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Quantifying Rooftop Solar Power for the City of Waterloo, Ontario

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By

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

Climate change, pollution, and energy security are driving a worldwide transition away from traditional fossil fuel generated electricity. As the world moves away from fossil fuels and towards renewable energy, electricity generated from photovoltaic solar panels is one of the most promising and capable technologies available today. Arguably the most suitable location to generate this electricity is at the source of consumption. Placing solar panels on unused rooftop space can subsidize the electricity demand that that building requires. This research quantifies the amount of electricity that can be generated within the City of Waterloo, Ontario. Using Natural Resources Canada data, examples from the literature and existing rooftop solar data, a range of possible values were calculated to illustrate the generating potential rooftop solar panels could have for the City of Waterloo. The range in values illustrated the overall potential of electricity generation from rooftop solar power under best to worst case scenarios. An overall value was then calculated based on total available area for five different land use types to illustrate the potential each sector could have for the City. Additionally, a range of values was also applied to the largest and cumulative average rooftop size for each land use type to further examine potential based on each land use type. This research is intended to serve as a possible template for similar studies in different geographic areas of Ontario as well as to influence future policy development surrounding renewable energy generation.

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To my wife Leslie, you've been my support and motivator. Thank you for being there to listen, discuss my ideas and keep me focused.

To my mother and father, thank you for always believing in me and for pushing me to do more.

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Definition of Terms

The following terms have been defined to provide context and understanding of their use throughout this research paper:

Azimuth – The position of a celestial object along an observer's horizon

Building – Permanent, dwelling or structure that may or may not be occupied

Development – Presently occurring or newly constructed dwelling or structure

Electricity – Type of energy caused by the presence and flow of electric charge

Energy – The capacity for work

Feed-In Tariff (FIT) – An economic policy created to promote active investment in and production of renewable energy sources. Feed-in tariffs typically make use of long-term agreements and pricing tied to costs of production for renewable energy producers.

Geographic Information Systems – Computer software used to store, view, and analyze geographical information

Institution – An established organization dedicated to education, public service, or culture

Insolation – The act of solar radiation striking the Earth

Kilowatt hour (kWh) – A unit of energy equal to 1000 Watt hours or 3.6 megajoules

Local Distribution Company (LDC) – Distribution company that maintains electrical grid closest to residential and commercial consumers

Megajoule (MJ) – Equal to the amount of 1 million joules or the kinetic energy of a one ton vehicle moving at 160km/h

MicroFIT – policy mechanism designed to accelerate investment into small renewable energy projects. A MicroFIT project in Ontario is considered any renewable energy project <=10kW in size.

Rooftop – The outer surface of a building's roof

Rural – Of, or relating to farming or agriculture

Solar Array (Solar Panel) – Collection of solar cells (or photovoltaic modules)

Solar Cell – Semiconductor device that collects sunlight and converts it to electrical energy

Solar Energy – Energy from the sun that is converted into thermal or electrical energy

Urban - Relating to or concerned with a city or densely populated area

Chapter 1

Introduction

The installed capacity of solar photovoltaic panels has grown from 1.5 gigawatts (GW) in 2000 to over 70GW in 2013 worldwide with an increase of 74% in 2011 alone (IEA, 2013). Government incentive programs, declining material and installation costs along with a change in political will toward renewable energy have been major influences to this growth. With the introduction of attractive government incentive programs, many home and business owners are now installing photovoltaic panels on building rooftops in urban centers. This has been the case within the City of Waterloo. For homes and small businesses the return on investment and installation costs are primary drivers in the decision to install rooftop solar power. To achieve a reliable aggregate estimation of cost or return on investment however, the quantity of electricity needs to be accurately calculated. In Canada, there is need for a demonstrated methodology for quantifying rooftop solar power. This thesis sets out to develop such a methodology for the City of Waterloo.

The City of Waterloo, located approximately 100km west of Toronto, is a city experiencing rapid growth in population and building development. Waterloo is a diverse city with a variety of mixed land use ranging from high-rise apartments and office towers to sub-urban housing and rural farm land at the city limits. A large portion of the City landscape is dominated by two university campuses along with a large and diverse technology industry. Numerous student residences, high-rise condos, and campus buildings have transformed the urban landscape over the past decade. The growth and expansion of Blackberry (formerly Research in Motion) and other technology companies have also led to the construction of several new office and industrial buildings. As businesses grow and the population of the City increases, so does the demand for electricity. As electricity prices continue to rise, and both the costs and incentives for installing solar power become more attractive, the residents of Waterloo are presented with a unique opportunity. Rooftop solar panel installations take advantage of government incentives while making use of unused rooftop space. This is a practical solution not only to reducing energy costs, but also to producing electricity in a more sustainable way. This application begs the question as to how much electricity can potentially be generated if all suitable buildings within the city had solar panels installed. In this research, this question is explored using GIS, aerial imagery, building footprints and land use information for the City to estimate how much electricity can be generated if all buildings had rooftop solar power generators installed. As various influential factors to this estimation were examined more closely, a process of refining this data was developed. This process ultimately led to values illustrating the best and worst case scenarios. Under the best case scenario, the maximum suitable rooftop was calculated given the developed methodology. Under the worst case scenario, the resulting value illustrated what was achievable when the most conservative parameters were used to estimate suitable rooftop space. Each scenario was use to calculate the overall potential of electricity generation for the city. Values were broken down by land use to illustrate which land use type had the most potential. The average residential rooftop size was also used to compare potential generation rates to average household consumption. Detailed discussion on the resulting values, calculation methods and the potential of rooftop solar power in the City of Waterloo are then thoroughly covered in the Discussion and Results section of this research.

1.0 Research Objectives

The general objective of this research is to produce a range of values representing the possible electricity output that can be achieved in the City of Waterloo if all suitable buildings in the City were outfitted with rooftop photovoltaic solar panels. Due to the variability of seasons, weather and solar output and the general complexity of this problem, a range in values from best to least favorable conditions are provided based on several factors. These include:

1) Suitable rooftop size to accommodate solar panels
2) Suitable rooftop angle
3) Solar panel angle
4) Solar panel direction in relationship to the sun
5) Seasonal variability in incoming solar radiation
6) Shadow from trees, neighboring buildings and other features
7) Rooftop obstacles and physical barriers to construction
8) Size of solar panel array

Considering the above factors, the aim of this research was to answer the following two questions in regards to rooftop solar power for the City of Waterloo:

1) If all suitable rooftop space within the municipality were outfitted with photovoltaic panels, how much electricity could be generated for the City on an average annual basis?

2) What land use types, roof types and locations within the City are most promising for this technology?

To begin, base line values on solar generation potential need to be calculated using the Natural Resources Canada photovoltaic potential mapping tool. This tool will identify locations considered to be most favorable for rooftop solar power. Five different solar inclination angles are illustrated using this tool and average solar radiation values for each month are shown in kWh/kW of installed capacity. This method considers the entire rooftop area (e.g. suitable space) and is not limited by such factors as rooftop size, physical barriers to construction, shadow or seasonal variation.

The second step in this process will be to refine the aforementioned values to present a more realistic view of what may be achievable in the field. To do this, formulas from the literature on similar topics will be used to develop a methodology of refining the data. The latest academic research on several of the limiting factors mentioned above will be referenced to provide direction and reinforce decisions made in the methodology. The purpose of this refinement will achieve a more realistic view of how much potential electricity can be generated from available rooftop space in the City of Waterloo. For example, concessions based on shadow, suitable array size, and barriers to physical construction will produce a more conservative and realistic estimate.

Lastly, the results identified in this research will be compared to the characteristics and locations of existing rooftop solar projects within the City. The purpose here will be to understand the relationship between existing and potential sites and to examine any additional characteristics that may determine where or what type of solar installation can be built.

The general principle of this research will provide a range of possible generation potentials for all buildings within the City of Waterloo. Land use and various building sizes within each land use category will be broken down further to highlight potential generation capacity within different sectors across the City. The range of values resulting from the consideration of several limiting factors will ultimately be used to answer how much electricity can be generated from rooftop solar power if all suitable buildings had these generators installed.

Chapter 2

Background

Solar panel development and research has progressed considerably over the past several decades. Major advancements to the manufacturing and performance of solar panels in the 1970's have lead to wide spread use of this technology today. Programs in the U.S., China, Japan and Europe continue to advance this technology further with their research, innovation and implementation of solar power. Today, these countries boast the highest implementation rates of photovoltaic (PV) systems in the world (University of Central Florida, 2014). More specifically, Germany since 2005 has been the world leader in installed solar power with over 36GW which contributes to roughly 6% of the countries demand for electricity. China is currently a distant second place with 18GW of capacity although with the growth rate at which China is developing solar power, they will likely catch up to and even surpass Germany in the near future (IEA, 2014).

The high density of electricity consumption found in urban environments along with attractive government incentives installing rooftop solar power are shifting the focus of solar power development towards cities and the location of electricity consumption (Gharakhani Siraki, A. and P. Pillay (2012). Incentive programs in many markets around the world continue encourage the construction of smaller scale solar projects. Individual homes and business owners can now purchase and install solar panel technology on their own buildings and expect a reasonable rate of return on their investment.

There are many advantages of installing solar panels on individual rooftops over traditional point source power generation stations such as coal, hydro-electric or nuclear. Rooftop solar essentially places a small scale source of electricity generation at the source of electricity consumption. There are a number of advantages to this setup. The need to construct large scale power stations commonly outside the urban center is greatly reduced or eliminated. In many locations, power generation systems place all or most of the focus on the few dozen sources of electricity production. Hydro-electric stations are limited to sources of fast moving water, nuclear stations need to be next to water sources to cool spent uranium and fossil fuel stations are typically located far from residents because of the emissions they produce. Rooftop solar disperses power generation across the existing grid infrastructure. This dispersion not only reduces or eliminates the need to construct or upgrade existing infrastructure to these large power plants, the many smaller generation stations in a sense reinforce the electrical network by not putting the onus on a handful of power sources (Sovacool, B. K., 2008).

In addition to improvements to the electrical grid reliability and reduced infrastructure costs, there are a number of advantages for the individual home or business owners as well. The province of Ontario offers both companies and individuals a guaranteed incentive for producing electricity and selling it back to the Ontario electrical grid. To cover the relatively high upfront costs of installing rooftop solar panels, the government has offered very attractive rates to entice individuals to invest in this technology (Wiginton, L. K., H. T. Nguyen, et al., 2010). The Feed-In Tariff (FIT) programs offered by the Ontario government since 2009, discussed in the next section, have spurred local job growth, reduced costs to producing and installing solar power, as well have provided attractive income potential to individuals who choose to invest in this technology (Branker, K. and J. M. Pearce, 2010). Additionally, the FIT programs also have the potential to ease some of the strain on the aging Ontario electrical distribution system by delaying the construction of new lines and generation stations to meet growing demands. By installing smaller wind, solar or hydro-electric projects as they are needed, generation can be added to the system as needed versus building a single large generating station (Sovacool, B. K., 2008).

Finally, with electricity rates predicted to rise dramatically over the next several years, the emphasis on generating electricity through rooftop solar power for environmental purposes may become a moot point. Residents may turn to rooftop solar power installations with or without a government subsidy to either help subsidize their income through the FIT program or simply to reduce their overall net electricity consumption by generating their own electricity on site. Electricity prices are slated to rise 7.9% annually from 2010-2015 (46% total over this period) (Dewees, 2012). Electricity costs and net consumption could be mitigated with the installation of rooftop solar panels on a home or business building.

2.0 Feed-In Tariffs (FIT)

By 2010, over 50 countries offered a renewable energy incentive called a Feed-In Tariff program (FIT) (Renewable Energy Policy Network, 2012). There are many variations of a FIT program with various rates and conditions. The general purpose of these programs is to spur innovation and development of renewable energy projects, reduce costs of installing renewable energy and ultimately move away from traditional fossil fuel energy generation.

Ontario introduced a FIT program under the provincial Green Energy Act of 2009, effectively establishing incentives for a whole range of renewable energy generation systems. This program is essentially broken into two streams. One stream is the FIT contracts and pricing schedule and approval process is designed for larger scale projects commonly developed by large corporations. The second stream is the microFIT program which operates much in the same way, but is designed for smaller projects often taken on by individuals and small companies. A microFIT project is considered any project that is 10kW in size or less while a FIT project is anything that is greater than 10kW.

One of the primary objectives of the Ontario government was to replace aging coal-fired generation with wind, solar, biogas or biomass. These FIT programs offer individuals and companies a guaranteed fixed price per kilowatt rate for the amount of electricity their project generates and supplies to the Ontario electric grid. Not only do companies and individuals benefit from the rates paid for generating electricity, these projects are helping to fill the need for electricity demand throughout the province while producing electricity with zero greenhouse gas emissions.

