SOLAR 2009: WEB-BASED SOLAR PHOTOVOLTAIC MAPPING TOOLS

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ABSTRACT

As the demand for renewable energy has grown, so too has the need to quantify the potential for these resources. Understanding the potential for a particular energy source can help inform policy decisions, educate consumers, drive technological development, increase manufacturing capacity, and improve marketing methods. In response to the desire to better understand the potential of clean energy technologies; several approaches have been developed to help inform decisions. One technology-specific example is the use of solar photovoltaic (PV) maps.

A solar PV mapping tool visually represents a specific site and calculates PV system size and projected electricity production. This paper identifies the commercially available solar mapping tools and provides a thorough summary of the source data, visualization software program, user inputs, calculation methodology and algorithms, map outputs, and development costs for each map.

1.0 INTRODUCTION

Visual, Web-based solar photovoltaic (PV) mapping products are increasing in prevalence. These tools quantify the potential for solar PV at a specific location to educate the user about the benefits of solar PV and its associated costs and savings. This paper details the layers of information that are used in solar mapping applications and outlines the commercially available solar mapping tools.

Most of these tools are being developed as a part of the U.S. Department of Energy's (DOE) Solar America Initiative (SAI). This initiative aims to make solar electricity from PV cost competitive with conventional forms of electricity by 2015 through R&D and market transformation. Many of the 25 Solar America Cities, part of SAI, are pursing solar mapping to educate their populaces.

These maps empower a resident, business owner, or decision maker to take the first step in analyzing the potential for solar PV at a particular location.

2.0 LAYERS OF INFORMATION

Web-based solar PV mapping tools contain three levels of input data that are used to estimate the performance of a PV array at a given location:

- Topographical data associated with a given location or city. Some of the maps use 3D digital elevation models (DEMs) to analyze the impacts of shading obstructions, identify roof tilt, and estimate the amount of roof area that can be used for a particular installation. Some simplified maps skip this step and do not take into account local topographical interactions associated with shading or roof tilt. The user is then responsible for defining roof area, tilt, azimuth angle, and an appropriate derate factor to account for the impacts of any shading obstructions.
- The climate data that are used to estimate the solar resource. Some maps make simplifying assumptions to calculate an annual solar resource estimate; others use hourly weather data that are derived from ground-based meteorological stations or satellite-derived meteorological data. The third layer consists of the financial and incentive data that are used to calculate the economics associated with an installation. Some tools have predefined financial and incentive data built into the model, some of which

cannot be changed. The financial and incentive data typically consist of:

- Electricity rate ($/kilowatt-hour [kWh])
- Electricity escalation rate (%/yr)
- Installed cost ($)
- Federal tax credit ($)
- State, local, and utility incentives

- The input data are processed to provide an estimate of system size, electricity production, installed cost, and various levels of financial and environmental data. Some solar maps have features that serve as an all-encompassing source of renewable energy information about an area. They link consumers to local installers, provide information about how to capture local incentives, and provide educational information about the technology. Some maps are also used to track the total number of local PV installations, which helps the city understand how well it is meeting its solar installation goals.

3.0 ELEVATION AND SURFACE MODEL DATA

Most Web-based solar PV mapping tools discussed here incorporate topographical elevation data in a city to analyze the solar potential of building rooftops. In lieu of using a solar pathfinder to analyze every rooftop within a city, this is one of the most accurate ways of identifying the rooftop solar potential. A light detection and ranging technique or stereo pair imagery is used to create 3D maps of the city.

3.1. Light Detection and Ranging

Light detection and ranging (LIDAR) technology uses laser pulses to measure elevation at a remote site and produces a 3D elevation image file. The distance to an object is measured from the time delay between the pulse that is transmitted and the reflected signal. LIDAR technology is similar to radar; however, it uses light from laser pulses rather than radio waves.

