TOWARDS VALIDATED URBAN PHOTOVOLTAIC POTENTIAL AND SOLAR RADIATION MAPS BASED ON LIDAR MEASUREMENTS, GIS DATA, AND HOURLY DAYSIM SIMULATIONS

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ABSTRACT

We present a method for generating detailed geometric urban massing models combined with building footprint and material information from large GIS datasets and LiDAR elevation measurements. An example model for the city of Cambridge, Massachusetts, USA that contains over 17,000 buildings is used as input for annual solar radiation calculations using the RADIANCE / DAYSIM simulation engine. Based on hourly irradiance calculation results, we find it possible to make recommendations for PV placement on a building and to intelligently determine the total and useful roof area of buildings. Simulation results are compared to those typically used in practice to produce solar radiation maps of other US cities. It is found that the presented method yields better geometric accuracy and higher irradiation predictions compared to previous methods. This results in increased predicted PV energy production at lower installation costs and more accurate estimates of useful rooftop area.

INTRODUCTION

It has become increasingly popular for cities and municipalities to create solar potential maps with the intent of promoting renewable energy generation through photovoltaic (PV) panel installations within those jurisdictions. In the United States, large cities such as Boston, Los Angeles, New York City and Portland provide online maps which allow building owners to look up their address and view personalized predictions of,

- electric production from a PV system (kWh)
- energy savings from a SHW system (Therms)
- resulting annual electricity savings (dollars)
- carbon savings (lbs)
- useful roof area (sq. ft.)
- system payback period (years)
- system costs (dollars)
- local rebates and incentive programs

The objective of these maps and accompanying personalized property information is to reduce summer time peak loads, increase the environmental awareness of residents, reducing greenhouse gas emissions and to improve the sustainable image of a city through the expansion of solar energy technology.

While a number of cities have already generated such solar maps, to the authors' knowledge, limited attention has been paid to the assumptions and calculation methods underlying these maps. The objectives of this paper are hence threefold.

We initially present a method of how a validated solar radiation calculation algorithm, thus far only been used at the individual building scale, can be applied to a city-sized model of Cambridge, Massachusetts, USA. The new method creates city-wide solar potential maps with a high degree of spatial and predictive accuracy based on the generation of a high resolution three-dimensional (3D) model sourced from available geographic information systems (GIS) data. Our model applies validated simulation methods which take into account detailed geometric data including shadowing from surrounding buildings, typical climate data, and reflections between buildings and the urban landscape. The results from this model are spatially and temporally rich; the variation of irradiation across a rooftop is displayed, and data is available at hourly time-steps for detailed peak load analysis and PV energy yield calculations. Secondly, we use the simulation results generated during the first step as a reference against which we compare results that one would obtain using the methods underlying other solar radiation maps. Finally, we discuss what relevance varying simulation results may have at both the individual building owner and city-wide policy level.

REVIEW OF CURRENT METHODS

Irradiation Calculations

In a review of eleven solar potential maps for North American cities (Table 1), we found that there are three typical predictive methodologies in place for calculating rooftop irradiation. Three (27%) of the surveyed maps used a constant assumption for solar

Table 1 Survey of Existing Solar Potential Mapping Methods in North America

CITY	URL	FLAT ROOF	CALCULATION METHOD
Anaheim	http://anaheim.solarmap.org/	No	Solar Analyst
Berkeley	http://berkeley.solarmap.org/	Yes	Constant Multiplied by Usable Roof Area
Boston	http://gis.cityofboston.gov/SolarBoston/	Yes	Solar Analyst
Denver	http://solarmap.drcog.org/	?	Unknown
Los Angeles County	http://solarmap.lacounty.gov/	No	Unknown (Assumed, Solar Analyst)
Madison	http://solarmap.cityofmadison.com/madisun/	?	PVWatts with Sunlit Hours Graphic
New York City	http://nycsolarmap.com/	No	Solar Analyst
Portland	http://oregon.cleanenergymap.com/	Yes	Constant Assumption
Salt Lake City	http://www.slcgovsolar.com/	No	Solar Analyst
San Diego	http://sd.solarmap.org/solar/index.php	?	Unknown
San Francisco	http://sf.solarmap.org/	Yes	Constant Multiplied by Usable Roof Area

irradiation reaching a building rooftop. One (9%) reported using the National Renewable Energy Laboratory's (NREL) PVWatts calculation module. Another five (45%) used the Solar Analyst plugin within Esri's ArcGIS program. The remaining maps did not report their calculation methodology.

The use of a constant, global horizontal, solar radiation value across a rooftop will be inaccurate in many cases, for example buildings with peaked roofs. Such a constant value also does not consider local urban context such as trees and neighboring buildings which shade building rooftops. Also, the complex forms of individual roofs are ignored. Advocates of this approach determine the useful roof area for PV installation by using either a constant percentage (Boston, Portland) or based on orthophotographic image analysis techniques (San Francisco, Berkeley). The NREL PVWatts module is essentially a modified version of the constant approach (Marion, et al. 2001). Solar irradiation is distributed on a 40km square grid for the entire United States based on the typical meteorological year 2 (TMY), dataset. Local TMY2 irradiation data is used in combination with PV panel tilt, orientation, and urban temperature conditions to determine energy production. While roof shape is treated with greater detail than in a solar constant approach, shading from adjacent urban surfaces also cannot be modeled using the PVWatts module.