The general model for a FIT program is to start with very attractive rates to attract potential developers. As more solar or wind projects are added to the grid, production and development processes become streamlined, materials become mass produced and ultimately costs to install these projects come down. As the price to install these projects declines, the FIT contract rates for these projects also decline accordingly. Over time, the renewable energy projects that were once not able to compete with the traditionally cheaper and subsidized fossil fuel projects are now on a more level playing field. Ontario has recently reduced the FIT and microFIT contract rates for the province due in part to the falling costs of purchase and installation of solar power.

As of July 12th 2012, any new wind, solar, biogas or biomass projects are now subject to a different price paid per kilowatt generated by one of these projects. Table 2.1 below outlines the changes in price for rooftop and ground mounted solar power.

Table 2.1: FIT/MicroFIT Price Schedule (Ontario Power Authority):

FIT/microFIT PRICE SCHEDULE (August 26, 2013)

Renewable Fuel	Project Size Tranche*	Price (¢/kWh)	Escalation Percentage**
Solar (PV) (Rooftop)	≤ 10 kW	39.6	0%
	> 10 ≤ 100 kW	34.5	0%
	> 100 kW	32.9	0%
Solar (PV) (Non-Rooftop)	≤ 10 kW	29.1	0%
	> 10 kW	28.8	0%
On-Shore Wind	All sizes	11.5	20%
Waterpower	All sizes	14.8	20%
Renewable Biomass	All sizes	15.6	50%
On-Farm Biogas	≤ 100 kW	26.5	50%
	> 100 kW ≤ 250 kW	21.0	50%
Biogas	All sizes	16.4	50%
Landfill gas	All sizes	7.7	50%

* The FIT program is available to Small FIT projects; that is, projects generally ≤ 500 kW.
**Escalation Percentage based on the Consumer Price Index will be applied to eligible Renewable Fuels as calculated in the FIT Contract. The Base Date is January 1 of the year in which the Project achieves commercial operation, unless the Project achieves commercial operation in October, November, or December, in which case the Base Date is January 1 of the following year.
http://fit.powerauthority.on.ca/sites/default/files/news/2013-FIT-Price-Schedule-Tables.pdf

The Ontario Energy Board's Regulated Pricing Plans dictates that the average home or business owner pays between 7.8¢ and 9.1¢ per kWh of electricity consumed depending on the total amount of electricity they have consumed within a month (IESO: Regulated Price Plan, 2013). Comparing these prices to the incentives of the FIT and microFIT rates outlined in the above table clearly shows the benefit to installing a solar, wind or bioenergy project large or small.

2.1 Study area

The City of Waterloo was chosen for this research. Waterloo is 64.10 square kilometers in size, has a population of 98,780 (Statistics Canada, 2013) and is located approximately 100km west of the City of Toronto.

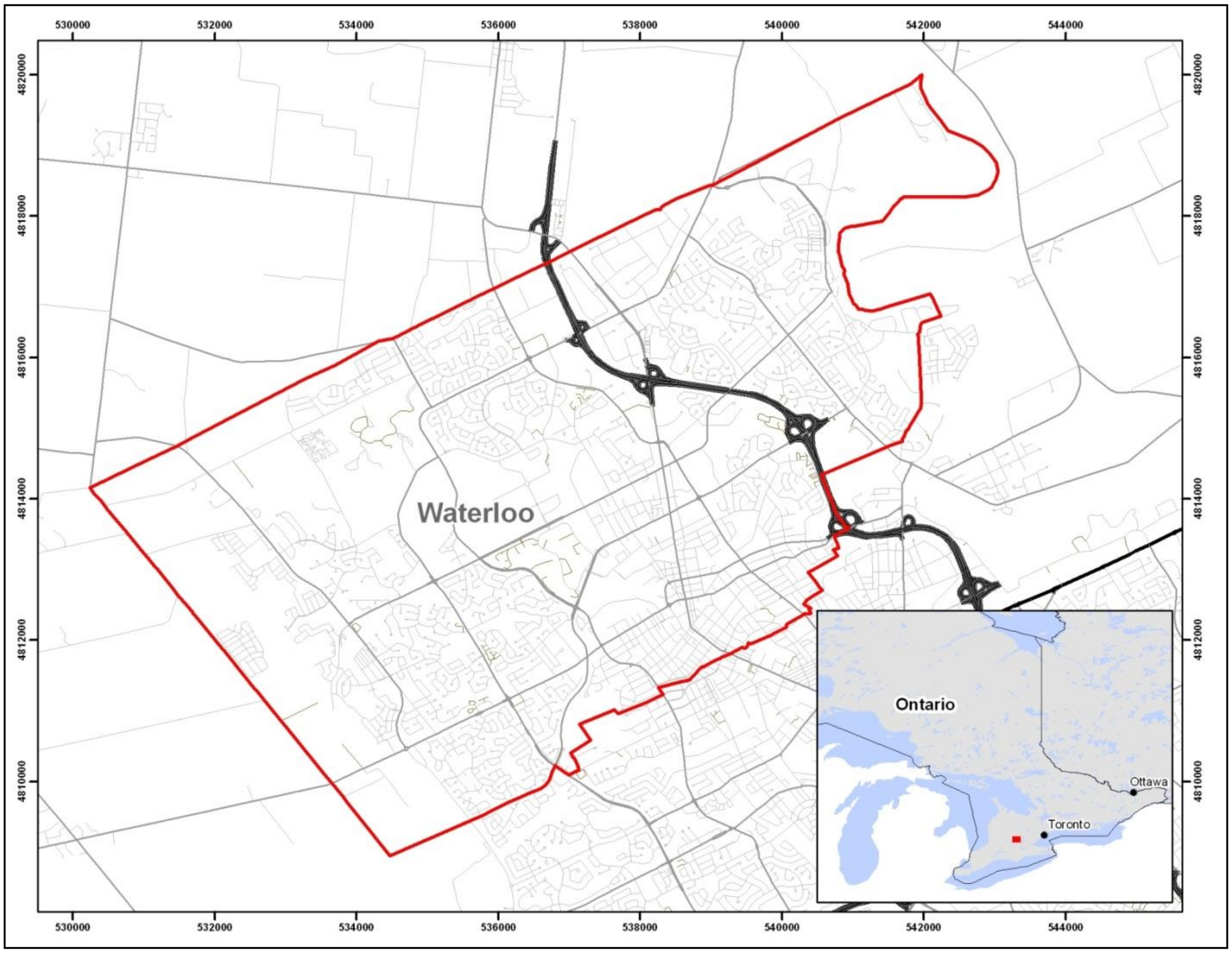


Figure 2.1: Study Area - The City of Waterloo

The City of Waterloo is home to two major Ontario Universities (University of Waterloo and Wilfrid Laurier University) as well as Conestoga College. The computer science programs and graduating students from these schools have spurred several large technology companies. Blackberry, Open Text, and Google along with a host of other technology companies have flocked to Kitchener-Waterloo. In doing so, these companies have transformed the City of Waterloo and its surroundings into a major technology hub of North America. This transformation is evident to me every day since Waterloo is where I live, work and attend school. Waterloo's potential to generate electricity from rooftop solar is fascinating to me because it will impact me directly.

Chapter 3

Literature Review

3.0 Introduction

Photovoltaic panels have started to reach a point in the market where they are feasible to install not only on large scale commercial operations but at the individual level as well. By the early 21st century, programs promoting rooftop solar power in Japan and Germany have been a major influence in driving down the price of installing solar panels and adding to this push for rooftop solar in urban areas (Payne et al. 2001). The reductions in costs and increases in both efficiencies and general acceptance for this technology have led to several research objectives to study the feasibility of this technology further. Japans' "Sunshine Project" (starting in 1974) and more recently "New Sunshine Project" (1993) set major targets for achieving utility connected rooftop mounted PV systems. Capacity targets of 4.6GW by 2010 (now achieved) were made possible because of the research, development and investments that these programs brought forth (Tatsuta, 1996). Similarly, Germany as part of a 2009 European Union directive has set out to meet 20% of its energy needs through renewable energy by 2020. Solar power installations have increased more than 20 times over the past 15 years. Over this same period, German research publications solely on the study of solar power have accounted for over 80% of all renewable energy publications (Sanz-Casado, 2014). Globally, recent research has now also moved beyond questions of whether solar power is the right choice for generating electricity to rather the logistics, obstacles and cost feasibility analysis of this technology both on the large and small scale. Many specific aspects of solar power have been studied by various authors around the world. These areas include very specific topics from optimal tilt angle, solar panel efficiency, and barriers to optimal operation to general studies on site suitability, cost analysis and feasibility of large scale implementation. Understandably, the locations for much of this research is typically found in sunny countries such as Spain, Italy, Turkey, and the Middle East where installing solar power (thermal and photovoltaic) seem logical, given the high number of peak sun hours for these locations. Relatively few studies make any attempt to quantify power generation potential for a specific region and of those studies the study area is often either very large (entire countries) or very small (neighborhood within a city). This lack of research for not only mid-latitude locations and city sized study areas highlight the need for the current study. The following will examine the locations and specific areas of research for solar power and more specifically, rooftop solar power and will highlight how the current study can build on this information and add to a growing body of knowledge on this subject.

3.1 General Research

Research on rooftop solar power ranges from the general feasibility of installing rooftop solar panels, to the complex and influential factors of installing rooftop solar power. This range from general to specific has grown considerably over the past decade as solar power technology has become more ubiquitous in society. General themes such as evaluating, quantifying or selecting suitable locations for rooftop solar power have been studied by Bergamasco and Asinari 2011; Izquierdo et al. 2011; Izquierdo et al. 2008; La Gennusa et al. 2011; Vardimon 2011 and Wiginton et al. 2010. These authors do an excellent job of addressing these bigger questions in their research and their findings are worth closer examination.

Vardimon, (2011) found enormous potential for generating electricity in Israel by placing solar panels on all suitable rooftops across the country. Although residential dwellings were found to have, on average, a smaller rooftop size in comparison to other building types, these buildings were the most numerous and therefore held the greatest potential for generating electricity.

Additionally, larger buildings such as warehouses were found to have significant potential for generating electricity despite the relatively small number of these larger buildings found across the country. Overall, Vardimon's (2011) research concluded that even after taking into consideration the variability of solar energy captured across many different regions and many different building types across the country, 10-15% of Israel's electricity demand could be met by rooftop solar power installations. Perhaps most significantly, estimates made using only large building rooftops with lower efficiency photovoltaic panels suggest that up to 7% of Israel's electricity demand can be met from these buildings alone.

Izquierdo et al. (2008) and later Izquierdo et al. (2011) examined the technical potential of rooftop photovoltaic panels for generating electricity across the entire country of Spain. Izquierdo et al. (2008) developed a novel method for estimating suitable rooftop area for a region the size of an entire country. The most challenging aspect of this research was the ability to find good and reliable data for building types and sizes across all regions of the country. By using a scalable methodology, Izquierdo et al. (2008) were able to focus on smaller regions of Spain and then use various statistical and vector based datasets to apply results to the entire country. With a confidence level of 95%, the average suitable rooftop for solar panel placement was found to be $14.0 \pm 4.5 m^2$. As a continuation of this research Izquierdo et al. (2011) examined solar rooftop potential for not only generating electricity but supplying the surrounding municipality with hot water. They concluded that with roughly 17% of the available rooftop area, 70% of municipal hot water could be generated through the placement of thermal hot water systems on the rooftops of all suitable buildings across the country. Further, by fitting the remaining 83% rooftop area with photovoltaic panels 4% of the overall electricity demand for the entire country was able to be met.

La Gennusa et al. (2011) focused on just the adoption of solar power (both thermal and photovoltaic) within the urban area. This study calculated how much of an urban rooftop surface could be used for solar power technology. Focusing on the city of Palermo, Italy, buildings were divided up into photovoltaic collector and solar thermal categories based on building and territorial characteristics that were identified throughout the city. Not only were dense urban territories within the city found to be the most promising for solar power, these locations also proved to be the most economically feasible based on current renewable energy incentives offered in the region.

Wiginton et al (2010) quantified potential power generation for an area in eastern Ontario. This study used image recognition software to extract and extrapolate building footprints from imagery for both urban and non-urban locations in and around three complex urban areas (Peterborough, Ottawa and Kingston, Ontario). This research found that if appropriate building rooftops were fitted with commercial photovoltaic panels, their study area could potentially meet 5% of Ontario's peak electricity demand. Further, Wiginton et al (2010) suggest that up to 30% of Ontario's electricity demand could be met using rooftop solar technology. Wiginton et al. (2010) is one of only a handful of studies that have examined Ontario, Canada in the context of solar power. Not only are there few studies for this geographic area, but Wiginton et al. (2010) is the only study with the similar goal of quantifying rooftop solar power for an urban area within Ontario.

3.2 Specific Areas of Study

The many variables that comprise quantifying rooftop solar power generation make it a very complex issue to research. Specific topics such as shadow from tree and building cover, calculating suitable rooftop space, and analysis of optimal solar panel tilt angles have been well researched. Research by Jafarkazemi and Saadabadi, 2013; Gharakhani Siraki and Pillay, 2012; Nguyen and Pearce, 2012; Rowlands et al., 2011; Hofierka and Zlocha, 2012; Bergamasco and Asinari, 2011; and Tooke et al., 2011 often use tools such as 3D modeling, LiDAR, remote sensing, and Geographic Information Systems (GIS) either separately or collectively to answer such research questions on these topics. Some more notable research on these specific topics and their findings are explained further below.

