# Toward comprehensive solar energy mapping systems for urban electricity system planning and development

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## Abstract:

Continued growth of distributed solar energy capacity in urban environments is expected to create a new range of intersectional challenges for urban planners, utility operators, policy makers and renewable energy system owners. One example is the 'duck curve' phenomena, which occurs when the rate of rooftop PV system adoption begins to disrupt the daily pattern of electricity supply to which utility infrastructure and practices have adapted. As more PV is adopted within a given service area, utility companies are forced to adapt accordingly. Such challenges carry a spatial component due to the inherent distributed nature of solar energy installations. This paper assesses and demonstrates the role of spatial decision-support systems (SDSS) in producing reliable data that can facilitate communication and planning between multiple stakeholder groups. A review of tools that already exist in this space demonstrates weaknesses in three crucial areas: functional capacity, spatial capabilities and/or transparency. We propose a workflow that models a suitable solar SDSS and demonstrate its application. A case study of "duck curve" effects in the City of Philadelphia allowed net load ramp-rate mitigation strategies related to rooftop orientation to be compared. This demonstration serves as the first step of work aimed at development of a fully functional and generalizable SDSS that can help to better understand the implications of one stakeholder's decisions on another, and to foster communication across those stakeholder groups – in this case, building owners and utility companies. More of these tools are needed to quantitatively inform stakeholder conversation, supporting continued growth of urban solar energy.

## 1. Introduction

During the five-year span from 2010-2015, residential solar electric power showed greater than 60% annual growth in the USA. Now, more than 2500 $MW_{dc}$ are installed each year, as distributed systems individually connected to respective local distribution grids (Solar Energy Industries Association, 2017). The implementation of distributed photovoltaic (PV) technologies is transforming the urban environments of cities from spaces of energy consumption to those of energy production (Droege, 2008). Distributed solar power systems are micro-scalable and open up new investment opportunities for electricity generation within a city, empowering consumers to become producers (so called 'prosumers') (Rickerson et al., 2014). The changes involved in a rapidly expanding solar contribution inside of cities are expected to have disruptive implications to urban electricity infrastructure and its related institutions, and will require tools to evaluate and plan for the coming shifts.

Urban electricity systems evolved to carry flows of electricity primarily in one direction, from relatively large, centralized generation facilities at distant and isolated locations. Urban energy planners and policymakers traditionally focus primarily on variable energy consumption, with little attention given to energy production in the context of urban design and governance. Indeed, the disruptive nature of distributed PV systems is leading to new relationships within and between various stakeholder groups within the city. As residents, commercial building owners, and community groups become prospective investors they search for profitable, low-risk sites to deploy distributed PV systems. Their investment potential is shaped by zoning and bylaws set by city officials, along with infrastructural investment decisions by system operators. All of these local level choices are shaped by state and federal level government regulations, tax breaks, subsidies, or secondary carbon markets. In order to realize the full potential of distributed PV systems and to manage their impact on urban energy systems, it is important to coordinate decision-making process and outcomes across these stakeholder groups.

Although there is no central authority controlling exactly where distributed PV systems are located, we argue that spatial decision-support system (SDSS) can simultaneously help to target investment decisions, inform strategic-level decisions about generation goals and targeted policies/utility incentives, and support scenario modeling to allow various stakeholder groups, especially electric utilities, to understand the challenges they may face with greater levels of distributed PV deployment within their region of interest. The purpose of this paper is to report on the development and application of a comprehensive tool that is being designed to facilitate informed decisions related to distributed PV implementation and planning in an urban setting. By comprehensive, we mean a system that has capacity to coordinate decisions across geographic scales and stakeholder groups. Although great strides have been made in the development of SDSS for energy planning, there is a clear need to develop SDSS that can communicate within and between multiple stakeholder groups rather than just investors (Camargo et al., 2015). Our research aims to close this gap. To demonstrate how, we provide a case-study of a duck-curve analysis in Philadelphia.

The paper is broken down into four parts. First, peer-reviewed literature is surveyed in order to situate our research in emerging ‘best practices’ (see also Freitas et al., 2015). Second, we describe the conceptual workflow of our tool. Third, we apply the tool in a case study region to demonstrate its functional capacity and highlight ways it might help to coordinate and communicate stakeholder expectations and decisions. We conclude with a discussion about the role of collaborative GIS and online platforms in improving the ability of these tools to contribute to stakeholder engagement and institutional capacity for more intensive distributed PV development.

## 2. Mapping solar energy: building on the state-of-art

Investment decisions, policy decisions, and planning decisions related to distributed PV systems are underpinned by questions of a geographical nature. What is the full potential of the distributed PV resource base? Where are distributed PV systems viable? How will resource access and system viability change under targeted policies, new regulation, and / or new technology? With these questions in mind, distributed PV and urban energy planning has been a growing application area for geographic information systems (GIS). GIS tools can be used to map the resource in-place, based on empirically generated solar radiation data or by modeling solar radiation in a spatial environment. These geophysical data can be combined with a range of other data in order to build a cartographic model from which to identify suitable or low-risk areas for RE development, according to preferred attributes such as proximity to a feature of interest, or spatial correlation with a variable of interest (Calvert et al., 2013; Freitas et al., 2015; Resch et al., 2014). Once in a digital spatial environment, distributed PV resources can then be queried for analysis across scales, from the site-level to the full spatial extent of data availability.