The data are collected from a LIDAR laser scanner mounted on the bottom of an aircraft. The scanning system requires a ground-base location determined from the global positioning system (GIS) associated with the plane (1). The time delay of the reflectance data depends on the distance to the surface and the type of surface that is reflected. The percentage that is reflected is known as the *LIDAR intensity data*. Light can reflect off metal and nonmetal objects such as snow or leaves. Thus, the datasets contain discernible features such as trees, buildings, and power lines. The scanning system collects the first and last returns or reflections. The first are the reflection off the highest points; the last are the reflection off the ground level. The laser scanner uses a narrow beam that allows high-resolution elevation mapping of terrain. The vertical precision from a LIDAR scan is 15 cm (6 in.) (2).

3.2 Stereo Pair Imagery

Stereo pair imagery consists of images of a single location taken from two offset vantage points. The imagery can be taken from satellite-based cameras or from cameras mounted to the bottom of an aircraft. Sequential photographs need to be taken along common flight lines that overlap by at least 60% (3). The accuracy of the final product is directly tied to the resolution of the original stereo pair imagery. Once the imagery is collected, it is radiometrically and geometrically corrected to create a 3D image of the city. Exact contour lines of buildings and objects are acquired from vector geodata and are used to create a 3D digital elevation map. The imagery can then be used to extract elevation and contour data needed to analyze impacts of shading, orientation, and slope. The primary advantage of stereo pair imagery is that it can capture geographical characteristics of man-made and naturally occurring structures.

4.0 SOLAR RESOURCE DATA

Similar to localized weather patterns, solar radiation characteristics vary with geographic location and time. A significant amount of work has gone into the development of standardized tools and models that can be used to understand the spatial and temporal variations in solar radiation. Solar resource data can be collected from ground-based meteorological stations or derived from weather satellites.

A key requirement of any solar PV mapping tool is its ability to accurately calculate the spatial and time-dependent characteristics of the solar resource at a given location. The National Renewable Energy Laboratory (NREL) and the National Climatic Data Center were among the first to develop a set of standard solar resource models with the National Solar Radiation Data Base (NSRDB) (4). The database used meteorological and cloud cover observations at National Weather Service stations around the country as inputs into models to simulate the solar resource at a site. The database, published in the early 1990s, contains solar resource estimates for 239 stations in the United States between 1961 and 1990 (4). Of the 239 stations, 56 are primary stations and used some ground-based solar measurements; the remaining 183 stations used only modeled solar radiation data derived from meteorological data including cloud cover observations. From these 30 years of hourly data for each station, datasets containing 8,760 hourly records were selected from the NSRDB to represent a typical single meteorological year (TMY) at a given location.

4.1 TMY2

TMY2 datasets are derived from the 1961–1990 NSRDB. The designation of TMY2 was given to differentiate the dataset from earlier datasets derived between 1952 and 1975 from the SOLMET/ERSATZ database (5). The TMY2 datasets provide hourly values of solar radiation and meteorological data for a TMY at a given location, and are intended to be used in computer simulations of solar energy conversion systems. The hourly values represent long-term average values and are not suited for worst-case design condition analysis. The typical values for a month are taken by examining all 30 years of weather data in that month; the one judged most typical is selected for the TMY dataset. The other months are similarly selected. The 12 typical months were chosen based on global horizontal radiation, direct normal radiation, dry bulb temperature, dew point temperature, and wind speed (5).

4.2 TMY3

The TMY3 dataset was based on recently updated weather data from the NSRDB between 1991 and 2005. It was created with recent data from the 239 historic ground-based meteorological sites used in the TMY2 dataset and a number of additional sites. The TMY3 dataset currently includes data from 1,454 weather stations (6). A number of improvements were made to the TMY3 dataset, including a significant increase in the number of sites. The solar radiation data in the TMY3 dataset include satellite-modeled data for 1998–2005, and surface-modeled data for earlier years. The satellite modeled hourly solar data are also available for any location on a 10-kilometer (km) grid. These data were created by the Atmospheric Sciences Research Center at the State University of New York – Albany (SUNY) for 1998 to 2005.