Since Esri's Solar Analyst plugin, based on the work of Fu and Rich (1999), currently constitutes the most widely used irradiation calculation method, it is discussed in greater detail. In this method, a sky mask is initially generated based on the surroundings of each pixel of a digital elevation model (DEM). A DEM is a geolocated raster image where the values of individual pixels correspond to elevation measurements. The direct and diffuse components of irradiation are calculated based on what amount of the sky can be seen from each pixel. Direct irradiation is calculated in accordance with the sun position, the slope of the DEM, a fixed transmissivity coefficient, and the distance a solar ray must travel through the atmosphere. Diffuse irradiation is calculated in much the same way as the direct component, based on either a uniform sky model or a standard overcast model; however, no solar map reports on its website which sky model was used.

In Solar Analyst, sky transmissivity and the ratio between direct and diffuse insolation are fixed, constant values throughout the year. These assumptions can have a significant effect on the calculated annual radiation. For example, the Boston Logan TMY3 weather data illustrates a ratio between direct and diffuse irradiation which varies widely throughout the year (US Department of Energy 2012). The mean value of the hourly direct-to-total ratio of insolation is 64.2% for the 4,604 daylit hours in the Boston TMY3 weather file; however, the standard deviation from the mean is 31.3%. Further, the amount of cloud cover and thus atmospheric transmissivity varies throughout the year. Therefore, it is inaccurate to pick one value to adequately represent these factors. The extreme variance in direct and diffuse radiation throughout the year and cloud cover is shown in Figure 1 for the Boston climate TMY3 dataset.

As Solar Analyst uses only a sky mask based on a DEM, it has no capacity to model reflections between buildings, from surrounding trees or from the urban terrain. It has been proposed to assume a directional constant of reflected irradiation for obscured sky areas (Rich, et al. 1994), but it would be inadequate to consider complex reflections from surrounding buildings.

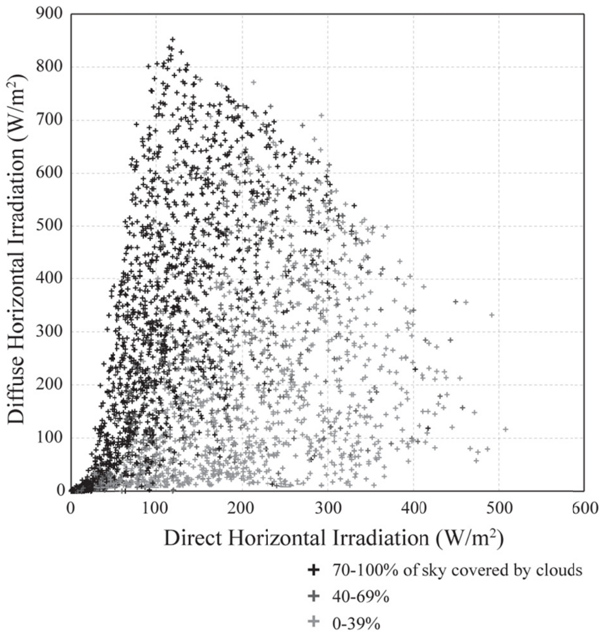


Figure 1 Hourly Direct and Diffuse Radiation and Cloud Cover from Boston Logan TMY3 Weather Data

Observed Geometric and Material Assumptions

Of the 11 solar potential maps surveyed, four (36%) assumed that all buildings in the city had flat roofs at a known elevation, four (36%) used a detailed DEM to represent the roof, and the remaining 3 did not report their assumptions. Of cities utilizing the flat roof assumption, half assumed that a fixed percentage of the roof is suitable for PV (Boston, Portland). The others relied on a proprietary orthophotograph method for locating rooftop obstructions (Berkeley, San Francisco). With DEMs, useful roof area is either determined by the predicted rooftop irradiation or by the number of daylit hours.

None of the surveyed cities use a method which considers reflections or building materials.

METHODOLOGY

Our implementation of an urban solar potential map is based on the creation of a detailed 3D model in the validated RADIANCE/DAYSIM backward-raytracing daylight simulation engine (Ward 1995, Reinhart and Walkenhorst 2001).

LiDAR Data and Geometric Accuracy

The geometric information used in creating the detailed digital model of Cambridge comes from a publicly-funded 2010 LiDAR survey. LiDAR, Light Detection And Ranging, is an established, accurate measurement system wherein a surveying aircraft emits rapid laser bursts and records the time until their visual return while tracking its location via Global Positioning Systems (GPS). The collected location and timed return data is later processed into geographically located point data. The vertical accuracy of the data in the urban context of Cambridge was bounded to less than 1m root mean squared error (RMSE), and in selected validation tests the RMSE between LiDAR and traditional GPS measurement methods was shown to be 0.062m (Alliance for Sustainable Energy 2010).

Our process of creating a detailed 3D model is illustrated with an example surrounding the Kresge Oval at the Massachusetts Institute of Technology (Figure 2a). As LiDAR data is not uniformly sampled in plan, it creates an awkward data space (Figure 2b) where different point densities are present depending on the airplane path of flight. Initially, there were 126,624,764 points spread across all of Cambridge which has a total area of approximately 4,500 acres (18.5 km^2). We uniformly resampled the LiDAR data over a plan grid of approximately 4’x4’ (1.2x1.2m) spacing, taking the mean of the first return data where multiple points existed. Resulting neighboring points which did not vary by greater than one foot vertically were discarded. This resulted in a simplification of the data space to a mere 9,403,750 points without losing much geometric resolution.

