic (PV) Cell Technology** relies upon the direct conversion of solar radiation into electricity using semiconductors that exhibit a photoelectric effect, such as crystalline silicon or different combinations of thin-film materials [21]. Figure 2-1 shows the world's largest solar PV power plant in commercial operation in Sarnia, Ontario, Canada, with a total installed capacity of 80 MW as of October 2010. It is operated by First Solar on behalf of Enbridge Inc. and occupies 950 acres of land with 1.3 million recyclable thin-film PV modules. This investment, which exceeds $400 million, became economically feasible after signing a 20 year Power Purchase Agreement (PPA) to sell energy to OPA under RESOP [22].

Figure 2-1. The 80 MW, Sarnia Solar PV Project, Ontario, Canada.
(Photo credit: Behnam Tamimi)

- **Concentrated Solar Power (CSP) Technology** relies on concentrating the solar radiation, using lenses and mirrors onto a small area. The concentrated light/heat is then used as a heat source for a conventional power plant; this phenomenon is known as solar thermo-electricity [23]. The four most common forms of this technology are: parabolic trough, dish stirlings, concentrating linear Fresnel reflector, and solar power tower. This classification is based on the different techniques used to track solar radiation and focus it; however, the underlying principle is essentially the same. Ongoing research in this field is enabling these technologies to become cost competitive and commercially viable. Among them, the most notable plants in commercial use are: the PS10 Solar Power Plant (Planta Solar 10) in Spain [24], which is Europe's first commercial CSP tower with an installed capacity of 11 MW and 624 large movable mirrors (heliostats), and Solar Energy Generating System (SEGS) in California-USA, which is the largest solar energy generating facility in the world, consisting of 9 plants across the Mojave Desert with about 1 million parabolic mirrors covering over 1600 acres. Although the SEGS combined installed capacity is 354 MW, the average gross output is just 75 MW indicating a low capacity factor (21%) [25].

Since the focus of this thesis is restricted to electricity generation through PV cells, the following sub-section discusses the elements of a PV system and its various applications throughout the world.

2.1.1 Elements of a Solar PV System

PV cells are the building blocks of a PV system as they utilize the photoelectric effect to convert sunlight into electricity. Although crystalline silicon PV cells are the earliest and most successful PV devices used largely in the world today, they are being gradually replaced by the cheaper thin-films or ribbons, mainly composed of Cadmium Telluride (CdTe), Copper Indium Gallium Selenide (CIGS), amorphous and microcrystalline silicon, etc. Generally, PV cells are a few inches across in size and are connected together to form PV modules which are typically 1 square meter in size. These PV modules may be connected and/or combined to form PV arrays which yield a desired output (Figure 2-2). These PV modules represent the core of any PV system.

However, a PV system cannot be complete without the balance of system components, which include, power conditioning equipment (inverters, maximum power point trackers, etc.); mounting hardware, electrical connections and if required, batteries. Depending on the size of the system, type and positioning of the power conditioning equipment, the need for energy storage, grid-interconnection standards/policies, efficiency and overall system costs, there exists a variety of PV system topologies such as central, string, multi-string and ac-module topology (Figure 2-3) [26].

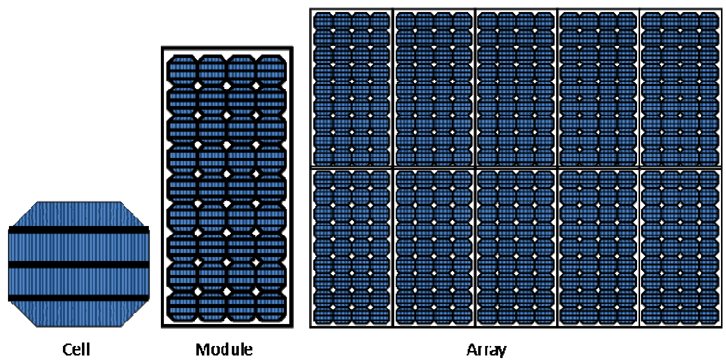

Figure 2-2. Depiction of PV system modularity.

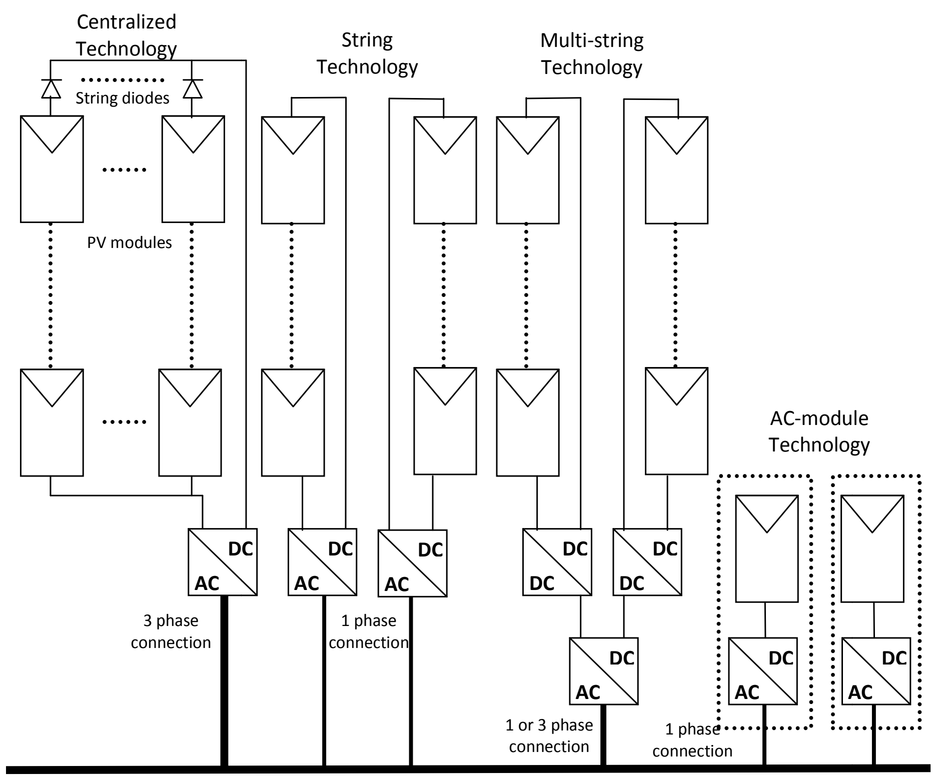

Figure 2-3. Historical overview of the PV system inverter topology [26].

2.1.2 Classification of Solar PV Power Plants

A solar PV power plant can be categorized based on the way it supplies power to the consumer, as shown in Table 2-1 [1].

Table 2-1. Classification of solar PV plants.

Type of system	Application	Features
Off-grid, domestic	To meet the energy demand of remote house-holds and villages, far-off from the grid.	Most appropriate technology utilized globally to provide electricity for off-grid communities.
Off-grid, non-domestic	Provide power for telecommunication, water-pumping, vaccine refrigeration and navigational aids.	The first commercial application of terrestrial PV systems. Instigated competition with small conventional generation technologies.
Grid-connected, distributed	Provide power to a number of grid-connected customers on their premises or directly to the grid.	Can be integrated into the customer's premises to increase reliability and reduce dependency on the grid. Plays a role in the smart-grid.
Grid-connected, centralized	Provide bulk power as a centralized power station.	Oil independence and reduction in green-house-gases with minimum operation and maintenance expenditure.

2.2 Economic Evaluation Criteria of Solar PV Systems

Solar PV systems are generally characterized by high fixed cost and low operation cost, unlike conventional generation sources which have substantially high operational costs that cannot be ignored in investment planning programs [27]. Several economic criteria have been proposed in the literature for the evaluation of solar PV investments [28], as explained next.

2.2.1 Least-cost solar energy

Least-cost energy is a reasonable criterion to choose among various alternatives. The system with the least cost of installation and operation is regarded as the desired plan.

2.2.2 Life cycle cost (LCC)

LCC is the sum of all the costs associated with an energy delivery system over its entire useful life or over a specific period for analysis, taking into account the time value of money. The concept of LCC is to determine how much to be invested, considering the market discount rate, so as to have funds when they are needed in the future. The process works by bringing back the anticipated future cost at the present cost. LCC analysis also considers inflation. This concept is slightly modified to consider the revenues generated by the system as well as the cost, discount rate and inflation, and termed as life cycle savings or Net Present Worth (NPW) or Net Present Value (NPV), discussed below.

2.2.3 Annualized life cycle cost (ALCC)

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. The same idea can be applied to consider annualized life cycle savings.

2.2.4 Payback Period (PBP)

PBP is a non-life cycle criteria and simply calculates the time needed to recover the investment made. PBP is defined in many ways, but in the context of solar PV system cost analysis, PBP can be appropriately defined as the time needed for the cumulative revenue earned to equal the total initial investments, i.e. how long it takes to recover the initial investment made by selling energy. PBP is commonly calculated without discounting the revenue earned, which results in much faster and simpler calculations. It can also be calculated considering the discount rate, to arrive at a more realistic estimate.

2.2.5 Return on Investment (ROI)

ROI is the market discount rate that results in zero NPV or zero life cycle savings. This is illustrated in Figure 2-4.

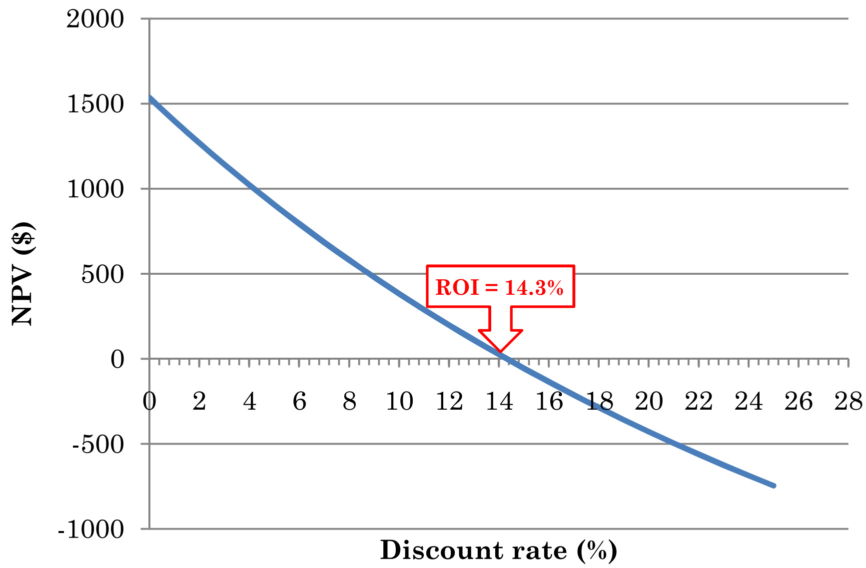

Figure 2-4. An example illustrating NPV as a function of discount rate.

2.2.6 Net Present Value (NPV) or Net Present Worth (NPW)

NPV is the discounted sum of the revenue from selling the generated energy net of all costs associated with the energy delivery system. This criterion takes into account the time value of money and the useful life of the project. All anticipated costs are discounted to the present time, and are termed as the present worth of the cost. The NPV is the sum of all the present-worths, where present worth Ω' of $\$P$ at k years in the future, for a market discount rate a, can be calculated as:

$$\Omega' = \frac{P}{(1+a)^k} \tag{2.1}$$

Apart from the market discount rate, the recurring future cash flows might be assumed to inflate (or deflate) at a fixed percentage g. Hence, the worth of $\$P$ at the end of the k^{th} year would be greater than $\$P$, and equal to $\$P(1+g)^{k-1}$. Furthermore, the present worth Ω'' after considering the inflation rate g of $\$P$ at the end of year k can be given as:

$$\Omega'' = \frac{P(1+g)^{k-1}}{(1+a)^k} \tag{2.2}$$

Consequently, the sum of the present-worths of all the anticipated future savings would yield the NPW or NPV.

From a review of the literature it is observed that the most appropriate economic criteria for solar PV investment analysis is the NPV analysis [10], [11], [13], [18], [19], [28], [29], as it incorporates the entire life-cycle of the projects and hence the time value of money. Conventionally, NPV is calculated for all the proposed projects, and the project with the highest NPV is selected.

2.3 Mathematical Modeling Tools

A discussion is presented next of some of the tools adopted and used for the development of the solar PV planning optimization model as well as its solution and analysis.