Recently, GIS applications for distributed PV research have leveraged the strengths of data from light detection and ranging (LiDAR) systems (Bayrakci Boz et al., 2015). LiDAR data can produce highly accurate digital surface models, vastly improving upon previous efforts based on photogrammetry and aerial photos (e.g., Wiginton et al., 2010).

As these spatial models improve, they are being extended into more comprehensive spatial decision support systems (SDSS) by combining with technology models which estimate energy and financial returns at sites of interest. These SDSS are increasingly made available online, albeit in a simplified form, in order to improve public access to data and information about distributed PV potential and actual development within a city (Kanters et al., 2014). According to Nyerges and Jankowski (2010), a fully functioning SDSS should perform three functions - data management, data analysis and data visualization – and help to facilitate informed decisions across multiple timescales - strategic (programming), tactical (planning) and operational (implementation).

## 2.1. Shortcomings in existing tool capabilities

Although significant progress has been made in the development of SDSS to facilitate informed decisions related to distributed PV and energy system planning, a review of existing tools has revealed three primary shortcomings:

i) functional capacity: *an inability to address and vary financial parameters and technological performance parameters within the model*

ii) scalar discordance: *a mismatch of low-resolution spatial resource data with high resolution site-specific models*

iii) lack of transparency: *users are unable to explore the underlying assumptions, inputs, and code used to construct estimates of outputs of electrical power, financial estimates, and uncertainty*

***i) Functional capacity:*** Two aspects of functional capacity are relevant to development of a suitable SDSS for solar PV analyses: model functionality and user interface functionality. An effective SDSS must have the ability to model the solar resource, the production of useful electrical energy from the resource, and the lifecycle financial cost/value proposition related to the sale of said electricity in place. The variety of stakeholders who may have an interest in using this type of SDSS necessitates that the tool enable users to implement variations in parameters related to each of these modeling goals. In terms of functional capacity limitations in existing tools, most tools capable of supporting spatial decision-support analyses, such as the r.sun package in GRASS and Solar Analyst in ArcGIS, focus specifically on solar irradiation modeling rather than on assessing solar energy potential. Tools have been developed to extend this functionality by way of cartographic models that identify suitable areas for distributed PV implementation and technology models which simulate electricity generation potential (e.g., Masa-Bote and Caamaño-Martín, 2014; Santos et al., 2014). In the past ten years, there have been a growing number of web-based tools that perform these functions; notable among them the systems developed by the companies Critigen and Mapdwell. Tools developed by Mapdwell are based on a paper form Jakubiec and Reinhart (2013), who integrate a GIS-based three dimensional model of urban morphology with hourly irradiation simulations as well as a crude financial module to predict city-wide electricity gains and estimate site-specific financial returns of solar PV in their study area (Cambridge, MA, USA). Although their methodology for mapping solar potential is found to be within 4-10% of real world conditions, the user of their online tool is unable to control all key parameters of the financial module (e.g., tax rebates, panel costs, cost of debt). Inability to change key parameters in the techno-economic model limits the ability of the user to simulate new connections between policy and technology that ultimately shape system economics and likely spatial patterns of development within a city.

There is additionally limited capacity for these tools to inform different stakeholder groups beyond project developers. In all cases discussed above, prospective sites for distributed PV are identified and ranked using primarily techno-economic criteria, including relative access to solar irradiation, site accessibility and surface area (e.g., Bayrakci Boz et al., 2015). Although these features are helpful for the prospective investor, they are only a starting point for a city planner or an electricity distribution system operator who might measure 'suitability' differently. For these stakeholder groups, investing in low income areas or in congested areas, respectively, might be important criteria to layer into the map for the purpose of targeting investments that achieve multiple objectives. As such, there is a need for solar PV SDSS to be built in a way that enables more customized siting criteria, and / or to layer additional siting restrictions onto investor-oriented site-suitability models.

***ii) Scalar discordance:*** Part of what has contributed to the gaps identified above is the lack of appropriately scaled SDSS. One on hand, solar resource data and resource decomposition tools are often low spatial and temporal resolution from national databases that reach broad audiences with state- or national-level coverage (e.g., the PVGIS tool at http://photovoltaic-software.com/pvgis.php). Although this coarse scale of analysis can inform a geographically dispersed audience, the data do not provide sufficient detail to allow individual system modeling that supports local stakeholders directly involved in distributed PV systems in a specific municipality. On the other hand, data and tools that provide high levels of detail are site-specific, able to provide information for only a single spatial unit at a time (e.g., Kanters et al., 2014; RETScreen; PV Watts Version 2; System Advisor Model). Here we notice a trade-off between informing a large audience and providing relevant information. Neither end of the scalar spectrum is sufficient to help coordinate the decisions and expectations of local decision-makers who are in the best position to actually implement and control PV system uptake.