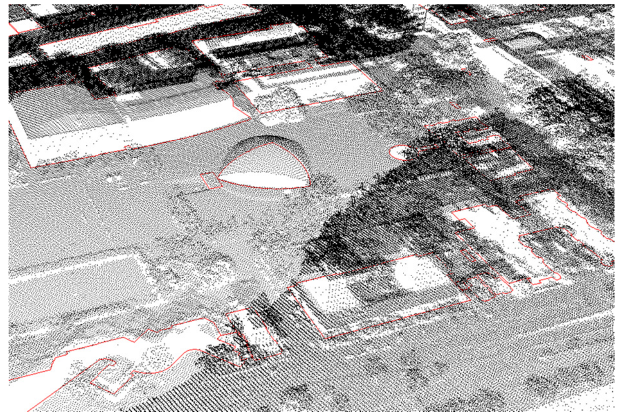
The simplified LiDAR-derived points were then divided into two categories using publicly available GIS datasets from the City of Cambridge: buildings and ground scape (Figure 2c) (City of Cambridge 2004). As a last step the two point groups were triangulated using a Delaunay algorithm (Figure 2d), resulting in a highly accurate and detailed 3D model of the entire City of Cambridge that consists of 16,547,790 triangular surfaces.

Hourly Simulations with Radiance/DAYSIM

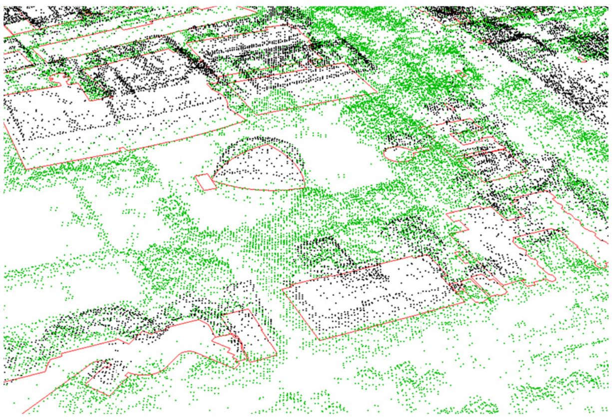
The triangulated surface model was then converted into the RADIANCE backward raytracer format. In RADIANCE each surface may have different, highly customized, optical surface proteries. In our model we assumed that building walls were Lambertian diffusers with a 35% reflectance while building roofs and ground were assigned a diffuse reflectance of 20%. Annual irradiation was then calculated on each building roof surface at a grid resolution of 5’x5’ (1.5x1.5m). Simulation sensor points are located approximately 1/64” (0.4mm) above and facing in the normal direction of the roof surface.

Simulations are performed with DAYSIM, a validated RADIANCE plug-in which uses a daylight coefficient approach and the Perez all weather sky model (Perez, et al. 1993) to predict annual point illumination and irradiation (Reinhart and Walkenhorst 2001). DAYSIM works by performing one raytrace operation to a sky dome consisting of 145 diffuse sky segments,

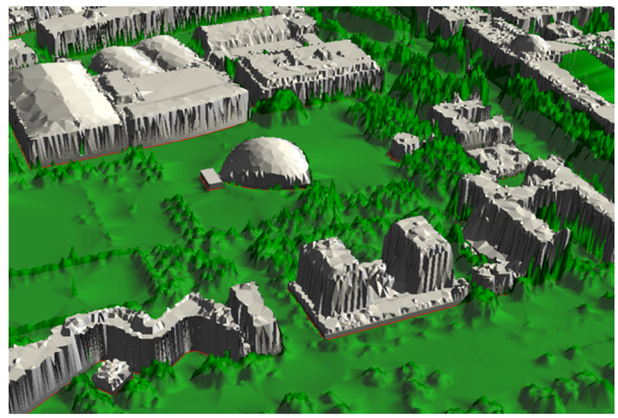
(a) Birds-eye image of the Kresge Oval (Google)



(b) Initial, nonuniformly dense LiDAR point data



(c) Resampled and categorized LiDAR points



(d) Resulting 3D model

Figure 2 Process Images of 3D Model Generation from LiDAR and GIS Data

3 ground segments and a second raytracing run with approximately 65 direct solar positions that are distributed along the solar path. By tracing backwards from the simulation sensor points, each sky segment is then weighted relative to its contributions to each point in the scene. In this manner, irradiation can be simulated across an entire year in any incremental time step without running thousands of separate and lengthy raytrace calculations for each time step.

In order to ensure accuracy, the RADIANCE simulation parameters were considered in relation to the unusually large size of the Cambridge model. Errors in the ambient calculation were calibrated to be acceptable for surfaces spaced four feet apart and larger. As our model was resampled at this resolution in plan and our simulation sensor points are spaced beyond this threshold, the assumption seems reasonable. According to Ward, error will "increase on surfaces spaced closed than the scene size divided by the ambient resolution." Thus the Radiance scene size (26,526.5 ft.) divided by four gives an ambient resolution of approximately 6,750. Table 2 documents the DAYSIM simulation parameters used.