2.3.1 DC Power Flow

In addition to provide the system operator with the "state" of the system at an instant, for a specific load demand and power generation, power flow analysis also plays a very useful part in planning studies, allowing to examine the feasibility of new investments in the power system. Particularly, for long-term policy studies or studies involving economic operation, the following DC Power Flow model is extensively used [30]:

$$P_i^{gen} - P_i^{dem} = \sum_j B_{ij}\left(\delta_i - \delta_j\right) \tag{2.3}$$

where P_i^{gen} represents the real power generator output at bus i, P_i^{dem} is the load demand at bus i, B_{ij} is an element of the B-matrix, representing the impedance of the transmission lines between bus i and bus j, and δ_i is the power angle at the bus i. This power flow is usually optimized considering an economic objective function along with constraints on the upper and lower limits of P_i^{gen}, δ_i and the power flowing between the buses.

2.3.2 Mixed Integer Linear Programming

Mixed Integer Linear Programming (MILP) is a useful mathematical framework, in which both discrete and continuous variables can be used to describe a linear optimization problem. Generally, an MILP problem can be defined as [31]:

$$\begin{aligned} &\min \mathbf{c}^{\mathbf{T}}\mathbf{x} \\ &\text{s.t. } \mathbf{Ax} \geq \mathbf{b} \\ &\mathbf{l} \leq \mathbf{x} \leq \mathbf{u} \end{aligned} \tag{2.4}$$

where the matrices $\mathbf{c}(n \times 1)$, $\mathbf{A}(m \times n)$, $\mathbf{b}(m \times 1)$, $\mathbf{l}(n \times 1)$, and $\mathbf{u}(n \times 1)$ are input parameters, and $\mathbf{x}$ is an n-vector of decision variables with g integer elements $(1 \leq g \leq n)$. Incorporating discrete variables in an optimization problem allows its applicability to realistic problems. The size of the new solar PV capacity addition in this work is thus considered a discrete variable.

The branch-and-bound algorithm is commonly used to solve MILP problems [32]; however, branch-and-price and branch-and-cut algorithms are also known to be efficient. The CPLEX solver [33], which is used in this work, utilizes a branch-and-cut algorithm for solving MILP problems. CPLEX allows the user to set an optimality tolerance using the parameter `optcr` to set a relative termination tolerance, which means that the solver will stop and report on the first solution found, when the objective value is within `100*optcr` of the best possible solution. In the present work, `optcr` was set to 0.001, resulting in a 0.1% tolerance.

2.3.3 Monte Carlo Simulations

Results of the optimization problem are directly dependent on the accuracy of the input parameters. Generally, these input parameters are evaluated from measurements, estimations, assumptions and historical data, and are prone to errors which cannot be accounted for with certainty. In order to account for the uncertainty in the input data, sensitivity analysis and stochastic programming techniques are generally used.

The typical deterministic model depicted in Figure 2-5, usually has a certain number of definite input parameters that yield a definite set of outputs, irrespective of how many times the output is evaluated. On the other hand, in a probabilistic or stochastic model even if the input parameters are known, there may be many possibilities of the outcome. Some outcomes can be more probable than others, described by probability distributions.

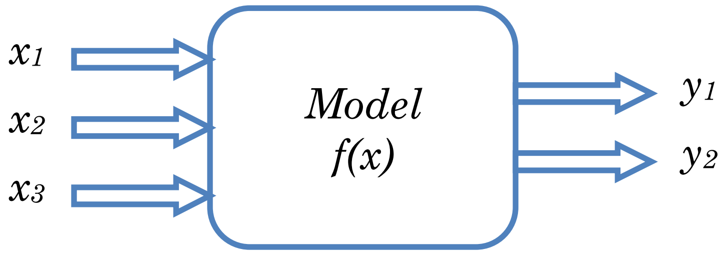

Figure 2-5. A typical deterministic model.

The Monte Carlo simulation method is a computational algorithm that relies on the analysis of repeated simulations of a sample set in order to consider uncertainty in the most critical input parameters of a deterministic model. The input parameters are assigned suitable probability distributions around their nominal or expected value or best estimate. Random values of the uncertain input parameters are generated from the probability distributions, which serve as the input to the deterministic model to yield a set of outputs; this comprises one iteration. The outputs are then recorded and this process is continued for a large number of iterations, until a convergence of the expected value of the output variable is observed. Typically, Monte Carlo simulations require iterations in the range of thousands for convergence to a solution. The recorded outputs are then analyzed and their frequency distributions are plotted, which reveal the probability distribution of the output variable, thus allowing a greater understanding of the model behavior, such as the likelihood of an output variable to have a certain desired value. This method is illustrated in Figure 2-6.

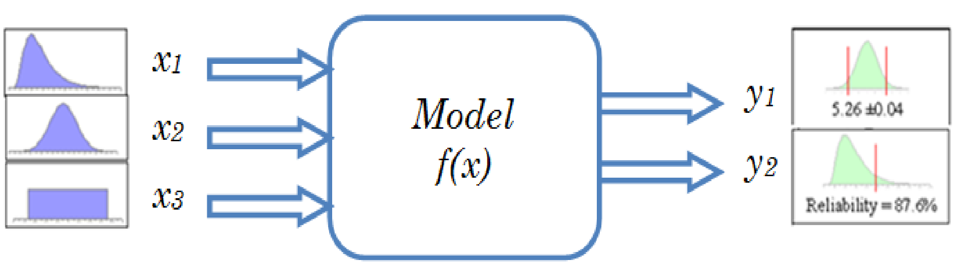

Figure 2-6. Monte Carlo simulation method representation.

2.4 Summary

The major technologies utilized in harnessing solar energy were discussed in this chapter. The current trend of solar PV systems, the basic components, configurations and their classification was presented. Of the various economic criteria used to evaluate the economic feasibility of solar PV systems, it was determined that the most appropriate criteria is the NPV analysis. A brief background of power system planning and mathematical modeling techniques was also presented in this chapter, focusing on the dc power flow model and MILP, which are the most suitable mathematical models for the current work. Finally, uncertainty analysis through a Monte Carlo simulation approach was also discussed.

Chapter 3
An Investor-oriented Large-Scale Solar PV Planning Model

3.1 Introduction

This chapter presents the optimal investment planning model for large-scale solar PV generation in an existing power grid. The model incorporates dc power flow models to maintain a nodal supply-demand balance over the plan period, while considering some grid security aspects. The present and future generation and demand information, transmission system parameters, solar PV and conventional generation capacity factors are considered with adequate accuracy for a planning problem of this nature. The entire model is designed from the perspective of a prospective investor. Thus, the objective of the model is to arrive at decisions that yield the most profitable investment while satisfying relevant technical and financial constraints.

3.2 Optimization Model Development

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 the Nomenclature section. 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 can be solved, for example, in GAMS using the CPLEX solver [33], as in the case of this thesis.

3.2.1 Objective Function

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

$$Maximize\ \Omega = \sum_{k} \frac{\sum_{i}\left(Revenue_{k,i} - Cost_{k,i}\right)}{(1+a)^{k}} \tag{3.1}$$

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:

$$Cost_{k,i} = \left(EC_{k,i} + TC_{k,i} + LC_{k,i} + LbC_{k,i}\right)NC_{k,i}^{PV} + OM_{k,i}E_{k,i}^{PV} \tag{3.2}$$

In (3.1), 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 contact price ρ:

$$Revenue_{k,i} = \rho\, E_{k,i}^{PV} \tag{3.3}$$

The aforementioned cost components and revenue stream are annualized considering the total plant life L. Also, note that the variable $NC_{k,i}^{PV}$ is discrete in 5 MW capacity investment blocks. The negotiated contract price is assumed to remain constant over the total plant life; however, the period of contract may not always be equal to the plant life.

3.2.2 Constraints

3.2.2.1 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 dc power flow model.

$$P_{k,i}^{conv} + P_{k,i}^{PV} - PD_{k,i}^{eff} + \sum_{j} P_{k,ij} = 0 \tag{3.4}$$

3.2.2.2 Line Flow Limits

The power transferred between the zones depends on the impedance of the transmission lines. The power transfers must not exceed the maximum transfer limits of each of the transmission lines. Thus:

$$P_{k,ij} = -B_{k,ij}\left(\delta_{k,i} - \delta_{k,j}\right) \tag{3.5}$$

$$P_{k,ij} \leq P_{k,ij}^{MAX} \tag{3.6}$$

3.2.2.3 Power Angle Limits

The power angles are constrained to be within a range to ensure system stability. Hence:

$$\delta_{min} \leq \delta_{k,i} \leq \delta_{max} \tag{3.7}$$

3.2.2.4 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:

$$E_{k,i}^{conv} \leq 8760\ Cap_{k,i}^{conv} CF_i^{conv} \tag{3.8}$$

$$E_{k,i}^{conv} = 8760\ P_{k,i}^{conv} \tag{3.9}$$

3.2.2.5 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 Section 4.4 for the Ontario case. Based on these capacity factors the annual energy available from the solar PV generation sources $E_{k,i}^{PV}$ is constrained as follows:

$$E_{k,i}^{PV} \leq 8760\ Cap_{k,i}^{PV} CF_i^{PV} \tag{3.10}$$

$$E_{k,i}^{PV} = 8760\ P_{k,i}^{PV} \tag{3.11}$$

3.2.2.6 Dynamic Constraint on Solar PV Capacity Addition

This constraint ensures that the solar PV capacity for the next year is the sum of the new capacity installed in a year and the cumulative capacity of previous years. This cumulative sum is considered only for the investment period as follows:

$$Cap_{k+1,i}^{PV} = Cap_{k,i}^{PV} + NC_{k,i}^{PV} \qquad \forall\ k = 1, 2, \ldots, (N-1) \tag{3.12}$$

3.2.2.7 Constraint on Initial Year Investment

This constraint ensures that there are no investments made during the first few years to account for budgeting delays, policy changes and other transitory effects. Thus:

$$Cap_{k,i}^{PV} = 0 \qquad \forall\ k = 1, 2, \dots, DB \tag{3.13}$$

3.2.2.8 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:

$$Cap_{k+1,i}^{PV} \leq\ Cap_{k,i}^{PV} \qquad \forall\ k = N \tag{3.14}$$

3.2.2.9 Decommissioning of Solar PV Units

After a useful life of L years, each solar PV investment is considered to be phased out of operation. Hence:

$$Cap_{k+L+1,i}^{PV} =\ Cap_{k+L,i}^{PV} - NC_{k,i}^{PV} \qquad \forall\ k = 1, 2, \dots, (N-1) \tag{3.15}$$

3.2.2.10 Annual Budget Limit

This constraint ensures that the annual cost of new solar PV installations is constrained by an annual budget limit. Thus:

$$\sum_{i} CC_{k,i}^{PV} NC_{k,i}^{PV} \leq ABud_k \tag{3.16}$$

3.2.2.11 Total Budget Limit

This constraint ensures that the total investment cost of new solar PV installations over the entire plan period is constrained by a budget limit. Hence:

$$\sum_{k}\sum_{i}\left(CC_{k,i}^{PV} NC_{k,i}^{PV} +\ OM_{k,i} E_{k,i}^{PV}\right) \leq TBud \tag{3.17}$$

3.3 Solar PV Power Generation and Capacity Factor Model

Zonal solar PV capacity factors can be evaluated based on zonal solar radiation and ambient temperature data, as demonstrated later in Section 4.4 for the Ontario case and depicted conceptually in Figure 3-1. These parameters, along with the number of daylight hours available at a certain location and the rated power of the module, determine the capacity factors, as discussed next.

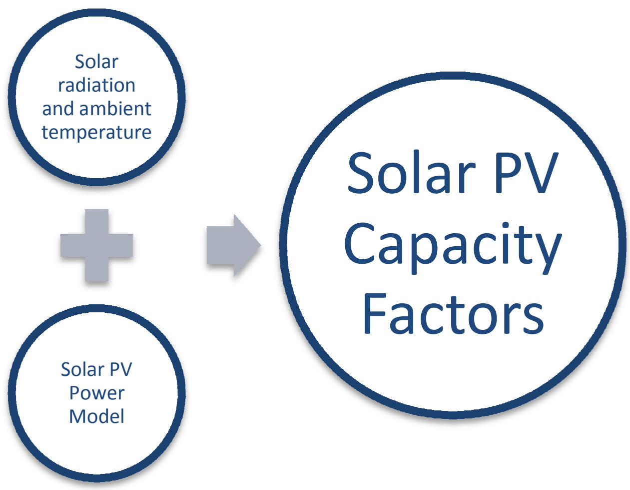

Figure 3-1. Conceptual depiction of solar capacity factor evaluation.

