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Modeling Urban Solar Energy with High Spatiotemporal Resolution

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MODELING URBAN SOLAR ENERGY WITH HIGH SPATIOTEMPORAL RESOLUTION

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Abstract

Alternative sources of energy are being sought after in the world today, as the availability of fossil fuels and other non-renewable resources are declining. Solar energy offers a promising solution to this search as it is a less polluting renewable energy resource and can be easily converted into electricity through the usage of photovoltaic systems. This thesis focuses on the modeling of urban solar energy with high spatiotemporal resolution. A methodology was developed to estimate hourly solar PV electricity generation potential on rooftops in an urban environment using a 3-D model. A case study area of Ryerson University, Toronto was chosen and the incident solar radiation upon each building rooftop was calculated using a software tool called Ecotect Analysis 2011. Secondly, orthophotos of the case study area were digitized using Geographic Information Systems in order to eliminate undesirable rooftop objects within the model. Lastly, a software tool called HOMER was used to generate hourly solar PV electricity estimates using the values generated by the other two software tools as input parameters. It was found that hourly solar PV output followed the pattern of a binomial curve and that peak solar generation times coincided with summer peak electricity consumption hours in Ontario.

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List of Abbreviations

AC	Alternating current
CERES	Canadian renewable energy wind and solar resource
CWEC	Canadian weather year for energy calculation
CWEEDS	Canadian Weather Energy and Engineering Data Sets
DC	Direct current
ECO	Ecotect file
EPW	EnergyPlus Weather format
ESRU	Energy Research Systems Unit
FIT	Feed-in-tariff
GHG	Greenhouse gas
GHI	Global horizontal irradiation
GIS	Geographic Information Systems
GRASS	Geographical resources analysis support system
HDKR	Hays-Davis-Klucher-Reindl
HOMER	Hybrid optimization model for electric renewables
HVAC	Heating, ventilation and air conditioning
ICUE	Irradiation mapping for complex urban environments
IESO	Independent Electricity Systems Operator
MOE	Ministry of Energy
NRCan	Natural Resources Canada
NREL	National Renewable Energy Laboratory (U.S.)
PV	Photovoltaic
SEP	Solar Energy Planning
STIMAP	Spatio-temporal irrradiation mapping
TOU	Time-of-use
WEA	Ecotect Weather Manager data

1. Introduction

The demand for energy is on an increasing rise worldwide, with its primary needs being met predominantly by the burning of fossil fuels. The excessive burning of fossil fuels is detrimental to the environment and produces vast amounts of greenhouse gases (GHG), which pollute and harm the atmosphere (Wiginton et al., 2010). Fossil fuels are a non-renewable resource and increase the risks for climate change. It is for these reasons that alternative sources of renewable energy are being sought after. One such alternate source of energy is solar energy. Solar energy is a less polluting renewable energy source that can be easily converted into electricity through the usage of photovoltaic (PV) systems (Natural Resources Canada [NRCan], 2002).

In order to provide for the huge electricity consumption by urban environments, it is important for buildings to be pre-assessed for their solar energy potential in order to check for their suitability for PV systems and other forms of use, such as solar heating. Since the ability to harvest insolation on buildings in an urban environment is limited by complex interactions with the local environment, key characteristics must be identified and analyzed. Some key characteristics that have been identified to limit the amount of solar radiation received on buildings include weather conditions, location, sky obstructions (shading), facades, green roofs, heating, ventilation, and air condition systems (HVACs) (Izquierdo et al., 2008; Chow et al., 2005). The study of these characteristics together with the performance of an in-depth analysis for the modeling of the higher spatiotemporal variations in solar radiation for urban environments is imperative to accurately estimate total hourly solar PV generation potential. The term "high spatiotemporal" in this thesis refers to the analysis performed on a three-dimensional surface on the individual building level (as compared to conventional large scale analyses performed on two dimensions), as well as the hourly (instead of yearly) time interval analysis for a more accurate estimate of electricity generation potential. Analysis on a high spatiotemporal resolution is needed because the demand for electricity is very high in urban areas. In order to understand this demand, the hourly analysis of solar PV electricity generated on the individual building level is necessary in order to provide good input for the planning and management of the electricity grid, especially during peak hour demands.

1.1. Research Objective

The goal of this thesis is to develop a methodology to estimate hourly solar PV electricity generation potential on rooftops in an urban environment.

1.2. Research Questions

In order to accomplish this task, the following issues need to be addressed:

- What are the factors that affect the amount of solar energy available to a PV system in an urban environment?
- What solar dataset should be used?
- What are the solar radiation models and software tools available?
- How much roof space is suitable for PV installation?
- How much electricity is generated per hour?
- What percentage of electricity is produced by PV systems on an hourly basis as compared to the actual consumption of electricity?

- How much will PVs help alleviate off the load of the electricity grid during peak generation hours?

1.3. Significance

Ontario's electricity system is entering a new phase and challenge towards a more participatory and sustainable industry. The province is under a huge task of renewing its electricity infrastructure, looking towards renewable energies in order to reduce its GHG emissions (Independent Electricity System Operator [IESO], 2009). With the new Feed-in-Tariff (FIT) and microFIT programs that have been implemented through the Green Energy Act (2009), owners of PV systems are able to sell their electricity back to the grid and help alleviate off the load of on-peak demand periods. Since solar energy has the ability to reach full capacity on hot sunny days when demand is at its highest, it becomes a valuable component to the electricity system (IESO, 2009). With the province implementing time-of-use (TOU) pricing through its smart metering initiative, it is becoming ever more important to determine how much solar PV electricity is generated on an hourly basis.

1.4. Previous Work

Forgione (2010) developed an integrated workflow for the modeling and mapping of solar energy potentials in urban areas on an annual basis. Forgione's (2010) research identified some important factors that affected the total irradiation on a surface, such as the location, meteorological conditions, the size, shape and orientation of a surface and the local environment. He performed a case study on a typical urban area, the City of Toronto, in specific the Ryerson University Campus, and successfully modeled the annual solar energy potentials of the buildings using a software called Ecotect Analysis. The annual electricity generation potential due to solar PV systems was found to be 4.7% of the actual needs of Ryerson University.

This thesis will address some of the gaps and limitations to Forgione's (2010) research and refine the workflow accordingly. A more time sensitive approach on an hourly basis will be taken in order to better understand the amount of electricity that can be generated by PV systems. An hourly estimate provides a more useful estimate than an annual estimate, and provides good input for peak generation hours, especially for smart metering systems.

In order to accomplish this, new softwares will be evaluated and added to the procedural workflow. Also, in order to increase the accuracy of the predicted hourly solar energy potentials, new weather datasets will be used. Lastly, Forgione (2010) consulted Google Maps to eliminate any undesirable rooftop areas. In the new method, orthophotos and Geographic Information Systems (GIS) will be used instead to increase the accuracy of the measured roof space suitable for PV deployment.

1.5. Scope

The scope of this thesis will be strictly limited to creating a methodology to estimate solar PV generation potential on an hourly basis. Aspects such as solar panel technologies, mechanics, return of investments and any other financial issues are not the focus of this research and will not be addressed.

2. Literature Review

This chapter will be a detailed literature review about solar energy and photovoltaic (PV) systems. This chapter will start off by discussing the driving force behind the use of renewable energies and Ontario's smart meter initiative. Solar energy, issues and factors affecting rooftop PV systems in the urban environment will be examined and a detailed review of the software tools used to estimate solar energy potentials will be provided. Through this in-depth analysis of the solar software tools, criteria were formed in order to select programs to be used for the hourly solar PV generation potential analysis.

2.1. Ontario's Smart Meter Initiative

Ontario has committed to phasing out the use of all coal-fired plants by 2014, and to establishing itself as "North America's leader in renewable energy" (Ontario Power Authority, 2009). The driving force behind this goal is the Green Energy Act (2009), and the Feed-in-Tariff (FIT) and microFIT supporting incentive programs for renewable energies (Independent Electricity System Operator [IESO], 2009). The mission for a greener Ontario is being accomplished by the introduction of smart meters in the province (Ministry of Energy [MOE], 2010a). A smart meter is a meter that measures the amount of electricity consumption in a building on an hourly basis, and sends this information to the local electricity distribution companies automatically (MOE, 2010b).

The knowledge of hourly electricity consumption is important as it allows for the introduction of time-of-use (TOU) pricing, which enables the electricity companies to charge different prices for different time periods. The reason for TOU pricing is to promote a more conservative culture in Ontario (lower electricity consumption), generate less air pollution and to also help alleviate the demands on peak electricity consumption to provide a more reliable energy supply (Ontario Energy Board, 2010).

TOU pricing are divided into three time periods for when electricity demand is at its highest, moderate and lowest points, and they are respectively called the on-peak, mid-peak and off-peak TOU periods (MOE, 2010b). Figure 1 depicts the established time frames for the on-peak, mid-peak and off-peak TOU periods in the summer. The on-peak periods are in the middle of the weekdays (from 11am to 5pm) mainly attributed to high electricity consumption caused by air conditioning usage. From 7am to 11am and 5pm to 9pm the TOU period is considered mid-peak, and from 9pm to 7am off-peak. Weekends are considered off-peak periods (IESO, n.d.).

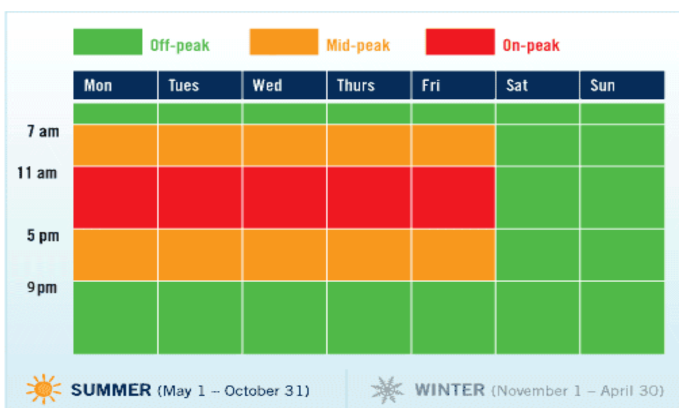


Figure 1. Summer time-of-use periods adopted from (IESO, n.d.).

The electricity system in Ontario has gone through a significant change in the past ten years. Electricity demand is the highest during the summer in Ontario, and a solution is needed to help alleviate the intense load off the electrical grid in order to provide a more reliable energy supply. Alternative sources of energy are needed, and in particular solar PV systems offer a promising solution to this problem. Solar PV systems are a clean energy source, and their peak generation times coincide with the on-peak electricity demands in Ontario during the summer. Thus, it is important to find out how much electricity can be generated by PV systems on an hourly basis to see how much it can help alleviate off the electrical grid during peak summer generation hours. In order to accomplish this task, solar energy models and softwares need to be understood and assessed in order to estimate hourly solar PV generation potential.

2.2. Solar Energy and Photovoltaics

Solar energy has been recognized for a long time as a major source of renewable and sustainable energy (Wiginton et al., 2010). PV systems are comprised of building blocks called modules or cells, which connected together converts sunlight directly into electricity (Natural Resources Canada [NRCan], 2002). PV systems do not have any moving parts and generate low GHG or other emissions during their operation and offer a clean source of energy (NRCan, 2002; Pelland & Poissant, 2006). They have been used since the 1950's on spacecraft, and it was not until the 1970's in which the interest in their land-based use exploded (Green, 2004). This growth in interest of renewable energy technology, specifically PV technology, was fueled by the urgency in reducing carbon emissions and government incentive FIT programs towards a more sustainable culture (Nguyen &

Pearce, 2010). A major shift has occurred in the past few years, where PV technology is moving from applications in remote and rural areas to those in urban environments (Green, 2004).

PV systems are basically made of a variety of semiconductor materials that allow for electrons to be freed from their atoms through direct sunlight exposure. This enables them to carry an electric current and ultimately produce electricity (NRCan, 2002). There are four major types of PV modules (solar panels) that are used and they are crystalline silicon, multi-crystalline silicon (polycrystalline), amorphous silicon multi-junction and thin-film polycrystalline silicon (micro/nano-crystalline) (Green, 2005). Each of these PV modules (or PV arrays for multiple linked modules) have different efficiencies for their nominal power which is marked by their manufacturers (McKenney et al., 2008; Wiginton et al., 2010). The overall losses and performance of these PV technologies depend not only on their material, but also the operating conditions such as temperature, the solar radiation intensity, angle of incidence and overall design of the system (McKenney et al., 2008).

Importantly, the orientation and location of a PV array severely affects the amount of electricity it can generate. It is for this reason that the amount of solar radiation received at any particular instance on the PV array needs to be understood for maximal efficiency. There are two types of PV arrays: a mobile version, which tracks the sun, and fixed surface orientations. Array orientation refers to the direction in which a fixed array faces, and maximum electricity generation occurs when its surface is perpendicular to the sun's rays (Pelland et al., 2006). In Canada, PV arrays are almost always south facing, since the sun is due south at solar noon in the northern hemisphere (NRCan, 1991). The angle of inclination of a PV array away from the horizontal and toward the south (known as the tilt or slope) is then chosen based upon the intended use (year long vs. summer) of the system (Pelland et al., 2006; McKenney et al., 2008).

There are many different tilts used for PV arrays, however, five have been identified as particularly significant. Four out of the five key array tilts are fixed in orientation. The four fixed orientations are south facing with tilts of: 90^o (vertical), latitude tilt (L), tilt = L – 15^o, and tilt = L + 15^o. The final orientation is the sun tracking surface commonly referred to as follow-the-sun which receives maximum global radiation at any time (Pelland et al., 2006; McKenney et al., 2008). This system however, is more susceptible to damage and needs regular maintenance (NRCan, 1991). It should be noted that depending on the application of the PV system, an increased tilt favours maximum power output in the winter, and a decreased tilt favours maximum power output in the summer (Bergamasco & Asinari, 2011). In particular, for large flat roof spaces, a tilt of 0^o is optimal as it maximizes the space available for installation. For example, PV systems installed with a 10^o tilt need approximately 30% more roof space (Chaudhari et al., 2004). Thus it can be seen that the tilt of the PV system is a highly subjective area, and that the decision for the tilt is based upon the intent of use (maximal efficiency in summer, maximal efficiency in winter, maximizing surface area, etc.). It is for the above reasons that much research needs to be taken into consideration before the installation of any PV systems in an urban environment for maximum potential. In order to accomplish this task, accurate solar radiation data and models are required to assess the potential and performance of these solar PV systems.

2.3. Solar Radiation

Solar radiation is the result of complex interactions of energy between the atmosphere and surface (Dubayah & Rich, 1995; Suri & Hofierka, 2004). According to Natural Resources Canada (1991), solar irradiance is defined as the intensity of solar radiation received on a surface at a given time and is usually expressed in Watts per square metre [W/m^2], and insolation is defined as the amount of solar energy received on a surface over a period of time and is expressed in units of kilowatts-hours per square metre [kWh/m^2]. As a disclaimer, these terms will be used interchangeably within this thesis. Solar radiation are affected by many factors such as weather conditions (e.g., cloud cover, haze, seasonal ground effects, and water vapour), inclination of the surface, time of day, effects of local features (shading, topographical features, and urban landscapes), ecological and biological processes and human activities (NRCan, 1991; Nguyen & Pearce, 2010; Mardaljevic & Rylatt, 2003). The complex interactions of these factors affect the spatiotemporal variation in solar radiation patterns and make it difficult to accurately estimate (Hofierka & Kanuk, 2009).

There are three main components of solar energy that need to be taken into consideration in order to accurately estimate hourly solar irradiance on a horizontal or tilted surface. These three are the direct beam, sky-diffuse and the ground reflected components (Perez & Stewart, 1986). Difficulties are sometimes encountered with these three components of solar radiation since most ground based stations measure primarily total radiation (composed of direct plus diffuse) only (Liu & Jordan, 1960). This data is measured at some stations on horizontal surfaces, but the data is not always available for tilted surfaces and thus must be calculated (Pandey & Katiyar, 2009). Direct solar radiation is that part of the solar radiation arriving at the Earth's surface without first being intercepted, commonly referred to as the direct beam component (Rylatt et al., 2001). It is generally the easiest to calculate and its algorithm is identical in all models. The source of error for this component is generally negligible (Perez & Stewart, 1986).

Diffuse solar radiation refers to the part of the solar radiation arriving at the Earth's surface after first being scattered by obstructions in the atmosphere, such as haze, dust, and reflection by natural and man-made surfaces (e.g., buildings and mountains) (Rylatt et al., 2001). This is also known as the sky-diffuse component and it is very difficult to accurately estimate. The estimation of diffuse solar radiation is considered to be the predominant source of error associated with the models and where the main discrepancies arise (Perez & Stewart, 1986). Sky models are used in order to calculate diffuse solar radiation and the most commonly used models are the circumsolar, isotropic and anisotropic models (Perez & Stewart, 1986; Duffie & Beckman, 1991; Chow et al., 2005; Pandey & Katiyar, 2009). These sky models are based upon conditions for clean and cloudless skies, overcast skies, and partly cloudy skies respectively for the circumsolar, isotropic and anisotropic models (Perez & Stewart, 1986; Pandey & Katiyar, 2009). Anisotropic models are generally more favored upon than isotropic models because isotropic models tend to underestimate solar radiation (Duffie & Beckman, 1991). Famous anisotropic sky models such as the Perez, Hay, Klucher and Reindl are considered to have the least amount of errors, and are used in present day simulation models to simulate the diffuse component of sunlight (Chow et al., 2005).

Lastly, the ground-reflected component refers to the radiation reflected by the surrounding terrain, which does not include the building reflected component (Dubayah & Rich, 1995; Chow et al., 2003). It is considered to be challenging to model with great accuracy, but generally has the least amount of weight in the determination of hourly solar radiation (Perez & Stewart, 1986). Data for these three components of radiation is necessary for any solar energy applications, specifically PV generation potential.

2.4. Solar Radiation Data

Solar radiation data sets are required in order to create reliable and accurate models to estimate solar energy potential for PV systems. Solar radiation data can be collected from ground-based meteorological stations or derived from satellites, thus making insolation data very expensive to collect (Dean et al., 2009). If the nearest ground-based station is beyond twenty-five kilometres away, satellite-derived insolation data is generally used and is considered to be the most accurate form of data, with a mean basis error of only two to five percent (Dean et al., 2009). Since there are few meteorological stations (especially in Canada) that collect this type of data, it can be quite difficult to develop accurate spatiotemporal models (McKenney et al., 2008; Pelland et al., 2006; Nguyen & Pearce, 2010).

Many solar programs and simulation softwares have been developed in order to help with the planning process and calculations for building suitability for PV installation, however accurate data is needed. In most parts of Canada, solar radiation data from the meteorological station closest to the proposed study area can be used. If that is not feasible, the interpolation between two or three stations within the vicinity is recommended (NRCan, 1991). However, there could be potential sources of errors associated with the simple interpolation of measurements, because solar radiation values can vary by a significant amount within short distances, due to variations in topography and features of the local environment (Fu & Rich, 1999).

Currently, in Canada one of the most reliable and complete sources of solar radiation data is the Environment Canada's CERES CD (*le disque Canadien des Energies Renouvelables Eolienne et Solaire, The Canadian Renewable Energy Wind and Solar Resource CD*). It provides a summary of statistics related to solar radiation taken from 144 locations across Canada. It provides monthly solar radiation data and includes the data for direct beam, reflected and diffuse solar radiation on thirty-two PV array surface orientations (Pelland et al., 2006; McKenney et al., 2008).

2.5. The Urban Environment

Urban areas are very complicated in infrastructure and provide a series of challenges for the evaluation of total available irradiation for PV systems. Cities have the ability to provide large surface areas for PV systems; therefore much research has gone into finding suitable buildings and surfaces that would receive maximum irradiation for these PV arrays. It is very challenging to calculate the total amount of irradiation received within urban areas, as the complex local environments must be taken into consideration since most buildings will experience periods of sky obstruction (shading) on their rooftops and facades (Mardaljevic & Rylatt, 2003). Even partial shading of the PV system by nearby obstructions (e.g., trees and buildings) can negatively affect its electricity generation potential. If one or more cells in a PV array are affected by shading, it not only fails to generate energy, but it also blocks the power being produced by the other connected cells. This can have many detrimental effects as it reduces the power output of the full PV array system (NRCan, 1991), and can incur losses in net energy of approximately twenty-five percent (Norton et al., 2010).

Some main factors that need to be taken into consideration in order to perform an in-depth analysis of total available irradiation in an urban environment include the geographic location, prevailing local weather patterns (clear skies, overcast, and partly cloudy), urban micro-climate factors, the orientation and inclination of the building surfaces and the local environment (such as inter-reflection between buildings) (Mardaljevic & Rylatt, 2003; Hofierka & Kanuk, 2009). Other urban variables that should be taken into consideration as well are the shape of city blocks, the orientation of city blocks ($+90^{o}$ to -90^{o}), tree structures (ranging in magnitudes from 1-5, classified according to height), the configuration of neighbourhoods, width of the streets, and construction lines (Arboit et al., 2008). About ten percent of solar energy lost can be attributed to shading from trees and buildings in surrounding areas (Levinson et al., 2009).

In regards to building morphology and characteristics, buildings can be divided into different categories associated with specific socio-demographic and cultural features such as residential homes, industrial, facilities, and schools

(Hofierka & Kanuk, 2009). It should also be noted that in particular, the rooftops and facades of buildings are of particular significance and provide a potentially large surface area for PV installations. The amount of surface area on a rooftop and façade that are actually suitable for PV installation may not necessarily be the entire area. The main reasons include aspects such as angle inclination, shading, historical building considerations, and other competing uses (including HVAC installations, elevators, windows, vents, and roof terraces) (Izquierdo et al., 2008). The above features are very important, as they are input parameters for almost all simulation models and software tools used to estimate solar PV potential. The performance of an in-depth analysis for the modeling of the spatial and temporal variations in irradiation data is thus imperative to accurately estimate total solar PV generation potential in urban areas.

2.6. Solar Radiation Models

Over the past five decades, many building energy simulation programs and models have been created in order to analyze solar energy potential in buildings (Crawley et al., 2008), with significant progress being made, especially in the past two decades (Suri & Hofierka, 2004; Dubayah & Rich, 1995). These models and simulations are becoming ever more important with the increasing demand for electricity throughout the world, and in particular, the urban environment. The following discussion will be divided into three sections pertaining to the different types of solar radiation models: (1) Geographic information system (GIS) based solar radiation models, (2) Open source solar radiation models, and (3) Other solar radiation modeling software tools. This section will conclude with a table summarizing the advantages and disadvantages of the solar software tools that were reviewed.

2.6.1. Geographic Information Systems (GIS) based solar radiation models

There has been much technological advancement in the past twenty years towards the development and implementation of solar radiation models incorporated with Geographic Information Systems (GIS). One of the first solar radiation models that were created for the GIS was SolarFlux (Suri & Hofierka, 2004; Dubayah & Rich, 1995; Hetrick et al., 1993). SolarFlux was implemented in the Arc/Info (vector based) and GRID (raster based) GIS platform on a UNIX workstation, which enabled for it to have a variety of GIS capabilities (Dubayah & Rich, 1995; Hetrick et al., 1993). A later series of solar radiation algorithms were further implemented into Genasys GIS. In order to account for the computation of all three components of solar radiation (direct beam, diffuse, and reflected) a later standalone model called Solei was released under MS Windows that was linked to IDRISI (a GIS software) (Hofierka & Suri, 2002; Suri & Hofierka, 2004).

As technological advancements were made in GIS, methods to account for meteorological and environmental assessment applications were further created and implemented into a model called Solar Analyst, developed as an ArcGIS extension using C++, Avenue, and the GridIO library (Suri & Hofierka, 2004; Fu & Rich, 1999). This latest expansion included updates in algorithms that could take into account the influences of viewshed, orientation, and weather conditions. The Solar Analyst model used digital elevation models for the calculation of solar radiation maps and expanded the functionality, accuracy and calculation speed of existing GIS solar radiation models. Solar Analyst is also considered to be an overall geometric solar radiation modeling tool (Fu & Rich, 1999).

An example of a major program that is coupled with the GIS is the simulation system called Irradiation Mapping for Complex Urban Environments (ICUE). ICUE is an approach created by Mardaljevic and Rylatt (2003) to simulate the amount of solar insolation received in complex urban environments. It accounts for many details that other solar radiation models previously excluded, such as limitations placed on the complexity of the scene, sky patterns, accurate prediction of irradiation on facades based on an hourly basis and the inter-reflections between buildings.

