PV ENABLED NET ZERO EV CHARGING STATION: SYSTEM DESIGN AND SIMULATION STUDY

by

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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

A paradigm shift in the transportation sector is being witnessed due to resurgence of electric vehicles (EVs). They are ideally considered to be non-polluting and eco-friendly, however it has its own demerits of overloading existing grid infrastructure and, could significantly contribute towards carbon emissions depending on the source used for charging them. The ideal solution to counteract the critical shortcomings is by developing a charging infrastructure integrated with renewable energy technology.

The main aim of this thesis is to design such a charging station coupled with solar energy for urban cities. Simplified EV load models are developed by considering most popular commercial EV in the market. The designed solar powered charging station is tested with the developed EV load models and, would be located in selected urban cities within Ontario.

Firstly, literature review on effects of EV charging directly from grid, benefits of EV charging with renewables, and amalgamation of EV charging with Net Zero (NZ) concepts is introduced. Later, three types of system architectures are studied for solar powered charging station. Selection of architecture for this work is done considering the economics of installation, and operation. Optimization in design of solar powered charging station is presented by varying the power ratio and, obtaining the annual energy yield for different types of orientation considering all EV load models. Then, NZ Photovoltaic (PV) enabled charging station is designed and, is tested with selected load models and, energy economic analysis is done for all designs. Finally, recommendations are made encompassing the selection of net-zero based charging stations along with economic considerations and its short and long term effects on environment.

Acknowledgements

First, I would like to thank almighty for bringing me to *University of Waterloo* and showing me the righteous path on enhancing my technical capability, and also providing me the chance to grow further as a responsible individual.

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Dedication

To my beloved parents: Kothandaraman & Lakshmi Raman

(For their love, support and motivation)

And

In loving memory of my dearest Grandmother: Padma Sundaram

(For her determination and guts to fight cancer)

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Chapter 1

Introduction

Since the convening of *Paris Climate Conference* in 2015, the world has witnessed tremendous efforts towards greenhouse gas (GHG) reduction and carbon footprint improvement through market and non-market based approaches [1]. The transportation sector has a major part to play in this sustainable mission and with the penetration of electric vehicles (EVs) both *Plug-in Hybrid Electric Vehicles (PHEVs)* and *Battery Electric Vehicles (BEVs)*, possibilities for creating a significant impact on the electric power grids and existing distribution infrastructures have increased in multi-fold. Also, in Canada, the government has put forth *Federal Renewable Regulations* for gasoline, diesel fuels and heating oil distillate as measures to enhance efficiency and curb GHG impacts in the transportation sector [2]. Specifically in Ontario, the provincial *Electric Vehicle Incentive Program* allows customers to apply for incentives and rebates for purchasing or leasing eligible new PHEV or BEV [2]. Further, with the introduction of *The Big Move: Transforming Transportation in Greater Toronto Area and Hamilton Area*, the province of Ontario has established a long term sustainable plan for one of Canada's largest and rapidly growing urban localities [2]. Figure 1.1 illustrates the sector wise GHG emissions in Canada [2].

Even in the *Conservation framework for Climate Change* by **IESO** (Independent Electricity Systems Operator), emphasis has been laid on deployment of EVs to reduce GHG. According to [3], 37% of CO_2 emissions in the province of Ontario is accounted by the transportation sector, of which on-road vehicles, i.e., gasoline based trucks, motorcycles and cars contribute to roughly 46 MT of CO_2. The IESO's potential alignment plan has outlined few actions pertaining to EVs for GHG reduction as well as to lower grid system peaks [3], that includes:

- Free EV overnight charging
- Wide availability of EV charging infrastructure

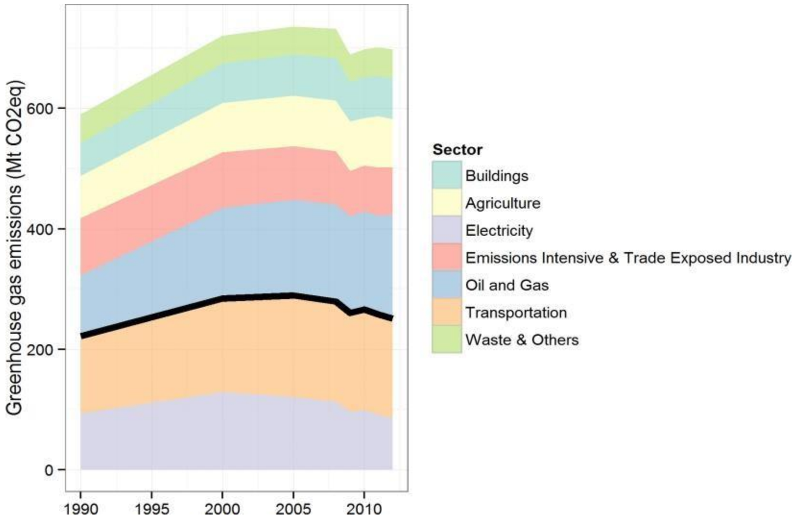


Figure 1.1: GHG emissions in Canada [2]

- Mandate EV charging in surface lot
- Building EV ready homes

With the implementations of aforementioned actions, the IESO envisages off-peak charging of EVs which will have least impact towards increase in GHG [3]. Further, with emphasis on smart electrification of road transport system, the government plans to incentivize the purchase of EVs in an effort to support development of a low-carbon energy technology by phasing out fossil fuel based cars and becoming a carbon-neutral society by 2030 [3].

The *Mobility, Vehicles, and Electricity System (MOVES)* lab, formerly known as Berkley Lab, indicate that tailpipe emissions are a serious cause for public health hazards, especially in densely populated regions [4]. MOVES lab developed the Vehicle-to-Grid Simulator (V2G-Sim) to perform high fidelity simulation and complementing experiments to develop improved vehicle powertrain technologies [4].

With the rapid increase in EV adoption, the growing demand for EV charging stations at home or public places (offices, malls or gymnasiums) is inevitable. According to [5], more than 80% of the EV charging occurs at either home or public places (mostly workplace). The typical charging infrastructure mix according to [6] is depicted in Figure 1.2. Further, in urban cities where there is scarcity of land, it will be beneficial to setup charging stations

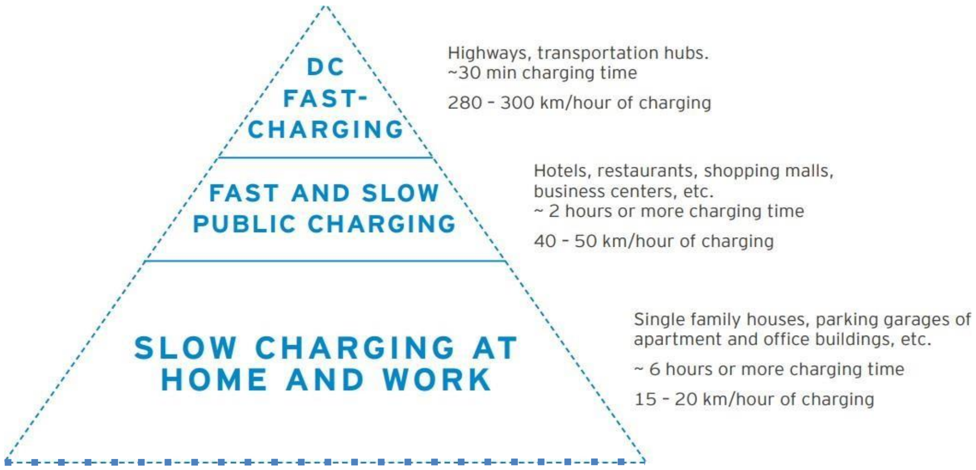


Figure 1.2: Charging infrastructure mix in cities [6]

by the city (through dedicated municipal budgets) with direct access to general public [6]. [6] also suggests a few directives that can be implemented in public spaces for urban areas:

- Allocating spaces (10-20%) for EV charging in areas without reserved parking,
- Creating charging hubs to attract users in collaboration with various service providers,
- Policy adoption for installing public charging stations as per requirements of local residents.

With recent advancements in the transportation sector, emphasis has been given to the development of grid independent EVs and one of the major technology facilitating this aspect is Solar Photovoltaic (PV) systems. The EV-PV duo has immense potential for alleviating CO_2 emissions and fossil fuel consumption over the next few decades [7]. However, large scale penetration of this technological amalgamation is a challenging endeavor primarily owing to the variable and un-reliable of electricity output through solar PV systems. Other key challenges accompanied with this aspect involve cost and performance characteristics of including an energy storage system (battery, flywheel or ultra-capacitors) that limits the smooth economic deployment. Further, the limited access to charging infrastructure and increasing driving range anxiety has also impacted adoption of EV-PV systems to a certain extent. Also, social and political barriers hinder the development of these technologies in general market especially in developing countries where the scope is multi-fold [7]. However, many extensive researches have been carried out in the past years to mitigate the issues associated with the adoption of EV-PV based charging infrastructure setups through multiple charging system configurations [7]. As it is said that the night is darkest before the dawn, with the declining prices for solar panels across the globe and easy availability of optimized technological solutions, populating the EV-PV infrastructure in a distributed manner seems to be the most optimum option elevating economic growth, creating job opportunities, improving sustainability and climatic conditions [7].

1.1 Motivation

Climate change has been seen and identified as a long term problem by people across the globe leading to various actions countering this effect in different sectors of society. Transportation sector is one of major contributors to the aforementioned climate issue and needs immediate attention. EVs are envisaged to be the future transportation medium and demonstrate energy efficiency levels much higher than the conventional gasoline or diesel based vehicles. However, the sustainability of EVs is justified only if the electricity used to charge these EVs is availed from a sustainable source of energy and not from any fossil fuel or carbon generating source. Many of the recent researches regarding EV charging through sustainable sources have intriguing insights encouraging budding researchers to emphasize on developing EV charging stations based on renewable energy source especially solar PV based charging stations. From general reading, the following has been observed regarding solar based EV Charging making it an alluring option:

- Solar PV cost has been declining rapidly over the past decade [8]
- PV systems have low maintenance and operational costs (no major mechanical or rotational parts)
- Ease of accessibility, as the PV systems can be installed practically in all kinds of terrain (roof-top, parking places, plains etc.)

Further, with the blooming of net zero systems for commercial and residential premises, more opportunities have risen for implementing PV-EV based charging infrastructure to attain net zero status (overall zero energy consumption). All these factors have been the basis and motivation to pursue this thesis in performing a system design and simulation study for PV enabled EV charging station. Along the research process, the author has invested time and effort through deep introspection for attaining a feasible and efficient EV charging solution with net zero site energy status for the urban cities in Ontario, Canada.

1.2 Research Objectives

The primary objectives of this thesis are:

- *To design a cost-effective EV charging station infrastructure based on solar photovoltaics.*
  In the path to achieve this objective, various EV charging models will be developed, simulation setup will be demonstrated for optimized energy extraction and results will be presented supporting the selection of PV enabled EV charging station (with economical orientation) including the payback period analysis.
- *To demonstrate reduction in CO_2 emissions with the use of EV-PV charging station infrastructure.*
  In reaching this objective, comparisons will be drawn with existing charging facilities (grid based) and the potential of EV-PV based systems in reducing GHG emissions in the longer run.

1.3 Thesis Organization

The introduction chapter has extensively established the context of existing GHG emissions across the globe with increased transportation penetration and the need to deploy EVs on a large scale to overcome these effects. In this process, it has been identified that a PV-EV based charging infrastructure would be the most viable and economic option to achieve the sustainable goals set with the Paris Agreement.

Chapter 2 will present the theories associated with charging of EVs using conventional grid and renewable energy sources along with advantages and effects on the environment and economics of transportation sector. Finally, this chapter will also introduce the amalgamation of EV charging stations with Net Zero setups.

A comprehensive background encompassing on PV module types, effects of tilting and tracking of PV, EV charging standards, types of system designs, selection of appropriate system architecture, and parameters to evaluate the design are discussed in *chapter 3*.

Chapter 4 & *Chapter 5* will deal with the complete system design of Grid Connected Photovoltaic system (GCPV) for EVCS (Electric Vehicle Charging Station) & Net Zero (NZ) GCPV for EVCS, wherein the methodology, analysis and simulation results will be presented.

Finally, *Chapter 6* will outline the conclusions based on the thorough analysis along with directions for future work related to EV-PV and Net Zero systems.

Chapter 2

Literature Review

2.1 EV Charging through Grid

Though it may seem simple and convenient, charging EV through grid is a complicated process with numerous impacts on the existing grid infrastructure. Depending on the kind of charging station, the power demand may vary anywhere between 1kW to 50kW during peak or non-peak hours creating increased power demand and straining grid infrastructure. According to [9], there is potential for increase in demand during daytime when EV users arrive at their respective workplace and start charging. Further, the research carried out in [9] indicates that peak energy demand observed on the grid due to EV interaction was between 3 pm - 5 pm on a typical work day. The penetration levels and the discharge or charging strategies of EVs will have a major influence on the economics, emissions and grid stability [10]. Also, without proper scheduling or planning of charging EV batteries, the load of these vehicles may compromise the reliability of grid [10]. Other prominent impacts on grids due to inclusion of EVs would be [10]:

- Overloading of distribution transformers
- Increased cost of generation with increase in demand
- Transmission line congestion
- Increased transmission line losses
- Phase imbalance issues
- Voltage fluctuations in EV charging localities
- Probable black outs

- Wear and tear of grid infrastructure

However, implementing a coordinated charging strategy with the use of distributed generation (DG) using renewable sources, the aforementioned impacts could be minimized to a large extent making EV charging a fruitful and economic prospect [9].

Table 2.1: Electrical Characteristics for Uncoordinated and Coordinated EV Charging [10]

	No EV load	Uncoordinated Charging	Coordinated Charging
Line Current (A)	105	163	112
Node Voltage (V)	220	217	220
Peak Load (kVA)	23	36	25
Power Loss (%)	1.4	2.4	2.1

Charging of EV through grid also doesn't have any silver lining on the environment. It is quite the misconception where people believe that CO_2 emissions associated with EVs are zero. However, generation of electricity through other carbonizing sources (coal, gas, etc.) result in large CO_2 emissions which is used to charge these EVs. According to [11], in the United States, the regions with high carbon intensity grids, there isn't a significant realization in achieving reduced CO_2 emissions. This is owing to the fact that emission reduction benefits from charging stations diminish as the CO_2 intensity of the grid increases. Further, [11] suggests that carbon intensity of the grid has a much significant contribution on total emissions associated with EVs than the charging scenario, making it a cumbersome and complicated exchange process. A comparison between emissions for charging scenarios at home and workplace for different fuel sources has been depicted in Figure 2.1 [11].

However, in regions where the energy mix is predominantly based on carbon-free sources viz., nuclear, hydro or renewable, penetration of charging stations may not have huge impact of CO_2 emissions. For instance, in Ontario where the energy mix is inclined more towards carbon-free sources as depicted in Figure 2.2 [12], introducing more charging stations, especially renewable source based will have positive impact towards the environment with reduction in CO_2 emissions. This will be the focus in further sections of this thesis.

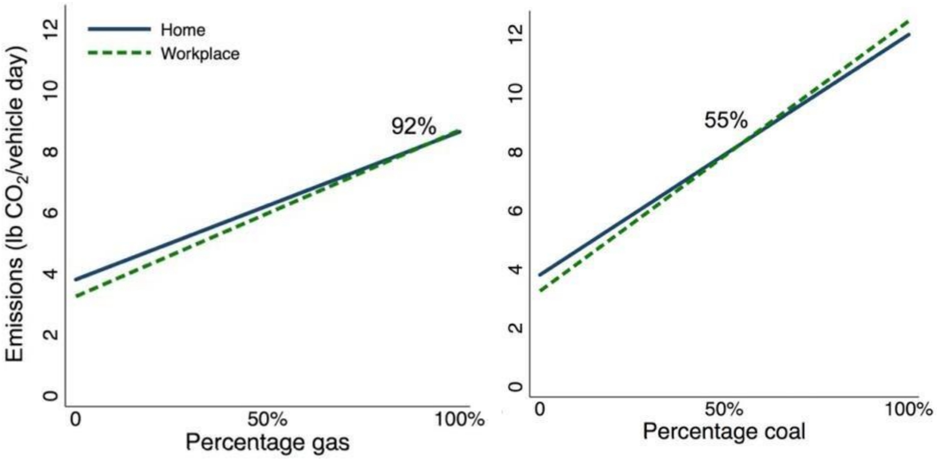
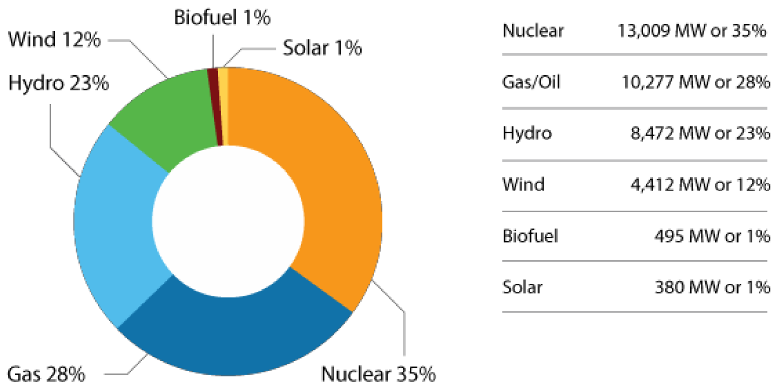


Figure 2.1: Comparison of Home and Workplace Emissions for different Fuel Sources [11]

2.2 EV Charging through Renewable Energy Sources

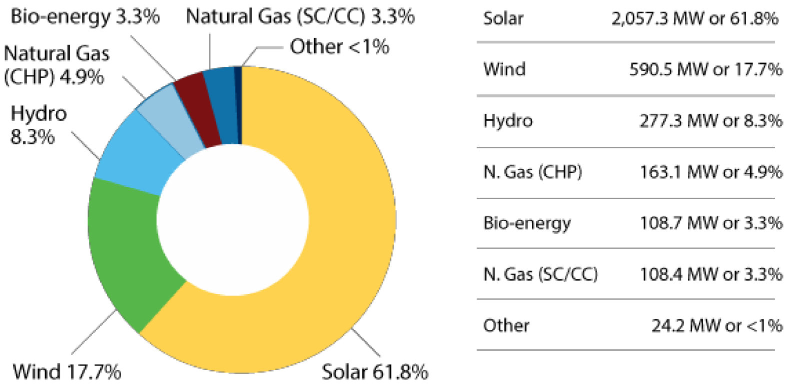
In recent times, renewable energy sources (RES) have made a mark as an alternative to conventional fossil fueled sources. Further, as these energy sources can be located near the load center, the system efficiencies can be improved to a large extent with the reduction in losses, voltage fluctuations and power infrastructure costs [13]. The amalgamation of RES with EVs present a plethora of prospects towards sustainable development with minimum environmental impacts. *Shaaban et. al* present a multi-objective planning model to minimize GHG emissions and system costs by determining optimal level of EV penetration along with the location, size and installation year for the RES units [14]. Further, through multiple researches in [15] [16] [17], it has been established that the variable nature of RES over power system networks can be mitigated by smart coordination and usage of storage capabilities of PHEVs.

A clean and alternative charging station infrastructure has been witnessed with the development of solar photo voltaic based charging stations or **solar powered charging stations (SPCS)**, typically in parking lots to generate electricity of EV charging as well as to support grid [18]. It is possible to generate 25% to 33% of the total electricity produced in the United States just by covering 200 million parking spaces with solar panel canopies [18]. The collaboration of EVs with SPCS infrastructure and smart grids is still a far cry



Nuclear	13,009 MW or 35%
Gas/Oil	10,277 MW or 28%
Hydro	8,472 MW or 23%
Wind	4,412 MW or 12%
Biofuel	495 MW or 1%
Solar	380 MW or 1%

(a) Transmission System



Solar	2,057.3 MW or 61.8%
Wind	590.5 MW or 17.7%
Hydro	277.3 MW or 8.3%
N. Gas (CHP)	163.1 MW or 4.9%
Bio-energy	108.7 MW or 3.3%
N. Gas (SC/CC)	108.4 MW or 3.3%
Other	24.2 MW or <1%

(b) Distribution System

Figure 2.2: Energy Mix for Transmission and Distribution Systems in Ontario [12]

owing to the useful life of currently operating gasoline based vehicles and power plants [18]. However, with the tremendous decrease in prices of solar panels and battery technologies this transformation has been visioned and idealized. For instance, Envision Solar International Inc., developed *EV ARC* a standalone SPCS system with battery storage that has been designed to be self-contained without any grid interaction [19].

The locations of SPCSs would primarily depend on the duty conditions of the EVs:

- EVs at home
- EVs along the route
- EVs at work place (more than 1 hour of parking)

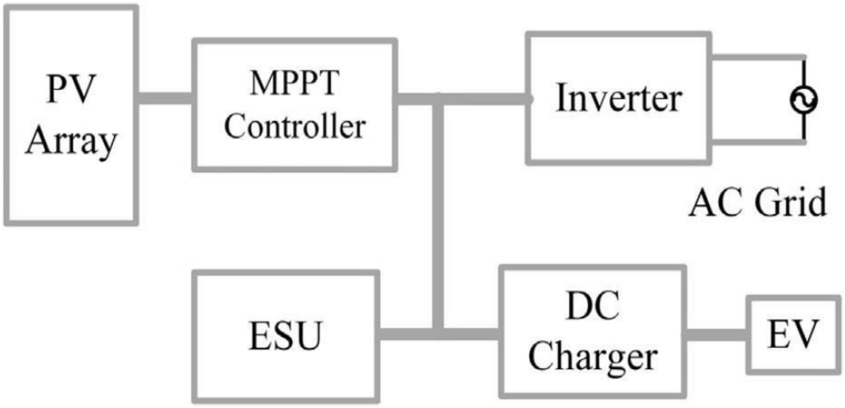


Figure 2.3: Basic schematic of a SPCS based EV charging [20]

In most cases, the users have SPCS at home by means of roof-top solar panels or panels over the car port [18]. In other cases, the EV manufacturers provide the charging infrastructure to their customers at a premium. For instance, Tesla Motors has a network of SPCS across the United States and Europe [18].This is a classic example of charging EVs along the route. Also, it is becoming common to install SPCSs at public locations like malls, convention halls, gymnasiums, parks [18] etc. A basic schematic of a SPCS with energy storage unit (ESU) is depicted in Figure 2.3 [20].

