Rooftop Solar Capacity Modeling using GIS
Within the City of Stillwater, MN

By

David C. Brandt

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Master of Science in Agricultural Education
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Charles Rader	Date
Tim Buttles	Date
Kelly Cain	Date
Director, Graduate Studies	Date

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ABSTRACT

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By David C. Brandt

Chairperson of the Supervisory Committee: Professor Charles Rader
Department of Geography

Solar power has long been looked to as a source of renewable power. Expensive and inefficient solar materials and methods have become more attractive as technology and costs have improved. Coupled with an aging and deteriorating energy grid and increasing fossil fuel prices, the future of solar power is a promising alternative. As more homeowners and businesses investigate the feasibility of small scale photovoltaic solar installations, more accurate methods for predicting solar capacity are necessary.

The purpose of this study was to analyze the total rooftop solar capacity within the city of Stillwater. This study utilized light radar (LiDAR) data and Geographic Information System (GIS) technology to analyze rooftop solar capacity for residential and commercial properties within the city of Stillwater, MN. The use of LiDAR data is preferred to previously available digital elevation data due to a higher precision and ability to identify trees and buildings. The research was conducted by creating a digital terrain dataset that takes into account the shadows from trees and buildings. The terrain model was also used to calculate roof slope and aspect to identify optimum rooftop location for installation of photovoltaic solar cells. With the total solar insolation calculated, structures were analyzed for viability of roof mounted solar power.

Although this study focused on residential properties, commercial properties showed higher insolation values. Older residential structures proved to be better candidates than originally thought. In part due to their east-west orientation, size, height and roof angle. Also, there has been some loss of large, mature trees that may have affected shading. These favorable results may impact future planning and zoning decisions in the historic areas of Stillwater. While a number of homes in the newest residential areas have high potential, they also have fewer mature trees which may greatly affect future solar potential. Also, the curvilinear nature of the roads in these neighborhoods negatively affects solar potential for many properties due to house orientation. Nearly half of all residential properties within the city of Stillwater were found to have the potential to offset at least half their energy usage through solar power.

ACKNOWLEDGMENTS

First and foremost, I would like to thank my supportive and understanding wife Karen. Without her ability to juggle the needs of our children and myself, I would not have been able to complete this work.

Secondly, I would like to thank to Dr. Rader for convincing me to take up this effort after a 20 year absence from a graduate degree program. His guidance and support was greatly appreciated. I would also like to thank Dr. Buttles for his patience in dealing with an over-committed individual and my complicated schedule.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER I

INTRODUCTION

This study is carried out within the context of sustainable community development. Sustainable development implies meeting the needs of the present without compromising the ability of future generations to meet their own needs (World Commission on Environment and Development, 1987). Within sustainable community development, there is an attempt to balance environmental, economic, and social needs (Figure 1- Sustainability Diagram). While this study concentrates on the feasibility of solar PV production as part of meeting environmental goals for reduction of greenhouse gasses, there are also social and economic aspects that arise when considering the viability of solar energy. In theory, all the various energy sources can contribute to the future energy mix worldwide. But each has its own economic, health, and environmental costs, benefits, and risks - factors that interact strongly with other governmental and global priorities. Choices must be made, but with the knowledge that choosing an energy strategy inevitably means choosing an environmental strategy (World Commission on Environment and Development, 1987).

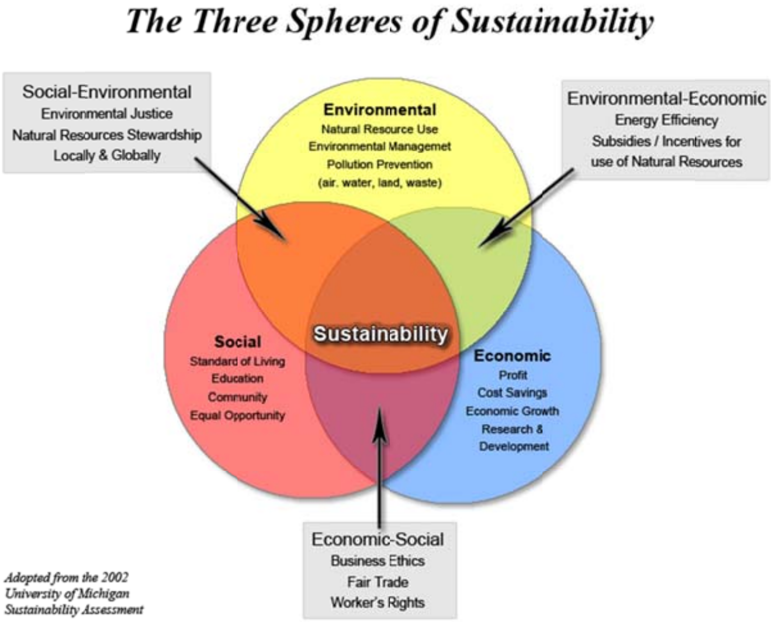


Figure 1- Sustainability Diagram

Once viewed as an expensive, inefficient method of generating electricity, solar photovoltaic (PV) panels have become more affordable and attractive when viewed against rising energy prices from non-renewable sources. Solar power has also become more attractive and available to homeowners. This may have occurred in part, due to Federal tax incentives that were renewed and expanded in October 2008, and further revised in February 2009. With low operating costs and zero emissions, solar PV may be positioned well to be part of the world-wide energy solution and locally for sustainable community development.

Worldwide solar photovoltaic (PV) market installations in 2010 reached a record high of 18.2 gigawatts (GW) which represented growth of 139% over the previous year

(Solarbuzz, 2011).This record was again broken in 2011 when the market grew to 27.4 GW (Solarbuzz, 2012). Also over the past decade, Geographic Information System (GIS) technology has made significant advancements in the ability to analyze potential sites for solar systems.

Virtually every region in the United States has sufficient solar energy to produce electricity from the sun, and Minnesota is no exception. In 2013, a new 2 megawatt system came online near Slayton, MN. This installation was double the size of the Ikea rooftop installation that was completed in Bloomington, MN in August 2012 (Schaffer, 2013). In 2008, the U.S. Department of Energy named Minneapolis-St. Paul as one of 25 Solar America Cities for their effort to deploy solar throughout Minnesota (MN Department of Commerce - Office of Energy Security, 2013).

This paper will examine the use of a LIDAR derived terrain model to calculate the optimum rooftop locations for placing solar PV cells within the City of Stillwater. The corresponding solar capacity results will then be used to examine differences between older and newer neighborhoods and potential for meeting electricity demand with rooftop solar installations.