The ICUE simulation system approach was implemented on a UNIX workstation as an expert user tool. It was composed of a variety of models and scripts put together in order to start, process and view irradiation images. The Radiance simulation program for lighting was used to create the irradiation images for ICUE, which were then analyzed by the program. The program then created outputs that can be linked directly to GIS for end-user applications because ICUE is not user-friendly at all (nor is it available to end-users at the moment). The end-user application called the Solar Energy Planning (SEP) system takes irradiation maps from ICUE and outputs it into the GIS program through a connection called a soft-link. The SEP system is made and targeted for planners that would like to take into consideration the effects of solar energy in the urban environment to help aid in the estimation of electricity generation potential for PV systems (Mardaljevic & Rylatt, 2003).

Recently, there have been many advances in the development of web-based solar estimation tools for quantifying solar PV potential and informing the public the benefits and costs associated with the usage of solar energy. A few examples include Solar Boston, In My Backyard, PVWatts and San Francisco Solar Maps. Web-based PV estimation tools can also be linked with GIS and are commonly referred to as Photovoltaic Geographical Information Systems (PVGIS). PVGIS can be effectively used for on-site evaluations of PV installations and are composed of a spatial database and the methodology from r.sun, which is a popular open source software which will be detailed in the next section (Hofierka & Kanuk, 2009). GIS based solar radiation models can be very beneficial for researchers because of its ability to map and interpolate complex spatial information. It also has the ability to integrate environmental and socio-economical data to produce interesting complex scenarios (Suri & Hofierka, 2004; Nguyen & Pearce, 2010).

Although there have been many advancements, there still remains a huge need for improved functionality, algorithms and calculation speed for GIS-based solar radiation models (Fu & Rich, 1999). Further research is needed in order to create more complete and detailed 3-D solar radiation models in GIS that are capable of analyzing and considering the complex dynamics within an urban environment such as hourly insolation, vertical facades, inter-reflections between buildings, and HVACs.

2.6.2. Open source solar radiation models

Currently, the four most popular open source solar radiation models, which are available on the Internet for free that are used in wide circulation are r.sun, ESP-r, Radiance and EnergyPlus. R.sun, ESP-r and Radiance can generate 3-D models of buildings and calculate solar radiation. EnergyPlus, however, is not capable of generating 3-D models directly and is typically used in conjunction with other solar softwares. The default algorithm used to calculate diffuse solar radiation for all four softwares is the popular Perez model (Chow et al., 2003; Chow et al., 2005). These four softwares are highly recognized and will be discussed in the following order: (i) R.sun, (ii) ESP-r, (iii) Radiance, and (iv) EnergyPlus.

(i) R.sun

The r.sun solar radiation model was implemented as a module in the Geographical Resources Analysis Support System (GRASS) GIS open source environment using the C programming language and was created by Hofierka & Suri (2002). R.sun is a very complex and flexible solar radiation model and is based on the comprehensive methodology for the spatially and temporally distributed computation of solar radiation data (Hofierka & Suri, 2002; Suri & Hofierka, 2004; Hofierka & Kanuk, 2009). It is able to calculate all three components of solar radiation for different weather conditions (overcast, clear skies), horizontal or inclined surfaces, but not for vertical facades (Suri & Hofierka, 2004; Hofierka & Kanuk, 2009). R.sun is a raster-based program with spatially variable data (for inputs and outputs). It can be used for long-term calculations at different map scales and is especially applicable for modeling large and complex areas (Suri & Hofierka, 2004). A shadowing algorithm is built into r.sun which allows for easy analyses to be performed for sky obstructions (shadows) cast by the local environment such as buildings and objects. It can be used to compute the spatio-temporal variation of albedo due to solar radiation as well (Nguyen & Pearce, 2010).

Hofierka & Suri (2002) implemented r.sun in two modes and they are:

- Mode 1: the instant time (seconds) - calculates raster maps and the three components of solar irradiance (Wm^{-2}) and solar incident angle (degrees).
- Mode 2: the raster maps of the daily summation of solar irradiation in (Whm^{-2}) and duration of the beam irradiation (minutes) – evaluated at a specified time interval.

These two modes can be used in conjunction or separately to calculate solar irradiance data at specified times or intervals, with the option of including the effects caused by the local environment and can be used with shell scripts. With the usage of shell scripts, r.sun can calculate shadows up to thirty minutes in time interval increments (Neteler & Mitasova, 2008). R.sun is a very powerful program and can be used to evaluate shadows for horizontal and inclined surfaces, however it requires expert programming skills. Since r.sun was implemented in an open-source GRASS GIS environment, the general public license allows for the source code to be easily accessible by anyone, allowing for improved modifications in the future (Hofierka & Kanuk, 2009).

(ii) ESP-r

The second major open source software ESP-r, is an integrated multipurpose building energy simulation software program which has been extensively used for over twenty-five years (Crawley et al., 2008). It was developed as an open source software and implemented in the UNIX operating system. ESP-r is capable of working with other software tools such as computer-aided-design (CAD) for visualization purposes, EnergyPlus and Radiance (Energy Systems Research Unit [ESRU], n.d.). ESP-r is composed of a variety of support modules, and some of the main features of these modules include climate display and analysis, calculation of shading and insolation patterns and 2-D and 3-D model builders (Crawley et al., 2005). Most importantly, ESP-r is capable of simulating PV electricity power generation potential and is able to account for building facades and rooftops. It, however, is not very user-friendly and requires specialist skills in programming and looks too much like a research tool (ESRU, n.d.). ESP-r also appears to have more research merits than for practical applications.

(iii) Radiance

Radiance is a computer simulation lighting software that calculates the global solar radiation and illumination reaching buildings, facades, and rooftops. Radiance was developed in 1984 at the Lawrence Berkeley Laboratory as a backward ray tracing method (Compagnon, 1997). It is based upon the Perez model for diffuse solar radiation and is considered to be highly accurate (Compagnon, 2004; Chow et al., 2005). This software can accurately quantify the energy potential for active and passive solar heating (Compagnon, 2004). It is a UNIX based program and is used as the rendering engine in STIMAP (spatio-temporal irradiation mapping). It produces very accurate results for daylight modeling and is based upon the computation of images of total annual irradiation based on hourly meteorological data (Mardaljevic, 2004). Radiance has the ability to accurately quantify the sunlight reaching rooftops and facades (Compagnon, 2004). The setback however, is that it is a very script driven lighting simulation program and is mainly intended for the modification and research of ray tracing algorithms, and used as a rendering engine (Mardaljevic, 2004).

(iv) EnergyPlus

EnergyPlus is a modular, structured software tool that acts primarily as a building energy simulation engine (Crawley et al., 2005). It was developed by the United States Department of Energy in the 1970s using the Perez algorithm and receives input and outputs as text files only, and does not have a user-friendly graphical interface (Chow et al., 2005). A lot of solar radiation modeling software tools support data exchange with EnergyPlus as it is considered to be a very accurate estimation tool. Its main limitation is that it is a command line driven software and outputs only text files.

2.6.3. Other solar radiation modeling software tools

This section will provide a brief summary of the other major solar radiation modeling software tools that do not specifically fit into any category that are used in the research community. The programs that will be reviewed in this section include: (i) BSim, (ii) TRNSYS, (iii) Ecotect, (iv) RETScreen, and (v)HOMER.

(i) BSim

BSim is one of the most commonly used simulation tools in Denmark, and has been in use for the past two decades. It is a user-friendly simulation package and integrates several different computer modules together and the main modules are:

SimView (a graphic editor), SimLight (daylight analysis), XSun (direct sunlight and shadowing analysis), SimPV (PV electricity potential), and SimDXF (allows for import from CAD programs). SimPV can produce results calculated on an hourly basis making it possible to compare the estimated hourly electrical output from a PV system with other hourly electricity consumption information (Wittchen, 2003). BSim is capable of creating detailed analysis of shadows from neighboring buildings and can produce animation sequences for the solar effects (Crawley et al., 2005). It is growing in popularity worldwide and is good for providing detailed analyses for PV electricity generation potential for buildings. It however is still considered as a simple design tool due to simplified routines and algorithms in the SimPV module (Wittchen, 2003).

(ii) TRNSYS

TRNSYS is a transient system simulation program with a modular structure that provides dynamic simulations for PV systems (Norton et al., 2010). It was designed to solve complex energy system problems and was developed in the 1970s (Chow et al., 2005). TRNSYS is a very suitable program for performing detailed analyses on any system whose behavior is dependent on time. One of its main applications is the calculation and modeling of solar radiation potential for PV systems. TRNSYS is capable of generating and building 3-D geometric models and supports data exchanges through different tools such as Matlab, and Simulink (Crawley et al., 2008; Klein et al., 2010). Its main limitation is that the software for 3-D modeling is not directly built into the program, and one must run and download an additional plugin called TRNSYS3d for Google SketchUp based on the open source program called OpenStudio (Klein et al., 2010).

(iii) Ecotect Analysis

Ecotect Analysis is a highly innovative software program developed by Autodesk, which is a world leading company in 2-D and 3-D design software. Ecotect is a very powerful analysis tool that has the capability to estimate total solar energy potential for buildings in a highly complex urban environment. It is linked to a comprehensive 3-D modeler with a variety of performance analysis functions that are capable of handling the visualization, thermal performance, solar energy analysis, sun-path diagrams, shading, ventilation, environmental impacts and cost aspects of the simulation process (Marsh, 2003; Crawley et al., 2008). Ecotect has many benefits compared to other solar radiation modeling software as it is capable of producing almost instantaneous feedback at any stage in the design process, provides interactive information displays and can create highly visually appealing drawings (Crawley et al., 2008). Also, it is capable of importing and exporting data to other solar radiation analysis software tools such as EnergyPlus, ESP-r, Radiance and includes an array of suitable formats for most CAD programs (Crawley et al., 2005). Ecotect is also equipped with a very powerful scripting engine for invoking analysis functions and analysis results for versatility (Marsh, 2003). Most importantly, it is very user-friendly and provides highly accurate solar potential energy estimates all in one package.

(iv) RETScreen

RETScreen Clean Energy Project Analysis Sofware is a statistical energy decision-making software. It is one of the world's leading clean energy decision-making softwares and is available for public download for free by the Government of Canada (NRCan, 2011). RETScreen is a spreadsheet-based software and is an overall energy and financial analysis tool for clean energy technologies such as wind and solar. It can analyze energy production, life-cycle costs and greenhouse gas emissions reductions. The main limitation with RETScreen is that it can only generate the twelve monthly electricity values for PV systems, and is not capable of producing the full 8760 points of data that other hourly simulation models are capable of.

(v) HOMER

The hybrid optimization model for electric renewables (HOMER) is an energy modeling software and was developed by the U.S. National Renewable Energy Laboratory (NREL). It is a very powerful analysis tool that contains optimization and sensitivity analysis algorithms, and is primarily used as an economic optimization model (Brown & Rowlands, 2009). HOMER has a wide range of capabilities and technology options, and allows the user to model a power system's physical behaviours and its life-cycle costs (Lambert et al., 2006). It is capable of estimating hourly electricity output based on input parameters for solar PV applications as well as other renewable energy sources. HOMER simulates the PV system by making energy balance calculations for each of the 8760 hours within a year (NREL, 2005).

One of the main benefits of HOMER is that it is capable of synthesizing 8760 hourly electricity values from twelve monthly average daily radiation values. HOMER does this through an algorithm developed by Graham & Hollands (1990) specifically for solar simulation design work. It generates synthetic hourly solar irradiation data sets using only the twelve monthly means of daily events called the global horizontal irradiance (GHI) and the latitude of the location (Graham & Hollands, 1990). HOMER then uses the Hays-Davis-Klucher-Reindl (HDKR) model to finally calculate the global radiation incident on the PV array. The HDKR model is an improved sky model based upon the theories that were previously mentioned in Section 2.3, and divides the diffuse solar radiation into three components: an isotropic component (takes all parts of the sky equally), a circumsolar component (emanates from the direction of the sun), and a horizon brightening component (emanates from the horizon) (Duffie & Beckman, 1991). These values are then used to calculate the power output of the PV array (HOMER Energy, 2010).

2.6.4. Summary

There are a great number of solar modeling software tools that exist in the world today. The most commonly mentioned softwares were summarized in this review. These softwares offer unique capabilities and have different strengths and weaknesses. Not all programs are widely used around the world, and some are seen in the literature more often than others. Table 1 provides a summary of the capabilities of these different softwares.

Table 1. Summary of the capabilities of the solar software tools.

Software Tool	Strengths	Weaknesses	3-D data	Level of Expertise	Open-source	Time Sensitivity of Estimate
ESP-r	-Accurate calculation algorithms -Can work with other solar software such as Radiance	-Very difficult to use and detailed modeling knowledge is needed -Non-user friendly interface -Looks too much like a research tool	Yes	High	Yes	Hourly
r.sun	- Generates beautiful maps -Ideal for large scale analysis -Can handle complex terrains on maps	-Not ideal for small scale analysis of a few buildings	Yes	HIgh	Yes	-Can generate up to 30min interval; however must be an avid programmer to do this
Radiance	-Can quantify solar potential -Beautiful 3-D images generated	-Mainly intended for use as a light simulation and for rendering images	Yes	High	Yes	Could not identify
EnergyPlus	-Modular structured software -Accurate calculations	-No visual user interface -Command line driven -Inputs and outputs as text only	Yes	High	Yes	Hourly
TRNSYS	-Can perform detailed calculations -Modular structure software	-Not capable of performing analysis on multiple buildings	Yes	Moderate	No	Hourly
BSim	-Simple model for the calculation of PV electricity	-Not widely used -Simple calculation algorithms	Yes	Moderate	No	Hourly
Ecotect	-Can calculate detailed incident solar radiation on 3-D surfaces	-Cannot generate PV electricity results -Need to use another software to calculate electricity values	Yes	Moderate	No	-Can perform hourly analysis on a single day basis only
RETScreen	-Spreadsheet based software –User-friendly	-Cannot generate hourly electricity potential	No	Low	Yes	Monthly
HOMER	-Can generate accurate predictions for hourly PV estimations	-Does not have a visually appealing interface	No	Moderate	No	Hourly

3. Methodology

In brief, this chapter will start by explaining the software selection criteria and process in order to reach a decision for the optimum software tools chosen to perform the solar analysis in this thesis. It will be followed by a summary of the overall workflow and the detailed descriptions of every step and theory taken to produce this methodology.

3.1. Software Selection Criteria and Process

In order to be able to determine what solar software tools would be suitable for this thesis, a list of criteria was made in order to establish the terms of functionality, availability, computational skills and level of learning required. The following list of criteria were made in order to help with this software selection process, and they are:

1. A software that is able to analyze complex 3-D data with multiple buildings and zones.
2. A software package that has the ability to draw and edit large 3-D models with ease.
3. A software that can account for solar radiation losses due to shading caused by obstructions.
4. A software tool that has a built-in weather database or the ability to import popular weather data sources.
5. A software package that has a user-friendly interface, is visually appealing and does not require specialist programming skills.

6. A software package that is highly sensitive to time and location.
7. A software that is able to calculate incident solar radiation values upon chosen surfaces within the 3-D model.
8. A software that has the ability to accurately measure the gross surface area of building rooftops and occupied areas by undesirable objects (such as HVACs, green roofs, piping, etc.) in order to find total suitable areas for PV applications.
9. A software that has ability to calculate the full 8760 hourly solar PV electricity output values for a simulated year within a reasonable time frame.
10. A software that is not overly computationally intensive.

After much deliberation and consideration of the criteria, a few software tools were chosen from the literature review and evaluated in detail. The first program of choice was the open-source software ESP-r. ESP-r was found to be a very powerful software capable of analyzing 3-D models, importing weather data, calculating incident solar radiation and yielding hourly PV electricity outputs. This program however, was not chosen because its main limitation was in its capability of drawing complex 3-D models with multiple zones. In order to start modeling in this software, the user must manually define the x, y and z coordinates of each point within the model. This was very difficult and impractical for such a complicated drawing of high detail that was required in this thesis. Also, since the 3-D data was obtained from a third party, there was no way to import the drawing into the software, as ESP-r had strict requirements on how the CAD file must be drawn.

Another setback of this program was that it calculated the solar potential upon every surface of the drawing and was too computationally intensive for a complicated 3-D model. Lastly, ESP-r does not have a visually appealing interface and requires specialist skills in computer programming and was thus dismissed from this thesis due to multiple violations in the criteria list.

The second software of choice was r.sun from GRASS GIS, as it was capable of generating analyses up to time-intervals of thirty minutes. R.sun was evaluated and it was found that it was not ideal for analysis on the city block level and optimal only for large-scale analyses such as on the citywide level or larger. Also, r.sun required specialist-programming skills in order to write scripts to analyze solar irradiance on an hourly basis. Hence r.sun was taken off the list as a potential software for this thesis' methodology. The next software that was briefly evaluated and rejected was TRNSYS. TRNSYS was rejected because it was not capable of handling multiple building analyses.

Ecotect was the final software to be evaluated. It was found to have a visually appealing interface, the abilities to handle complex 3-D data, the ability to account for shading from obstructions, and allows for the user to manually select which surfaces to be analyzed. This program was chosen because it satisfied the criteria list best out of the software tools evaluated, and was thus employed in this thesis to analyze the incident solar radiation upon rooftops in the 3-D model. Orthophotos were then used to supplement this methodology using ArcGIS to identify the surface areas that were already occupied on the rooftops by undesirable objects such as HVACs and piping to obtain an accurate measurement of total usable rooftop areas suitable for PV deployment. Lastly, a software called HOMER was utilized to accept the incident solar radiation values generated from Ecotect in order to estimate the annual hourly solar PV electricity outputs, since HOMER does not have 3-D modeling capabilities.

3.2. Workflow Overview

The overall workflow of the methodology employed in this thesis is represented in Figure 2. The flowchart in Figure 2 is divided into four main sections describing the steps taken in order to obtain the results along every way of the methodology. These four main steps summarize the tasks taken to: (1) obtain and manipulate the 3-D data, (2) to find the incident solar radiation upon each rooftop, (3) to find the surface area on these rooftops suitable for PV deployment, and (4) to find the hourly solar PV electricity estimates.

The first section in this methodology deals with the selection of the study area and the acquisition of 3-D data from the City of Toronto. The 3-D data of the study area was then edited accordingly for compatibility with the chosen solar software for analysis using computer-aided design (CAD) software. The edited 3-D data was then imported into the chosen solar software of Ecotect Analysis 2011 in order to estimate the amount of incident solar radiation upon each rooftop.

The 3-D data was further edited and organized using Ecotect and the appropriate data was loaded into the software to prepare for analysis. The Solar Exposure function was then used in Ecotect to find the incident solar radiation (Wh/m^2) upon each rooftop. Once all the buildings were analyzed in Ecotect, the surface area suitable for PV deployment was deduced using digital orthophotos acquired from the Ryerson University Library.

The orthophotos were digitized using ESRI ArcGIS 10 in order to measure and eliminate any areas on rooftops that were already occupied. Two scenarios were then employed to find the usable surface area deduced from the measured gross rooftop surface area: (1) through the application of PV access factors and (2) through the eliminated occupied areas and the application of a module coverage factor. The PV system size was then estimated for each rooftop based upon the measurements obtained from both scenarios. The results from Ecotect and the two scenarios were then inputted into HOMER to yield annual electricity PV estimates for the entire study area.

3.3. Case Study area

Ryerson University was chosen as the case study area because it exhibits characteristics from a typical urban environment. It is located in the heart of the City of Toronto, in a densely populated area, has high electricity demands and has buildings of different morphology and characteristics such as age, height and function. This area provides a good range of diverse characteristics to be analyzed for solar energy potential.

The data for the 3-D model was obtained from the City of Toronto, Planning Office. One square block of data was requested, from Yonge St. to Jarvis St., and from

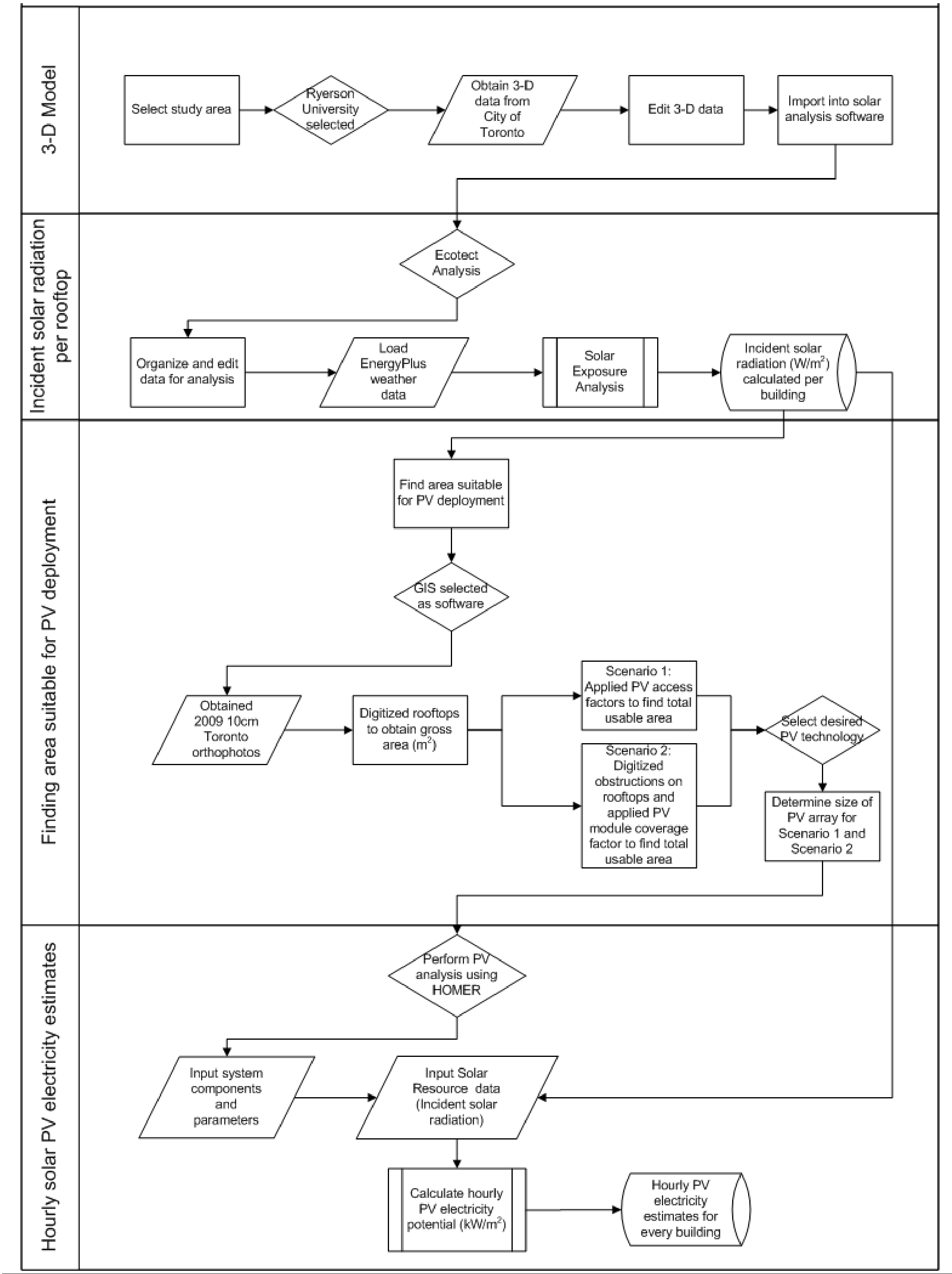


Figure 2. Procedural workflow for 3-D analysis and hourly solar PV generation potential.

Dundas St. East to Gerrard St. East. Buildings that were not a part of the campus were excluded from the model, unless if they had a shadowing impact or were significantly close to any of the Ryerson buildings. Ryerson buildings that were missing information or not included in the original model were excluded from the Ecotect file (ECO) of the campus, depicted in Figure 3. Figure 4 is a campus map of Ryerson University, followed by Table 2, which provides a comprehensive list of the Ryerson University buildings and their acronyms, and whether they were included in the 3-D model or not and the reason.

Figure 3. 3-D building model of study area in Ecotect, with Ryerson owned buildings in grey and non-Ryerson owned buildings in black (and in print colored red).