Jafarkazemi and Saadabadi (2013), Gharakhani Siraki and Pillay (2012) and Rowlands et al. (2011) examined optimal tilt angle at which to position solar panels (ground or roof mounted). Studying optimum tilt angle for the city of Abu Dhabi, UAE and using empirical methods, Jafarkazemi and Saadabadi (2013) concluded that positioning solar panels at a 22° yearly angle would harness the greatest amount of solar radiation. Additionally, they found that by adjusting the panel angle twice per year to account for changes in the sun's position in the sky would produce even better results. Finally, their research found that overall there was a close correlation between the latitudinal angle of their study area (24.4° N) and the optimum yearly tilt angle for a solar project.

Similarly to Jafarkazemi and Saadabadi (2013), Gharakhani Siraki and Pillay (2012) examined optimum tilt angle but specifically within the context of an urban environment. They found that although optimum tilt angle is closely tied to latitude of the project study area, this correlation is less so for locations at higher latitudes. Studying optimum tilt angle within an urban environment proved to skew this correlation even further. Solar panels in an urban area contend with shadow from trees or buildings, rooftop obstacles, smog, reflectance from the ground and neighboring objects such as buildings and are subject to weather patterns dissimilar to rural locations outside the city. To accommodate for these unique factors, Gharakhani Siraki and Pillay (2012) found optimum tilt angle overall for urban area should be at a slightly flatter angle to accommodate for surrounding obstacles such as buildings. Initially a 37.7° optimal tilt angle was chosen using their equations, however, when factoring in surrounding buildings this angle was lowered to 33.1°.

Rowlands et al. (2011) examined optimum tilt angle for solar projects in two of the largest cities in Ontario (Ottawa and Toronto). This study aimed to determine at what tilt angle maximum revenue could be achieved. Using electricity market prices from 2003 to 2008 and meteorological data for each study area, the tilt angle and azimuth was calculated for Ottawa and Toronto. In both cases, the optimum tilt angle was found to be less than the latitude for each area. Depending on price regime used, optimum tilt angle for Ottawa was between 36° and 38° (latitude 45°) and Toronto 32° and 35° (latitude 44°). The optimal azimuth position also deviated slightly for each location depending on which price regime was used, but it generally remained within a few degrees of due south.

Remote sensing software, LiDAR and different GIS software have been used in studying various aspects of urban rooftop solar power. To quantify potential power of an urban area, studying shade loss from nearby trees or simply to identify suitable rooftop space, many authors (Bergamasco, and Asinari, 2011; Hofierka and Zlocha, 2012; Tooke et al., 2011; and Nguyen and Pearce, 2012) have used unique algorithms and software applications to study one or more aspects of rooftop solar power.

Bergamasco, and Asinari, (2011) developed an algorithm that accounts for shadow, rooftop barriers to construction, azimuth angle, and rooftop typology (through the analysis of brightness). Using GIS and remotely sensed imagery, this algorithm was applied to the city of Turin, Italy and compared against a previous study performed by the same authors. In this application they found their older results to be much more conservative with their latest study showing up to 41% higher rooftop photovoltaic potential with a confidence interval of 90% based on site inspections.

Also employing software and unique algorithms to address the technical aspects of rooftop solar power, Hofierka, and Zlocha, (2012) developed a 3-D solar radiation model for an urban area to present a clearer picture of rooftop solar power within an urban environment. Specifically examining possible temporal and spatial fluxes of solar radiation related to neighboring buildings and trees, this research used the *v.sun* module (developed by Hofierka and Zlocha) and the GIS software GRASS to study 3-D buildings using an existing solar radiation methodology from the *r.sun* model that was already present in the GRASS software itself. By applying these algorithms to a small subset of buildings, their study found that strong spatial and temporal variations in radiation flows are present across an urban area. The implications of this research could therefore lead to better locations for solar panels through an urban area and even more efficient heating design for buildings.

Solar arrays located in large open spaces such as a farm field do not have to contend with shadow from nearby objects such as trees. Many neighborhoods within an urban center can be limited by trees, buildings and other objects casting a shadow at some point during the day. Tooke et al. (2011) used LiDAR remote sensing technology to examine the seasonal effects that shadow from trees can have on the effectiveness of rooftop solar power. After studying a subset of buildings and vegetation in the City of North Vancouver, they determined that vegetation played a significant role in amount of radiation received at the rooftop level of a building. For residential buildings they found roughly a 38% reduction in incoming solar radiation to rooftop solar arrays and a strong correlation between tree structure and the amount of radiation intercepted. By avoiding areas influenced by vegetation cover, rooftop space and solar panel arrays can be used more efficiently to generate the maximum amount of electricity for the space available.

Aerial imagery and remote sensing has played a significant role in various studies on rooftop solar power. Nguyen and Pearce (2012) used LiDAR, GIS and uniquely developed algorithms to study 100 buildings in the downtown area of Kingston, Ontario, Canada. Using the *r.sun* solar irradiation model in the GIS software GRASS, their aim was to identify which buildings were most suitable for PV installation based on factors such as shadow and annual daily solar insolation. Through this process an algorithm was developed that attempted to take into account shadowing, global irradiation components at the municipal level while remaining flexible and easy to upgrade if necessary. The resulting raster display from running this process within the software clearly identified building surfaces ranging from best to worst suitability based on their defined criteria.

Academic literature on rooftop solar power or solar power in general has progressed over the past decade from studies by Alsema and Nieuwlaar, 2000; Payne et al., 2001; Rylatt et al., 2001; Gadsden et al., 2003; and Gong and Kulkarni, 2005, which asked general questions on solar power technology itself, to more sophisticated and focused research on single aspects of this technology. Questions over whether solar power and rooftop solar power is the right choice as an economically and technologically feasible alternative have given way to research centered on answering where and how this technology can be utilized most efficiently. The research on this subject has employed several novel techniques and technologies with the aim of answering one or two specific aspects about solar power that may contribute to the overall success of a project. However, there are still several areas worth further exploration. (1) Research on this topic covers both very large and very small study areas for various topics with study areas the size of a city left relatively overlooked. (2) Very few studies have combined the findings of this research to answer the questions of how much solar power can be generated in a particular location. More research is needed on quantifying overall generation potential rather than simply examining one isolated factor (e.g. only shadow from trees) that perhaps influences the overall amount of potential electricity generation. (3) Research tends to focus on warmer locations such as Italy or Spain for rooftop solar power leaving relatively few areas within Ontario or even Canada examined. (4) Finally, quantifying rooftop solar power can be highly influenced by a number of factors. Many research topics tend to isolate one factor and provide a specific result based on the conditions they have set forth under their methodology. Providing a range of possible values based on different conditions or factors seems to be more appropriate for this topic to better understand the possibilities that exist when attempting to provide an accurate estimation of potential. This research will attempt to fill the needs mentioned above and determine a range of potential power that can be generated from rooftop solar power at the municipal level for the City of Waterloo, Ontario.

In the next section, the methods used for data collection, processing and calculation of range values mentioned above are discussed. The needs for further research, as mentioned above, (points 1-4) are also further addressed.

Chapter 4

Methodology

4.0 Introduction

This chapter describes the research process undertaken for this study. It first outlines the overall sequence of steps or workflow involved in the analysis. It then discusses in detail the techniques of data collection, processing and error checking along with the calculation of optimal tilt angle and the formulation of appropriate estimates of rooftop area reduction. The final potential electricity generation range from rooftop solar power is also compared to the locations of existing rooftop solar projects for discussion.

4.1 Data

Many of the datasets used in this research were created from municipal, provincial and federal data sources but were obtained through the Wilfrid Laurier University Map Library data warehouse. Table 4.1 outlines the dataset, source, date collected or provided.

Table 4.1: List of Data Sources

Dataset Name	Source	Date Collected / Obtained	Data Type	Purpose
2010 Southwestern Ontario Orthophotography Project (SWOOP)	Land Information Ontario (LIO)	2010	Raster	Data extraction / verification
Building Footprint	City of Waterloo	2012	Vector	Calculations / verification / comparisons

Land Use	DMTI Spatial	2011	Vector	Calculations / verification / comparisons
Roads	DMTI Spatial	2011	Vector	Reference
Municipal Boundary	DMTI Spatial	2011	Vector	Reference
Parcel Fabric	Region of Waterloo	2009	Vector	Reference / verification
Rivers	City of Waterloo	2012	Vector	Reference
Water Bodies	City of Waterloo	2012	Vector	Reference
Forest	City of Waterloo	2012	Vector	Reference
Zoning	City of Waterloo	2012	Vector	Reference / verification
Photovoltaic Estimates	Natural Resources Canada	2006	Tabular	Calculations / comparisons
Existing Solar FIT/microFIT Data	Waterloo North Hydro	2013	Vector	Calculations / comparisons
Energy Use Trends and Statistics	Waterloo North Hydro	2012	Table	Calculations / verification / comparisons

The land use and building footprint data were both equally the most important pieces of information to perform this study. The accuracy of these data directly influenced the outcome of the study. Current building footprint polygons and land use data were needed to correctly calculate the available rooftop area. Misclassification of the resulting data would occur if the age of these two datasets differed by more than a few years. This would lead to some building footprint polygons being misclassified as an incorrect land use type and ultimately skew the analysis of the results late on. Both the land use and building footprint polygon layers had some data inaccuracy. As realized during the quality control portion of the methodology, some issues with the data needed to be addressed. These issues included incorrect land use categorization in some areas and missing or incorrectly drawn building footprint polygons. These issues and how they were corrected are discussed further in section 4.7 Error Checking.

The values obtained through the Natural Resources Solar Mapping tool, although somewhat older by comparison, served as an appropriate base line to compare all subsequent findings. Air photo imagery collected under the Southwestern Ontario Orthophotography Project (SWOOP) allowed for validation of other datasets and helped to clean up any inaccuracies that appeared in the Land Use and Building Footprint layers. Existing FIT and MicroFIT locations were perhaps the most useful as they were 100% accurate, and the most current information available. This was important for comparing the potential results to actual existing locations. These existing values could then be used to validate results by examining the spatial relationships between both existing and potential data.

4.2 Work Flow

Using previous research as a guide, a research process was developed to quantify potential power generation and achieve a range of values. Table 4.2 outlines the steps that were taken to process the data and analyze the results:

Table 4.2: Work flow

1. Data Processing
2. Spatial Join (Building Footprint and Land Use)
3. Removal of Smallest Structures
4. Addition of missing or inaccurate building polygons and attributes
5. Error Checking and QA/QC
6. Base Values – Natural Resources Canada Tool
7. Half Roof Calculation (Pitched Rooftops Only)
8. Reduction Formula for Pitched and Flat Rooftops
9. Suitable Rooftop Area Calculations – Best and Worst Case Scenarios
10. Relationship to electricity usage and utility demand
11. Examining Existing FIT/MicroFITs Data

4.3 Preprocessing and Examination of Datasets

In step 1 of Table 4.2, several datasets were compiled and examined from various private, municipal and regional sources before any data processing or analysis took place. Air photo imagery was taken of the City in 2010 at a resolution of 30cm. Each of the 98 air photo tiles were examined for completeness and to get a sense of how current the imagery was compared to known construction projects throughout the City. Several known construction areas throughout the City were examined in addition to a visual assessment of every air photo tile. Building footprint polygons created in 2012 were also obtained through the City of Waterloo and used to determine the various developments or changes to the land use (e.g. several condos have replaced smaller two storey homes in recent years, as shown by Figure 4.2). The land use layer, created in 2011 and obtained from DMTI Spatial enabled the analysis of building footprint data by several groups. Results could then be quantified based on land use type which allowed for better analysis on which land use had the greatest potential for the development of rooftop solar power. There were 7 different types of land use found throughout the City. These categories included:

- Commercial
- Government and Institutional
- Open Area
- Parks and Recreational
- Residential
- Resource and Industrial
- Water body

"Open Area" and "Water body" were removed from the dataset because no buildings or structures were located on these particular land use types. All three datasets (air photo, building footprint and land use) were used in conjunction to illustrate the accuracy and currency of the data as a whole which ultimately influenced the final building footprint layer used for quantifying rooftop solar power potential. As mentioned above, there were some data inaccuracies that accompanied the land use and building footprint polygon layers which required some quality control measures to increase their value. Air photo interpretation, field checks and local knowledge played a significant role in resolving some of these inaccuracies.