According to [18], the life cycle analysis (LCA) of SPCS is positive in nature. The LCA depicts that SPCS is quite promising and an appropriate measure when it comes to GHG emission reduction. Two key benefits of charging EVs from solar PV systems include sustainability and economics of operation. As the global prices for PV systems have drastically dropped, electricity through solar is economical than conventional sources in many parts of the globe. Also, SPCS are preferable for the below reasons:

- PV and EV both operate on DC
- DC charging will facilitate with the V2G (Vehicle to Grid) protocol concept

Another potential candidate as an RES for EV charging would be wind energy. However, the challenges for continuous operation of wind power system for EV charging are its mechanical stability and, maintenance issue as it has lots of mechanical components. Unlike solar based systems, the control method in wind based systems are much complex as wind turbine speeds have to be adjusted in real-time according to varying wind speeds [21]. However, with smart and careful integration, the wind based systems could act as supplementary sources to SPCSs. But commercialization, maintenance and large scale adaptation of this integration is something that hasn't really interested the research community and strong motivation is envisaged in future.

2.3 Net Zero (NZ) for EV Charging

Net zero energy is a growing phenomenon across the globe in relation to smart and sustainable grid development. Basically, *net zero energy* is a concept of self-sufficiency for energy by minimizing demand and using RES locally or remotely. This phenomenon can be attained in buildings or establishments that consequently contribute to less overall GHG emissions [22]. Some of the key definitions related to Net Zero energy are described below [22]:

- ***Zero net site energy use*** **-** Here, the amount of energy provided by local RES should be equal to the amount of energy used by the establishment and building. This concept is mainly used in this thesis work for designing NZ GCPV charging station.
- ***Zero net source energy use*** **-** In this case, the amount of energy is used as generated to support the building or establishment including the energy spent in the transport. This type accounts for the losses incurred due to the transmission and distribution of electricity.
- ***Net zero emissions*** **-** Typically, in regions apart from North America, a zero energy site relates to zero net energy emissions wherein, the carbon emissions generated on-site or off-site fossil fuel are balanced by the energy produced by on-site RES.
- ***Net zero cost*** **-** In this type of site, the income generated through the sales of on-site energy production is balanced with cost of purchasing electricity from the utilities.
- ***Net off-site zero energy*** **-** This is described as the type of establishment where 100% of the energy purchased is availed from RES (on-site or off-site).

- ***Off-the grid* -** These are standalone sites that are not interfaced with the utilities in any manner. These sites depend on distributed RES and energy storage systems (ESS) for their operations.

Net zero energy can be achieved with buildings or residential with the introduction of V2G system in which a controllable, bi-directional energy flow is established between a vehicle and the electric grid [23]. The V2G system would highly attract local utilities for two major reasons:

- *As a storage medium and load leveling interface for intermittent RES*
  The intermittent nature of the power produced from RES like solar or wind may not coincide with the daily peak usage and also the lack of cost-effective electricity storage systems may destabilize the electric grid leading to low prices of renewable sources [23].

- *For fulfilling grid support and ancillary services*
  The V2G systems can support the grid during peak demands as it would be expensive for utilities to develop new infrastructure for these peaks. The energy storage system of vehicles can store off-peak energy and then selectively discharge into grid during peak demands [23].

Attaining net zero energy status can be made viable by including EVs as part of the grid-home loop. The battery-solar combination can provide offset to utility imposed peak demand prices and it can also provide direct renewable-to-PHEV source power while providing peak power to the utilities [23].Though this process seems simple, it has to undergo a myriad of implementation issues that needs to be properly addressed at multiple stakeholder levels. From the resale perspective, having a net zero premise with an intelligent EV charging station will elevate the retail value encouraging more house and commercial establishment owners to invest. Finally, from the sustainability perspective a complete net zero premise (residential or commercial establishment) will be generating equal or more electricity using RES than what it is consuming from the grid, thus laying more emphasis in clean energy production and reducing GHG emissions.

2.4 Summary

In this chapter, the basic EV charging interfaces have been discussed that includes:

- Charging of EVs through existing grid infrastructure
- Charging of EVs through RES (Solar or Wind energy based)

Along the process, plight of existing grid infrastructure was presented demonstrating the effects of large scale EV charging penetration. It was also established that with continuing use of electricity from grid has negative impact on sustainability as grid energy is primarily supported through fossil fuels in most developing countries. Alternative options for EV charging were introduced which included solar PV based systems and wind energy systems. It was inferred that out of these, solar PV is more accessible, cost-effective and viable option to power EV charging stations and also attain sustainability with minimal GHG emissions. Further, the concept of net zero is introduced associating it with the solar based EV charging infrastructure for domestic users. The key terms associated with net zero systems were defined and the concept of V2G was explained. Finally, it was realized that with the combination of net zero system with RES for a commercial or residential premise, huge potential can be visioned towards achieving clean energy generation as well as reduced GHG emissions.

Chapter 3

Component, System Design and Evaluation Parameters Selection

3.1 PV Module Types

From [24], detailed information regarding different solar cell types is described (combining several cells results in PV module), and chronological order of all solar cell types along with its maximum field efficiency is outlined in Figure 3.1 [25]. From [26], it is observed that the production of multi-crystalline PV module have dominated the market in recent years, and one such module[1] (CS6U-320P) would be used in this thesis work. PV module is the main component for converting solar insolation to electrical energy. '*Maxpower CS6U-320P*' is one of the most popular module which is used for EV charging station applications in Ontario. The important characteristics of this module has been taken from [27] and is outlined in table 3.1.Also from [27] the information of the I-V characteristics of the PV module is obtained, and shown in Figure 3.2.

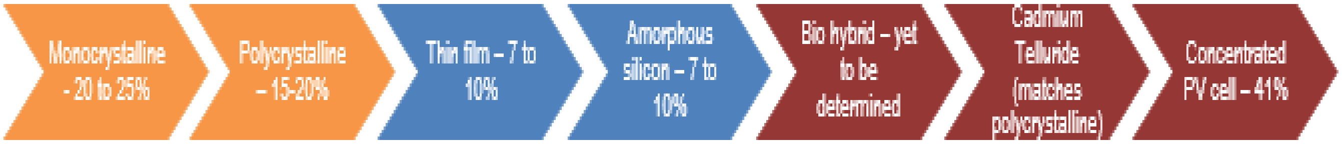


Figure 3.1: Evolution of solar cells

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[1] This research has been sponsored by Canadian Solar Inc., and this module has been most popular for EV charging stations

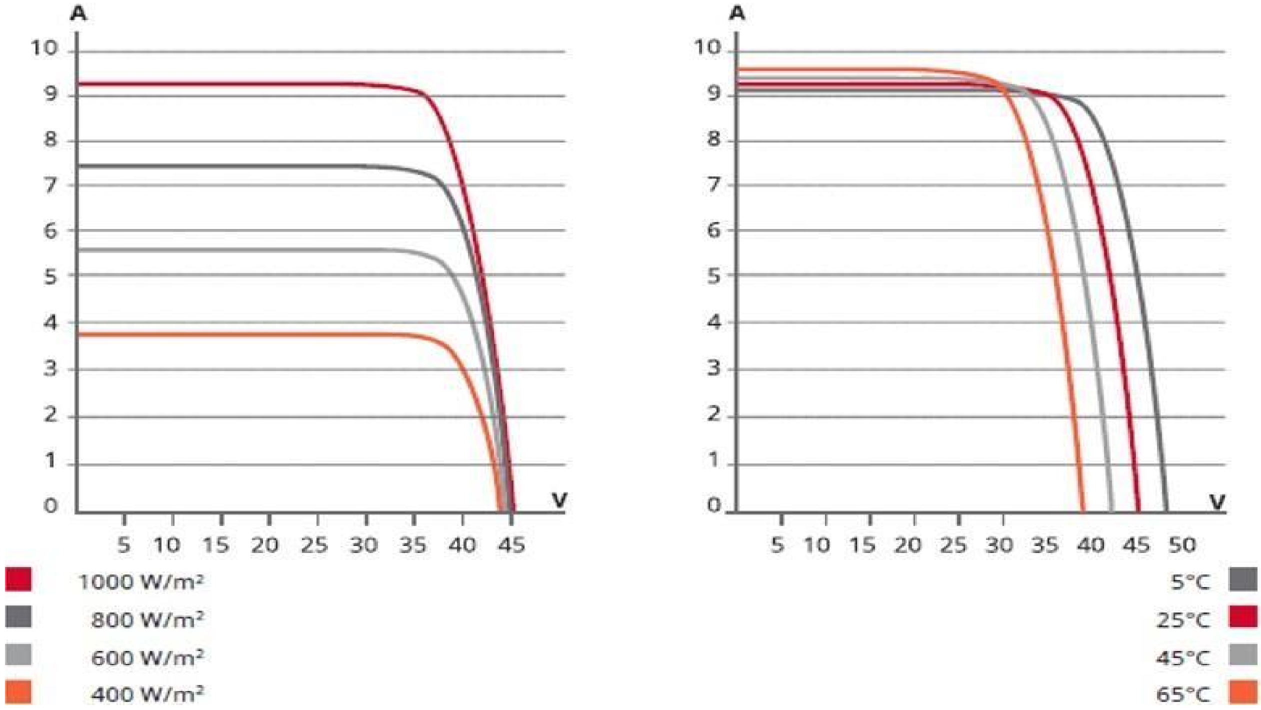


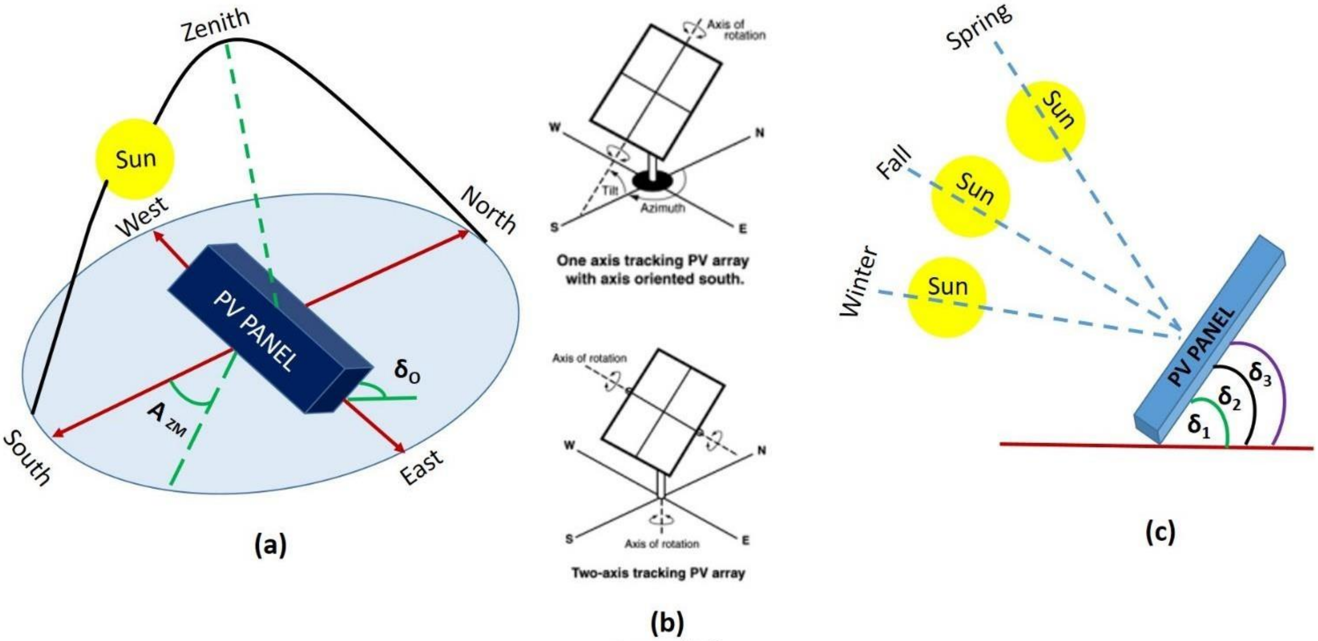
Figure 3.2: CS6U-320P Panel IV characteristics

Table 3.1: Characteristics of Canadian Solar - CS6U-320P

Maximum Nominal Power (Pmax at STC), Watts	320
Optimum Operating Voltage (Vmp), Volts	36.8
Optimum Operating Current (Imp), Ampere	8.69
Open Circuit Voltage (Voc), Volts	45.3
Short Circuit Current (Isc), Ampere	9.26
Module Efficiency at STC %	16.46
Cell type – Polycrystalline, inch	6
Operating temperature, ^{o}C	-40 to +85

3.2 Effect of Tilting and Tracking in Panels

From [28], [29], and [30] it is quite evident that solar energy generation from the PV panel increases when orientation is either tilted (or) allowed to track sun's position. Figure 3.3 provides complete information regarding the orientation of PV panels i.e., fixed tilt, tracking, and seasonal tilt mechanisms.



(a) (b) (c)

Source: [48]

Figure 3.3: Orientation of PV panels

The formula outlining relationship between tilt angle and, solar power is given in equation below [31]:

$$P_s = \frac{P_m \times N \times G_m[1 - \mu(C_t - 25)]}{1000} \;\; Watts \tag{3.1}$$

$$C_t = A_t + \left\{ \frac{G_m}{800}(T_{NC} - 20) \right\} \tag{3.2}$$

$$G_m = G_m^{DNI} + G_m^{DHI} \tag{3.3}$$

$$G_m^{DHI} = G^{DHI} \frac{(1 + cos\delta_o)}{2} \tag{3.4}$$

$$G_m^{DNI} = G^{DNI}(sin\delta_o \; cosa_L \; cos(A_{zm} - A_{zs}) + cos\delta_o \; sina_L) \tag{3.5}$$

Where,

P_s - Solar power generated, Watts

P_m - Rated PV panel power, Watts

G_m - Solar irradiance on one module, W/m^2

C_t - Cell temperature, ^{o}C

N - Number of solar module interconnected

A_t - Ambient temperature, ^oC

G_m^{DNI} - Global direct normal irradiance incident on a module, W/m^2

G_m^{DHI} - Global direct horizontal irradiance incident on a module, W/m^2

δ_o - Tilt Angle, degree

a_L - Altitude of the sun throughout the year measured from the location

A_{zm} - Specific azimuth angle for specific tilt angle

A_{zs} - Azimuth angle measured from the location

μ - Temperature co-efficient of Pmax

T_{NC} - Nominal operating cell temperature (45 ± 2 ^oC)

Energy yield from PV modules varies based on seasons, so separate tilting mechanisms are also incorporated to take benefit from seasonal variation of solar energy. Formulae to calculate seasonal tilt for North America has been obtained from [32]. Equations are given below:

$$\textbf{Winter (Dec - Mar)},\ \delta_1 = Latitude \times 0.9 + 30^o \tag{3.6}$$

$$\textbf{Spring (Apr - Aug)},\ \delta_2 = Latitude - 25^o \tag{3.7}$$

$$\textbf{Fall (Sep - Nov)},\ \delta_3 = Winter\ Angle - 52.5^o \tag{3.8}$$

δ_1, δ_2 & δ_3 are tilt angles of PV panels for appropriate seasons in deg.

3.3 EV charger standards

Charging stations are the pivotal entities in an EV infrastructure. The levels of charging can be classified depending upon the location of charging station.

Level 1 [33]

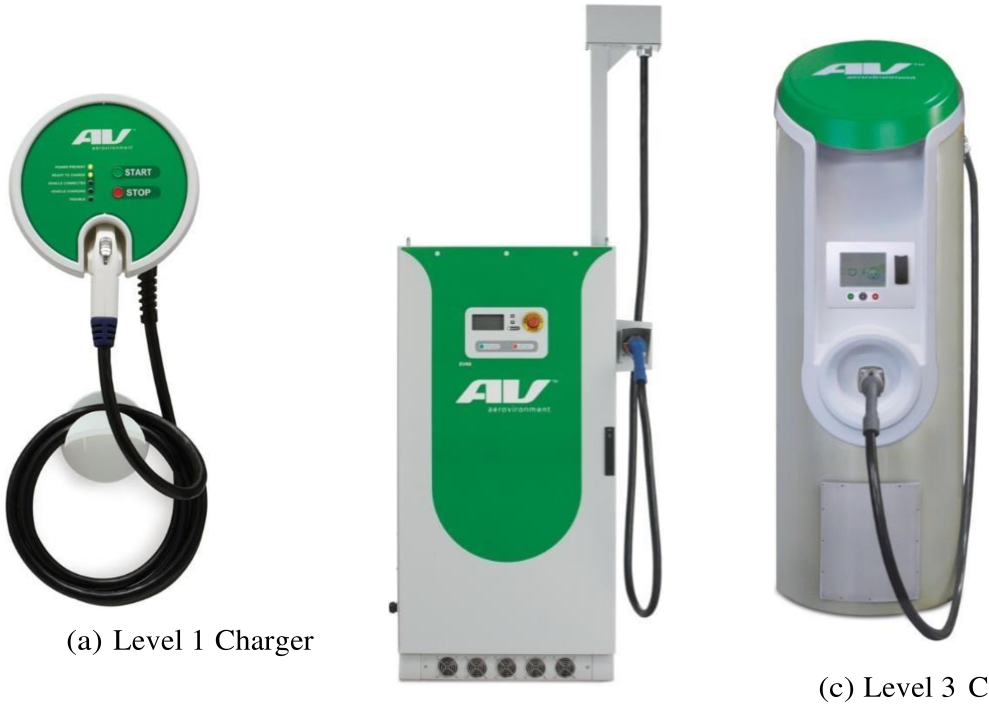
At this level, charging occurs when the EV uses standard 120V outlet socket through the charger included with the car. Depending on the vehicle capabilities, the level 1 charging stations typically operate at 1kW power and take 8 to 15 hours to completely charge a drained battery.

Level 2 [33]

The charging at this level takes place at 240V level with chargers that are sold separately from the car. The setup for this kind of charging station is a bit complex than the level 1 and would often require support from an electrician. These charging stations are rated in between 3kW and 20kW, typical being 6kW and takes approximately 3 to 8 hours to completely charge a drained battery. This charger is considered in this thesis work and, its selection is justified in section 3.4.4.

Level 3 [33]

These are fast charging stations operating at higher voltages requiring three phase power network. These charging stations are custom developed with typical rating of 50kW. Commonly known as DC Fast Charge (DCFC), these stations have the capabilities to charge an EV in 20 minutes to 1 hour. Figure 3.4 [34] provides the physical representation of the above mentioned charging stations.



(a) Level 1 Charger

(b) Level 2 Charger

(c) Level 3 Charger

Figure 3.4: Types of Charging Stations

3.4 System Design Architectures for Solar Powered Charging Stations

[35], [36] suggest that for any PV based system to operate effectively, the entire system design should be done by considering the following constraints: I) Site location, which includes the weather forecast, solar radiation and, wildlife activity, II) Available space for installation of the complete system, III) Electrical load requirements and, electrical codes at the specific location. Solar based EV charging stations must also comply with above design constraints, and there are three major types of system design for such charging stations [37]:

- Off-grid PV system with Energy Storage Device (ESD)
- GCPV system with ESD
- GCPV system without ESD

3.4.1 Off-grid PV System with ESD

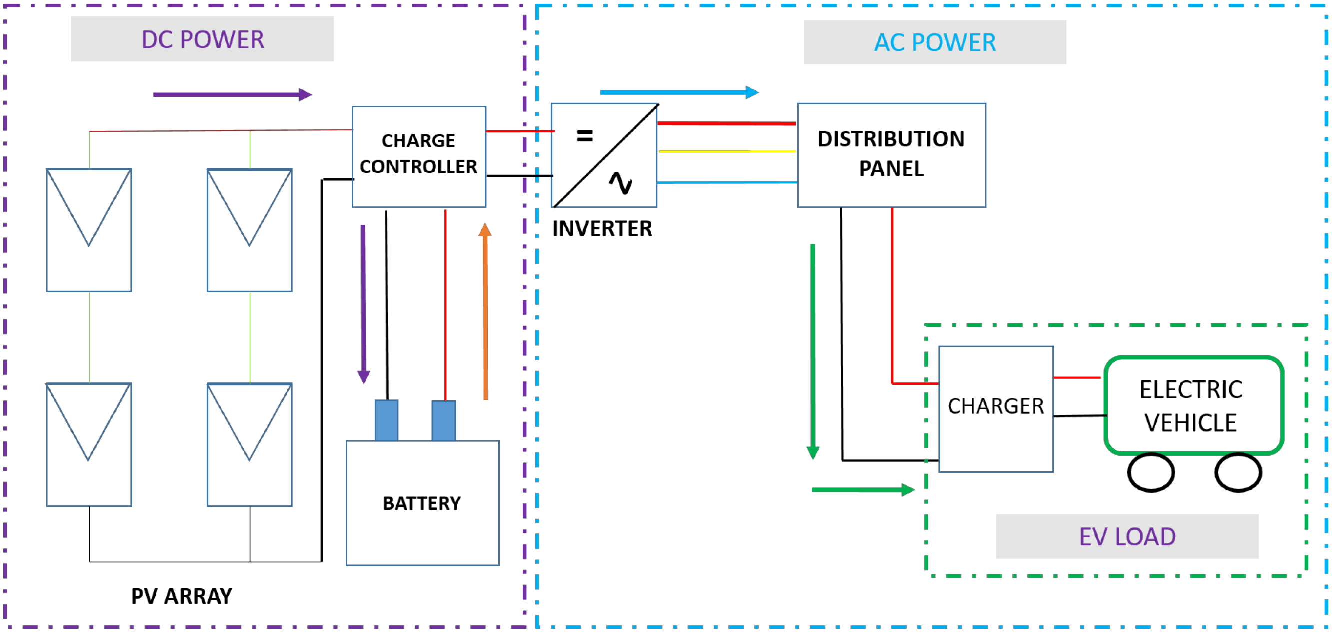


Figure 3.5: Block diagram of off-grid system for EVCS

In this type of architecture, energy from PV module and, ESD (battery) together is used for meeting the load power requirements, and any excess power is fed back into ESD. ESD acts as a storage unit in this type of architecture. This type of system is preferable for remote locations (rural areas) [35] [38], and it is not considered for design in this work. Figure 3.5 represents this architecture [39].