Statement of Problem

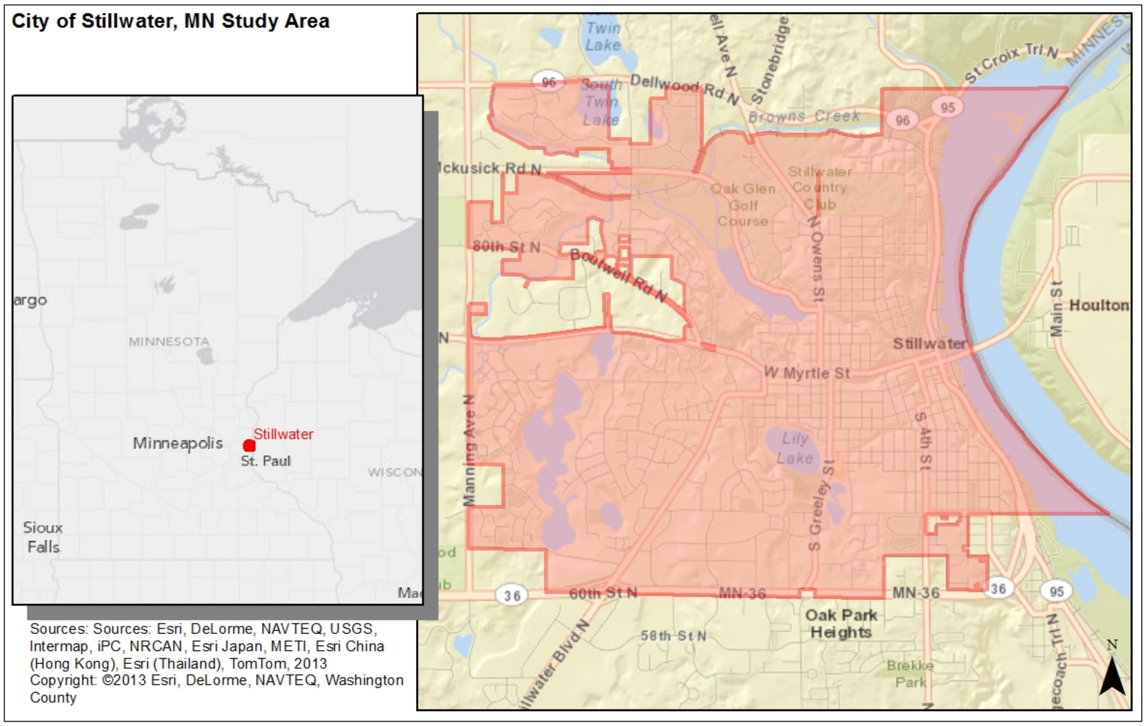
In 2013, Minnesota Governor Mark Dayton signed into law an energy bill that is projected to give the state a more than thirtyfold increase in solar generation by the end of the decade. Minnesota has also set a goal to reduce greenhouse gas emissions by 30% by 2025. As part of these goals, Minnesota will increase solar generation from 13 megawatts in 2013 to over 450 megawatts by 2020. Of this increase in solar generation, 10% of the solar power is to come from small systems up to 20 kilowatts. Although most of the new solar installations will be regulated by local governments, few cities or counties know how to identify, prioritize, or manage Distributed Energy Resources (DEMs).

The purpose of this study is to examine the solar capacity of rooftop mounted solar PV cells as determined by LiDAR data analysis for the City of Stillwater, MN. As of 2013, the city of Stillwater does not have any ordinances or long term strategy regarding installation of rooftop solar panels. This study will aid as a first step toward developing a plan by measuring the solar potential and how many properties may be candidates for rooftop solar panels. Using GIS technology and LiDAR data, a more accurate predicted solar capacity can be calculated for structures throughout the city. Previous methods have typically relied on less accurate data sets such as bare earth Digital Elevation Models or time intensive individual property assessments. This research will utilize LIDAR data collected in 2011 through the MN Department of Natural Resources which was originally intended for surface water runoff analysis.

The result of the analysis will provide an indication of the best locations for flush mount roof-top solar PV installations based on land use type and age of structure as well as total city capacity for solar generation. Solar generation output is dependent on a multitude of factors, including time of year, time of day, ambient temperature, wind, installed collector elevation angle, installed collector azimuth angle, type of solar material, and/or technology and solar insolation. All of these factors are predictable with a relatively high degree of accuracy, except solar insolation - as that is strongly impacted by clouds (Hansen, 2007). Total solar capacity is important in the context of sustainable communities as energy from the sun is one of several renewable resources such as wind, water, biomass, and geothermal energy.

Study Area

Stillwater, MN was chosen as the study area because of the author's familiarity of the city and the increased interest in solar energy by local government leadership (Figure 2- Stillwater, MN Study Area). An example of this interest is the installation of solar panels at nearby Lake Elmo Park Reserve in 2011. The LiDAR data provided by the MN DNR is representative of the standard data deliverables that counties across Minnesota will receive as part of a state-wide LiDAR collect. Therefore, any conclusions and methodology from this research should be applicable to any community in the state of Minnesota.



City of Stillwater, MN Study Area

Sources: Sources: Esri, DeLorme, NAVTEQ, USGS, Intermap, iPC, NRCAN, Esri Japan, METI, Esri China (Hong Kong), Esri (Thailand), TomTom, 2013
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Figure 2- Stillwater, MN Study Area

Another unique aspect is the historic place Stillwater holds in within the state of Minnesota. Stillwater, MN was platted in 1848 as a town of about 600 people, nearly all lumbermen. When Wisconsin entered the union that year, leaving lands now in Minnesota without government, delegates from the area met in Stillwater. The Stillwater Convention that August appointed Henry Sibley to petition Congress for the early organization of Minnesota Territory. This resulted in Minnesota becoming a Territory on March 3, 1849 (Johnston, 1982). The population reached a high of more than 13,000 in the 1880s, but declined to around 7,000 in 1940. In the 1970s, the first planned developments occurred west of downtown and businesses started appearing along Highway 36 (Washington County Historical Society, 2013). By 2010, the city had expanded to nearly 8 square miles and a population of 18,225 (2010 census). The mix of historic properties and newer properties creates a unique challenge when dealing with addition of new technology such as solar panels. New community rules and regulations may need to be developed to deal with the new energy possibilities.

Definitions

ASPRS – American Society for Photogrammetry and Remote Sensing.

DEM (Digital Elevation Model) – An elevation model of a bare earth surface made up of regularly spaced grids or square cells. Each cell has an elevation value in meters or feet.

DSM (Digital Surface Model) - An elevation model created for use in a GIS that depicts the elevations of the top surfaces of buildings, trees, towers, and other features elevated above the bare earth. Similar to DEM and DTM.

DTM (Digital Terrain Model) – An elevation model using bare earth mass points and breaklines.

Environmental Systems Research Institute (Esri) – A GIS Software company headquartered in Redlands, California.

Geographic Information Systems (GIS) - A computerized system for creating, maintaining, analyzing and displaying spatial data.

Global Positioning System (GPS) – A satellite based system that provides location information to receivers based on triangulation.

Insolation - A measure of solar radiation energy received on a given surface area in a given time. In this paper, it is reported in average watt-hours per square meter per day ($Wh/(m^2 \cdot day)$) or kilowatt-hours per square meter per day ($kWh/(m^2 \cdot day)$). In the case of photo voltaics it is commonly measured as kWh/(kW$_p$·y) (kilowatt hours per year per kilowatt peak rating).

kWh -The kilowatt-hour (symbolized kWh) is a unit of energy equivalent to one kilowatt (1 kW) of power expended for one hour (1 h) of time. The kilowatt-hour is not a standard unit in any formal system, but it is commonly used in electrical applications. An energy expenditure of 1 kWh represents 3,600,000 joules (3.600 x 106 J). The consumption of electrical energy by homes and small businesses is usually measured in kilowatt-hours. The kilowatt-hour is rarely used to express energy in any form other than electrical. A quantity of gasoline, oil, or coal contains potential energy that is liberated when the fuel is burned. The heat energy resulting from combustion of such fuels is usually expressed in joules according to the International System of Units (SI) or in British thermal units (Btus) according to the foot-pound-second (fps) or English system. If this energy is used to operate an electric generator, the output of the generator over a certain period of time can be expressed in kilowatt-hours (TechTarget killowatt-hour definition, 2013).

Light radar (lidar) or Light Detection And Ranging (LiDAR) – While there is some debate on whether it is an acronym, for this paper LiDAR is used. LiDAR is an optical remote sensing technology that can measure the distance to, or other properties of a target by illuminating the target with light. The data used in this paper was collected by aircraft using laser pulses. By measuring the return time to the source using the value of speed of light, the range can be collected.

LAS- The LAS file format is a public file format for the interchange of LiDAR data between vendors and customers.

Remote Sensing - Remote sensing refers to obtaining information about an object, area, or phenomenon through the analysis of data acquired by a device that is not in contact with the object, area, or phenomenon under investigation (Lillesand & Kiefer, 1996).

Solar Capacity- For the purposes of this paper, this is the maximum potential power output from a photo voltaic installation for a given parcel or area.

Sustainable Community Development – A community that plans for adequate social, environmental, and economic resources to meet current needs while ensuring that resources are equitably available for future generations.

CHAPTER II
REVIEW OF LITERATURE

Three separate, but related technologies have matured to a point that now makes studies such as this feasible. The technology used to analyze the LiDAR data is called a Geographic Information System (GIS). GIS technology began in the 1960s as a process for the input, storage, retrieval, analysis, and output of geographic information (Calkins & Tomlinson, 1977). LiDAR sensors work on the same principle as radar. In LiDAR, a laser (pulse or continuous wave) is fired from a transmitter and the reflected energy is captured. The distance between the two points can be measured by timing the delay of the pulse returned to the source off the object or bare earth. The deployment of Global Positioning Systems (GPS) in the 1980s allowed for the precise positioning of aircraft which made airborne surveying via LiDAR possible.