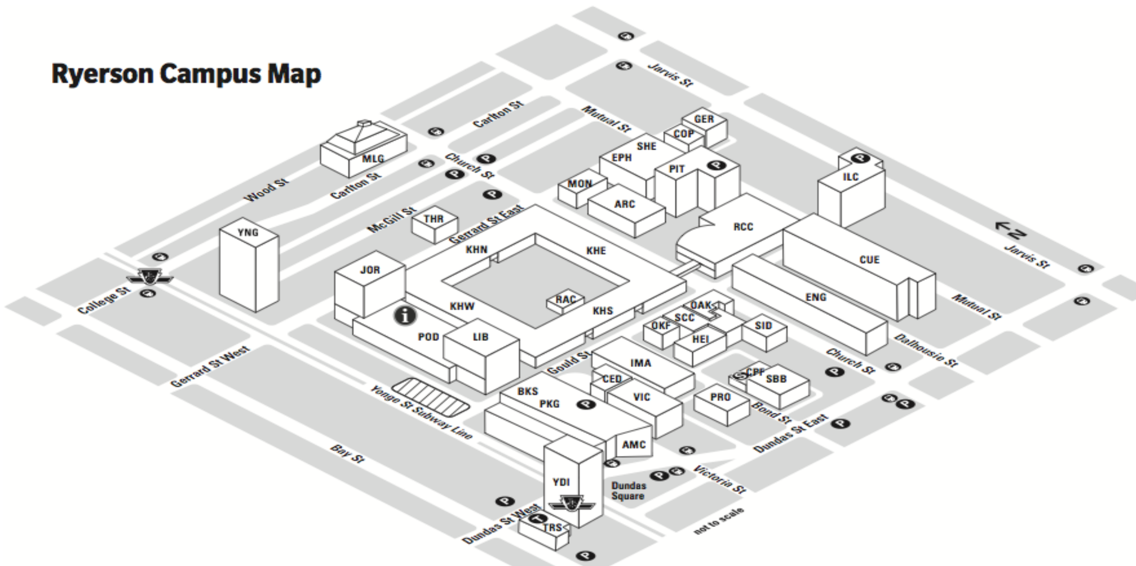


Figure 4. Ryerson University campus map.

Table 2. Ryerson University buildings included in the 3-D model and their acronyms

BUILDING CODE	NAME	STREET ADDRESS	INCLUDED IN 3-D MODEL	REASON NOT IN 3-D MODEL
AMC	Toronto Life Square (AMC)	10 Dundas Street East	Yes	
ARC	Architecture Building	325 Church Street	Yes	
BKS	Bookstore	17 Gould Street	Yes	
CED	Heaslip House, The G. Raymond Chang School of Continuing Education	297 Victoria Street	Yes	
COP	Co-operative Education	101 Gerrard Street East	No	Missing info
CPF	Campus facilities and sutainability	111 Bond Street	Yes	
CUE	Centre for Urban Energy	159 Dalhousie Street	No	Not in study area
ENG	George Vari Engineering and Computing Centre	245 Church Street	Yes	
EPH	Eric Palin Hall	87 Gerrard Street East	Yes	
GER	Research/Graduate Studies	111 Gerrard Street East	No	Missing info
HEI	HEIDELBERG Centre-School of Graphic Communications Management	125 Bond Street	Yes	
ILC	International Living/Learning Centre	133 Mutual Street	No	Missing info
IMA	School of Image Arts	122 Bond Street	Yes	
JOR	Jorgenson Hall	380 Victoria Street	Yes	
KHE	Kerr Hall East	340 Church Street/60 Gould Street	Yes	
KHN	Kerr Hall North	31/43 Gerrard Steet East	Yes	
KHS	Kerr Hall South	40/50 Gould Street	Yes	
KHW	Kerr Hall West	379 Victoria Street	Yes	
LIB	Library building	350 Victoria Street	Yes	
MON	Civil Engineering Building	341 Church Street	Yes	
OAK	Oakham House	63 Gould Street	Yes	
OKF	O'Keefe House	137 Bond Street	Yes	
PIT	Pitman Hall	160 Mutual Street	Yes	
PKG	Parking Garage	300 Victoria Street	Yes	
POD	Podium	350 Victoria Street	Yes	
PRO	Projects Office	112 Bond Street	Yes	
RAC	Recreation and Athletics Centre	40 and 50 Gould Street	No	Underground Facility
RCC	Rogers Communication Centre	80 Gould Street	Yes	
SBB	South Bond Building	105 Bond Street	Yes	
SCC	Student Campus Center	55 Gould Street	Yes	
SHE	Sally Horsfall Eaton Centre for Studies in Community Health	99 Gerrard Street East	Yes	
SID	School of Interior Design	302 Church Street	Yes	
THR	Theatre School	44/46 Gerrard Street East	Yes	
TRS	Ted Rogers School of Management	575 Bay Street	No	Not in study area
VIC	Victoria Building	285 Victoria Street	Yes	
YDI	Yonge-Dundas 1	1 Dundas Street West	No	Not in study area
YNG		415 Yonge Street	No	Not in study area

3.4. 3-D Model

The 3-D model was modified accordingly for compatibility with Ecotect. The original files that were received from the City of Toronto Planning Office were in the 3-D CAD formats of DWG or DGN. This 3-D data was not drawn in the correct format for Ecotect, nor available in the desired format. In addition, there were many errors in the 3-D model that was obtained from the City. In order to solve this dilemma, AutoCAD was used to redraw and edit the campus model, to ensure that all solids were properly enclosed, that there were no floating surfaces and that each building had properly drawn rooftops and vertical facades. The layers in the model and any complicated structures had to be simplified so that Ecotect would be able to calculate the solar potentials faster, since Ecotect is very computationally demanding. The new model was created in a 3-D format called 3DS, which is the format that Ecotect reads best and was triangulated before successful importation into the software. The triangulation merged all coplanar triangles into single complex planes, since Ecotect is highly sensitive to the number of objects in a model. The successfully modified campus model was then saved as an ECO file.

3.5. Ecotect Analysis

Once the triangulated campus model was successfully imported into Ecotect, there were numerous issues that needed to be corrected before the model was scaled and ready for solar analysis. First, the model needed to be fixed to an axis and an origin. Second, the buildings in the model needed to be organized into different zones for categorization. Buildings that were not part of the campus were separated into their own zone. After the categorization was completed, the surface normals of all planes were checked and reoriented. In order for the performance of an accurate solar exposure analysis, all external-facing surfaces must have an outward pointing normal. If not, Ecotect treats it as an internal surface that receives zero solar radiation. Once that was accomplished, the inter-zonal adjacency of the buildings was calculated which told the software how close each building was in relation to each other in order to account for shading.

Another significant issue that had to be overcome was the linking and the unlinking of object nodes. This issue was first noticed when the software was producing incorrect surface area measurements for correctly drawn buildings. The reason for this occurrence was found to be the way the original CAD file was drawn, which was in violation of parent child object relationships. This meant that for a chosen plane, that one or more of its nodes have become non-coplanar (e.g., a door is no longer inside its parent wall). Luckily, this issue was easily rectified by the "fix links" operation.

Ecotect's main work area or window is comprised of five different pages. These five pages are tabs that run along the left side of the screen which control the main window and how you work with the model. Figure 5 illustrates the main interface with the Project Page selected. These five tabs are the:

1. Project Page – Where the details and site specifics about the model are kept.
2. 3-D Editor – Allows for the drawing and editing of the model.
3. Visualize – Displays a full rendered view of the model.

4. Analysis – Performs a variety of analyses on the model.

5. Reports - Generates tabular reports.

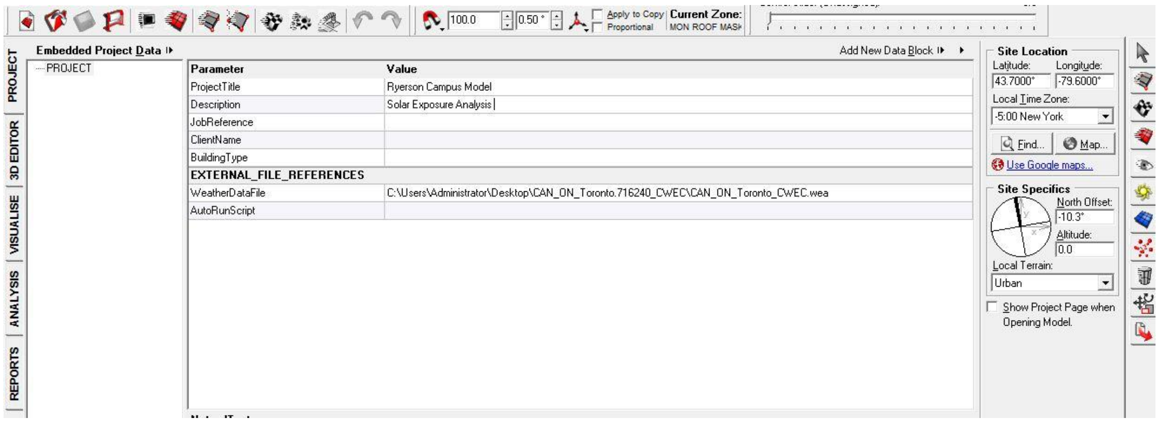


Figure 5. Ecotect Project Page Tab

Upon the successful importation of the scaled campus model into Ecotect, the next step was to correctly setup the Project page tab in the Ecotect window. The Project page is where the user may add additional information about the model, such as title, site location, weather data file and site specifics. For the site location, the latitude and longitude of the model was required (latitude: 43.7, longitude: -79.6) along with the local time zone (-5:00 New York). Under site specifics, the North Offset of the model was requested. The North Offset refers to the magnetic declination of the site, which is the angle between magnetic north and true north. This value was calculated for the City of Toronto using Natural Resource Canada's Magnetic Declination calculator (NRCan, 2010), and was found to be -10.3^{o}. The altitude of the site was also requested by Ecotect, but was not inputted, as it is not used internally within any of Ecotect's calculations.

The next step for the preparation of the analysis was choosing a weather dataset. Weather data for various locations around the world are built in by default within the Ecotect software. This weather data is in a format called WEA, which is produced by Ecotect's home built in Weather Manager utility program. The Weather Manager can import a wide variety of commonly used weather data and then convert it to a WEA file for compatibility with Ecotect. Since WEA files are not widely used for analysis in solar literature, a more reputable source was sought.

The CERES solar database was the first option that was looked at. However, upon closer inspection of the data, it was found to be lacking certain weather information that was needed by the Ecotect software. The source of the CERES database was then looked at and it was found to be derived from the Canadian Weather Energy and Engineering Data Sets (CWEEDS), by Environment Canada. The CWEEDS data is a comprehensive weather database that contains detailed records of forty-eight years of data including twenty-one weather elements from approximately 145 Canadian locations. The weather data was recorded for some locations starting from as early as 1948 and most ending at 2001. The files were created for the purpose of providing long-term weather records for use specifically in urban planning, design of energy efficient buildings, solar renewable energy systems and any areas of weather applicable studies (Environment Canada, 2008). It contains a lot more detail than the CERES database and is perfect for input for hourly analysis building simulations such as the analysis of solar energy potentials.

The default CWEEDS weather files were not in a format that was compatible with Ecotect's Weather Manager, since it was a text file. A conversion or alternative format was thus needed. The second format of the CWEEDS files called CWEC, which stands for the Canadian Weather year for Energy Calculation, was used. This data contained hourly weather data representing an artificial one-year simulation period (typical weather year), designed for building energy softwares and calculations (U.S. Department of Energy, 2011). Conveniently, the CWEC data are readily converted and available in EnergyPlus weather (EPW) format, which is a format that is finally compatible with Ecotect's Weather Manager. The Toronto EPW file, derived from the Toronto CWEC file was successfully imported into Ecotect's Weather Manager and then converted to the necessary WEA format for compatibility. This now completed the Project page setup and the model is now ready for solar analysis.

Ecotect is capable of calculating the amount of solar radiation incident on one or more closed planar surfaces within a model. The Solar Exposure function, which is under the Analysis page, is used to perform this calculation. Ecotect calculates incident radiation by the following equation:

$$E_{incident} = \left[(E_{beam} \times \cos(A) \times F_{shad}) + \left(E_{diffuse} \times F_{sky}\right)\right] \times ExposedArea$$

where,

$E_{incident}$ = insolation,

E_{beam} = direct beam normal,

A = angle of incidence of the radiation,

F_{shad} = the fraction of the surface in shadow from surrounding geometry,

$E_{diffuse}$ = diffuse radiation,

F_{sky} = the fraction of the diffuse sky actually visible from the surface and

ExposedArea = actual exposed surface area to solar radiation (Autodesk, 2010).

This calculation takes into consideration the full geometry of the model as well as the hourly direct and diffuse solar radiation values obtained from the loaded weather file. It is for this reason that the analysis can take from a few minutes to hours, depending on the type of analysis, complexity and number of surfaces chosen.

Under the Solar Exposure analysis tab, the time period and type of analysis can be chosen. This determines the period over which the solar radiation values will be calculated and the tabular and graphical display of the results. Figure 6 is a screenshot of the Solar Exposure analysis page.

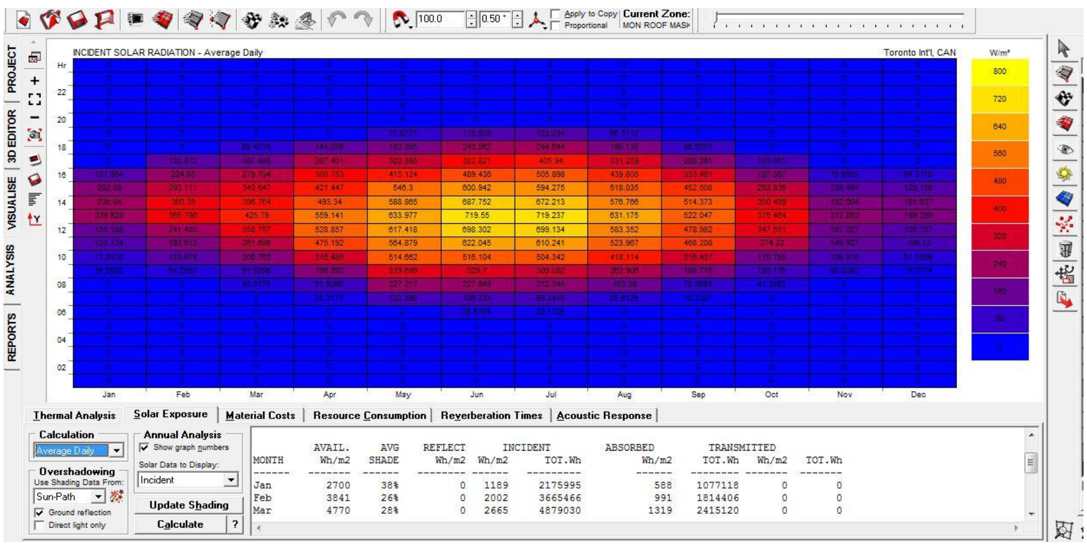


Figure 6. Solar Exposure analysis page

In the Solar Exposure analysis page, there are four choices available for calculation and they are:

1) Single Day - This calculates and graphs the hourly incident solar radiation upon the chosen surface(s) for the date selected only (Wh/m^2).

2) Average Daily - This calculates the hourly incident solar radiation hitting the selected surface(s) for an average day within each month. The total solar

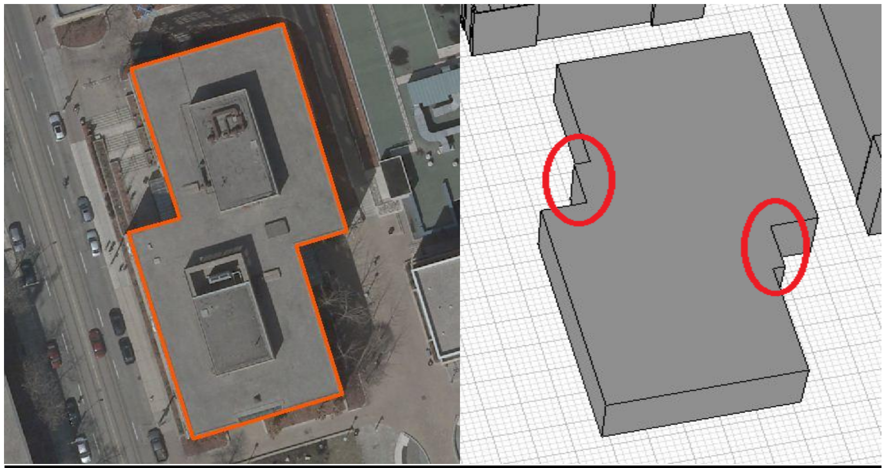
radiation is summed and then divided by the number of days in that month. The graph displays the average hourly values for any one day within that month (Wh/m^2).

3) Total Monthly - Is similar to the Average Daily calculation, except the hourly values are cumulated together for the twelve months (Wh/m^2).
4) Full Hourly - Uses the same calculation as Total Monthly (cumulative total), the only difference is that the results of each day are displayed on the graph (Wh/m^2).

An efficient method does not exist in Ecotect to generate tabular data for an annual hourly analysis of incident solar radiation. The only way to generate the full annual hourly 8760 points of data would be to perform the Single Day analysis 365 times. This methodology would be highly impractical since twenty-five buildings were in need of analyses. The Average Daily analysis method was then evaluated, since it outputted data that were based upon the calculations for the average hourly values within an average day per month. In order to assure that these values did not deviate too much from the Single Day analysis, a Single Day analysis was performed for the thirty-one days in the month of January for the ARC building. The average value found for the ARC building under the Single Day analysis for January was found to be 1229.3 Wh/m^2. This value was then compared to the value generated by the Average Daily calculation estimate of 1189 Wh/m^2 and the difference was found to be not significant. The Average Daily analysis was thus chosen and then performed manually for the twenty-five building rooftops. An option was not found for the batch processing of these rooftops for this analysis. The twelve points of data generated per building for the estimated monthly incident solar radiation values were then used in HOMER to generate full annual hourly electricity estimates. On a last note, the Total Monthly and Full Hourly analysis functions were not applicable to this thesis, since both analyses produced daily cumulative hourly values of the month.

3.6. Determining Rooftop Area Using GIS

The rooftop surface area in the 3-D city model was compared to orthophotos of the City of Toronto generated from the Enterprise Stereoscopic Model from 2009 at a 10 cm resolution obtained from the Ryerson University Library. Upon inspection, it was clear that there was a discrepancy between the two data sources. The geometries of the buildings did not match exactly. This discrepancy in surface area measurement is mainly attributable to the fact that the City of Toronto's data was derived from building footprints and sometimes structures such as porches were extruded up to the top elevation as a part of the roof, leading to inaccuracies. The surface area measurements obtained from this 3-D model are thus not very accurate. Figure 7 provides an example of the ARC building, where it clearly illustrates two small structures that had been extruded and added on as an additional part of the rooftop in the 3-D model, whereas in the orthophoto it is obvious that it is not a part of the roof.



(a) (b)

Figure 7. Comparison of the ARC building (a) with the orthophoto image and (b) the 3-D Ecotect image, with the discrepancy circled.

In order to determine the rooftop area suitable for PV panel installation, a method was needed to identify the gross surface area of each individual rooftop. The gross area was determined through the digitization of the Ryerson campus using the orthophotos with ESRI ArcGIS 10. GIS was chosen because it is a software that provides a convenient mechanism for the analysis and visualization of geographic data, has a rich set of analysis functions and allows for powerful transformations to be performed on geographic data (Shekhar & Chawla, 2003). The 2009 orthophotos at 10cm resolution were used in this thesis because it was the highest resolution orthophotos that the Ryerson Library has to date. An orthophoto can be digitized through the Editor tools in GIS to create a new layer with the extracted rooftops. The digitized rooftop surface areas can then be determined by using the calculate geometry tool within the attribute tables. This process provided a more accurate measurement for the gross surface area estimates. The next step after determining the gross surface area was to find total usable area for PV installation. Two methodologies for determining usable rooftop area were chosen and they are: (1)

Based upon best-published practices for the assessment of usable rooftop area using PV corrective factors and (2) Based upon digitized obstructions using GIS on rooftops reduced by a PV module coverage factor, and they are further explained below.

1. Usable Area – PV Corrective Factors

In recent studies, there has been a growing amount of literature being published about the assessment of rooftop areas suitable for PV deployment. These papers attempt to produce methodologies to accurately estimate the amount of usable area suitable for installation of PV systems through the usage of corrective factors called PV access factors. There are different PV access factors for different representative building type categories. The two main categories identified in the literature are either based upon population density and building density, or building type such as residential and industrial.

Studies conducted by Izquierdo et al. (2008) and Wiginton et al. (2010) produced PV access factors based upon population density and building density. This type of representative building typology is defined as the ratio between the number of inhabitants or the number of buildings, and the surface area within the location of interest (Izquierdo et al., 2008). It is a known fact that in urban areas, with increasing population density, a decline in roof surface area per capita is observed (Wiginton et al., 2010). It is for this reason that building density and population density was not used as a categorization factor in this thesis. The reason is because Ryerson University is mainly located in an office building setting and it would not accurately assess the usable roof space available for PV deployment.

Also, this method is ideal for large-scale studies, and not on the individual detailed buildings level. Thus, only PV access factors that were formed based upon building type were taken into consideration.

Research conducted by Chaudhari et al. (2004), Frantzis et al. (2007), and Paidipati et al. (2008) categorized their PV access factors based upon building types. These authors identified two main building types, residential and industrial/commercial. Their studies were found to be significant because PV access factors were identified for both cool and warm climates conducted in various parts of the United States. The major solar access issues identified were:

1) Roof Type – There are two major types of roof types, flat and pitched. This is important because it determines the potential tilt of the PV systems to be installed.
2) Structural Adequacy – This takes into account for the structural soundness of the rooftop, since PV systems add loads to rooftops. Building code requirements (wind loading, snow loading) and the structural adequacy of the roofs therefore need to be analyzed. It should be noted that this is not an issue for most cases.
3) Material Compatibility – This refers to the material suitability and aesthetic appeal for PV installation. This issue is however, almost never considered.
4) Shading – This factor takes into account for the reduced solar radiation that may be caused on the rooftops by trees, HVACs, other equipment, vents, chimneys and other roof structures.

5) Orientation – The direction in which the roof surface is oriented. It is not an issue for flat rooftops, however it has a significant impact upon pitched roofs.
6) Module Coverage – This factor accounts for the space needed between PV modules, inverters, wiring, access to modules and other maintenance requirements. This value was applied as a "packing factor" to modify and lower the power density of the PV system.

The equation identified by Chaudhari et al. (2004), Frantzis et al. (2007), and Paidipati et al. (2008) to calculate the roof space available in commercial/industrial buildings for flat rooftops in cool climates was:

$$\begin{aligned} Usable\ area &= Gross\ Area \times Material\ Compatibility \\ &\times Structural\ Adequacy \times Shading \times Orientation \\ &= Gross\ \ Area \times 100\% \times 100\% \times 65\% \times 100\% = 65\% \end{aligned}$$

This means that sixty-five percent of rooftop space was identified as available for PV deployment. The module coverage factor was accounted for in their methodology by applying a packing factor to lessen the power density output of the PV array size after the application of the formula. A percentage value was not given in this method and only a ratio value was provided to reduce PV power output. The percentage values for this factor however, were found in other literature.

Two papers of particular significance were found which provided a percentage value for the module coverage factor. Wiese et al. (2010) conducted research about PV access factors for rooftop space in Austin, Texas, based upon the research of Paidipati et al. (2007). A module coverage factor of fifty percent was found. In another study conducted by Bergamasco and Asinari (2011) based on pitched residential and industrial rooftops in Italy, a module coverage factor of forty-five percent was found. This meant that forty-five percent of the space is suitable. Since both values are not affected by climate and geographical location, both factors were found to be applicable. An average of the two numbers thus was taken, and a module coverage factor of 47.5% was decided upon for this thesis.

After applying this factor, the equation used for the determination of the fraction of the rooftop that is available for PV installation is:

$$\begin{aligned} Usable\ Area &= Gross\ Area \times Material\ Compatibility \times Structural\ Adequacy \\ &\times Shading \times Orientation \times Module\ Coverage \\ &= Gross\ Area \times 100\% \times 100\% \times 65\% \times 100\% \times 47.5\% \\ &= Gross\ Area \times 30.875\% \end{aligned}$$

This equation will be used for the results in Scenario 1.