These layers, plus additional base data from DMTI Spatial, the Region of Waterloo and the City of Waterloo, were compiled in a base map before any processing took place. The purpose of this was to examine the quality of data and to identify any problem areas that would require further investigation. Layers such as zoning, roads, water, and forest were explored for their attribute information and spatial coverage. Although these layers were not useful to the main purposes of this research they provided some basic understanding and context of the City. Finally, since the aerial imagery, land use, and building footprint layers were all created at different times, it was especially important to examine any spatial differences or changes to attribute information between each of these layers that could potentially cause confusion or pose problems during analysis later on. These differences between datasets, although noticeable between layers, did not pose a significant impact on the overall results as will be discussed in the Results section in greater detail.

Figure 4.1: Aerial imagery showing newly developed apartment complex while polygons show houses once present at that location.

4.4 Spatial Join

Once the initial data were organized and examined for usefulness, step 2 was to combine the attribute information from the land use layer with the spatial information from the building footprint layer. To achieve this, a spatial join was performed between the two datasets. The purpose of performing this join was to combine the spatially significant building footprint polygon information with the land use polygon layer, to provide these buildings with a spatial context that could then be analyzed and quantified by each land use category later on. In Figure 4.2, the result of combining this data is shown. The land use layer possessed 1,934 records and was a province wide dataset while the building footprint layer held over 33,796 records and was made up of only buildings found within the City of Waterloo. Once this join was performed, several polygons in the building footprint layer did not have complete attribute information. To correct this problem, proper land use types of a few thousand polygons were identified and classified manually. Additionally, several building footprint polygons were far too small in size to be suitable for rooftop solar panels. These unsuitably small polygons were identified and removed as explained in greater detail in the next section.

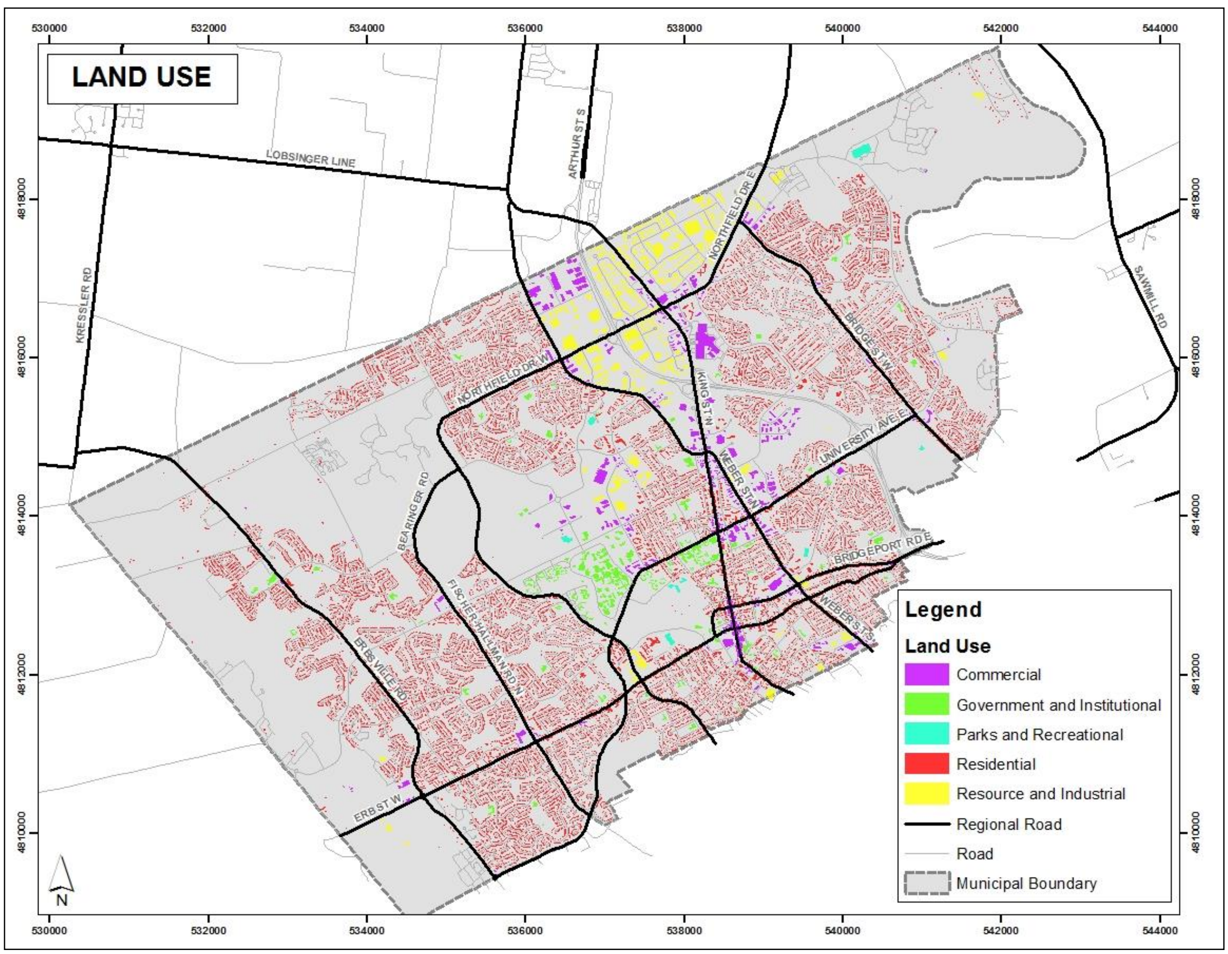


Figure 4.2: Result of spatial join showing added Land Use information within the Building Footprint shapefile.

4.5 Building Removal

The result of combining the building footprint and land use layers revealed that numerous small polygons sheds, garages and storage units were captured in the dataset. These structures were too small to hold more than one or two solar panels and thus removed from the dataset in step 3 of the work flow. To remove these buildings, a set size restriction was applied to filter out all polygons of a certain size or smaller. After examining several buildings the size of a shed or small garage, a value of 20 square meters was determined to be a suitable cut off for removing these smaller structures. An average sized solar panel is roughly 2 square meters and produces around 250 watts per panel (Canadian Solar, 2014). According to the existing rooftop solar data, the average sized installation in the City is roughly 6.6kW. If 10 of these 250Watt solar panels were installed in a 20 square meter space, the size of that installation would be roughly 5kW. With the average existing rooftop solar project being 10.18kW in size, and the size of a project being directly related to the amount of electricity and government incentive, larger projects are favoured under the current FIT/MicroFIT system. Another consideration would include the potential labour and material costs of installing a small number of panels on a separate roof system. Using this logic, any structure that was less than 20 square meters would not be suitable for rooftop solar panels. Figure 4.3 shows the product of this building removal for a typical residential neighbourhood. Polygons for small sheds have been removed leaving only larger buildings (blue colour) for the study. The smallest structures used for this research would be that of a large garage or shed. In addition to the size restrictions placed on the dataset, some larger and complex rooftop types were later removed due to their shape and size. Structures such as sports domes, tents and other semi-permanent structures such as school portables were also removed.

Figure 4.3: Typical residential area where small structures such as sheds or garages have been removed from dataset

4.6 Additional Attribute Information

In step 4, additional information was added to the attribute tables of the data. Using air photo imagery, building rooftop types (either sloped or pitched) were add as attributes to the data. This enabled building types to be classified not only by land use type but now also by rooftop type as well. Having these categories was essential because potential power and available rooftop space of flat rooftops differs from that of buildings with pitched rooftops. After examining the air photo imagery, there appeared to be a connection between rooftop types and the type of land use they belonged to. For instance, the majority of suburban residential homes almost always had pitched rooftops while commercial, industrial and institutional buildings, typically had flat rooftops. Beginning with the residential land use type (the largest category), air photo imagery was used to identify buildings with pitched rooftops. Major roadways were used as a guide to compartmentalize larger areas of the city. Quite often a residential neighbourhood or business district bound by major roadways consisted almost entirely of one rooftop type or another. Air photo imagery clearly showed certain buildings with either flat or pitched rooftops. In some cases, buildings that were difficult to classify as either pitched or flat, were done based on the characteristics of a similar looking building within the same location. That is, if 98 buildings in an area were clearly pitched rooftops and the two unknown buildings looked similar to the other 98, then those two would be considered pitched rooftops as well. For many residential neighborhoods this was easily done since subdivisions tended to be homogeneous in nature and could be quickly identified using the high resolution air photo images. In other cases where building types tended to be more mixed land use, closer examination was required. This was especially apparent in the uptown Waterloo area and the neighborhoods surrounding both universities. To properly classify these building rooftops as either pitched or flat, areas were broken up into smaller more manageable zones. Larger buildings, simply due to their size, almost always had a flat rooftop type. Some small exceptions to this were churches with their large steeples and complex building characteristics. In addition to residential neighborhoods having easily identifiable characteristics, industrial and commercial zones located in the north and central west part of the City were also visibly homogenous. Figure 4.4 illustrates the overall composition of flat and pitched rooftop buildings for the entire city.

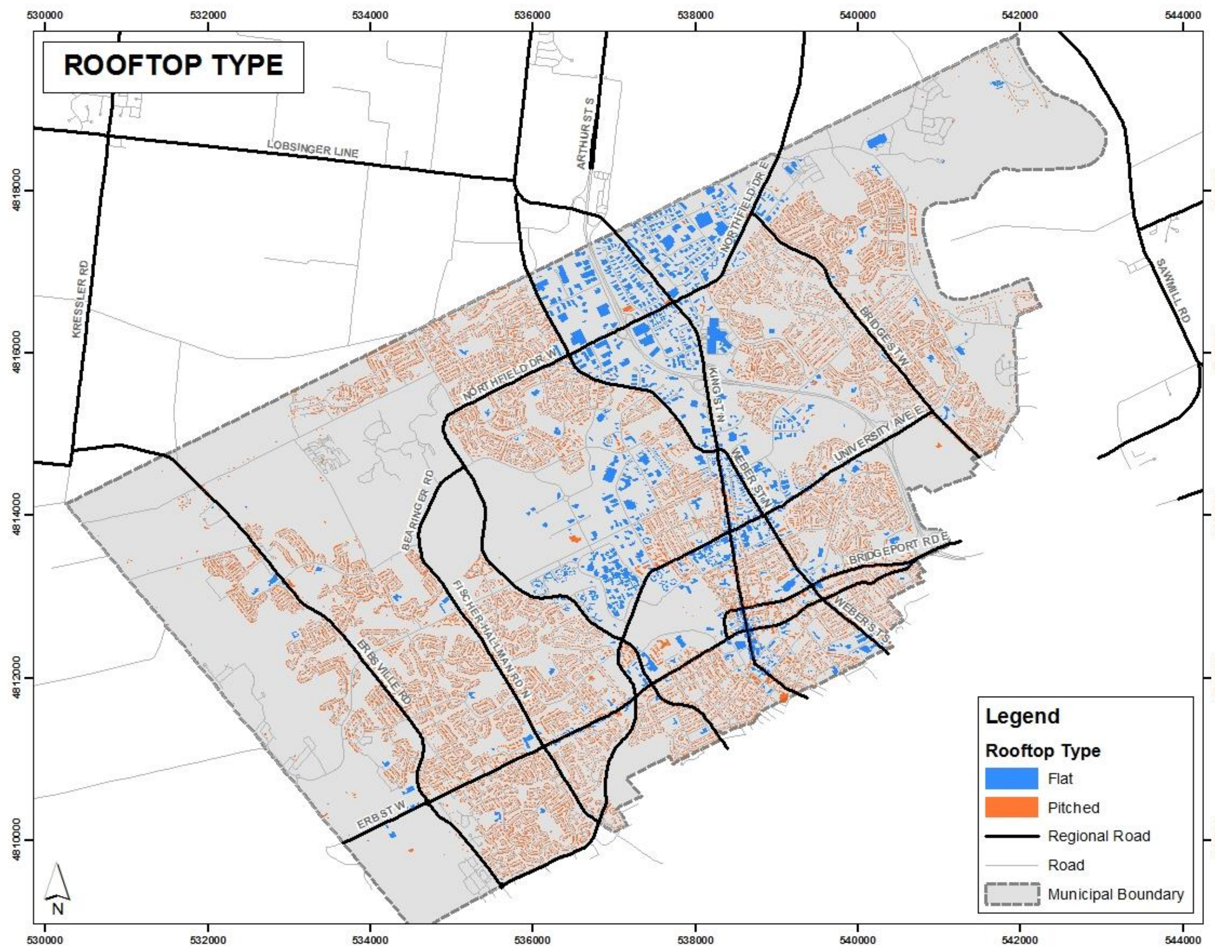


Figure 4.4: Pitched and Flat rooftops in the City of Waterloo

Although many locations across the City were easily identified due to their like properties, there was the potential for buildings to be misclassified in some locations. An example of this would be a large residential neighborhood composed predominantly of small pitched roof buildings. These neighbourhoods often included small pockets of flat rooftop commercial buildings (e.g. corner stores or strip plazas). Each air photo individually was examined to locate these outliers; however it was possible that some were missed in this check. The process of properly classifying each building as either having a flat or pitched rooftop was extremely time consuming but at the same time crucial to the accuracy of the dataset overall.