Table 2 Key Radiance/DAYSIM Simulation Parameters

PARAMETER	DESCRIPTION	VALUE
ab	ambient bounces	2
ad	ambient divisions	2048
as	ambient super-samples	16
ar	ambient resolution	6750
aa	ambient accuracy	0.1

Calculation of Photovoltaic Potential

As previously discussed, a key benefit of this method is direct access to hourly simulated irradiation data and the detailed Perez sky model that mimics actual sky radiance distributions for each time step in the year. Knowing in addition the explicit area beneath each simulated point and information about the urban climate, a reasonable approximation can be made for the performance of a PV panel in an urban context.

A direction vector is assigned to each simulation point based on the roof surface normal immediately below it. Assuming that the roof is planar and unvarying below the area the point represents, ~$25ft^2$ in our case, a method of calculating the area is shown in Equation 1,

$$A_{proj} = \frac{A_{flat}}{[0 \quad 0 \quad 1] \cdot \vec{n}} \tag{1}$$

where $\vec{n}$ is the unitized roof surface normal vector.

We further realize that photovoltaic performance is dependant on many factors which are unknown at the time of making a conceptual irradiation map such as module efficiency, panel orientation and maintainance. However, it is known that temperature and radiation heating up the panel will have an adverse effect on its production. The urban ambient temperature (T_{amb}, $°C$) and the incident irradiation (E, Wm^{-2}) at each timestep can be used to estimate the temperature of the photovoltaic panel (T_c), shown in Equation 2, by relying upon knowledge of the nominal operating cell temperature at ideal conditions (T_0) (Luque and Hegedus 2011) Further, the photovoltaic maximum power at ideal conditions (P_{mp0}, W) can be derated based on a temperature correction factor (γ) equal to $0.0038°C^{-1}$ (Equation 3) (Marion, et al. 2001).

$$T_C = T_{amb} + (T_0 - 20°C)E/800Wm^{-2} \tag{2}$$

$$P_{mp} = P_{mp0} * \ [1 + \gamma * (T_C - T_0)] \tag{3}$$

Equations 2 and 3 above are used as a first-order approximation in derating panel efficiency based on temperature and point irradiation at each hourly timestep.

Determination of Useful Rooftop Area

Useful rooftop area in our model is calculated based on predicted economic feasibility of panels installed at a location. Further, any roof surface sloping greater than 60 degrees (67%) was discarded as it is approaching being considered a vertical surface or wall.

On average, PV installations cost approximately $5.67 per watt in Cambridge in 2011 (MassCEC, 2012). We assume that a panel is rated at 17.2 W/ft^2 (185W/m^2) (Sunpower E18/230W 2012), installation cost is $97.52/$ft^2$ ($1049.70/$m^2$), and the cost of electricity is $0.15/kWh. If we consider a 10 year investment period with a 10% discount rate per year, 115.7 kWh/ft^2/yr (1244.9 kWh/m^2/yr) must be generated to have a net present value (NPV) in which the investment breaks even (NPV equals zero). In ideal circumstances this would require a panel efficiency of nearly 80% in Cambridge! To achieve a simple payback over the same 10 year period, only 65kWh/ft^2/yr (699.7 kWh/m^2/yr) must be generated. Still, this requires a panel efficiency of approximately 50%.

However, there are national and state rebate programs that dramatically improve the feasibility of the installation of PV for residential properties. The federal government offers a 30% tax rebate on the cost of a PV installation up to a maximum of $2,000 (Energy Improvement and Extension Act 2008). Further, Massachusetts offers a 15% rebate up to a maximum of $1,000 that can be carried over for three years (Residential Renewable Energy Income Tax Credit 1979). The Massachusetts Clean Energy Center offers a minimum $0.40/W rebate on new PV systems (MassCEC 2012). Finally, Massachusetts offers a 100% protection from increased property taxes due to PV installations for a 20 year period (Renewable Energy Property Tax Exemption 1975). Factoring these rebates into the previous NPV calculation, it is possible to have a break even point for an unshaded panel at ~24% efficiency, which is still not an ideal financial incentive, but things are markedly improved. Looking at simple payback over a period of 10 years for our example Sunpower panel, any point with over 56.6 kWh/ft^2 (609 kWh/m^2) irradiation per year is likely to recoup its value while providing additional savings after the initial 10 year period as the effective lifetime of a PV system is known to be typically greater than 30 years. Thus, points with greater than 609 kWh/m^2 and their associated roof areas are considered to be useful to install PV panels. As such sensor points are displayed spatially across the roof (see results section), it is possible to determine optimal placement locations for PV panels.

Geolocation of Data From GIS to Radiance Models

All GIS models including the LiDAR data and building footprints were constructed in the projected North American Datum 1983, Massachusetts State Plane Mainland coordinates system (Schwarz and Wade 1990). This is a serendipitous choice as distances and areas can still be measured without necessitating corrections. Thus, the Radiance simulation model was built in an identical coordinate system. The Massachusetts State Plane system also has a known relationship between X and Y coordinates and latitude and longitude global coordinates. It is possible to translate easily between the two coordinate systems by use of an Inverse Lambert Conformal Conic Projection with proper parameters.