Merits

- No dependence on grid and, it can be located in remote communities [38][39]
- It can be assembled, disassembled easily, and can be made into portable system [19]

Demerits

- Investment cost on PV, and ESD must be very high to satisfy the demand of EV load
- ESD maintenance may become a problem if continuously operated
- Effective utilization of this type of architecture can be done only if an external control system is incorporated
- It is not a reliable system, if solar energy is unavailable it becomes difficult to use only ESD to charge EV [35]

3.4.2 GCPV System with ESD

Basic structure of this system is shown in Figure 3.6. The major difference from earlier architecture is the additional element of grid, and a bimodal inverter. If grid fails, ESD acts as back up. This poses to be a good solution for a less grid reliant system with optimal sizing of PV and energy storage system to effectively meet load requirements. Dissimilar to the inverter as seen in previous section, this inverter has capability to switch charging modes i.e. when battery's energy is low it will use solar energy to charge battery via charge controller, if battery is full it supplies solar power to EV load, and at no load condition solar power is fed into the grid. This type of system is more preferable for urban cities than remote locations.

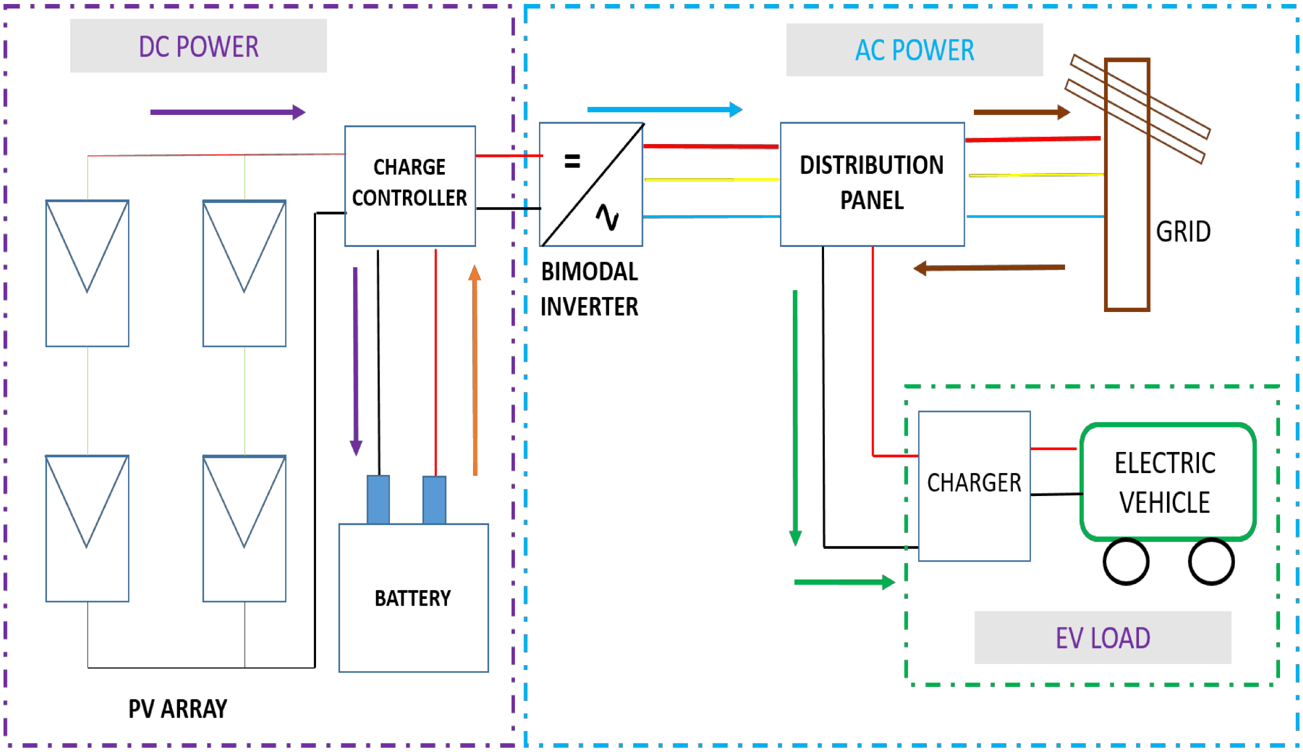


Figure 3.6: Block diagram of GCPV system with ESD for EVCS

Merits

- More reliable system compared to the one in previous section, as this system will continue to satisfy loads even when the grid fails. Also, it can be designed to have less reliance on grid.
- 100% utilization of Time of Use (TOU) pricing is possible in this type of system with the presence of an additional controller to control the power injected into grid from the DC side.

Demerits

- The storage system increases the overall costs [35]
- The safety and maintenance requirements for this type of system is more than the previous one

- In some cases, an external controller and, battery monitoring system needs to be added for ensuring reliable system operation

3.4.3 GCPV System without ESD

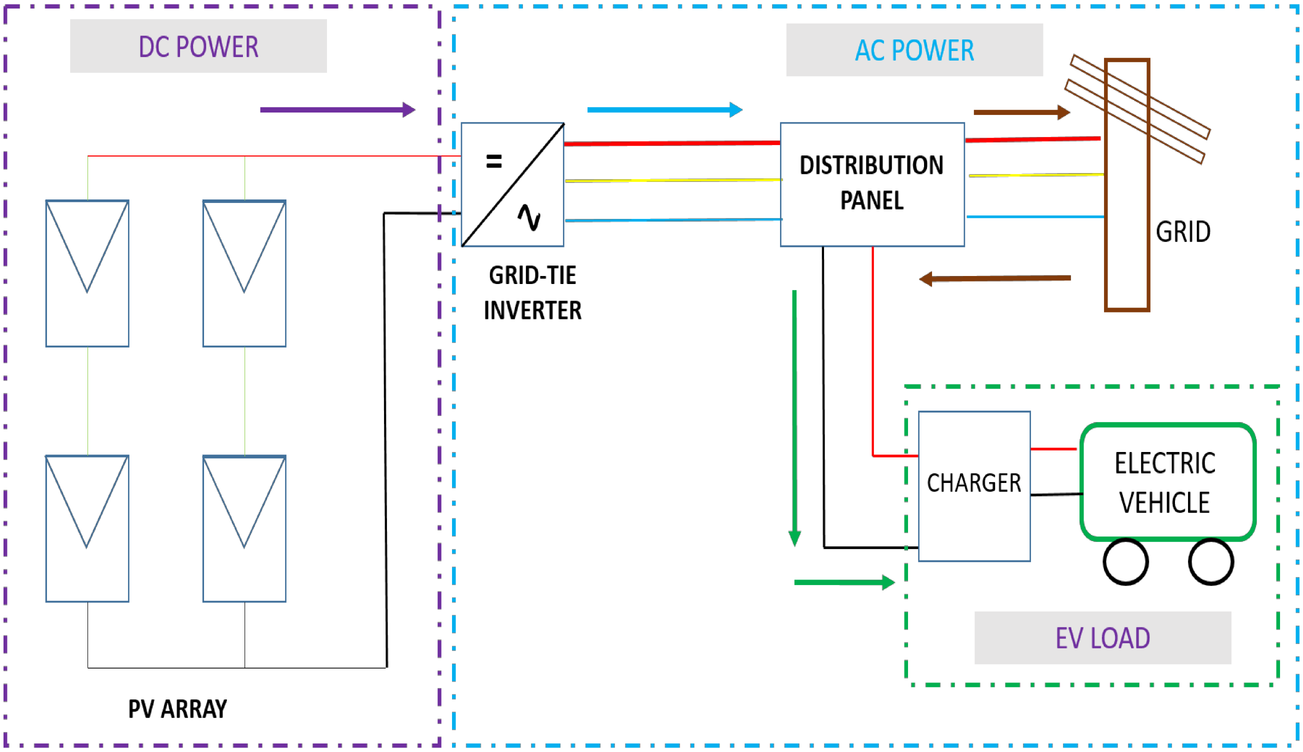


Figure 3.7: Block diagram of GCPV system without ESD for EVCS

In this type of architecture, the PV power generation is mainly used for meeting the load power requirements and the excess power other than charging EV load is injected into grid. Grid acts as a storage unit in this type of architecture. Similar type of system has been installed at Wilfrid Laurier University [42].

Merits

- Reliable system i.e. when the solar insolation is less (or) not available, grid will power the EVs.

- With the absence of storage system, the additional installation cost is reduced.

- With the presence of Feed-in-Tariff (FIT) and micro-FIT programs in Ontario [43], possibilities of achieving faster payback (with proper sizing of system components) is maximized.

Demerits

- Loss of energy storage capabilities with grid failure could pose a difficulty to meet load requirements.
- For large scale implementation, approval is needed from respective distribution utility companies.
- This system cannot be implemented in places where grid interconnectivity is not permissible.

3.4.4 Choice of System Architecture and Charging Level

One of the main objective of this work is to develop an economical system design for major urban cities. Rationality for choosing the architecture of section 3.4.3 are as follows:

- Reduced cost of investment compared to 3.4.2
- No complexity in system interconnection and installation
- Annual energy yield in 3.4.3 architecture is greater which is later discussed in section 4.3.

Some of the major technical benefits using this system at distribution level includes increase of renewable energy penetration in existing energy supply mix, reduction of electrical demands at peak and non-peak hours, diminution of adverse effects on distribution transformers, supports economic electricity generation and consumption, de-congestion of transmission lines, minimization of transmission line losses, curbs phase imbalance and, prevention of generator outage. The level II charging standard is considered for analysis of designed GCPV system in this work due to the fact that the amount of charging time almost matches with available sun hours.

3.4.5 Functions of Each Component in Selected Architecture

The major components used in selected architecture are: PV modules, grid-tie inverter, cables, connectors, mounting system, disconnects and, EVCS. PV module, and EVCS used have been discussed earlier in section 3.1, and section 3.3 respectively.

Grid-tie Inverter

Grid-tie inverter is the functional component that converts 'DC Power' generated from solar panels to 'AC Power' and, is interfaced with the distribution system [35]. Also, it performs other key functions such as synchronizing the system generated voltage and frequency with the grid, guarantees the Maximum Power Point (MPP) tracking from array, ensures anti-islanding and, prevents injection of harmonics into the grid (deformation of current signals/waveform due to grid-tie inverters). Grid-tie inverters are typically similar to the operation of a current source inverter and their efficiencies in real world lies between 94 to 96% [45]. The grid-tie inverter rating used in the simulation model is obtained by varying power ratio (PR) (ranging from 0.5 to 1.5) and attains 95% peak efficiency at its rated load.

Cables, Connectors, Mounting System and Disconnect

The system interconnection is incomplete without cables (copper conductors), connectors, mounting racks for placement of PV panels, and safety disconnects on DC power and AC power side [35] [36]. Without these axillary components energy transfer from PV panels to EV charger cannot take place.

3.4.6 Losses Associated with Selected Architecture

Designing (or) developing a PV system to operate at 100% efficiency is practically impossible. Reason being the associated components in the system will not be 100% efficient, losses are integral with them. Losses in the system may incur due to manufacturing of PV panel, switching and operational losses in the inverter module, ohmic (copper wire) losses, external climatic conditions (dust), shading and snowing (which is not considered in this thesis work), system integration losses such as current and voltage mismatch, etc.

The flow of energy losses from solar panel to EV charger of the selected GCPV architecture is shown in Figure 3.8. The detailed explanation of critical losses associated with this type of system is presented in below in detail.

Mismatch and dust loss

When solar panels are interconnected in series (or) parallel to obtain the desired voltage and current specification, the IV characteristics of the interconnected panels must be identical. If not, this results in either voltage mismatch loss (or) current mismatch loss. So proper attention should be given towards solar panel interconnection which will help in minimizing this type of loss. Mismatch loss also occurs when shading occurs on a region of the panel while the other section is unshaded, this effect can be minimized by the use of bypass diodes in circuit interconnections. Dust loss is one phenomenon which cannot be controlled from occurring but can be minimized by proper monitoring of the solar panels and removing dust placed on the panels either manually or through some automatic cleansing system.

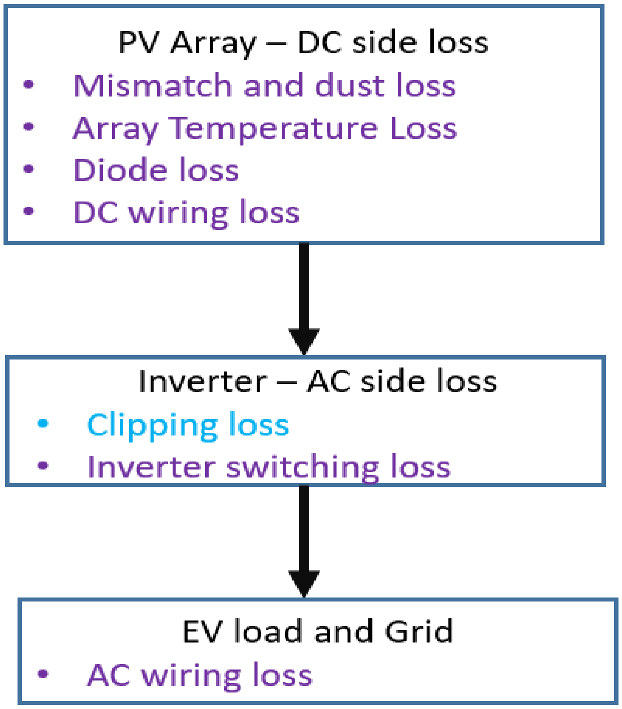


Figure 3.8: Loss components in the GCPV

Array Temperature Loss

Array temperature loss occurs generally due to inherent characteristics of solar cells in the module, with increase in temperature, generally the power output of the PV module is reduced and with decrease in temperature the power output increases [35] [36]. The efficiency of the panel used is 16.46% at STC [27] (Standard Test Conditions i.e. the incident solar insolation is 1000 W/m^2 at 25 ^{o}C ambient temperature) but this will vary depending upon the insolation and temperature. Due to the variation in temperature there will be reduction in voltage from panel output, despite increase in current, the overall power generated decreases. The temperature coefficients of the panel used are as follows: Temp.coefficient (Pmax), μ = -0.41% / ^{o}C, Temp.coefficient (Voc) = -0.31% / ^{O}C, Temp.coefficient (I_{sc}) = 0.053 / ^{o}C. First order behaviour of PV output can be captured using these coefficients.

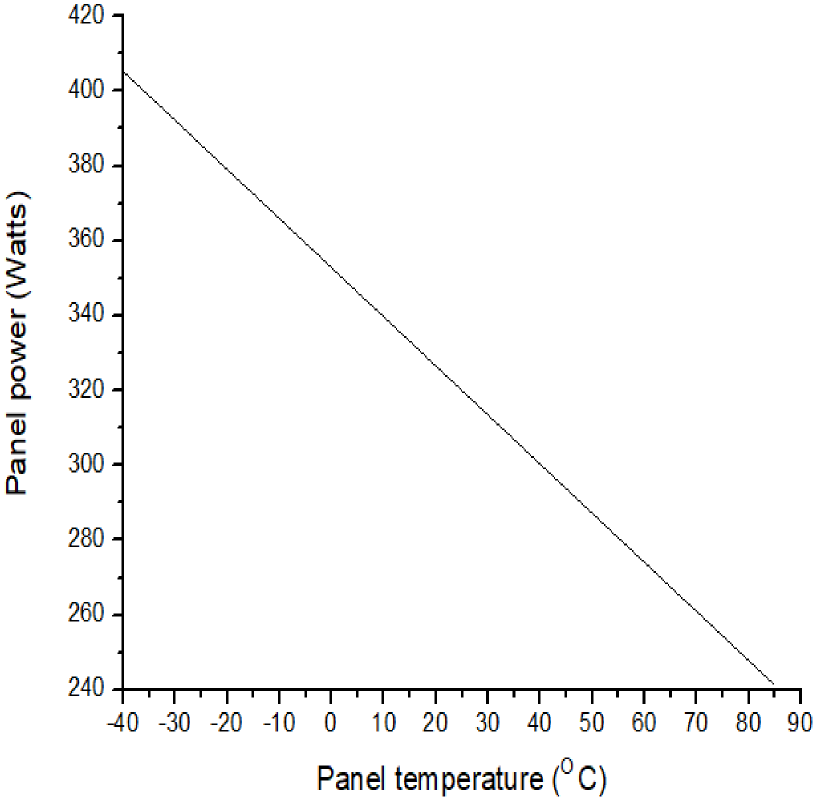


Figure 3.9: Panel power variation with temperature of CS6U-320P

Figure 3.9 shows the variation of power generated with respect to temperature. The equation used for estimating the power generated by the solar panel is given below:

$$P_T = \frac{P_{max} + ((\mu)(T_c - T_{stc})(P_{max}))}{100} \qquad (3.9)$$

Where,

P_T - Power to be calculated at required temperature, Watts

T_c - Temperature of cell, Celsius

T_{stc} - $25\,^{o}$ C (Standard Test Condition)

P_{max} - Nominal maximum power at STC, Watts

Diode Loss

Diodes are typically used in all PV systems either as a bypass switch or blocking device. Loss occurs in diodes when switching takes place in circuit. Figure 3.10 provides information on positioning of diodes in PV systems. This is one of the loss components that cannot be eliminated or reduced.

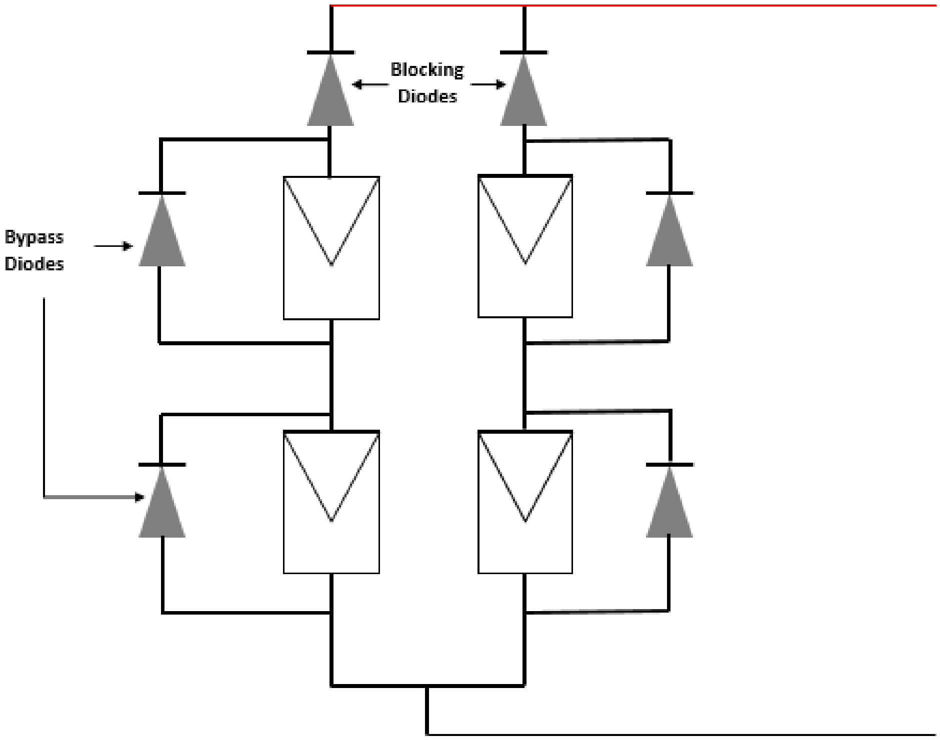


Figure 3.10: Example of diode interconnections with PV systems

DC Wiring Loss

This refers to the copper loss occurring when current flows from the PV panel to the inverter [35] which can be calculated using the following equation:

$$P_{DCL} = I^2_{PVO} R_{DC},\ Watts \tag{3.10}$$

This loss cannot be eliminated but can be reduced by choosing appropriate copper gauge. Where,

P_{DCL} - Power loss due to DC wiring from PV panel to Inverter, Watts

I^2_{PVO} - DC current from PV panel output, Ampere

R_{DC} - DC resistance of cable and interconnecting wires, Ohm

Inverter Clipping Loss

This type of loss generally occurs when the PV array is oversized compared to that of inverter rating and, outlined in Figure 3.11 [44]. Such type of designs are also present in real world applications, reason being in certain places, the solar insolation is very less (example: Netherlands). However, certain designers purposefully oversize the PV array in order to reduce conversion losses and, also due to economic constraints. The optimized design must ensure that even when the panels are tilted or utilizes tracking system, the effect of clipping loss is insignificant. This will be one important loss phenomenon that would be looked into keenly in this thesis work.

AC Wiring Loss

This is the copper loss occurs when current flows from inverter to EV load and grid which is calculated using the following equation:

$$P_{ACL} = I^2_{INO} R_{AC},\ Watts \tag{3.11}$$

This loss cannot be eliminated but can be reduced by choosing the appropriate copper gauge.

Where,

P_{ACL} - Power loss due to AC wiring from Inverter to EV load and grid, Watts

I^2_{INO} - AC current from PV panel output, Ampere

R_{AC} - AC resistance of cable and interconnecting wires, Ohm

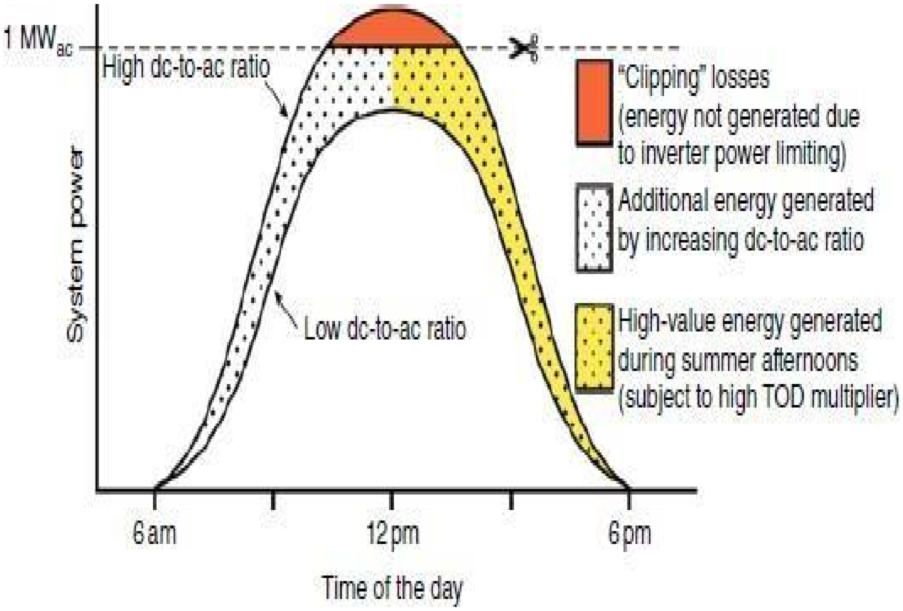


Figure 3.11: Impact of Inverter clipping loss

3.5 Parameters for Evaluating System Design

Given below are definition of certain key parameters used to evaluate the system design in this thesis work and, are obtained from [41].

