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# Net solar generation potential from urban rooftops in Los Angeles

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ABSTRACT

Rooftops provide accessible locations for solar energy installations. While rooftop solar arrays can offset in-building electricity needs, they may also stress electric grid operations. Here we present an analysis of net electricity generation potential from distributed rooftop solar in Los Angeles. We integrate spatial and temporal data for property-level electricity demands, rooftop solar generation potential, and grid capacity constraints to estimate the potential for solar to meet on-site demands and supply net exports to the electric grid. In the study area with 1.2 million parcels, rooftop solar could meet 7200 Gigawatt Hours (GWh) of on-site building demands (~29% of demand). Overall potential net generation is negative, meaning buildings use more electricity than they can produce. Yet, cumulative net export potential from solar to grid circuits is 16,400 GWh. Current policies that regulate solar array interconnection to the grid result in unutilized solar power output of 1700 MW. Lower-income and at-risk communities in LA have greater potential for exporting net solar generation to the grid. This potential should be recognized through investments and policy innovations. The method demonstrates the need for considering time-dependent calculations of net solar potential and offers a template for distributed renewable energy planning in cities.

## 1. Introduction

Distributed rooftop solar generation arrays are increasing in many North American cities. Such installations can help offset net energy use of buildings, which accounts for 40% of total energy demands across the United States (EIA, 2015). Meeting in-building electricity demand through on-site rooftop solar generation provides a significant opportunity to increase local renewable energy capacity utilization. Some properties can generate sufficient electricity through rooftop arrays to offset on-site usage and additionally export renewable energy back to the grid, which would be available for other energy uses in lieu of fossil fuel generation sources. At the metropolitan scale, rooftop solar installations in cities can offset on-site building demands and export electricity to the local grid for use or storage elsewhere.

Yet, this potential is moderated by existing technology, investments, and infrastructure operations. The time-dependent nature of solar generation and electricity demand can result in an over-supply of electricity during peak daytime hours, followed by an increase in demand during later afternoon hours as solar generation subsides (Denholm et al., 2008). During periods of net positive generation, if renewable energy production in excess of demand cannot be stored, grid operators must maintain the balance of supply and demand through generation curtailment. Alternatively, during periods of net demand, electric generation providers and grid operators must quickly ramp up power plants to balance the grid.

In California, this mismatch in demand and supply has grown particularly acute during some seasons, when the electric grid demonstrates a so-called "duck curve" phenomenon in warmer months (Denholm et al., 2015). California grid operators have even curtailed hydropower outputs and paid other western grid systems on occasion to accept excess generation (Trabish, 2017). To mitigate potential detrimental consequences of distributed solar generation on electric grid operations, utilities with grid management responsibilities in California impose limits on the size of solar generation capacity that can connect to

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each individual distribution circuit. While the daily balance of generation and demand on the grid is a current and pressing problem for sunny regions everywhere, similar issues of latency may arise for other intermittent renewable sources (Twite, 2018). Without infrastructure for storing energy, a generation portfolio highly reliant on renewable generation will face these technical challenges.

Thus, assessing the potential contribution of distributed solar energy to a broader generation portfolio must consider effects on the electric grid. For rooftop solar arrays, estimating the maximum net potential for solar energy production, defined here as the time-dependent net generation from rooftop solar exported to the electric grid after meeting onsite demands, is an important contribution for cutting-edge energy policy research. It requires integrating high detail spatial and temporal data to understand how electricity use in buildings, and the buildings' potential to generate solar, is distributed throughout a metropolitan region. The task is also challenging from a policy and institutional standpoint. The dispersion of activities across property owners, municipal and investor-owned utilities, electric grid operators, and regulators means that no single entity has all of the data needed for comprehensive empirical assessments of the net potential for solar energy in a city (Vine, 2008).

Policies and institutional practices can affect the ultimate estimates of potential net solar electricity from urban rooftops. Several terms are used in renewable energy resource studies to describe maximal generation potential, constraints, and resultant policies and practices. The theoretical potential is the total potential energy that can be generated from a renewable source such as solar. The technical potential is the output based on technologies and system parameters, such as rooftop solar array size. The economic potential is the potential generation given financial considerations with costs and revenues (Lee et al., 2017). Finally, we add to these the regulatory potential, which is the potential generation considering any limitations that regulations and policies impose.