The monthly solar radiation I_i and ambient temperature T_i data are commonly available in meteorological or solar energy data sets. These parameters can be used to find the solar PV system conversion efficiency η_i as given by (3.18), for a solar PV module efficiency η_o and dc to ac conversion efficiency η_{inv} [12], as follows:

$$\eta_i = \left[1 - 0.0042\left(\frac{I_i}{18} + T_i - 20\right)\right]\eta_o\eta_{inv} \tag{3.18}$$

Consequently, the solar PV power output $Po_{i,m}^{PV}$ with the total module area A is given by:

$$Po_{i,m}^{PV} = AI_i\eta_i \tag{3.19}$$

Equations (3.18) and (3.19) can be used to evaluate the energy available per unit area per period (month, quarter, etc.) for a particular type of solar module [28]. The energy produced is determined based on the number of daylight hours $n_{d,m}$ available [34]. Therefore, the capacity factors are evaluated using the rating of the solar PV module P_r^{PV} as follows:

$$CF_i^{PV} = \frac{\sum_m \left(Po_{i,m}^{PV} n_{d,m} \right)}{P_r^{PV} \sum_m n_m} \tag{3.20}$$

3.4 Summary

This chapter presented a generalized modeling framework to determine the optimal investment decisions in solar PV capacity addition from the perspective of an investor. Unlike the traditional and centralized planning models where minimization of total cost is considered as an objective, the present model seeks to maximize the net present value of the investor's profit. This chapter also discussed the development of the solar PV power generation and capacity factor model used in the planning framework. The input parameters for this model, for the case of Ontario, are discussed in the next chapter.

Chapter 4

Ontario's Electricity System Model and Input Parameters

4.1 Generation Plan and Forecast Estimates

The solar PV investment planning model presented in chapter 3 requires zonal generation capacity growth estimates for the future. According to the Integrated Power System Plan (IPSP) of Ontario [35], and information provided by the OPA and IESO, a generation forecast estimate for each zone is determined for the period from 2008-2025 and is shown in Figure 4-1. The generation capacity forecast presented in Figure 4-1 is obtained by combining the information presented in [35] and [37] to arrive at the generation capability contributing to the peak load, rather than just the base load. Due to lack of sufficient data from 2025 onwards, the approximate zonal generation capacity growth rates shown in Table 4-1, as per historical data, are used to extrapolate the generation capacity until 2038.

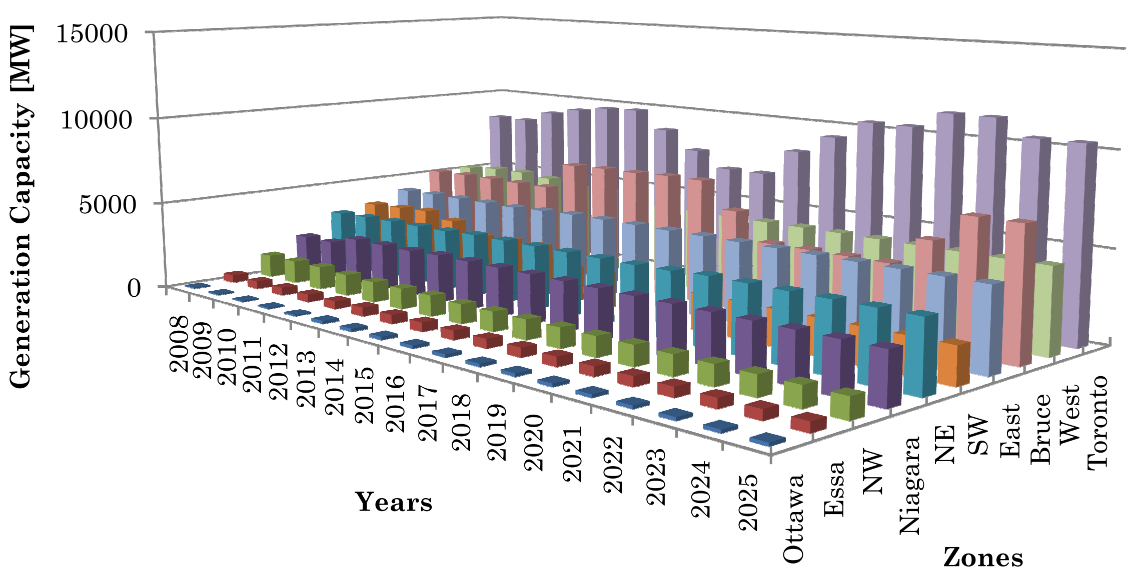

Figure 4-1. Conventional generation capacity plans of Ontario (2008-2025).

Table 4-1. Generation growth rate estimates.

Zone	Bruce	West	SW	Niagara	Toronto	East	Ottawa	Essa	NE	NW
Generation Growth Rates beyond 2025 [%]	3.00	0.00	0.00	2.00	2.00	0.00	0.00	1.00	1.00	0.00

4.1.1 Conventional Generation Capacity Factor Evaluation

Based on a two-month historical data of generation capability and production available from the IESO [38], and attributing each generator to its respective zone according to its location, the conventional generation capacity factors can be evaluated, as represented in Table 4-2.

Table 4-2. Zonal conventional generation capacity factors.

Zone	Bruce	West	SW	Niagara	Toronto	East	Ottawa	Essa	NE	NW
Capacity Factor [%]	91.76	24.28	27.82	73.55	83.46	35.63	15.20	71.24	43.89	52.47

4.2 Demand Forecast Estimates

The model also requires the zonal peak demand forecast. Considering the zonal demand forecast for the period from 2007-2015 provided by the IESO, the zonal demand growth rates are calculated [35], as shown in Table 4-3. However in the present work, the conservation and demand management (CDM) plans presented in Ontario's IPSP, shown in Figure 4-2, have been considered to estimate the effective demand forecast and shown in Figure 4-3.

Table 4-3 Demand growth rates [35].

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	0.1

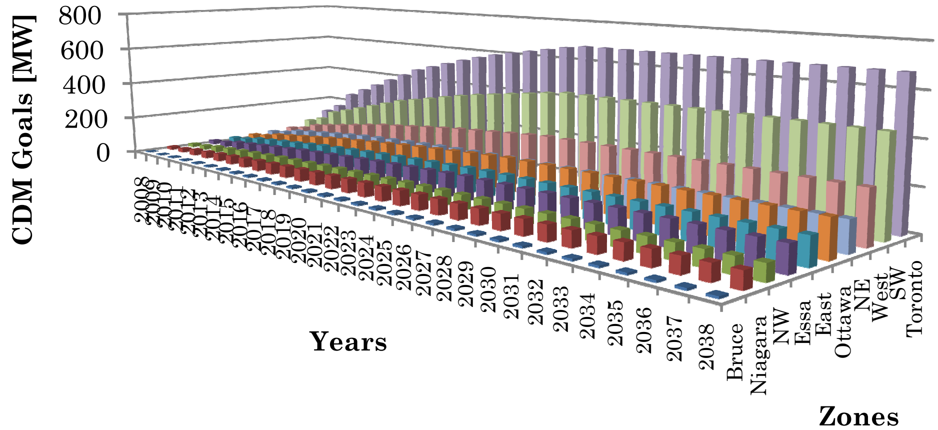

Figure 4-2. CDM plans and estimates for Ontario (2008-2038).

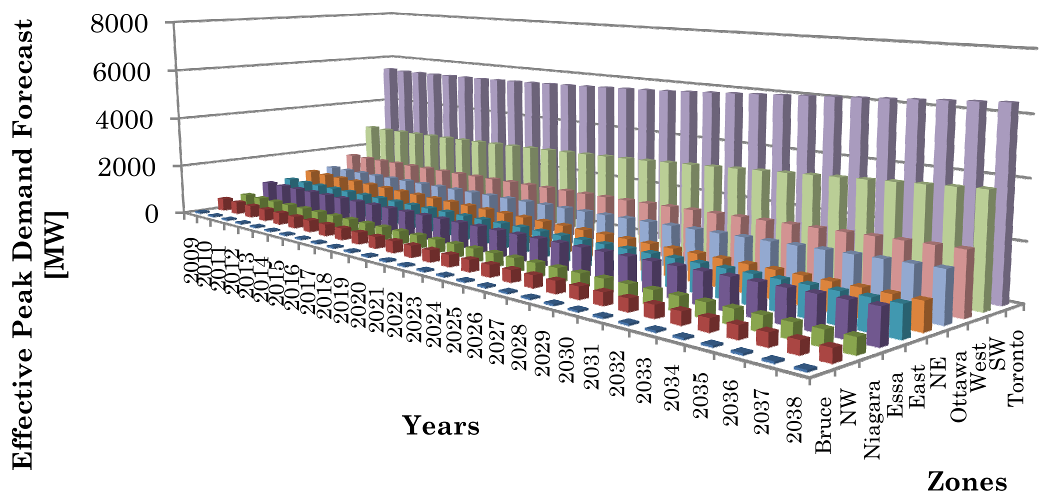

Figure 4-3. Effective peak demand estimates for Ontario (2008-2038).

4.3 Transmission System Model Framework

In this work, a ten-zone transmission system model shown in Figure 4-4 has been developed based on information available from various resources, mainly the OPA, OPG and IESO [35]-[37], [39]. The model so developed represents the system in a detail that it is adequate for the proposed investment planning studies. It should be mentioned that the IESO also considers a similar model to provide forecast and assessments of reliability of existing and committed resources and transmission facilities of the Ontario power system [39].

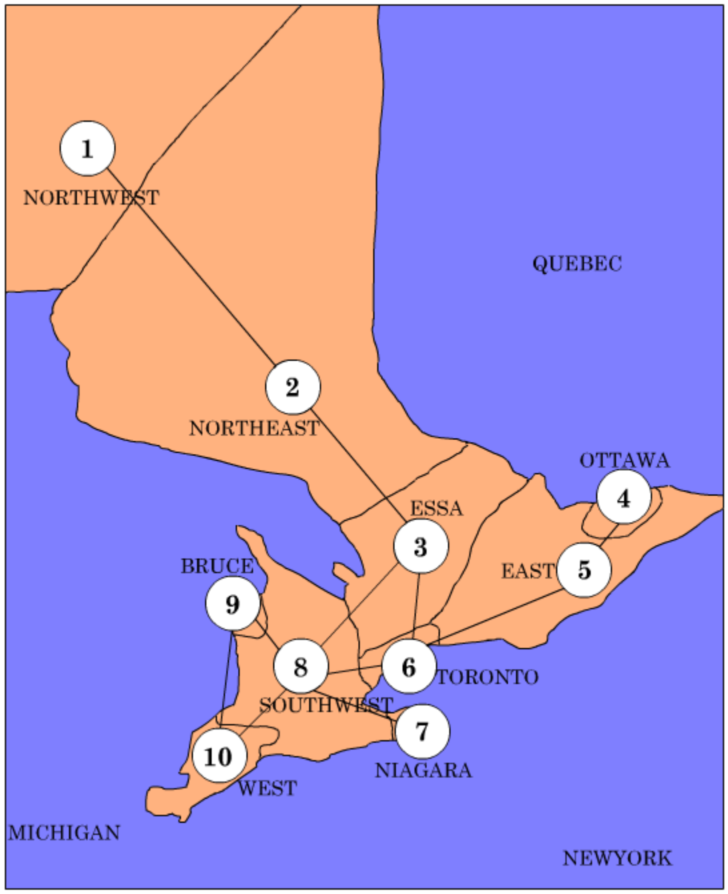

Figure 4-4. Ontario transmission network representation.

The simplified model obtained is shown in Figure 4-5, which depicts Ontario's transmission network, mainly comprising 500 kV and 230 kV lines. The transmission line parameters are evaluated from 2008 to 2038 based on Ontario's transmission expansion plans (Table 4-4), using typical values of transmission line parameters at these voltage levels [40]. The 115 kV and lower voltage level networks are neglected for the sake of simplicity. The approximate distances between zones, transmission line capacities and the line loading limits are also considered [35]. The transmission line capacities so evaluated serve as the upper limit for the line flows in (3.6).