Much of the research utilizing GIS technology to analyze LiDAR data for the determination of rooftop solar capacity has occurred only since the late 1990s. A partial explanation for this may be the limited availability of data, combined with the difficulty of analyzing a large point cloud. Even in 2013, analysis of a LiDAR point cloud requires advanced software on a computer with a large amount of disk space, adequate memory, and processing power. Early research using GIS to analyze solar capacity relied on Digital Elevation models created from interpolated stereo pair orthogonal-imagery. As the primary purpose of this data was to determine bare-earth elevations, the data lacked building roof planes that could greatly improve solar capacity calculations. With only bare earth digital elevation information, the application of this data was limited to large area calculations more suitable to solar farm locating (Vandenbergh, 1999). Annual radiation, slope of land, proximity to electricity transmission and road network infrastructure, economic suitability of land, and current land use were of primary concern for these early analyses. The task of the Vandenbergh study was to identify the minimal site requirements needed for the power tower design in conjunction with the economic feasibility of future development. As Table 1 - Previous Studies (Clifton & Boruff, 2010), below shows, many studies utilized a resolution much too coarse to be used for building detection.

Table 1 - Previous Studies (Clifton & Boruff, 2010)

Application	**Geographic Approach to Modeling**	**Approach to Solar Radiation Modeling**	**Resolution**	**Geographic Data**	**Comments**
Spain (Casal, 1987)	Site specific once identified	Direct normal irradiation on a flat surface	Not available	Slope;agricultural productivity; road transportation	Does not use a GIS
Tunisia (Vandenbergh *et al*., 1999)	Site specific once identified	- Not stated	Not stated	Arid lands; slope; gas network; power network; cost of production and operation	Solar radiation surface not used in site selection application
Morocco (DLR-ITT, 2001)	Grid surface modeled using cloud cover, aerosols and water vapor	Direct normal irradiation on a flat surface	1km x 1km	Land cover; land use; slope; cost of production and transmission	Conceptual model only. Coarse resolution
Central and Eastern Europe, (Huld *et al*., 2003)	Grid surface modeled using turbidity values	Global irradiation on a horizontal surface and inclined surface	1km x 1km	None	Coarse resolution Does not incorporate other geographic data Innovative model developed in GIS GRASS
Southwest USA (Anders *et al*., 2005)	Grid surface modeled incorporating cloud cover	Direct normal irradiation on a flat surface	10km x 10km	Slope; environmentally sensitive lands; contiguous area	Very coarse resolution. Topography not considered in solar radiation modeling. Power network not considered in modeling procedure
Various countries: Geospatial Toolkit (SWERA, 2005)	Grid surface modeled incorporating cloud cover	Direct normal irradiation on a flat surface	10km x 10km to 40km x 40km	Slope; land use; political boundaries; road transportation; power network	Very coarse resolution. Topography not considered in solar radiation modeling. Availability of data depends upon contributions from partners.
Boston, USA (ArcNews Online, 2008)	ArcGIS solar radiation modeled	Total normal irradiation (direct and diffuse) incorporating topography	Not stated	Slope; topography	Solar potential calculated based on a flat roof scenario Does incorporate shading from adjacent buildings
Solar Powered Prospector tool (NREL, 2009)	Grid surface modeled, incorporating cloud cover	Direct normal irradiation on a horizontal surface	10km x 10km	Slope; environmentally sensitive lands; contiguous area	Same data used for the Southwest USA Study (Anders *et al*., 2005) now available in a web-based GIS

As the price of LIDAR data collection has decreased, more government agencies have been able to turn to the technology to assist with flood plain detection and disaster planning. In July 2009, the Minnesota Legislature appropriated $8.3 million ($2.8 million each in fiscal year 2010 and 2011; $1.35 million each in fiscal year 2012 and 2013) from the Clean Water Fund of the Clean Water, Land, and Legacy Amendment (Loesch, 2011).

Recognizing that current elevation data was inadequate for hydrologic modeling, the goal of this project was to create a seamless elevation model for Minnesota by filling in the areas where data either does not exist or is deemed to be old enough to be replaced. To date, the most cost-effective way of determining roof-top solar insolation is to use LiDAR data for calculating aspect and slope of rooftops (Brito, Gomes, Santos, & Tenedório, 2012). As this study did not account for shading from tree canopies, it is missing a key component for accurate calculations for an older Midwestern US town such as Stillwater, MN which has numerous mature trees.

As LiDAR data contains multiple returns of information it can be separated into vegetation, structures, and water. The potential advantages of using such datasets include: greater automation, fewer field campaigns, accurate and objective measures of environmental features, and extensive coverage; all of which lead to substantial savings in time and monetary costs (Tooke, Coops, Voogt, & Meitner, 2011). Tooke’s study represents trees as solid objects with no transmittance. This simplistic approach enables a high degree of automation but neglects potential physiological interactions between the internal tree structure and intercepted radiation. While tree canopy can be determined using LIDAR, it is still difficult to determine tree species using the data.

Studies using LIDAR data to identify individual trees in an urban setting have realized some success in determining coniferous vs. deciduous tree types. This would allow for better calculation of tree shading effects, especially in winter. In a 2012 study researching the use of LIDAR data for biomass calculations in an urban area, Shrestha and Wynne were able to more accurately determine tree types based on crown data than using traditional multi-spectral imagery. This was a result of using the LIDAR point cloud instead of a derived interpolated raster surface as had been done in earlier studies. Urban tree inventories are very time and labor intensive, so any improvement using LIDAR data can be very cost effective. Using the methodology from this study in solar capacity modeling should yield more accurate shading effects. Recent work presented at the 2012 ESRI User Conference introduced a perhaps more accurate raster model. Kramer utilized the point cloud of the tree canopy and interpolated a raster surface which resulted in a volume for the tree canopy (Kramer, 2012). As this effectively creates a pattern that could potentially be compared to known tree types, it may have interesting applications.

Esri has developed solar radiation analysis tools to calculate insolation across a landscape or for specific locations based on methods from the hemispherical viewshed algorithm developed by Rich et al. (Rich, Hetrick, Saving, & Dubayah, 1994) and further developed by Fu and Rich (Fu & Rich, Topoclimatic Habitat Models, 2000) & (Fu & Rich, 2002).

In 2010, Denver, Colorado launched an effort to encourage solar adoption using analysis tools from Esri and LiDAR data from Woolpert Inc. This effort was backed by funds from a New Energy and Economic Development (NEED) grant from the Governor's Energy office and facilitated by the Denver Regional Council of Governments (DRCOG) (McClurkin, 2010). The Denver effort followed a similar methodology as proposed in this study.

CHAPTER III
METHODS

Significant preparation of the data was required for this analysis. The software used was Esri’s ArcGIS Advanced Desktop (ArcMap) version 10.1 Service Pack 1 with the Spatial Analyst extension. This version was preferred over version 10.0 due to the addition of LiDAR specific tools and data support. The hardware used for processing the data was a Dell Precision Workstation with dual, quad-core 3.3GHz Xeon processors, 16GB of RAM running Windows 7 operating system.

Preparation of the LiDAR data

Raw LIDAR LAS format data from fall, 2011 and collected at 1.5 points per square meter resolution was obtained from the MN DNR. The LiDAR vendor classified the points into the following ASPRS categories:

1 Unclassified
2 Ground (Bare Earth)
3 Low Vegetation (less than 1.1 meters)
4 Medium Vegetation (1.11 - 2.4 meters)
5 High Vegetation (2.41 - 200m)
6 Buildings
7 Noise

8 Model Keypoint

9 Water

10 Water Edge (withheld / ignored ground) (Bare-earth points within 1-meter of the water polygons are re-classified to Class 10)

11 Scan Edge (unreliable points near the extreme edge of swath)

14 Bridge Decks

The LAS to Multipoint tool within ArcMap was used to convert the raw LAS file into an Esri geodatabase multipoint format that is designed to work within the ArcMap tools. The return classification was retained when converting from LAS to multipoint to allow for inclusion of trees and buildings in the analysis. The study area consisted of tiles 3542-30-37, 3542-30-38, 3542-30-39, 3542-31-37, 3542-31-38, and 3542-31-39 from the MN DNR LiDAR data collection for Washington County in 2011.