The objective of this study is to better understand how net generation potential of local distributed solar energy resources in a city is shaped by spatial variability in grid infrastructure, household demands, and potential installations of rooftop solar arrays. We present a method to quantify the potential for distributed rooftop solar generation capacity to meet in-building demands and export additional electricity to the grid, given account-level electricity billing data, solar generation potential, electric grid constraints, and socio-economic factors. The method estimates the total percentage of metropolitan electricity demand that could be met through rooftop solar installations based on an hourly assessment of the net difference between local demand and generation capacity (technical potential). The analysis also incorporates the constraint of local electric grid capacity and utility policies governing grid interconnected solar systems, illustrating how existing infrastructure and policies can inhibit the deployment of renewable energy resources (regulatory potential). Results are available through a dynamic web-mapping tool to help inform new policies for equitable deployment of distributed solar energy resources in Los Angeles, providing a blueprint for energy planning in modern industrialized cities (http://solar.energyatlas.ucla.edu). For this analysis, we do not include additional potential generation from parking lot structures, public buildings, or other possible community-owned solar asset locations, but describe implications of the results for such installations. We also assume utility guidelines about available grid capacity to absorb solar rooftop generation detailed in publicly available datasets and mapping tools (SCE, 2017).

### 1.1. Data availability and integration

Identifying high-priority locations for installing rooftop solar arrays is a complex task requiring data integration (Cohen et al., 2016; Cohen and Callaway, 2016; Sultan et al., 2016; Wegertseder et al., 2016). In particular, a multi-step approach using Geographic Information Systems (GIS) is necessary to consider the spatial variability in demand and supply in evaluating technical and regulatory potential net generation (Lopez et al., 2012).

First, assessments must quantify the maximum potential electricity generation in a city from distributed rooftop arrays. Imagery analysis of unobstructed rooftop area in a city, combined with estimates of time-dependent solar radiation, can yield estimates of potential generation solar array with high temporal and spatial resolution (Perpiña Castillo et al., 2016; Šúri et al., 2007; Tsalikis and Martinopoulos, 2015).

Second, estimates of property-specific electricity demands with high temporal resolution are necessary to calculate the net electricity exports to grid infrastructure from grid-connected properties with solar arrays (Mikkola and Lund, 2014). Such openly-available, account-level energy use data, while having multiple applications for energy efficiency and reliability planning, is often unavailable, especially at hourly or sub-hourly intervals (Hamilton et al., 2013a, 2013b; Huebner et al., 2016, 2015; Medrano-Gómez and Izquierdo, 2017; Porse et al., 2016; Wyatt, 2013).

Third, the capacity for circuits in the existing electric grid infrastructure to accept incoming power generated by distributed solar arrays must be known. This allows for assessing the potential peak and total net solar generation that can be exported to the grid for use elsewhere (Carollo et al., 2015; Walla, 2012).

Finally, socio-economic effects of installing distributed solar energy across cities should be assessed given current policies. In particular, understanding net potential generation capacity across socioeconomic classes is critical for evaluating the equity of regulatory policies that, to date, often favor higher-income communities (Fournier et al., 2019; Porse et al., 2016). Innovative management and financing schemes may help contribute to the task of equitable infrastructure deployment. Estimates of net solar generation potential can incorporate schemes to conjunctively use energy from various sources to maximize outputs (Lund, 2012). New policies and market incentives are important for transitioning current systems dependent on central control and financing (Poudineh and Jamasb, 2014). Distributed solar generation can also provide economic benefits for the electric grid, especially by reducing electricity losses over transmission lines, although assessed benefits alone may not justify widespread investments in such technologies (Cohen et al., 2016; Cohen and Callaway, 2016). Available assessments to date have not evaluated the tradeoffs in the degree of centralization in solar energy production, such as reduced transmission construction costs associated energy losses for locating distributed solar near areas of high demand. In particular, large centralized solar plants have opportunity costs of land, which could otherwise be used for agriculture, habitat, or open-space. Some of these costs are not easily monetized. Further, as the state experiences more heat days, transmission and distribution infrastructures will be affected (Burillo et al., 2019).

Due to challenges of data availability and integration, studies to date of large-scale distributed solar electricity generation potential are limited (Cohen et al., 2016; Cohen and Callaway, 2016). The proprietary nature of electricity distribution and consumption data has constrained systematic assessments of potential for and benefits of net solar potential in cities. One area that has received attention is the design and operation of microgrids, which balance generation and demand in a small and usually contiguous area. Translating this knowledge into the deployment of systems at larger geographic scales, however, is difficult. It requires tackling challenging questions of governance, systems integration, and entrenched practices. The influence of institutional inertia on system investments and data availability in current policy-making processes is significant (CPUC, 2014).