***iii) Transparency:*** In order for an SDSS in renewable energy to meet the needs of users, clear attribution of work-flow methods, data sources, and processing algorithms is necessary to permit users to evaluate uncertainties and mechanisms of data processing, key for decision-making and future research purposes. Users who wish to build on these tools have a sense of where they might contribute in a meaningful way. The identified existing SDSS for solar energy either utilize methodologies that do not meet the full range of functional capacity identified, or do not disclose their solar enery estimation methodology in a transparent way. Almost all solar resource, solar power conversion, and financial estimation algorithms are public knowledge from decades of prior research in academia and the national labs. A number of simulation software are available, including PVFROM, PVSIM, PVSYST, Sandia PV Array Performance Method, and System Advisor Model (SAM) from the National Renewable Energy Laboratory. Though each of these tools utilize transparent methodologies, and is suited for detailed analysis of solar energy technical and financial performance, they suffer from the scalar discordance problem already discussed, and are unable to intrinciscally incorporate geographically distributed analyses for coupling with other spatial data.

To support further development, we have chosen to apply the modeling provided by SAM, as a highly transparent framework with clear attribution and mature integration of both systems performance models for solar resource decomposition, and component-based modeling (beam and diffuse irradiation components projected on the plane of array) of technological equipment (PV modules, power inverters, and batteries) and financial instruments necessary for project evaluation. In addition to detailed public documentation of the methodology, SAM is freely available, offering a relatively low barrier of entry for both students and professionals. It has been popular with project managers, engineers, policy analysts, and researchers, and provides a software development kit (SDK), called the SAM Simulation Core (SSC) (National Renewable Energy Lab, 2014), that allows it to be easily integrated into other software applications. Within SAM, system parameters, including model input and financing options, can be specified and even modified. .

## 2.2. The need for further Solar SDSS development

Generally, tools that are strong on providing spatial data tend to be weak on techno-economics, and vice-versa; while tools that cover large geographic areas are able to capture a large audience, but are not sufficiently technically detailed to provide meaningful decision-support. What is required is a tool that works toward integrating transparent, detailed local technoeconomic models  with appropriate spatial scalability and while providing users with the ability to control and modify all parameters affecting the analysis. In sum, current SDSS in solar energy are not capable of answering ‘what if’ types of questions which measure and communicate risk within a stakeholder group, and which highlight interdependencies across stakeholder groups. What are the system consequence of long-tail, high impact events, such as a period unusually high demand or unusually low irradiation? One could also consider the impact of a hike in electricity charges to homeowners and businesses. What is the scale under which we can accomplish virtual net metering that makes sense for my apartment building? What level of penetration is possible based on solar gains in the city? What level is likely based on existing electricity rates, distribution system capacity, and other factors? Addressing questioning along these lines is partly a matter of balance and scale, and definitely focuses the tool needs more toward homeowners, renters, business owners, and city planners (as opposed to project developers and financiers).

## 3. Toward SolarPVAnalyst 2.0

This study proposes a workflow framework that can serve as a model for suitable distributed solar SDSS development. The breadth of stakeholder interests at play in solar energy development make identification of a single suitable tool difficult, and makes the use of a one-size-fits-all approach extremely difficult. Rather, we propose a workflow that advocates a modularized understanding of solar analysis, allowing independent conceptualization of each individual step of the process and greater flexibility in implementation.

Three steps describe the workflow required: Analysis of geographic data results in the selection of a set of rooftops subject to criteria of interest. Modular technoeconomic modelling is performed to simulate the performance of solar systems using the characteristics of each rooftop. A set of general results are produced and returned, allowing the interpretation of the data’s impacts by the user. Intrinsically, such a workflow follows an iterative process, by which variations on policy or planning scenarios can be considered. A sketch of this workflow is shown in Figure 1.

Our workflow is designed to enable, among other things, 'what if' type scenarios about spatial patterns of rooftop solar implementation for utility developers, and to help direct targeted approaches for developer campaigns or infrastructure investments, and to communicate urban solar energy plans. In this way, the tool can not only facilitate informed decisions within stakeholder groups, but also help to coordinate the conversation across stakeholder groups.