4.7 Error Checking

Several errors in the data became apparent when adding attribute information to the dataset. Some building footprint polygons and their land use categories were misclassified for several areas across the City. These areas seemed to be primarily located in newly developed sections of the City (e.g. old industrial land that have been rezoned for residential condominiums). The residential land use category was impacted by this the most. To ensure data accuracy, the entire dataset was carefully inspected in step 5 of this work flow process. Examination of the entire dataset was very time consuming but necessary to ensure proper data integrity. To make this task more manageable, the dataset was examined against each of the ninety-eight 1km by 1km air photo tiles. All buildings were inspected by colour coding each category as Flat or Pitched rooftop type and then by land use type while using each air photo tile as a reference. In many cases, the errors in the data were easily identifiable. Resource and Industrial classed buildings often appeared in a residential neighborhood, for example. In several areas, a huge subdivision was classified as residential land use while a small pocket of that subdivision was misclassified as a different land use type along the boundary of this larger area. This is likely the result of residential development expanding into areas once classified as farmland or brownfield development.

Other attribute data errors were noticed while examining each air photo tile and building footprint polygon layer. Some specialized buildings and other structures were identified using the air photo imagery. These structures were considered not suitable for rooftop solar panels because they were either (1) too small and not worth the financial investment to install only one or two panels; (2) the roof was too complex with many small pitched surface areas that would make it conducive to installing a contiguous array of panels; or (3) the roof was too steep for solar panels to be installed (e.g. churches). In other rare cases such as sports domes or recreational centers, the unique architecture of these buildings with their soft or curved rooftops meant that installing panels on these structures would not be possible due to lack of adequate structural support.

The proper classification of some rooftop types (Flat or Pitched) led to some noticeable errors in the data during this error checking process. In one or two cases, missing buildings that were not originally drawn in the building footprint layer from the City were added to the data. Additionally, any changes to land use classification of existing building footprint polygons was based on several sources of information. In many cases, the incorrect data were obvious through visual examination of the air photo. Incorrect buildings were easily identified based on examining adjacent buildings and their size, shape or classification. Field checks and Google Street View were used to determine some buildings with missing or incorrect attribute information. Knowing where new commercial and residential projects have been taking place throughout the City also helped identify some of these problem areas. Some specific locations within the downtown core (Figure 4.5) and along University Avenue and King Street where several residential and commercial developments have been constructed in recent years were noted. In rare cases where the land use type of a building was not apparent, it was assumed that the land use type of a building within that same area was the correct land use type. This was the case in the Davenport and Northfield area where there are large sections of Resource and Industrial classed buildings. By zooming into each air photo tile at a scale of roughly 1:2000 metres, a clear level of detail could be achieved while still making the data manageable for error checking and other analysis.

Figure 4.5: Uptown Waterloo where several buildings needed to be added manually along with their attribute information (rooftop type and land use)

4.8 Natural Resources Canada Data

In step 6, the Photovoltaic Potential and Solar Resource Map presented by Natural Resources Canada was used to provide a general sense of how much solar energy was possible for the City of Waterloo. This tool produces both maps and value tables showing the number of kilowatt hours (kWh) that can be produced per kW of solar power installed for any location across Canada. The dataset for this tool is based on Environment Canada monthly mean daily global insolation records taken from 144 meteorological stations across the country between 1974 and

1993. Values falling between meteorological recording stations have been determined using a spline interpolation method. Over 3500 municipalities can be searched through this tool and the values can be presented to show this information for each month of the year as well as the annual average for each category. Five possible solar panel angles are shown for each month. These angles are shown in Figure 4.6 below:

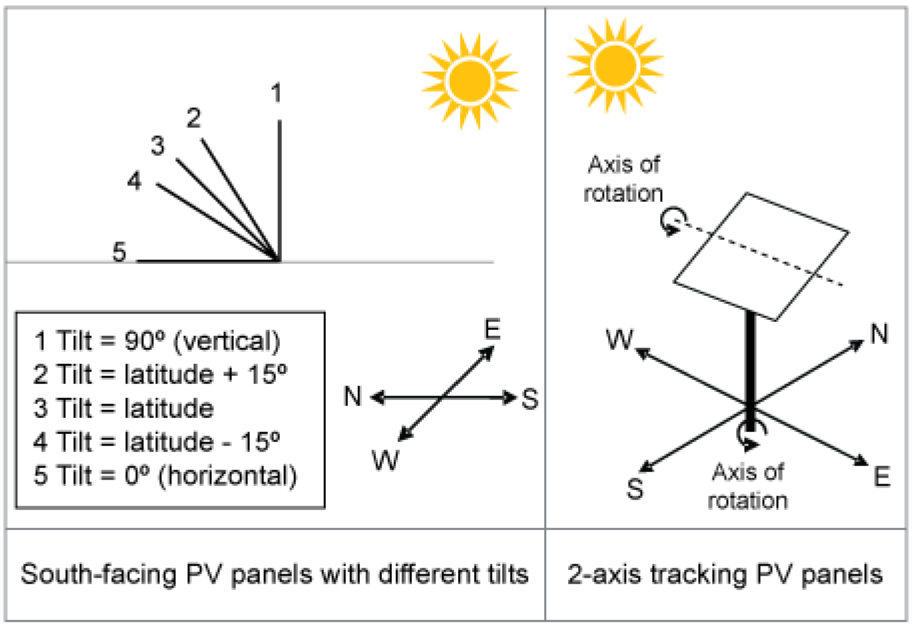


Figure 4.6: Methodology Diagram (Natural Resources Canada: http://pv.nrcan.gc.ca/index.php)

One additional value that is presented in this dataset is 2-axis tracking. This value is included on solar panels that are designed to track the sun as it moves across the sky from morning till night and also through the seasons as it rises higher and lower in the southern sky. This type of solar panel that has the ability to track the sun is more suited for ground mounted systems and is more commonly found in rural solar generation installations. These values were not considered in the overall results due to the unlikelihood of them being used in an urban area.

This interactive map was developed by the Canadian Forest Service (Great Lakes Forestry Centre) in collaboration with CanmetENERGY Photovoltaic systems group. The solar insolation dataset was provided by the Data Analysis and Archive Division, Meteorological Service of Canada, Environment Canada. The data shown by this tool are presented on 300 arc seconds (0.8 degrees) 10km grid for any given location across Canada. To account for overall system losses due to climatic factors, inverter operation and operational losses, a performance ratio of 0.75 was used on all values produced under each of the aforementioned 5 solar panel angles. This ratio indicates that values presented in this table have already been reduced by 0.25% to account for the factors mentioned above.

Using this tool, the values for the City of Waterloo are presented below in two tables. In Table 4.3 the amount of kWh per kW of solar power capacity installed (PV Potential) is given for every month. Four columns are also presented which show what values are possible based on the angle the solar panel is tilted. The PV potential did not include the Horizontal (tilt=0°) angle:

Waterloo, Ontario
Geographic location -> -80.51E,43.47N

Table 4.3: PV potential (kWh/kW)

	South-facing vertical (tilt=90°)	South-facing, tilt=latitude	South-facing, tilt=latitude+15°	South-facing, tilt=latitude-15°
January	61	61	64	54
February	74	79	82	73
March	83	105	103	102
April	71	114	105	118
May	62	120	105	130
June	57	121	104	134
July	60	125	108	137
August	66	118	106	125
September	70	102	97	102
October	74	90	90	85
November	51	54	57	50
December	50	49	52	44
Annual	780	1139	1073	1153

Looking at the annual values of each calculated angle, the best angle to place solar panels appears to be at an angle of slightly less than "Latitude" minus 15° or 30°. Since values of this chart appear higher for angled panels, it would suggest that the ability to capture the solar energy is greater for panels angled at or near latitude versus ones that were completely flat or angled vertically. When considering flat versus pitched rooftops, it can be argued that the angle at which a solar panel is position likely has greater meaning to flat rooftops only. In the case of pitched rooftop installations, the existing rooftop angle is more likely to be the primary driver behind the angle at which the panels are placed. Cost of installing additional material for the purpose of changing this angle to achieve a slightly better reception of solar radiation is also likely a primary factor. According to Jafarkazemi and Saadabadi (2013), Gharakhani and Pillay (2012) and Rowlands et al. (2011) a correlation exists between optimal tilt angle of solar panels and the latitude of where the project is located. Generally speaking, solar panels perform best at an angle similar to or slightly less than the latitude for which the project is located. Since the highest values in the Natural Resources Canada Solar Resource Tool were at an angle of 30°, annual value 1153kWh/kW was used in the calculations found in step 10. These values presented by Natural Resources Canada should also be considered best case scenario since they fail to account for several factors such as rooftop orientation, shadow from trees or rooftop barriers to construction.

These values will be applied to the total area for all buildings in the city. To account for several unknown variables, these values will be refined to present a more realistic view of what might be achievable under real world conditions. The resulting values from this refinement will then be applied to additional formula to provide context in relation to average consumption rates and electrical demand for the Waterloo area overall. The next section will attempt to refine pitched rooftops space only to present a more realistic view of a typical rooftop system.

4.9 Available Rooftop Space – Half Roof (Pitched Rooftops Only)

Solar panels on pitched rooftops are typically located on just the south or southwest side of the building. This is due to the sun's path which tracks along the southern horizon at an angle dependent on position of latitude and the time of season (lower in winter/higher summer).

Positioning solar panels to face southward would take advantage of the best possible sun exposure available.

Because solar panels are often placed on only one half of a pitched rooftop, the result obtained through the Natural Resources Canada Solar Map Resource Tool alone requires slight modification. Although the values obtained through the Solar Resource Tool have a general built in performance ratio of 0.75, further concessions are needed to calculate a more precise portion of the rooftop that will likely receive sunlight. In step 7 only pitched rooftop values were divided in half to account for the more realistic practice described above. All values obtained for flat rooftops were simply left unchanged. Flat rooftops were assumed not to require a reduction of surface at this point since they do not contend with a south, north, east, or west sloping rooftop that would limit optimal solar panel placement. Solar panels placed on a flat rooftop were then assumed to utilize the entire available roof. This calculation is intended to be a generalization of the typical pitched rooftop buildings that may be found within the City of Waterloo. This half rooftop calculation also assumes all pitched rooftop buildings within the City have suitable southern or western roof exposure that is unobstructed by trees, buildings and other objects. To account for these issues, further concessions will be made to these calculations in the next section to obtain an even more accurate representation of a typical building.

4.10 Suitable Rooftop Space - Reduction

For rooftop solar panels to collect and convert solar energy into electricity with optimal efficiency, (1) no shadow from buildings or trees would block the rooftop throughout the day, (2) obstacles and other barriers to construction would not limit available space for installing the panels and (3) all pitched rooftops would slope south where they could get the best sun exposure. This, of course, is not the case for many buildings in the City of Waterloo. To account for these factors, a reduction in the overall suitable rooftop area was applied in step 8 of the work flow. Extensive research has been performed on the topic of reduction as it relates to estimating suitable solar panel placement. An estimate for reduction can be applied towards the dataset calculated for this research, by looking at several studies. Several authors (Izquierdo, S., M. Rodrigues, et al., 2008; Lehmann, H. and Peter, S., 2003; Montavon, M., Scartezzini, J-L., Compagnon, R., 2004; Pillai, I. R. and R. Banerjee, 2007; Ghosh, S. and Vale, R., 2006) have gone into great detail analyzing each of the specific factors mentioned above. In a study by Wiginton, L. K., H. T. Nguyen, et al. (2010) the factors covered in each of these studies have been summarize and quantified using a unique formula. The calculation below uses estimated values derived from the building polygon dataset created for this research. The purpose of this initial calculation is to account for rooftop space, pitched roof orientation, percentage of flat rooftops and the size of the solar panels themselves. In this formula f_o equals the fraction of buildings with properly oriented roof area for rooftop solar. The proportion of flat rooftops r_{flat} equaled 0.05 or 5% of total buildings. Conversely the proportion of pitched rooftop buildings r_{peak} is equaled to the remaining 95% or 0.95. All flat rooftops are assumed to be unaffected by their rooftop orientation. More simply, because they have a flat rooftop, it does not matter which direction the building is facing to receive optimal sun exposure. Because of this, the reduction factor for flat rooftops $f_{flat,}$ is equal to 1. For pitched rooftops however, half of all peaked rooftops in the dataset were assumed to have suitable southern exposure. This assumption meant that the f_{peak} value was equal to 0.5 or 50%. These were then applied to the formula used in Wiginton, L. K., H. T. Nguyen, et al. (2010) seen below. The result of this calculation shows that roughly 0.5225 or 52% of rooftop area are properly oriented for what is considered to be optimal orientation for rooftop solar.

$$f_o = f_{flat} * r_{flat} + f_{peak} * r_{peak} = (1 * 0.05 + 0.5 * 0.95) = \mathbf{0.5225}$$

The result of this calculation was then multiplied with the result of a second formula (below) in step 9 of the work flow which takes into account other unknowns such as shadow from trees, area needed for the installation of the solar panels themselves and other barriers to construction. The reduction fractions used for this formula are taken directly from the literature. These studies focused directly on the issue of reduction as it relates to rooftop solar power. In the research by Wiginton, L. K., H. T. Nguyen, et al. (2010), a fraction of 0.30 formulated by Ghosh and Vale (2006) was used and represented as f_s. This 0.30 represents the fraction of available rooftop area suitable for solar panels when accounting for unknowns such as shadow and area needed for installation. Unlike Wiginton, L. K., H. T. Nguyen, et al. (2010), the purpose of this research was to show a range in estimation from best to worst case scenario. To show this, the more liberal estimation of 0.90 from Lehmann and Peter (2003) was taken from the available literature. Each value was multiplied to the result of f_o to find the total roof area available for PV installations. The formula for this estimation is presented below.