4.3 Satellite-Derived Climate Data

In many U.S. locations, the absence of ground-based meteorological stations has led to the development of modeled solar data from geostationary satellites (GOES). Currently three GOES satellites monitor the Western Hemisphere, one at 75 degrees west longitude to monitor the East, one at 60 degrees west longitude for South America support, and a third at 135 degrees west longitude over the Pacific Ocean. The satellites are positioned at an exact height so they orbit around the Earth at the same speed that the Earth rotates around its axis. This results in stationary positioning. The satellites are used to continuously monitor the atmospheric characteristics, including cloud coverage, of a location and have a resolution approaching 1 km in the visible irradiance range (7). Satellite-derived solar resource estimates are the most accurate form of solar data beyond 25 km from the closest ground-based station. The ability to accurately characterize solar microclimates becomes important when analyzing solar energy systems at locations with no nearby ground-based solar measurement station. The models that process these data provide hourly estimates of global horizontal, direct normal, and diffuse horizontal irradiance levels.

4.4 Data Resolution and Accuracy

The satellite-derived weather data discussed previously have a mean bias error of only 2%–5%, when compared to ground-based meteorological stations (8). This is an incredibly low level of inaccuracy and validates the sophistication of the algorithms that calculate the hourly estimates of solar irradiance. Based on these results, solar measurements from nearby ground-based meteorological stations would provide the most accurate representation of solar irradiance and satellite-derived solar estimates would provide the most accurate representation of solar irradiance when the closest ground-based weather station is more than 25 km from that location.

Regardless of the solar radiation data source, TMY2, TMY3, and satellite-derived solar data taken at a 10-km grid should provide a similar characterization of solar radiation at a given site.

5.0 CALCULATION /ALGORITHMS

5.1 PVWatts

NREL developed PVWatts, an online performance calculation tool for grid-connected PV systems. It is used to estimate the electricity produced from a crystalline silicon PV array at any of the 239 locations in the TMY2 dataset. PVWatts Version 1 (PVWatts V.1) uses a set of internal calculation algorithms originally developed by Sandia National Laboratories called PVFORM. The PVFORM calculation module is built from a series of individual calculation modules. Each module is configured according to the following equations (9):

PV array efficiency:

$$\eta_a = \eta_0[1 - \beta(T_c - T_R)]$$

Direct current (DC) power model:

$$P_{dc} = \eta_a POA$$

The Perez anisotropic diffuse radiation model is used to compute the POA irradiance (10).

Alternating current (AC) power conversion model:

Power conversion unit efficiency:

$$\eta_{pr} = 0.774 + 0.663F - 0.952F^2 + 0.426F^3$$

$$\eta_p = \eta_{pr}(\eta_{RL}/0.91)$$

PVWatts then uses a set of predefined inputs to populate the program with the rest of the data needed to run the calculation algorithm:

- Location (state and city)
- Electricity rate ($/kWh)
- DC size (kilowatts [kW])
- Derate factor
- Tilt angle (degrees)
- Azimuth angle (degrees)

PVWatts V.1 is one of the most widely used PV system calculation tools in the United States. PVWatts V.2 uses the same calculation algorithms as PVWatts V.1; a few corrections are associated with 40-km resolution solar resource data. In My Backyard (IMBY) uses PVWatts V.2 to calculate the performance of a given PV array (11).

6.0 SOLAR AUTOMATED FEATURE EXTRACTION™

CH2M Hill developed the Solar Automated Feature Extraction (S.A.F.E.) methodology to quantify roof area exposed to year-round solar radiation for specified locations. To calculate this area, this technique uses aerial imagery, either LIDAR or other 2D images, to build 3D models. It uses an integrated time-series analysis that combines individual snapshots of the shadows cast from the 3D model at a point in time. These images are combined into an annual shade-free image used to compute the rooftop area that does not receive shade throughout the year. This methodology can account for shading that is attributable to chimneys, air-conditioning units, or other structures, as well as the slope and orientation of the roof. The process does not currently account for shading from trees, but the inclusion of vegetation in the shade simulations is currently under development. The output from this analysis is the shade-free area on a rooftop. This information is presented through a Web mapping portal that enables users to enter an address to retrieve the data about shade-free area on their rooftops.