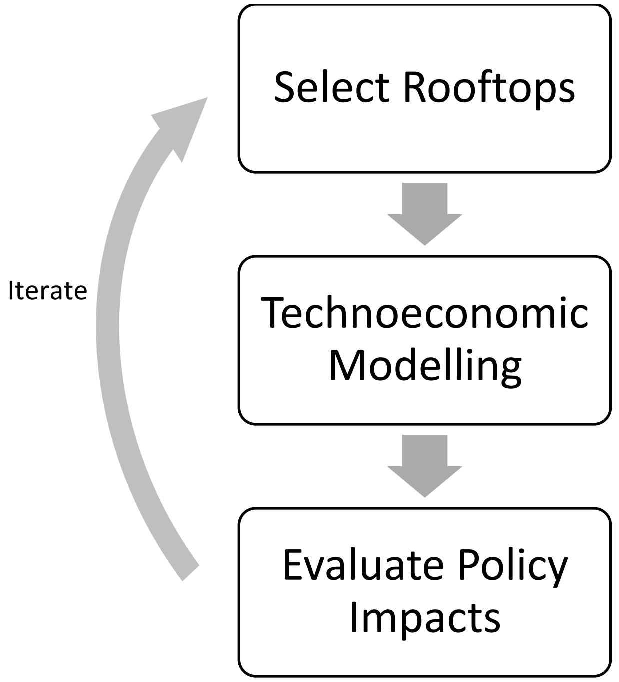


**Fig. 1: Model workflow for SDSS development**

As described previously, technoeconomic modelling in the workflow we implemented is provided by SAM, which was selected for its transparency and complete, physics-based, model functionality. Three modules of the SSC (pvsamv1, utilityrate, and cashloan) provide the functionality needed to simulate the performance of a solar system, and to perform a life-cycle cost economic analysis. These modules require a large number of input parameters, and are accessed in a format that is difficult to automate. Therefore, a wrapper was created for the three modules, providing a streamlined interface for the programmer to pass input parameters and acquire output data. The wrapper has been publicly released as an open source package (https://github.com/hardisty/pv-analyst), and will be used to facilitate future development.

The workflow we have developed represents a flexible platform, enabling functionality for a variety of comparative analyses to inform policy decision making. Integration of renewable energy technical models with existing spatial platforms allows users to combine information and open the door to crosscutting analyses that consider a breadth of variables not well explored and stakeholders not served using traditional approaches with the component models in isolation. An interesting example lies at the intersection of technological development of renewables and social access to resources; policies may be considered to provide pathways for renewable energy benefits to those least able to gain such access on their own in an urban environment, including the economically disadvantaged, or those lacking access to locations for installation (e.g. those who live in rental housing). Ideal application of this workflow for this purpose would allow these target groups to be identified using existing GIS tools based on economic criteria, and would allow the introduction of additional quantitative technoeconomic data about perspective solar energy systems. This multidisciplinary approach to renewable energy enables to state-of-the-art tools in both spatial and solar analyses to conjoin for a shared purpose.

## 4. Case Study: Philadelphia Duck Curve Net Load Profile

The following section demonstrates the use of the workflow we describe to generate quantitative spatially-sourced data that can be used to interpret policy proposals aimed at a potential challenge: rapid load ramp rates caused by distributed PV generation throughout the City of Philadelphia.

The term "duck curve" was first coined to describe the shape of the daily net load (electric demand) profile across the entire state of California (~424,000 km$^2$ of space), containing rapid morning and afternoon ramping of the daily net load as a modeled result from different levels of solar penetration, as distributed solar growth (Lazar, 2016). Overgeneration, particularly in California, may result in a variety of both economic and reliability challenges on the grid management level (Lew et al., 2015). Shaker et al. (2016) describe some of the expected effects on the net load curve shape and ramping behavior. Bird et al. (2014) describe current curtailment practices in the western states, with a specific focus on renewables and describe the role that adjustments to the transmission system have reduced the need for curtailment. Recent analyses have also determined that the net load effects are occurring in California more rapidly than initially predicted, and that utility scale solar appears to be a relatively large driver as compared to distributed PV (St. John, 2016). Careful planning for renewables' impact on grid operations may help to ameliorate these challenges (Denholm et al., 2015) and maintain grid stability.

A number of studies have investigated or modelled the influence of renewable generation on net load. A case study conducted by Azzopardi and Gabriel-Buenaventura (2014) demonstrates the impact of renewable generation on net load profiles and analyzes the economics of various amelioration strategies, specifically identifying demand management and energy storage as having potential. Huber et al. (2014) describe the flexibility needs of power systems at various scales and with respect to various renewable scenarios, identifying a greater need for flexibility in smaller, regional networks with regard to wind power. Lave and Ellis (2016) compare various penetration scenarios consisting of a mix of wind and solar to observe the effect on the reductions in net load. Schill (2014) analyzes net load in Germany and develops an optimization for the degree of energy storage required to reduce curtailment of renewables. Belderbos and Delarue (2015) propose a model to identify an optimal mix of base and peak generation based on a given level of wind penetration. Zhu et al. (2017) report a model for appropriately sizing distributed storage capacity at small scales (residential or distribution level) within a grid with high solar penetration. Models of energy storage (Lamadrid, 2015) identify grid congestion as an important parameter in understanding the shared roles of storage and renewable generation.

Policy and planning proposals to deal with net load issues on grid stability have been discussed in reports from various levels of stakeholder groups. Like the generation challenges, solutions are likewise spatial in nature. Schwartz et al. (2012) recommend careful planning of renewable installations to ensure that anticipated generation and utility load profiles are favorably matched. Lazar (2014) proposes west-facing solar to mitigate high ramp rates in the net-load profile, along with planned distributed storage and demand management. CAISO (2016) identify enhanced participation in regional efforts, increased storage and time-of-use incentives as possible strategies to prevent oversupply. Models already exist to help plan for energy storage to perform time-shifting of the generated energy (Lamadrid, 2015; Schill, 2014; Zhu et al., 2017).