$A_{PV/cap} = (A_{roof/cap}) * f_o * f_s$

Where:

$A_{PV/cap}$ = the total available rooftop area

$A_{roof/cap}$ = the rooftop area available reduced by f_o and f_s

The **worst case scenario** using the above values and above formula would then be:

$A_{PV/cap} = (A_{roof/cap}) * 0.5225 * 0.30 = \mathbf{0.16}$

The **best case scenario** using the above values and formula would be:

$A_{PV/cap} = (A_{roof/cap}) * 0.5225 * 0.90 = \mathbf{0.47}$

This means that under a worst case scenario only 16% of available rooftop space would be suitable for solar panels and under a best case scenario 47% of available rooftop space would be suitable. As an example, if these values were applied to the total available rooftop area (both flat and pitched) of all buildings for the city (6,832,785.39m^2), the following values would be used:

Worst Case Scenario (0.16)

$A_{PV/cap}$ = 4,554,745.04 * 0.5225 * 0.16 = **380,776.68m²**

Best Case Scenario (0.47)

$A_{PV/cap}$ = 4,554,745.04 * 0.5225 * 0.47 = **1,118,531.51m²**

The results of this reduction will be applied to the value chosen from the Natural Resources Canada tables mentioned in section 4.8. In step 10 the the amount electricity generation potential from available rooftop space will be calculated. The amount of electricity generation potential from rooftop solar will be calculated in relation to average residential consumption rates. Additionally, a simple formula will also illustrate what amount of the electrical utilities average demand could be met through rooftop solar power.

4.11 Relationship to electricity usage and utility demand

To calculate how much electricity can be generated from the refined area value in step 10, some additional variables needed to be considered. As mentioned above in step 6, the value chosen from the Natural Resources Canada tool was 1153kWh per kW of installed solar panels. Knowing this, the number of kilowatt capacity can be calculated for the entire City using the refined rooftop area totals.

Located in Guelph, Canadian Solar is one of the leading manufacturers of solar panels in the world. Because Canadian Solar is a local company and is recognized globally, specifications on solar panel size and output were chosen from their website. Of the solar panels mentioned from their website, the average Watt sized seemed to be 250 while the average physical size of each panel was roughly $1.92m^2$ (Canadian Solar, 2014). Using these values, the following process applied to calculate the amount of kilowatts that can be installed in the city.

As an example, if refined total areas calculated in step 9 are used, the following can be assumed:

Table 4.4: kWh/yr potential for total available rooftop area

TOTAL	
2,278,040.36	Pitched after half roof reduction
2,276,704.68	Flat Total
4,554,745.04	Grand Total

	Reduction (m^2)	**Panels**	**Kilowatts (250W)**	**kWh/yr**	**MWh/yr**
WORST (16%)	380,776.69	198,321.19	49,580.30	57,166,083.05	57.17
BEST (47%)	1,118,531.51	582,568.50	145,642.12	167,925,368.97	167.93

Where:

Panels is the number of solar panels that can fit into the available rooftop space (assuming 1.92m^2 panel)
Kilowatts is the number of panels multiplied by 250W (to give total Watts) and divided by 1000 to give kilowatts
kWh/yr is the number of kilowatts multiplied by the annual kWh value 1153 provided by in the Natural Resources Canada tool.
MWh/yr is the result of kWh divided by 1,000,000 to give Megawatts.

To better understand what land use types had the greatest potential for generation, these calculations were also applied to the best and worst case total area for each of those categories. Similarly, the same process was used again on both flat and pitched residential building average rooftop size values. The purpose for this was to see how much electricity could be generated from residential buildings (the most populous land use type for the city) and compare that against the known electrical consumption of an average household for Ontario. Table 4.5 takes the average size for both flat and pitched residential rooftops and calculates the kWh/year values for both best and worst case scenarios.

Table 4.5: Average residential rooftop size and kWh/yr potential

Average Size	
82.81	Average pitched size after half roof reduction
753.78	Average flat rooftop size

PITCHED

	Reduction	**Panels**	**Kilowatts (250W)**	**kWh/yr**
WORST	6.92	3.61	0.90	1039.34
BEST	20.34	10.59	2.65	3053.06

FLAT

	Reduction	**Panels**	**Kilowatts (250W)**	**kWh/yr**
WORST	63.02	32.82	8.21	9460.61
BEST	185.11	96.41	24.10	27790.53

How these totals compare to average household demand will be discussed further in the Results and Discussion sections. Overall MWh/yr will also be discussed in these sections to illustrate how this potential measures up to the average demand of the local hydro utility. The value tables for each of these calculations can be found in the appendices. The characteristics of current rooftop solar generators and how they may compare to generation potential is discussed next in step 11.

4.12 Existing FIT/MicroFIT data

In the final step, the results of the best and worst case scenario calculations were compared to the existing locations and characteristics of FIT and MicroFIT projects located across the City of Waterloo. The spatial locations, sizes, building types and land use types they are located on were compared against the best and worst case scenario results calculated above. The purpose of this comparison was to identify which land use types, building types or general spatial locations within the City could benefit from further development of rooftop solar as well as to identify the accuracy of the estimations versus what actually exists on different buildings throughout the City.

As of July 2013, there were a total of 144 FIT and microFIT projects within the City of Waterloo. There were 6 FIT projects and 138 microFIT projects with an overall capacity of 2429kW (Figure 4.6). The average kW size for these projects is 16.98kW with the largest project at 250kW and the smallest at just 1kW. There were two projects from the Waterloo North Hydro supplied dataset that did not have a kW rating and were left out of any calculations. Since the Green Energy Act was introduced in 2009, the majority of projects have been constructed after this date. There was however 4 projects that were installed pre-2009. The fact that most of these projects were installed after the introduction of the FIT/MicroFIT program speaks to the success of the program to spur on this form of renewable energy development.

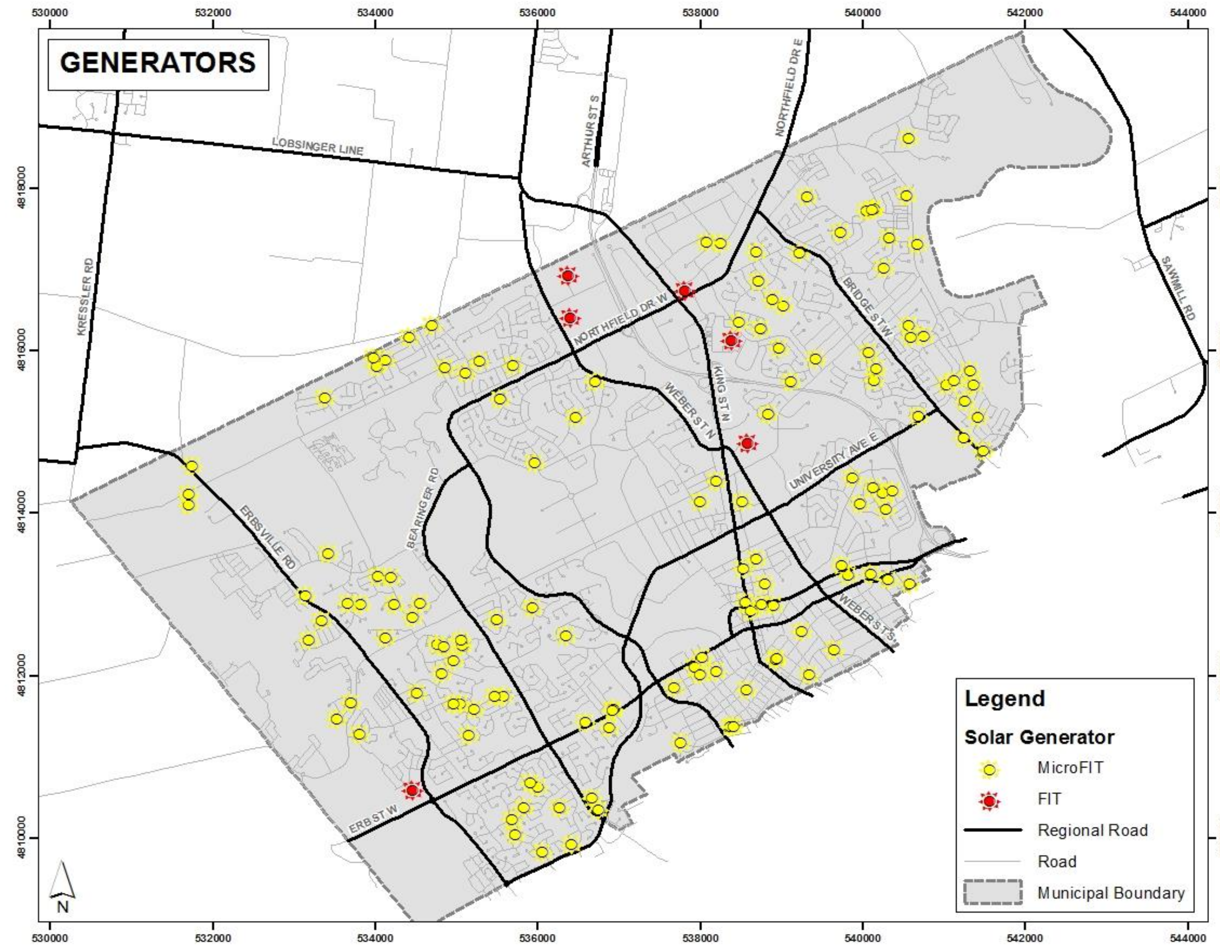


Figure 4.7: City of Waterloo FIT and MicroFIT rooftop solar generators.

Of the 144 projects, only 14 are built on flat rooftops. Of these 14 projects, 8 are 10kW microFIT's (the largest a microFIT can be) and the other 6 are very large FIT projects which have been installed on large factory and commercial buildings. Of the 144 solar projects, the majority (131) are located on Residential buildings while Resource/Industrial, Commercial and Government/Institutional buildings had 4 projects for each of these land use types.

The average rooftop size for just microFIT projects was 706.14 sq. meters. Looking at this data further, microFIT projects ranged in rooftop size from about 68.75 square meters to RIM

Parks' enormous facility of 26,452.65 square meters. The two FIT projects, which take up a much larger rooftop space, were actually smaller in size when compared to the RIM Park facility at 9,603.16 square meters and 18,006.24 square meters indicating that a sizable portion of available rooftop space for RIM Park was not suitable or not utilized for their rooftop solar project.

The spatial characteristics and patterns in the development of FIT/MicroFIT projects across the City is compared and discussed further in the Discussion section.

Chapter 5

Results and Discussion

5.0 Introduction

In this section, the results of the above calculations are presented and discussed. The reasoning behind the selection of certain values used in the calculations above is explained with support from findings in the literature. The values from the calculations are presented below in a manner which illustrates the potential electricity generation overall, the electricity generation for the average residential home and a rough cost estimate for installing this amount of solar power. These values are also broken down based on land use type and represented as a bar graph to illustrate the generation potential of each type.

5.1 Results

A reduction value of 0.5225 was determined to account for available rooftop space, size of the panels and pitched rooftop orientation. Additionally, a best (47%) and worst (16%) value was chosen from the literature to account for such things as shadow from trees or buildings, suitable rooftop space and rooftop orientation. The total area of both pitched and flat rooftops for the city is 4,554,745.03m^2. To calculate the energy potential of this total, the amount of solar panels and total kW size for this area was calculated based on average panel specifications chosen from the Canadian Solar website. To account for suitable rooftop orientation, this value was then multiplied by 0.5225. In the liberal estimation of reduction to account for various unknown factors such as shadow and suitable rooftop area, this value was further multiplied by 0.47 to yield a final result of 582,568.50m^2. Using this same process, the conservative estimation for the combined pitched/flat rooftop total was calculated to be 198,321.19m^2. Using a solar panel size of 1.92m^2 and Wattage size of 250W per panel, the kilowatt size for these totals were calculated to be 145,642.12kW for the best case scenario (47%) and 49,580.30kW for the worst case scenario (16%). Multiplying these values by the annual 1153kWh total chosen from the Natural Resources Canada solar mapping tool, the kWh for best and worst case scenarios become 167,925,368.97kWh/yr and 57,166,083.05kWh/yr respectively. Waterloo North Hydro is a local distribution company that includes a service area for the City of Waterloo, the Township of Wellesley and the Township of Woolwich with most of the electricity demand coming from the City of Waterloo. The 2012 average annual demand for Waterloo North Hydro (WNH) was calculated to be 236.9MWh (OEB, 2013). Taking these values one step further, the best and worst case scenario MWh/yr values were calculated to be 167.93MWh/yr and 57.17MWh/yr respectively. Under best case scenario, roughly 70% of Waterloo North Hydro's average demand could be met through rooftop solar power installations. The calculations of these values were also performed for overall totals of each land use type in the City. Figure 5.1 shows the MWh/yr values for best and worst case scenarios of each land use type. Residential land use is clearly the most promising type of rooftop to place solar panels on. The calculations and value tables that were used to create this graph can be found in Appendix A.