6.1 ESRI ArcGIS Solar Analysis Tools

The Solar Analysis Tools of ArcGIS, which were introduced in ESRI's ArcGIS version 9.2, calculate solar insolation (W-h/m^2) at a location on the Earth's surface. Insolation maps are calculated with inputs from DEMs. This tool uses point-based imagery of local level elevation, slope, and aspect to determine the amount of energy available. Optimized algorithms account for variations in surface orientation and atmospheric weather data.

Total global radiation ($Global_{tot}$) is calculated from the sum of the direct and diffuse radiation of all sectors on the topographic surface. These are calculated separately for each location and the total produces an insolation map for the whole study area. Detailed models and algorithms used to calculate the direct and diffuse solar radiation can be found in the Solar Analyst design document (12). The outputs from the Solar Analysis Tools include a map of direct, diffuse, and global radiation along with direct radiation duration. The tool also calculates sky maps and horizontal angles for specific cells over the entire DEM.

7.0 SOLAR MAPPING TOOLS

7.1 In My Backyard

7.1.1 Tool Overview

IMBY is Web-based solar simulation tool, and is meant to introduce homeowners to the possible benefits of renewable energy. The main purpose of IMBY is to provide an easy-to-use interface to estimate the hour-by-hour amount of electricity produced by a PV system over a year. IMBY provides a map-based interface and allows a user to specify an address at which to place a PV system. The map centers itself on that address and the user may draw a potential PV system anywhere on the map.

After the user has drawn a system, several default values are used to populate information about the PV system's configuration. These values are the size, derate, tilt, and azimuth of the PV system. The size represents the DC rating of system, the derate is the amount of energy lost in the conversion from DC to AC, the tilt represents the angle at which the system is to be tilted (this defaults to the latitude of the user's location to maximize output), and the azimuth is the primary direction that the system is facing (this is a range of 0 to 360 where both 0 and 360 equal north).

The user then selects the data year. This is the year of resource data used to drive the simulation of the system's output. After the user has reviewed the inputs and made changes, the simulation may be performed. When the simulation is a complete, the user sees a summary window that shows a monthly breakdown of energy generated by the system, as well as a series of inputs used to calculate the system's payback in years. The user can select a second tab that shows an interactive graph of the system's hourly energy output.

Finally, the user can select an example load profile that aims to represent a household's hourly electricity use. The user can select one from a pre-generated list of cities or upload a personal profile that is used to calculate the amount of energy that the PV system might feed back onto the grid. IMBY uses a local utility's residential purchase rate to determine the user's monthly electricity costs and shaves the cost based on the amount of electricity that is fed back onto the grid.

7.1.2 Model Assumptions

IMBY makes no assumptions about local shading or topography; the map is used only as a guide for placing PV systems. Systems may be drawn anywhere in the map space, and are therefore not always realistically placed.

7.1.3 Calculation Algorithm/Methodology

The calculation for the IMBY solar power estimate is based on a modified version of NREL's PVWatts calculator. NREL's SUNY/Perez solar resource data are used to calculate the solar resource. The SUNY/Perez data are included in a satellite-derived hourly dataset that has a spatial resolution of 10 km. The hourly data for the user's location and year are fed into PVWatts and used to generate an hourly time series of AC energy.

This time series represents the estimated output from the user-defined PV system, and is used to generate several statistics that are presented to the user. A table shows month-by-month the sum of AC energy output and the corresponding dollar value that is based on a local utility electricity rate. The PV system's calculated payback is also generated. This number represents the number of years until the system has generated the same amount of revenue as it cost to pay for the PV system. This value takes into account several values:

- The total cost of the PV system, scaled to the system size by the cost per Watt
- A rebate value taken from DSIRE (13)
- Tax credits (state and federal), also taken from DSIRE (13)
- The local utility's residential electricity rate

7.1.4 User Inputs

A drawing tool is used to draw the outline for the potential PV array on a map. The resulting polygon is used to pre-populate several needed (and adjustable) inputs:

- DC size (kW)
- Derating factor
- Tilt angle (degrees)
- Azimuth angle (degrees)
- Data year

7.1.5 Model Outputs

IMBY outputs the following values:

- Initial cost, rebates, and tax credits ($)
- Simple PV payback period (years)
- Monthly production of electricity and respective dollar amount saved

If a load profile is chosen and a comparison is done, IMBY provides a bar graph of the monthly bill reduction after PV is added.