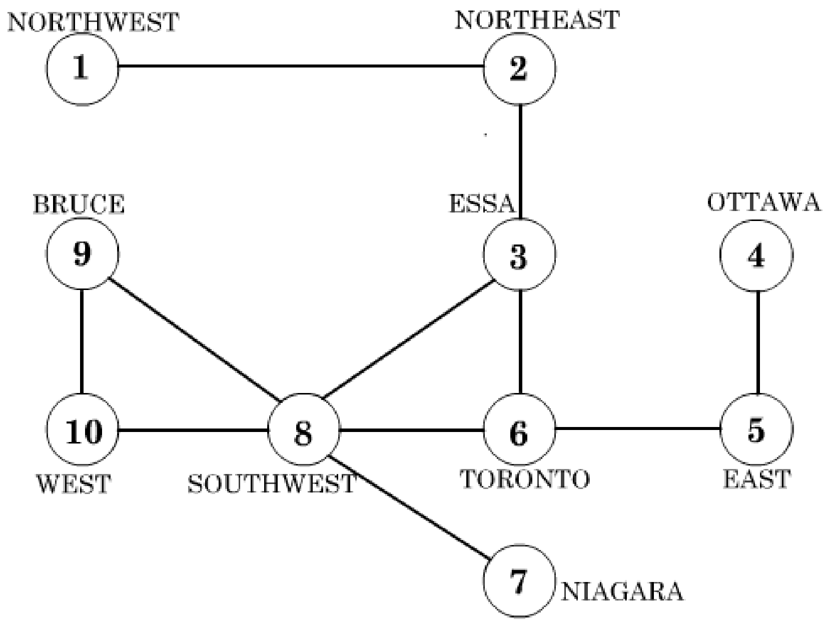

Figure 4-5: Simplified transmission network model.

Table 4-4. Planned transmission expansions in Ontario (2012-2017) [35].

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

4.4 Solar PV Capacity Factors Evaluation

In this work, zonal solar PV capacity factors are evaluated based on the zonal solar radiation and zonal ambient temperature data provided in NASA's Surface Meteorology and Solar Energy (SSE) data base [41].

4.4.1 NASA SSE Dataset

To promote the use of global solar and meteorological data, NASA supports the development of a comprehensive SSE dataset that is formulated specifically for solar PV and renewable energy system design needs. These datasets contain over 200 satellite-derived meteorology and solar energy parameters averaged monthly from 22 years of data. The data tables are available for a specific location on the globe for 1195 ground sites [41]. To use the data available in the SSE dataset, the geographical location of each zone in the model under consideration is approximately determined and respective data tables are retrieved from the database. From these data tables, the monthly solar radiation I_i and ambient temperature T_i are extracted for this work.

4.4.2 Zonal Solar PV Monthly Energy Yield and Capacity Factors

For a typical solar PV module and dc to ac conversion efficiency, presented in Table 4-5, the energy produced per month, per module, is evaluated using equations (3.18)-(3.20) and shown in Figure 4-6. The energy produced, if the module operated on rated power for the whole month with specified number of daylight hours, helps determine the capacity factors of the solar PV system shown in Figure 4-7.

Table 4-5. Input parameter values for solar PV capacity factors evaluation [12], [42].

Parameter	Value
Rated power of solar PV module, P_r^{PV} [W]	140
Total module area, A [m^2]	1
Module efficiency, η_o [%]	15
DC to AC conversion efficiency, η_{inv} [%]	85

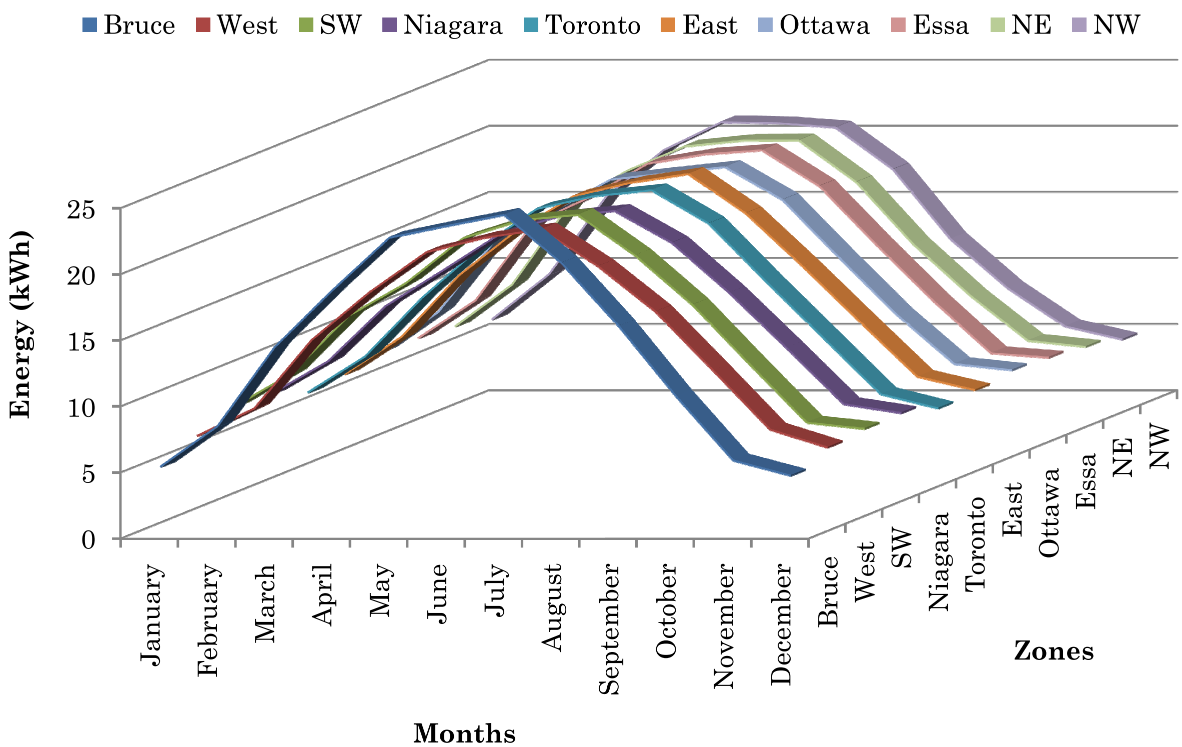

Figure 4-6. Average monthly energy yield from a typical solar PV module.

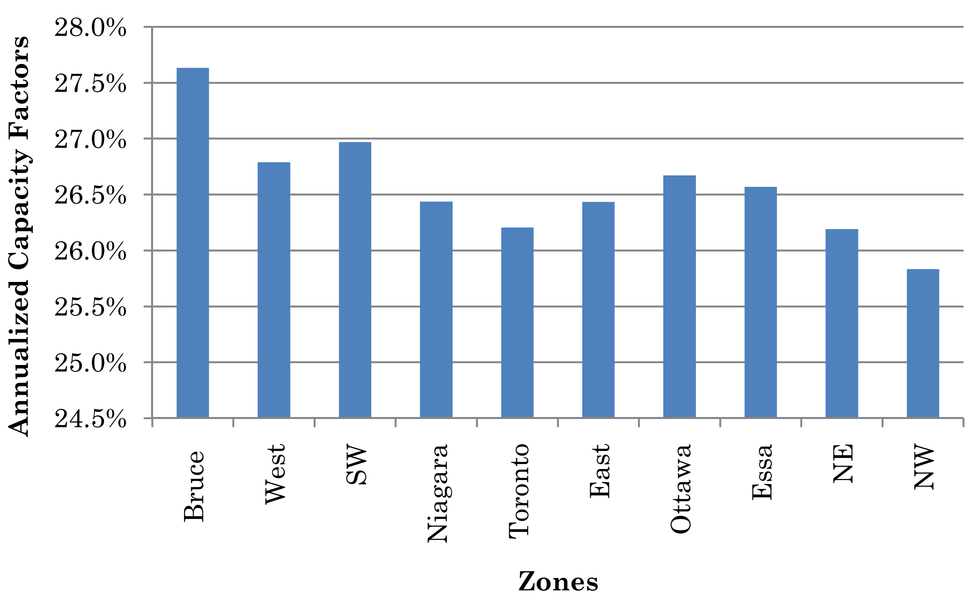

Figure 4-7. Annualized solar PV capacity factors.

4.5 Development of 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 [43]. These costs are dependent on a variety of parameters, as discussed next.

4.5.1 Equipment cost

This cost reflects the cost of modules, inverters and balance of system (BOS). 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, as follows:

$$\begin{pmatrix} Equipment\ Cost \\ \$/kW \end{pmatrix} = \begin{pmatrix} PV\ module\ cost \\ \$/kW \end{pmatrix} + \begin{pmatrix} Inverter\ cost \\ \$/kW \end{pmatrix} + \begin{pmatrix} BOS\ cost \\ \$/kW \end{pmatrix} \tag{4.1}$$

The effect of technology change and the consequent expected reduction in module and inverter costs over the next 30 years, based on the trend over the last 10 years, is also taken into consideration, as shown in Figure 4-8 [44]. Note that BOS Cost is 20% of the module and inverter costs.

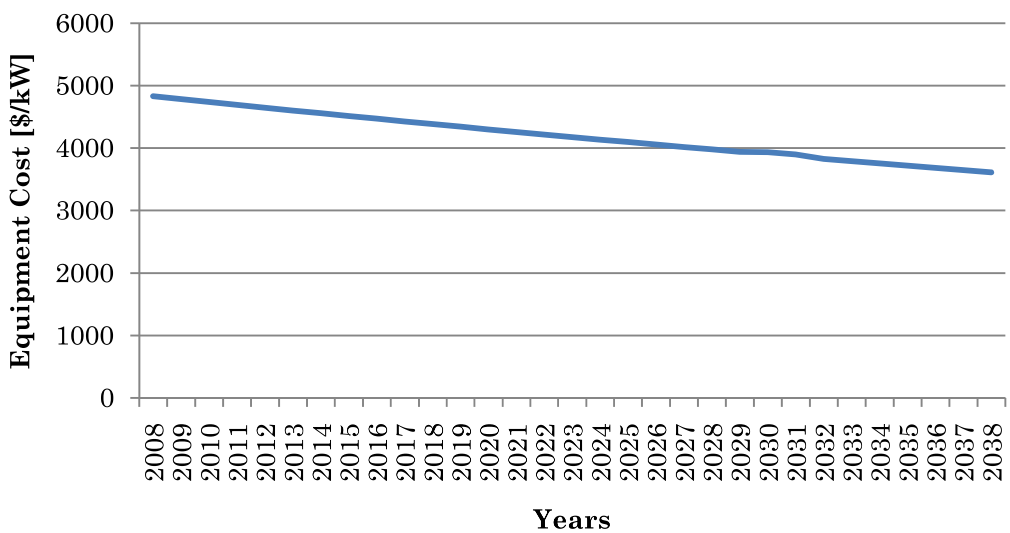

Figure 4-8. Solar PV equipment cost long-term projection.

4.5.2 Land cost

The land cost reflects the cost of land required for the installation of the solar PV system. The per unit land cost $LC_{k,i}$ is determined based on the proportional land market values (LMV) associated with the type of land available in abundance in each zone [45], as follows:

$$\binom{Land\ Cost}{\$/kW} = \binom{Land\ required\ per\ kW}{acre/kW} \times \binom{Unit\ cost\ of\ land}{\$/acre} \times (LMV\ Factor) \qquad (4.2)$$

The increase in the land costs observed from 2005-2009 is extrapolated to obtain the land cost trends in the future [46], shown in Figure 4-9. Note that land required per kW is determined based on the past solar PV projects, and the unit cost of land is based on information provided by industrial experts in Ontario.

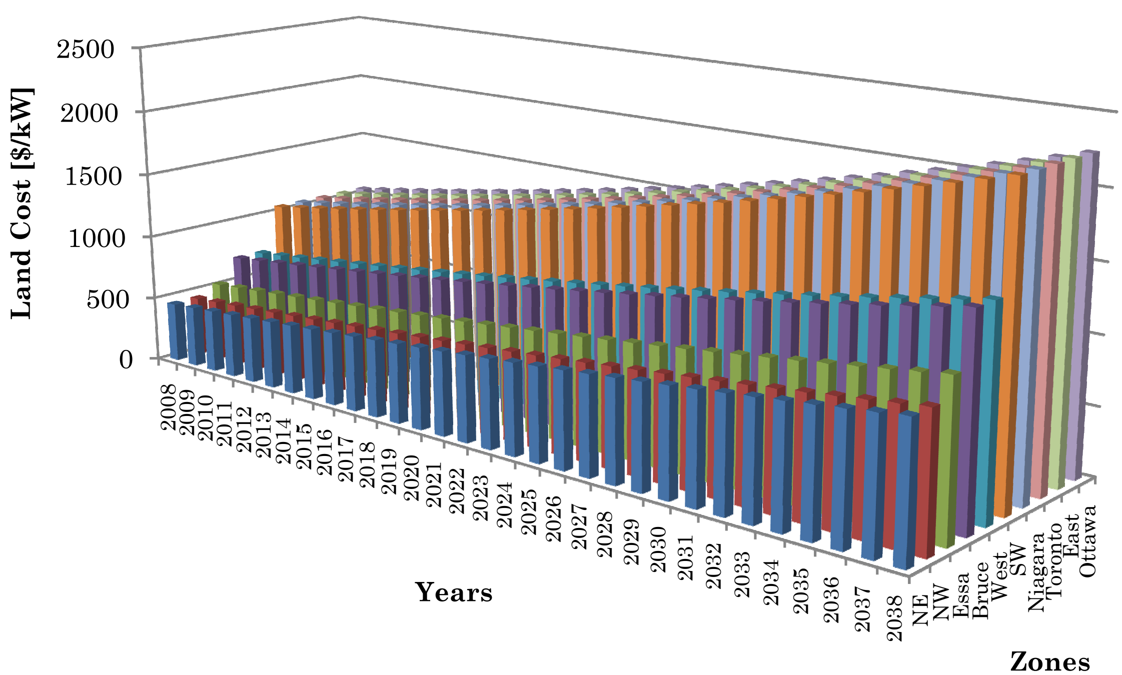

Figure 4-9. Ontario's zonal land cost projection for 2008-2038.