The multipoint data was then converted to single point data to allow more flexibility of data processing including identification of first return points. This process yields a very large dataset and is not recommended for large geographic areas. The single point data retains the coded values from the LiDAR classification performed by the vendor that did the data collection.

Preparation of the Digital Surface Model

LiDAR first return data was used in the generation of the digital surface model (DSM) to ensure shadows from tree tops and other tall structures were included in the analysis. (Figure 3 - Digital Surface Model with draped aerial photo) demonstrates an aerial orthophoto draped over the DSM. Later steps also made use of first returns that were coded as a structure to determine building footprints.

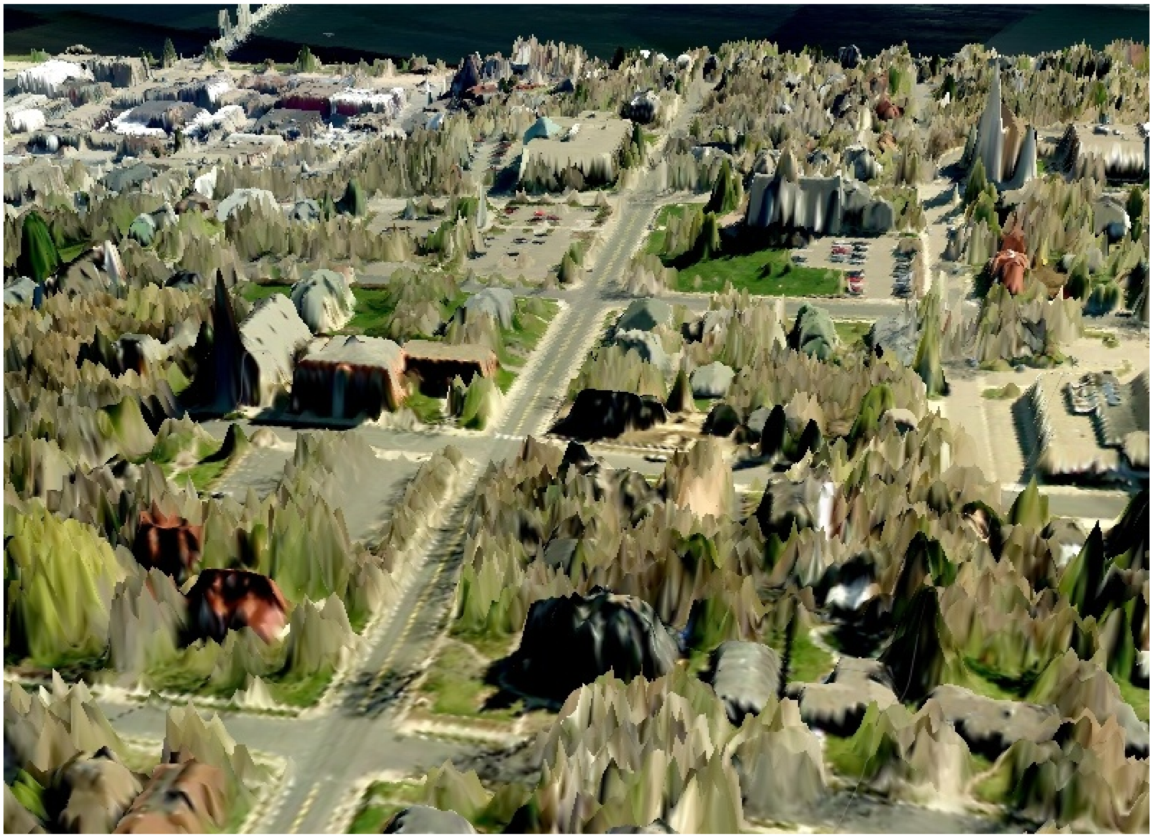


Figure 3 - Digital Surface Model with draped aerial photo

Solar Insolation Analysis

Outside Earth's atmosphere, the sun's energy contains about 1,300 watts per square meter. About one-third of this light is reflected back into space, and some is absorbed by the atmosphere. By the time it reaches Earth's surface, the energy in sunlight has fallen to about 1,000 watts per square meter at noon on a cloudless day (The George Washington University, 2013).

The DSM from the first returns was utilized to calculate direct solar insolation. The Area Solar Radiation tool within the ArcMap Spatial Analyst extension was used to calculate the insolation across the city. Within the insolation analysis, the calculations are repeated for each location in the DSM, producing insolation maps for the entire city. A helpful way to visualize this process is to think about lying on your back and looking up at the sky. Some of what you can see is blocked by structures, trees, or terrain. The software can also calculate the sun angle throughout the year and account for shadows. The result from this analysis is reported in watt hours per square meter (WH/m^2). The Minnesota LiDAR data was collected at a sufficient resolution to yield a 1 meter resolution solar insolation grid.

Another important variable in the calculation is the sky size. Sky size is the resolution of the viewshed, sky map, and sun map rasters which are used in the radiation calculations. These are upward-looking, hemispherical raster representations of the sky and do not have a geographic coordinate system. While a larger sky size would potentially yield a more accurate result, a size of 512 cells was used out of a maximum 2800 cells for calculation of annual solar insolation as a trade-off on processing time. Even so, this analysis took more than 40 hours to calculate for the roughly 8 square mile study area with 67 million LiDAR return points.

Preparation of structure data set

One benefit of using Stillwater, MN as a study area is that there were existing building footprint polygons available for most of the city. Where building footprints were not available, buildings were interpolated from the LiDAR return data. This involved isolating points from the LAS file with a signature coded as structure. These points were then aggregated into polygons and simplified. Visual examination of the interpolated structures proved them to be not as accurate as the human interpreted building footprints. To partially overcome this issue, a buffer of 1 meter was applied to the structures layer. Also discovered were a significant number of duplicate building footprints in the city data. Any duplicate polygons found were dissolved into a single polygon.

Rooftop Analysis

Building polygons were used to extract the total annual solar insolation in watt hours per square meter previously calculated from the first return digital terrain model thereby isolating solar insolation for the rooftops.

In Figure 4 - St Mary's Church Oblique View, most structures were built before 1900. The street layout in this neighborhood was aligned with the river in a northeast to southwest orientation. Complex roof angles and large mature trees are common in older neighborhoods such as this. Figure 5 -St Mary's Church Insolation Map demonstrates the total insolation for the roof by using red for the highest values and blue for the lowest. The large, flat, angled roofs with no tree shading have the highest solar insolation values. Buildings with dormer windows and multiple peaks show as a mix of values.