7.1.6 Future IMBY Enhancements

Two primary activities focus on making IMBY a versatile and robust tool:

- Using more realistic building load profiles. NREL is developing the capability to generate several types of building loads for each Solar America City to allow for a more accurate estimate of how the PV system might affect the user's load profile.
- Creating an IMBY version 2. This will provide a more user-centric platform so city planners and developers can return to IMBY again and again. Each time they return to IMBY their previous PV systems will be available. A user could run many simulations of the same PV system against many load profiles and aggregate PV systems to explore with greater detail the impact of several PV systems on a particular load profile.

7.2 CH2M Hill Solar Map and Solar ESTIMATE

7.2.1 Tool Overview

CH2M Hill has developed two products for estimating PV potential on roofs in defined geographic areas: the Solar Map and the Solar Estimate. Both use Google Maps as the visualization platform, enabling users to view an aerial image of a location. These tools allow the user to define an address and output the quantity of PV that could be installed on the roof. They can also project energy and cost savings.

CH2M Hill is currently developing maps for many entities and Cities, and has completed the development of the San Francisco Solar Map (14), which provides mapping analysis of 48 mi^2 and cost the city approximately $250,000.

7.2.2 Model Assumptions

Both the Solar Map and the Solar Estimate incorporate the PV cost assumptions listed in Table 1.

TABLE 1: PV COST ASSUMPTIONS

PV System Size (kW)	Cost ($/W)
0–5	10.50
5–10	9.80
10–50	9.25
50–100+	8.50

The Solar Estimate assumes that only one quarter of the shade-free roof area will be usable for solar because of roof obstructions, shading, pitching, etc.

The San Francisco Solar Map algorithms include an assumption that 100–200 ft^2 of roof space is needed per kilowatt. Annual electricity savings were calculated assuming an electricity tariff equal to Pacific Gas and Electric's average total rate of $0.16474/kWh for residential E1 customers as of May 2008. Carbon savings were calculated based on an assumption that 0.746 lb of carbon dioxide are offset per kilowatt-hour produced by PV (15).

7.2.3 Calculation Algorithm/Methodology

The CH2M Hill Solar Map is a Web portal that uses the S.A.F.E. analysis and other calculations to assess the solar PV potential on rooftops. The S.A.F.E. methodology quantifies the roof area exposed to solar radiation throughout the year for a specified roof. The data produced by S.A.F.E. are then stored in a database and accessed through a portal that can include Google Maps. CH2M Hill relies on tools such as PVWatts or the Clean Power Estimator to compute the size of the PV system and the amount of electricity that would result from a PV system installed in these shade-free roof areas.

The Solar Estimate is also a Web portal that bases its estimates on the area of structures. These data are usually procured from a city's or locality's assessor database. From these data, the Solar Estimate tool calculates potential available roof area for solar PV. The Solar Estimate does not take into account items such as chimneys, air-conditioning units, other structures, or trees that could shade the roof. It also does not consider the slope or orientation of the roof. The resulting roof area value is then used in PVWatts or Clean Power Estimator to determine the size of the PV system and amount of electricity that could be produced for the given roof space.

The San Francisco Solar Map employs the S.A.F.E. methodology. Each building's estimated roof square footage, as obtained from the San Francisco Office of the Assessor-Recorder, was used to estimate available roof area. The S.A.F.E. methodology was then used to calculate the shade-free roof area for each location. The PV system was sized and the system electricity production was estimated by applying the value of peak sun-hours per day. The average peak sun-hours per day were measured in each neighborhood by the San Francisco Public Utility Commission's 11 solar monitoring stations. The solar insolation in San Francisco ranged from 4.1 to 4.6 kWh/m^2/day (16).

7.2.4 User Inputs

The user enters an address for examination of PV potential.