2. Usable Area – GIS Extracted Area and Module Coverage

The second methodology employed in this thesis to determine usable rooftop area is based upon the digitization of obstructions using GIS, the relevant PV corrective factors and the module coverage factor of 0.475 as discussed prior. Any unusable area on the rooftops that are occupied by structures such as HVACs, green roofs, chimneys, and so forth were manually digitized and extracted into a new layer. The "erase" function was then used in GIS to overlay the "gross area" of the rooftop with the "unusable area" to form a new layer that contained the "GIS extracted area". This GIS extracted area represented the areas on the rooftop that were not occupied by any structures. The next step was to apply the module coverage factor value of 0.475 to the GIS extracted area. This would then ensure enough space for the proper installation and maintenance of the PV systems. The following equation was used for the analysis in Scenario 2.

$$\begin{aligned} Usable\ Area &= GIS\ Extracted\ Area \times Material\ Compatibility \\ &\quad \times Structural\ Adequacy \times Orientation \times Module\ Coverage \\ &= GIS\ Extracted\ Area \times 100\% \times 100\% \times 100\% \times 47.5\% \\ &= GIS\ Extracted\ Area \times 47.5\% \end{aligned}$$

From the estimated usable area measurements for both scenarios, the PV system size was calculated for each building.

3.7. Estimating PV array size

In order to accurately assess the PV array capacity size (kW) and surface area (m^2) on the rooftop of each building, a desired PV technology must first be chosen. Since there are many solar panel technologies currently in the market, the top panel module for Ontario suitable for fulfilling the criteria of large-scale deployment was chosen. According to research conducted by Rowlands et al. (2011), the top three panels that currently lead the market are: SHARP ND-198U1F 198W, SUNTECH STP200-18/Ub-1 200W, and SANYO HIT Series HIP-200BA3 200W. These panels were selected based on economy, performance and availability recommendations rated by their Ontario distributors.

Upon review of the manufacturer datasheets, the SHARP ND-198U1F 198W was not chosen because it was advertised for use primarily as a residential module (Sharp Electronics Corporation, 2008). The SANYO HIT Series HIP-200BA3 200W was targeted for buildings with limited roof space with its small design (Sanyo

Energy (USA) Corp, 2007) and was eliminated from the list as well. Lastly, the SUNTECH STP200-18/Ub-1 was chosen as the desired PV technology for this thesis because it was ideal for large-scale commercial deployment (Suntech Power, 2008).

In order to determine how many panels could fit onto a desired rooftop of a building, the available surface area for panel installation needed to be determined. This was done through the digitization of the orthophotos of the campus using GIS as detailed in Section 3.6. From the determined available surface area for installation, the area of the panel which was found to be 1.47m^2, was divided into the available surface area for installation to see how many could fit on the rooftop for maximum space efficiency. The next step was then to deduce the number of panels that could fit upon the available area for panel installation, and the total kW size of the array was found. The kW size of the array was simply calculated by multiplying the number of panels by the kW size of each panel, which was 0.2kW in this case. Finally, all the data is now ready for input into HOMER for full hourly solar PV generation potential.

3.8. HOMER

The first step in starting an analysis with the HOMER version 2.81 software is the selection of the correct system components and resources to add to your model. Figure 8 is a screenshot of the main window of the HOMER software. In order to create a model that can estimate solar PV electricity potential, PV components must first be added to the model under the Equipment to Consider tab, which is located in the top right corner of Figure 8. The selected PV component was then added to the grid. Figure 9 provides a screenshot of the equipment options available in HOMER.

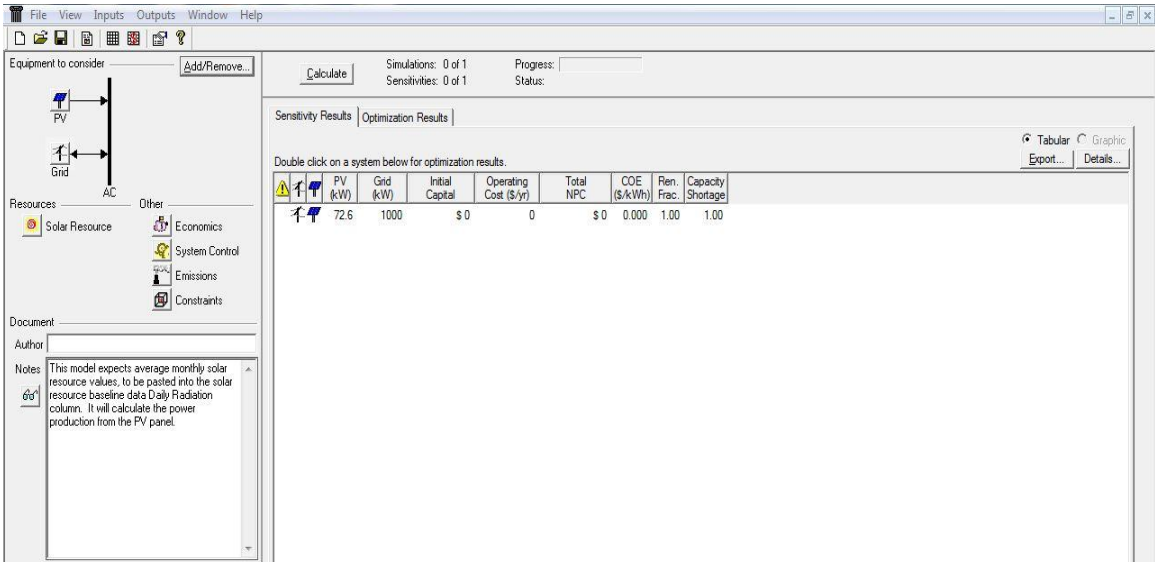


Figure 8. HOMER software main window.

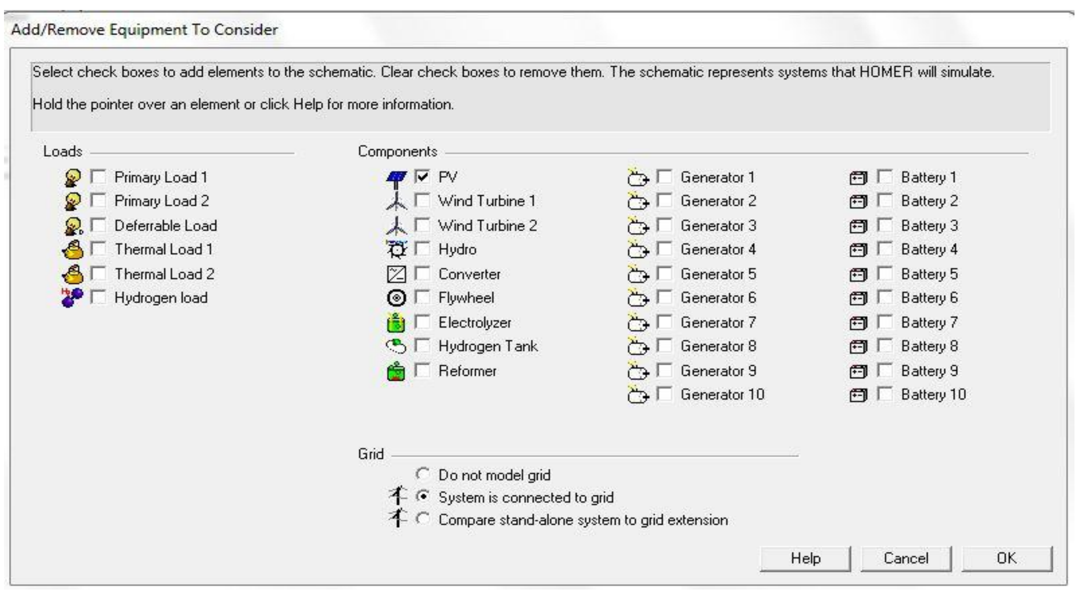
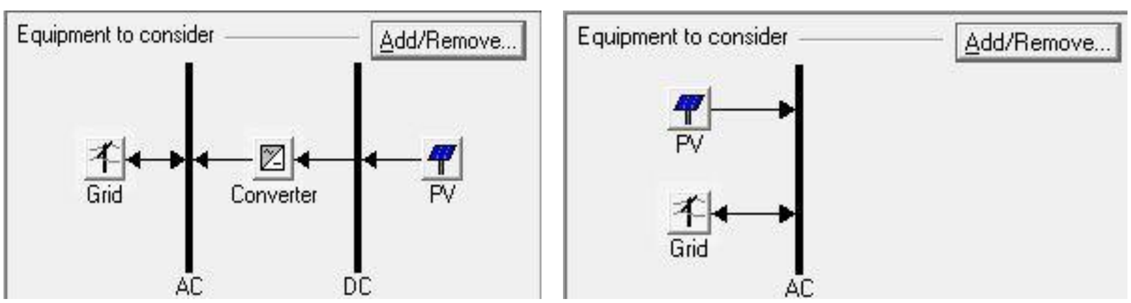


Figure 9. HOMER Add/Remove Equipment to Consider option.

The next step would be to add an inverter, which is referred to as a converter in HOMER to the model. A difficulty that arose was in determining which type of inverter to choose since there are many out on the market. This was particularly challenging since it was heavily dependent on the PV type. In order to solve this problem, instead of setting the PV output as direct current (DC) and needing an inverter to convert it to alternating current (AC), the default parameters of the PV option was changed to output AC directly. Figure 10 illustrates the HOMER options of: (a) How a conventional solar PV system is connected to the grid with an inverter and (b) How the system was modified to output AC current directly without the need for an inverter. In this way, the model would maximize the electricity output produced by the solar panels, since inverters are never one hundred percent efficient.



(a) (b)

Figure 10. (a) How a conventional system is connected to the grid with an inverter (b) How the system was modified in order to output AC current directly without the need of an inverter.

The PV parameters that were inputted into the model and their values are summarized in the following section and Figure 11 provides a screenshot of these PV parameters. The PV inputs used are:

1. Slope – The slope of the PV panels were set to 0^o to maximize roof space and panel installation.
2. Azimuth – The azimuth was set to 0^o for south facing.
3. Tracking system – No tracking system was used for the modeling.

4. Ground reflectance – This was set to a value of 20% in order to account for the third component of radiation due to albedo from the ground. This 20% value is a valid approximation, as it does not particularly influence the results in any significant amount (Glassmire, 2011).
5. Derating factor – A derating factor is a scaling factor that accounts for losses in the system due to dust, wiring or anything not ideal. The value 80% is the default estimate value used by HOMER.
6. PV array size – This refers to the size in kW of the desired PV array.

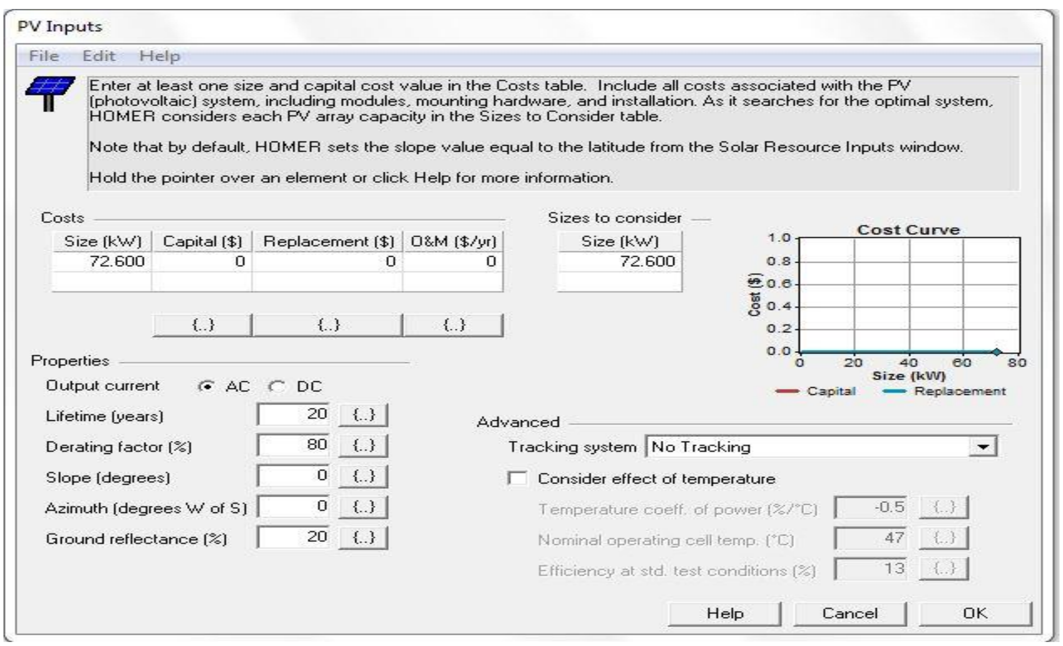


Figure 11. PV Inputs for analysis.

The next task after setting up the PV inputs was to set up the solar resource data. The Solar Resource Inputs window requires the latitude, longitude, time zone and baseline data for each building, which was generated using Ecotect. The latitude and longitude input affects the curve of the graph of the baseline solar resource data. In particular, the latitude of the site affects the breakdown between the direct and diffuse radiation that affects the timing and the heights of the peaks in the solar resource. Generally speaking, the southern latitudes receive more solar resource and these values gradually decline throughout the day, whereas northern latitudes receive less solar resource and experience larger differences in peaks throughout the day. The longitude on the contrary, affects the timing of the power output, thus the location of the site has a very significant impact upon the PV power output of HOMER.

HOMER understands the baseline data in one of three forms, hourly average global solar radiation on the horizontal surface, monthly average global solar radiation on the horizontal surface, or monthly average clearness index (Lambert, 2006). The baseline data that was outputted by Ecotect was for the incident solar radiation hitting each building rooftop and was in none of the acceptable default formats from HOMER. In order to solve this dilemma, John Glassmire from HOMER Energy was consulted to change the default input formats of the software. A small consultation fee was paid as HOMER was not an open source software and the input parameters for the twelve monthly global horizontal irradiation (GHI) values were changed. The input parameter for the baseline solar resource data was changed from GHI values to average daily incident solar radiation values. This modification in the software finally provided a solution for the incompatibility issue with the Ecotect data. Figure 12 and Figure 13 are screenshots of the solar resource inputs for the ARC and POD building which illustrates the spatial sensitivity of the data. Of particular importance is the difference in incident solar radiation values received on these surfaces as calculated by Ecotect can be observed between the two buildings. The POD receives less radiation than the ARC because of shading caused by its neighbouring LIB and JOR buildings, whereas the ARC building receives more solar due to less surrounding obstructions.

There are a few remaining tasks to be performed before the calculation of hourly electricity can commence, and these tasks were to set the electrical grid rates to zero and to set the capacity constraints to one-hundred percent. The reason for this is that the life-cycle costs and payback rates are not being analyzed in this thesis and the capacity constraints had to be set to one-hundred percent in order to force the PV system to be feasible.

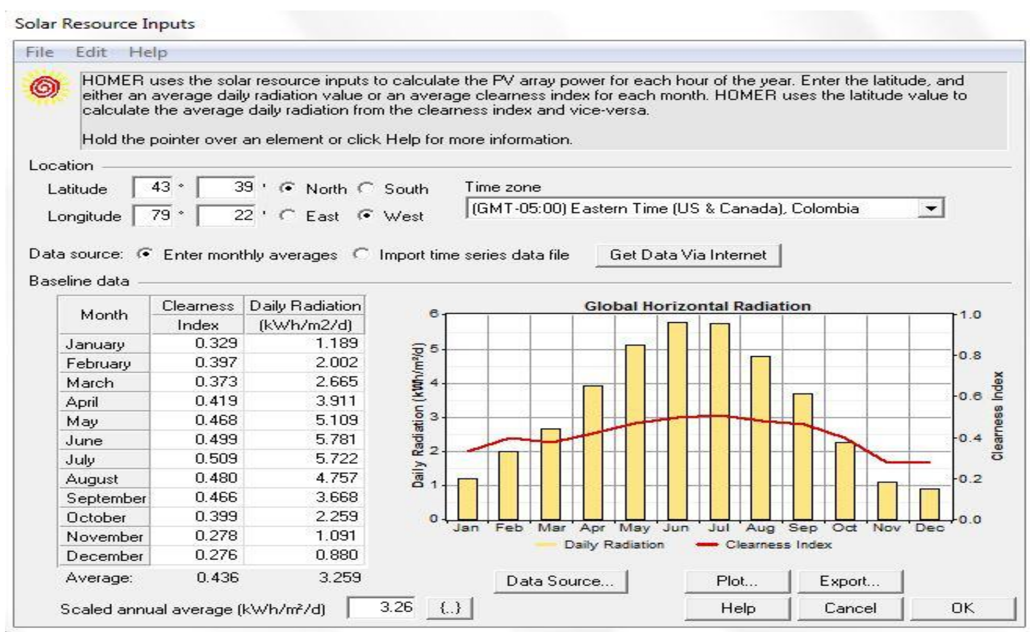


Figure 12. ARC solar resource radiation data.

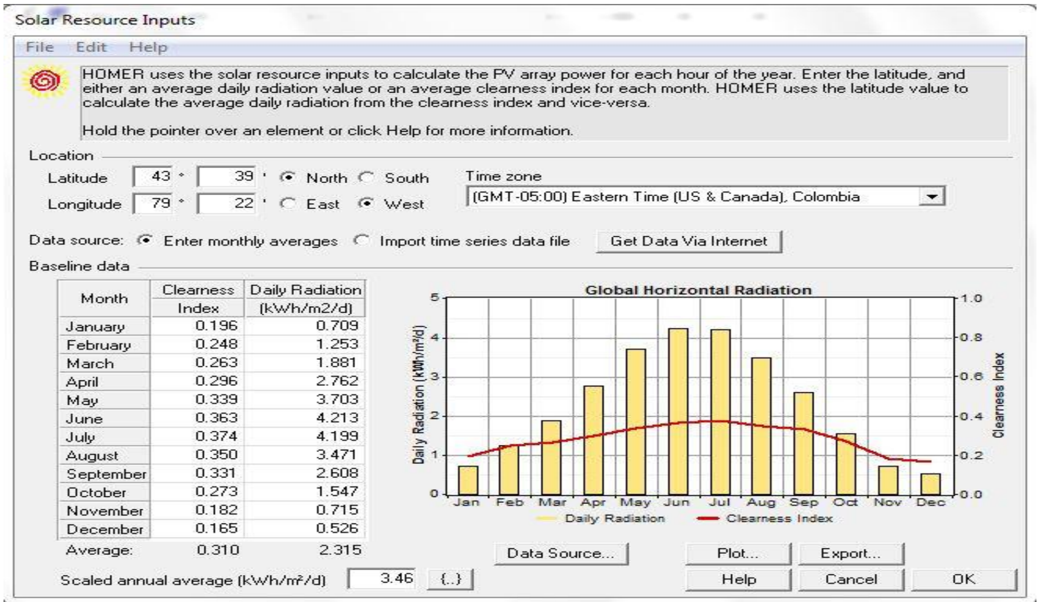


Figure 13. POD solar resource radiation data.

Finally, after inputting all the necessary data into the model, the power production from each PV array system was calculated. PV arrays are modeled as an object in HOMER that produces electricity directly proportional to the global solar radiation incident upon it, which is independent of its exposed voltage and temperature. The PV array output is calculated using the following equation:

$$P_{PV} = f_{PV} Y_{PV} \frac{I_T}{I_S}$$

Where,

f_{PV} = derating factor of the PV (accounts for losses due to dust, wire losses, elevated temperatures or anything else that would cause a lower performance)

Y_{PV} = the rated capacity of the PV (commonly called peak capacity)

I_T = global solar radiation, including both direct and diffuse radiation, incident on the PV panel

I_S = 1kW/m^2 – the standard amount of radiation used to rate the capacity of

PV systems (Lambert et al., 2006).

The PV electricity generation potential was calculated for the study area and the results were found under the Optimization Results window tab of the software. Notably, the Optimization Results also calculated the amount of carbon dioxide emissions reduced by the solar PV arrays, using a GHG emission factor of 0.170kg/kWh (Environment Canada, 2010). The analysis was performed for all the Ryerson owned buildings for both scenarios, totaling to fifty analyses. This was a very tedious process since there was no way to analyze all the scenarios at once. Data for the full annual 8760 hourly electricity estimates data points were produced as the final result for each building under each scenario.

4. Results

This chapter will describe the results that were generated by the developed workflow to estimate the hourly solar PV generation potential. The chapter will present the results generated by Ecotect, the roof top assessment for PV deployment, the hourly PV electricity generation potential as estimated by HOMER, and lastly the limitations of this research.

4.1. Incident solar radiation upon each rooftop

The methodology discussed in Section 3.5 was implemented in Ecotect Analysis to find the solar exposure of each rooftop. Appendix A depicts the geometries of the rooftops that were used to perform the analysis. Ecotect generated tabular data, which showed the average daily solar exposure on the roof, most important of this information being the incident solar radiation values. This column represents the average amount of incident solar radiation the rooftop would receive on an average day in the month. Table 3 provides an example of the data generated by Ecotect and the incident solar radiation values that were later used for input in the HOMER analysis. A detailed table of the values estimated by Ecotect for the amount of average monthly incident solar radiation for each building can be found in Appendix B. All of these values were later used to estimate hourly electricity generation potential in HOMER.

Table 3. An example of the Average Daily Solar Exposure estimated from Ecotect for the ARC building.

	AVAIL.	AVG	REFLECT	INCIDENT	ABSORBED	TRANSMITTED	
MONTH	Wh/m2	SHADE	Wh/m2	Wh/m2	TOT.Wh	Wh/m2	TOT.Wh
------	-------	------	--------	------	---------	------	--------
Jan	2700	38%	0	1189	2175995	588	1077118
Feb	3841	26%	0	2002	3665466	991	1814406
Mar	4770	28%	0	2665	4879030	1319	2415120
Apr	5754	24%	0	3911	7160192	1936	3544295
May	6950	10%	0	5109	9353034	2529	4629752
Jun	7677	15%	0	5781	10581920	2861	5238050
Jul	7706	15%	0	5722	10474895	2832	5185072
Aug	6615	15%	0	4757	8707941	2355	4310431
Sep	5757	24%	0	3668	6714709	1816	3323781
Oct	3951	28%	0	2259	4135092	1118	2046871
Nov	1892	29%	0	1091	1997006	540	988518
Dec	2097	38%	0	880	1610792	436	797342

4.2. Scenario 1: Gross area and available solar PV roof area

The total roof area or gross area was determined as discussed in Section 3.6 for Scenario 1. The detailed orthophoto rooftop images that were used to determine these values can be found in Appendix C. The gross areas of the orthophotos were further reduced in order to find the area that is suitable for PV deployment. This usable rooftop area measurement was then used to determine the maximum PV array size and capacity as described in Section 3.7. Table 4 provides a summary of the findings from Scenario 1, showing the values obtained for the digitized gross area in m^2, the area suitable for PV deployment determined through the usage of PV corrective factors, the number of PV panels and the PV array size in kW.

Table 4. Scenario 1 results: Gross area, usable area and solar PV size and capacity.

Building	Gross Area (m^2)	Usable Area = Gross Area x 0.30875	Number of Panels	PV Array Size (kW)
ARC	1729	533.828	363	72.6
CED	572	176.605	120	24
CPF	746	230.327	156	31.2
ENG	4533	1399.563	952	190.4
EPH,SHE	3703	1143.301	777	155.4
HEI	778	240.207	163	32.6
IMA	2496	770.64	524	104.8
JOR	824	254.41	173	34.6
KERR EAST	3370	1040.487	707	141.4
KERR NORTH	6723	2075.726	1412	282.4
KERR SOUTH	955	294.856	200	40
KERR WEST	2888	891.67	606	121.2
LIB	1699	524.566	356	71.2
MON	523	161.476	109	21.8
OAK	624	192.66	131	26.2
OKF	269	83.053	56	11.2
PIT	1336	412.49	280	56
POD	3580	1105.325	751	150.2
PRO	606	187.102	127	25.4
RCC	4304	1328.86	903	180.6
SBB	1591	491.221	334	66.8
SCC	1233	380.688	258	51.6
SID	1139	351.666	239	47.8
THR	935	288.681	196	39.2
VIC	1561	481.958	327	65.4

4.3. Scenario 2: GIS determined usable roof area and solar PV available

The rooftops were analyzed for a second scenario using GIS in order to determine the area suitable for PV deployment and the PV array size and capacity according to the methodology described in Sections 3.6 and 3.7. The usable area (m^2) that was digitized by GIS was multiplied by the module coverage factor of 0.475 in order to estimate the number of panels and the PV array size for every building. The digitized orthophoto images used to find the usable rooftop area are depicted in Appendix C. The findings for Scenario 2 are summarized in Table 5, showing the GIS determined usable areas and the PV array sizes and capacities for each building in the study area.