Figure 5 - St Mary's Church Oblique View

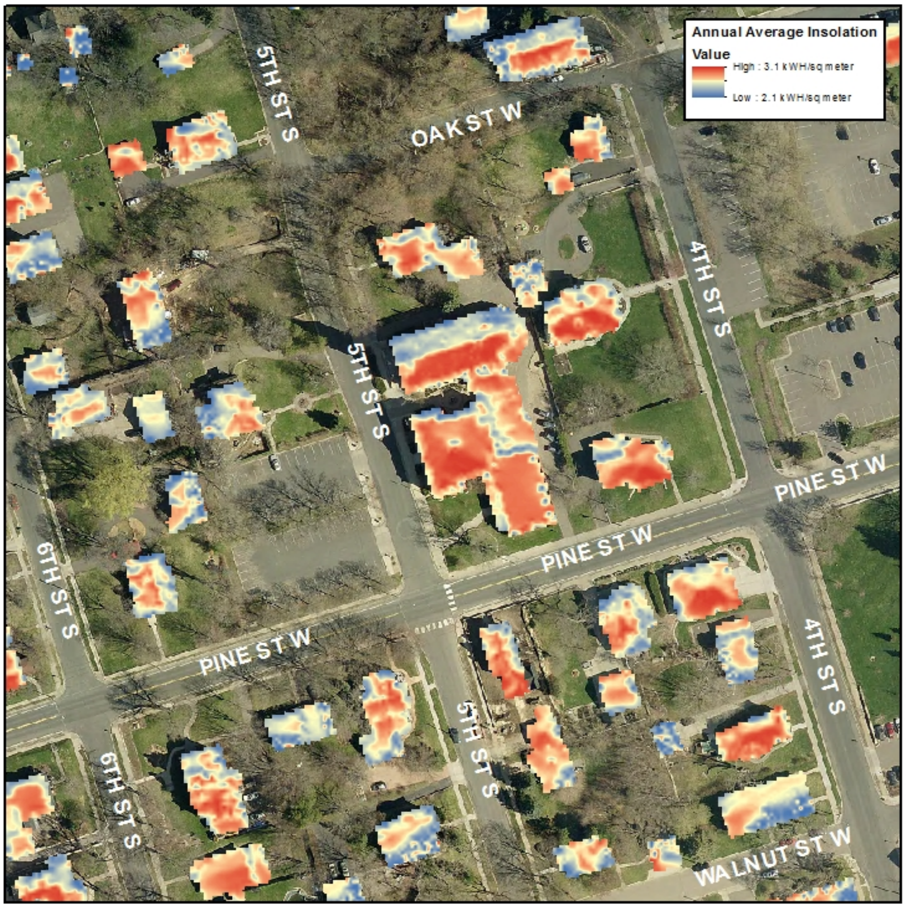


Figure 4 -St Mary's Church Insolation Map

In Figure 6 - Nelson School Neighborhood Oblique View, the streets are aligned in an east-west, north-south direction. Most housing in this neighborhood was built before 1880. As can be seen in Figure 7 - Nelson School Insolation Map, the effect of large tree shading is evident on several houses.

Figure 6 - Nelson School Neighborhood Oblique View

Figure 7 - Nelson School Insolation Map

Verification of Results

To verify the results obtained from this study in Stillwater, the same analysis was run on a structure in Minneapolis which was chosen as detailed data from TruNorth Solar was available for comparison. The 8,820 Watt fixed angle system in Minneapolis was installed at a tilt angle of 30.50 degrees by TruNorth Solar. The subject latitude of 44.905 compares to Stillwater latitudes between 45.036 and 45.079. Detailed panel input and output information for each of the 36 panels was provided for use in this study which allowed for verification of the model calculations. The LiDAR data for Minneapolis had 8 times the resolution of Stillwater which did lead to a more detailed DSM model. An initial model using a 0.2 meter resolution raster of solar insolation was resampled to a 1 meter grid size for all calculations to match the Stillwater model parameters. To more closely match the total daylight available to the Minneapolis property on March 21, 2013, the total solar insolation calculations were limited to between 7am-5pm.

The calculated values from the GIS LiDAR model were then compared to the

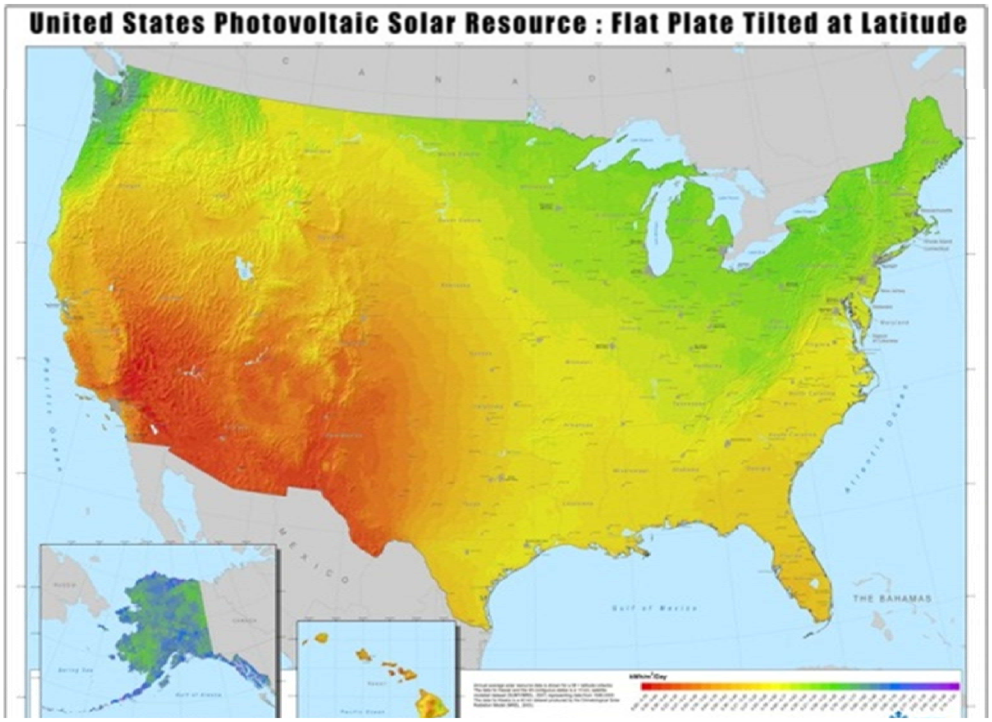


Figure 6 - Average Daily Solar Radiation per Month

actual output for March 21, 2013 which was a cloud-free day. GIS calculated values for the area with installed panels averaged 3.6 kWh/square meter. Compared to an industry estimate of 1000 watts/sq meter at noon on a cloudless day, the model calculated 620 watts/sq meter at noon assuming cloudless day for this location. While seemingly low, this number does fall within the George Washington University Solar Institute and NREL estimates for this latitude (The George Washington University, 2013). (Figure 8 - Average Daily Solar Radiation per Month)

Total watt-hours from each of the installed panels on the Minneapolis house specified for March 21, 2013 were converted to kWh/panel and kWh/square meter/panel (Figure 7 - Minneapolis Property Analysis). An assumed 1000 watts/square meter at 100% efficiency was used to create hypothetical 1000 watt panels (Appendix A). These calculations yielded an average of 3.95 kWh/m^2 (Morud, 2013). The GIS model calculated average values of 3.6 kWh/m^2 over the area where the panels are installed. This is 91% of the actual values of energy output from the solar panels for that date.