4.5.3 Transportation cost

The transportation cost $TC_{k,i}$ reflects the cost of 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 [47], and the weight of the equipment [42], [48], as follows:

$$\binom{Transportation\ Cost}{\$/kW} = \binom{Freight\ cost}{\$/kg \cdot km} \times \binom{Equipment\ Weight}{kg/kW} \times \binom{Distance}{km} \quad (4.3)$$

The increase in the trucking costs since 2003, as per [49], are considered and used to determine future trucking costs, as shown in Figure 4-10.

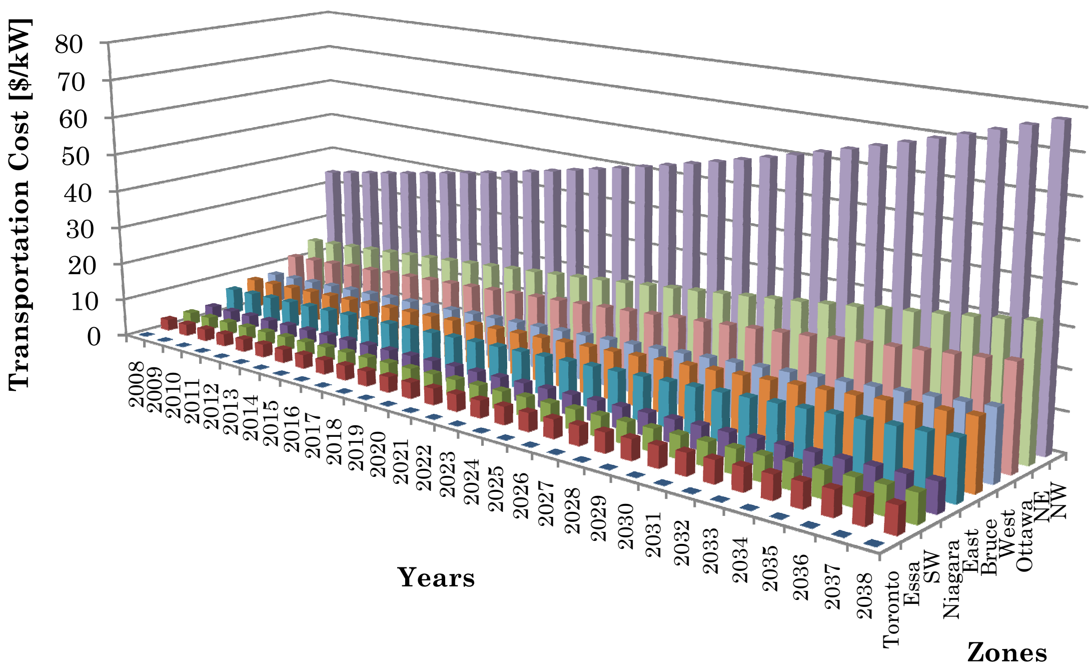

Figure 4-10. Ontario's zonal transportation cost projection for 2008-2038.

4.5.4 Labor cost

This cost reflects the cost of labor in each zone and is determined using the median income in the zone [50], after calculating the number of labor required for the construction of unit capacity solar PV power plant [2], as follows:

$$\begin{pmatrix} Labor\ Cost \\ \$/kW \end{pmatrix} = \begin{pmatrix} Median\ income \\ \$/man \end{pmatrix} \times \begin{pmatrix} Labor\ requied \\ man/kW \end{pmatrix} \tag{4.4}$$

The increase in the median income is forecasted based on the census data of Ontario for the period from 2000 to 2005 [50], and is shown in Table 4-6. Note that the labor required is determined based on past solar PV projects.

Table 4-6. Annual growth rates for median income in Ontario beyond 2010.

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

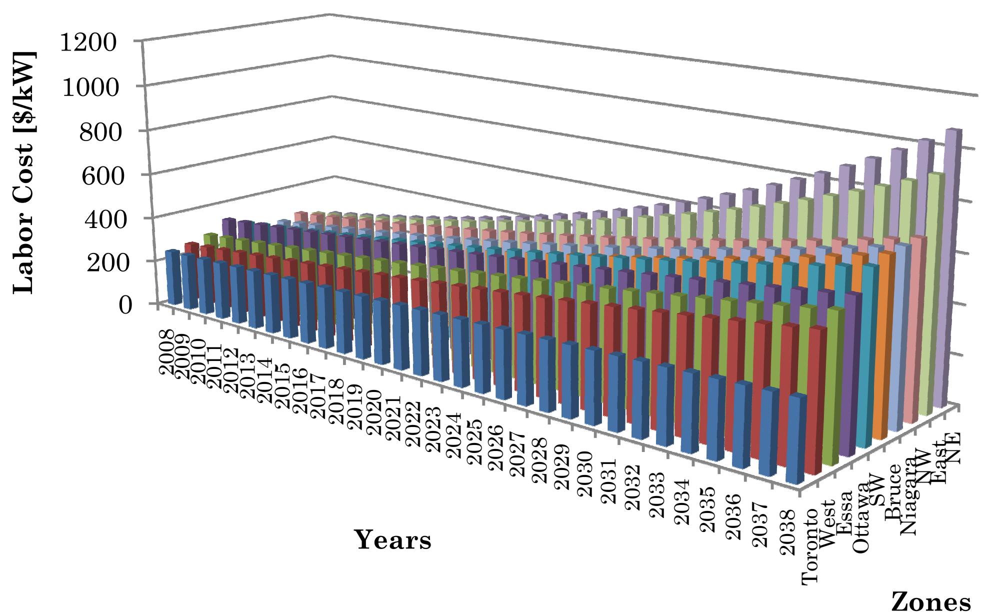

Figure 4-11. Ontario's zonal labor cost projection for 2008-2038.

4.5.5 Total Capital Cost

The solar PV cost model thus developed, realistically reflects the trends in these components in different zones in Ontario. The long-term capital cost projections, excluding the equipment cost component, are presented in Figure 4-12. The actual cost components obtained for 2010 are shown in Figure 4-13. The cost models realistically reflect the fine trends in the various components in different zones in Ontario. Even though the equipment cost component is the largest, it would not affect the spatial aspects of investment decisions because the equipment would cost the same wherever it may be installed. Figure 4-13 shows a break-up of the three components of capital cost, except the equipment cost, for each zone in Ontario for 2010. The long-term cost components are also forecasted based on a variety of reliable resources [2], [44]-[50], and are presented in Table 4-7.

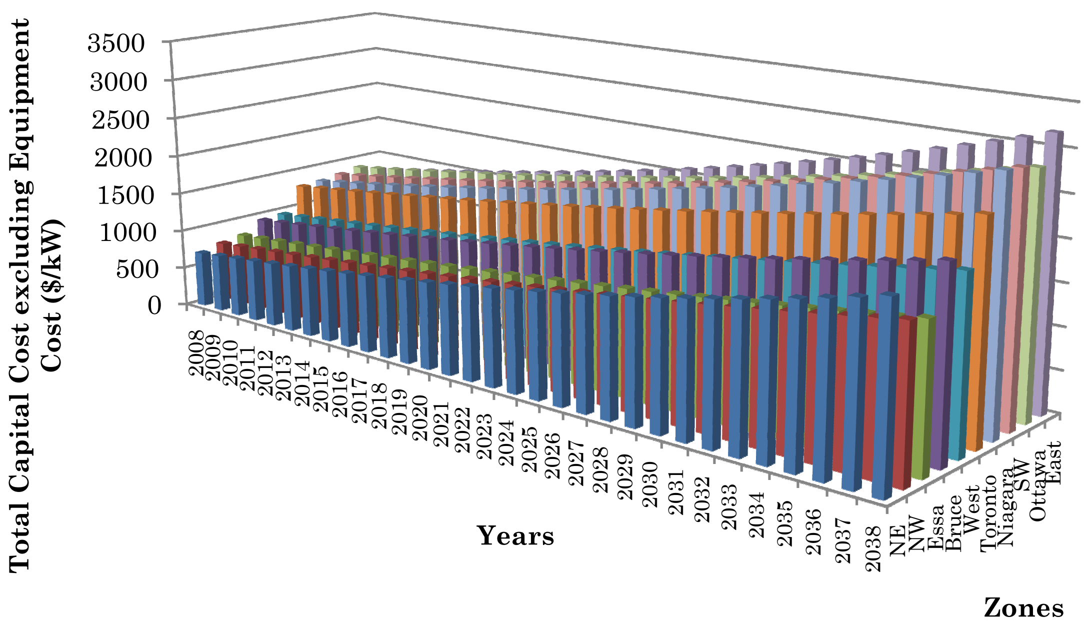

Figure 4-12. Ontario's zonal capital cost projection for 2008-2038.

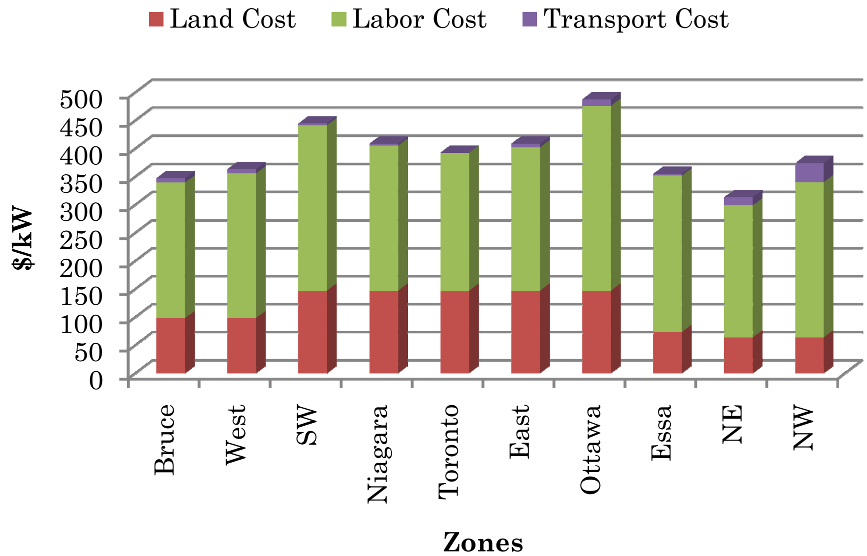

Figure 4-13. Capital cost components (excluding equipment cost) of a solar PV system in 2010.

Table 4-7. Annual growth rates for solar PV cost components.

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

Figure 4-14 shows the percentage distribution of solar PV capital cost components for zone 9 (Bruce) for the year 2010. The equipment cost component, which is independent of location, is the most significant followed by the cost of land and labor, while the transportation cost is just a fraction of the total capital cost.