Table 5. Scenario 2 Analysis – GIS determined usable area and PV array size

BUILDING	GIS Extracted Area (m^2)	Usable Area = GIS Extracted Area x 0.475 (m^2)	Number of Panels	PV Array Size (kW)
ARC	1312	623.2	423	84.6
CED	271	128.725	87	17.4
CPF	651	309.225	210	42
ENG	2960	1406	956	191.2
EPH,SHE	2198	1044.05	710	142
HEI	644	305.9	208	41.6
IMA	2455	1166.125	793	158.6
JOR	664	315.4	214	42.8
KERR EAST	2781	1320.975	898	179.6
KERR NORTH	5818	2763.55	1879	375.8
KERR SOUTH	478	227.05	154	30.8
KERR WEST	2484	1179.9	802	160.4
LIB	702	333.45	226	45.2
MON	345	163.875	111	22.2
OAK	573	272.175	185	37
OKF	239	113.525	77	15.4
PIT	1182	561.45	381	76.2
POD	3086	1465.85	997	199.4
PRO	540	256.5	174	34.8
RCC	4222	2005.45	1364	272.8
SBB	1291	613.225	417	83.4
SCC	1023	485.925	330	66
SID	844	400.9	272	54.4
THR	860	408.5	277	55.4
VIC	1491	708.225	481	96.2

4.4. Hourly electricity generation potential

The software HOMER was lastly used in the methodology to determine the annual hourly PV electricity generation potential for all twenty-five building for the two scenarios, totaling to fifty analyses. The 8760 points of data for the hourly results were summed in a loop using Microsoft Excel, to find the total PV electricity generation for each hour of the day over the course of the year. To be explicit, all 365 hourly values at 1:00 for the year were summed together in order to find the cumulative generation at that hour, and the process was repeated to account for the twenty-four hours within a day. An example of the results obtained for this section from the analysis will be shown for the ARC building under Scenario 1. Table 6 is an example of the results obtained for the annual cumulative hourly PV electricity production and Figure 14 depicts the solar PV electricity generation normal curve. A detailed summary of the cumulative hourly electricity generation potential for each building is provided in Appendix D for Scenarios 1 and 2. An example of the annual electricity production graph can be found in Figure 15, illustrating the pattern and variations in PV output over the course of the year. Figure 16 provides a series of twelve graphs illustrating the difference in peak solar output during the different months of the years, and Figure 17 is a summary of the average monthly PV array outputs. Examples of annual and monthly graphs generated from the analysis in HOMER can be found for a few other buildings in Appendix E. It is evident from these figures that PV electricity generation follows a normal curve.

Table 6. Cumulative hourly PV electricity estimates in kW for the ARC building for Scenario 1.

Time	PV Output [kW]
1:00	0
2:00	0
3:00	0
4:00	0
5:00	0
6:00	334.01
7:00	1295.14
8:00	2858.94
9:00	4707.47
10:00	6506.20
11:00	7848.21
12:00	8485.65
13:00	8910.89
14:00	8266.87
15:00	7281.48
16:00	5709.26
17:00	3771.53
18:00	2090.33
19:00	814.78
20:00	146.49
21:00	0
22:00	0
23:00	0
0:00	0

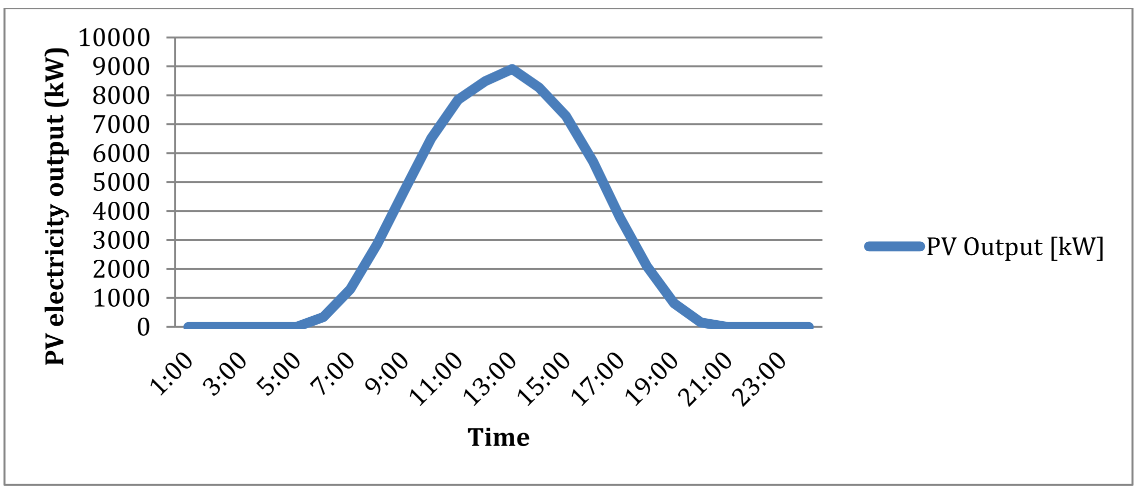


Figure 14. PV hourly electricity production curve for the ARC building in Scenario 1.

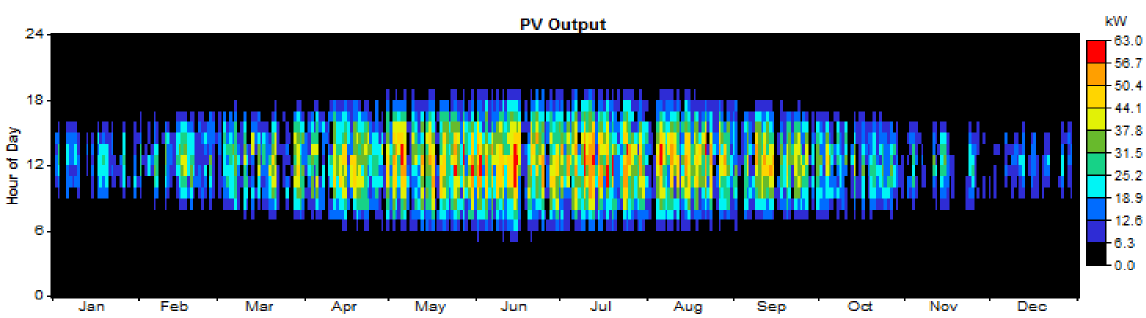


Figure 15. Annual electricity production graph for ARC building Scenario 1.

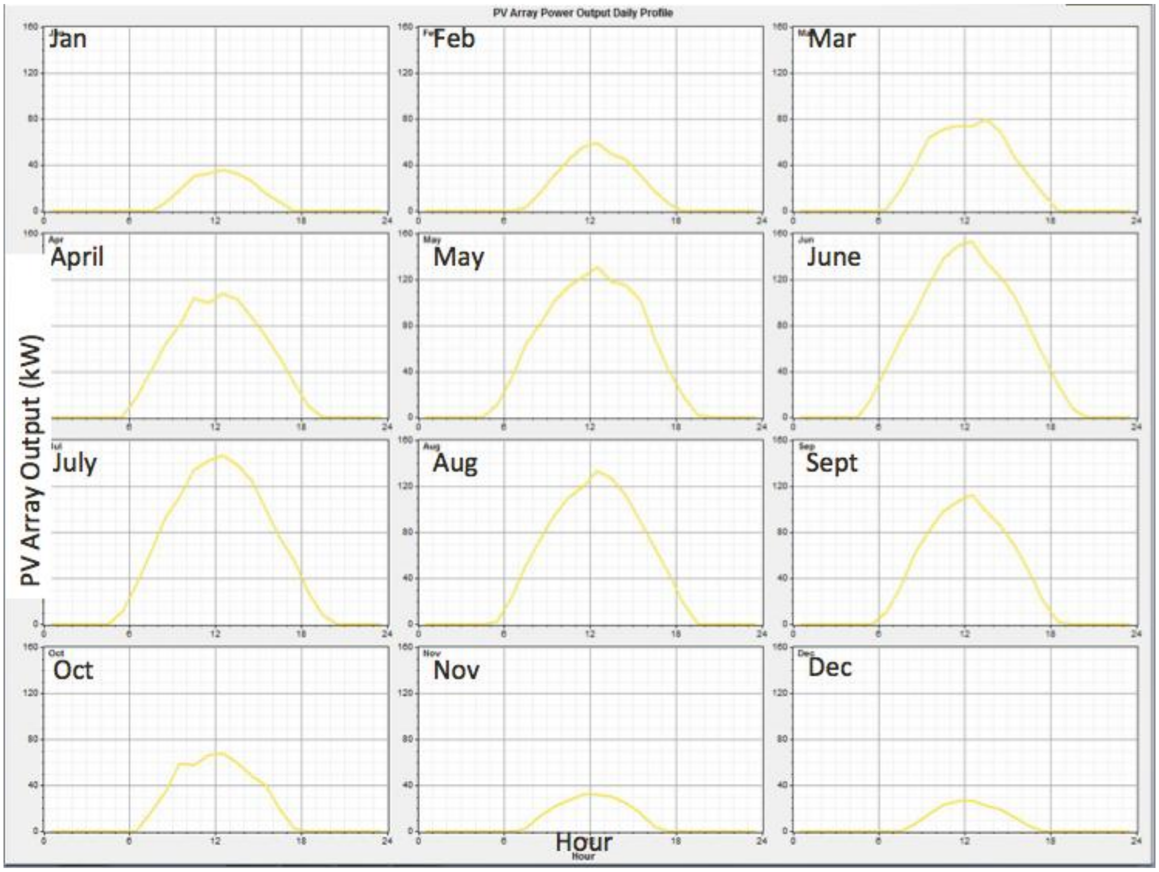


Figure 16. PV array electrical power output profile for the twelve months, for the ARC building in Scenario 1.

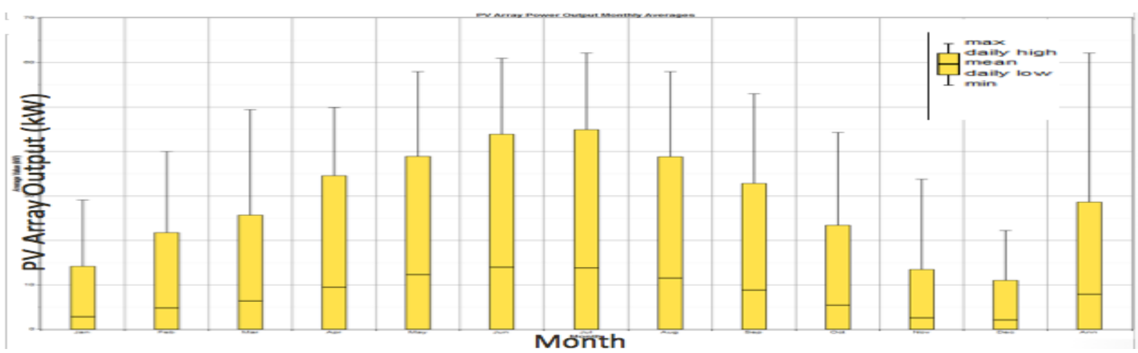


Figure 17. Average monthly PV array power outputs, for the ARC building in Scenario 1.

4.5. Errors and Limitations

This section will address the limitations and sources of error in this research. There are three main sources of error that can be identified in the workflow and they are, the integrity of the 3-D model, the digitization process of the orthophotos and the modified coding in the HOMER software. These issues will be discussed below respectively.

The geometry of the buildings in the 3-D model that was obtained from the City of Toronto did not completely match the geometry of the buildings in the orthophotos. This issue was mentioned before and can be reviewed in Figure 7. The only way to correct this issue would have been to redraw the 3-D model completely using the measurements derived from the orthophotos or other geospatial data sources, which requires separate in-depth studies on its own and is beyond the scope of this thesis. There was no other 3-D model available from the City, hence, it was the best data available and was used in Ecotect to calculate the incident solar radiation for each rooftop. As a result of the impossibility of merging the two types of data due to mismatched building geometries, the surface area derived from the orthophoto was considered most accurate. The reason why the orthophotos were necessary was because they provided valuable information in regards to the amount of surface area occupied on the rooftops by obstructions such as HVACs, piping and green roofing which the 3-D model did not.

The next source of error is the manual digitization of the rooftops using GIS. This can be mainly attributed to human error, as the digitization process is very tedious and done by hand manually. There was not enough time in this thesis to develop a tool for the automatic surface extraction feature for identifying both rooftops and occupied areas on these surfaces. Future work in this area would be recommended.

There are some issues that need to be raised with the modification of the HOMER software. First, since HOMER is a model performed over a simulated year, there is no way to one hundred percent accurately simulate the amount of electricity received on any particular day for any particular year. In order to address this issue, HOMER automatically introduces variability to the PV solar output. The next significant source of error from HOMER would be due to the change in the initial coding of the software in order to accommodate for the different solar resource input values, as discussed with Glassmire (2011), and they are:

1. Since Ecotect's calculation for monthly incident solar radiation already took into consideration the losses due to shading, there is no way to 100% reconstruct it into hourly data precisely. HOMER accounts for losses within its algorithm already, therefore, the calculation will average any losses over the whole time period, and smooth out the radiation losses. There would not be any sudden interruptions to power that would normally be expected caused by shading.
2. The algorithms within HOMER that determine the proportion of radiation that is diffuse versus direct cannot be altered because it is dependent on the time of the day and latitude.
3. In regards to the tilt of the panels:
    a. This modified algorithm cannot accommodate for different tilts on the panels and works best only on horizontal surfaces (0^{o} slope). This is because the HOMER algorithm is updated under the assumption that the Ecotect incident solar radiation is normal upon the surface. Any

adjustments to tilt away from 0° will introduce error to the model, unless if the surface has a slope, in that case then the tilt should be adjusted to the angle of the surface on which it is to be mounted. For the purpose of this thesis however it is ideal for the simulation to be run with a tilt of 0°. For example, if this analysis is to be performed on a building façade, and the tilt is set to 0°, that means that the panel is completely vertical.

b. When the PV panel tilt is set to 0°, the ground reflectance of 20% will have no impact upon the results. This is because the panel will not see the ground at all and will only receive direct and diffuse radiation.

c. All rooftops were analyzed with a PV panel tilt of 0°, since almost all campus buildings have a flat rooftop. For the three buildings OKF, OAK, and THR that do not have flat rooftops, the analysis was still performed with a tilt of 0°, as the exact slope or pitch of the roof was not known. In addition, these buildings have flat areas as well, thus, a tilt of 0° was chosen, as it would introduce the least amount of error into the analysis.

5. Discussion

This chapter will begin by providing a comparison of the estimated hourly electricity potentials to the actual building electricity consumption data to see how much solar photovoltaics can actually help to alleviate off the load, especially at peak consumption hours. The seasonal pattern in solar PV electricity will be then discussed followed by a comparison of the two methods for assessing rooftop suitability for PV deployment. The results obtained by Forgione (2010) will be used for comparison as a basis for the results obtained in this thesis. Lastly, this chapter will close with a discussion about the environmental impact and the carbon dioxide offset by the solar PV installation.

5.1. Estimated hourly electricity potential vs. actual building consumption

The hourly PV solar electricity estimates were compared to actual consumption data from the Ryerson University Campus Planning Office. However, not all of the Ryerson owned buildings had hourly electricity consumption information for a year. Data for thirteen of the twenty-five analyzed buildings were obtained and their consumption was compared against the PV electricity estimates. The percentage offset that the solar PV panels alleviated off of the actual consumption was calculated on an hourly basis. This information can be found in Table 7 for Scenario 1 and Table 8 for Scenario 2. The annual electricity percentage offset for Scenario 1 and 2 was found to be six percent and seven percent, respectively. Of particular importance, it was found that the solar PV panels could help alleviate up to nineteen percent off of the electrical load during peak hours.

Significantly, the time frame in which solar PVs produced the most electricity coincided with the peak demand times for electricity consumption on the grid during the summer. From the peak hours of 11am to 5pm the estimated PV electricity output contributed from 9% to 15% off the actual electrical load for Scenario 1, and from 12% to 19% for Scenario 2. Figure 18 and Figure 19 are graphs of the hourly PV electricity estimate against total actual electricity consumption for Scenario 1 and 2. It is clear from these graphs, that the solar PV electricity potential follows a binomial curve.

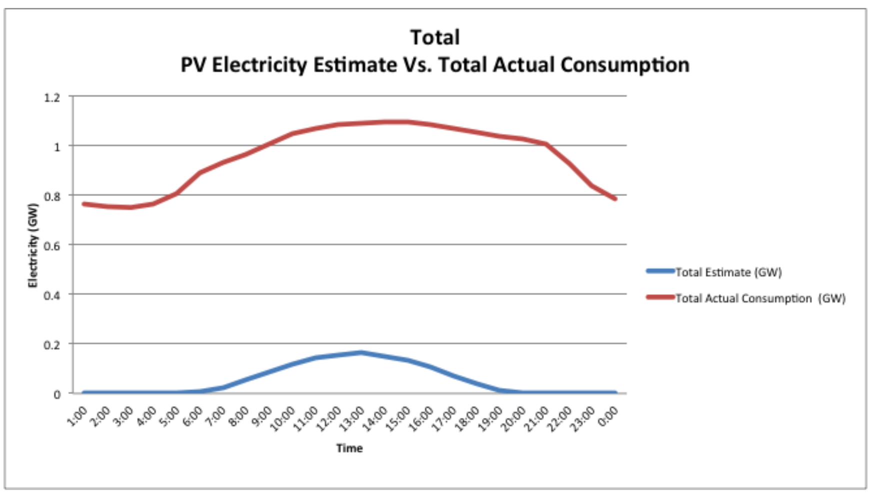


Figure 18. Scenario 1: Hourly electricity estimate vs. actual electricity consumption

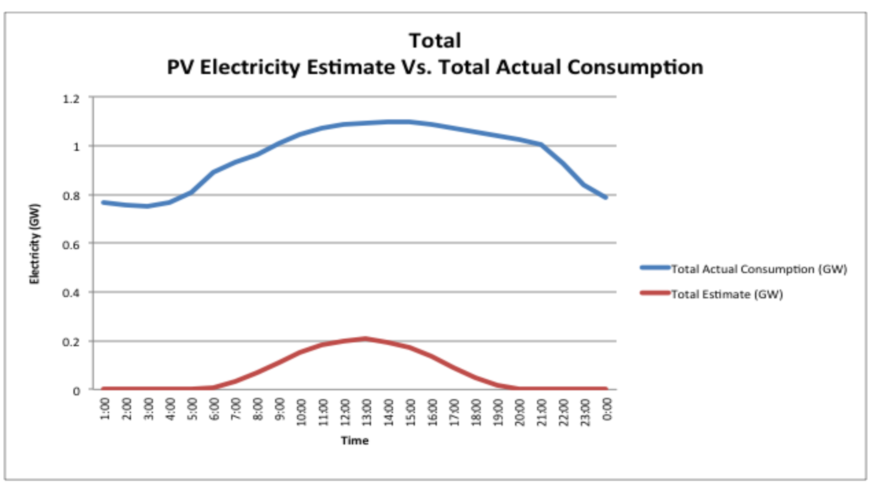


Figure 19. Scenario 2: Hourly electricity estimate vs. actual electricity consumption

Table 7. Scenario 1 – Cumulative estimated hourly solar PV electricity output and the actual electricity consumption percentage offset.

	PV Outuput (kW)															
	CED	**ENG**	**EPH,SHE**	**HEI**	**IMA**	**KERR NORTH**	**KERR WEST**	**OAK**	**PIT**	**RCC**	**SBB**	**SCC**	**VIC**	**TOTAL ESTIMATE**	**TOTAL ACTUAL CONSUMPTION (kW)**	**% OFFSET**
Time																
1:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	764864.07	0
2:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	756138.12	0
3:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	750751.74	0
4:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	765313.09	0
5:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	807546	0
6:00	122.51	617.24	707.15	157.07	500.65	1338.88	579.82	127.72	250.44	864.75	336.65	254.44	313.35	6170.67	889871.22	0.01
7:00	464.46	2369.7	2753.29	612.52	1957.74	5241.36	2264.95	490.49	978.6	3334.25	1299.11	986.43	1222.79	23975.69	931544.22	0.03
8:00	1015.33	5117.84	6088.13	1356.48	4351.09	11674.07	5027.41	1091.44	2177.37	7298.3	2844.1	2172.37	2719.16	52933.09	964820.97	0.05
9:00	1623.1	8339.27	9982.5	2239.82	7196.65	19361.13	8318.3	1772.01	3608.34	11775.54	4618.03	3560.79	4494.73	86890.21	1008860.54	0.09
10:00	2218.02	11617.52	13759.16	3101.88	9977.26	26881.07	11536.57	2470.08	5009.05	16089.94	6328.79	4906.64	6230.42	120126.4	1046922.33	0.11
11:00	2644.42	13826.87	16571.5	3749.3	12065.93	32545.39	13952.91	2952.47	6058.9	19253.02	7595.99	5909.96	7512.56	144639.22	1071250.66	0.14
12:00	2835.55	14904.79	17902.01	4053.75	13042.85	35198.96	15088.59	3168.89	6552.24	20750.3	8196.65	6385.9	8132.68	156213.16	1085152.08	0.14
13:00	2996.44	15645.69	18797.27	4252.27	13684.06	36923.91	15826.82	3343	6876.61	21835.59	8621.19	6704.45	8541.36	164048.66	1092266.15	0.15
14:00	2767.6	14373.3	17441.04	3949.63	12708.63	34309.2	14703.38	3071.21	6382.4	20109.34	7958.05	6221.88	7915.98	151911.64	1097611.8	0.14
15:00	2474.23	12766.14	15367.81	3473.64	11172.62	30142	12923.96	2742.78	5610.81	17790.71	7017.8	5483.64	6966.67	133932.81	1097699.79	0.12
16:00	1968.07	10063.2	12075.34	2719.7	8741.95	23563.41	10111.55	2161.55	4387.22	14126.77	5564.03	4307.92	5454.69	105245.4	1086660.94	0.1
17:00	1331.71	6771.83	8003.43	1790.65	5747.94	15464.91	6644.81	1439.96	2881.5	9508.3	3719.35	2855.04	3592.35	69751.78	1069754.02	0.07
18:00	757.74	3836.45	4451.66	989.5	3168.15	8487.81	3662.25	798.42	1585.59	5392.28	2095.01	1590.13	1983.93	38798.92	1056128.36	0.04
19:00	299.15	1546.21	1728.44	383.75	1224.39	3270.85	1415.7	314.1	612.65	2117.26	822.43	620.11	767.73	15122.77	1038964.14	0.01
20:00	56.99	328.24	310.57	68.14	218.34	580.97	251.65	60	109.83	399.49	151.24	111.03	139.29	2785.78	1026157.12	0
21:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1007176.2	0
22:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	928765.17	0
23:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	838481.27	0
0:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	786057.37	0
ANNUAL TOTAL	23575.31	122124.28	145939.28	32898.08	105758.25	284983.93	122308.66	26004.11	53081.56	170645.84	67168.44	52070.74	65987.71	1272546.19	22968757.37	0.06

Table 8. Scenario 2 – Cumulative estimated hourly solar PV electricity output and the actual electricity consumption percentage offset.

