Solar Plymouth: An Accessible Solution for Residential Rooftop Solar Siting Using Geographic Information Systems and LiDAR

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Abstract

Minnesota is not the first state that comes to mind when considering solar availability. When compared to the latitude of the leader in solar production, Germany, the concept of Minnesota solar does not sound as unachievable. Currently, residents of Minnesota do not have a state or city specific interactive rooftop solar resource mapping service available to the public. This project acts as the initial step to providing this service. The use of Geographic Information Systems (GIS) delivers a different perspective on the renewable energy front. Communities, states or nations can begin to make a difference in energy production by becoming aware of what rooftop solar energy can provide. This project is intended for application to the City of Plymouth, Minnesota to estimate the solar potential of rooftops for photovoltaic (PV) systems.

Introduction

The growing demand of clean energy is not restricted to governmental mandates for industrial companies. Educating communities of renewable energy sources on their own roof is crucial to diminishing the byproducts of fossil fuels. There are thousands of residential and nonresidential buildings within the City of Plymouth, Minnesota. Rooftops are individualized gold mines for the home owner's solar potential. If a rooftop fits the criteria for good solar radiation capture, the energy production versus the energy consumption offset could dramatically lower energy bills and shrink the home's carbon footprint. The physical platform for rooftop solar is already available; there is a need for the public to be educated on the potential resources available.

Renewable solar energy is commonly envisioned as enormous solar farms that encompass tens to hundreds of acres. Although some utility scale projects can be extremely large, solar installations can also be small enough to fit on the roof of a home. Dean, Kandt, Burman, Lisell and Helm (2009) found the demand for renewable energy has been increasing rapidly, requiring tools allowing for quantification of the solar resources. The use of solar PV maps, or solar maps, has been a growing trend to allow site specific calculations of solar potential, costs, and savings. "In the past two decades the photovoltaic has developed into a mature technology and has become acceptable worldwide (Gong and Kulkarni, 2005)."

According to an email correspondence with the City of Plymouth staff in 2014, to date, "The city has not

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discussed initiating a renewable energy plan." This project addresses the insufficient technological services and research available to the public concerning rooftop mounted photovoltaic (PV) solar capturing systems. Although there are solar web maps that display the potential solar resource of a building rooftop available, there are virtually none available to the public for any specific city in Minnesota. The goal of this project was to provide geospatial research exploring solar potential of Plymouth, Minnesota.

Study Area

The study area (Figure 1) is centered on the thirty-six square mile municipality of Plymouth, Minnesota. This project aims to aid in the progression of rooftop solar and to spread to surrounding communities and eventually the metro counties and State of Minnesota. Plymouth, a suburb of Minneapolis is a city of over seventy two thousand residents in 2012 according to the Metropolitan Council (2013). Northern latitudes are not normally perceived to be ideal zones for abundant solar radiation, but when compared to the leader in solar PV installations and energy production, Germany, the latitudes are nearly the same making feasible to compete in the solar realm. Plymouth lies within the northern 45^{th} latitude while Germany's northern and southern latitudes are located between the northern 54^{th} and 47^{th} latitudes (American Planning Association, 2013 and ArcGIS 10.2, 2013). "…every state in the U.S. receives as much, or more, sunlight than Germany according to the American Planning Association (APA) (2013) and "Minneapolis receives 90 percent of the incoming sunlight that Miami sees each year, despite the difference in climate between these locations" (APA, 2013). Figure 2 displays a comparative solar radiation map of the United States produced by the Natural Resources Environmental Laboratory (NREL).