3.5.1 Annual energy (AE)

The term annual energy indicates sum of energy generated by the GCPV system and, measured from output of inverter.

$$AnnualEnergy = \sum(AC\ Energy\ Output\ of\ Inverter\ of\ all\ Months)\ kWh \tag{3.12}$$

3.5.2 Levelized cost of energy (LCOE)

LCOE is defined as the unit cost of electricity from any generating asset, it is usually calculated for the lifetime of generation asset. Formula for calculating LCOE is given below [44]:

$$LCOE = \left\{ \frac{(FDCR \times CC) + FAOC}{ANEP} + VC \right\} cents/kWh \tag{3.13}$$

Where,

FDCR - Fixed charge rate

CC - Capital Cost, \$

FAOC - Fixed annual operating cost, \$

ANEP - Annual electricity production, kWh

VC - Variable Operating Cost, \$

3.5.3 Payback period (PBP)

It is defined as the number of years taken to return the capital cost of investment used for GCPV system (solar modules and inverter), charging station and, associated BOS. However, SAM calculates it using the formula given below [44], wherein the debt of the GCPV system is not considered:

$$PBP = \frac{(N_y \times x) - (M_y \times z)}{(N_y - M_y)} \ years \tag{3.14}$$

Where,

N_y - Cash flow in payback year +1, \$

M_y - Cash flow in payback year, \$

x - Payback year, years

z - Payback year +1, years

In this work, parameter 3.5.1 is considered to be performance metric whereas parameter 3.5.2 and parameter 3.5.3 are economic metric for system design.

3.6 Summary

This chapter not only provides complete background for this thesis work but it also provides information on the type of PV module, effects of orienting PV modules, levels of EV charger, different possible system design architecture for charging station with PV integration, losses associated with selected architecture, and finally the parameters to evaluate system design.

Chapter 4

Design One – GCPV for EVCS

In this Chapter, first detailed information about methodology of system design of GCPV system for EVCS will be discussed. Then analysis set-up for testing the designed system is provided, followed by results and discussion of analysis. Finally, summary of the complete system design and, analysis is provided.

4.1 Methodology

The methodology for designing the system for selected architecture (explained in section 3.4.1) is demonstrated in Figure 4.1. For PV sizing several approaches have been suggested in [40] [47], however here we have used an approach to match power demand of EV load. Formula used for PV array sizing is given in equation 4.1. Simplified load profiles are developed by taking peak value from [49], it is outlined in Figure 4.2. Efficiency of components are assumed.

$$P_{PV} = \frac{P_{EV_p}}{\eta_{ACC} \times \eta_{inv} \times \eta_{DCC} \times \eta_{MM} \times \eta_{DiC} \times \eta_{ASL}} \tag{4.1}$$

Where,

P_{PV} - Panel power sizing, kW

$P_{EV p}$ - Peak power of one EV, kW

η_{ACC} - 98% (Efficiency of AC Cable)

η_{inv} - 95% (Efficiency of Inverter)

η_{DCC} - 99% (Efficiency of DC cable)

η_{MM} - 99% (Efficiency of panels after module mismatch)

η_{DiC} - 99.5% (Efficiency after diodes & connections loss)

η_{ASL} - 95% (Efficiency after annual soling loss)

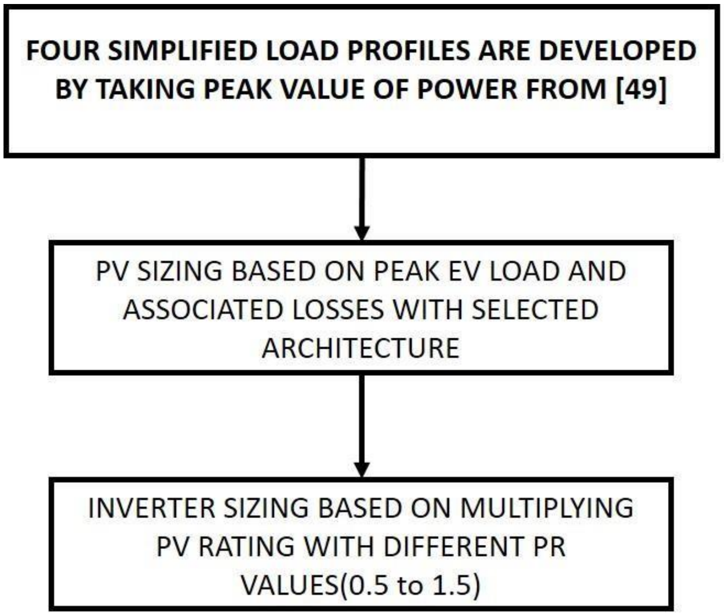


Figure 4.1: Design Approach

By using the above mentioned efficiency in equation 4.1, the power of PV panel needed was calculated and value obtained was 7.689 kW. Since there is constraint due to the panel manufacturing size, 7.675 kW was utilized as the PV panel power rating right through the analysis in this thesis work. The electric vehicle considered for this complete simulation study is ‘Volkswagen e-golf’ with battery capacity of 36 kWh [50] and, different load models are developed considering this EV. 4 types of electric vehicle load models are employed in this thesis work and it is clearly shown in Figure 4.2, they are described below:

a. During the daytime matching the sun hours

b. During the nighttime considering the reduction in price

c. Anytime charging within the day

d. All time charging (4 EVs charging at the station one after another)

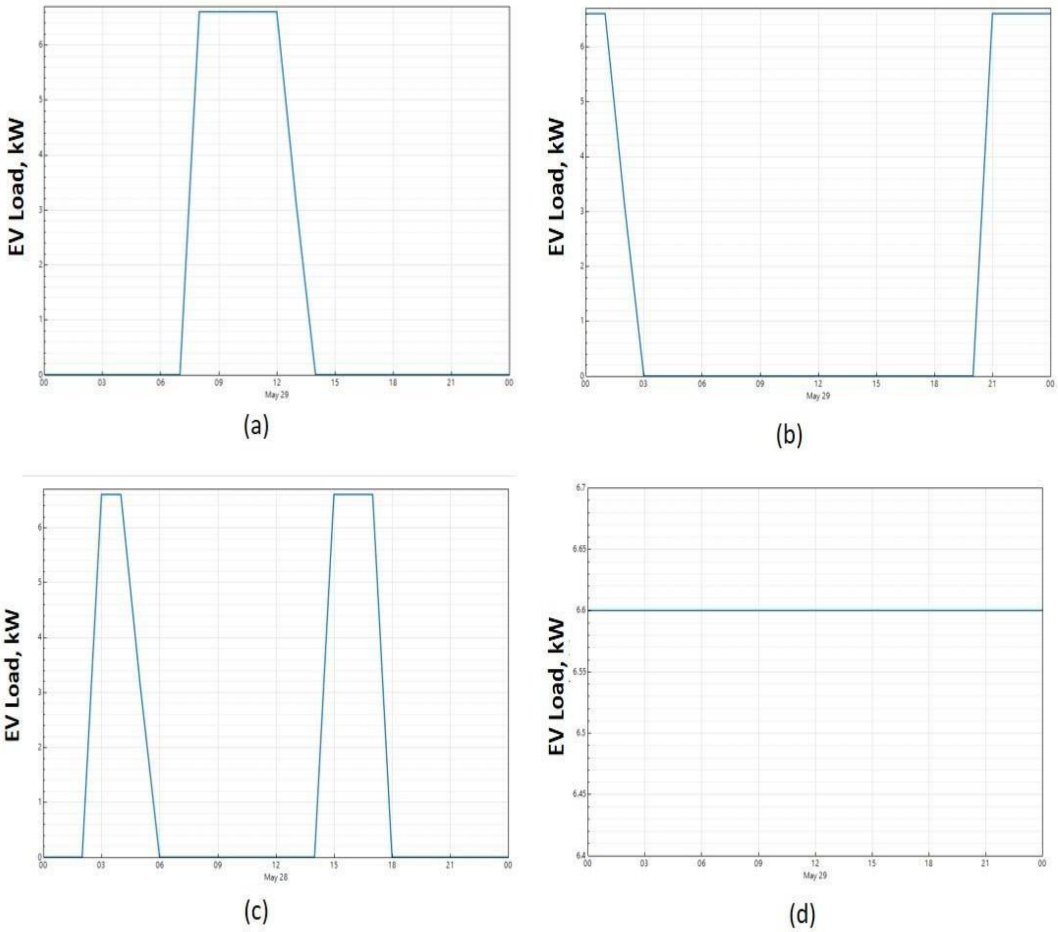
Power Ratio (PR)

It is an important design variable used in this thesis work. It is the ratio between rated output DC power of PV array to the rated AC power output of the inverter [52].

It is also a unit less quantity.

$$PR = \frac{Rated\ Array\ DC\ Power\ Output\ (kW)}{Rated\ Inverter\ AC\ Power\ Output\ (kW)} \tag{4.2}$$

It is one of the key parameter used in this thesis work to size the inverter. The inverter rating is calculated by multiplying the power ratio (Ranging from 0.5 to 1.5) with peak power of PV, it is outlined in Table 4.1.



(a) (b) (c) (d)

Figure 4.2: Developed EV load models

4.2 Analysis Set-up

The designed simulation based GCPV system will be tested with above mentioned load models. Performance of the system will be tested in 3 selected urban cities within Ontario. The simulation model has been done using SAM 2017.9.5 (System Advisor Model) developed by

National Research Energy Laboratory (NREL), USA. Complete analysis set-up is outlined in Figure 4.3. Sample GUI of SAM is shown in Figure 4.4.

Table 4.1: Inverter Sizing

Solar PV Rating = 7.675 kW	
DC to AC Ratio	Inverter Rating, kW
0.5	15.350
0.6	12.791
0.7	10.964
0.8	9.593
0.9	8.527
1.0	7.675
1.1	6.977
1.2	6.935
1.3	5.903
1.4	5.482
1.5	5.116

Table 4.2: Difference in simulation models

Description	A (At PR 0.9)	B (At PR 0.9)
Energy storage type	Not applicable	Li Ion battery [1]
Rating, kW and kWh	Not applicable	(1 to 15 kW and 1 to 15 kWh)
Total installed cost, $	17,435.40	17,749.54 to 22042.79

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[1] Batteries are most popular energy storage devices for renewable energy systems [58] [59] [60], in this work, Lithium ion battery was chosen for faster charging rate, faster discharging capability and, high power density compared to other battery types [61].

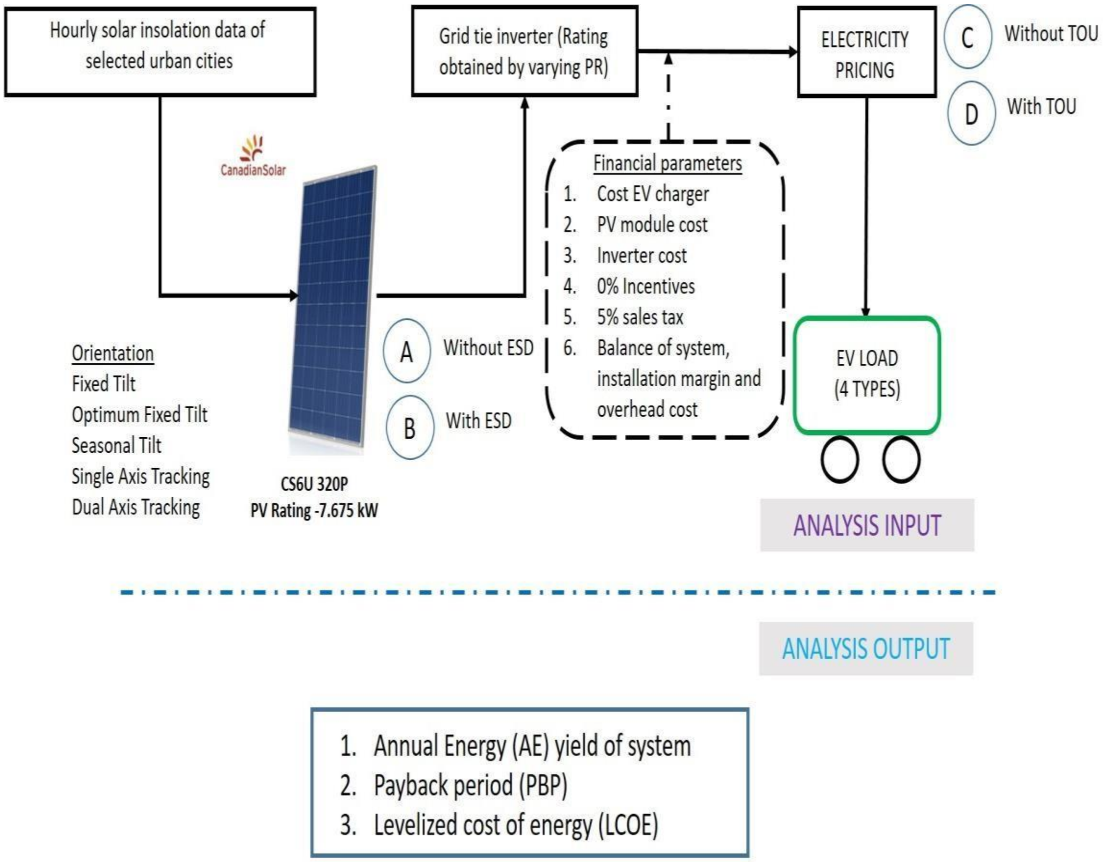

Figure 4.3: Analysis set-up

For the above analysis setup, solar insolation is sourced from [51], cost of EV charger is obtained from [54], PV module cost from [55]. Inverter cost, balance of system, installation margin and overhead cost are obtained from [56] and Time of use rates from [53]. Various analyses on selected architecture along with its outputs in this thesis work are outlined in Table 4.3. Parametric analysis[2] was done in SAM for the above simulation models outlined in Table 4.2. Results of Pay Back Period vs Battery Bank Capacity vs Battery Power for the above set up are shown in Figure 4.5 and, AE is shown in Table 4.4. Also, system without ESD was analyzed with and without TOU - (Time of Use) electricity pricing, and PBP results of both set up are shown in Table 4.5.

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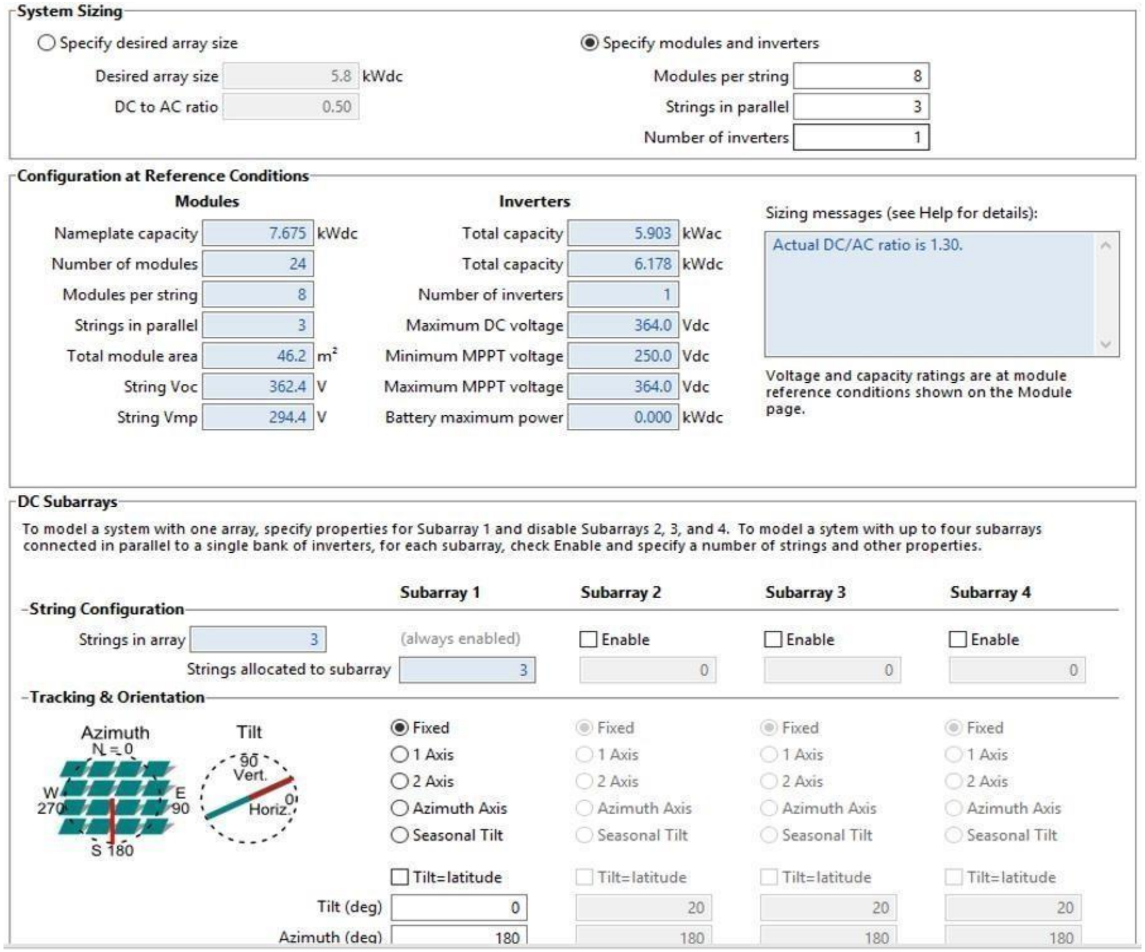
[2] will be explained with its appropriate GUI in the appendix



System Sizing

○ Specify desired array size

Desired array size 5.8 kWdc

DC to AC ratio 0.50

● Specify modules and inverters

Modules per string 8

Strings in parallel 3

Number of inverters 1

Configuration at Reference Conditions

Modules			Inverters		
Nameplate capacity	7.675	kWdc	Total capacity	5.903	kWac
Number of modules	24		Total capacity	6.178	kWdc
Modules per string	8		Number of inverters	1	
Strings in parallel	3		Maximum DC voltage	364.0	Vdc
Total module area	46.2	m^2	Minimum MPPT voltage	250.0	Vdc
String Voc	362.4	V	Maximum MPPT voltage	364.0	Vdc
String Vmp	294.4	V	Battery maximum power	0.000	kWdc

Sizing messages (see Help for details):

Actual DC/AC ratio is 1.30.

Voltage and capacity ratings are at module reference conditions shown on the Module page.

DC Subarrays

To model a system with one array, specify properties for Subarray 1 and disable Subarrays 2, 3, and 4. To model a sytem with up to four subarrays connected in parallel to a single bank of inverters, for each subarray, check Enable and specify a number of strings and other properties.

String Configuration

Strings in array 3

	Subarray 1	Subarray 2	Subarray 3	Subarray 4
	(always enabled)	☐ Enable	☐ Enable	☐ Enable
Strings allocated to subarray	3	0	0	0
Tracking & Orientation	● Fixed ○ 1 Axis ○ 2 Axis ○ Azimuth Axis ○ Seasonal Tilt	● Fixed ○ 1 Axis ○ 2 Axis ○ Azimuth Axis ○ Seasonal Tilt	● Fixed ○ 1 Axis ○ 2 Axis ○ Azimuth Axis ○ Seasonal Tilt	● Fixed ○ 1 Axis ○ 2 Axis ○ Azimuth Axis ○ Seasonal Tilt
	☐ Tilt=latitude	☐ Tilt=latitude	☐ Tilt=latitude	☐ Tilt=latitude
Tilt (deg)	0	20	20	20
Azimuth (deg)	180	180	180	180

Figure 4.4: SAM GUI sample

Table 4.3: Analysis models and its output

Simulation Model **7.675 kW PV array, with varying inverter rating** **Urban cities utilized: Toronto, Ottawa, Thunder Bay**	Output to be shown **in section 4.3**
With zero tilt angle orientation, AE vs PR	Figure 4.6
Energy balance with zero tilt orientation (Toronto)	Table 4.6
Designed system annual performance with load (a), load (b), load(c) (Toronto)	Figure 4.7, Figure 4.8, and Figure 4.9
Electricity bill comparison with and without system for all loads	Table 4.7
PBP, LCOE vs PR	Figure 4.10
AE, PBP vs Tilt angles - For Toronto at 1.1 PR	Figure 4.11
AE, PBP vs Tilt angles – For Ottawa at 1.1 PR	Figure 4.12
AE, PBP vs Tilt angles – For Thunder Bay at 1.1 PR	Figure 4.13
AE vs PR - For all locations with optimum tilt angle	Figure 4.14
Seasonal tilt angles for all locations	Table 4.8
AE vs PR - For all locations using seasonal tilt angles	Figure 4.15
AE vs PR - Using single axis (opt) tracking for all locations	Figure 4.16
AE vs PR – Using dual axis (opt) tracking for all locations	Figure 4.17
AE, PBP vs PR[3] – Comparison with all orientations (Thunder Bay)	Figure 4.18

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[3] Assuming 500 $, 1000 $ per kW for implementing 1 axis and, dual axis tracking methodology

4.3 Results and Discussion

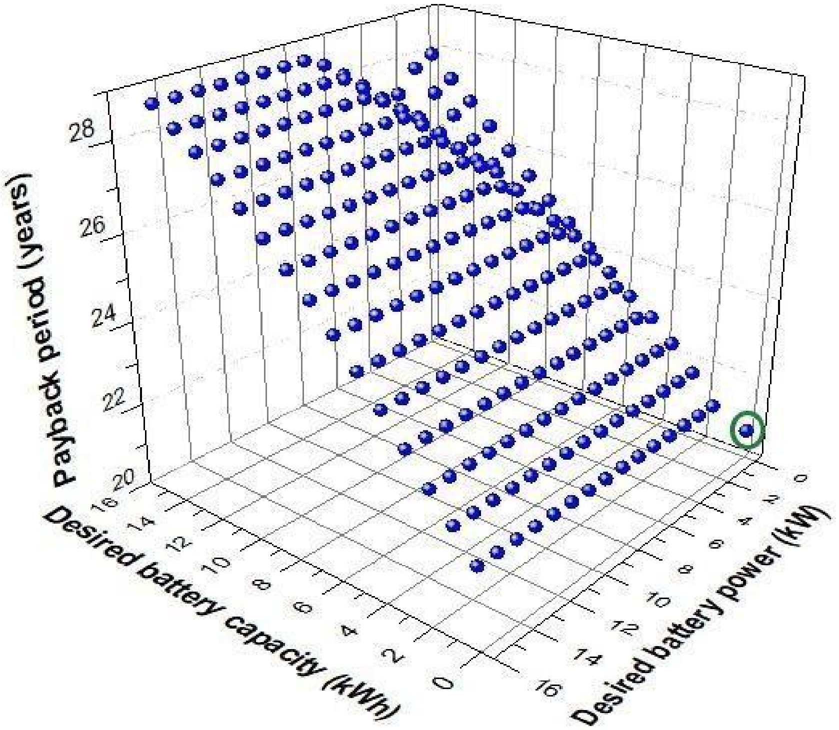


Figure 4.5: PBP VS Battery bank capacity VS Battery power

Table 4.4: AE Comparison

	GCPV for EVCS without ESS	GCPV for EVCS with ESS
Annual Energy Yield, kWh	7947	7900

Table 4.5: PBP comparison at 1 PR for Thunder Bay location

	GCPV for EVCS without TOU	GCPV for EVCS with TOU
Payback period, years	24.8	21.5

Results from Figure 4.5, and Table 4.4 prove that by employing the GCPV architecture without ESD, faster payback can be attained. Also, its annual energy yield is greater than the architecture with ESD.