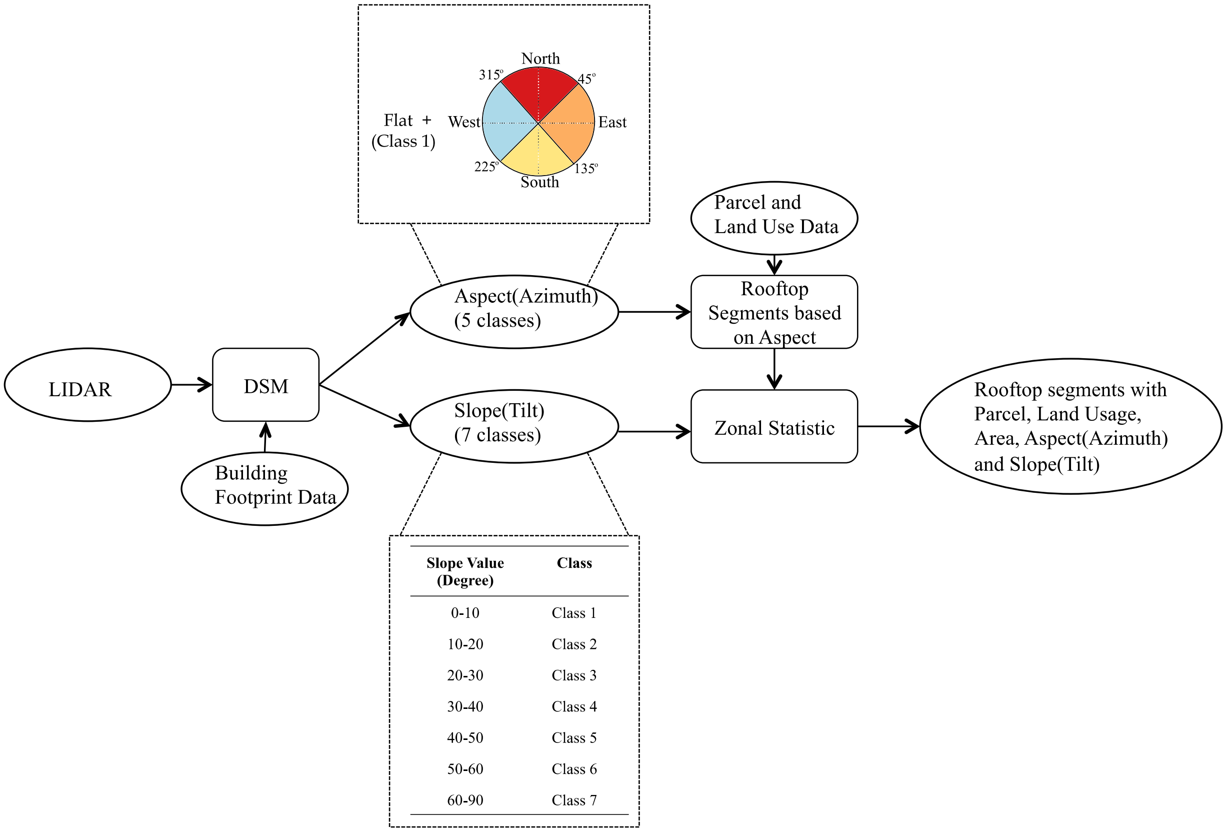
This problem remains inherently spatial in nature, due to the intrinsic distribution of the new generation and its location within the existing transmission infrastructure. Continued expansion of utility scale solar will add semi-localized sources to the grid that need to be accounted for. These installations may develop in remote areas relative to demand. Additionally, from a D-PV perspective, the availability of urban sites with suitable solar resource does not necessarily coincide with availability of suitable transmission capacity to utilize and route the additional remote generation. Though a great deal of discussion in literature has been generated about the net load issues at various scales and in various parts of the world, little truly addresses the geographic nature of the problem in a generalizable sense. While studies in literature commonly make use of geographic information in creating a setting or case study for the research, the results and analysis are not truly generalizable. Utilization of GIS or other SDSS would allow models in literature to be applied in different regions and would make progress toward unifying approaches to the problem. SDSS may assist in integrating data from projections of future growth of load or generation, evaluating the effects of renewables on net load, and evaluating the efficacy of strategies to mitigate net load impacts by modelling relationships to existing transmission capacity and economic drivers.

The workflow developed here allows a simple platform for investigation of outcomes related to these duck curve mitigation strategies. Specifically, we have conducted a case study demonstrating calculation of the annual net load impacts of growing solar penetration in the City of Philadelphia and how, following Lazar (2016), systematically planning the orientation of renewable installations affects ramp rates in the aggregate net load profile.

## 4.1. Rooftop selection

The rooftops were extracted using Light Detecting and Ranging (LIDAR) and building footprint data with an ArcGIS model. Parcel data and land use data were utilized to obtain information about the extracted rooftops. Following the extraction, aerial photography was used to verify the rooftops. In total, 1041 las (LIDAR) files were available for City of Philadelphia. In the analysis, given the bulk size of data files and consequently the computational time concerns, the City of Philadelphia was separated into 45 parts using census tracts. This resulted in running the analysis in different computers at the same time and allowed the ability to stitch the parts together at the end.