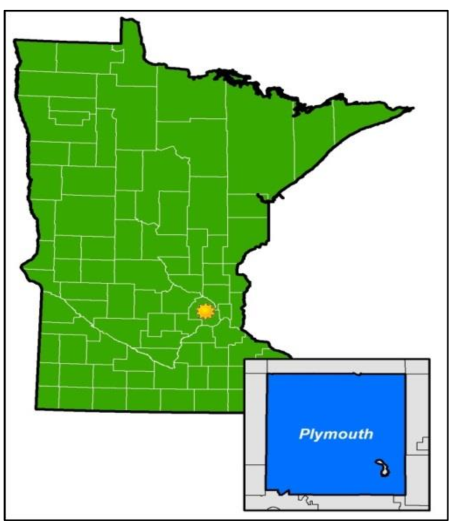

Figure 1. A geographic map of the City of Plymouth, Minnesota.

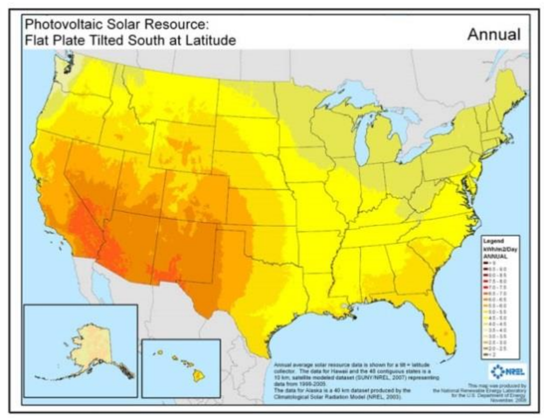

Figure 2. Annual PV Solar Resource of the U.S. provided by the National Renewable Energy Laboratory (2008).

Nearby Plymouth, the Cities of Minneapolis and St. Paul average 196 sunny days annually (Current Results, 2014). Through 2004, the last fifty-eight years on record have averaged 58% days annually of full or partial sunshine in Minneapolis and St. Paul (NCDC, 2014). These statistics reinforce in overturning the common misconception that northern regions are not suitable for solar energy harvest. Minnesota may have lower annual average temperatures but this does not translate into a lack of a significant amount of sunlight.

In Plymouth, rooftop solar is still in its infancy, there are only three known solar installations by the City of Plymouth staff. The existing sites offer a diverse assortment of renewable solar energy. The first is a ground-mounted unit at a residence, the second is a commercial rooftop system and the third is a ground-mount unit on a commercial property. The lack of solar installations exposes a need to enlighten community members and aid Minnesota in becoming more energy independent.

Methods

Data Collection

Topographical data is the cornerstone to calculating a solar surface. Utilizing Light Detection and Ranging (LiDAR) technology, an accurate one meter resolution digital elevation model (DEM) is the basis in the determination of rooftop attributes (Leitelt, 2010). LiDAR uses a laser pulse to measure an elevation from an aircraft similar to radar but light is used rather than radio waves (Dean *et al.*, 2009). LiDAR coverage for the project area was provided by the Minnesota Geospatial Information Office (MnGeo). MnGeo is a state run program and a source of geospatial datasets that cover the state of Minnesota. LiDAR data are broken down into 55,296 tiles that cover the entire state, of these; twenty were used for the coverage of the municipal boundary of Plymouth (Figure 3). Equally as important as elevation data are the building footprint features. The outline of a building allows for an individualized value of solar potential. Two building footprint layers were utilized in this project. The first was

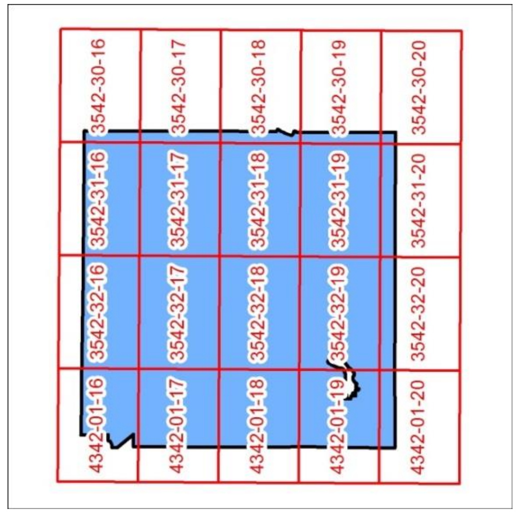

Figure 3. LiDAR tile coverage for Plymouth, MN.

a partial coverage provided by the City of Plymouth. Second was a predetermined building footprints derived from LiDAR returns.