7.2.5 Model Outputs

The CH2M Hill Solar Map and Solar Estimator output the following values:

- Roof size (ft^2)
- Usable roof area (ft^2)
- Estimated solar PV potential (kW)
- Estimated electricity produced (kWh/yr)
- Estimated electricity savings ($/yr)
- Estimated carbon savings (lb/yr)

The San Francisco Solar Map also outputs these values:

- Currently installed solar PV systems (some or all of these)
  - Building owner type (municipal, residential, commercial, schools/libraries, nonprofits, monitoring stations, Environmental Justice Program)
  - Location
  - System size (kW)
  - System output (kWh/yr)
  - Electricity savings ($/yr)
  - Installer
  - Picture of system
- Case studies of local businesses and homeowners who have already installed solar PV systems
- Information about installing a solar PV system, including contact information for local solar installers

7.2.6 Future Enhancements

CH2M Hill is currently developing maps for the Cities of Berkeley, Portland, Sacramento, Pasadena, Anaheim, and San Diego, as well as Forest City military communities and Los Angeles County. The Berkeley map will be a Solar Map that uses the S.A.F.E. methodology and will provide analyses of 12 mi^2. It cost the city $74,000 and is being developed as part of the Solar America Cities Initiative. The Portland map will use the Solar Estimate methodology. It will cost the City $25,000 to develop; it is also being developed as a component of SAI. The Sacramento map will leverage work done through the Sacramento Municipal Utility District Safe Solar Mapping and will result in a homeowner self-assessment tool. It will cost the City $46,000 and is part of SAI. San Diego is having a map developed that will be a Solar Map and that will use the S.A.F.E. methodology to analyze 8.4 square miles. It is part of SAI and is costing the City $65,000.

7.3 Solar Boston Map

7.3.1 Tool Overview

The City of Boston, in cooperation with the Boston Redevelopment Authority, has developed the Solar Boston Map to help track its solar initiative goals and to help residents, business owners, and decision makers calculate the solar potential power available at a given location (17). Boston's Web site was built entirely with ESRI ArcGIS software tools. The Spatial Analyst extension was used to calculate solar radiation. The tool allows the user to define an address for consideration and the output includes usable roof area, potential size PV system (kW), potential annual output, and cost savings resulting from the PV system.

7.3.2 Model Assumptions

The Solar Boston Map algorithms assume that the roof is flat. The calculations for potential PV system size assume the Evergreen Spruce Line solar panel is used and delivers 11.8 W/ft^2 of available roof space. The user selects roof obstructions and shading with a variable roof percent slider. The maximum usable area of the roof is 75% and is assumed to be south facing and free from shading. Annual electricity output is calculated assuming 1200 kWh per installed kilowatt. The potential annual cost savings are determined from the potential annual output (MWh) and an electricity rate of $0.18/kWh. The Boston Solar Map also calculates the potential annual avoided emissions by using the multipliers developed for Massachusetts by Segue Consulting under subcontract to NREL through the City of Boston's Solar City Partnership with DOE. The multipliers for Massachusetts are carbon dioxide 1,146 lb, sulfur dioxide 2.4 lb, and nitrogen oxide 1.1 lb for every megawatt-hour of solar electricity produced.

7.3.3 Calculation Algorithm/Methodology

The Boston Redevelopment Authority used in-house staff to develop the Solar Boston Web site. A bare-earth DEM was used as the foundation of the spatial analysis. A supplementary DEM was created using building elevation attributes from a building footprint feature class that were tagged with first return LIDAR values. The resulting DEM reflects bare earth conditions and building structures. The algorithm for calculating the solar radiance does not account for shading from the trees. The actual pitch of the roof is also not considered and all roofs are assumed to be flat. The resulting roof area is used by the solar tools to determine the size of the PV system.

7.3.4 User Inputs

The user may enter an address or select a rooftop to examine PV potential. The Boston Solar tool also has a drawing tool that can be used to outline the area of the roof for the PV array.