From Table 4.5, designed system attains faster payback when it uses electricity rates with TOU. From Figure 4.6, it can be seen that AE starts to increase from initial PR of 0.5 to 1.3 PR, after which decreases. Reason for the reduction of AE after 1.3 PR is clipping losses of the system. GCPV system located in Toronto generates 558, 531 kWh more energy than Thunder Bay and, Ottawa respectively. Toronto receives more of global horizontal and normal irradiance than Thunder Bay and, Ottawa as per [51]; simulation results validate it.

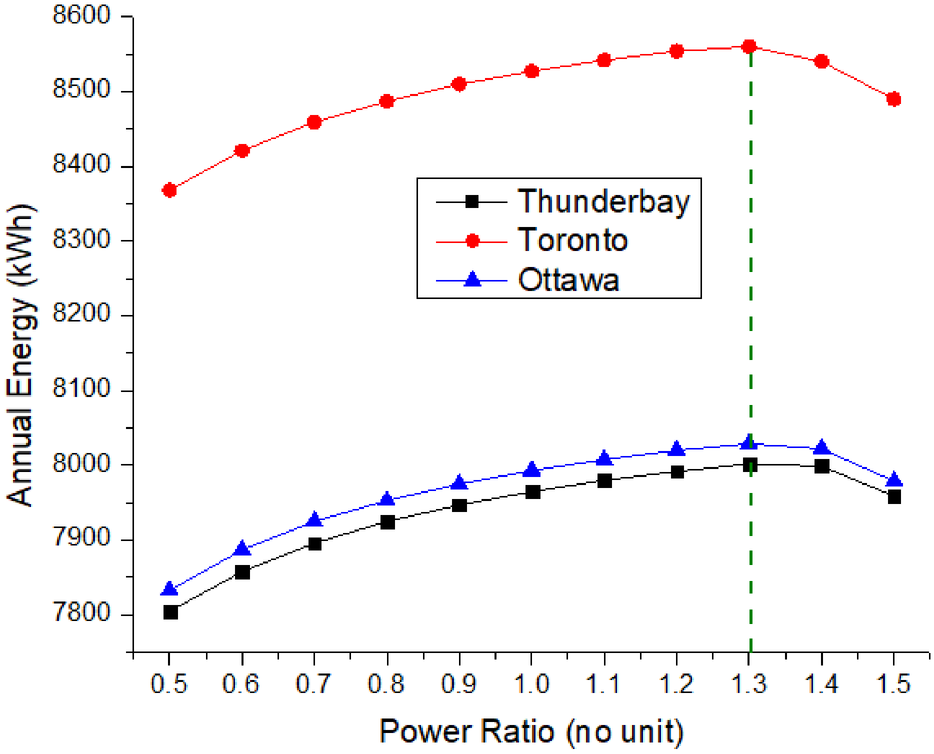


Figure 4.6: AE vs PR for zero degree tilt

Table 4.6: Energy balance of the System

Month	**System AC Energy (kWh/mo) E_S**	**Electricity to/from Grid (kWh/mo) E_G**	**Electricity Load (kWh/mo) E_L**
Jan	290.089	-825.911	1116
Feb	446.589	-561.411	1008
Mar	735.271	-380.729	1116
Apr	904.19	-175.81	1080
May	1095.78	-20.220	1116
Jun	1200.71	120	1080
Jul	1161.08	45.08	1116
Aug	1017.14	-98.86	1116
Sep	783.038	-296.962	1080
Oct	450.655	-665.345	1116
Nov	274.244	-805.756	1080
Dec	201.45	-914.55	1116

Negative sign of E_G from Table 4.6 indicates that grid is supplying more energy than solar panels to satisfy the demand. Positive sign indicates that solar energy has met the demand and, excess energy has been injected into the grid. Using this above table system performance can be validated using simple formula below:

If $E_S < E_G$,

$$E_L = E_S + E_G \tag{4.3}$$

If $E_S > E_G$,

$$E_L = E_S \tag{4.4}$$

If E_S is not available,

$$E_G = E_L \tag{4.5}$$

If E_L is not available and solar insolation is available,

$$E_S = -E_G \tag{4.6}$$

$$E_S = P_s \times H_S - E_{LOS} \qquad (4.7)$$

Where,

E_L - Monthly energy demand from EV load, kWh

E_S - Monthly energy supplied from PV system, kWh

E_G - Monthly energy supplied from grid, kWh

E_{LOS} - Energy lost (due to cabling, clipping, inverter internal losses), kWh

H_S - Number of sun hours

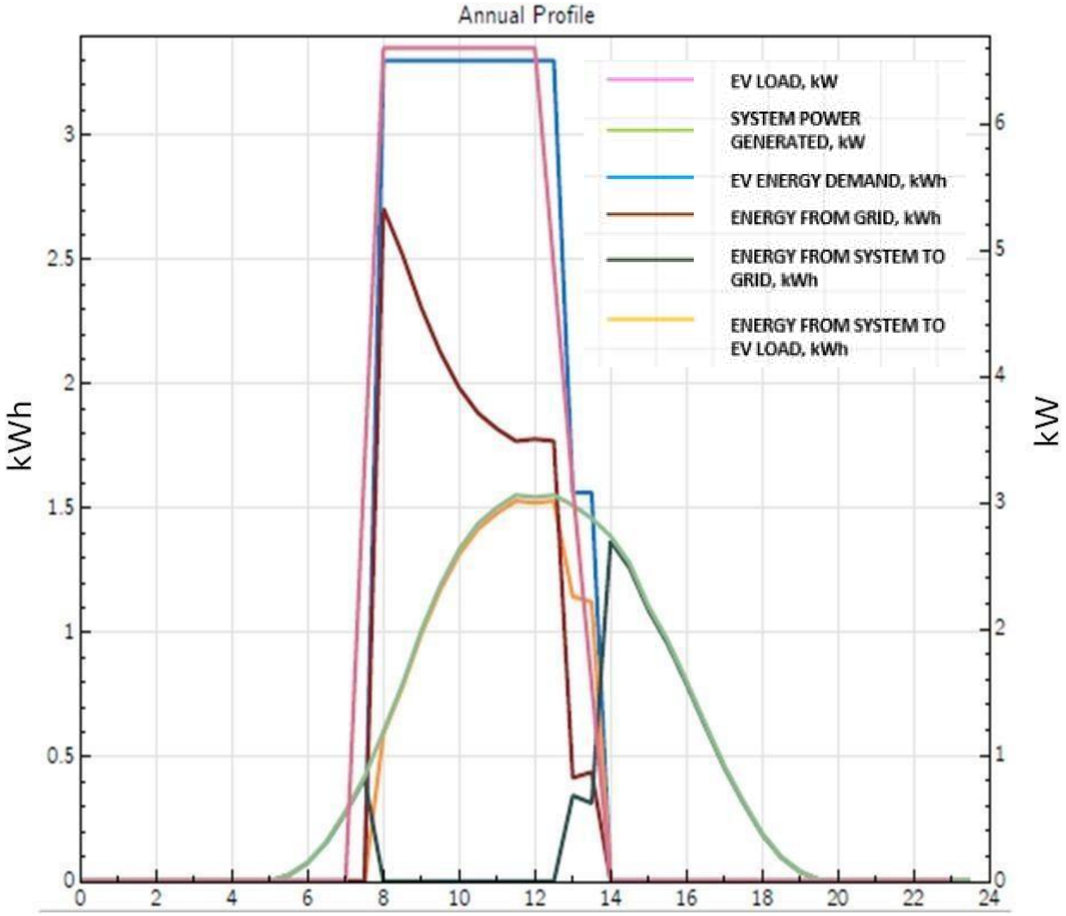


Figure 4.7: Designed system's annual performance at Toronto with load (a)

From analysis with different loads a, b, and c, there is no change with respect to AE, PBP, and LCOE but difference is observed in the electricity billings. It is because with load (a), participation of system energy in charging EV is higher; with load (b) there is no effect, and with load (c) there is appreciable energy in charging. Detailed comparison of system performance with load (a), load (b) and, load (c) is provided in Table 4.7. Performance profile with load (b), and load (c) is outlined in Figure 4.8 and Figure 4.9 respectively.

Table 4.7: Comparison of different EV load with designed system

EV Load	Electricity Bill without system, $	Electricity Bill with system, $
Load (a)	1568	364
Load (b)	1295	91
Load (c)	1006	-199

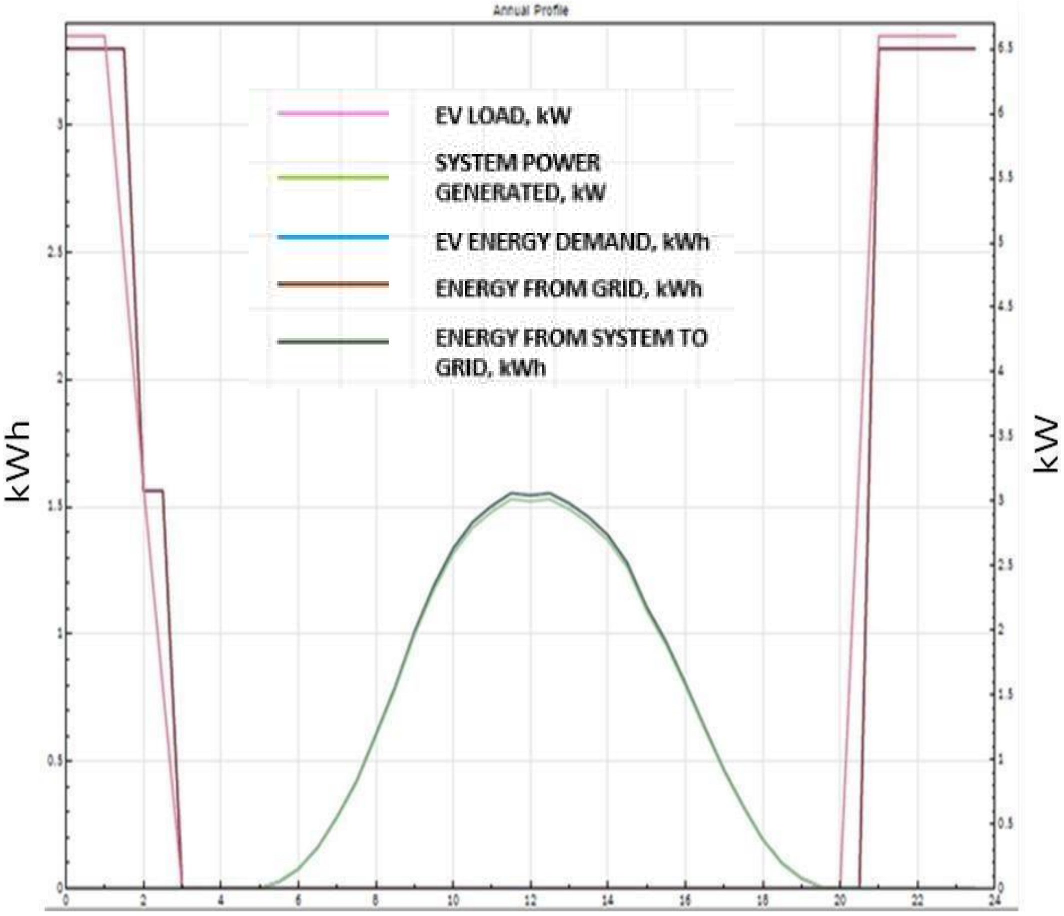


Figure 4.8: Designed system's annual performance at Toronto with EV load (b)

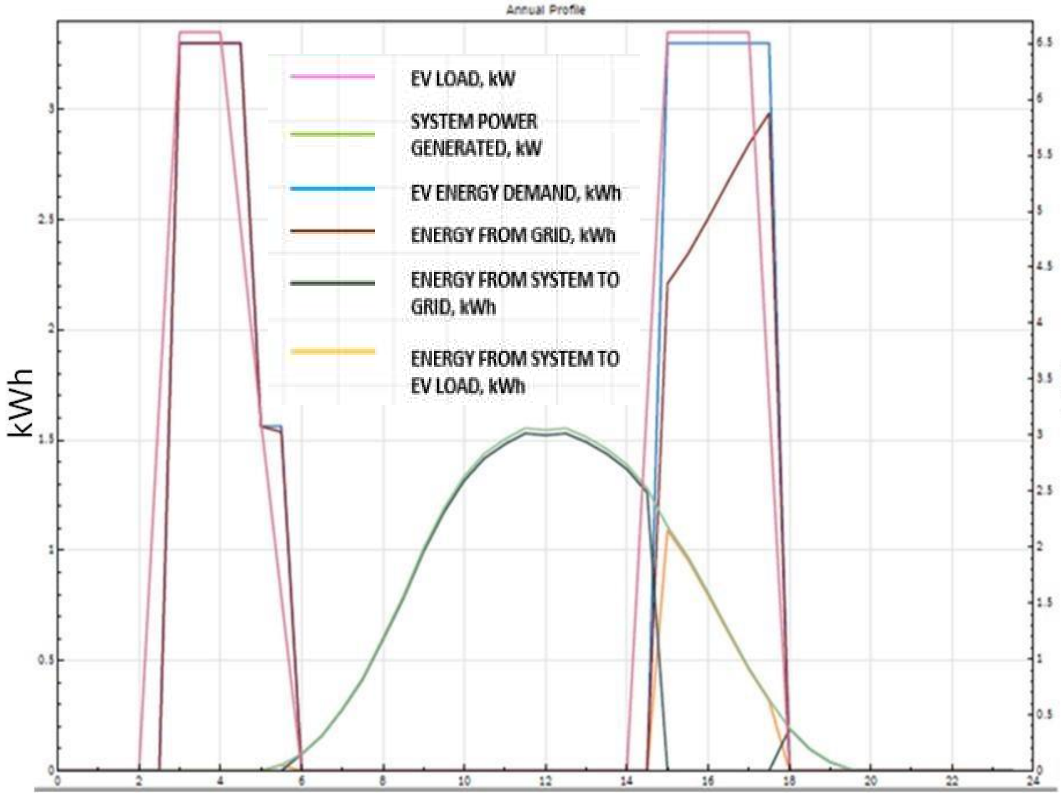


Figure 4.9: Designed system's annual performance at Toronto with EV load (c)

PBP, LCOE vs PR plot for all three cities is shown in figure 4.10. Faster payback and, lowest LCOE is observed at 1.3 PR for all locations. Parametric analysis has been done in SAM and, optimum tilt angle for all selected cities are obtained by identifying highest AE and, lowest PBP. Results are outlined in Figure 4.11, Figure 4.12 and Figure 4.13. The optimum tilt angle obtained from analysis for Toronto is 33.5^o, Ottawa is 37^o and, Thunder Bay is 39.5^o. These optimum angle can be verified with [57] and, selecting appropriate city from it. From Figure4.11, Figure 4.12 and Figure 4.13, it can understood that system energy yield increased with appropriate optimum tilt angle which results in less energy from grid to charge EVs. There is nearly 12 to 15% increase in AE comparing optimum tilt angle orientation of all locations with respect to zero tilt orientation. Clipping losses occur very quickly with optimum tilt angle hence there is shift in selection of PR.

With seasonal tilt angle orientation there is nearly 14 to 16% increase of AE compared

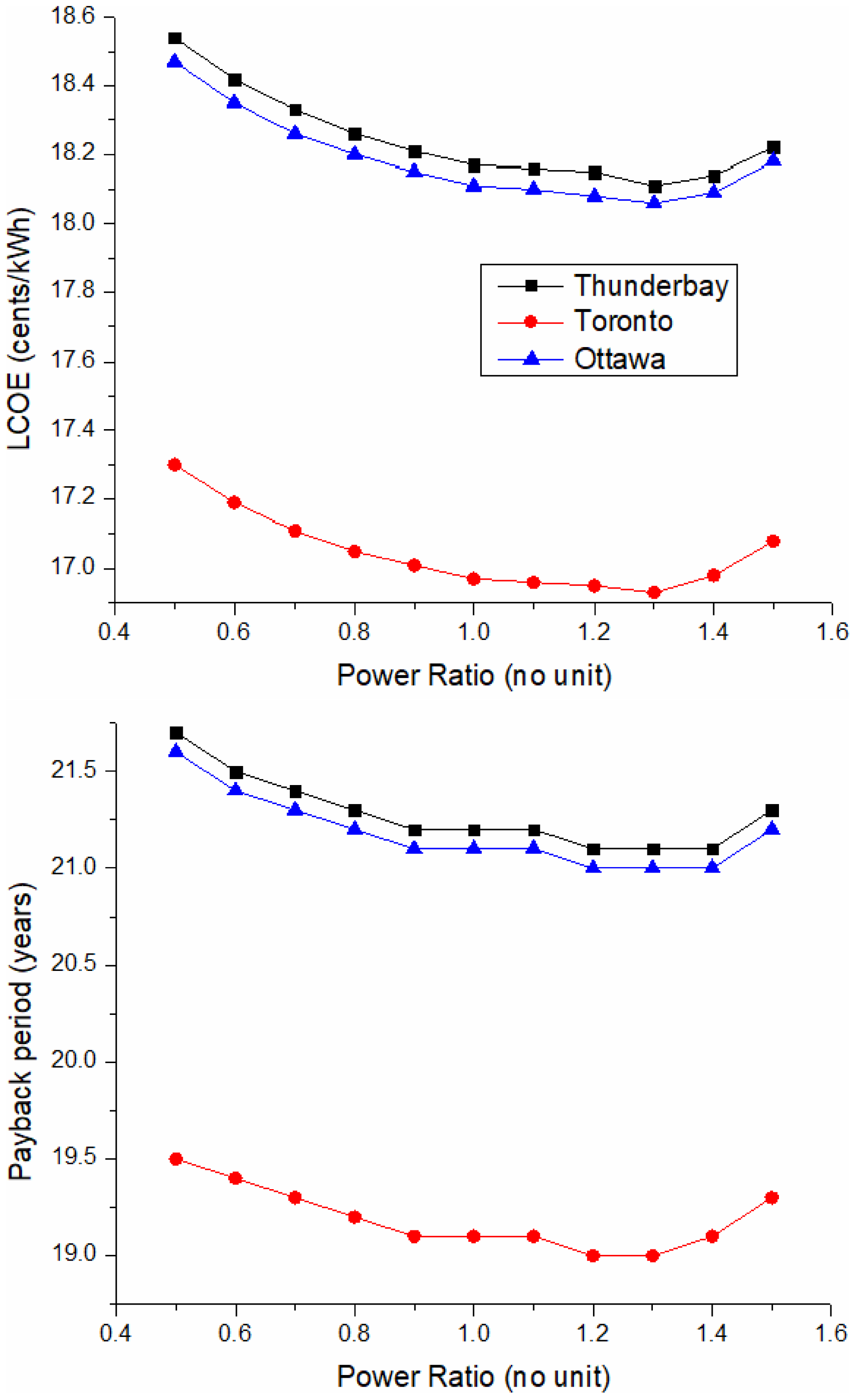


Figure 4.10: PBP vs PR, LOCE vs PR – For All locations

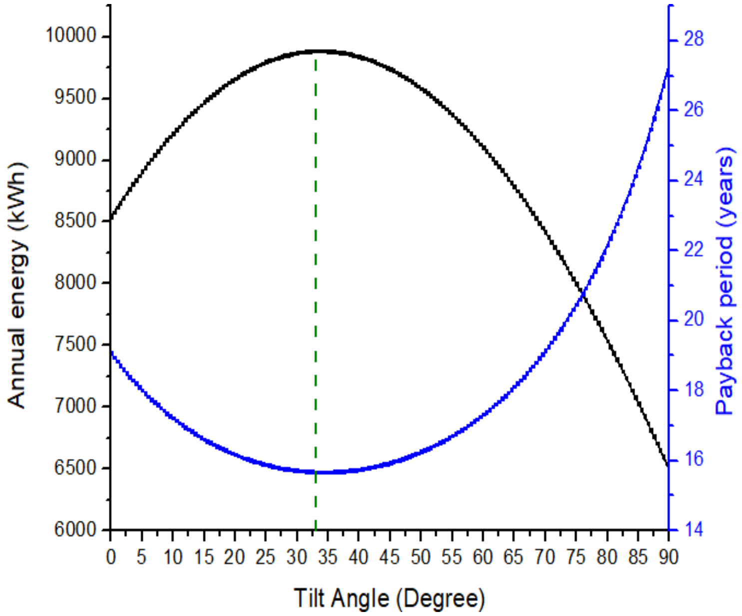


Figure 4.11: AE, PBP VS Tilt angles for location of Toronto for 1.1 PR

to zero tilt angles. From parametric analysis, angles were found to be 32.5^o, 35^o, and 39.5^o for Toronto, Ottawa and, thunder bay respectively. Using the angles, again analysis was performed to obtain AE vs PR plot for all locations were found and it is shown in Figure 4.16. The best PR for single axis tracking with optimum tilt angle was found to be 1. By using single axis tracking AE was increased by 30 to 40% compared to zero tilt angle with respect to all locations. With dual axis tracking implementation AE vs PR was obtained and it outlined in Figure 4.17. With dual axis, AE increases by 45 to 53%. However, the important aspect is to obtain the PBP for all these systems to determine the economical aspect of it. Comparison of AE, PBP VS PR for different panel orientations (for location of Thunder Bay) is done and, it is demonstrated in Figure 4.18. Dual axis tracking provides maximum AE followed by 1-axis, seasonal tilt (optimum), fixed optimum tilt and, zero tilt orientation; however from an economic stand point seasonal tilt seems to be an ideal solution for GCPV system for EVCS by keenly observing PBP from the plot.