Basemap imagery was downloaded from the United States Department of Agriculture's (USDA) Natural Resource Conservation Service (NRCS) geospatial data gateway. The 2013 ortho-image of Hennepin County, MN is one meter resolution imagery. The basemap imagery for this project was a combination of the NRCS data and data from the Environmental Systems Research Institute's (Esri) imagery.

Auxiliary material such as parcel data was also used. Parcel data were provided by the Hennepin County GIS department. Municipal boundaries, roads and hydrography from the USDA's geospatial data gateway were used as background data for visual reference.

The study area for this project is within Xcel Energy's electric service territory. A residential electrical pricing fact sheet provided by Xcel Energy offers helpful pieces of information concerning rates and average usages by Xcel's customers. Energy is priced per kilowatt hour (kWh), one kilowatt hour is a measure of 1000 watts used or produced over one hour (Department of Energy, 2014). According to an Xcel Energy rate book in 2014, the charge per kWh for June through September is $0.08671 and $0.07393 October through May (Xcel Energy, 2014). This is the last important item that was required for an accurate estimate in the determination of energy offset and cost benefit of the PV System.

PVsyst is a PV system development tool used to calculate accurate predictions for energy output for solar projects. A brief introduction to capabilities was utilized to obtain important calculations in estimating the potential energy of a rooftop PV system.

Data Specifications

The building footprint data that was provided by the City of Plymouth included 880 hand digitized footprints. Plymouth's data accounted for 18,490,822 square feet of building footprints putting the average size of digitized buildings at 21,012 square feet. This large square footage is due to the commercial buildings Plymouth staff selected to digitize.

The building footprints derived from LiDAR calculations included 20,278 buildings totaling 73,564,648 square feet. LiDAR buildings averaged a smaller 3,627 square foot building due to the additional smaller homes and sheds that were extracted from the data.

The analysis used a combination of the two building datasets. Both were merged together, removing LiDAR generated overlapping buildings. Data quality control analyses were then conducted to verify that buildings were being correctly identified. Each PLSS section that encompasses Plymouth was broken down into 1/16th blocks. 576 blocks were manually scanned for major discrepancies. As long as there was one polygon representing one building it passed. On numerous occasions feature outlines were removed as they would not be a logical location for a solar panel (i.e. playground equipment, baseball dugouts, water towers, electric substation facilities, or above ground pools). Some buildings fell on and were separated by flight path boundaries creating a split in the polygon creating two features for one building. In these cases they were merged into one polygon. The end result of the data used for the analysis accounted for 19,814 buildings totally 73,440,315 square feet of building footprints. On average the building size for Plymouth came to 3,706 square feet (Figure 4).

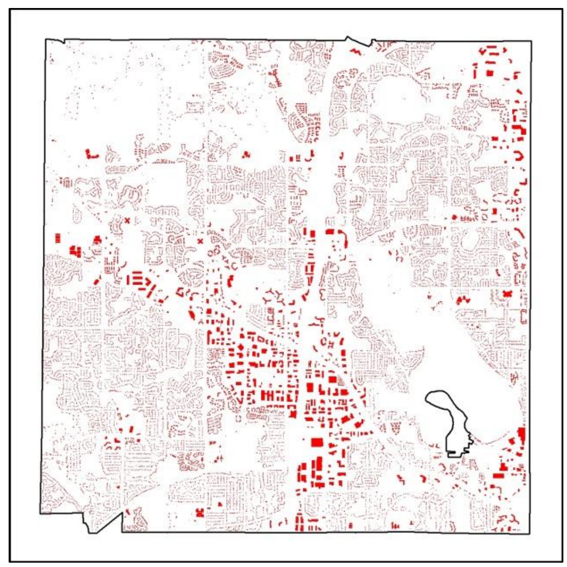

Figure 4. Combined building footprints after data quality control analysis are displayed in red.