In the ArcGIS model, two key parameters were considered: slope (tilt) and aspect (azimuth). The workflow of the model is presented in Fig. 2. All geo-processing steps were conducted within the ArcGIS environment. A Digital Surface Model (DSM) was first created by the LIDAR data and was clipped using the building footprint data in order to select out the rooftops. Then, slope and aspect layers were created from the DSM. The aspect (azimuth) layer was classified into five azimuth bins representing the four cardinal directions along with "flat" rooftops, with had no sensible orientation. Next, the slope (tilt) layer was grouped into 10° bins (e.g. 0° - 10°). All rooftops with measured slope less than 10° were assumed to be flat. If the slope exceeded 60 degrees, the polygon was eliminated, as it was deemed not suitable for the PV rooftop panels. As a result, the slope (tilt) layers were classified into seven classes. Finally, the rooftop segments were created based on the aspect (azimuth) classes and their slope information were calculated using zonal statistic with slope classes. Additionally, land usage and parcel data were added into the rooftops segments. This resulted in the creation of a final rooftop segment which included parcel ID, aspect (azimuth), slope (tilt), land use, and area information.



| Slope Value (Degree) | Class |
|---|---|
| 0-10 | Class 1 |
| 10-20 | Class 2 |
| 20-30 | Class 3 |
| 30-40 | Class 4 |
| 40-50 | Class 5 |
| 50-60 | Class 6 |
| 60-90 | Class 7 |

**Fig. 2: Workflow the ArcGIS model**

## 4.2. Technoeconomic modelling with SAM

Solar PV systems were simulated on each of these rooftops using the SAM SSC. The array configuration and electrical connections were determined for each rooftop using some simple details of the modeled system components and the rooftop area. The allowable number of modules per string was first computed based on the inverter maximum operating voltage. The maximum number of modules that could be placed on each rooftop was found by scaling the module area to the rooftop area, with the restriction that an integral number of resulting strings were required. No detailed, geometry specific module placement was performed. Inverters were simulated using a fixed set of voltage and efficiency characteristics, and were sized at 115% of the array’s power capacity.

Electrical load data were obtained for the PECO (the utility) coverage area from PJM (the regional transmission operator). Load data for the 2014 calendar year were processed to produce average hourly values for each month (PJM, 2016). The solar resource was modelled using both actual meteorological conditions for 2014, and Typical Meteorological Year version 3 (TMY3)

(Wilcox, 2012) data for the location. The conclusions drawn from the results were observed to be very similar for these two datasets, and as a result, only TMY3 results will be shown as indicative of long-term average behavior. A summary of the workflow used in this process is shown in Fig. 3.

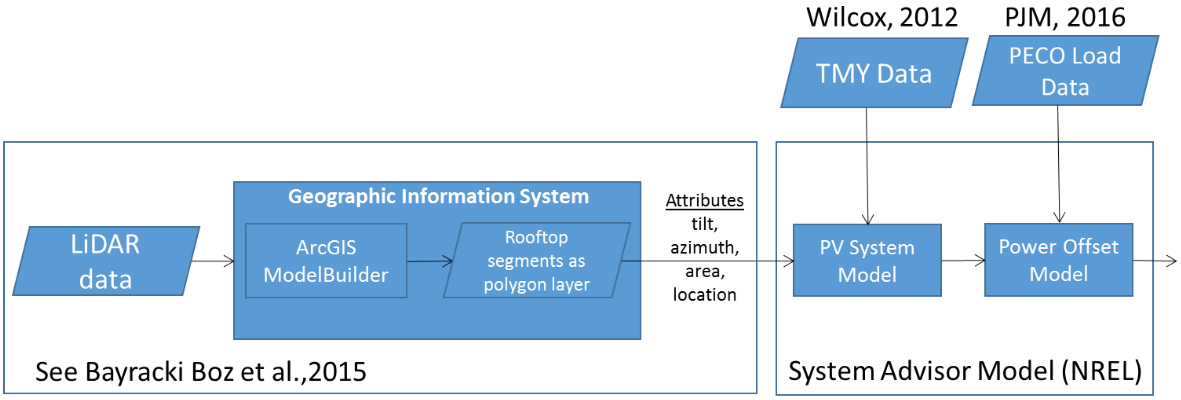


**Fig. 3: Workflow of the process for computing net utility load**

AC production from each rooftop was binned into the five rooftop orientation categories (the four cardinal directions, and flat roofs). Annual characteristics of these bins are given in Table 1. This approach mimics installing solar on every available rooftop throughout the entire city. In order to make a valid comparison between the natural rooftop orientation case, and specific policies (e.g. favor west-facing installations), we produced results that scale the east- and west-facing rooftops production to match the total annual production for the natural case. An additional case that modelled solar installed in an even split of east- and west-facing rooftops (still scaled to match annual production) was considered.