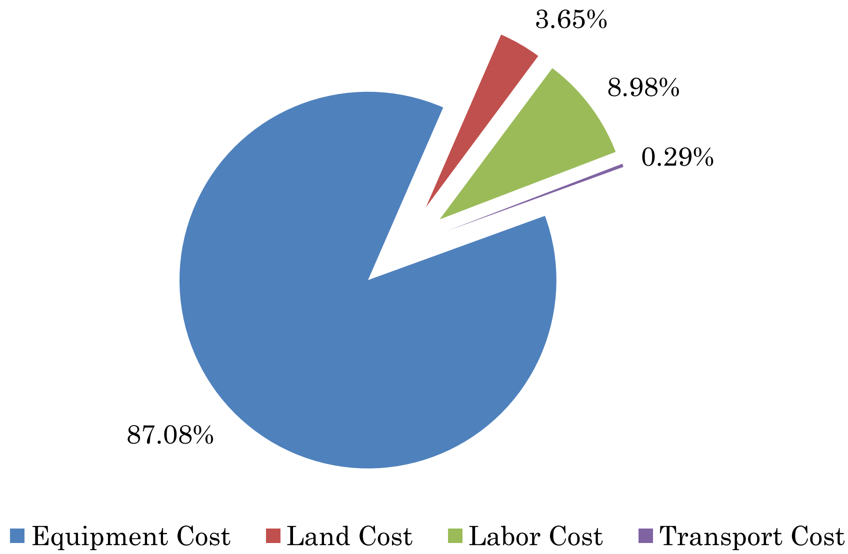

Figure 4-14. Percentage distribution of solar PV capital cost components in Bruce in 2010.

The annual maintenance cost associated with the periodic check-ups and repairs of the modules and inverter replacements, as per [51], is also considered in the model as shown in Table 4-8, along with the remaining parameters considered in this work.

Table 4-8. Other input parameters considered in this work.

Parameter	Value
Annual maintenance cost, $OM_{k,i}$ [$/kWh]	0.01
Power angle, $\delta_{min/max}$ [rad]	±0.523 (±30°)
Investment dead-band, DB [years]	2
Discount rate, a [%]	8
Net inflation rate [%]	4
Useful life, L [years]	25
Energy price, ρ [$/kWh]	0.42
Annual budget, $ABud$ [$/year]	100,000,000
Total budget, $TBud$ [$]	500,000,000
Investment period, N [years]	2010 – 2018

4.6 Summary

This chapter presented the Ontario's electricity system model considered as a ten-zone network, with its generation, demand and transmission capabilities, considering their future expansions. The development of solar PV capacity factors was described and the zonal variation of these factors was illustrated. The various cost components associated with the installation of a solar PV system were discussed, evaluated and long-term trends estimated. Finally, a summary of the remaining input parameters was also provided. This chapter lays the ground-work for the solar PV planning case study for Ontario to be discussed in the next chapter.

Chapter 5
Results and Discussions

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

5.1 Deterministic Case Study

The deterministic optimal investment plan for solar PV projects in Ontario is shown in Figure 5-1 which indicates that Zone 9 (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 9) over the first four years (2010-2013) of the plan period. It is also noted that the planning model does not select any other zone for possible investment in solar PV capacity. This may be attributed to the fact that the proposed planning model is investor oriented and essentially seeks to maximize economic returns. This is in line with the current solar PV investment pattern in Ontario, which is driven by government supported financial incentives and zonal aspects of solar PV potential.

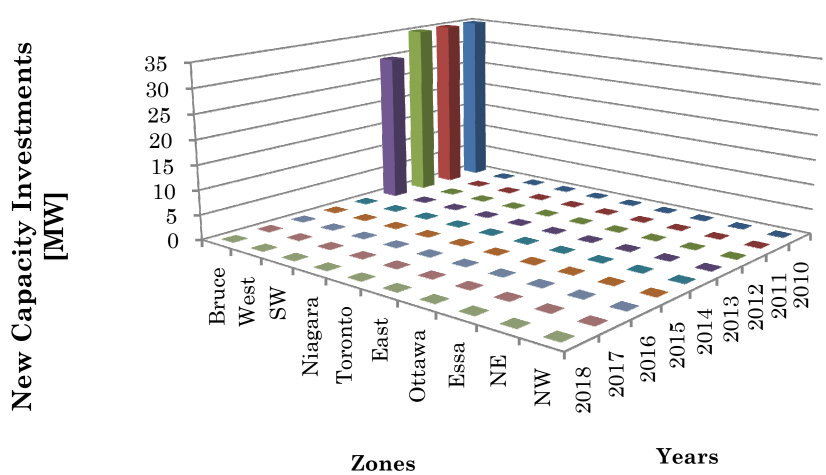

Figure 5-1. New solar PV capacity investments in Ontario.

Figure 5-2 shows the transmission line flow changes in the Ontario system over the investment period (2010-2018) arising from solar PV investments and the ongoing demand increase. Note that the tie-line linking Zone 9 to Zone 8 is the most affected transmission corridor in terms of transmission loading, which can be attributed to the 135 MW new solar PV capacity being commissioned in Zone 9, besides the increase of over 800 MW conventional generation and a slight decrease in the effective demand.

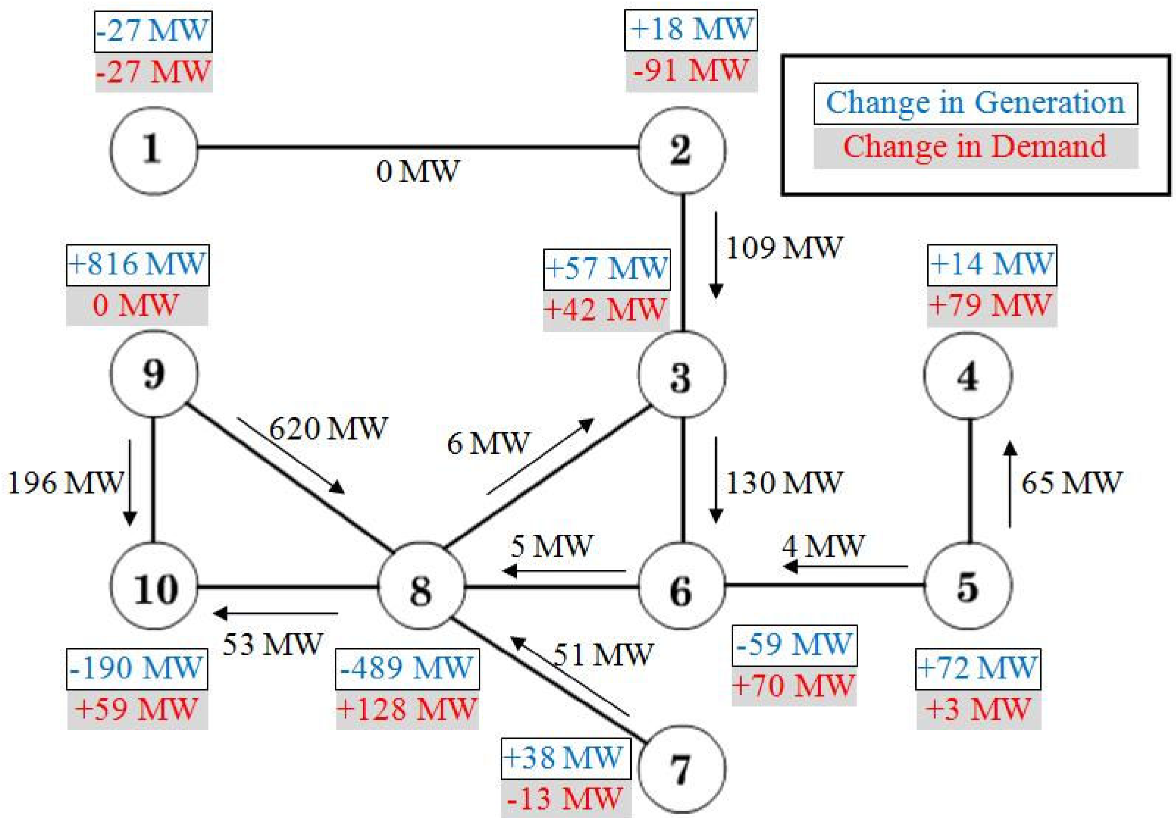

Figure 5-2. Transmission line flows, generation and demand changes 2010-2018.

The energy injected into the system annually over the plan period from new solar PV units is compared with that from conventional generation sources in Figure 5-3. Observe that although the conventional energy sources continue to serve the largest share of the demand, the contribution of solar energy increases over 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 of 37% (Note that the current best average annual rate of return in emerging markets is about 10%).

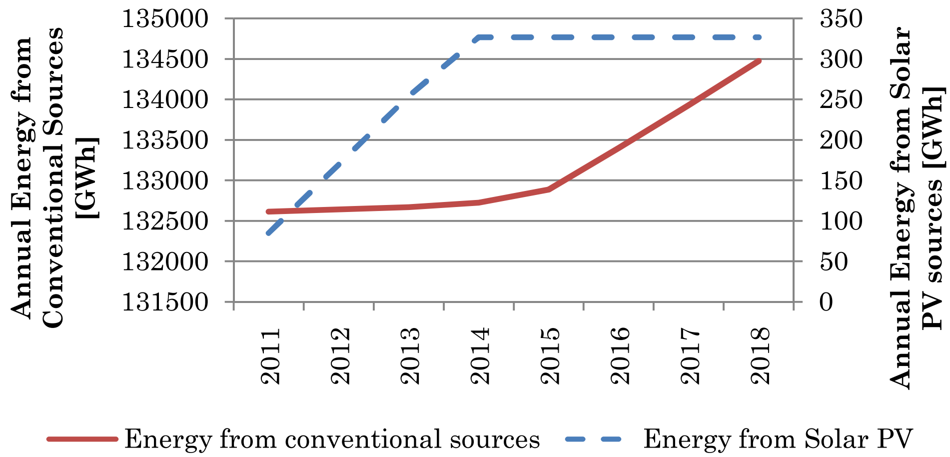

Figure 5-3. Energy from solar PV and conventional generation sources.

5.2 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 Figure 4-7, with a standard deviation of 10% to account for their unpredictability.

5.2.1 Scenario 1: Variation in Discount Rate

The average cumulative NPV of the investment plan is plotted over 2000 iterations of Monte Carlo simulations in Figure 5-4, resulting in an expected NPV of $765 million. It should be highlighted that the expected NPV converges in about 1000 Monte Carlo simulations.

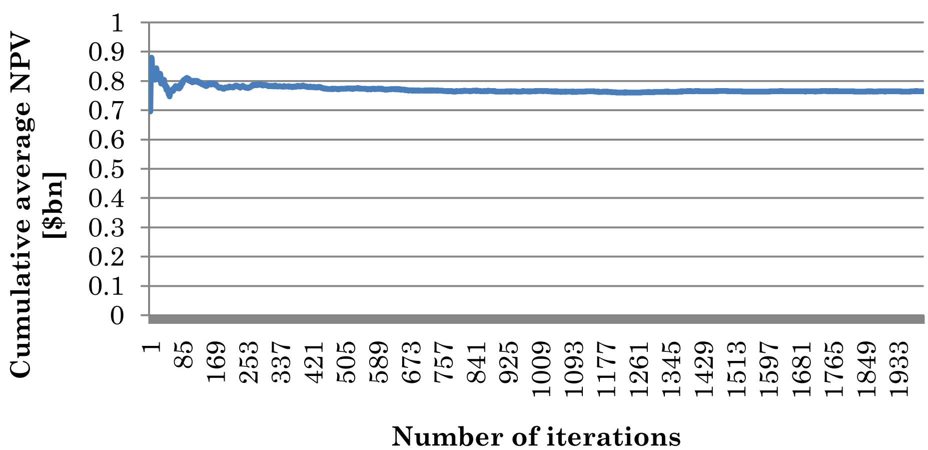

Figure 5-4. Cumulative average of NPV over 2000 iterations.

Figure 5-5 shows the resulting histogram of the NPV of the probabilistic investment plan, resulting in a lognormal distribution with $\mu = 20.409$ p.u. and $\sigma = 0.30071$ p.u. Analysis of the histogram reveals that there are no negative values of NPV, which theoretically represents 100% project profitability even if the discount rate is varied.