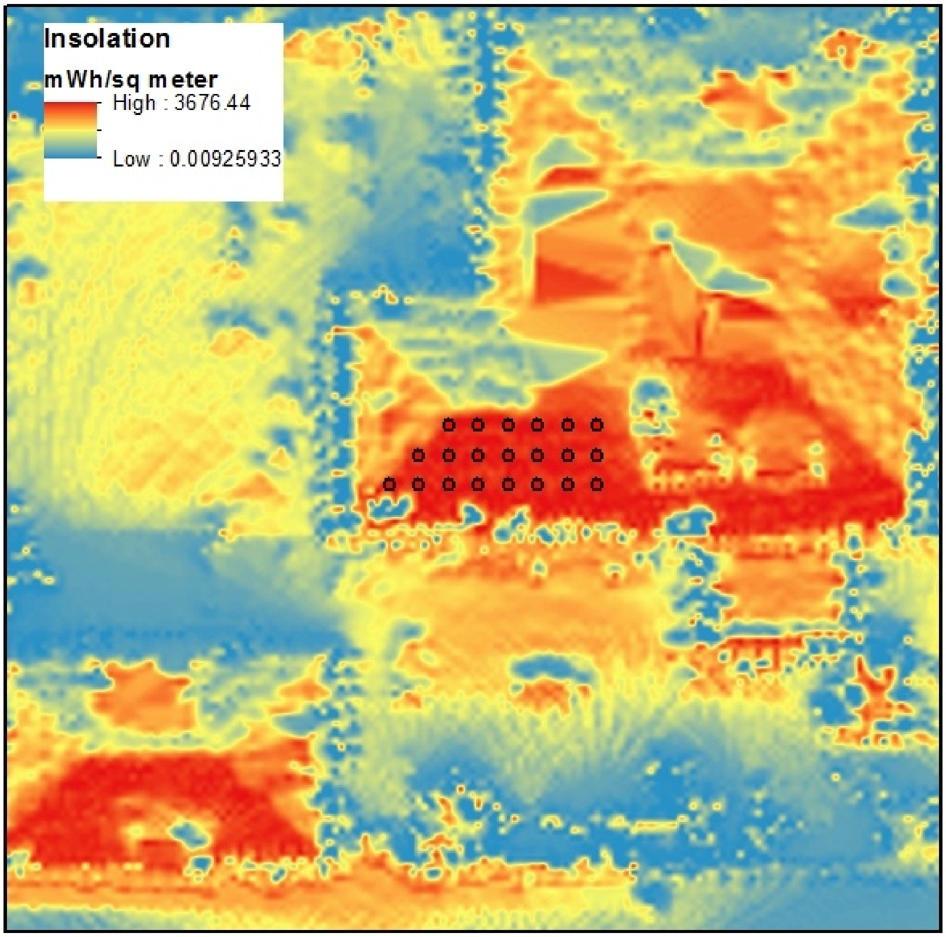


Figure 7 - Minneapolis Property Analysis

Isolating the optimum roof locations

While average watt hours per sq meter are calculated for the entire rooftop, that measure alone is not sufficient to identify the best candidate structures to receive solar panels. A minimum threshold of 2.7 kWh/m^2 was used to eliminate roof areas that may be marginal for panel use (Morud, 2013). If the predicted value is assumed to be within 10%

of the actual output, the threshold is closer to 3 kWh/m^2. This data was then reclassified to five classes with 2.7 kWh/m^2 and higher ranked as a 5 decending to 1 for values less than 1 kWh/m^2.

To further separate optimum panel locations, the aspect raster data set was reclassified to weight south facing (120-240 degrees) at 5 with west, southwest, east and southest facing(60-120 degrees and 240-300 degrees) receiving a 3. All other aspects received a value of 1. These values were chosen as the solar insolation analysis already accounts for aspect and to help group contiguous areas of insolation values.

The raster calculator was then used to multiply the two raster data sets resulting in optimum roof locations for panel installations. Figure 10 - Optimum Panel Areas shows an example of the result overlayed by points representing the watt hours per square meter values for the rooftop.

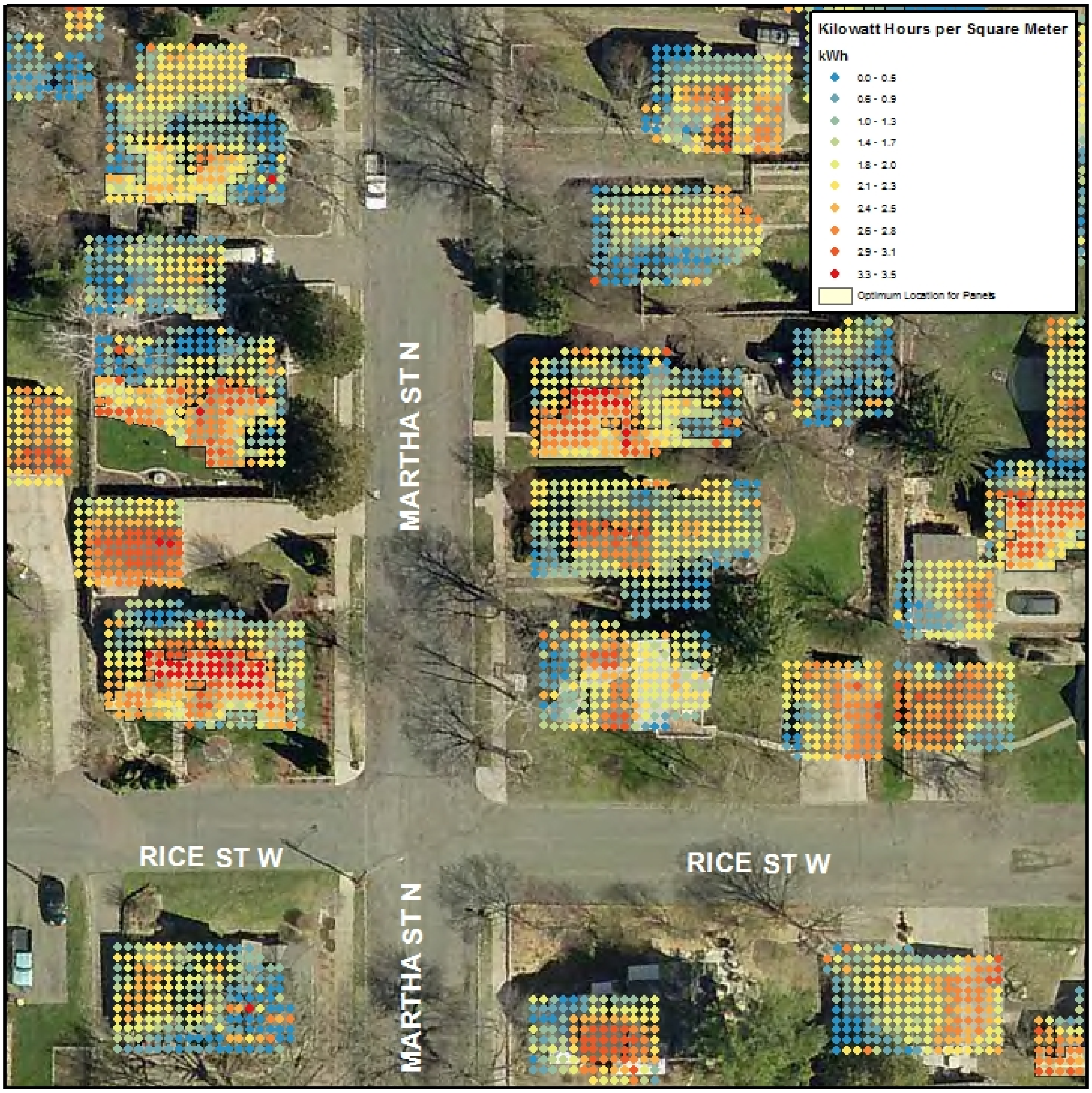


Figure 8 - Optimum Panel Areas

CHAPTER IV

RESULTS

The following results are based on LiDAR data collected in November 2011 and Washington County parcel information from May, 2013. LiDAR collections at higher resolutions should yield more accurate area values, but not necessarily more accurate solar capacity.

As the focus of this study was to analyze residential solar capacity, only those properties are included. Furthermore, not every property had information available for the year the structure was built so those properties are not included in the age of structure results. The results represent 7,288 structures on 5,626 parcels. Structures include houses, carriage houses, garages, sheds and condominiums (Table 2 - Residential Structures).

When analyzed for structures that may be well suited for solar panels, 4,004 structures have at least 50 sq meters projected to be good locations for solar panel installation. For purposes of this paper, the criteria for good location was determined in consultation with a solar installer (Morud, 2013) and based on 2.7 kWh per square meter minimum insolation value and primarily a southernly facing slope. This 50 sq meter area is calculated to produce a minimum of 135 kWh. The results of the anlaysis show that 55% of the structures in the city have good solar capacity potential.