	PV Outuput (kW)														TOTAL ACTUAL CONSUMPTION (kW)	% OFFSET
Time	CED	ENG	EPH,SHE	HEI	IMA	KERR NORTH	KERR WEST	OAK	PIT	RCC	SBB	SCC	VIC	TOTAL ESTIMATE		
1:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	764864.07	0
2:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	756138.12	0
3:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	750751.74	0
4:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	765313.09	0
5:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	807546	0
6:00	88.82	619.83	646.16	200.43	757.66	1781.7	767.34	180.36	340.77	1306.24	420.31	325.45	460.92	7896	889871.22	0.01
7:00	336.74	2379.66	2515.87	781.62	2962.76	6974.87	2997.5	692.67	1331.59	5036.45	1621.95	1261.72	1798.66	30692.07	931544.22	0.03
8:00	736.11	5139.34	5563.14	1730.97	6584.76	15535.11	6653.43	1541.34	2962.78	11024.24	3550.87	2778.61	3999.74	67800.43	964820.97	0.07
9:00	1176.74	8374.31	9121.71	2858.17	10891.11	25764.57	11008.7	2502.46	4909.93	17787.17	5765.62	4554.5	6611.52	111326.51	1008860.54	0.11
10:00	1608.07	11666.34	12572.73	3958.23	15099.18	35771.62	15267.87	3488.28	6815.89	24304.19	7901.51	6275.93	9164.62	153894.46	1046922.33	0.15
11:00	1917.21	13884.97	15142.56	4784.38	18260.09	43309.33	18465.75	4169.52	8244.43	29082.09	9483.62	7559.25	11050.59	185353.78	1071250.66	0.17
12:00	2055.77	14967.43	16358.34	5172.88	19738.52	46840.54	19968.72	4475.15	8915.73	31343.76	10233.55	8168.01	11962.75	200201.14	1085152.08	0.18
13:00	2172.42	15711.45	17176.39	5426.21	20708.89	49136.02	20945.76	4721.04	9357.1	32983.1	10763.59	8575.46	12563.9	210241.33	1092266.15	0.19
14:00	2006.51	14433.7	15937.12	5040.02	19232.72	45656.49	19458.94	4337.2	8684.62	30375.57	9935.65	7958.22	11643.99	194700.74	1097611.8	0.18
15:00	1793.82	12819.78	14042.65	4432.62	16908.19	40111.07	17104	3873.4	7634.7	26873.23	8761.75	7013.96	10247.61	171616.77	1097699.79	0.16
16:00	1426.85	10105.47	11034.09	3470.54	13229.71	31356.69	13381.95	3052.57	5969.75	21338.78	6946.71	5510.13	8023.57	134846.81	1086660.94	0.12
17:00	965.49	6800.28	7313.28	2285	8698.69	20579.73	8793.94	2033.54	3920.9	14362.48	4643.62	3651.79	5284.17	89332.91	1069754.02	0.08
18:00	549.36	3852.57	4067.79	1262.67	4794.54	11295.06	4846.74	1127.54	2157.54	8145.15	2615.62	2033.89	2918.26	49666.74	1056128.36	0.05
19:00	216.88	1552.71	1579.41	489.69	1852.94	4352.64	1873.59	443.58	833.65	3198.17	1026.81	793.16	1129.29	19342.51	1038964.14	0.02
20:00	41.31	329.61	283.79	86.95	330.43	773.11	333.03	84.74	149.45	603.43	188.83	142.01	204.88	3551.58	1026157.12	0
21:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1007176.2	0
22:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	928765.17	0
23:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	838481.27	0
0:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	786057.37	0
ANNUAL TOTAL	17092.11	122637.44	133355.02	41980.37	160050.19	379238.55	161867.27	36723.37	72228.84	257764.05	83859.99	66602.11	97064.48	1630463.78	22968757.37	0.07

5.2. Seasonal variations in the estimated solar PV electricity outputs

The hourly electricity estimates generated by HOMER were graphed for all fifty cases and a few samples can be found in Appendix E. Figure 20 and Figure 21 are examples of outputs generated by the RCC building under Scenario 2, depicting the average monthly power outputs of the PV array and the monthly PV array hourly power output profile, respectively. Upon inspection of the data, it is clear that there is a trend in the PV electricity outputs. The summer generates more solar electricity than the winter. In the winter months from November to March, solar potential is significantly lower. As the months change from March to April, solar potential starts to rise and continuously increases until the peak months of June and July. After that point, the solar potential gradually declines as the winter approaches. It is clear from the analysis of this data that the monthly and hourly solar potential follows a binomial distribution, and that peak solar generation coincides with the on-peak electricity consumption hours in the summer for Ontario. This means that solar energy can help to alleviate the intense load off the electrical grid during peak consumption hours in Ontario in order to provide a more reliable energy supply in the summer.

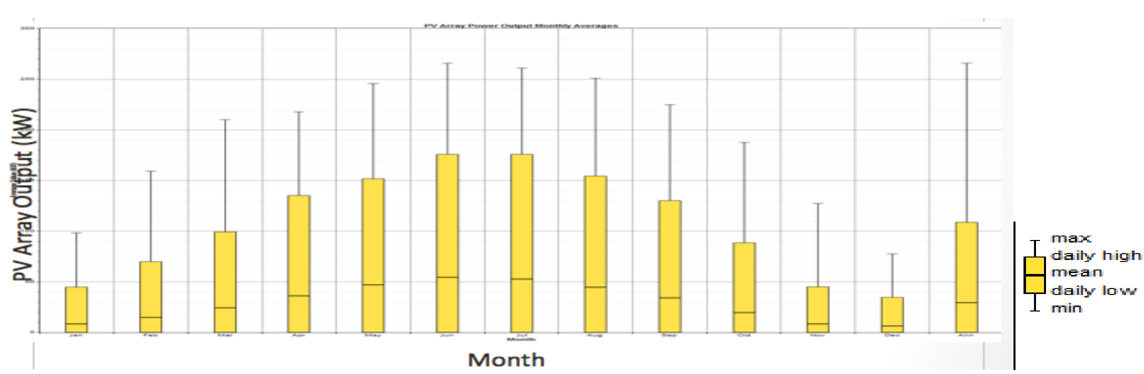


Figure 20. Average monthly PV array power output for the RCC building in Scenario 2.

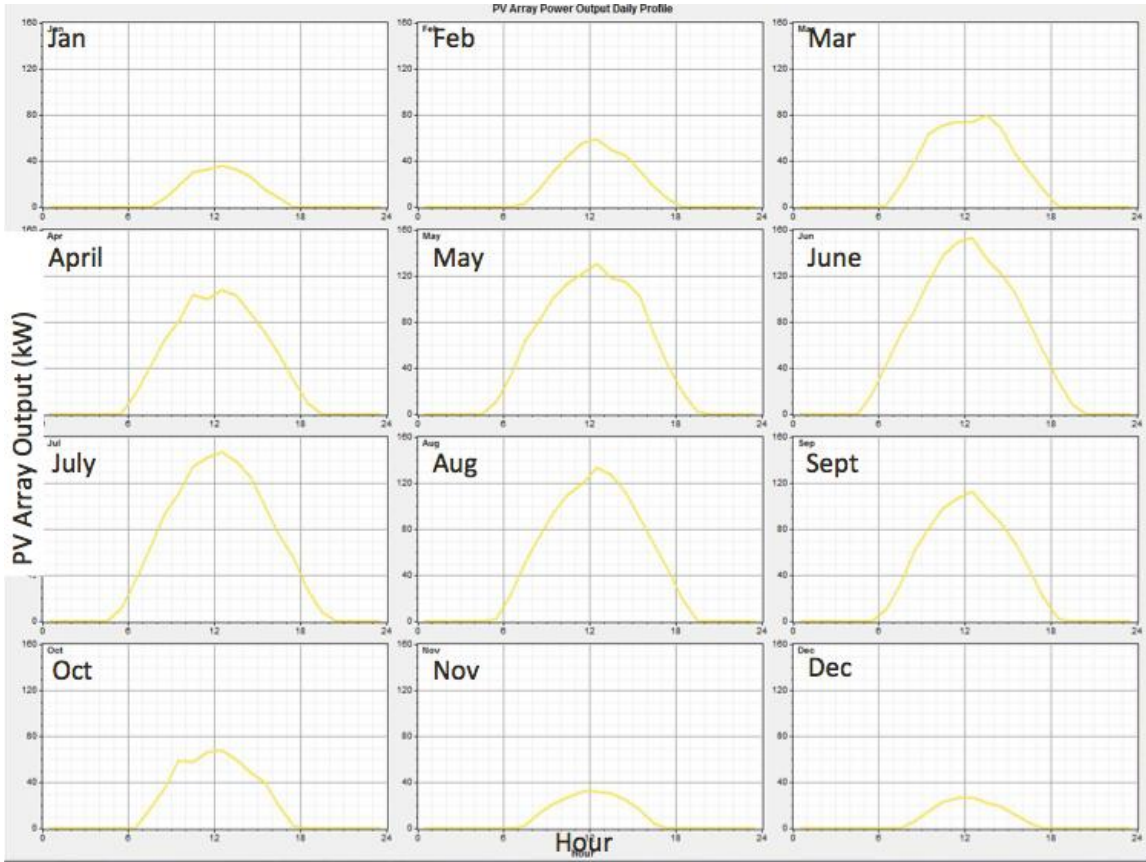


Figure 21. PV array monthly hourly power output profile for the RCC building in Scenario 2.

5.3. Analysis of the two methods for assessing usable rooftop area

There were two methods used to estimate suitable rooftop PV area in this thesis. Scenario 1 is based upon PV corrective factors, which reduced the usable area of all buildings by 69.125% meaning that 30.875% of roof space is suitable regardless of rooftop structure. Scenario 2 on the other hand, took into account the fluctuations in individual rooftop structures, and the surface area usable was manually digitized and scaled down for PV applicability. The total usable surface area for all buildings estimated by Scenario 1 and Scenario 2 summed to a value of 15, 041 m^2 and 18, 579m^2, respectively. This is an approximate 19% difference in surface area estimation. Scenario 1 produced a more conservative estimate than

Scenario 2, and this trend can be seen on the individual building level as well. This difference can be mainly attributed to buildings having unusually high or low occupancy on the rooftops from objects such as piping and HVAC systems. Figure 22 is a graph depicting the estimated roof area suitable for PV applications for the two scenarios.

Overall, it can be seen that the estimations between the two scenarios are not too far from one another. Nonetheless, it is obvious that there are four buildings with an unusually large surface area difference. These buildings are KERR N, IMA, POD and the RCC. The reason for this significant difference is because these four buildings have particularly low occupancy on their rooftops, hence resulting in a larger digitized usable area in GIS for Scenario 2. It can be seen that for circumstances where there is unusually low occupancy on the rooftops, that Scenario 1 would underestimate the usable area with a significant amount of error, and that Scenario 2 would provide a more accurate estimate.

On the contrary, there are four out of the twenty-five buildings measured in which Scenario 1 produced higher estimates in surface area than Scenario 2. These four buildings are the CED, EPH & SHE, KERR S, and LIB. Upon inspection of the orthophotos, the reason for this anomaly can be found and is quite obvious. These four buildings have particularly high occupancy on their rooftops with more than half of the surface area occupied by objects such as HVACs and piping. Again, the measurement for Scenario 2 would be considered more accurate.

Overall, Scenario 2 can be seen to be the better option for assessing usable roof space for PV systems. Nevertheless, this method is very tedious and labour intensive. It should be noted that however, for the PV panel electricity output, there was only a one percent difference in the estimate between the two scenarios. As a result, it can be said that that both methods for deducing suitable rooftop area are feasible.

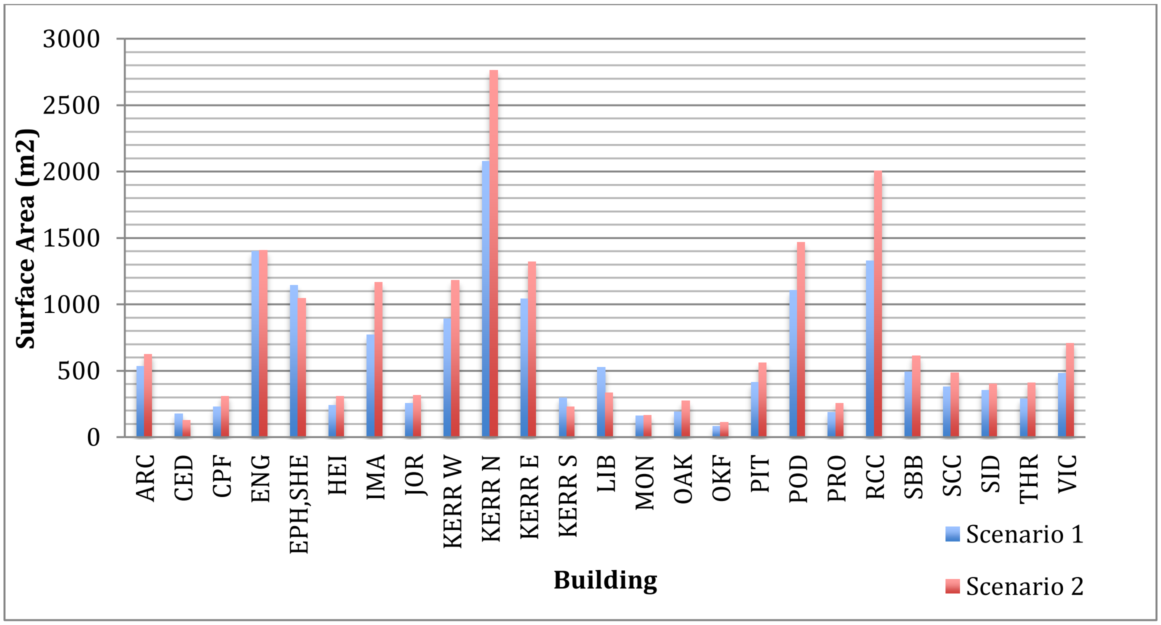


Figure 22. Estimated roof area suitable for photovoltaic applications for Scenario 1 and Scenario 2.

5.4. Comparison to Forgione (2010) results

The previous research conducted by Forgione (2010) for the modeling and mapping of solar energy potentials on Ryerson University found that a total rooftop surface area of 12, 624 m^2 is suitable for PV applications. He found that this space was suitable for the installation of 6,312 panels totaling to a total PV array capacity of 1.5MW capacity (at 240W each panel) for the entire campus. This led to a total annual solar PV estimate of 1.872 GWh per year and alleviated 4.7% off the electrical load of the University.

The results found in this research were a total rooftop surface area of 15,041 m^2, for Scenario 1 and 18,579m^2 for Scenario 2 were suitable for PV deployment.

This totaled to a maximum installation size of 10,220 panels and 12,626 panels for the two scenarios, leading to a maximum array capacity of 2.044 MW and 2.525 MW respectively at 200W each panel. This summed to an annual solar PV electricity production of 1.94GWh and 2.42GWh and alleviated 6% and 7% off the electrical load of Ryerson University.

Forgione's estimates were found to be more conservative than the estimates obtained in this research. There are some significant issues that lead to the discrepancy in values and these reasons include:

1. Forgione analyzed twenty rooftops in the Ryerson University study area, whereas twenty-five rooftops were analyzed in this thesis. The five additional buildings that were analyzed in this thesis are the: (1) MON, (2) EPH, SHE, (3) KERR S, (4) CPF, and (5) OKF buildings.
2. Forgione used a function in Ecotect called Solar Access Analysis to generate images of solar irradiation upon rooftops, whereas the Solar Exposure function was used in this thesis to calculate the incident solar radiation on each roof surface.
3. Different weather data files were used to perform the solar analysis in the Ecotect software; Forgioine used the default WEA weather files within the Ecotect's Weather Manager Tool, whereas the Toronto EnergyPlus (EPW) weather files were used in this thesis.
4. A completely different methodology was employed to find the usable rooftop surface area suitable for PV applications; Forgione consulted Google maps and derived rooftop measurements from the 3-D model, whereas in this

research, 2009 orthophotos at a 10cm resolution were used and digitized in GIS in order to measure and eliminate occupied areas on the rooftops. PV access factors based upon best-published practices were employed as well in this thesis to find rooftop usable area.

5. RETScreen was not used for electricity analysis, as it is not capable of generating hourly electricity results. A software called HOMER was used for generating the hourly solar PV outputs.
6. Through the hourly PV analysis in this thesis, it was found that PVs can help alleviate up to 19% off the electrical grid during peak generation and TOU hours, which provides significant incite into the hourly contribution of solar energy as compared to the annual analysis value of only 4.7% in Forgione's work.

5.5. Environmental impact – Photovoltaic carbon dioxide offset

Solar PV energy can help reduce the environmental footprint on the planet by reducing leading sources of greenhouse gases (GHG). In particular, carbon dioxide is considered to be the primary GHG responsible for climate change. The amount of carbon dioxide offset by solar panels can be calculated and was estimated using HOMER. A GHG emission factor of 0.170kg/kWh was used (Environment Canada, 2010). The results for the carbon dioxide offset by the solar panels for each building in Scenario 1 and Scenario 2 can be found in Table 9. On an annual basis, it was found that Scenario 1 and Scenario 2 would save approximately 330, 892 kg/year and 411, 385 kg/year of carbon dioxide, respectively. This has a very positive impact for the environment, as this is equivalent to the amount of carbon dioxide offset on an annual basis by approximately 92 acres of trees for Scenario 1 and 114 acres of trees for Scenario 2, since one acre of trees absorb approximately 3.6 tonnes of carbon dioxide per year, which is the same amount as a car being driven 26,000 miles (United States Environmental Protection Agency, n.d.).

Table 9. Carbon dioxide offset by solar PV for both Scenario 1 and Scenario 2

Building	Scenario 1: CO_2 (kg/yr)	Scenario 2: CO_2 (kg/yr)	Building	Scenario 1: CO_2 (kg/yr)	Scenario 2: CO_2 (kg/yr)
ARC	11734	13674	MON	3729	3797
CED	4007	2905	OAK	4420	6242
CPF	5266	7089	OKF	1921	2641
ENG	20761	20848	PIT	9023	12278
EPH,SHE	24809	22670	POD	23966	31817
HEI	5592	7136	PRO	4353	5964
IMA	17978	27208	RCC	29009	43819
JOR	5734	7093	SBB	11418	14256
KERR EAST	24527	30811	SCC	8852	11322
KERR NORTH	48447	64470	SID	8200	9332
KERR SOUTH	6841	5267	THR	6343	8965
KERR WEST	20792	27517	VIC	11217	16500
LIB	12210	7751	TOTAL	**330, 892**	**411, 385**

6. Conclusions

Solar energy is an alternative source of renewable energy that is non-polluting and can be easily converted into electricity through the usage of photovoltaic (PV) systems. It represents an important source of energy for the environment as it reduces the risks for climate change by helping to mitigate fossil fuel emissions and dangerous greenhouse gases, in particular, carbon dioxide. In order to encourage the implementation of PV systems to help alleviate the huge demands off the electrical grid, Ontario passed the Green Energy Act in order to facilitate government incentives through the Feed-in-Tariff (FIT) and microFIT programs to encourage the population to use and install solar PV systems.

With the ever growing demand for alternative sources of energy, it is important for buildings to be pre-assessed for their solar potential in order to check for their suitability for PV systems, since insolation on buildings can be lost due to many complex factors. Some main factors include losses of insolation due to shading from obstructions, prevailing local weather conditions, available rooftop surface area and the local environment. In order to address these issues, a methodology was developed in this thesis to model and assess the higher spatiotemporal variations in solar radiation in urban areas to estimate rooftop hourly solar PV generation potential.

The methodology developed to estimate the hourly solar PV electricity generation potential on rooftops in an urban environment was a success in this thesis. This method was inspired by previous work from Forgione (2010) who developed an integrated workflow for the modeling and mapping of solar energy potentials in urban areas on an annual basis. A case study area of Ryerson University was chosen and the 3-D data was obtained from the City of Toronto Planning Office. A total of twenty-five buildings were selected and analyzed for their solar PV applicability in the case study area.

Software tools that were able to perform solar analyses on highly detailed 3-D models and had the ability to estimate hourly solar PV electricity output were evaluated. In the end, three softwares were chosen to perform the solar analyses in this thesis in order to meet the needs of the objectives. The objectives were to find software tools and solar datasets that would be suitable for the estimation of hourly PV electricity outputs, determine the limiting factors to solar energy availability in urban environments, find the amount of usable rooftop surface area and to lastly estimate how much PV systems would help to alleviate off the electrical load during peak consumption hours.

The chosen softwares that were implemented in the methodology are Ecotect Analysis 2011, ESRI ArcGIS 10 and HOMER version 2.81, respectively. Ecotect was used to analyze the rooftops of a highly detailed 3-D model of the case study area in order to determine the incident solar radiation upon each building. This took into consideration the unique geometry of each rooftop, weather conditions, shading and the amount of solar radiation loss due to building obstructions. Orthophotos of the case study area were then consulted in order to identify areas occupied by existing HVACs and other installations on the rooftops that were not a part of the obtained 3-D model. Two methods were employed to estimate total usable rooftop area for PV installation: (1) based upon best-published practices for the assessment of usable rooftop area using PV corrective factors, and (2) based upon the digitized obstructions using GIS on rooftops and a PV module coverage factor. Once the suitable areas for PV installation were determined, the PV array size and capacity were calculated based upon the chosen solar panel technology. An updated algorithm in HOMER by Glassmire (2011) was then used to estimate the full hourly electricity generation potential of every building and the carbon dioxide emissions mitigated within the case study area.

The methodology was a success and the hourly electricity generation potential of each building was calculated for the two scenarios. These values were then compared to actual electricity consumption data that was obtained for the buildings in the case study area that had smart meters installed. It was found that on an annual basis, Scenario 1 offset 6% of the electricity demands of the buildings and Scenario 2 offset 7%. Scenario 1 produced a more conservative estimate than Scenario 2, which is mainly attributable to buildings having unusually high or low occupancy on the rooftops from objects such as piping and HVAC systems. Overall, Scenario 2 was found to produce a more accurate surface area estimate than Scenario 1, however, this method is very tedious and labour intensive.

The estimated hourly PV electricity output was graphed and the data was found to follow a binomial curve, and that the peak production hours coincided with on-peak time-of-use (TOU) periods for the summer in Ontario. From the peak hours of 11am to 5pm the estimated electricity contributed from 9% to 15% off the electrical load for Scenario 1, and from 12% to 19% for Scenario 2. Also, solar generation was found to be the highest during the summer months, which coincides with Ontario's high electricity consumption during that season which is mainly attributed to air conditioning usage. The amount of carbon dioxide emissions reduced by these solar panels on an annual basis was found to be equivalent to the amount of carbon dioxide 92 acres and 114 acres of trees would reduce for Scenario 1 and Scenario 2, respectively. This shows that solar energy offers a clean and promising solution for the future and can help to alleviate the intense load off the electrical grid during peak consumption hours in order to provide a more reliable energy supply in Ontario.

This thesis provided a method to model hourly solar PV potentials in an urban environment using a 3-D model. Forgione's (2010) workflow was revised and a new workflow was created using different software tools and datasets. Through this study, the hourly distributions in solar PV outputs were identified in order to better understand the hourly PV electricity outputs versus the actual electricity consumption. This contribution is significant as it provides good inputs for the planning and management of existing smart metering systems, the electricity grid, TOU pricing and in the management of electricity during peak hour demands.

The main limitations and sources of error identified in this methodology are due to the integrity of the obtained 3-D data, the digitization of the orthophotos using GIS and the modified coding in the HOMER software. There is definitely further room for improvement upon this workflow in the future. First, it would be ideal to have access to a 3-D model of the study area that is drawn 100% to scale with all rooftop obstructions such as HVACs, piping, green roofs and chimneys included, as there were many errors and missing details in the 3-D model obtained.

Secondly, in order to eliminate the human errors associated with the manual digitization process, the development of a tool for the automated surface extraction feature to identify rooftops and occupied areas would be recommended. A software that is open-source would be perhaps better suited for the future, as outside consultation was required with HOMER, as it was not possible to access the coding within the software. Lastly, a unified integrated approach within a single software package to perform this 3-D hourly PV analysis would be ideal.