Tools

Utilizing the building footprints interpreted from LiDAR and the City of Plymouth, polygons were extracted from the LiDAR elevation raster to create one raster containing individual building footprints. The Solar Analysis Tool in ArcGIS utilizes the LiDAR raster footprints to calculate solar insolation in watts per hour per square meter (W-h/m^2)

(Dean *et al.*, 2009). The results allow the user to "…analyze the effects of the sun over a geographic area for specific time periods" (ESRI, 2013). A monthly average for each month was calculated to estimate the amount of solar radiation falling upon each building footprint. The solar raster results were then converted to polygon features to revert back towards the original state of the building footprints. Each of these individual pixel cell polygon boundaries were then dissolved creating a singular footprint representing the mean W-h/m2 for each month of the year produced by the Area Solar Radiation tool. The conversion of raster to polygon carried the mean values of all cells within a building footprint raster to the polygon footprints to allow for easier calculations in the attribute table.

Calculations

The conversion of available W-h/m2 data from the Area Solar Radiation tool to the net kWh per month required numerous calculations. Utilizing a 250-300 watt solar panel (Figure 5) with a rounded 1.5 square meter surface area, the number of panels and total panel area were calculated. The panel area was input

Figure 5. Sample residential rooftop PV system. Image provided by Gerdes (2012).

into the calculation to obtain the net kWh per month. The output raster value from the Area Solar Radiation tool was then converted from W-h/m^2 to kWh/m^2 to produce the starting point for mean irradiation per month. A transposition ratio was then factored at a value of 1.23 by PVsyst software used to calculate and design PV systems (PVsyst, 2013). Transposition is the value of change in direct radiation from a horizontal surface to a tilted surface (Ineichen, Zelenka, Guisan, and Razafindraibe, 1988; PVPerformance, 2014a). When radiation falls on a solar panel the amount of radiation captured by the panel on average is 97% according to PVsyst (2013). Self-diffusion is the amount of solar radiation that is reflected by the panel due to the angle at which it is striking the surface. The closer the angle of the sun to 90 degrees or perpendicular to the panel, the higher the probability that solar energy will not be diffused away from the panel (PVPerformance, 2014b and PVsyst, 2013). Multiplying the transposition ratio and the self-diffusion factors result in an effective irradiance or energy that can be utilized from the sun. Incorporating the effective radiance and the total panel area from above, the total irradiance is produced. Multiplying the total irradiance by the rounded efficiency of panels in this wattage, 15%, the nominal energy is now available. Efficiency was determined by a list of manufacturers rated efficiency for a wide variety of solar panel power ranges. The efficiency for 250-315 watt panels spread from 15.37%-16.2% efficient. To simplify calculations, a whole number percentage was taken closer to the 250-300 watt range (ENF Solar, 2014). Finally, a performance ratio of 77% is calculated on the nominal energy to obtain the net kWh per month for a building footprint. "The value of 0.77 means that the AC power rating at Standard Testing Conditions is 77% of the nameplate DC power rating (National Renewable Energy Laboratory, 2014)." A workflow summary is presented in Figure 6.

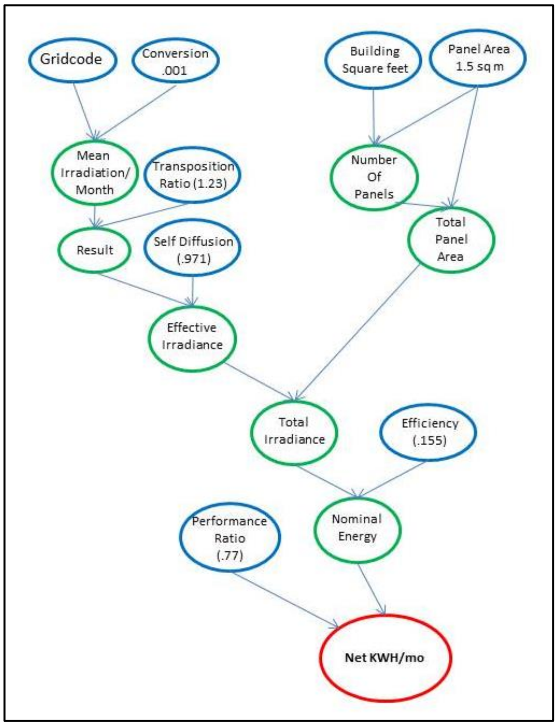

Figure 6. Workflow for determining net kWh per month. Blue circles are inputs, green circles are results and the red circle is the final output.