### 1.2. California's renewable energy transition

Despite these challenges, California is rapidly integrating renewable energy sources into its statewide generation portfolio. The state has set

 

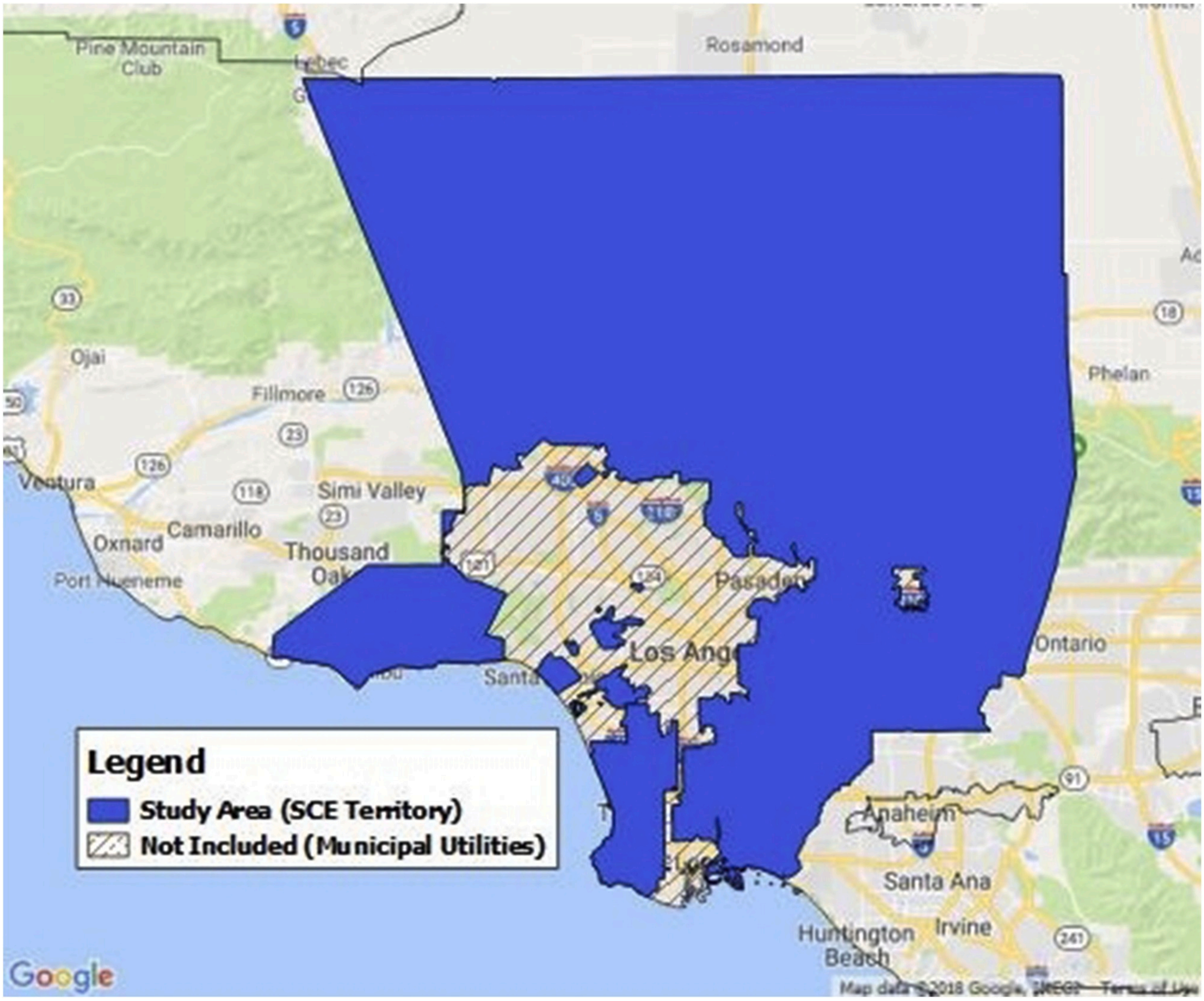


**Fig. 1.** Map of the study area in Los Angeles County, which was limited to the service territory of the local Investor-Owned Utility, Southern California Edison.

increasingly aggressive targets for the percentage of electricity supplied by renewable sources (50% by 2035) and energy efficiency (doubling by 2030) as part of legislation signed in 2015 (Senate Bill 350), as well as recent mandates for household rooftop solar generation capacity in newly constructed buildings. Municipalities throughout California are also participating in new Community Choice Aggregation (CCA) utilities, which offer residents the possibility of an alternative utility provider potentially more reliant on renewable energy than incumbent utilities.