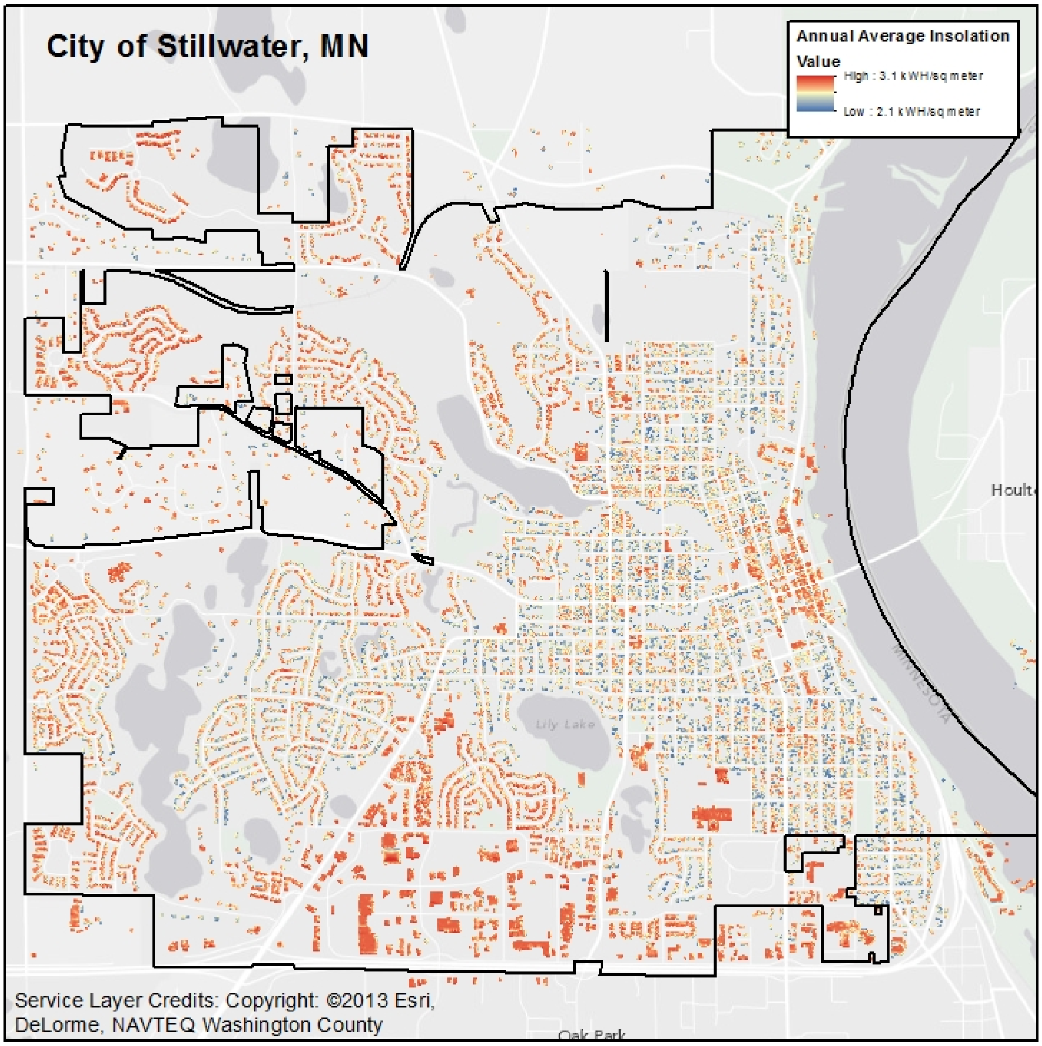
Table 2 - Residential Structures

	All Properties		Good Solar Potential Properties		
Age of Structure	**Parcels**	**Structures**	**Parcels with Structures**	**Structures**	**Percent of Structures**
Earlier than 1900	1,378	2,483	521	905	36%
1900-1925	173	330	66	131	40%
1925-1950	190	317	58	95	30%
1950-1975	1,319	1,636	625	782	48%
1975-2000	1,522	1,643	1,198	1,282	78%
2000-2013	1,044	879	779	809	92%
Totals	5,626	7,288	3,247	4,004	55%

	Good Solar Potential Properties		
Age of Structures	**Mean Potential Area (sq. meters)**	**Total Potential Area (sq. meters)**	**Total Average Annual kWH**
Earlier than 1900	79	42,777	116,789
1900-1925	79	5,285	14,362
1925-1950	73	4,221	11,402
1950-1975	90	56,516	152,580
1975-2000	108	136,414	397,778
2000-2013	116	106,072	319,492
Totals		351,285	1,012,403

CHAPTER V - DISCUSSION/CONCLUSION

Within the context of sustainable community development, this study was primarily focused on potential environmental benefits from solar panels and renewable energy. The results of this study confirm the potential for use of the standard Minnesota LiDAR data collection to predict solar rooftop capacity at a residential structure level. This methods of the analysis used in this study could be used for any community within the state of Minnesota. The results of this study identify that 55% of residential properties within the city of Stillwater may be good candidates for solar panel installations (Figure 9 - Stillwater Solar Insolation). The figure was much higher than expected as recent estimates by Xcel Energy are that only 20-25% of Minnesota households are suitable for solar (Shaffer, 2013). Such a high number of potential rooftop installations would raise questions regarding the impact of distributed solar energy on the utility-wide energy grid. Energy suppliers will need to plan for this impact as they work on upgrading an aging energy infrastructure.



Service Layer Credits: Copyright: ©2013 Esri, DeLorme, NAVTEQ Washington County

Figure 9 - Stillwater Solar Insolation

Gathering actual energy usage for each structure was beyond the scope of this study, therefore average amounts for energy consumption were used in the calculations. In 2011, the average annual electricity consumption for a U.S. residential utility customer was 11,280 kWh, an average of 940 kilowatt-hours (kWh) per month. Louisiana had the highest annual consumption at 16,176 kWh and Maine the lowest at 6,252 kWh. In 2011, Minnesota (2,308,736 customers) averaged 813 kWh per month (9,756/year) at a price of 10.96 cents per kWh (US Energy Information Administration, 2011). Using average consumption rates, a Minnesota house would require 394 sq ft (36.6 square meters) of solar panels to generate 50% of its energy needs (Solar Estimate, 2013). This study considered roof top areas of at least 538 sq ft (50 sq meters) for the optimum location of solar panels. This is a slightly larger area than the average home's 2-car garage. Of the 7,288 structures in the city, 4,004 structures met that criterion. However, the average area of adequate solar insolation for these rooftops was 87 square meters. If a 15% efficiency panel is assumed at the minimum insolation value of 2.7 kWh/m^2, a minimum of 0.41 kWh of energy is delivered for each square meter. Therefore, an average of 35.24 kWh of energy can be delivered per day by 4,004 structures in the city. Considering the average Minnesota daily consumption of energy is 27.1 kWh, there is the potential of an energy surplus being generated for these households using the minimum insolation value of 2.7 kWh/m^2. As the verification of model calculations for solar insolation were nearly 10% below actual measurements, the total output most likely will be higher than this.

The potential reduction of carbon dioxide released into the atmosphere could have a large environmental impact with adoption of more solar power. If all the calculated rooftop solar potential was realized for the candidate locations within Stillwater, the reduction of greenhouse gas emissions would be 5,250 metric tons per month of Carbon Dioxide equivalent (US Environmental Protection Agency, 2013) (Morud, 2013). The EPA

Greenhouse Gas Equivalencies Calculator that was used in this calculation uses the Emissions & Generation Resource Integrated Database (eGRID) U.S. annual non-baseload CO_2 output emission rate to convert reductions of kilowatt-hours into avoided units of carbon dioxide emissions. The conversion factor of PV generated kWh to carbon avoidance being used in the calculation is 7.0555×10^{-4} metric tons CO_2 / kWh (eGRID2012 Version 1.0, U.S. annual non-baseload CO_2 output emission rate, year 2009 data). Total kWh of electricity was calculated using the total area insolation values of kWh/m^2 and applying a typical 245 watt solar panel. If all rooftop area calculated as being a good candidate location was used, that equates to 7,441,162 kWh of electricity each month.

Adoption of solar technology will require support from government policies and education as to the realities of using solar panels in Minnesota and energy saving strategies. Xcel Energy is the utility company that provides power for the Stillwater area. They provide homeowners with energy saving tips and home energy use review assistance. However, the feedback to the homeowner by using solar panels and micro inverter technology provides an insight to energy use that the utility company has not yet matched. The micro inverter technology allows the homeowner to view their energy generation and usage in real time via a web browser. Using a toaster or a hair drier will result in a visible spike in your energy usage. This type of feedback has an impact on how the homeowner approaches energy usage.