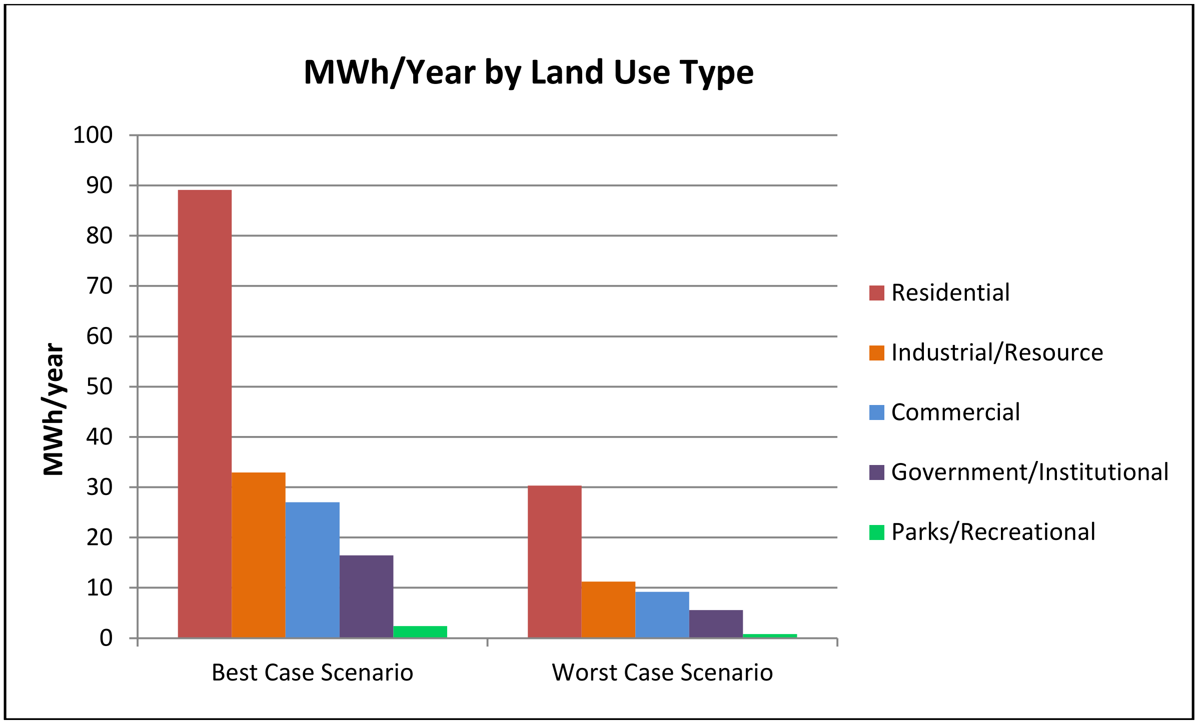
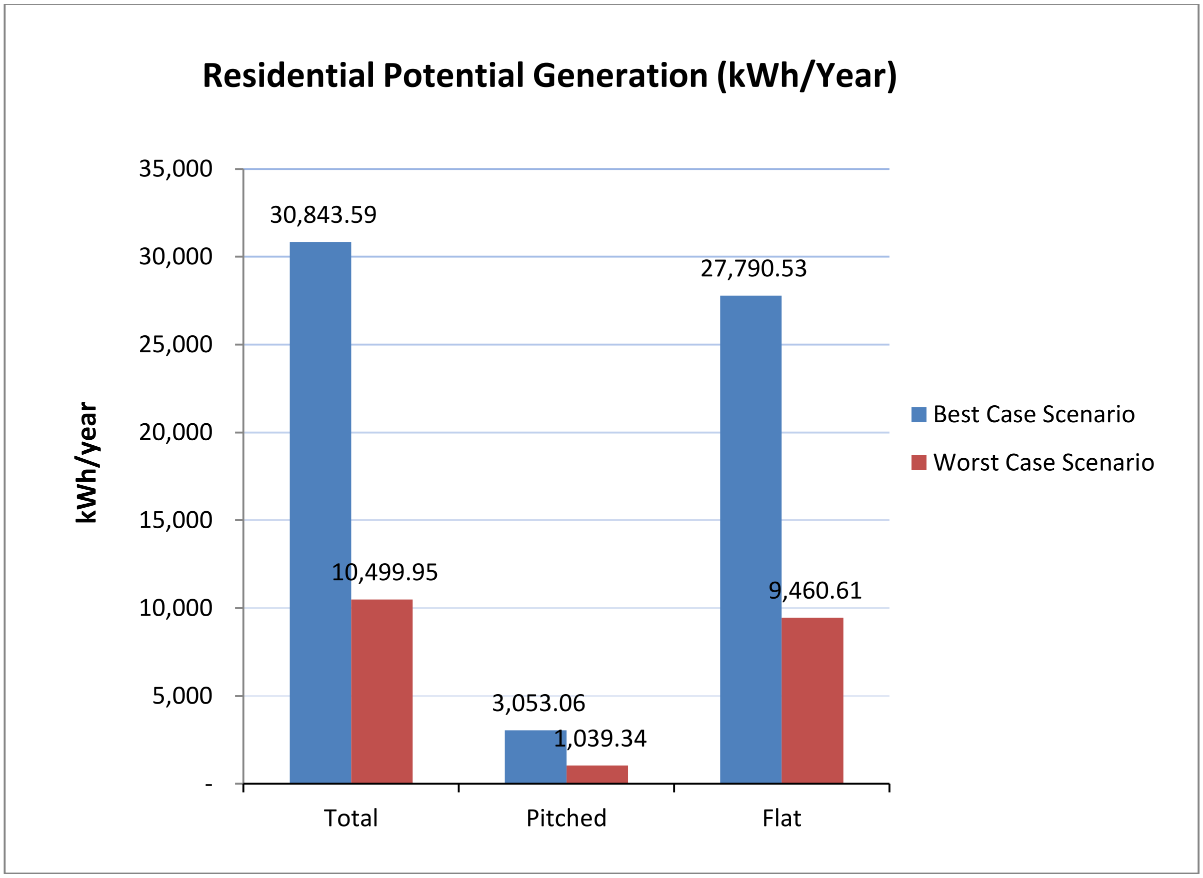


Figure 5.1: Land Use Type - Best/Worst Case Scenario Electricity Output (MWh/Year)

In addition to overall demand, the average rooftop areas for pitched and flat residential have been illustrated in a bar chart below. A typical family of four uses roughly 800kWh of electricity every month (9600kWh/year) (Ministry of Energy, 2012). The breakdown of this data offered a different perspective on the prospects of electricity generation from different buildings rather than simply examining each land use dataset as a whole. In Figure 5.2 below, the best and worst case scenario values for pitched, flat and overall total area residential rooftops are shown. This bar chart shows there is a clear potential for flat rooftop solar power to meet average household electricity demand however pitched rooftop potential on its own falls short.



5.2: Average Residential Rooftop Size (kWh/year)

The overall potential and average residential potential and the results in general will be discussed next in greater detail in the Discussion section.

5.2 Discussion

Collecting accurate data is essential to achieving a reasonable final estimation of potential power production. In this study, building footprint data needed a significant amount of cleanup and scrutiny to ensure a relatively accurate representation of real world conditions for the City. Despite best efforts, data error will always be present to some degree. Building footprint polygons that were incorrect or missing from the dataset were modified and/or created by interpreting air photo imagery. Although every effort was made to obtain or create the most correct information, this process, no matter how precise, is never exact.

Quantifying rooftop solar power is a very complex process involving many variables that are not all easily measured. Finding the optimal angle to harness the greatest potential of the sun is vitally important to the success of a solar project. Rooftop solar projects are no different. Many studies (Rowlands et al., 2011; Mehleri, 2010; Gharakhani Siraki and Pillay, 2012; Lubitz, 2011; Bakirci, 2012; Gunerhan and Hepbasli, 2007; Chang, 2009; Benghanem and Asinari, 2011; Jafarkazemi and Saadabadi, 2013) have set out to find the best angle to place a solar panel array, all with varying results depending on their methodology. The purpose of this research is to review several studies that have focused on optimal angle to place solar panels and, depending on their application, take the average of these results and apply it to potential applications within the City of Waterloo. After reviewing several research papers that focused primarily on the aspect of optimal tilt angle, 6 papers with studies closely related to the goals of my research were selected. Each of these studies either examined some aspect of buildings and rooftop solar power, had a similar study area size or study area location and all studied latitude in relationship to optimal tilt angle. Other research on this topic tended to explore novel methods for studying various aspects of solar power and also used such tools as specialized software or highly technical formulas for their research. Due to the complexity and uniqueness of this more technical research, these papers were considered but not chosen for this study. These studies determined that solar panels should be positioned at an angle that is closely related to the latitudinal degree of the location that project is located in. For instance the City of Waterloo is located at a latitude is 43.47° north, so solar panels should be positioned at an angle of around 43.47° to generally achieve the best results. Depending on the time of year, this angle can vary slightly. A lower angle was often used during summer months when the sun tends to be higher in the sky and a higher tilt angle was used during winter when the sun tracked lower in the sky (Chang, T. P., 2009; Gunerhan, H. and A. Hepbasli, 2007; Bakirci, K., 2012; Rowlands, I. H., B. P. Kemery, et al., 2011; Benghanem and Asinari, 2011; Jafarkazemi, F. and S. A. Saadabadi, 2013). In terms of solar panel orientation (azimuth), all studies concluded that south facing orientation was by far the most optimal position to harness the greatest amount of solar energy from the sun. From observing pitched rooftop buildings throughout the city first hand, a 45° angle does not seem to be chosen for these buildings. In the case of pitched rooftops, the easier and more cost effective method would be to simply lay the panels flat on the rooftop and assume the existing angle that the rooftop was constructed at. In the case of flat rooftop solar applications, the 45° angle or less would be much more applicable. For these installations, shadow cast by the angled solar panels may influence what angle is best to receive the most amount of sun light. Since the Natural Resources Canada Solar Resource Tool provides a 45° - 15° (30°) with the highest kWh results, this value was chosen as the most suitable angle to place solar panels on a rooftop. Comparing what research examples to what exists in the field is worthy of further exploration. Optimal tilt angle and the direction solar panels are positioned are very important to achieving the best results. Both factors can afford some degree of variability within reason. Panels placed vertically/horizontally and away from southern exposure will definitely result in less than optimal results.

Similarly, shadow from trees or buildings and rooftop obstacles such as vents or chimneys can have a major influence on accurately assessing rooftop solar power potential. Mature trees in older neighbourhoods, tall buildings in downtown locations and numerous obstacles on some rooftops can easily influence the output or feasibility of a project. A large flat roof industrial building could have zero influence from neighbouring trees or buildings but if there are a large number of obstacles on that roof, the feasibility of installing solar panels on that roof is greatly reduced. At the same time, since solar panels output can drop dramatically when shaded an object, some rooftops or even entire neighbourhoods can be impractical because of trees. As is the case with solar panel angle and direction, electrical output from rooftop solar panels is strongly tied to the amount of suitable rooftop space and avoidance of shade conditions. Receiving the maximum amount of light from the sun is also highly dependent on the conditions surrounding each rooftop.

Other factors such as weather or more specifically temperature, as it relates to electrical generation efficiencies, is a topic well understood by electrical utilities and electrical engineering community. The transmission of electricity works at a more efficient rate in cold temperatures rather than hot. This relationship seems in direct contrast to the purpose of generating electricity from sun light. Whether temperature significantly impacts the feasibility and efficiency of rooftop solar is a topic worthy of further discussion but a topic beyond the scope of this papers objective.

Arguably, the size of a rooftop or solar panel array is sensitive to a number of factors. Larger projects are just as likely as small projects to contend with issues of shadow from trees or buildings and rooftop obstacles such as chimneys or vents. Smaller projects with limited amount of rooftop space may be slightly more susceptible simply because there is less room for error in estimation. Scale in terms of calculating an accurate estimate on rooftop solar based on these factors is perhaps more sensitive to scale. Examining variables at a smaller more defined study area should produce more robust results for that area. The challenge here however is extrapolating these results and maintaining this accuracy when wanting to scale up to a larger study area. One possible method to achieve reliable results for a large study area is to first identify several smaller locations with unique spatial characteristics, study those thoroughly and extrapolate the results to a larger scale.