The next step was to determine the estimated energy offset for the building. According to Xcel Energy, the average customer's home, with underground electric service, uses 850 kWh of energy per month (Xcel Energy, 2011). This number is an average number over the span of a year; months were not separated out by Xcel Energy. Unfortunately, this gives room for error as different months average different usage levels depending on the season and amount of energy used. For example, more electric energy is used during the summer months for cooling. This is one reason why summer months, June through September, are listed at a higher rate from the rest of the year when more energy needs to be produced.

Results Preparation

It should be noted that the solar coverage encompasses the entire footprint of a building. Pitch and aspect are not applied in this project; therefor the resulting calculations account for the entire footprint of the structure and not solely the ideal solar panel locations. This will include rooftops with north, west and eastward aspects in addition to the south facing roof in northern latitudes. To account for this over estimation of incoming solar availability, two estimation percentages were applied to the calculated results to provide a more realistic estimation. Simplified percentages were chosen by assuming half to a quarter or less of a structure's rooftop would have a southern aspect or has the capability to capture a sufficient amount of radiation.

Utilizing the net and estimation percentage kWh values, an offset calculation was made by comparing it to the mean monthly usage of 850 kWh. Granted this monthly mean does not account for fluctuations in seasonal usage, it still provides a reference for comparison.

Results/Analysis

Plymouth City-Wide Statistics

Results were divided into monthly intervals to show the fluctuation of incoming solar radiation throughout the year. The chart (Figure 7) displays the mean net kWh per month on all Plymouth building footprints resulting from the workflow above in the calculations section (Figure 6). The incoming solar radiation followed the expected path, a higher intensity the summer months than nonsummer months. The resulting net kWh per month are displayed in Table 1 as well as the percentage estimates of 50% and 25% of a footprint's net calculation. Figure 8 is a good representation of not only the incoming solar radiation, but the estimated energy offset as well. Compared

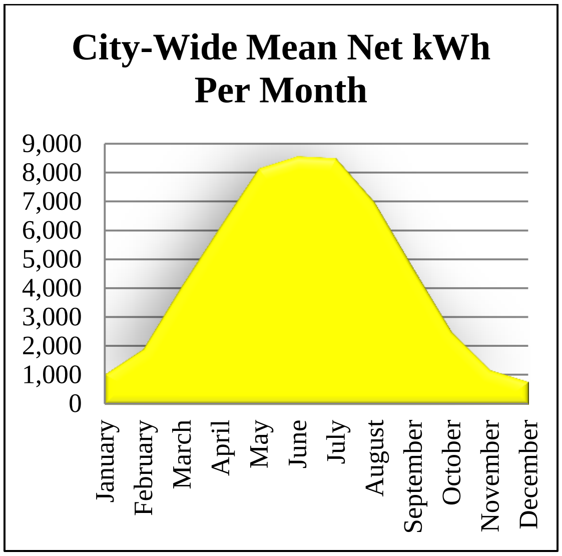

Figure 7. This chart represents the mean net kWh per month.

to the mean energy consumption of 850 kWh, the net kWh value is going to have a majority of surplus values, as it is essentially utilizing the entire footprint as useable panel space when in reality that is untrue. The first percentage estimate of 50% is still an inflated number as not all structures face the same direction and have half of a roof surface with a southern aspect. The second percentage estimate of 25% is the closer to reality when designating the potential of useable area of a rooftop.