The potential environmental impact extends beyond a reduction of carbon output through solar panel use. The results of this study could also be used to help with planned tree plantings. Through the addition or elimination of trees from the first return digital surface model, it would be possible to analyze for several scenarios of tree heights and locations. While this study utilized first return LiDAR data, it did not account for deciduous versus coniferous trees. Tree type may also have an impact on annual insolation as perhaps certain panel locations were calculated as completely shaded during winter sun angles and tree canopy may be under-represented in other cases. Using LiDAR for tree type identification is also a new area of research.

The pre 1900 structures that are identified as good candidates may raise social concerns as there is more demand for installation of solar panels. The City of Stillwater has a number of historically significant properties that are listed on the National Register of Historic Places. Adapting strategies to preserve the historic character of the community while meeting environmental goals may be challenging. There are currently no guidelines in the City of Stillwater for dealing with rooftop solar panel installations on historic structures. If there is reluctance to blend newer technology such as solar with historic structures, perhaps there are other options. One type of arrangement that may be feasible for this situation is a community solar farm where people could pay to install panels elsewhere in the city. However, there are some potential regulatory problems within the utility industry that may arise with this new concept. Currently, requests for solar installations within the city are handled on a case by case basis, and none have been denied to date. Another feature of older neighborhoods is that east-west, north-south street layout does have an impact on structure orientation and therefore solar capacity. This is community design aspect that may be worth noting when planning a sustainable community where solar power is a consideration. All of the newer residential developments in the city since 1970 have been developed with curvilinear streets.

The data also mirrors the boom and bust cycle of Stillwater as there were fewer structures built during several decades after the collapse of the lumber industry in the early 1900s. The population declined from a high of 12,818 in 1900 to a low of 7,013 in 1940. After World War II, the city began to rebound with slow growth. By 1990, the population had grown to 13,882 surpassing the earlier population numbers. A number of large 'Lumber Baron' houses from the Victorian period of the community are still preserved. The smaller houses of the 1930s through 1960s gave way to ever increasing square footage through the latest construction in 2013. While square footage of the properties was not included in the analysis, the effect was evident in the available roof area. Further analysis using size of structure may provide more insight into the viability of solar panels for parts of the city.

Adding to a need for rooftop solar research such as this, the Minnesota solar standard signed into law May 23, 2013 by Governor Mark Dayton requires major utilities to generate 1.5% of their power from the sun by 2020. The law also provides incentives for homeowners and businesses to install rooftop systems. To help local and state planners understand and manage solar energy opportunities, a Statewide Solar Resource Inventory and Mapping project was proposed to the Legislative-Citizen Commission on Minnesota Resources (LCCMR) in August, 2013.

For solar to be a sustainable technology, there will need to be adequate balance between the economies of solar, the industry impact on the environment and the social implications. Important to sustainability are the skilled jobs associated with development of new solar technologies, solar technology sales, installation technicians, and maintenance workers. There are large companies currently involved with solar installations, but there are also many smaller companies within the local economy.

While the costs associated with solar technology are heavily weighted on the front end, it is important to consider the long term investments of solar. It may take several years for a homeowner to save enough on energy to overcome the installation costs, but solar costs are fixed to the time in which you choose to install panels and utility energy prices continue to increase. Given that utility electricity rate increases are somewhat unpredictable and many solar panels have a 25 year warranty, solar panels may be an attractive option for long term energy stability for a homeowner. However, even with the reduction in solar costs over the past few years, solar panels remain unaffordable for most due to the high up-front costs. This social impact has so far been dealt with by rebates, subsidies, and power buy backs from the utility companies.

As this study was focused on residential properties, the solar insolation analysis did not include commercial properties. A summary of those results is beyond the scope of this paper, but a cursory review suggests they would be excellent candidates for larger solar installations. Many commercial buildings have large flat rooftops that would be well suited for solar farms or solar gardens. These have emerged as an alternative for people to buy into solar energy without having panels on their house. Further study into commercial solar capacity should prove equally promising as the residential study.

The results of this study are meaningful and reasonable for calculation of solar capacity from the freely available LiDAR data available from the state of Minnesota. As this study shows, there is good potential for residential solar energy production in Stillwater. As evidence to this, while this study was being conducted, some businesses within the city have already started installing solar panels (Figure 11 - Greeley Street 2013). There is increasing urgency to transition to a broader and more sustainable mix of energy sources. One goal of this study is to help with the larger challenge of creating social and institutional frameworks that can incorporate more renewables into our energy solutions by providing detailed information that was previously not available.

Figure 10 - Greeley Street 2011 Insolation

Figure 11 - Greeley Street 2013 Solar Installation

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APPENDIX

Document received from TruNorth Solar for Solar Panel values for Minneapolis property on March 21, 2013.

Per Suniva 245 Watt Panel			**Per Hypothetical 1000 watt panel**		
Energy Production (Wh)	**kwh/panel**	**kwh/sq meter**	**Energy Production (Wh)**	**kwh/panel**	**kwh/sq meter**
1622	1.622	0.966963472	6620.408163	6.620408163	3.946789683
1526	1.526	0.909732589	6228.571429	6.228571429	3.71319424
1588	1.588	0.946694201	6481.632653	6.481632653	3.864057964
1616	1.616	0.963386542	6595.918367	6.595918367	3.932189968
1651	1.651	0.984251969	6738.77551	6.73877551	4.017354973
1682	1.682	1.002732775	6865.306122	6.865306122	4.092786835
1685	1.685	1.00452124	6877.55102	6.87755102	4.100086693
1634	1.634	0.974117333	6669.387755	6.669387755	3.975989114
1510	1.51	0.900194108	6163.265306	6.163265306	3.674261666
1641	1.641	0.978290418	6697.959184	6.697959184	3.993022115
1627	1.627	0.969944248	6640.816327	6.640816327	3.958956113
1416	1.416	0.844155534	5779.591837	5.779591837	3.445532794
1665	1.665	0.992598139	6795.918367	6.795918367	4.051420976
1609	1.609	0.959213457	6567.346939	6.567346939	3.915156967
1695	1.695	1.01048279	6918.367347	6.918367347	4.124419552
1638	1.638	0.976501953	6685.714286	6.685714286	3.985722257
1652	1.652	0.984848124	6742.857143	6.742857143	4.019788259
1668	1.668	0.994386604	6808.163265	6.808163265	4.058720833
1677	1.677	0.999752	6844.897959	6.844897959	4.080620406
1586	1.586	0.945501891	6473.469388	6.473469388	3.859191392
1664	1.664	0.992001984	6791.836735	6.791836735	4.04898769
1636	1.636	0.975309643	6677.55102	6.67755102	3.980855685
1680	1.68	1.001540465	6857.142857	6.857142857	4.087920264
1670	1.67	0.995578914	6816.326531	6.816326531	4.063587405
1607	1.607	0.958021147	6559.183673	6.559183673	3.910290395

1626	1.626	0.969348093	6636.734694	6.636734694	3.956522827
1682	1.682	1.002732775	6865.306122	6.865306122	4.092786835
1686	1.686	1.005117395	6881.632653	6.881632653	4.102519979
1660	1.66	0.989617364	6775.510204	6.775510204	4.039254546
1522	1.522	0.907347969	6212.244898	6.212244898	3.703461096
1657	1.657	0.987828899	6763.265306	6.763265306	4.031954689
1687	1.687	1.00571355	6885.714286	6.885714286	4.104953265
1606	1.606	0.957424992	6555.102041	6.555102041	3.907857109
1664	1.664	0.992001984	6791.836735	6.791836735	4.04898769
1478	1.478	0.881117147	6032.653061	6.032653061	3.596396518
1633	1.633	0.973521178	6665.306122	6.665306122	3.973555828
58546	**58.546**	**0.969513691**	**238963.2653**	**238.9632653**	**3.957198739**

Panel Information

Portrait Length (ft)	3.33333333
Landscape Length (ft)	5.41666667
Sq ft	18.0555556
Sq meter	1.677416
total array sq meters	60.386976
245 to 1000 watt conversion	4.08163265

Total watt-hour data from each of the installed panels on the Minneapolis house specified for March 21st 2013. Converted to kWh/panel and kWh/sq meter/panel. With an assumed 1000 watts/sq meter at 100% efficient, the data was used to create hypothetical 1000 watt panels.