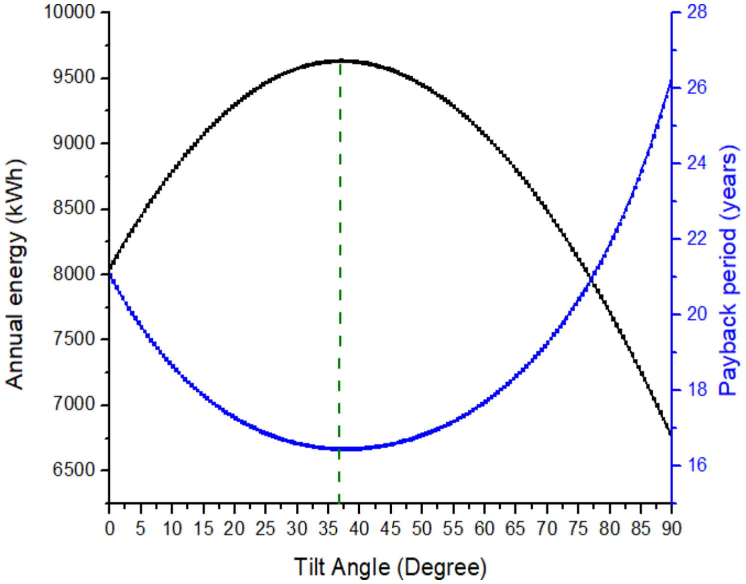


Figure 4.12: AE, PBP VS Tilt angles for location of Ottawa for 1.1 PR

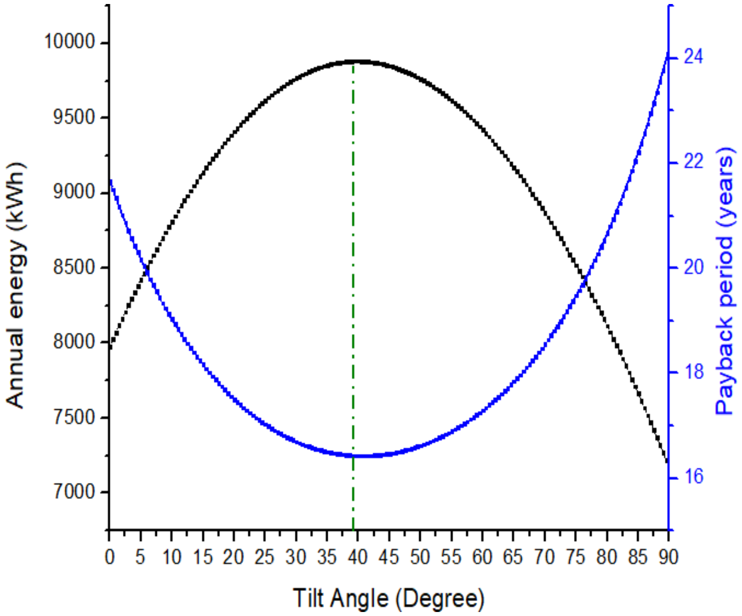


Figure 4.13: AE, PBP VS Tilt angles for location of Thunder Bay for 1.1 PR

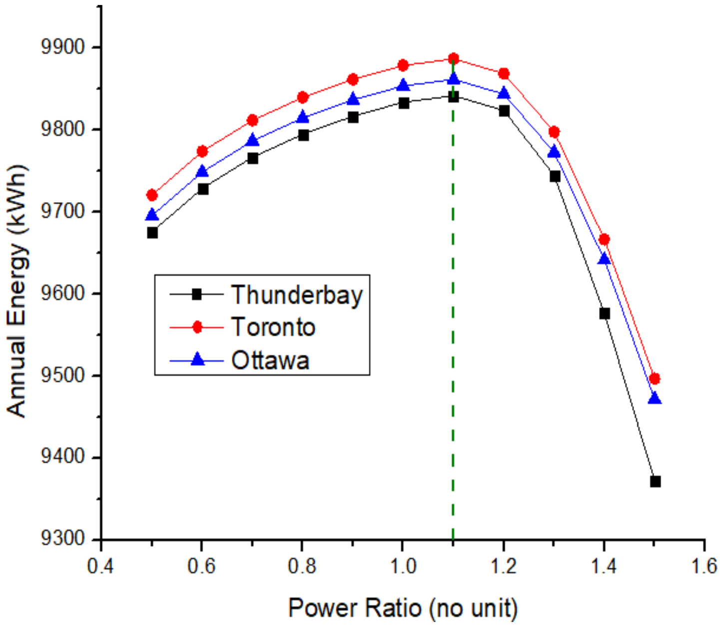


Figure 4.14: AE vs PR for Optimum tilt angle

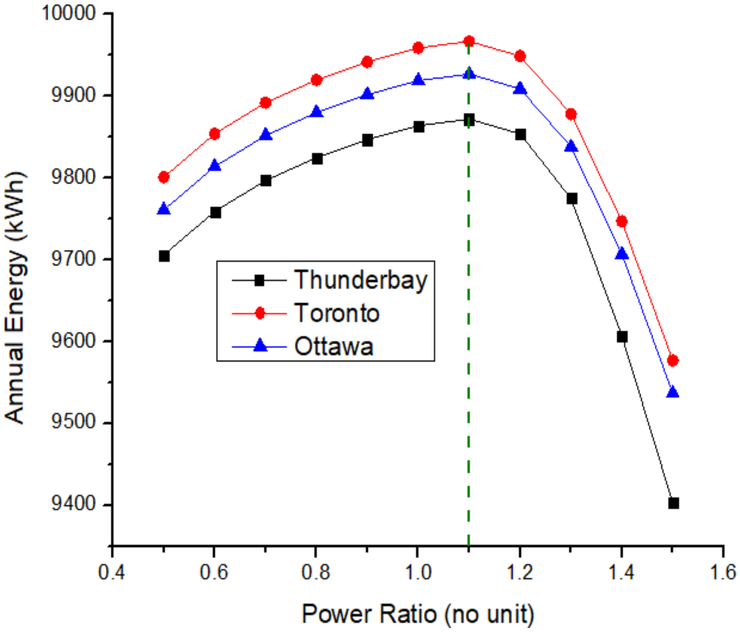


Figure 4.15: AE vs PR for seasonal tiltangles

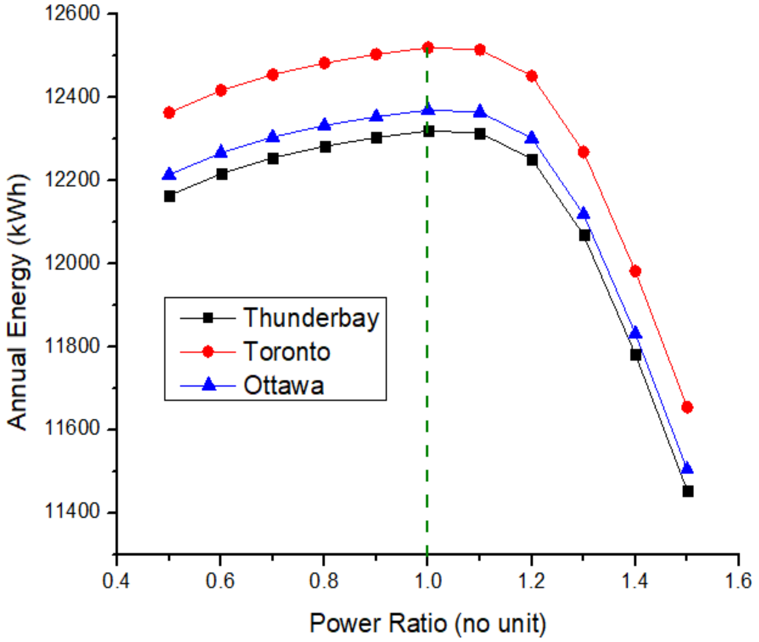


Figure 4.16: AE vs PR for Single axis tracking (with initial optimum tilt angle)

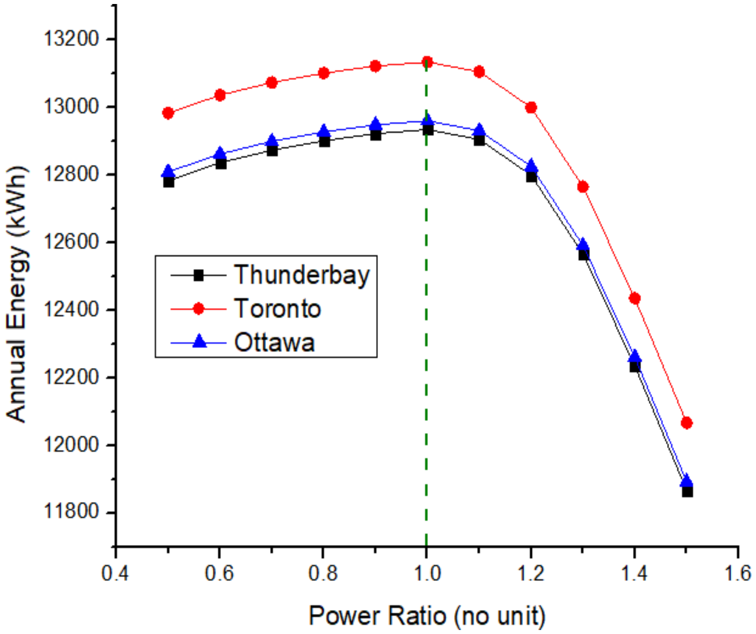


Figure 4.17: AE vs PR for Dual axis tracking

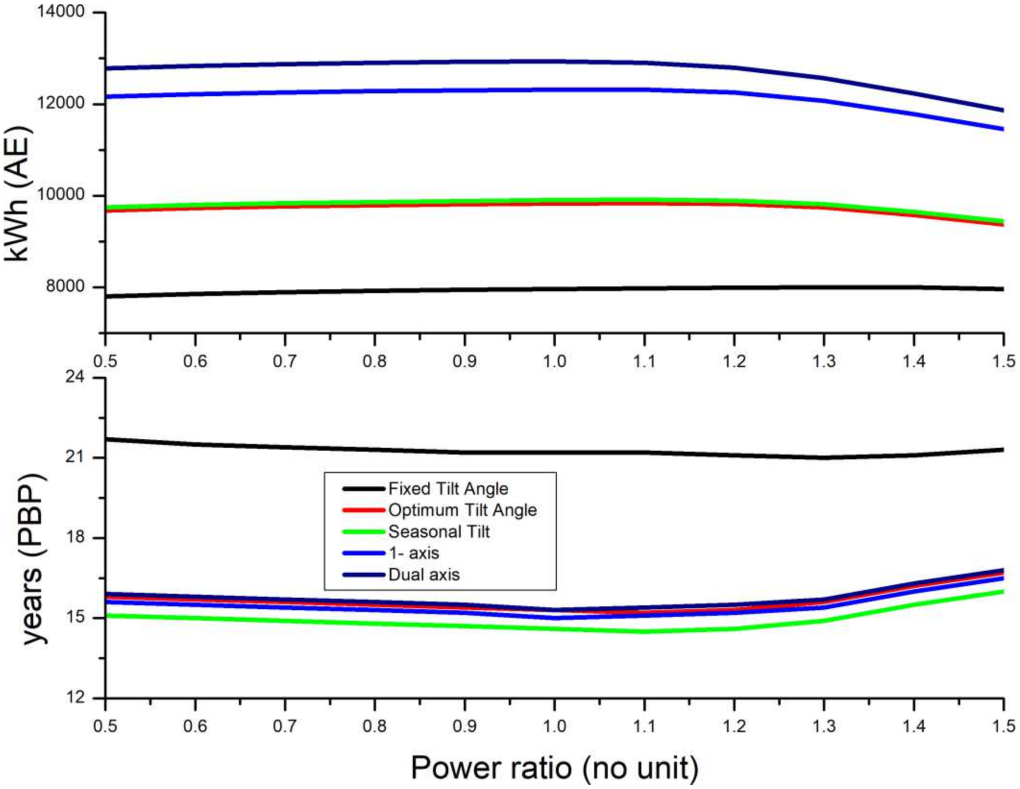


Figure 4.18: PBP, AE vs PR – Different orientation at Thunder Bay

4.4 Summary

GCPV system for EVCS: Design architecture without battery storage system yields faster payback period and, ensures greater annual energy yield that could be best suited for urban cities where grid is reliable and interconnectivity is permissible. Inverter modules used are not ones readily available, inverter sizing specified are customized for designed PV system.

Oversizing of PV panels could be done to get a system which is economical and with no inverter clipping loss, percentage of oversizing depends on the orientation of panels.30% oversizing could be done when panels are tilted at 0^o. 10% oversizing PV panels could be done whenever it is oriented with fixed optimum tilt angle, seasonal tilt angles, single axis tracking (without initial optimum tilt angle). With dual axis tracking AE is highest but PBP is slightly higher compared to 1-axis and, seasonal tilt orientation. No oversizing needs to be done for system with dual axis and single axis tracking (with initial optimum tilt angle). Seasonal tilt yields more energy than optimum tilt angle and, is better alternative as it is an economic option compared to single axis and, dual axis tracking systems due to faster PBP.

Chapter 5

Design Two – NZ GCPV for EVCS

From previous chapter, analysis of GCPV systems with different orientations was done, system with seasonal tilt angles yielded most economical option. In this chapter, we use this economical system for complete analysis and, methodology used for design will be different from earlier approach as final output required is the performance of NZSE (Net Zero Site Energy) based GCPV system for EVCS (considering all 4 types of load models stated in earlier chapter in section 4.1), and its environmental benefits. Results and discussion of new system designs will be provided, finally concluded with complete summary.

5.1 Methodology

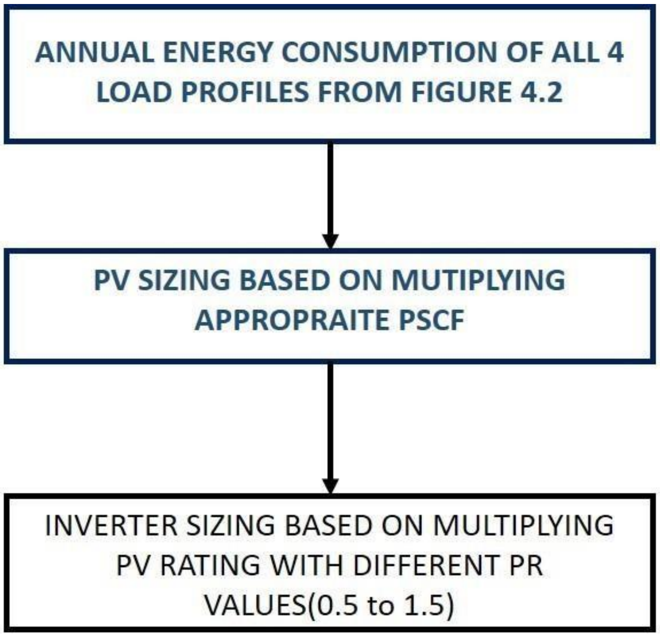


Figure 5.1: NZ Design Approach

For making changes to panel size, we will use the following formulae i.e., equation 5.1

and 5.2, monthly energy consumption of selected EV load (a) or load (b) or load (c) from Figure 4.2 is outlined in Table 5.1, and for load (d) it is outlined in Table 5.2.

$$P_{NZPV} = PSCF_i \times P_{PV} \tag{5.1}$$

$$PSCF_i = \frac{AE\ Demand\ (kWh)}{AE\ of\ seasonal\ tilt\ (kWh)} \tag{5.2}$$

Where,

P_{NZPV} - Net Zero Panel power sizing, kW

P_{PV} - Panel power sizing from equation 4.1, kW

PSCF - Panel Sizing Correction Factor (no unit)

i - 1 – Load Type a/b/c, 2- Load type d

5.1.1 NZ GPCV for EV load (a) or load (b) or load (c)

New panel sizing must be able ensure that it generates necessary energy to satisfy demand requirements of EV load. In order to do that, it would be ideal to take AE of seasonal tilt with location which yields less value i.e. Thunder Bay. PSCF1 calculated is 1.33 and, new panel size should be 10.207 kW. After several iterations, new panel sizing input which was given into the simulation set up is 10.233 kW (it is less compared to needed value due to manufacturing and dimensional difficulties). New inverter ratings were calculated by multiplying new panel rating with different PR values (0.5 to 1.5) and, it is outlined in Table 5.3.

5.1.2 NZ GCPV for load (d)

If the charging station is used all the time, the energy consumption will change and, similarly design must also change which is seen in this section. Annual energy consumption details with load (d) is exhibited in Table 5.2 above. With system designed in section 5.1.1 it would be very difficult to attain NZ status i.e. meeting energy demand of EV load (d), so new PSCF should be calculated for this scenario. Same equation of 5.2 was used and, new PSCF2 obtained was 4.24. With that new panel sizing was found to be 43.42 kW.

Table 5.1: Monthly energy consumption for load (a) or (b) or(c)

Month	Electricity Load, kWh
Jan	1116
Feb	1008
Mar	1116
Apr	1080
May	1116
Jun	1080
Jul	1116
Aug	1116
Sep	1080
Oct	1116
Nov	1080
Dec	1116
Annual	13,140

New panel size given as input in SAM was 43.49 kW. New inverter ratings were calculated by multiplying new panel rating with different PR values (0.5 to 1.5) and, it is outlined in Table 5.4.

Table 5.2: Energy consumption by EVs with load (d)

Month	**Consumption, kWh**
Jan	4910.4
Feb	4435.2
Mar	4910.4
Apr	4752
May	4910.4
Jun	4752
Jul	4910.4
Aug	4910.4
Sep	4752
Oct	4910.4
Nov	4752
Dec	4910.4
Annual	57816

Table 5.3: New inverter rating by varying PR for load (a)/load (b)/load (c)

Solar PV Rating = 10.233kW	
PR	**Inverter Rating, kW**
0.5	20.466
0.6	17.055
0.7	14.619
0.8	12.791
0.9	11.370
1.0	10.233
1.1	9.302
1.2	8.527
1.3	7.872
1.4	7.309
1.5	6.822

Table 5.4: New inverter rating by varying PR for load (d)

Solar PV Rating = 43.49kW	
PR	**Inverter Rating, kW**
0.5	86.98
0.6	72.48
0.7	62.12
0.8	54.36
0.9	48.32
1.0	43.49
1.1	39.53
1.2	36.24
1.3	33.45
1.4	31.06
1.5	28.99