RESULTS

In this section, the results from methodologies discussed in the "Review of Current Methods" section are compared with our own detailed method. Ten buildings are used for the purposes of the comparison from the over 17,000 in the Cambridge dataset. Of these ten buildings, five can be described as having flat roofs; however, they often have HVAC equipment present on the roof such that it is not truly flat. The other five have roofs of some complexity with at least one ridge line. These test buildings are shown in Figure 3. For our 5'x5' grid of analysis points across each building, annual and monthly irradiation data was used

Table 3 Calculated RMSE of Various Assumptions Compared to Detailed 3D DAYSIM Model Method

METHOD	**RMSE** (TOTAL)	**RMSE** (FLAT)	**RMSE** (COMPLEX)
Solar Analyst	339.2	365.8	274.1
Flat Roof	489.9	456.5	554.2
Constant Value	532.1	488.5	614.7

Table 4 Annual PV Production, Roof Area and Costs as Determined by Various Assumptions

METHOD	**PV PROD.** (MWh/yr)	**AREA** (ft^2)	**INSTALL COST** ($)
Detailed	2,445	113,863	$11,104,375
Solar Analyst	2,148	112,179	$10,940,144
Flat Roof	3,329	143,525	$13,997,132
Constant Value	3,473	143,548	$13,999,375

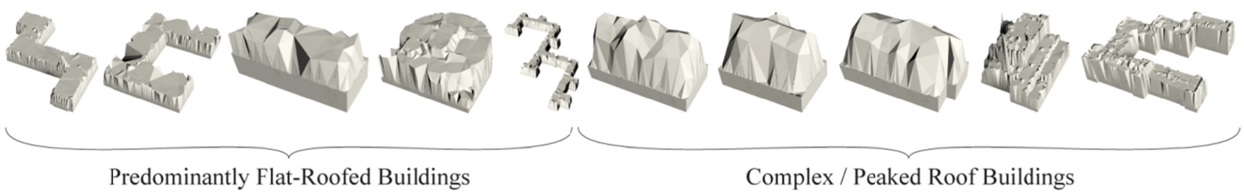
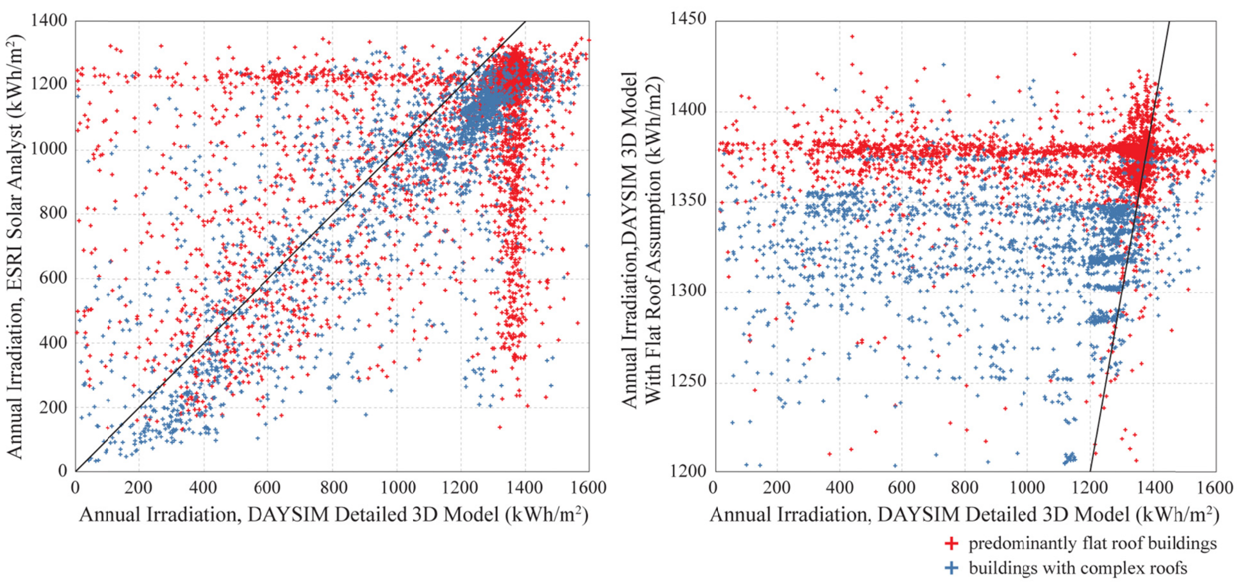


Figure 3 Ten Test Buildings Used in Comparing Results



(a) Comparison of Detailed DAYSIM Model with Complex Roofs and Solar Analyst with Detailed DEM

(b) Comparison of Detailed DAYSIM Model with Complex Roofs and with Flat Roofs

Figure 4 Comparison of Global Irradiation Calculation Using Varied Methods for 10 Buildings

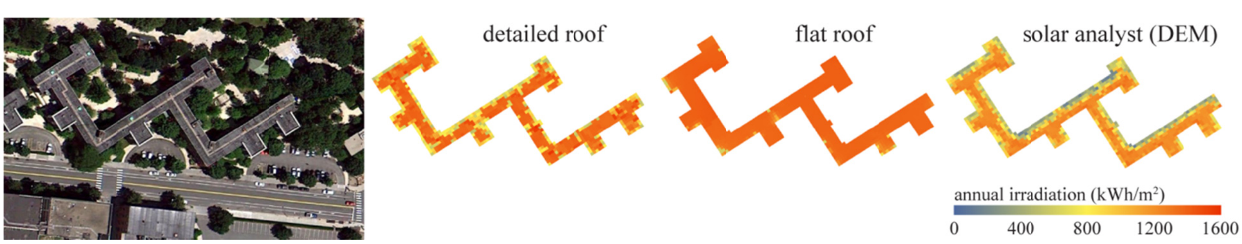


Figure 5 Resulting Point Irradiation Maps For Varying Calculation Methods

as a basis of comparison because the shortest timescale of data that Solar Analyst can return is monthly.