**Table 1: Annual energy produced by each azimuth bin**

| Bin | Tilt Range | Aspect Modelled | Area ($m^2$) | Annual AC (MWh) | Ann AC/area (kWh/$m^2$) |
|---|---|---|---|---|---|
| Flat | <10° | Any | 27,236,240 | 5,170,000 | 190 |
| North | 10°-60° | 0° | 4,466,487 | 577,000 | 129 |
| East | 10°-60° | 90° | 3,314,164 | 596,000 | 180 |
| South | 10°-60° | 180° | 3,385,850 | 743,000 | 219 |
| West | 10°-60° | 270° | 3,364,420 | 602,000 | 179 |
| TOTAL | | | 41,767,161 | 7,688,000 | 179 (avg) |

## 4.3. Net load results

The effects of solar production on hourly ramp-rate in net load profile were investigated subject to the proposed solar deployment policies based on rooftop orientation. The annual average hourly ramp rate subject to each of these orientation conditions is shown in Fig. 4. As compared to the natural rooftop orientations, east-only has the effect of mitigating evening ramp rate, while exacerbating morning ramp rate. West-only deployment has the reverse effect (slightly reduces morning ramp rate, while increasing evening ramp rate). An even mix of east- and west-facing systems creates slight reductions in ramp rate in both morning and evening.

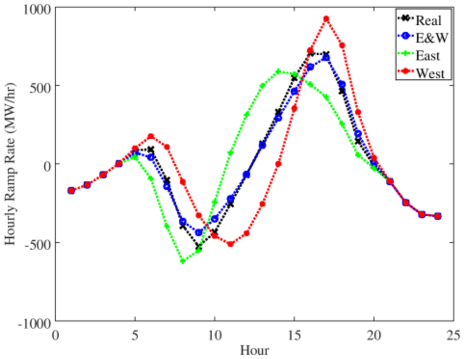


**Fig. 4: Average daily ramp rates for each of the solar strategies.**

We also considered these effects on a month by month basis, with results shown in Fig. 5. The trends shown in the annual average behavior are relatively consistent throughout the year, without any clear seasonally dependent behavior relative to the natural orientation case. East and west-only preferences continue to create favorable effects for only one half of the day (evening and morning respectively). When considering both morning and evening effects in tandem, the mixture of east- and west-facing rooftops still appears to provide the best mitigation of ramp rate throughout the year.

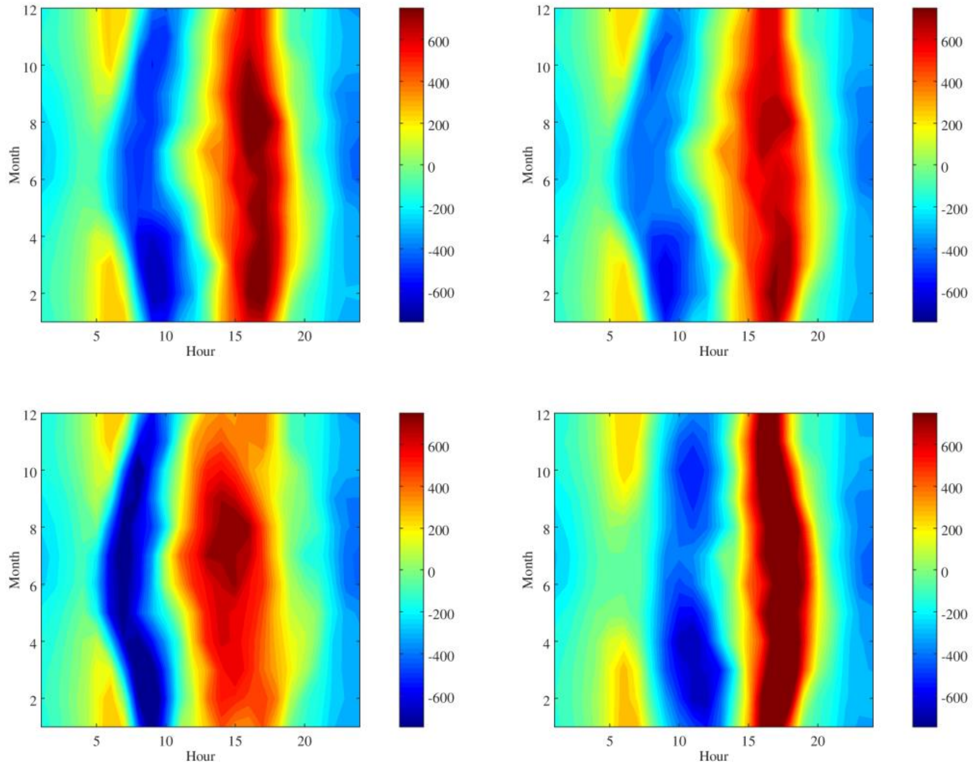


**Fig. 5: Comparison of ramp rates for different solar strategies, all scaled to match the real orientation output level. (Top Left)-Real rooftop orientations, (Top Right)-E & W scaled, (Bottom Left)-East only, (Bottom Right)-West Only**

## 5. Discussion

This case study demonstrates the ability of SDSS to provide technical data in support of policy decision making. The integration of spatial data (here, LIDAR-based rooftop characteristics) with technoeconomic modelling allows quantification of the policy outcomes. Preference toward east-only or west-only cases are able to create each able to result in beneficial effects for a portion of the day. In this case, the application of the model suggests that the goal of limiting ramp rate impacts of increased solar deployment throughout the whole day favors targeting an even mix of east- and west-facing rooftops. Spatio-technical coupled models, such as the one demonstrated here, enable new predictive capabilities to support these types of detailed, quantitative analyses.