5.2 Analysis set-up

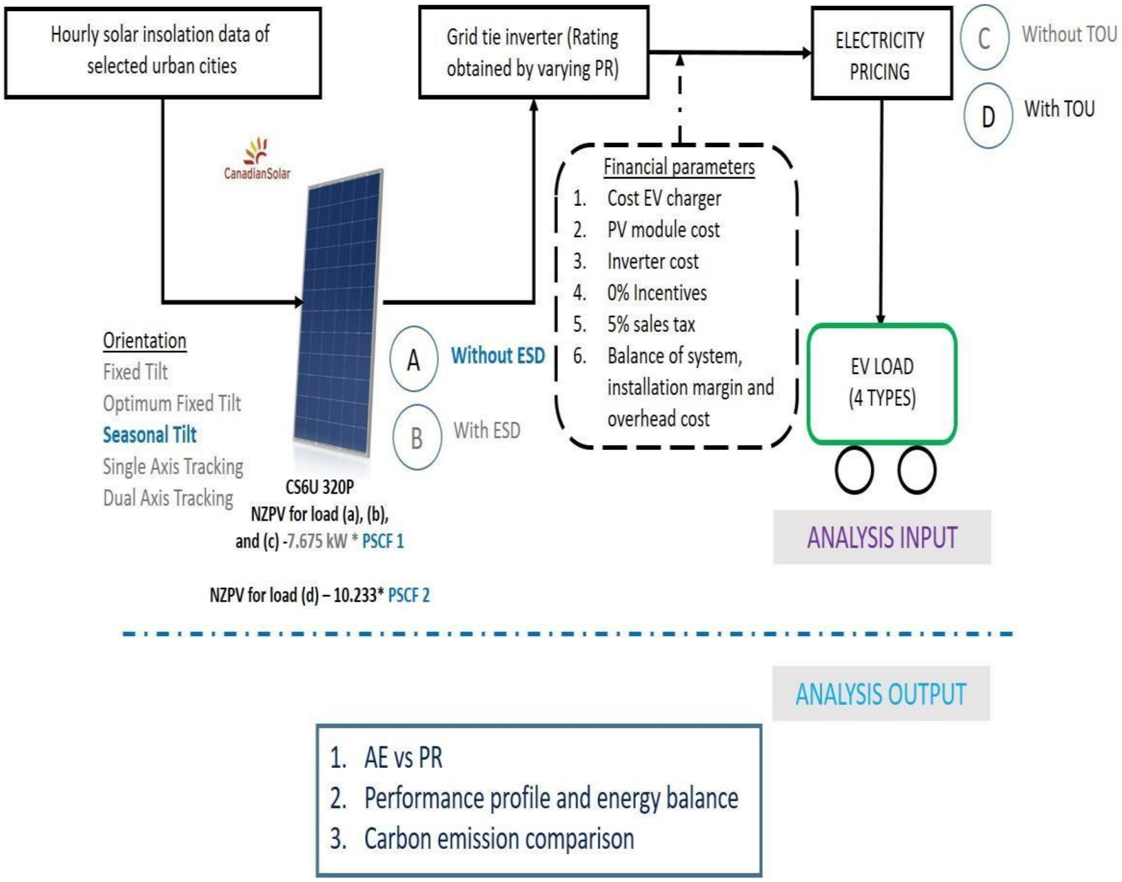
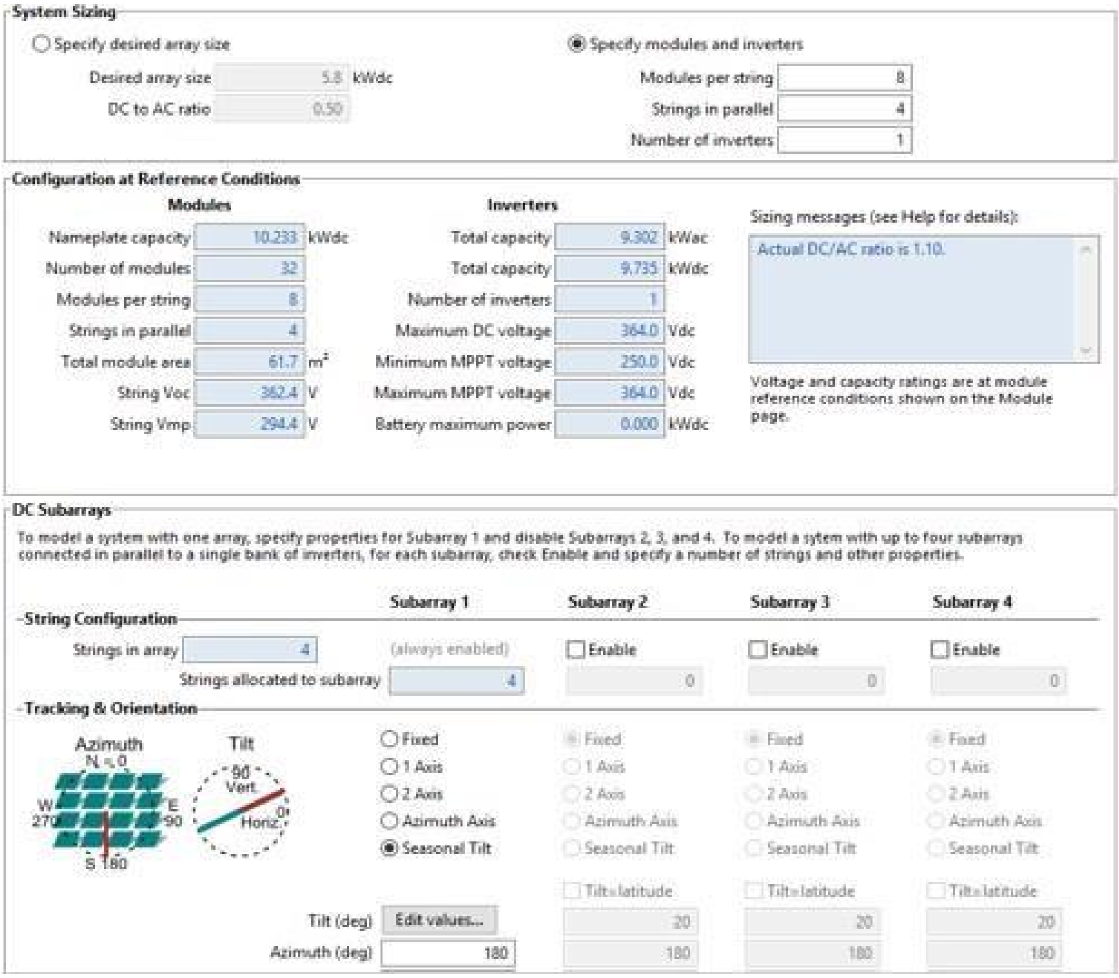


Figure 5.2: NZ GCPV - Analysis set-up

For the above analysis setup, solar insolation is sourced from [51], cost of EV charger is obtained from [54], PV module cost from [55]. Inverter cost, balance of system, installation margin and overhead cost are obtained from [56] and Time of use rates from [53].

5.3 Results and Discussion



System Sizing

○ Specify desired array size

Desired array size 5.8 kWdc

DC to AC ratio 0.50

● Specify modules and inverters

Modules per string 8

Strings in parallel 4

Number of inverters 1

Configuration at Reference Conditions

Modules			**Inverters**		
Nameplate capacity	10.233	kWdc	Total capacity	9.302	kWac
Number of modules	32		Total capacity	9.735	kWdc
Modules per string	8		Number of inverters	1	
Strings in parallel	4		Maximum DC voltage	364.0	Vdc
Total module area	61.7	m²	Minimum MPPT voltage	250.0	Vdc
String Voc	362.4	V	Maximum MPPT voltage	364.0	Vdc
String Vmp	294.4	V	Battery maximum power	0.000	kWdc

Sizing messages (see Help for details):

Actual DC/AC ratio is 1.10.

Voltage and capacity ratings are at module reference conditions shown on the Module page.

DC Subarrays

To model a system with one array, specify properties for Subarray 1 and disable Subarrays 2, 3, and 4. To model a sytem with up to four subarrays connected in parallel to a single bank of inverters, for each subarray, check Enable and specify a number of strings and other properties.

	Subarray 1	**Subarray 2**	**Subarray 3**	**Subarray 4**
String Configuration				
Strings in array 4	(always enabled)	☐ Enable	☐ Enable	☐ Enable
Strings allocated to subarray	4	0	0	0
Tracking & Orientation				
	○ Fixed	● Fixed	● Fixed	● Fixed
	○ 1 Axis	○ 1 Axis	○ 1 Axis	○ 1 Axis
	○ 2 Axis	○ 2 Axis	○ 2 Axis	○ 2 Axis
	○ Azimuth Axis	○ Azimuth Axis	○ Azimuth Axis	○ Azimuth Axis
	● Seasonal Tilt	○ Seasonal Tilt	○ Seasonal Tilt	○ Seasonal Tilt
		☐ Tilt=latitude	☐ Tilt=latitude	☐ Tilt=latitude
Tilt (deg)	Edit values...	20	20	20
Azimuth (deg)	180	180	180	180

Figure 5.3: GUI of SAM for NZ GCPV for load (a)/load (b)/load (c) from section 4.1

Sample GUI of new GCPV system which is designed for load (a), load (b), and load(c) is outlined in Figure 5.3. AE vs PR for this design for all chosen locations is shown in Figure 5.4. Performance profile is shown in Figure 5.5 and, energy balance of the 10.23 kW with load (a) is outlined in Table 5.5. Also, from Figure 5.5 it is observed that penetration of solar energy has increased significantly with new design. Designed system is able to meet the demand of EV load annually and also provide some energy to the grid. This is can be verified with annual energy balance between system, grid and the load with Table 5.5.

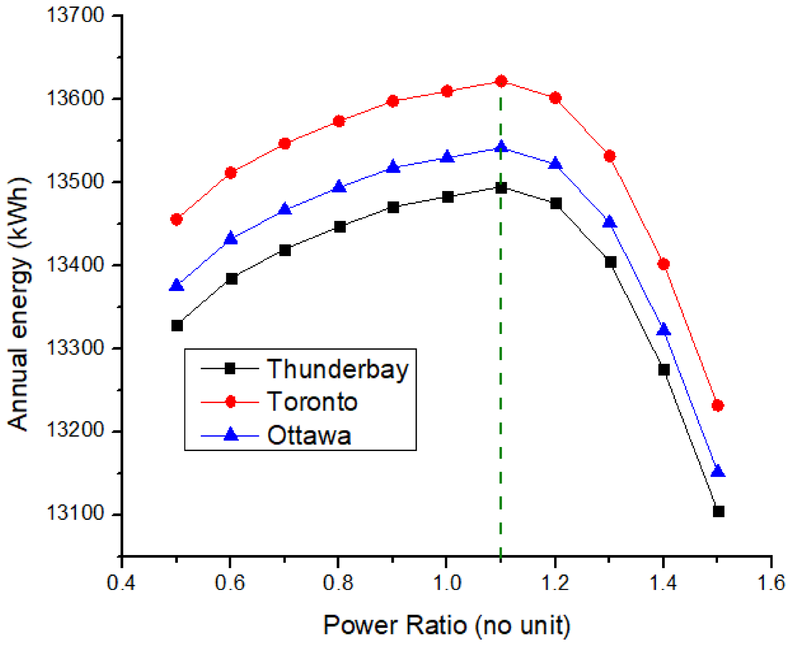


Figure 5.4: AE vs PR for 10.233 kW design – load (a)

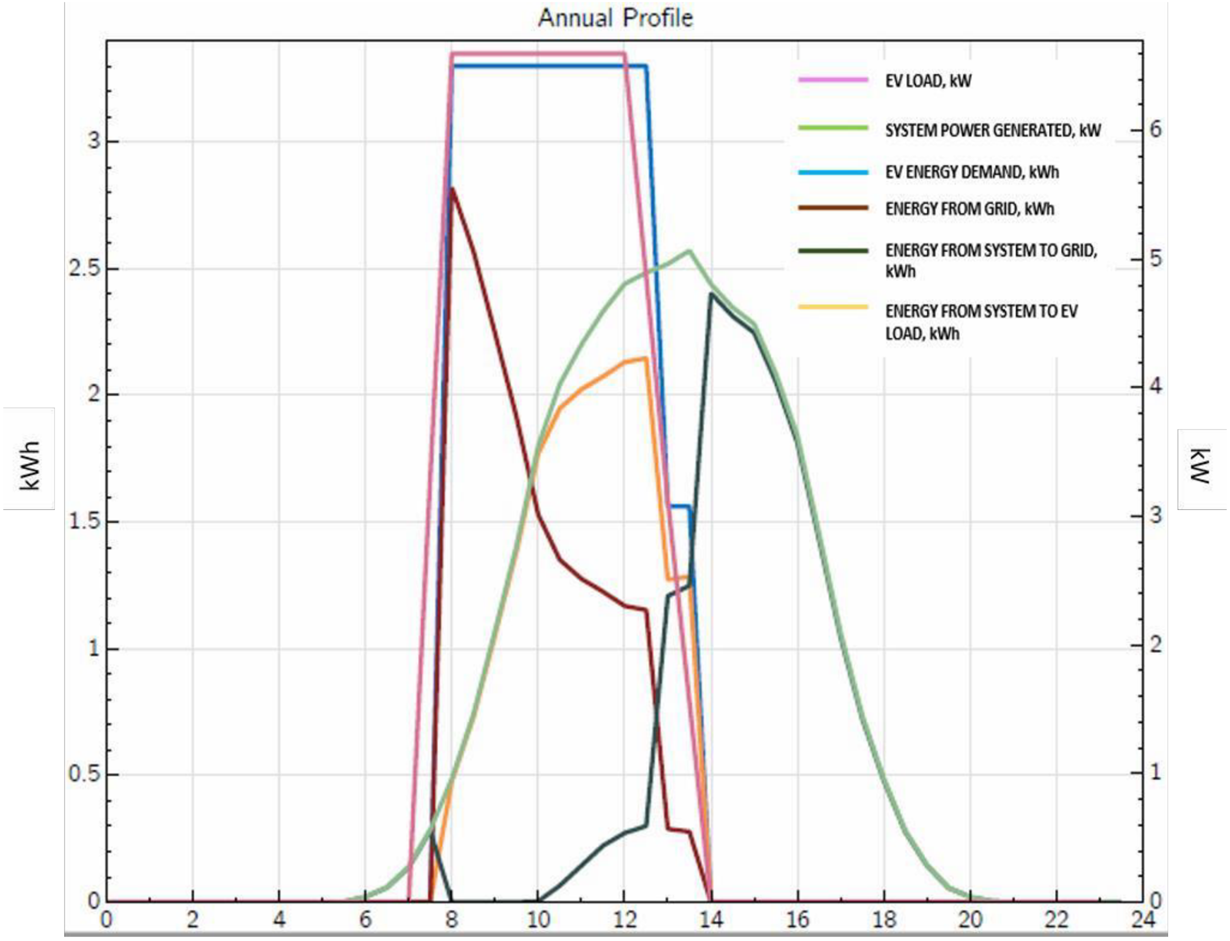
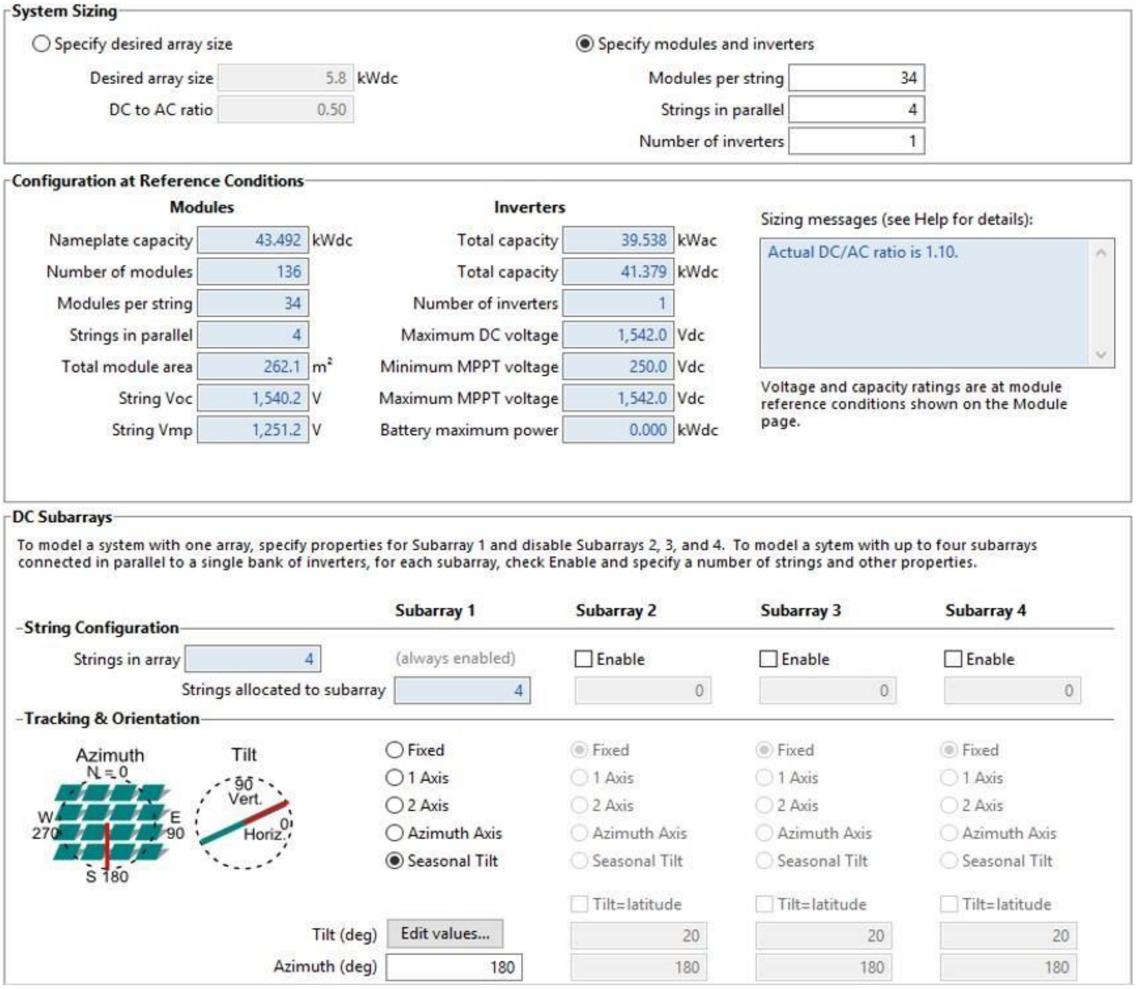


Figure 5.5: Annual performance profile for 10.23 kW system with load (a)

Table 5.5: Energy balance of System with load (a)

Month	**System AC Energy (kWh/mo) E$_S$**	**Electricity to/from Grid (kWh/mo) E$_G$**	**Electricity Load (kWh/mo) E$_L$**
Jan	884.514	-231.486	1116
Feb	908.614	-99.386	1008
Mar	1250.04	134.04	1116
Apr	1328.1	248.1	1080
May	1452.68	336.68	1116
Jun	1473.64	393.64	1080
Jul	1540.22	424.22	1116
Aug	1417.91	301.91	1116
Sep	1107.67	27.67	1080
Oct	935.607	-180.393	1116
Nov	708.877	-371.123	1080
Dec	614.426	-501.574	1116
AE	13622.298	482.298	13,140



System Sizing

○ Specify desired array size

Desired array size 5.8 kWdc

DC to AC ratio 0.50

● Specify modules and inverters

Modules per string 34

Strings in parallel 4

Number of inverters 1

Configuration at Reference Conditions

Modules			Inverters		
Nameplate capacity	43.492	kWdc	Total capacity	39.538	kWac
Number of modules	136		Total capacity	41.379	kWdc
Modules per string	34		Number of inverters	1	
Strings in parallel	4		Maximum DC voltage	1,542.0	Vdc
Total module area	262.1	m²	Minimum MPPT voltage	250.0	Vdc
String Voc	1,540.2	V	Maximum MPPT voltage	1,542.0	Vdc
String Vmp	1,251.2	V	Battery maximum power	0.000	kWdc

Sizing messages (see Help for details):

Actual DC/AC ratio is 1.10.

Voltage and capacity ratings are at module reference conditions shown on the Module page.

DC Subarrays

To model a system with one array, specify properties for Subarray 1 and disable Subarrays 2, 3, and 4. To model a sytem with up to four subarrays connected in parallel to a single bank of inverters, for each subarray, check Enable and specify a number of strings and other properties.

String Configuration

Strings in array 4

	Subarray 1	Subarray 2	Subarray 3	Subarray 4
	(always enabled)	☐ Enable	☐ Enable	☐ Enable
Strings allocated to subarray	4	0	0	0

Tracking & Orientation

	Subarray 1	Subarray 2	Subarray 3	Subarray 4
	○ Fixed	● Fixed	● Fixed	● Fixed
	○ 1 Axis	○ 1 Axis	○ 1 Axis	○ 1 Axis
	○ 2 Axis	○ 2 Axis	○ 2 Axis	○ 2 Axis
	○ Azimuth Axis	○ Azimuth Axis	○ Azimuth Axis	○ Azimuth Axis
	● Seasonal Tilt	○ Seasonal Tilt	○ Seasonal Tilt	○ Seasonal Tilt
		☐ Tilt=latitude	☐ Tilt=latitude	☐ Tilt=latitude
Tilt (deg)	Edit values...	20	20	20
Azimuth (deg)	180	180	180	180

Figure 5.6: GUI of SAM for NZ GCPV for load (d) from section 4.1

Sample GUI of new GCPV system which is designed for load (d) is outlined in Figure 5.6. AE vs PR for this design for all chosen locations is shown in Figure 5.7. Performance profile is shown in Figure 5.8 and, energy balance of the 43.49 kW with load (d) is outlined in Table 5.6. Also, from Figure 5.8 it is observed that penetration of solar energy has increased to a mammoth amount, such that it is able to meet the EV load demand and also provide energy back to grid. It can be observed with Table 5.6. Figure 5.9 and 5.10 provides the information of the payback period of the designed NZ systems for its appropriate load profiles and with 1.1 PR the systems are economical.