7. Appendix

Appendix A: Rooftops analyzed for incident solar radiation in Ecotect Analysis

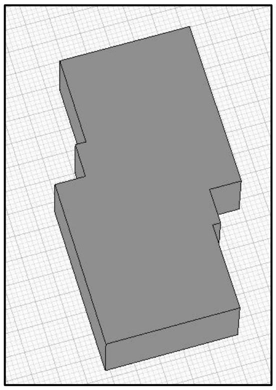


Figure 1. ARC

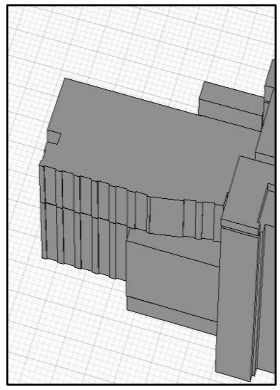


Figure 2. CED

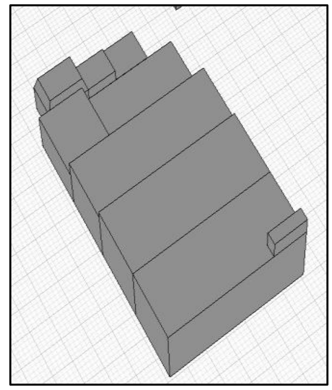


Figure 3. CPF, SBB

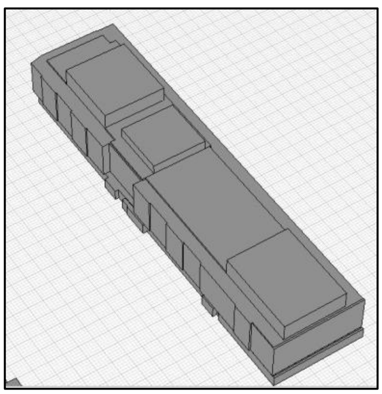


Figure 4. ENG

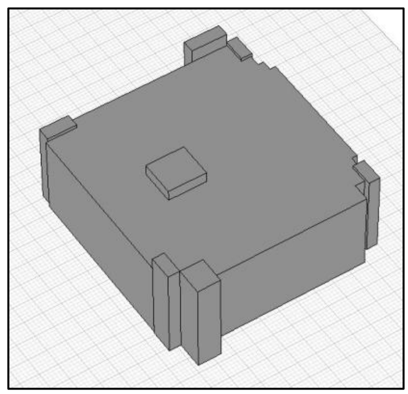


Figure 5. EPH, SHE

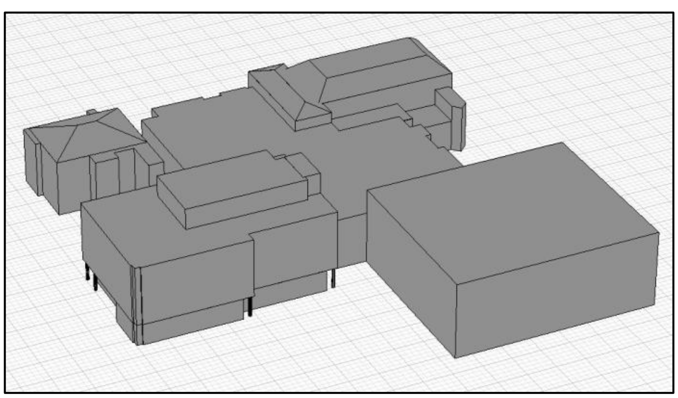


Figure 6. HEI, OAK, OKF, SID, SCC

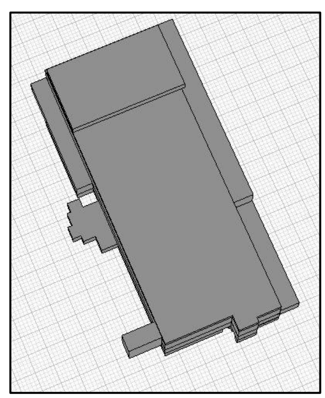


Figure 7. IMA

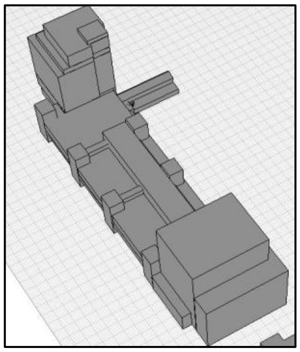


Figure 8. JOR, LIB POD

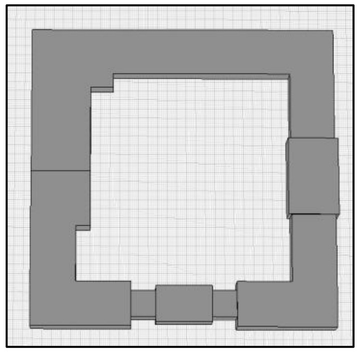


Figure 9. KERR E,N,S,W

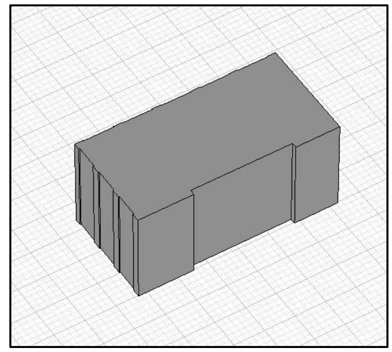


Figure 10. MON

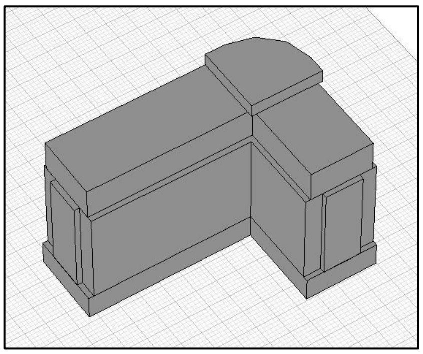


Figure 11. PIT

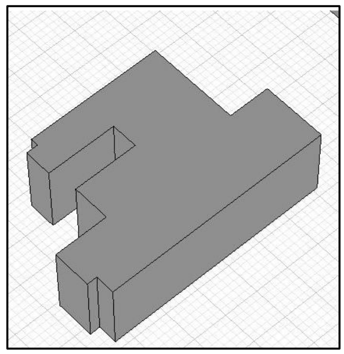


Figure 12. PRO

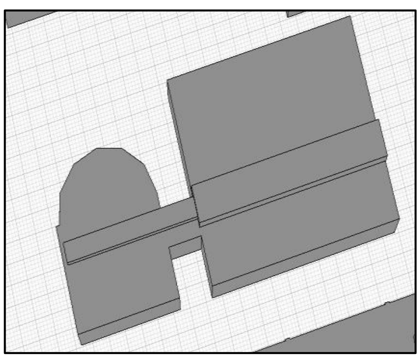


Figure 13. RCC

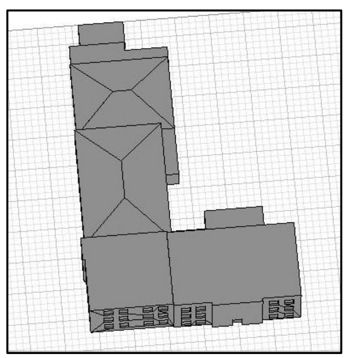


Figure 14. THR

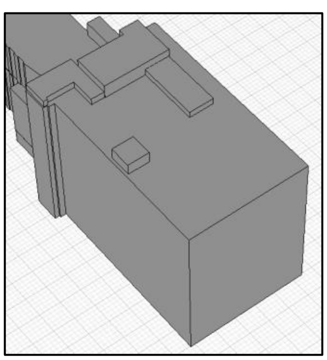


Figure 15. VIC

Appendix B: Incident solar radiation upon each roof calculated from Ecotect Analysis

Table 1. Average monthly incident solar radiation (Wh/m^2)

	Incident Solar Radiation (Wh/m^2)																								
	ARC	CED	CPF	ENG	EPH,SHE	HEI	IMA	JOR	KERR E	KERR N	KERR S	KERR W	LIB	MON	OAK	OKF	PIT	POD	PRO	RCC	SBB	SCC	SID	THR	VIC
Month	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------
Jan	1189	818	791	804	1079	1271	1261	978	1291	1323	1171	1300	1243	1317	1094	1229	1282	709	1108	824	977	1103	1312	814	1201
Feb	2002	1409	1515	1322	1885	2038	2033	1591	2103	2176	1904	2075	1989	2188	1730	2000	2071	1253	1802	1432	1635	1899	2185	1381	1973
Mar	2665	2232	2295	1811	2705	2763	2805	2194	2884	2923	2591	2836	2730	2940	2380	2675	2840	1881	2574	2326	2364	2661	2909	1882	2738
Apr	3911	3343	3413	2629	3917	4042	4036	3097	4054	4101	3636	4082	3780	4153	3366	3864	3973	2762	3692	3458	3602	3943	4137	2916	3860
May	5109	4411	4502	3353	5115	5245	5171	4105	5243	5277	4661	5259	4872	5386	4359	4932	5102	3703	4972	4481	4821	5217	5362	3931	4935
Jun	5781	4906	5128	3852	5667	5877	5801	4741	5897	5823	5260	5864	5420	5994	4901	5570	5732	4213	5544	5203	5452	5775	5988	4404	5552
Jul	5722	4871	5121	3760	5636	5823	5752	4664	5839	5766	5200	5800	5383	5928	4850	5517	5673	4199	5502	5091	5384	5733	5936	4446	5492
Aug	4757	4084	4241	3233	4759	4976	4909	3869	4978	4914	4441	4919	4591	5013	4134	4682	4847	3471	4550	4272	4537	4761	4992	3659	4683
Sep	3668	3120	3258	2449	3730	3836	3900	2931	3903	3950	3513	3923	3626	3979	3247	3736	3830	2608	3587	3291	3393	3666	3908	2748	3722
Oct	2259	1765	1957	1533	2229	2372	2427	1852	2459	2424	2197	2352	2305	2463	2013	2318	2395	1547	2160	1896	1985	2185	2457	1578	2302
Nov	1091	795	833	745	1033	1144	1132	903	1177	1168	1057	1171	1091	1189	986	1115	1150	715	1007	812	953	1080	1214	782	1089
Dec	880	578	607	598	811	958	976	737	968	972	877	992	947	968	819	928	968	526	815	618	739	834	1013	602	912

Appendix C: Orthophotos

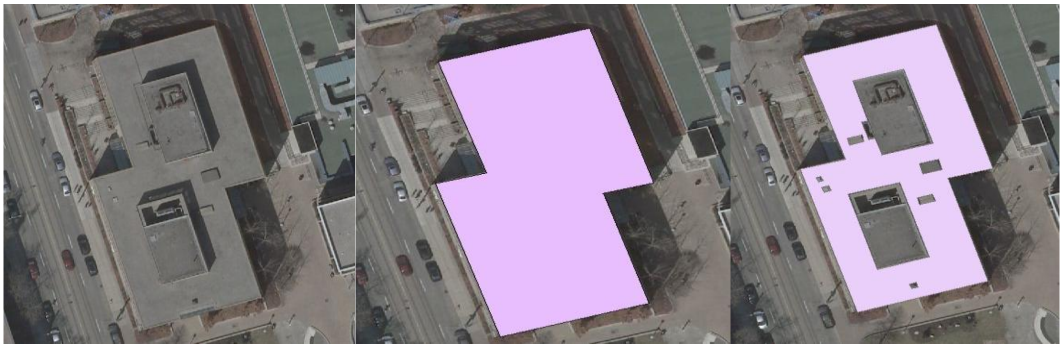


Figure 1. ARC building – orthophoto, digitized gross area and usable area

Figure 2. CED building –orthophoto, digitized gross area and usable area

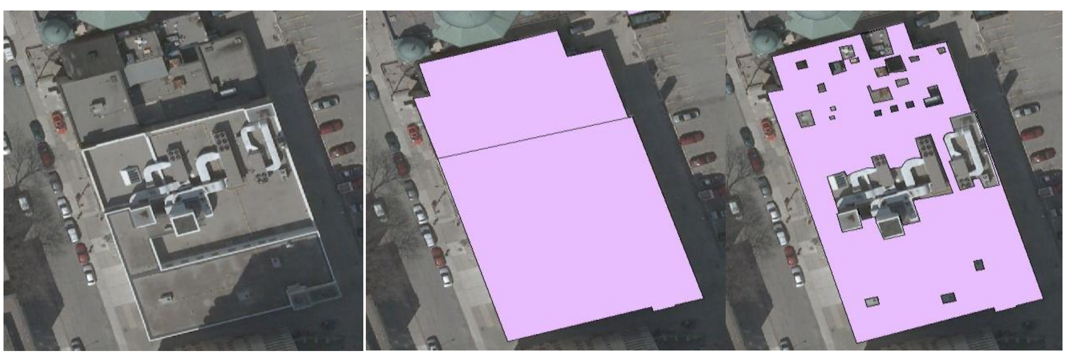


Figure 3. CPF & SBB buildings – orthophto, digitized gross area and usable area

Figure 4. ENG building

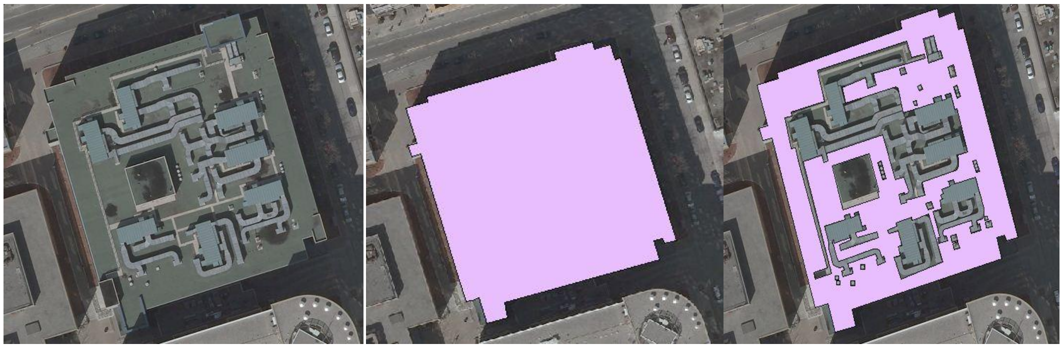


Figure 5. EPH, SHE

Figure 6. HEI, OAK, OKF, SCC, & SID

Figure 7. IMA

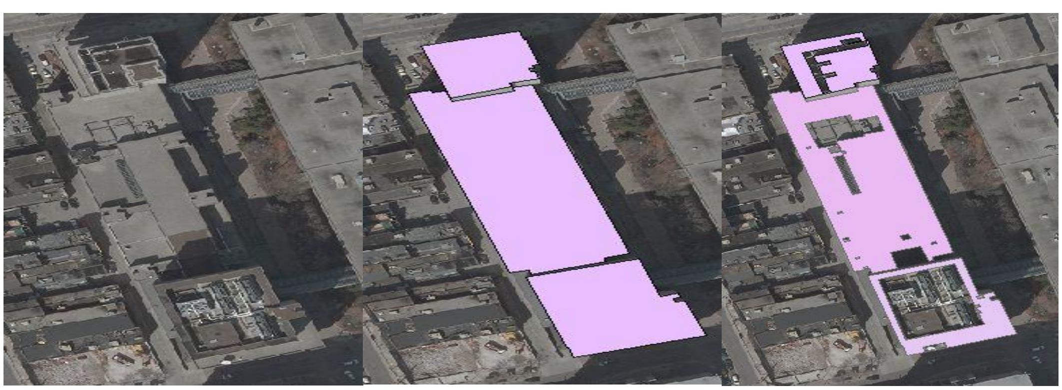


Figure 8. JOR, LIB & POD

Figure 9. KERR HALL

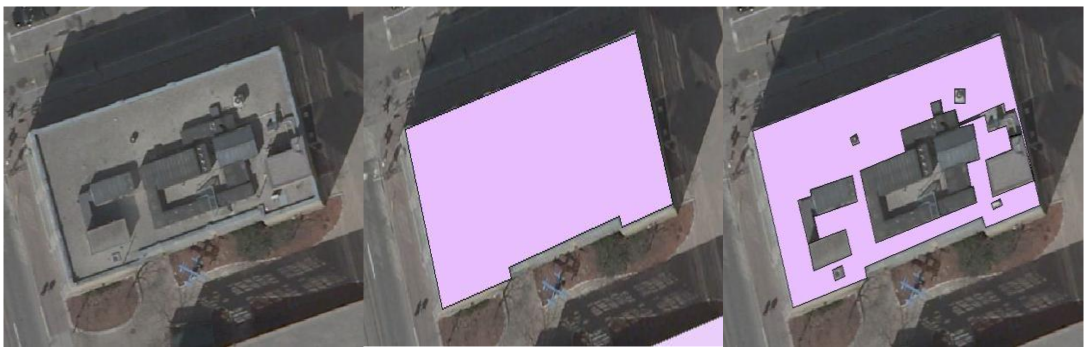


Figure 10. MON

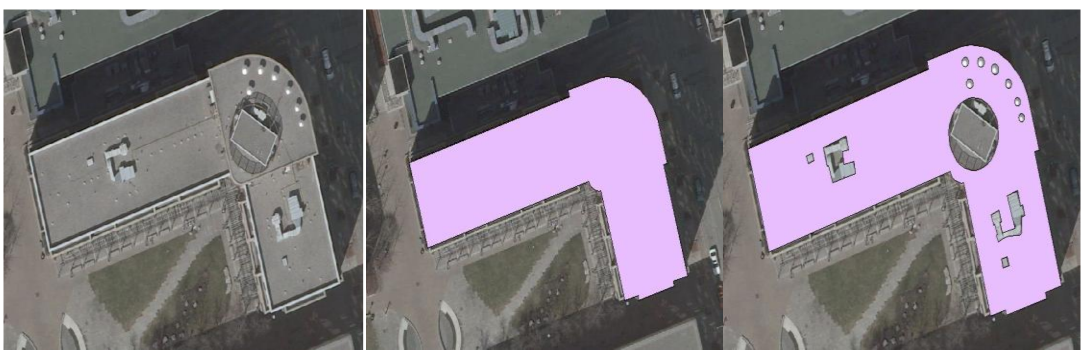


Figure 11. PIT

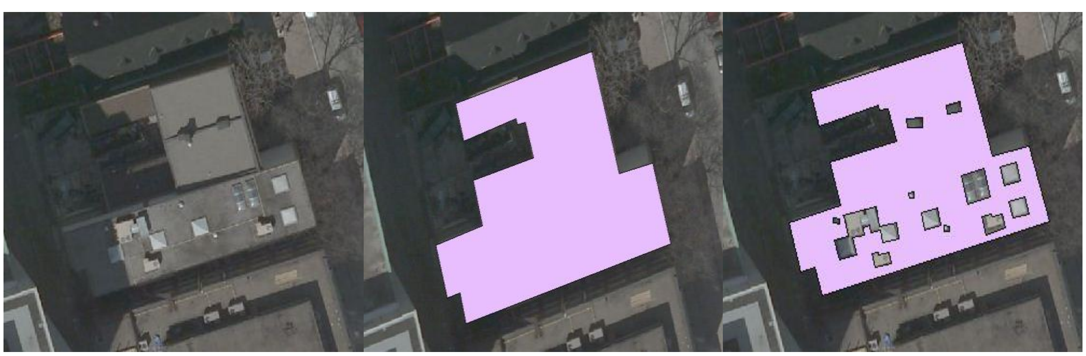


Figure 12. PRO

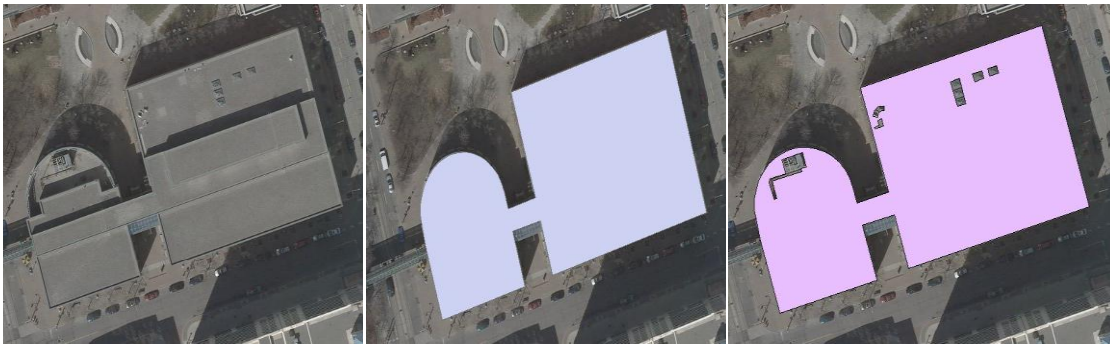


Figure 13. RCC

Figure 14. THR

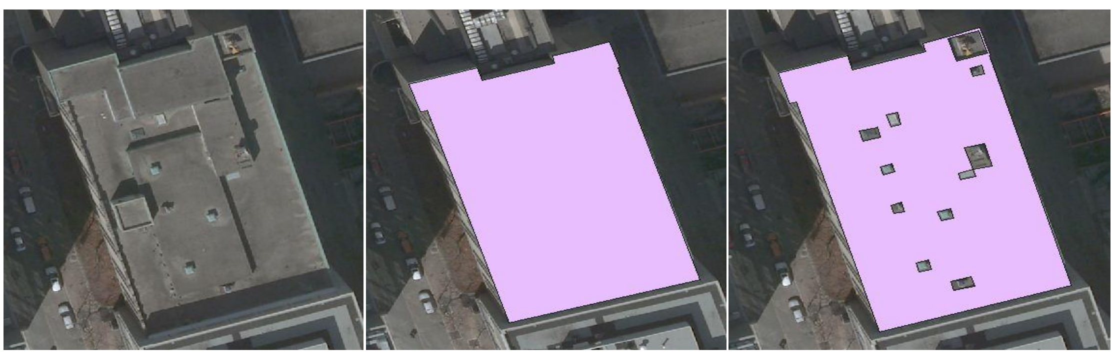


Figure 15. VIC

Appendix D: Cumulated hourly electricity generation potential calculated from HOMER

D.1. Scenario 1

Table 1. Scenario 1 hourly PV output

Time	Hourly electricity generation potential – PV Output (kW)																									
	ARC	CED	CPF	ENG	EPH,SHE	HEI	IMA	JOR	KERR E	KERR N	KERR S	KERR W	LIB	MON	OAK	OKF	PIT	POD	PRO	RCC	SBB	SCC	SID	THR	VIC	Annual Hourly Production
1:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6:00	334.0177	122.5071	158.2321	617.241	707.145	157.0657	500.6475	173.7414	675.084	1338.884	192.2363	579.816	339.4005	103.7576	127.7172	53.6311	250.437	770.922	125.3433	864.751	336.651	254.4437	228.4044	201.5297	313.3527	9526.959
7:00	1295.1438	464.4624	604.4687	2369.702	2753.285	612.521	1957.7402	653.3646	2635.895	5241.36	748.199	2264.947	1323.8113	405.0778	490.4885	209.1833	978.5978	2874.731	484.8702	3334.248	1299.1129	986.4318	890.2896	750.8789	1222.7929	36851.6027
8:00	2858.9442	1015.3267	1329.29	5117.838	6088.125	1356.4837	4351.0874	1427.0778	5860.243	11674.066	1662.3784	5027.406	2946.5966	900.5061	1091.4363	464.9643	2177.3719	6093.789	1069.0832	7298.304	2844.0994	2172.3708	1977.3901	1592.3158	2719.1584	81115.6521
9:00	4707.474	1623.0965	2130.8267	8339.274	9982.498	2239.8164	7196.652	2305.9052	9703.299	19361.128	2746.2016	8318.304	4884.4091	1491.2429	1772.0104	769.3049	3608.3439	9781.255	1752.975	11775.536	4618.0255	3560.7921	3277.2361	2592.0723	4494.7321	133032.4107
10:00	6506.2001	2218.0207	2929.9266	11617.518	13759.157	3101.8797	9977.2646	3185.7771	13458.865	26881.072	3806.2338	11536.569	6786.94	2067.8743	2470.0793	1066.9685	5009.0516	13244.908	2418.1883	16089.939	6328.7897	4906.639	4547.5892	3518.6389	6230.4202	183664.5096
11:00	7848.2138	2644.4247	3487.4175	13826.867	16571.503	3749.2997	12065.9338	3776.4289	16285.755	32545.392	4591.7351	13952.909	8188.1906	2504.1492	2952.4675	1287.1722	6058.901	15585.941	2905.8378	19253.024	7595.9943	5909.9565	5508.0809	4125.8747	7512.5618	220734.031
12:00	8485.6573	2835.5484	3740.6935	14904.788	17902.013	4053.7466	13042.8532	4078.3143	17606.206	35198.961	4950.9957	15088.591	8859.112	2707.1983	3168.8868	1393.5222	6552.243	16827.474	3139.0156	20750.304	8196.6541	6385.9019	5956.3938	4469.8196	8132.677	238427.5703
13:00	8910.8914	2996.4395	3961.4633	15645.69	18797.27	4252.267	13684.0617	4314.7433	18469.287	36923.914	5214.718	15826.824	9315.8215	2838.7435	3343.0035	1463.3226	6876.6111	17916.942	3302.6423	21835.59	8621.1945	6704.4538	6245.3808	4737.1816	8541.3638	250739.8202
14:00	8266.8761	2767.6045	3634.2027	14373.295	17441.035	3949.6303	12708.6336	3980.1355	17161.791	34309.197	4796.9677	14703.381	8625.9579	2640.0231	3071.2064	1356.2275	6382.3951	16453.451	3048.2322	20109.335	7958.0467	6221.882	5806.5071	4376.5435	7915.9811	232058.538
15:00	7281.4858	2474.2297	3252.9286	12766.137	15367.809	3473.6355	11172.6207	3565.8155	15081.356	30141.998	4234.0974	12923.961	7590.4786	2319.1214	2742.7827	1193.638	5610.808	14819.866	2693.4182	17790.713	7017.8045	5483.6438	5101.1826	3942.4681	6966.6713	205008.6704
16:00	5709.2687	1968.0671	2568.8389	10063.201	12075.342	2719.7037	8741.9457	2808.852	11796.742	23563.413	3327.6412	10111.548	5934.4389	1813.994	2161.5479	934.0404	4387.2211	11762.238	2119.3995	14126.773	5564.0345	4307.9188	3988.0222	3107.2666	5454.6932	161116.1514
17:00	3771.5357	1331.7089	1740.9283	6771.829	8003.426	1790.6477	5747.9361	1893.7132	7751.283	15464.907	2196.8874	6644.807	3899.0849	1191.9321	1439.9631	614.45	2881.5035	7938.228	1404.6438	9508.304	3719.3478	2855.0361	2617.456	2102.1565	3592.3541	106874.0692
18:00	2090.3385	757.7443	979.6379	3836.453	4451.662	989.4994	3168.1489	1063.8306	4266.099	8487.814	1215.7354	3662.246	2149.6364	654.9337	798.419	339.0387	1585.5917	4675.442	783.2788	5392.276	2095.0077	1590.1319	1438.7381	1220.2428	1983.9336	59675.8794
19:00	814.7814	299.1482	387.4865	1546.207	1728.444	383.747	1224.3873	419.761	1649.059	3270.853	471.5828	1415.702	832.1777	252.9488	314.1026	131.3599	612.6528	1849.644	305.4847	2117.255	822.4317	620.1109	556.8054	482.9682	767.7266	23276.8275
20:00	146.4986	56.986	73.0014	328.235	310.569	68.1406	218.341	82.9622	292.801	580.966	87.5125	251.648	151.9012	44.6286	60.0018	23.8305	109.8309	384.656	55.7461	399.486	151.2423	111.0298	98.3545	97.3764	139.2867	4325.0321
21:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ANNUAL TOTAL	69027.3271	23575.3147	30979.3427	122124.275	145939.283	32898.084	105758.2537	33730.4226	142693.765	284983.925	40243.1223	122308.659	71827.9572	21936.1314	26004.113	11300.6541	53081.5604	140979.487	25608.159	170645.838	67168.4366	52070.7429	48237.8308	37317.3336	65987.7055	1946427.724