Referring back to the 8 factors mentioned in the initial Research Objectives section of this paper, several opinions can be reached based studies from examining the literature, personal observation and the results of this research. In the following table, the 8 factors are summarized based on their degree of sensitivity to the analysis, importance to achieving reliable results, susceptibility to scale and other spatial properties and the degree of knowledge on each factor.

Table 5.1: Factors influencing rooftop solar power results.

Factor	Sensitivity	Scale/Spatial Influenced	Overall Importance	State of knowledge
Rooftop Size	High	Yes	Medium	Fair
Rooftop Angle	Moderate	Yes	Low	Good
Solar Panel Angle	High	Yes	High	Excellent
Solar Panel Direction	High	Yes	High	Excellent
Seasonal Variability	Moderate	Yes	High	Fair
Effects From Shadow	High	Yes	High	Excellent
Rooftop Obstacles	High	Yes	Medium	Excellent
Size of the Array	Low	Yes	Medium	Excellent

Future research done in this area could take this comparison further by performing a detailed regression analysis to assess the relationships between each of the influential variables.

The best and worst case percentages obtained in this research were unexpected. The "conservative" suitable rooftop space of 16%, which attempts to factor in a number of unknown or difficult to measure factors, seemed to be far too conservative based on visual assessment of existing rooftop systems located around the City. Even the more "liberal" result of 47% suitable rooftop space is likely the most conservative any real case example is likely to be. Figure 5.3 shows a typical residential home outfitted with a rooftop solar generator. In this image only the south and western portion of the rooftop contains solar panels. These panels also appear to cover the roof right to the very edges.

Figure 5.3: A typical residential home with rooftop solar panels

By examining aerial photos field checking some existing rooftop solar installations, it appears as though these numbers should be higher. In many cases, solar panels on either flat or pitched rooftops seem to cover the majority of available rooftop space. Perhaps a better understanding of how weather, shadow, or solar panels themselves behave under real world conditions would lead to a more accurate result in this regard. Despite these estimations, the results of this study still yielded some interesting revelations about the general potential of some buildings and general land use types throughout the City of Waterloo.

Residential buildings were generally small in size but large in number. This land use type seems to have the greatest potential when considering rooftop solar panels for these buildings.

Land use such as residential and small commercial buildings use almost half of the total electricity of a typical urban area (IESO: Price Overview, 2013). With a typical household in Canada consuming roughly 800kWh per month, the potential for residential development of rooftop solar power should be a logical first target of implementation. Conversely, large industrial and commercial buildings were much smaller in number than residential buildings but were far larger in individual size. These large buildings could potentially accommodate fewer in total but very large solar projects. Evidence of this is already becoming apparent in the handful of large FIT projects located solely on industrial and commercial buildings. Government/Institutional and Parks and Recreational land use buildings showed mixed results. Park and Recreational buildings were very few in numbers but had some of the largest building sizes of any land use type in the City. Like the large commercial and industrial buildings, these large structures often are unobscured by trees or other structures due to their size and have an enormous potential for rooftop solar power. Some developers and land owners have already taken advantage of these conditions and have installed large solar projects on these flat rooftops.

Spatial patterns of FIT and MicroFIT projects were only somewhat evident. Smaller microFIT projects seemed to be primarily in residential neighbourhoods and of those, mostly in newer neighbourhoods. FIT projects were almost exclusively on commercial or industrial buildings although there were relatively few of these larger installations. Further consideration could be given to studying the impact one home or business owner's choice to install rooftop solar has on the decision of neighbours to also install rooftop solar. Existing FIT/MicroFIT clearly rooftop solar has been a popular choice for many residents and businesses alike and rightfully so. Based information provided by several rooftop solar installation companies, a typical microFIT solar project for a residential home can cost anywhere from between $18,000 and in excess of $30,000. Under current microFIT pricing of 39.6 cents/kWh, a payback on such a cost would take at least 6-7 years depending on how much electricity can be generated (the more electricity per square meter, the better the return on investment)(Solar Dynamics, 2014). Given the government guarantee of the 39.6 cent per every kWh generated for a period of 20 years, rooftop solar can be an attractive investment for those who can afford it. For instance, even if the worst case scenario (16%) was used for the average residential rooftop size (69.94m^2) it is still possible to generate over 10,499.95kWh/yr using a 9.1kW rooftop system. This generation easily meets the demand for the average four person household at 9,600kWh/yr. Additionally, the 10,499.95kWh could also generate roughly $4,157.98 annually under the current FIT system in Ontario.

Based on air photo observation, it appeared as though fewer rooftop solar projects were located in older, more mature areas of the City. One possibility for this could be the greater likelihood of mature trees or large buildings that could create a significant amount of shadow. Downtown locations and older neighbourhoods may be more likely to contend with large trees or buildings which would make rooftop solar an unsuitable option for many buildings. This is perhaps a topic also worth further exploration.

Chapter 6

Conclusion

The objective of this research was to estimate rooftop solar power potential for the City of Waterloo. A range in values was produced beginning with liberal "best case scenario" results which were refined to more conservative "worst cases scenario" estimations after factoring in a number of variables.

The first objective of this research was to estimate how much electricity could be generated in the City of Waterloo if all suitable buildings installed a rooftop solar power generator. This estimate was achieved by using base values from the Natural Resource Canada solar mapping tool which were then refined. These values were presented as kWh/year and MWh/year for flat and pitched rooftops. These overall values were further broken down into best and worst case scenario totals for each of the 5 land use types found throughout the city.

The identification of which land use types, roof types and locations in the city hold the most promise for rooftop solar power was the second objective for this research. This question was answered by breaking down the results into their various land use and building type categories. Values specific to land use type can be found in the appendices. These results were also compared to locations and characteristics of existing rooftop solar generators. This comparison helped to further answer the above objective. Simply put, residential buildings hold the most promise for rooftop solar given they are the most commonly found land use type across the City.

Several limiting factors to rooftop solar power were examined using studies from the literature. Suitable array size, influences of weather and solar panel efficiency were areas not examined using examples from the literature but rather examined in terms of their sensitivity, variability, and importance in the Discussion section. These variables were indented to be addressed in this research however each of these topics are large and complex enough on their own to warrant individual examination as they relate to rooftop solar power potential. These topics should be examined in future studies.

6.0 Opportunities for future work

There are a number of opportunities to study the topic of solar power and rooftop solar power further. Many authors have studied a single specific aspect of rooftop solar power on a small scale and then extrapolated those results to a much larger scale therefore creating the possibility of introducing errors in the results. Other examples have taken a more general approach to quantifying rooftop solar power in the attempt to understand the potential for a large area without focusing much detail on the many different aspects that influence an accurate assessment of that potential. Further research on this topic could attempt to marry these two approaches by studying the many aspects of quantifying rooftop solar power at the small scale and then increasing the study area size to better understand the potential of a larger area. There are many unique circumstances (e.g. shadow from trees/buildings and different building types/sizes) across large urban area that can lead to highly variable results. These variables and situations could perhaps be studied at the small scale throughout many different pockets of an urban area and then extrapolated or generalized for the rest of the study area. Conversely, larger areas such as a city could be broken up into more manageable sections, examined closely and then combined to calculate an overall result. Regions of a city could be divided up based on building type, land use type, political boundaries, or population density. Deciding how to subdivide such a large study area based on which factors would be a topic for debate.

Focusing on the different factors that influence how much electricity can be generated from rooftop solar power continues to receive much study. Factors such as tilt angle, azimuth direction and shadow seem to be adequately covered by many authors. Other aspects such as seasonal variability and influence from weather are worthy of greater scrutiny. Weather and climate as it relates to any study requires years of data to accurately assess the influence or impact it may have on a subject. Meteorological data spanning decades is often cited as a reliable source of information. In many cases meteorological data is often not collected at the site of a potential solar generating station. Good meteorological data using instrumentation specifically for rooftop solar feasibility should be collected on location over a significant period of time to best understand the real world conditions a solar project may face. Shadow from buildings or trees, darkness from snow, or clouds have the potential to greatly influence the efficiency at which a solar panel operates over the course of a year or years.

Perhaps the greatest opportunity for further research is to examine the real world efficiency of solar panels themselves. New types of solar panels using different materials in different configurations are created every year as this technology advances. In practice, solar panels typically installed on buildings only convert 15-17% of incoming solar radiation to electricity. In laboratory testing, panel efficiency has reached over 44%, however these panels are not widely used by the industry (NREL, 2013). Significant testing is needed to better understand the potential of these panels and what can be achieved when using them under real world conditions as greater efficiencies for commercial panels are achieved. Another opportunity is to study panel efficiency and how it degrades over time. Rooftop solar panels have been operating under real-world conditions for a number of years with more than enough data to draw from. Additionally, a solar panel is just one component in the overall system that can impact the actual electricity generation that is realized. Further study could look at not only solar panels as part of a rooftop system but all aspects in that system from inverters to choice of wiring material and gauge.

Discussion of financial costs to solar power has been examined by many authors and in great detail. Societal externalities surrounding rooftop solar power are arguably a major topic worth exploring further. Understanding the impacts and reactions of a community when a solar project is constructed should be questioned. What is the reaction or impact on a community when one resident or local business decides to install several solar panels on their home? Has one neighbour's decision to install rooftop solar panels influenced the decisions of other residents in the area to do the same? What are the economic impacts locally or provincially when numerous home owners and businesses are being paid large amounts to generate electricity this way? How have these rooftop installations impacted the local distribution company (LDC) and electrical grid? What influence has this technology had on the actions of local business and local policy planning? The Ontario government now even offers free solar panels complete with installation and warranty to homes that may qualify. With such a strong push by the government to install renewable energy projects and promising very attractive incentives, will this program be sustainable over the long term? If the current pro renewable energy government changes, what will happen to these contracts and the local industry?

Worldwide trends in new energy installations continue to point out the significant role solar power is playing in our energy mix. As solar power becomes more common in communities across Ontario and the rest of the world, new challenges will undoubtedly emerge. There is no shortage of potential research that can be done on the topic of solar power generation. The question is not whether we should develop and research solar power generation further; it is how solutions to current and emerging challenges can be met. Industry and research institutions will continue to meet these challenges and guide policy so solar power can be developed and used more efficiently by all.

APPENDIX A

Total *4,554,745.04*					
	Reduction	**Panels**	**Kilowatts (250W)**	**kWh/yr**	**MW/yr**
WORST (16%)	380,776.69	198,321.19	49,580.30	57,166,083.05	57.17
BEST (47%)	1,118,531.51	582,568.50	145,642.12	167,925,368.97	167.93

Residential *2,417,630.81*					
	Reduction	**Panels**	**Kilowatts (250W)**	**kWh/yr**	**MW/yr**
WORST (16%)	202,113.94	105,267.67	26,316.92	30,343,407.28	30.34
BEST (47%)	593,709.69	309,223.79	77,305.95	89,133,758.87	89.13

Industrial/Resource *893,074.24*					
	Reduction	**Panels**	**Kilowatts (250W)**	**kWh/yr**	**MW/yr**
WORST (16%)	74,661.01	38,885.94	9,721.49	11,208,872.47	11.21
BEST (47%)	219,316.71	114,227.45	28,556.86	32,926,062.87	32.93

Commercial *733,550.50*					
	Reduction	**Panels**	**Kilowatts (250W)**	**kWh/yr**	**MW/yr**
WORST (16%)	61,324.82	31,940.01	7,985.00	9,206,708.23	9.21
BEST (47%)	180,141.66	93,823.78	23,455.95	27,044,705.42	27.04

Government					
445,945.71					
	Reduction	**Panels**	**Kilowatts (250W)**	**kWh/yr**	**MW/yr**
WORST (16%)	37,281.06	19,417.22	4,854.30	5,597,013.54	5.60
BEST (47%)	109,513.12	57,038.08	14,259.52	16,441,227.28	16.44

Parks/Recreational					
64,543.77					
	Reduction	**Panels**	**Kilowatts (250W)**	**kWh/yr**	**MW/yr**
WORST (16%)	5,395.86	2,810.34	702.59	810,081.41	0.81
BEST (47%)	15,850.34	8,255.38	2,063.85	2,379,614.16	2.38

APPENDIX B

Average Residential Rooftop Size

TOTAL				
	Reduction	**Panels**	**Kilowatts (250W)**	**kWh/yr**
WORST	69.94	36.43	9.11	10,499.95
BEST	205.45	107.00	26.75	30,843.59
PITCHED				
	Reduction	**Panels**	**Kilowatts (250W)**	**kWh/yr**
WORST	6.92	3.61	0.90	1039.34
BEST	20.34	10.59	2.65	3053.06
FLAT				
	Reduction	**Panels**	**Kilowatts (250W)**	**kWh/yr**
WORST	63.02	32.82	8.21	9460.61
BEST	185.11	96.41	24.10	27790.53

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