Expounding on the second percentage estimate, there are fewer months with a solar energy surplus but these five months still account for a considerable amount of the mean energy usage. January still provides 30.6% of the 850 kWh, February was 56.1%, October

Table 1. Result of net kWh work flow calculations. Summer months are yellow, other months are blue. Surplus energy is green font, deficit energy is red.

	Net	*% Estimate #1*	*% Estimate #2*
Month	**Net kWh**	**50% Net kWh**	**25% Net kWh**
January	**1041.4**	**520.7**	**260.3**
February	**1908.7**	**954.4**	**477.2**
March	**4083.6**	**2041.8**	**1020.9**
April	**6140.9**	**3070.4**	**1535.2**
May	**8142.9**	**4071.5**	**2035.7**
June	**8567.9**	**4284.0**	**2142.0**
July	**8495.8**	**4247.9**	**2124.0**
August	**6989.2**	**3494.6**	**1747.3**
September	**4733.2**	**2366.6**	**1183.3**
October	**2512.5**	**1256.3**	**628.1**
November	**1195.6**	**597.8**	**298.9**
December	**780.1**	**390.0**	**195.0**

was 73.9%, November was 35.1% and December was 22.9%. These months are in the lower energy rate period where not having a surplus is not as essential. All months in the summer rate period show a surplus, the time when the energy offset would be most beneficial financially.

Sample Residence Breakdown

The same process and workflow from above (Figure 6) was applied to a single residence in Plymouth to provide a more likely scenario as the square footage is for a single home footprint rather than an average of buildings ranging from small residences to large commercial buildings. Comparing the second percentage estimates, this mirrored approach resulted in dramatic differences. The individual residence compiled eight months with no surplus of energy over the average 850 kWh. January still provided 15.4% of the 850 kWh, February was 29.0%, March was 63.9%, April was 98.4%, September was 74.7%, October was 38.5%, November was 17.8% and December was 11.4% (Table 2).

When comparing the city-wide dataset to the individual residence net kWhs, the numbers vary dramatically.

Table 2. Result of net kWh work flow calculations for a sample residence. Summer months are yellow, other months are blue. Surplus energy is green font, deficit energy is red.

	Net	% Estimate #1	% Estimate #2
Month	**Net kWh**	**50% Net kWh**	**25% Net kWh**
January	522.9	261.5	130.7
February	986.4	493.2	246.6
March	2173.0	1086.5	543.2
April	3344.7	1672.3	836.2
May	4503.7	2251.8	1125.9
June	4774.7	2387.4	1193.7
July	4720.4	2360.2	1180.1
August	3834.1	1917.0	958.5
September	2540.6	1270.3	635.1
October	1309.4	654.7	327.4
November	605.2	302.6	151.3
December	387.5	193.7	96.9

This is primarily due to the mean building square footages between the two datasets. This is a reason why this project could be carried to the next level when calculations. This is a reason why this project could be carried forth and expanded when calculations are made on individual structures city-wide. The data processing for a large task encompassing a city would prove to be an enormous undertaking. Taking an average calculation and comparing it to a test sample demonstrates how results may differ depending on the data used. Figure 8 displays the difference in net kWh between the city-wide and single residence datasets.

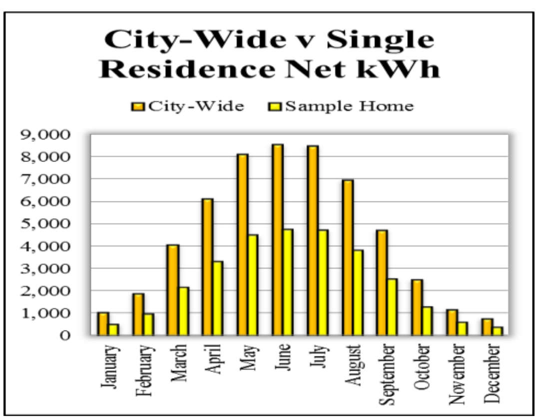

Figure 8. Comparison between the city-wide dataset and the individual residence net kWh.