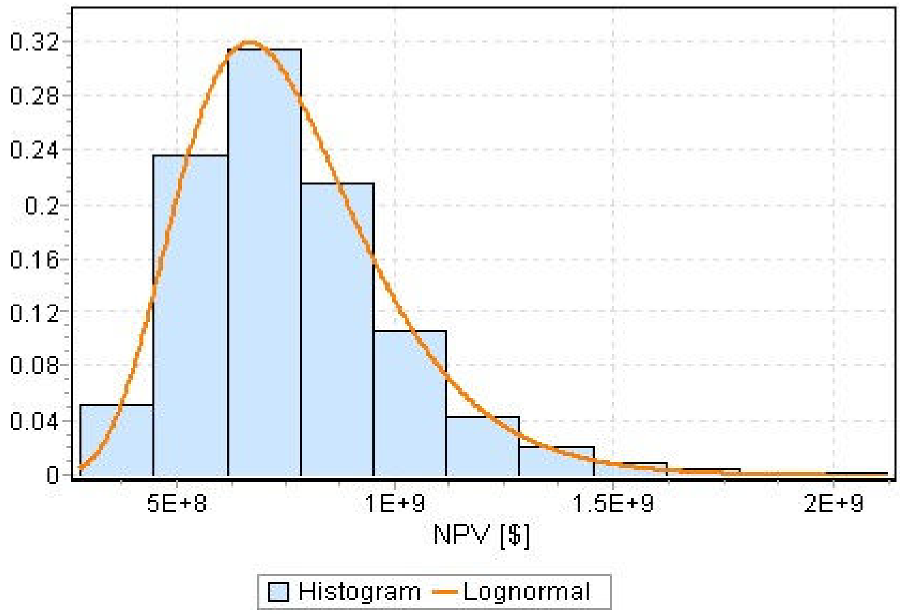

Figure 5-5. Histogram and best-fit probability distribution function of NPV over 2000 iterations.

The expected energy injected from new solar PV capacity addition depicted in Figure 5-6. Similar to the deterministic case, the conventional energy sources continue to serve the largest share of the demand, while the contribution of solar energy increases over the investment period and attains a steady-state share after 2013. Hence, the variation in discount rate does not affect the solar PV investments.

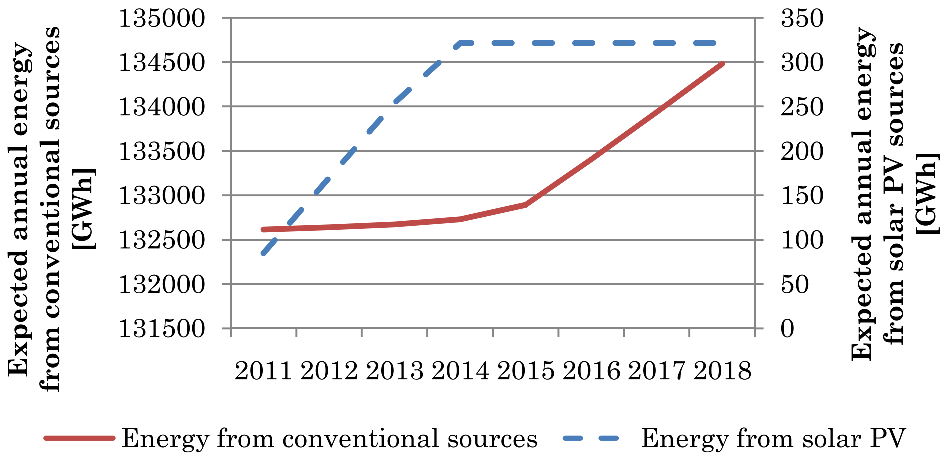

Figure 5-6. Energy from solar PV and conventional sources.

Observe in Figure 5-7 that the new investments are still concentrated in the first four years of the plan period and they are almost certainly to be installed in the Bruce region (Zone 9) mainly because of high solar energy availability in this zone. Thus, it can be concluded that the variation in the discount rate does not affect the investment decisions.

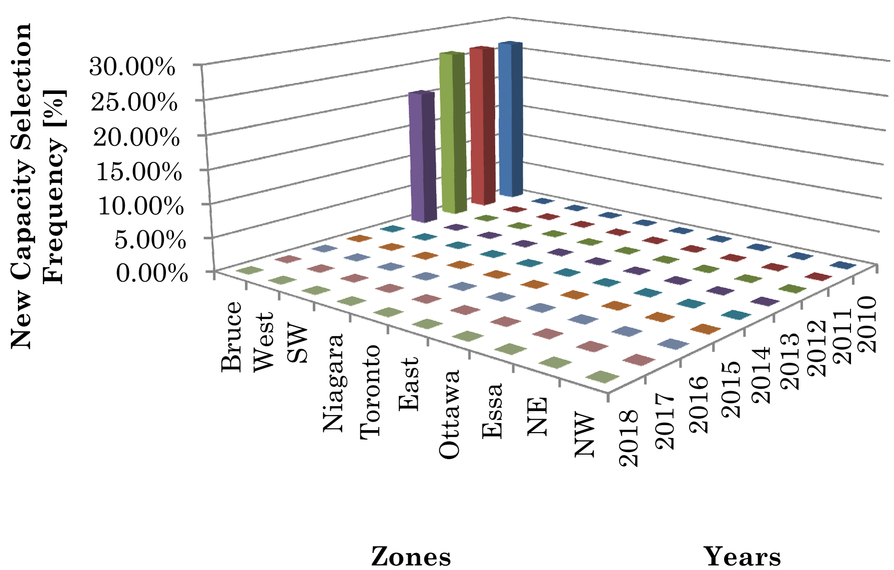

Figure 5-7. New solar PV capacity selection frequency.

5.2.2 Scenario 2: Variation in Solar PV Generation Capacity Factors

The average cumulative NPV of the investment plan is plotted over 2000 iterations of Monte Carlo simulations in Figure 5-8, resulting in an expected NPV of $1,087 million. It should be highlighted that the expected NPV converges in about 300 Monte Carlo simulations. (earlier as compared to the previous scenario).

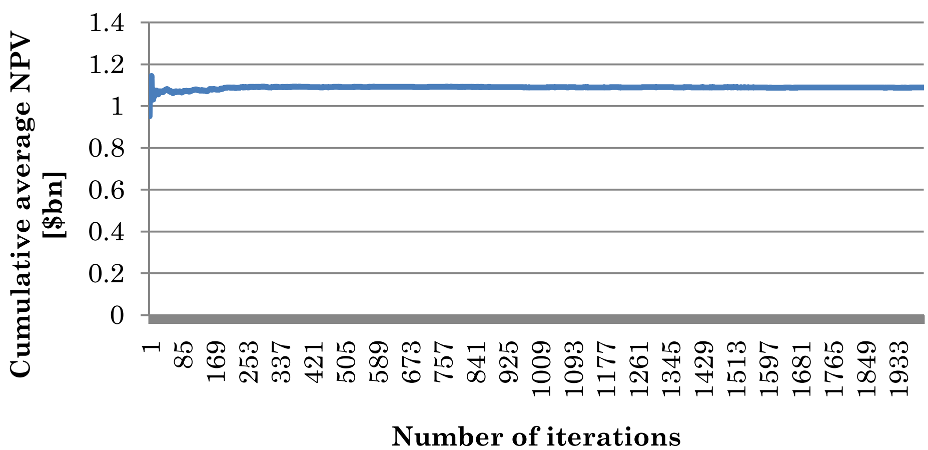

Figure 5-8. Cumulative average of NPV over 2000 iterations.

Figure 5-9 shows the resulting histogram of the NPV of the probabilistic investment plan, resulting in a normal distribution with μ = \$1.1 billion and σ = \$142 million. Analysis of the histogram reveals that there are no negative values of NPV, which theoretically represents 100% project profitability even if the discount rate is varied. Another interesting observation is that the NPV histogram constitutes an almost normal distribution, i.e. the same as that of the capacity factors.

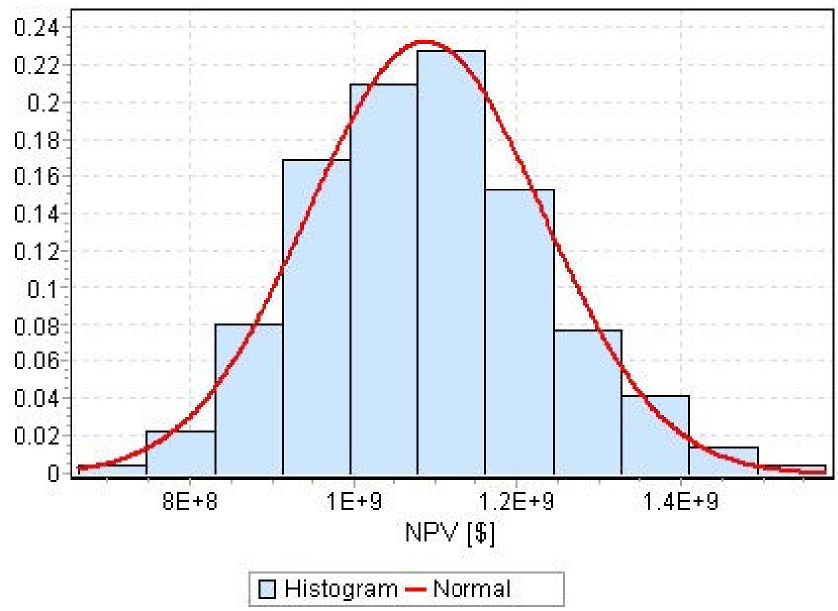

Figure 5-9. Histogram and best-fit probability distribution function of NPV over 2000 iterations.

The expected energy injected from new solar PV capacity addition is depicted in Figure 5-10. Similar to the previous case, the conventional energy sources continue to serve the largest share of the demand, while, the contribution of solar energy increases over the investment period and attains a steady-state share after 2013. Hence, the variation in capacity factor only slightly affects the solar PV energy injected into the system.

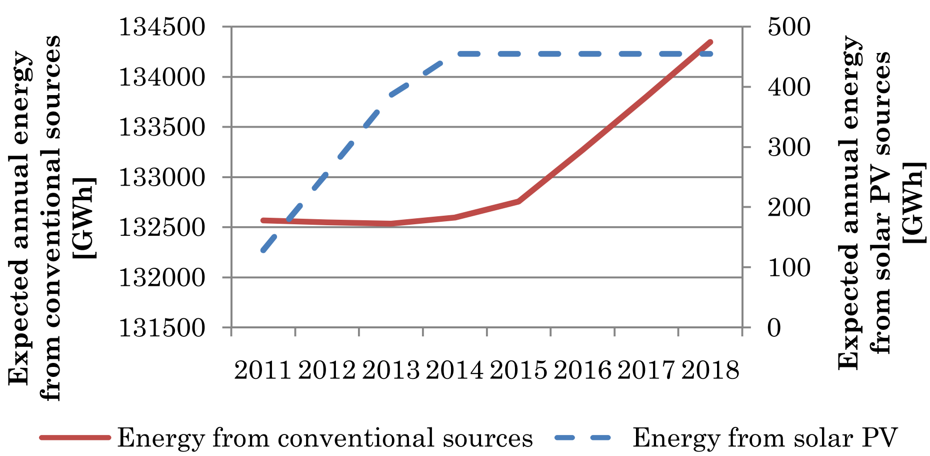

Figure 5-10. Energy from solar PV and conventional sources.

Observe in Figure 5-11 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 9) has the comparatively highest likelihood of investment. Hence, it can be concluded that, in order to account for the variability in the solar PV capacity factors, the investments have to be made in all the zones to achieve the maximum profits.

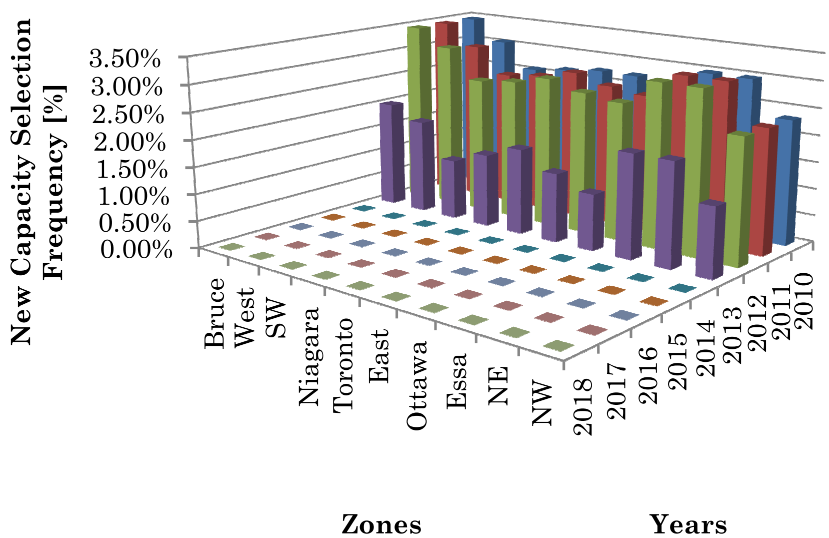

Figure 5-11. New solar PV capacity selection frequency.

5.2.3 Scenario 3: Variation in Discount Rate and Capacity Factors of Solar PV generation

The average cumulative NPV of the investment plan is plotted over 2000 iterations of Monte Carlo simulations in Figure 5-12, resulting in an expected NPV of $1,142 million. The expected NPV converges in about 1000 Monte Carlo simulations.