Table 3 shows the RMSE of the other methods compared to the detailed climate-based model. This should not be interpreted as absolute error, as both methods will necessarily introduce errors. Instead RMSE here represents deviation from a best-practice model. It can be seen that consideration of detailed roof geometry is important to accurate calculations as Solar Analyst has the smallest RMSE for buildings with complex roofs at an error of 274.1 kWh/m^2. As expected the flat roof method, even with detailed consideration of climate, performs poorly. Assumption of a constant solar irradiation performs worst.

Comparison with Solar Analyst

When compared to a climate-based raytracing simulation, Solar Analyst appears to estimate less annual radiation for each point. Figure 4(a) shows cumulative annual irradiation for each sensor location across the ten buildings as calculated by the detailed climactic model (X-Axis) and as calculated by Solar Analyst (Y-Axis). It can also be seen that while data is clustered about the identity line, there is a large degree of variance; the RMSE is 339.2 kWh/m^2.

It is expected that a raytracing simulation will on average predict higher values as reflections from the ground, trees and adjacent buildings are being considered where Solar Analyst assumes such effects to be zero. However, the high variance of the data suggests some other effect is at work, and this can be explained by the geometric quality of the simulation models at building edges. Figure 5 shows aerial photographs and planar projections of the predicted irradiation for a single building using different methods which is typical across the ten test buildings. In the process of creating a 3D model of a city we use the building polyline from GIS to create extra points which improve the model resolution at the edge of buildings. As Solar Analyst works across a pure DEM which does not differentiate between building and ground, the calculated slope at edge pixels is extreme and can lead to stratified errors as seen in the extreme outliers in Fig. 4(a) and the upper edge pixels in Fig. 5 (Solar Analyst). Such an error will increase with as the ratio of building perimeter to area increases.

It is useful to further qualify this data into PV electrical yields. Using a simplified equation of annual irradiation multiplied by panel efficiency (0.185) and area, the total electrical yield of systems can be calculated. Using the detailed climate-based method, 2,445MWh/yr was predicted across all rooftops with a combined 113,863 ft^2 (10,578 m^2) of useful roof area. Comparatively, the Solar Analyst method predicted 2,148MWh/yr across 112,179 ft^2 (10,421 m^2) of useful roof area. These differences may not seem large when looking only at predicted energy production in MWh; however, putting the figures in terms of installation costs (dollars) per predicted energy yield (kWh) reveals a different story. The detailed model predictions lead to a cost of \$4.54/kWh while Solar Analyst predictions lead to a cost of \$5.09/kWh – a difference of 10.8 percent. These results are documented in Table 4.

To attempt to quantify temporal differences between the detailed climate-based method and Solar Analyst, we chose a test building with little variation and plotted the monthly total irradiation at each point. This is shown in Figure 6 where points are colored by the monthly global horizontal radiation in the TMY3 data. Here again we observe that for most months the climate-based model calculates greater irradiation than does Solar Analyst, for the same reasons; however, the relative error is greater in months with less overall radiation. As these months have less direct component, it may be that the error will be greater in climates or periods with less direct radiation for the default parameters of Solar Analyst.

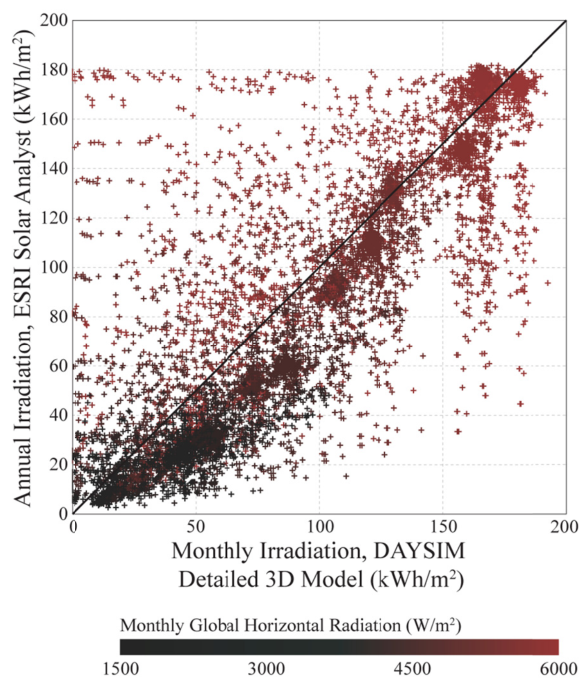


Figure 6 Monthly Point Irradiation for a Single Building Colored by Monthly Global Irradiation

Comparison with Flat Roof Assumptions

A second comparison was run using climate-based simulations for the ten buildings with complex roof forms and with flat roofs. The flat roof heights were derived by discarding points with a z-coordinate greater than one standard deviation from the mean and using the median value of the remaining points.