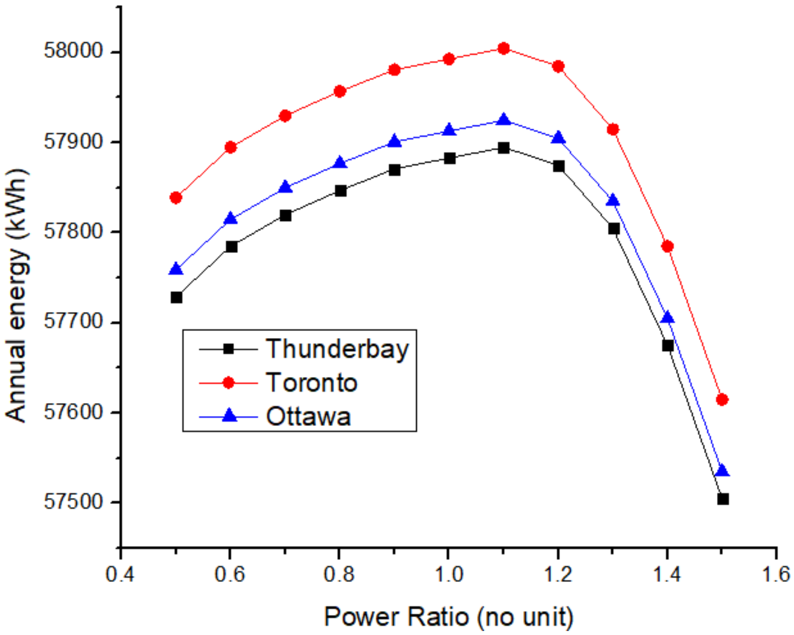


Figure 5.7: AE vs PR for 43.49 kW design – load (d)

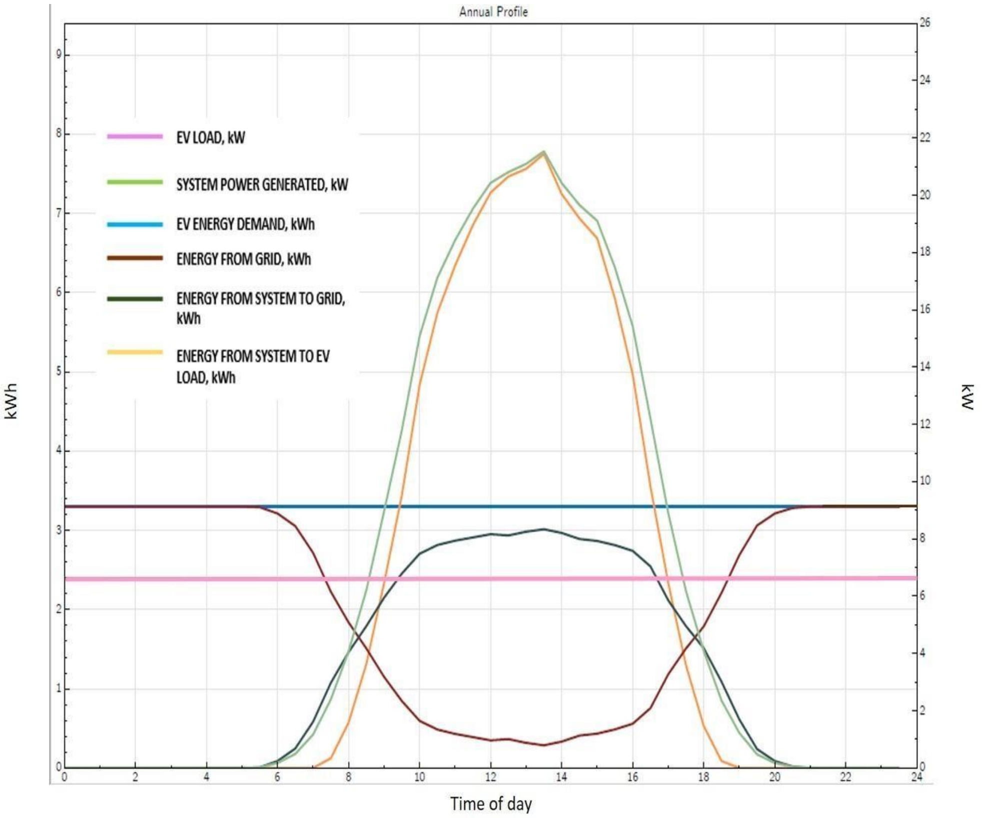


Figure 5.8: Annual performance profile for 43.49 kW system with load (d)

Table 5.6: Energy balance of System with load (d)

Month	**System AC Energy (kWh/mo) E$_S$**	**Electricity to/from Grid (kWh/mo) E$_G$**	**Electricity Load (kWh/mo) E$_L$**
Jan	3759.27	-1151.14	4910.39
Feb	3861.72	-573.479	4435.22
Mar	5312.77	402.388	4910.39
Apr	5644.42	892.426	4752
May	6173.87	1263.47	4910.39
Jun	6262.96	1510.96	4752
Jul	6545.94	1635.54	4910.39
Aug	6026.12	1115.7	4910.39
Sep	4707.58	-44.4221	4752
Oct	3976.32	-934.067	4910.39
Nov	3012.72	-1739.29	4752
Dec	2611.31	-2299.11	4910.39
AE	57895	78.8759	57816

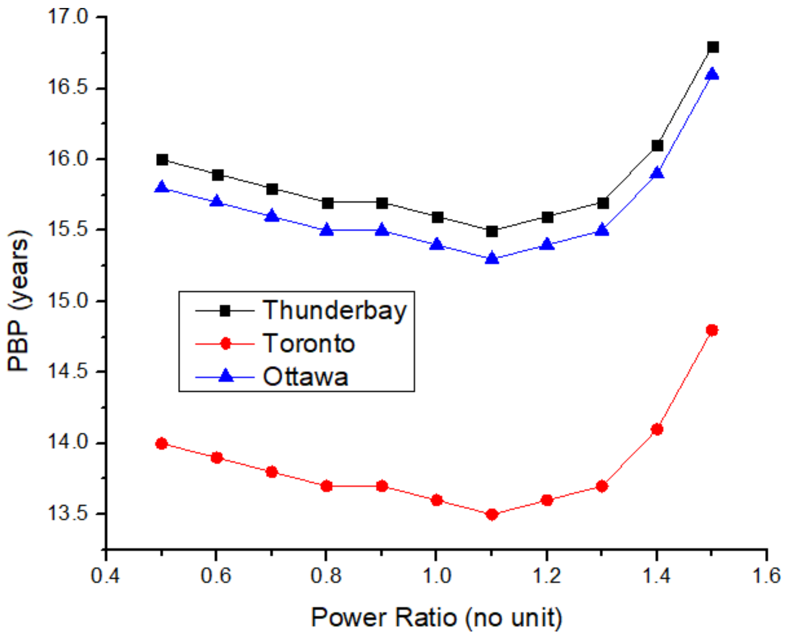


Figure 5.9: PBP vs PR for NZ design with load (a)

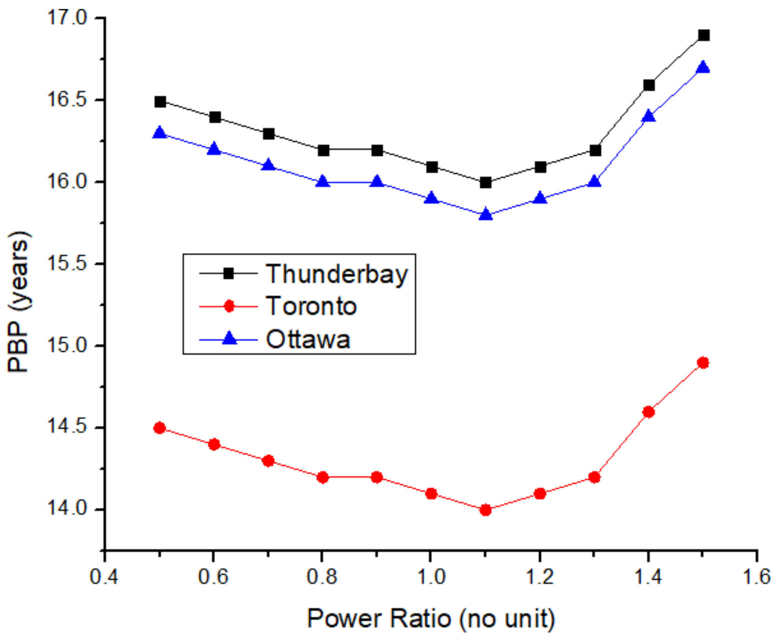


Figure 5.10: PBP vs PR for NZ design with load (d)

5.4 Environmental benefits

Annual carbon emission of charging EVs with existing energy supply mix, and with GCPV system would be compared in this section in detail. From [62] information on carbon emission per kWh depending upon the type of generating source, data of 50th percentile was considered for calculation, and Ontario's energy mix in 2015 was obtained from [63], and used in equation 5.3, and results of analysis is outlined in Figure 5.11. From Figure 5.11, it is lucid that there is around 150 - 200 Kg of carbon emission reduction using a GCPV system (10.23 kW) for charging one EV i.e. Load a/b/c, and there is emission reduction of 881 Kg by using a NZ system (43.42 kW) charging 4 EVs annually i.e. Load d. Assuming that there will be one million electric cars in the next decade, by using NZ system (i.e. 43.42 kW system per 4 EVs), it could reduce 242.78 kT of carbon emission.

$$CE = \frac{(Annual\ EV\ Energy\ Consumption) \times (\%\ Electricity \times gCO_2/kW\ h)}{1000} \quad (5.3)$$

Where,

CE is Carbon Emission, kg

% Electricity is for each source

gCO_2/kWh is for each source

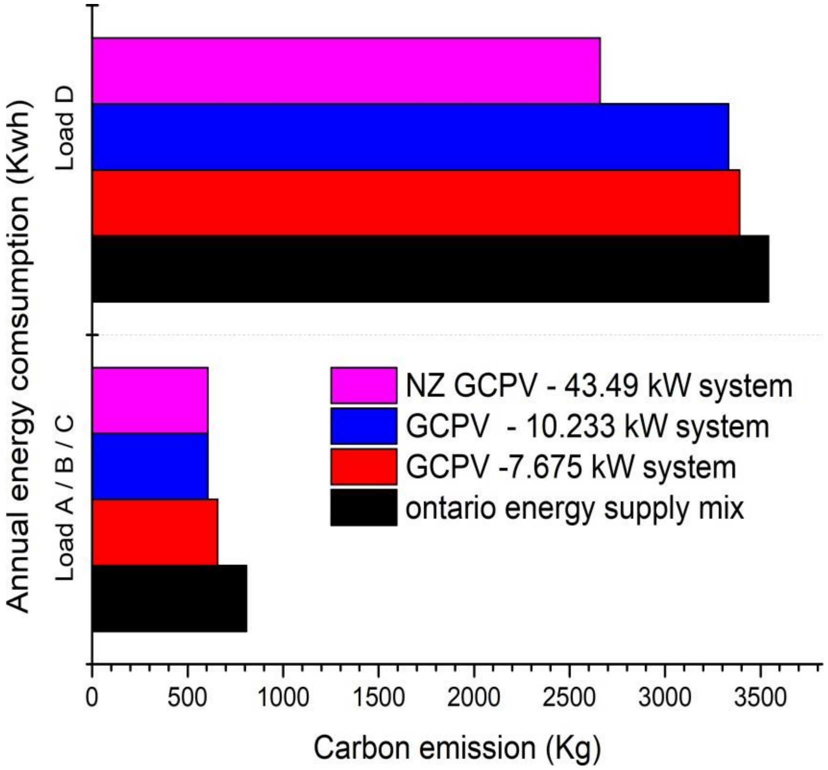


Figure 5.11: Carbon emission comparison

5.5 Summary

10.23 kW, and 43.49 kW GCPV system were designed for load (a)/load (b)/load (c), and load (d) respectively with new design methodology. Both designed systems were able to meet appropriate EV annual energy demand i.e. it achieved NZ site energy status. With 10% oversizing of PV panels, both designs were able to achieve 0% clipping loss. Neglecting clipping loss, annual energy was met even with 30% oversizing of PV panels. Fastest PBP for 10.23 kW system with locations ‘Toronto, Ottawa and, Thunder Bay’ are 13.5, 15.4, and 15.6 years respectively. Fastest PBP for 43.49 kW system with locations ‘Toronto, Ottawa and, Thunder Bay’ are 14, 15.9, and 16.2 years respectively. 150 – 200 Kg of carbon was reduced annually if one EV was charged with 10.23 kW system instead of current energy supply mix of Ontario. 881 Kg of carbon could be reduced annually if 4 EVs were charged with 43.49 kW system instead of current energy supply mix of Ontario.

Chapter 6

Conclusions and Recommendations

6.1 Summary and conclusions

Chapter 1 provided the main motivation for this thesis work. Motivation brought out the necessity to design ‘solar integrated Net-Zero EV charging station’. Also, the research objectives, and organization of this thesis work was presented in this chapter.

In Chapter 2, literature review of works pertaining to impacts on EV charging through grid, benefits of renewable powered charging stations, and ‘Net Zero’ concepts were briefly discussed.

Chapter 3 provided necessary background details of PV module types, effects of tilting and tracking in PV panels, EV charging standards, various system design architectures of solar powered charging stations, and key parameters to evaluate designed system.

In Chapter 4, new methodology of PV and Inverter sizing was proposed to design a GCPV system for EVCS. System designed were tested with different load models developed. Different orientations of PV modules were analyzed and, optimum solution was chosen based on faster PBP.

In Chapter 5, seasonal tilt oriented GCPV system was scaled to ‘NZ site energy’ system based on proposed methodology. NZ GCPV system was tested with selected load models from the previous chapter. Finally, carbon emission between proposed designs, and Ontario’s energy supply mix for charging EVs were compared.

6.2 Recommendations for future work

This research work could be extended, and few approaches are provided below:

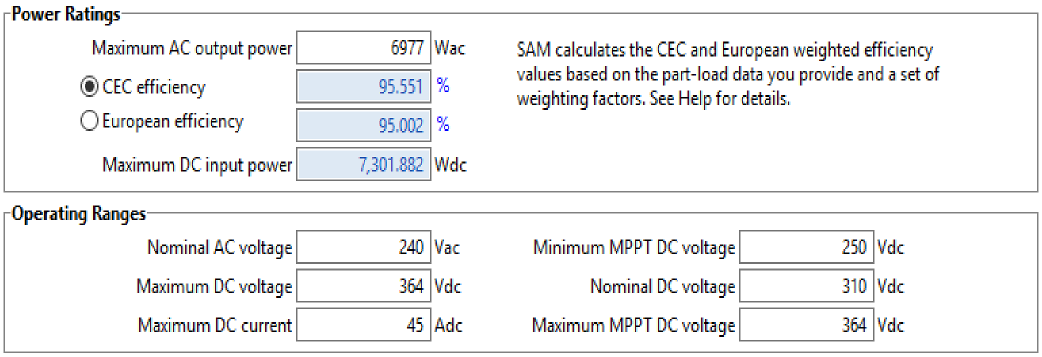
- In this work, complete analysis have been done utilizing simplified load models, instead an actual EV charging profile (From level 2) could be procured and used to determine more accurate energy generation, energy consumption and, payback period.

- In this work, specific PV module has been chosen for studies, whereas other types such as monocrystalline (or) thin film can be used. This would provide comparative economics of different types of solar PV systems.

- Electricity pricing and site location could be changed in the designed system, performance comparison could be changed in designed system. This would determine choice of PV module for specific regions and, also help to identify best locations for designed system.

Appendices

Appendix A



Power Ratings

Maximum AC output power 6977 Wac

● CEC efficiency 95.551 %

○ European efficiency 95.002 %

Maximum DC input power 7,301.882 Wdc

SAM calculates the CEC and European weighted efficiency values based on the part-load data you provide and a set of weighting factors. See Help for details.

Operating Ranges

Nominal AC voltage 240 Vac

Maximum DC voltage 364 Vdc

Maximum DC current 45 Adc

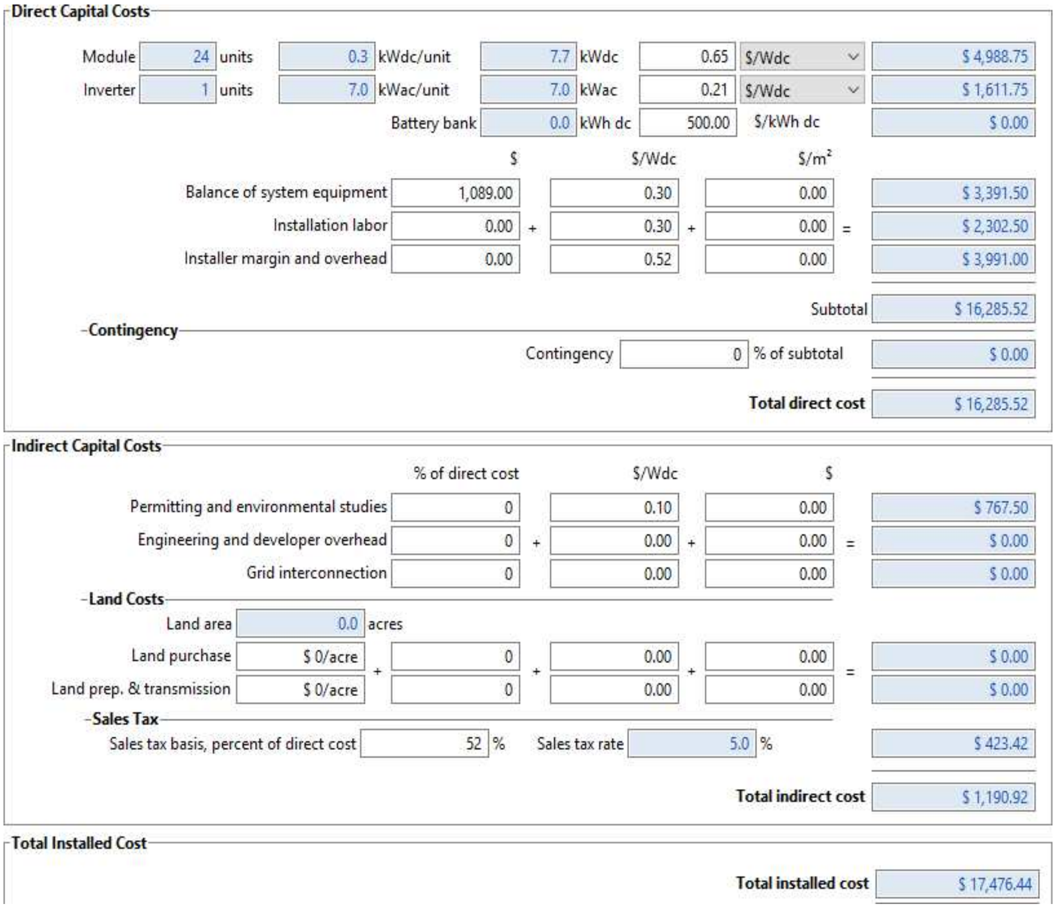
Minimum MPPT DC voltage 250 Vdc

Nominal DC voltage 310 Vdc

Maximum MPPT DC voltage 364 Vdc

Figure A.1: Inverter Design Page

Appendix B



Direct Capital Costs

Module	24	units	0.3	kWdc/unit	7.7	kWdc	0.65	$/Wdc	$ 4,988.75
Inverter	1	units	7.0	kWac/unit	7.0	kWac	0.21	$/Wdc	$ 1,611.75
				Battery bank	0.0	kWh dc	500.00	$/kWh dc	$ 0.00

	$		$/Wdc		$/m²		
Balance of system equipment	1,089.00		0.30		0.00		$ 3,391.50
Installation labor	0.00	+	0.30	+	0.00	=	$ 2,302.50
Installer margin and overhead	0.00		0.52		0.00		$ 3,991.00
					Subtotal		$ 16,285.52

Contingency

Contingency	0	% of subtotal	$ 0.00
		Total direct cost	$ 16,285.52

Indirect Capital Costs

	% of direct cost		$/Wdc		$		
Permitting and environmental studies	0		0.10		0.00		$ 767.50
Engineering and developer overhead	0	+	0.00	+	0.00	=	$ 0.00
Grid interconnection	0		0.00		0.00		$ 0.00

Land Costs

Land area 0.0 acres

Land purchase	$ 0/acre	0	+	0.00	+	0.00	=	$ 0.00
Land prep. & transmission	$ 0/acre	0		0.00		0.00		$ 0.00

Sales Tax

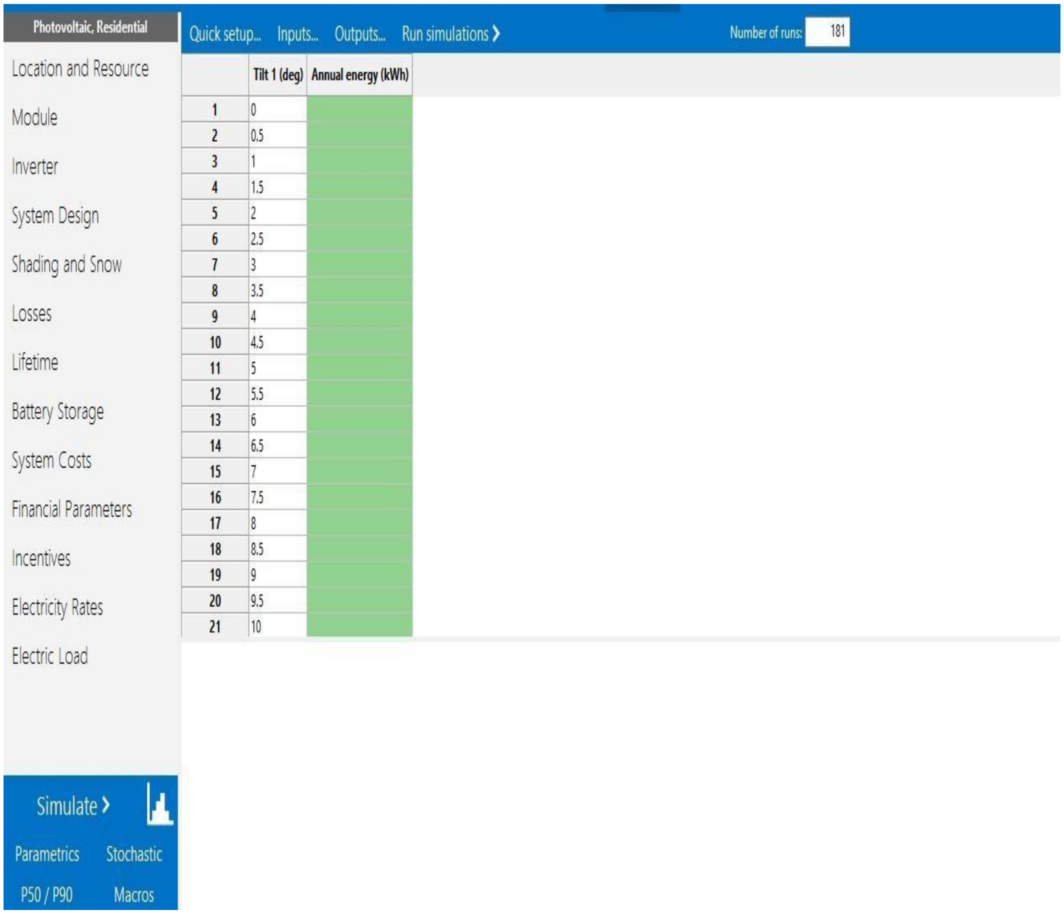
Sales tax basis, percent of direct cost	52	%	Sales tax rate	5.0	%	$ 423.42
					Total indirect cost	$ 1,190.92

Total Installed Cost

Total installed cost $ 17,476.44

Figure B.1: System Design Cost Page

Appendix C



	Tilt 1 (deg)	Annual energy (kWh)
1	0	🟩
2	0.5	🟩
3	1	🟩
4	1.5	🟩
5	2	🟩
6	2.5	🟩
7	3	🟩
8	3.5	🟩
9	4	🟩
10	4.5	🟩
11	5	🟩
12	5.5	🟩
13	6	🟩
14	6.5	🟩
15	7	🟩
16	7.5	🟩
17	8	🟩
18	8.5	🟩
19	9	🟩
20	9.5	🟩
21	10	🟩

Figure C.1: Parametric Analysis Set Up Page

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Glossary of Terms

EV	Electric Vehicle
PV	Photovoltaic
GCPV	Grid Connected Photovoltaic
SPCS	Solar Powered Charging Station
EVCS	Electric Vehicle Charging Station
AE	Annual Energy
PBP	Payback period
LCOE	Levelized Cost of Energy
ESD	Energy Storage Device
ESS	Energy Storage System
NZ	Net Zero
TOU	Time of Use pricing
PR	Power Ratio