D.2. Scenario 2

Table 2. Scenario 2 hourly PV power output

Hourly electricity generation potential – PV Output (kW)																										
Time	ARC	CED	CPF	ENG	EPH,SHE	HEI	IMA	JOR	KERR E	KERR N	KERR S	KERR W	LIB	MON	OAK	OKF	PIT	POD	PRO	RCC	SBB	SCC	SID	THR	VIC	Annual Hourly Production
1:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6:00	389.228	88.8177	213.0046	619.832	646.161	200.4278	757.662	214.9173	857.464	1781.701	148.0218	767.343	215.4613	105.6603	180.363	73.7421	340.7737	1023.438	171.7297	1306.238	420.3097	325.4499	259.9424	284.8149	460.9247	11853.4279
7:00	1509.2171	336.7356	813.7064	2379.66	2515.865	781.6208	2962.764	808.2092	3347.994	6974.874	576.1138	2997.503	840.3975	412.511	692.6741	287.6275	1331.5916	3816.379	664.3105	5036.453	1621.945	1261.7161	1013.2158	1061.1915	1798.6643	45842.9398
8:00	3331.4962	736.1119	1789.429	5139.336	5563.136	1730.9737	6584.757	1765.2866	7443.431	15535.106	1280.0322	6653.426	1870.5925	917.0283	1541.3408	639.325	2962.781	8089.881	1464.7275	11024.241	3550.8662	2778.6123	2250.4184	2250.365	3999.7415	100892.4421
9:00	5485.5699	1176.7449	2868.42	8374.308	9121.714	2858.1713	10891.109	2852.3905	12324.689	25764.567	2114.5766	11008.703	3100.7767	1518.6051	2502.4574	1057.7954	4909.9264	12985.226	2401.7133	17787.172	5765.6181	4554.5026	3729.7399	3663.286	6611.5168	165429.2989
10:00	7581.6052	1608.0653	3944.132	11666.336	12572.729	3958.2275	15099.18	3940.7899	17094.846	35771.622	2930.8003	15267.871	4308.5627	2105.8173	3488.2817	1467.0816	6815.8874	17583.448	3313.1081	24304.194	7901.5118	6275.9327	5175.5003	4972.7696	9164.624	228312.9234
11:00	9145.4397	1917.2103	4694.601	13884.967	15142.556	4784.3821	18260.086	4671.421	20685.446	43309.334	3535.6374	18465.746	5198.1211	2550.0969	4169.5157	1769.8609	8244.4315	20691.319	3981.2248	29082.092	9483.6214	7559.248	6268.6105	5830.9562	11050.5867	274376.5112
12:00	9888.2462	2055.7726	5035.5494	14967.429	16358.337	5172.8787	19738.523	5044.8501	22362.624	46840.544	3812.2681	19968.72	5624.0429	2756.8719	4475.1451	1916.0928	8915.7303	22339.53	4300.6981	31343.757	10233.5464	8168.0137	6778.8247	6317.0402	11962.7451	296377.7803
13:00	10383.7663	2172.4184	5332.7385	15711.447	17176.392	5426.2052	20708.892	5337.313	23458.874	49136.02	4015.3327	20945.759	5913.9767	2890.8318	4721.0354	2012.0682	9357.1035	23785.892	4524.8801	32983.101	10763.5873	8575.4637	7107.7136	6694.8941	12563.9023	311699.6078
14:00	9633.302	2006.5137	4892.1962	14433.696	15937.116	5040.0195	19232.722	4923.4052	21798.153	45656.49	3693.6664	19458.941	5476.03	2688.465	4337.1998	1864.8124	8684.6159	21843.009	4176.3188	30375.566	9935.6452	7958.2224	6608.2414	6185.2161	11643.9949	288483.5579
15:00	8485.0363	1793.8163	4378.9429	12819.778	14042.653	4432.615	16908.188	4410.8938	19155.673	40111.069	3260.2558	17103.997	4818.6752	2361.6748	3873.3961	1641.2512	7634.7046	19674.316	3690.196	26873.228	8761.7513	7013.9647	5805.5318	5571.7508	10247.6087	254870.9673
16:00	6652.9504	1426.8487	3458.0524	10105.469	11034.088	3470.5404	13229.705	3474.5337	14983.704	31356.687	2562.2834	13381.952	3767.3697	1847.2785	3052.5685	1284.3061	5969.7539	15615.116	2903.7436	21338.782	6946.7129	5510.128	4538.6688	4391.3914	8023.5701	200326.2035
17:00	4394.9301	965.4897	2343.5584	6800.282	7313.277	2284.9991	8698.687	2342.5128	9845.331	20579.73	1691.6034	8793.943	2475.2633	1213.8024	2033.5366	844.8687	3920.9048	10538.509	1924.472	14362.483	4643.6176	3651.7899	2978.8625	2970.9052	5284.1656	132897.5241
18:00	2435.8486	549.3642	1318.7432	3852.573	4067.794	1262.6718	4794.544	1315.9521	5418.61	11295.058	936.1157	4846.742	1364.6561	666.9512	1127.5382	466.1788	2157.538	6206.936	1073.1552	8145.145	2615.6224	2033.8891	1637.3928	1724.5268	2918.2624	74231.8086
19:00	949.4559	216.8826	521.6168	1552.71	1579.407	489.6888	1852.941	519.2416	2094.573	4352.642	363.1182	1873.594	528.2925	257.5905	443.5794	180.6194	833.6457	2455.519	418.5373	3198.166	1026.8081	793.1644	633.6874	682.5622	1129.2856	28947.3284
20:00	170.7134	41.3149	98.2708	329.612	283.791	86.9527	330.426	102.6243	371.9	773.11	67.3849	333.032	96.4321	45.4476	84.7354	32.7669	149.4487	510.65	76.3769	603.433	188.826	142.0149	111.9354	137.6181	204.8844	5373.7014
21:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ANNUAL TOTAL	80436.8053	17092.1068	41702.9616	122637.435	133355.016	41980.3744	160050.186	41724.3411	181243.312	379238.554	30987.2107	161867.272	45598.6503	22338.6326	36723.3672	15538.397	72228.837	187159.168	35085.1919	257764.051	83859.9894	66602.1124	54898.2857	52739.2881	97064.4771	2419916.023

Appendix E: HOMER Hourly Electricity Analysis Results Examples

E.1. Architecture (ARC) Building, Scenario 2

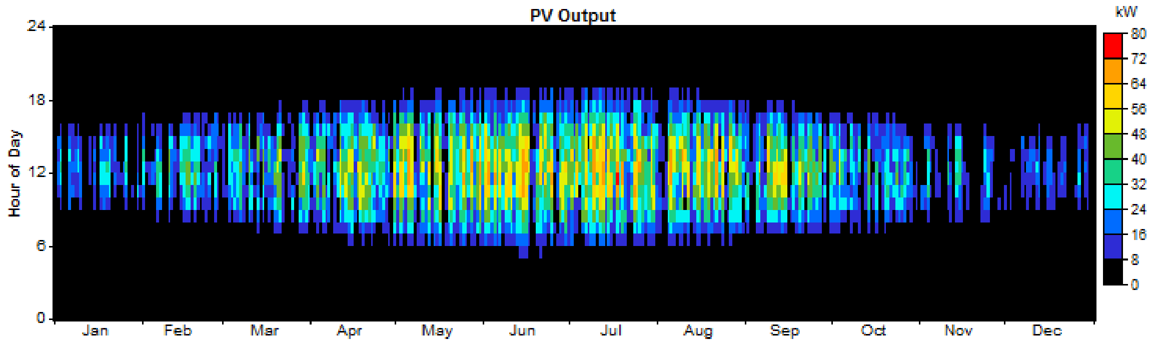


Figure 1. Annual hourly electricity production

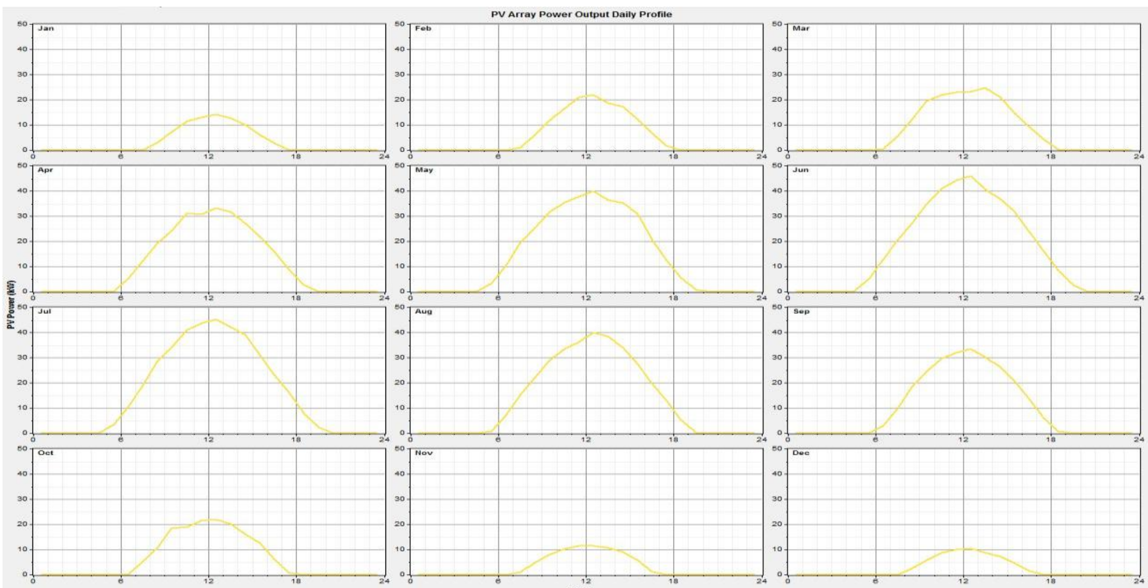


Figure 2. PV Array Power Output Daily Profile

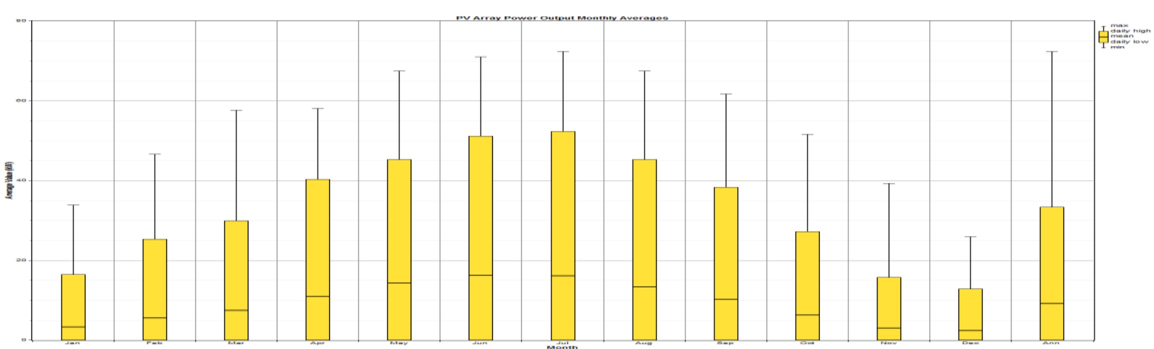


Figure 3. PV Array Power Output Monthly Averages

E.2. Monetary Times (MON) Building, Scenario 1

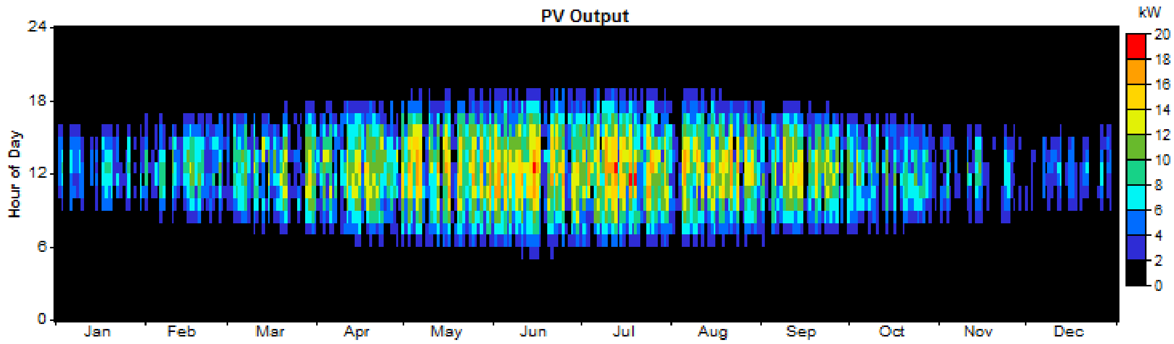


Figure 4. Annual hourly electricity production

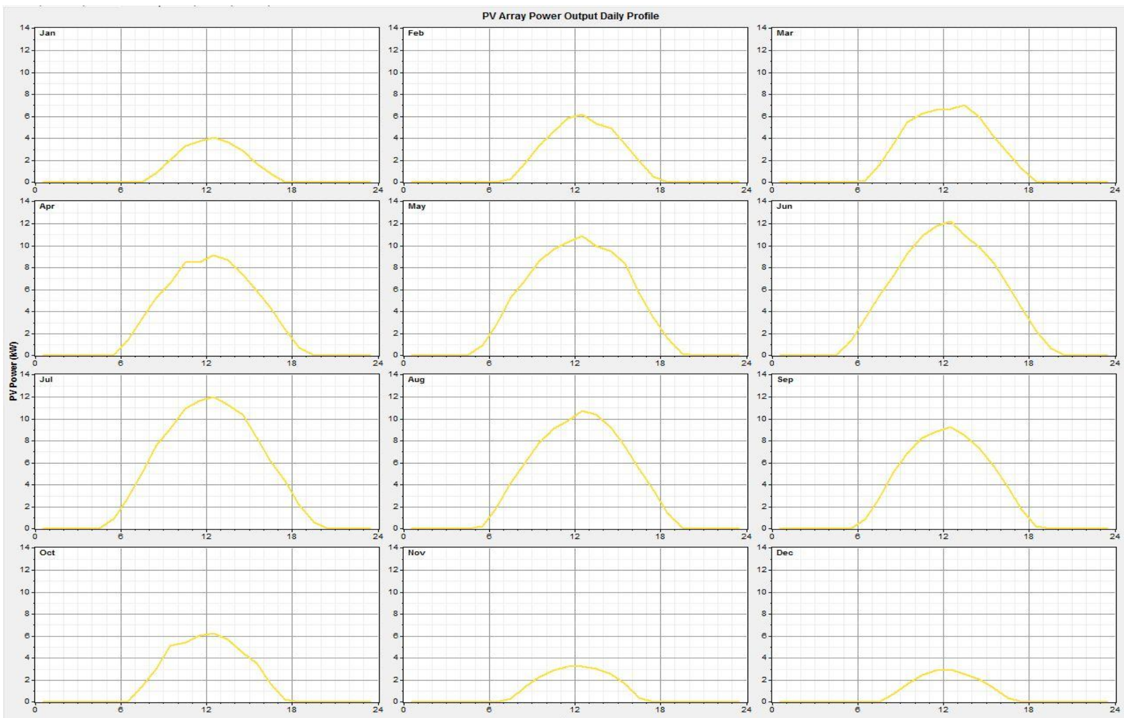


Figure 5. PV Array Power Output Daily Profile

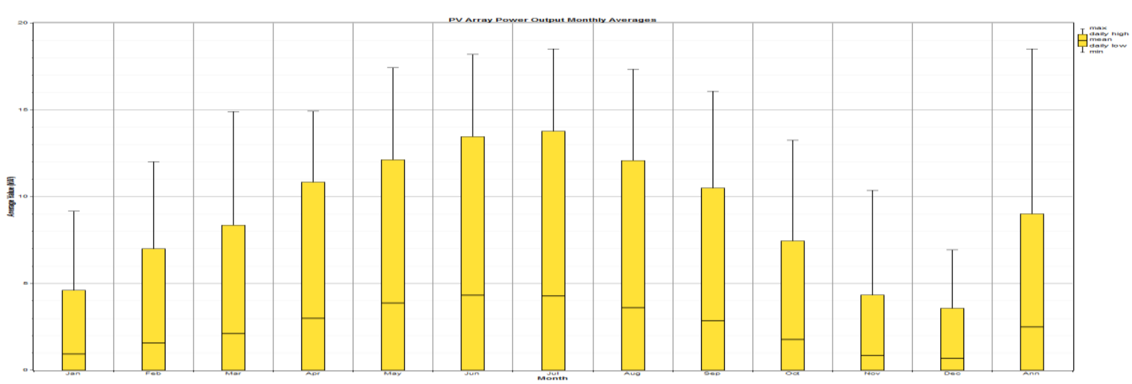


Figure 6. PV Power Output Monthly Averages

E.3. Eric Palin Hall & Sally Horsfall Eaton Centre for Studies in Community Health (EPH, SHE) Building, Scenario 1

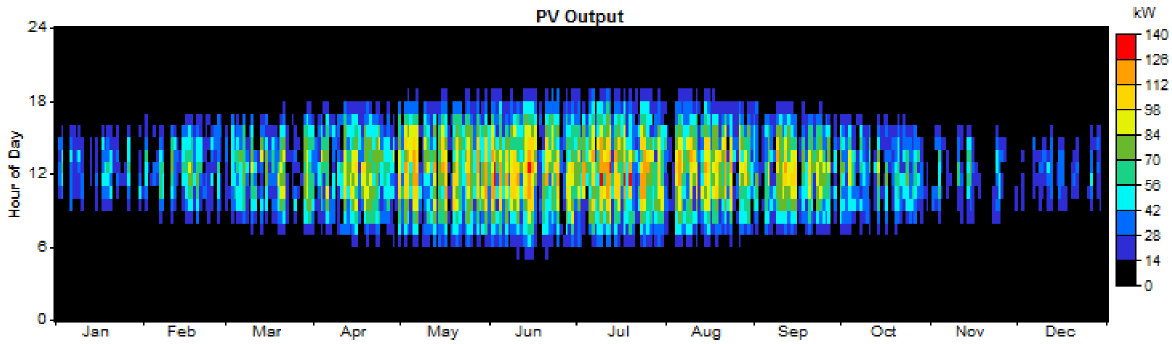


Figure 7. Annual Hourly Electricity Production

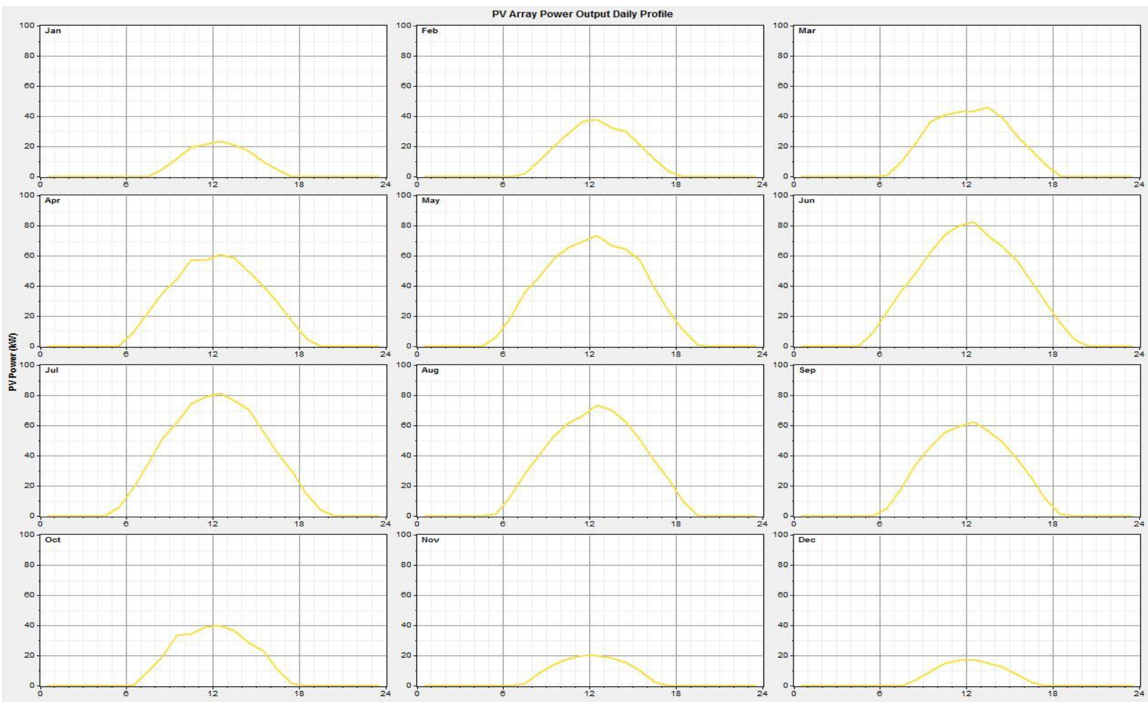


Figure 8. PV Array Power Output Daily Profile

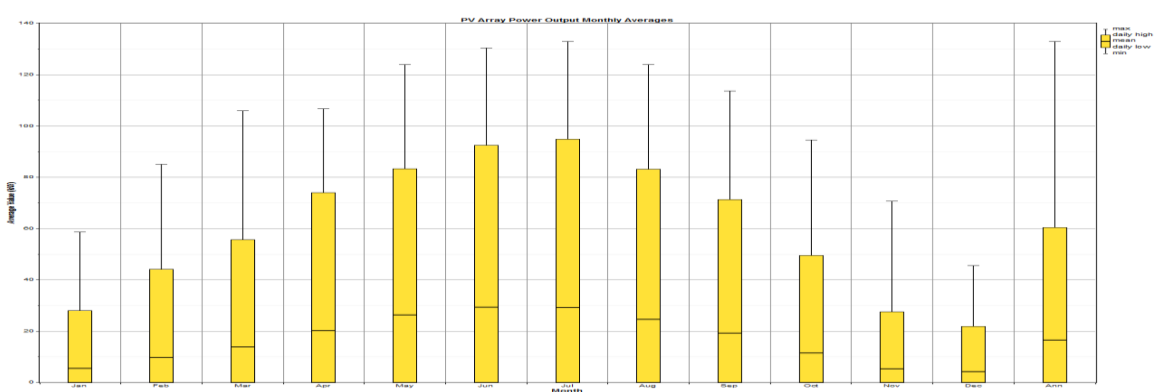


Figure 9. PV Power Output Monthly Averages

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