Figure 7 shows an irradiation map of a test building in context with a detailed roof and with an assumed flat roof; each image displays detailed irradiation calculations of the area using the cumulative sky method (Robinson and Stone 2004). From this image alone, it is clearly visible that a flat roof assumption is going to create extreme differences in the results. This is because roof slope will change the incident angle of radiation as well as the percent and portion of visible sky. Figure 4(b) illustrates a scatter plot comparison with point irradiation from the detailed model using complex roof forms on the X axis and using the flat roof assumption on the Y axis. The flat roof assumption overestimates available radiation as the majority of data points are to the left of the identity line. The reason for this is that there are no roof surfaces that slope to the north, nor are there any surfaces that face surrounding buildings; all surfaces look straight up towards the open sky above the building. Further, it is impossible for HVAC equipment or roof projections to shade another portion of the roof. The effects of roof orientation, in most of our ten test cases, are actually higher than the effects of inter-building shading for a city of predominantly low-rise buildings such as Cambridge.

Comparison with Constant Solar Insolation Method

If for every point the mean global horizontal irradiation from the TMY3 data is assumed, then the RMSE is 532.1 kWh/m^2 compared to the climate-based model with detailed roof forms. The large error shows that a constant assumed value is the worst performing method of solar irradiation calculations. It does not consider climate-specific data, roof shape, inter-building shading nor reflections from neighboring buildings.

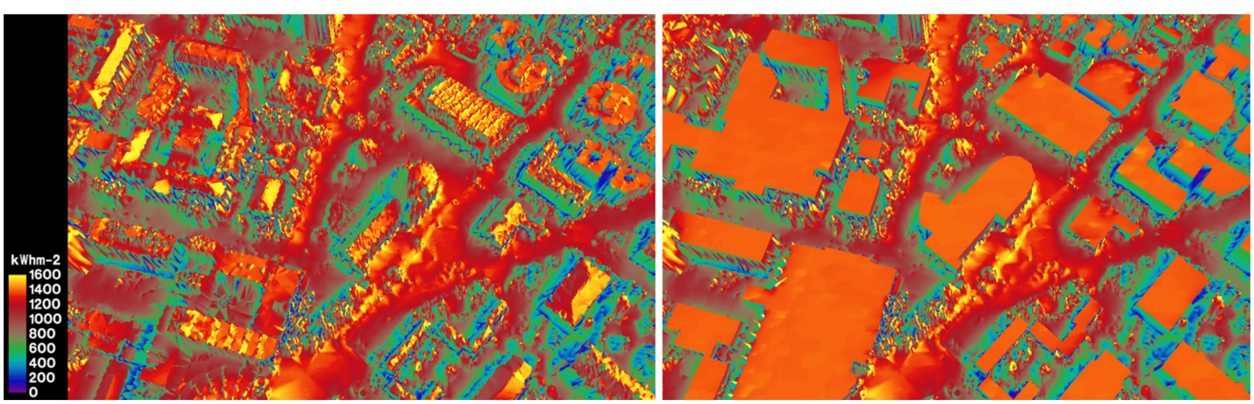
DISCUSSION

Admittedly, the detailed climate-based method takes significantly more time and processing power to achieve when compared to generating a model using the flat roof assumption or using Solar Analyst combined with a detailed DEM. Therefore the reader should ask, what benefits can be expected from using this new method?

First, the value of having a full 3D model of the city cannot be underestimated. Such a model provides opportunities to investigate wall mounted PV, and subsets of the model can easily be extracted to support further analysis by design teams or government entities who make policy. Figure 7 illustrates the utility of this model in analyzing the solar potential of building walls; It can be seen that the wall irradiation of most buildings in the area is less than rooftop insolation; however, in many locations walls can support PV with irradiation >609 kWh/m^2. Secondly, using the validated DAYSIM software provides extra confidence in the simulation results, considers typical climate-based weather information and radiative reflections. Using DAYSIM also provides access to hourly calculated irradiation data which facilitates the use of detailed equations of PV yield and peak load reduction. The simulations can also be run in parallel to increase calculation speed. Finally, detailed rooftop area information is available for quantifying useful rooftop area and the total incident irradiation (kWh) used in the energy generation equations.

Spatial Display of Photovoltaic Potential

To communicate photovoltaic potential effectively, it is necessary to provide useful visual output that aids in the understanding of the data. We divide the simulated rooftop irradiation for Cambridge into four bins meant to rank the relative predicted performance of a panel installed at that point. The thresholds were based on the previously calculated 609 kWh/m^2 cutoff value for



(a) City with Detailed Roof Models *(b) City with Flat Roofs*

Figure 7 Irradiation Maps (Cumulative Sky Method) For Varying Degrees of Geometric Accuracy