Discussion

The results for the city-wide calculations were surprising as they calculated more monthly surpluses of energy capture than expected. This is primarily due to the mean square footage of the city-wide dataset as it included everything from large sheds, to homes, to commercial buildings. The commercial buildings raise the average footprint size considerably. The sample residential footprint has a 2,099 square foot boundary compared to the city-wide average of 3,706 square feet. Nearly double the residential footprint. The second percentage estimated result for the sample residence was the most realistic interpretation to a true scenario as it includes a singular building footprint and accounts for unlikely useable area on a rooftop for solar panels.

The results, in general, pose evidence for positive attributes of solar rooftop energy in the City of Plymouth. The city should utilize similar data to initiate a city-wide renewable energy plan. There is need in the State of Minnesota for a city that can implement a city-wide demonstration project in the residential solar realm. Providing residents of an entire city with educational solar material and the notion that rooftop solar is an option could be a stride in the right direction.

Sources of Error

The first item that would affect the outcome is the building footprint outlines. The majority of the structure outlines for this project were extracted from LiDAR data and upon closer inspection they are far from perfect representations of the built structure when compared to aerial imagery. To account for this error, methods of a correction percentage were used when it came to square footage of buildings. When comparing those building footprints to imagery, the outlines did not match the actual footprint of the structure, thus not capturing the highest accuracy of square footage. To account for this difference, a sample building from each LiDAR tile was selected and a new footprint was hand digitized. After calculating square footage of both footprints, they were compared and averaged between all samples. The resulting difference when compared to the LiDAR coverage is, on average, 6% smaller than an aerial imagery digitized building footprint. This is important to note as it may affect the building potential by how many estimated modules could fit on a rooftop.

The progression of the data through the workflow from the beginning to end of the data transformation processes could also contribute to error. There are other intricate and technical calculations involved in siting a building for solar. This project touched on key elements with available data.

Recommendations for Future Work

In an ideal situation, future work would include the tedious task of manually digitizing each structure via aerial imagery to assure a greater level of accuracy. Unfortunately, in the case of this project, temporal limitations were present to draw over nineteen thousand buildings was not viable.

Although this project provides an excellent source of data for individual building statistics, they can be made more accurate. The use of ArcGIS's 3D Analyst toolbox would bridge a gap between the raw LiDAR point cloud data and more detailed roof features such as slope and aspect. Without this product license, limitations were present only allowing for a rough estimate of the solar radiation that falls on the footprint of a building using the interpolated elevation raster layer.

A potential expanded project would be similar to that of Boston or New York City's solar web map resources. A metro or county level application would be an achievable goal. Locating existing power generating roofs with images and output statistics as well as the solar resource for each building would be an ideal resource for our communities.

Conclusions

Rooftop solar energy is a viable source of energy at lower energy costs for residents and it also offer a reliability of energy. The first step to any successful goal is introducing a solid concept. A solar data resource does not need to be limited to only calculating solar potential however; web maps can go above and beyond for the user and locate existing rooftop solar installations, provide installer contact information or include incentive details (Dean *et al*., 2009).

Supporting renewable energy and saving money can go hand in hand by providing the satisfaction of two important types of green. Solar is not only for environmentalists, there are other reasons to utilize the sun other than simply being green. The other kind of green to be interested in is the money saved in energy costs. After the solar panels are installed, they are essentially collecting money to pay for electric bills, the cost of panels and installation. Solar is not restricted to environmentalists or citizens; municipalities, the US military and even NASCAR are utilizing the clean alternative to diminish energy costs (American Planning Association, 2013).

Acknowledgements

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A thank you is also required for the City of Plymouth for providing a portion of the building footprint shapefiles and information concerning solar information they had.

The majority of the credit goes to the researchers who provided the wealth of information on solar energy, calculating solar potential and utilizing solar maps as a method of mass media displayed to the public. They play a large role in the advancements in technology and promotion of renewable clean energy.

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