The rapid rise in grid-connected solar and photovoltaic installations in California, however, has been unexpected by even the most optimistic of renewable energy advocates (Kristov et al., 2016). In 2004, only 60 MW of total solar installations (residential and commercial) were installed across the state through utility-sponsored programs. Other renewable sources such as wind power, along with traditional renewable sources including hydropower, were more prominent. By 2016, over 5200 MW of solar was cumulatively installed through major Investor-Owned Utility (IOU) programs. A significant portion of the rapid increase owes to individual home and building owners installing solar arrays on rooftops. From 2004 to 2017, nearly 3300 MW of distributed residential solar generation capacity was installed across the state (Go Solar California, 2017).

The transition is quickly changing the operation of California's electric grid. The rise of distributed solar generation, with its time-dependent electricity exports and relative autonomy of operation, is causing significant shifts in grid management, notably the emergence of daily duck curves with net exports of solar generation in the daytime, but net demand from the grid from the same buildings during evening and night hours (Denholm et al., 2015). Traditionally, electricity demands were met through more consistent, or at least more directly controllable, large-scale generation sources, including hydropower, coal, and nuclear fission. Recently, utilities have expanded natural gas power plants, especially smaller "peaker" plants that can be quickly deployed to manage grid intermittency issues and short-term spikes in demand. The addition of intermittent power generated by rooftop solar arrays, which cannot be turned off, creates new management challenges for this system.

The governance of California energy also contributes to the complexity of integrating distributed rooftop solar installations. The California Independent System Operator (CAISO) coordinates the buying and selling of electricity within California's statewide interconnected electricity grid from many sources and providers. Large investor-owned utilities (IOUs), including Southern California Edison (SCE) and Pacific Gas and Electric (PG&E), own and operate high-voltage transmission lines that transmit electricity to end-users in all parts of the state. Customers of large utilities, as well as many smaller municipally owned utilities (MOUs) with separate distribution lines, rely on the proper functioning of this tiered system to ensure reliable