Eventually, this type of analysis would be suitable for informing a variety of renewable energy policy considerations. We make no attempt to provide an exhaustive list of such policies, but the following list exemplifies a few that could be considered based upon extrapolation of the case study demonstrated here:

- Establish maximum levels of solar deployment at a substation level with respect to ramp-rate and net load impacts

- Identify localities with room for growth that could be targeted with subsidies or other economic incentives
- Identify areas with favorable rooftop orientations that could be targeted by subsidies to address observed ramp-rate issues
- Identify areas technically favorable for solar growth, but facing economic obstacles, where community organizations could be engaged or established to pursue joint-ownership opportunities

In addition to these policy examples, this tool could provide the basis of integrating distributed PV geo-techno-economic models with electric utility power flow models. Geographic information systems (GIS) are becoming a common decision support tool for electric utilities. For these groups, GIS are mostly used for operation and maintenance; i.e., digital data are stored, organized and synthesized in GIS in order to locate and visualize physical assets (poles, wires, reclosures, etc) within a service area. This information helps utilities to respond rapidly and effectively to power outages, to coordinate infrastructure maintenance programs, and to perform cost engineering analyses related to infrastructure expansion plans. To the best of our knowledge, however, GIS are not used by utilities to plan for potential renewable energy system implementation, e.g., running scenario analyses in order to determine where investors are most likely to develop new systems; to simulate the potential impacts on their infrastructure and planning efforts of those decisions; or to identify a pattern of development that may minimize impacts on their system. The same is true for city planners and municipal policy-makers: many cities have invested in online tools to measure and use these tools to organize data about existing systems (e.g., Philadelphia), but have not expanded the capacity of these systems into planning domains.

## 5.1. Next steps for continued tool development

Having demonstrated the successful integration of GIS and rich technoeconomic modelling tools to create a SDSS for solar energy applications, we now identify the need for further refinement of the process in order to create a final tool that can be deployed for generalized use. The case study was able to successfully demonstrate the ability of the workflow described to produce quantitative data for interpretation, but was as yet unable to extend the results into this type of expansive analysis approach described above. At present, this limitation was caused by the reliance on a loose coupling between the spatial and technical components of the model. Rooftop data were generated and passed to the SAM model using external computer (ASCII) files for communication. This structure proved to be a limitation when considering the ability to implement rapid iteration and what-if analysis of modified case scenarios through the workflow. Implementing a tighter coupling to enable the iterative approaches to investigation is one of the key goals as we continue to study and improve upon this workflow. Tight coupling between GIS tools and the technoeconomic models of SAM is possible, and will allow quick modification of input parameters and results to be visualized directly within the GIS environment, both in spatial and aggregate models of analysis.

During further development, we advocate for the continued the use of open source and open access platforms to facilitate public dissemination of SDSS tools and to foster validation of their effectiveness in practical use cases. In order to allow the tool to operate efficiently on a spatial scale, the necessity of parallelization of final implementations is expected. Final steps in development of a successful tool would revolve around the solicitation of feedback from stakeholders to contribute to identification of the most useful parameterization of available technoeconomic inputs.

The goals for continued development of this tool are threefold:

- Identify pathways for further generalization that can allow the tool to be integrated with multiple data sources and types of analysis
- Bring more capacity to bear on tool development toward establishing a tighter coupling between GIS and SAM components
- Work with potential users (stakeholders for urban distributed PV) to ensure that tool development is best tailored to answering their questions

## 6. Conclusions

The fundamental value of the workflow in enabling analysis of the types of proposals discussed is the production of quantified results for the governing economic and technical parameters. Such quantification provides the certainty necessary for the guidance of informed decision making. As such, it is intrinsically a framework that can advocate for effective and productive communication amongst stakeholders in the renewable energy arena. Reliable, quantitative spatial data allows investors to identify the intersection of disposable income and suitable deployment sites, it feeds conversations about the variety of technical benefits offered by distributed PV and how to produce policies to encourage growth, and it creates a backbone for conversations between stakeholders with differing motivating interests (e.g. competing drives between producers and distributors of energy).

Worldwide, approximately 70 per cent of total energy consumption is used to maintain urban metabolisms (Butera, 2008). In community energy planning in particular, there is an assumption that (especially online and interactive) mapping systems will improve awareness of the potential opportunities, barriers, and impacts of local renewable energy development. Maps are often used as a medium to include the general public in planning decisions and to encourage home-owners to adopt renewable energy technologies. Future work will test these assumptions through stakeholder research.

In addition to providing a planning-stage tool for conducting policy analyses, online maps could conveniently serve as a clearing house for data and information relevant to each city. By choosing a transparent workflow for the development of maps and SDSS, we enable new data and techniques to be quickly integrated and validated, future-proofing the techniques and allowing for easy growth. Increased usage of autonomous aircraft may add to the availability of LIDAR data that could spread these analyses through more urban environments as time goes by. Open platforms foster development toward a collaborative modelling culture, capable of providing access to a diverse set of stakeholders and enabling data-based decision making on a spatial scale. Development will continue toward the ultimate goal of providing a flexible and open analysis tool based upon the workflow methodology.

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