7.3.5 Model Outputs

The Boston Solar Map outputs the following values:

- Roof size (m^2)
- Usable roof percent (max 75%) – adjustable slider
- Usable roof area (m^2)
- Estimated solar PV potential (kW)
- Incoming solar radiation (kWh/m^2)
- Estimated electricity produced (kWh/yr)
- Estimated electricity savings ($/yr)
- Estimated carbon savings (lb/yr)
- Currently installed solar PV systems (some or all of these)
  - Location
  - System size (kW)
  - Installer
  - Picture of system
- Information about installing a solar PV system, including contact information for local solar installers

7.3.6 Future Enhancements

The team that developed the Boston Solar Map hopes to update its LIDAR scan data to include the first and last returns with higher resolution. A more detailed DEM would distinguish trees and other objects that could shade the roof. The software calculations for solar radiance on the roof could be enhanced to include pitch and shading.

8.0 COMPARATIVE ANALYSIS

A comparative analysis was performed to examine the output results from the different mapping applications. The Solar Boston Map and the San Francisco Solar Map are location-specific, and could therefore not be compared against each other. Thus, two analyses were performed, comparing their outputs separately against those of IMBY and PVWatts. The first comparison will be called the San Francisco Tool Comparison, and the second will be called the Boston Tool Comparison. The same PV system size was used for the three analyses in each comparison.

The San Francisco Solar Map estimated that 319,375 kWh/yr of electricity would be produced by a 175-kW PV system; this was the highest output value of the three tools. The lowest value was 208,059 kWh/yr, which was generated by the IMBY tool. The difference between these highest and lowest output numbers is 42%. This is not negligible. The discrepancy in numbers could be attributed to an overestimate in solar resource or in PV system efficiency by the San Francisco Solar Map, or to an underestimate by the other tools.

TABLE 2: SAN FRANCISCO TOOL COMPARISON

Sample Address: 211 Main Street (Commercial)	**SF Solar Map**	**IMBY**	**PVWatts**
PV potential (kW)	175	175	175
Elect. Produced (kWh/yr)	319,375	208,059	219,902
Elect. Cost Savings ($/yr)	52,614	26,842	27,487
Assumed Elect. Rate ($/kWh)	0.16474	0.13	0.125

The highest projected electricity output from the Boston Tool Comparison was 128,647 kWh/yr, which was the output from the Solar Boston Map. The lowest value was 117,621 kWh/yr, which was generated by the IMBY tool. The difference between these numbers is 9%. This is not a large discrepancy.

TABLE 3: BOSTON TOOL COMPARISON

Sample Address: 61 Eutaw Street (Commercial)	**Solar Boston Map**	**IMBY**	**PVWatts**
PV potential (kW)	118	118	118
Elect. Produced (kWh/yr)	128,647	117,621	121,851
Elect. Cost Savings ($/yr)	23,156	17,229	14,378
Assumed Elect. Rate ($/kWh)	0.18	0.15	0.118

Both tool comparisons show a fairly large range in projected electricity cost savings—a difference of 65% between the highest and lowest values for the San Francisco Tool Comparison and a difference of 47% for the Boston Tool Comparison. These variations can be attributed to the differing electricity rates that the tools assume as well as the varying estimated amounts of electricity produced.

9.0 CONCLUSION

Solar mapping applications are increasing in prevalence; maps are being developed for geographic areas ranging from cities to the entire United States. Although these tools are still in their infancy, their potential for informing decisions is quite large. As an example, in just one month more than 3700 people have visited the San Francisco Solar Mapping Web site (18). However, the number of installed solar PV systems that have resulted from these maps is currently unknown. In the future, as cities and private entities make tough decisions about how to make the largest impact toward renewable energy technology adoption with minimal funds, they will need to weigh the costs associated with map development against the benefits, many of which are currently unknown.

10.0 NOMENCLATURE

η_a = Efficiency of the PV array
η_0 = Measured efficiency at the reference cell temperature
β = Rate of change of efficiency with respect to T_c
T_c = Calculated cell temperature
T_r = Reference cell temperature
P_{dc} = Direct current power
POA = Plane of Array (POA) irradiance, W/m^2
η_{pr} = Efficiency of the power conversion unit
F = Fraction of total rated load
η_p = Actual efficiency of the power conversion unit
η_{RL} = Efficiency of the power conversion unit at full load

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