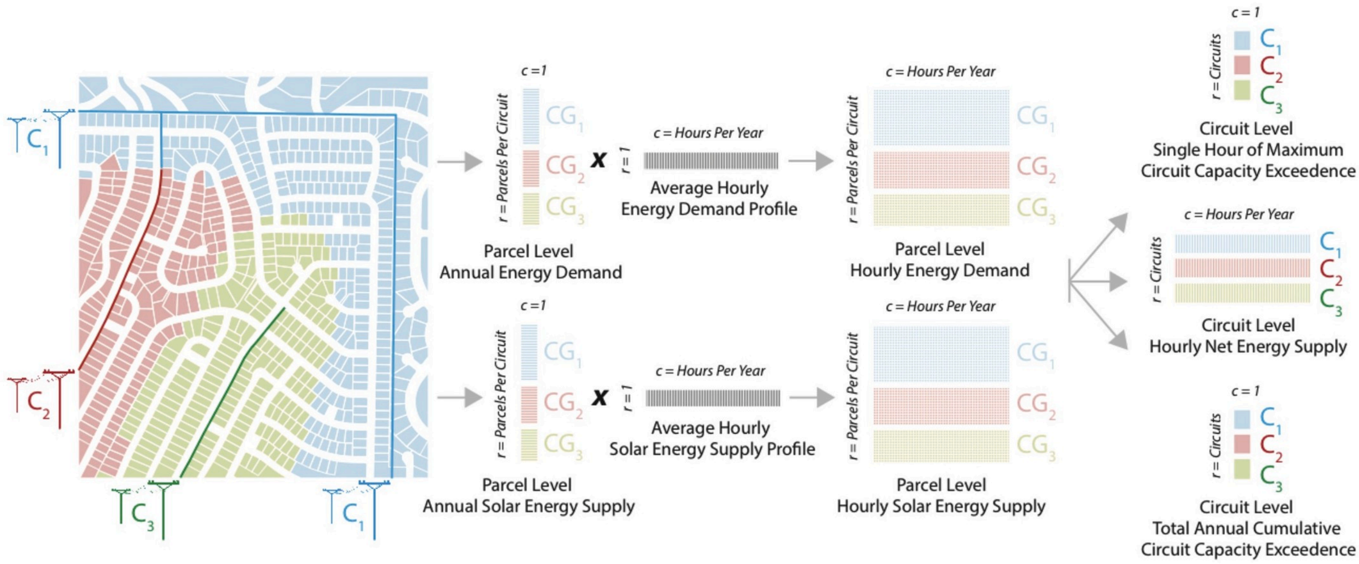


**Fig. 2.** Integrating data for solar generation and energy consumption through the analysis procedure. Circuits ($C_x$) are affiliated with groups of properties (left). The set of properties affiliated with each circuit is denoted as a Circuit Group ($CG_x$). Each property has an hourly profile of solar generation and demand (middle). The time-dependent net hourly balance of supply and demand yields the net export of solar generation capacity that can be provided to the grid after accounting for existing electricity demands (right).

electricity in homes, businesses, and schools. The growing penetration of distributed solar, while helping meet renewable energy goals, is causing significant reliability issues for established grid operations across the tiers, most especially because cost reductions and performance improvements in energy storage technologies have not proceeded at the same pace as with distributed solar, nor have the two technologies been tightly integrated.

### 1.3. Renewable energy and time-dependent operations

While many estimates of total energy use and production exist for aggregate numbers, the time-dependent nature of demand and supply is important. Typically, generation assets across a grid are scheduled to meet the profile of changing demands at the time. Utilities and grid operators seek to optimize the scheduling decisions (exporting electricity supplies to the grid) to meet reliability requirements and increase profits. Without energy storage solutions, supply must equal demand at all times.

For electric grid operations, the variable nature of renewable energy production can be problematic. Renewable energy generation timing does not always align with demand, which can strain current operations but also offer opportunities for innovation in grid operations (Denholm and Hand, 2011; Schleicher-Tappeser, 2012). While incorporating a mix of renewable energy sources may alleviate variations in generation, in practice, regions are often rich in resources for a limited number of renewable sources (Denholm et al., 2008; Grubb, 1991). To plan for increased renewable energy production as part of the generation profile across a grid, estimates of potential renewable energy supplies must consider *time* as part of the calculations. Without doing so, the temporal mismatches in demand and generation strain grid infrastructure. Such imbalances were predictable in western states as solar generation increased (Denholm et al., 2008). Yet, most studies of renewable energy planning do not incorporate these considerations.

### 1.4. Key research questions

The issues in California highlight challenging questions for managing transitions to renewable energy sources in cities. For any given city:

- How much current on-site demand could be met through distributed rooftop solar production?
- Can current infrastructure systems absorb the full potential of net exports to the electric grid of distributed solar installations without affecting operations? Are low-income and disadvantaged communities differentially impacted in this regard?
- How does potential generation compare with existing statewide electricity generation and use?
- How can the integration of openly available data inform planning for a future electric grid that supports distributed renewable energy, solves challenges of time-dependent demand and generation, and incorporates energy storage needs?

Using the case study of metropolitan Los Angeles County, we answer these questions using large-scale data integration and analysis. The methods and analysis to address each of these questions are described below.

## 2. Methods

The tool assembled data for building-level electricity demand, electric grid capacity, regional utility demand profiles, and land use characteristics to understand the cumulative net solar potential for Investor-Owned Utility areas in LA County, which are served by Southern California Edison (SCE) (Fig. 1). Combining these disparate data sets required aligning the spatial and temporal resolution of each to facilitate an estimate of net solar potential (see Fig. 2).

The task is particularly challenging due to the variable extent of data coverage across different sources. Data sets such as the current load and available capacity for utility electric grid circuits in California, along with aggregated hourly demand profiles across the service territory, are openly-available per guidelines from state regulatory agencies, but only for areas serviced by Investor-Owned Utilities that are overseen by the California Public Utilities Commission (CPUC). Other data such as land use classifications are available through local government tax assessor records, which must be obtained through individual jurisdictions (counties) or commercial providers. Finally, high-detail electricity consumption data (at the household level) is generally not available to the public or local governments. Combining these data sets to assess net solar potential through a bottom-up method can only be accomplished