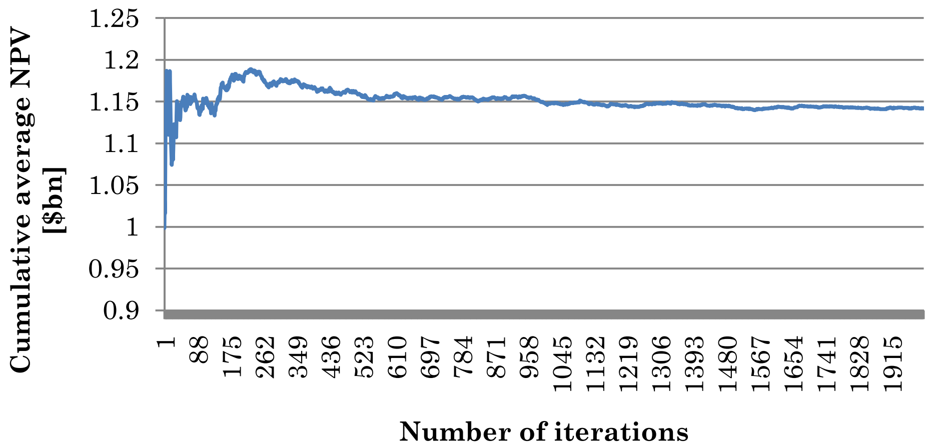

Figure 5-12. Cumulative average NPV over 2000 iterations.

Figure 5-13 shows the resulting histogram of the NPV of the probabilistic investment plan, resulting in a lognormal distribution with $\mu = 20.808\,\mathrm{p.u.}$ and $\sigma = 0.30657\,\mathrm{p.u.}$ Analysis of the histogram reveals that there are no negative values of NPV, which theoretically represents 100% project profitability even if both the discount rate and capacity factors are varied.

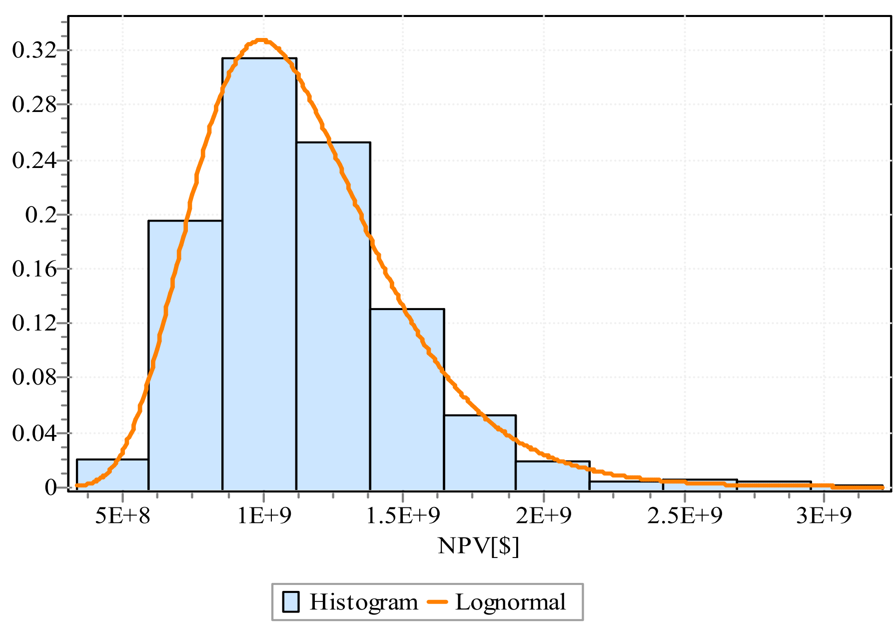

Figure 5-13. Histogram and best-fit probability distribution function of NPV over 2000 iterations.

The expected energy injected from new solar PV capacity addition depicted in Figure 5-14 is somewhat higher than that obtained for the deterministic case. Similar to the previous case, the conventional energy sources continue to serve the largest share of the demand, while the contribution of solar energy increases during the investment period and attains a steady-state share after 2013. Hence, the variation in discount rate and capacity factor only slightly affects the solar PV energy injected into the system.

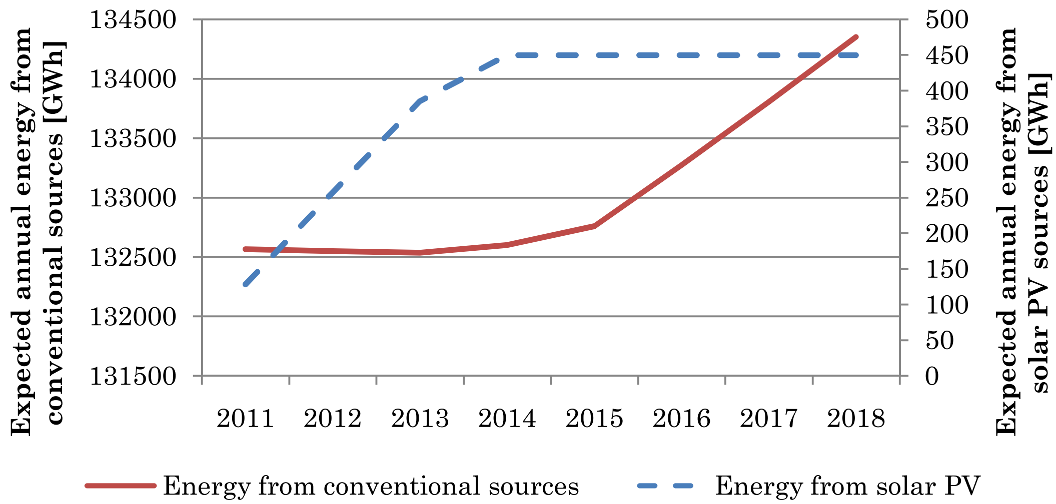

Figure 5-14. Energy from solar PV and conventional generation sources.

Observe in Figure 5-15 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 9) has the comparatively highest likelihood of investment.

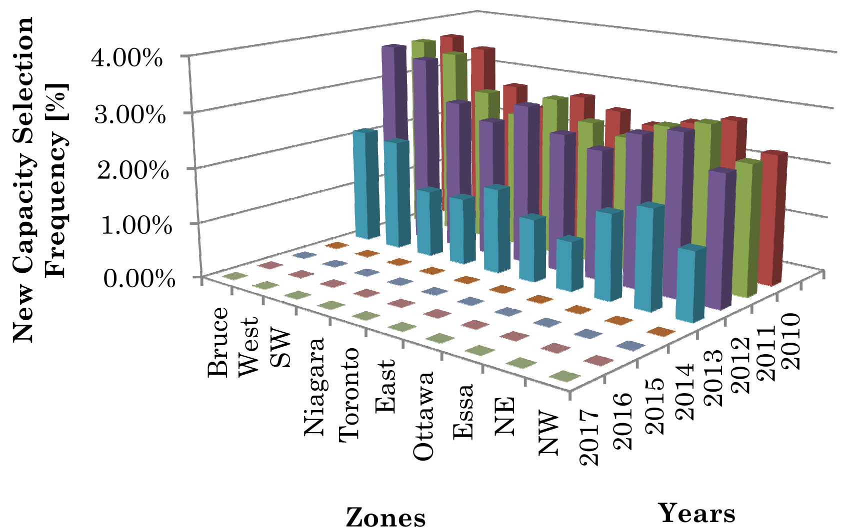

Figure 5-15. New solar PV capacity selection frequency.

5.3 Summary

This chapter presented the results obtained in the deterministic and probabilistic analyses of the proposed model for the Ontario case. The model was solved using the CPLEX solver in GAMS. In the deterministic case, the results showed that a total investment of 135 MW is made in Bruce for a maximum NPV of $725 million. For the probabilistic case studies, 3 scenarios were analyzed. In the first scenario, considering the variation in discount rate, expected investments were still made in Bruce with maximum NPV comparable with the deterministic case. In the second scenario, considering the variation in solar PV capacity factors, the expected investments were spread across Ontario to maximize NPV, which increased to over $1 billion with a standard deviation of $142 million distributed normally. The third scenario considered variation in both the discount rate and the solar PV capacity factors. In this scenario, the expected decisions were spread across Ontario to yield a maximum expected NPV of $1.14 billion. All probabilistic scenarios resulted in 100% project profitability, regardless of the parameter uncertainties.

Chapter 6
Conclusions

6.1 Thesis Summary

In this thesis, 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 following are the main contents and conclusions of the thesis:

- Chapter 2 reviewed the basics of solar PV power generation, system configurations and tools for their economic evaluation. A brief background of the mathematical modeling techniques used in this work (DC power flow, MILP and Monte Carlo simulations method) was also presented.
- Chapter 3 presented a novel MILP optimal investment planning model considering relevant electricity generation and transmission as well as financial constraints. This chapter also presented a solar PV power generation model based on solar radiation and ambient temperature inputs. The optimization framework, considering the balance between electricity supply and demand over the entire planning horizon, allows to determine the year, size and location of solar PV power plants on large-scale in the existing system for maximum investor profit.
- Chapter 4 presented the details of a reduced order equivalent electricity system along with a detailed representation of region-specific solar PV capacity factors and cost components. Generation, transmission expansion plans, and solar PV system cost trends from 2008-2038 were considered. All the model parameters described and developed in this chapter correspond to Ontario.
- Chapter 5 discussed the results obtained in the deterministic and probabilistic analyses of the proposed model for the Ontario case. The model was solved using

the CPLEX solver in GAMS. Results from the deterministic case study for Ontario suggested that investments are to be made in Bruce to yield maximum NPV. It was observed that these investment decisions were driven by the high solar energy availability in that zone. Parameter variability was also considered in the analysis through a Monte Carlo simulation approach. It was noted that variability in the discount rate only affects the NPV, as the investment decisions remained the same; however, variability in the capacity factors was overcome by spreading out the investments across Ontario. Another interesting observation was that regardless of the parameter uncertainties, all probabilistic scenarios resulted in 100% project profitability. The 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.

6.2 Contributions of the Thesis

The work carried out is from the perspective of an individual investor to serve as a useful feasibility analysis tool. The main feature of the proposed model is that it incorporates inputs from the transmission system, the governing authority, and the investor, represented as various constraints in a unified optimization model to provide a feasible optimal solution.

The following are the main contributions of the research presented in this thesis:

- A novel optimization framework for investment in large-scale solar PV in existing transmission system has been developed and tested in a realistic case. The model, which requires location-specific inputs on the solar energy, cost components, conventional generation, demand and transmission capacities, determines the maximum NPV of investor profits. This is achieved through finding the optimal size, site and time of investment for large-scale solar PV power plants. The main characteristics of the proposed model are the following:
    - Investment decisions to maximize NPV of investor's profits are constrained by the existing generation plans, demand reduction targets and forecasts, transmission line capacities and expansion plans. As well

as ensuring nodal supply-demand balance by incorporating dc power flow equations.

    - Location specific solar energy availability has been incorporated in the model through the development of zonal solar PV capacity factors. Cost models to determine the location specific cost components associated with solar PV installations have been developed. The future cost trends are based on the past trends which reflect the economic favorability of each zone for solar PV power plants.
    - Government incentives and policy mechanisms to support solar PV development have been considered through FIT, which determines the revenue earned. From the investor's perspective, the internal budgetary limits and delays associated with approvals and policy changes have also been accounted for.

- The proposed model has been applied to study solar PV investments in Ontario based on deterministic and probabilistic studies, demonstrating the advantages of investing in solar PV plants in the province. This is consistent with the current investment patterns being observed in Ontario.

The proposed model and part of the corresponding results presented in this thesis have been submitted for publication in the IEEE Transactions on Power Systems [52].

6.3 Future Work

Based on the work presented in thesis, further research may be pursued in the following directions:

- Sensitivity analyses to study the effect of variations of the input parameters, thus providing comprehensive information on how various model parameters impact the NPV and investment decisions.
- The effect of FIT and other support mechanisms on solar PV investments could be studied, using this model, from both private investor and central authority perspectives.

- Comparative studies on financing options, such as loan scheduling and debt retirement can also be incorporated in the model to make it more realistic.
- In this thesis, the smallest time step was considered to be 1 year, but the analysis could be extended to a monthly basis to yield more precise decisions.
- Renewable energy sources other than solar PV, such as wind, geothermal, CSP, etc., could be included in the study based on the potential zonal availability and corresponding cost models.

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