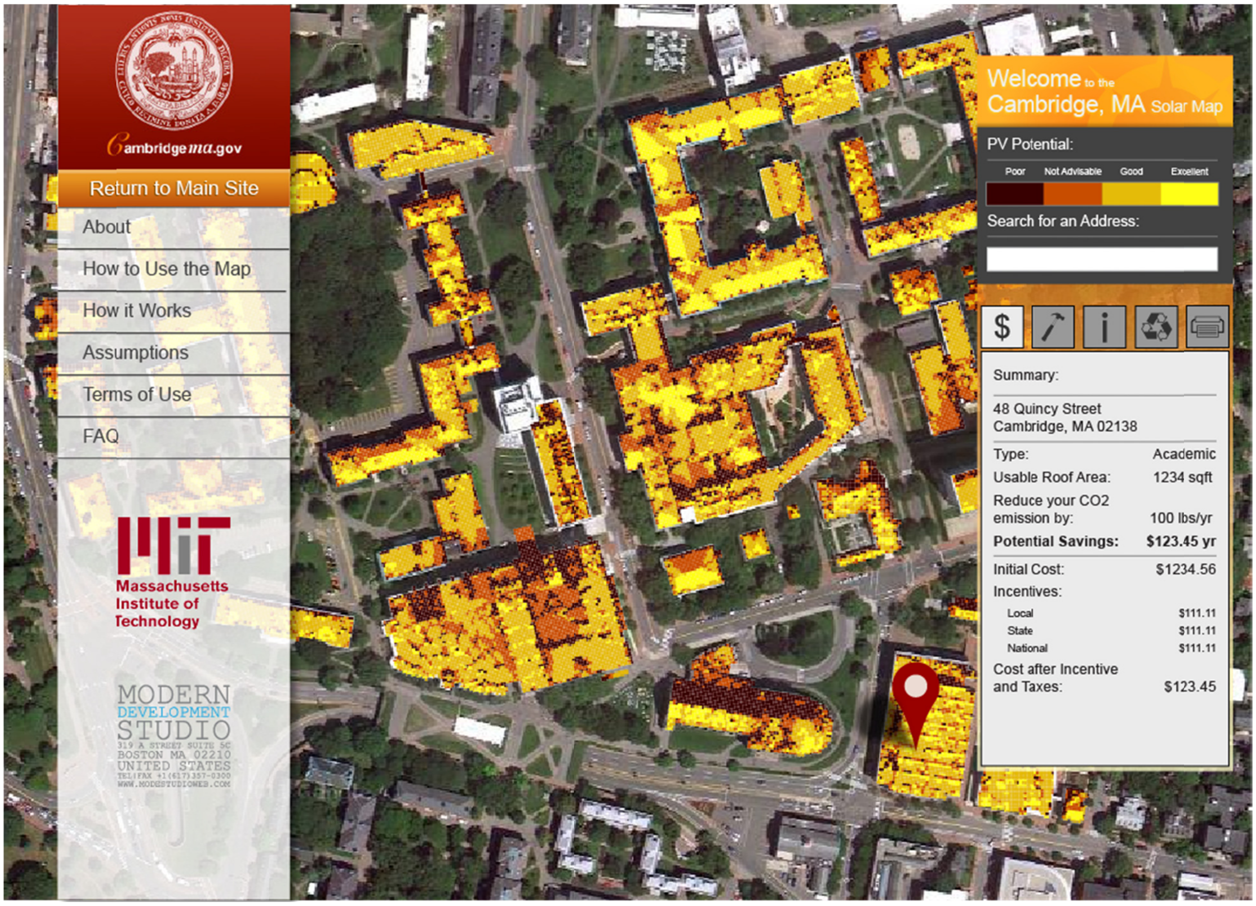


Figure 8 Google Maps API Mockup of Spatial Rooftop Photovoltaic Potential By Modern Development Studio

Massachusetts resident's payback and observations of the Cambridge simulation data. and are at 600kWh/m^2, 1000 kWh/m^2 and 1400kWh/m^2. These irradiation thresholds are then used in the display of data.

CONCLUSION AND OUTLOOK

We partnered with Modern Development Studio (http://www.modestudioweb.com/) to display our results on top of a searchable map document using the Google Maps API (Figure 8). This is the same approach taken by the LA county solar map; however, the irradiation thresholds are tailored to the Cambridge climate. In this way, homeowners and businesses can engage with the map through the ability to identify their roof specifically and notice how its unique form produces varied suitability for photovoltaic installations. Essentially, users of the map feel like the simulation results are personalized to their building which is important to produce confidence in the results and to increase interest in the goals of the map.

To use validated irradiation models at the city-scale is a new effort. We believe that in the future such models will support policy decisions as they allow the ability to predict hourly peak-load reduction at an urban scale or among a group of buildings whereas previous methods have not had this benefit. With increased model quality and certainty about results that can be (at least partially) visually assessed, we aim to increase user engagement with sustainable technologies. Further, our results showed good geometric agreement with the city and higher predictions of PV yield with a 10.8 percent cost reduction for ten typical buildings than the most popular method.

Limitations of Detailed Climate-Based Method

Beyond what was discussed previously, the model has several limitations. Currently all PV panels are modeled as parallel with the roof; however, we have found from discussions with local PV contractors that flat roofed buildings often have PV panels installed at a 45 degree tilt towards the South using standard angle brackets. Future versions of the map will have an additional layer atop flat-roofed buildings analyzing potential photovoltaic installations tilted towards the South in this manner. Further, while our model produces reasonably accurate roof forms, it should be noted that LiDAR data and our point-simplifying method still introduce errors in some buildings.

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