**Table 1**
Overview of procedures and methods used in the Prioritization Tool.

| Step | Description |
|---|---|
| 1 | **Calculate Annual Electricity Consumption** (kWh) for each property in LA County using the most recently available year in the *LA Energy Atlas* (2010). |
| 2 | **Derive the Annual Rooftop Solar Electricity Generation Potential and Maximum Potential Power Output** (kWh and kW) for each property based on values reported in the *LA Solar Map* database, which is integrated into the *Energy Atlas* database tables. |
| 3 | **Calculate Hourly Consumption and Generation Values** (kWh) for each property for the entire year, using best available estimates of hourly load and generation profiles within the SCE service territory. |
| 4 | **Determine on-site electricity use offsets from solar arrays and net exports of solar generation to the grid** for each property at each hour in a year, and aggregate to annual totals. On-site solar use, remaining grid demands, and solar exports, and are calculated based on the difference between hourly generation and consumption. The total amount of building electricity demand that is offset by solar generation is calculated for the whole region by summing values for all properties. |
| 5 | **Attribute Parcels to Electric Grid Circuits** ("Circuit Groups") based on a shortest-distance assessment of the proximity of parcels to local grid circuits. |
| 6 | **Calculate Totals for Each Circuit Group,** including annual rooftop electricity generation potential and potential peak power output potential |
| 7 | **Estimate Unutilized Net Solar Generation from Rule 21 installation limits** for Circuit Groups using SCE-defined grid capacity constraints for exporting power to local grid circuits based on the 15% peak load penetration maximum for distributed generation ("Rule 21"). |
| 8 | **Rank Grid-Constrained Net Solar Potential for Disadvantaged Community Boundaries** based on *CalEnviroScreen* rankings in LA County. |
| 9 | **Map Net Solar Potential** given grid management policies that affect net solar potential (Rule 21), as well as DAC boundaries that provide a geographic "filter" for highlighting areas to prioritize investments. |

by particular institutions with data and expertise.

This analysis for LA County benefited from established databases and openly-available sources of data. First, the LA Energy Atlas is a comprehensive platform for integrating and mapping parcel-level energy consumption (aggregated to protect customer privacy), U.S. Census data, local property tax records and parcel data to understand high-detail metropolitan energy use trends (Pincetl et al., 2015). It has been used to investigate energy use across land use types, building vintages, and sociodemographic trends (Derenski et al., 2018; Fournier et al., 2019; Pincetl et al., 2015; Porse et al., 2016). Second, the LA Solar Map, developed by LA County, displays high-detail gross solar potential for properties in LA County based on un-obscured and correct angle roofs, which also considers the efficiency of solar panel output (LA County, 2015). Third, the Distributed Energy Resources Integration Map (DERiM) is a spatially-explicit database of energy and power capacity for electric grid circuits in the service territories of Investor-Owned Utilities in California (SCE, 2017). Fourth, the California Solar Statistics database reports solar generation at 15-min intervals for a set of metered panels (Go Solar California, 2017). Finally, the *CalEnvironScreen* database identifies communities in California deemed at risk of socioeconomic insecurity along with disproportionate exposure to environmental hazards (OEHHA, 2016). Further descriptions of data sets are detailed in the Supplemental Data section.

Integrating these data sets required resolving discrepancies in spatial and temporal resolutions through a multi-step procedure (Table 1). This procedure is a template for calculating net solar potential in metropolitan areas across North America. However, it also included policy and planning considerations that are specific to California. For regions outside California, repeating similar analysis requires understanding local planning codes and energy regulations as well as collecting energy data. Key steps in the analysis procedure are outlined below.

### 2.1. Determine net solar potential and on-site use for each property in LA county (Steps 1–4)

For each property (parcel) in the study region within LA County, the hourly consumption and solar generation potential was estimated. For hourly consumption, published hourly demand data from 2010 for the service territory of the regional Investor-Owned Utility was applied to each property from the LA Energy Atlas to estimate hourly energy consumption over the entire year. Similarly, 15-min interval data of solar generation from the California Solar Statistics database, aggregated to hourly totals, was applied to the property-level solar generation potential reported by the LA Solar Map to estimate hourly solar generation from full installation of rooftop solar panel arrays. The hourly difference in on-site production and consumption values yielded a time-dependent estimate of net solar potential for properties in LA County. The remaining demand, not met by on-site solar production, represents demand that must still come from the grid. For these steps, an assumption is made that any solar electricity produced on-site is first used on that property to meet demands, with any excess available for export to the grid.

### 2.2. Net solar potential and grid capacity (Steps 5–7)

All solar installation projects in California's IOU territories undergo utility reviews as part of a *grid interconnection request*, which is typically handled through installation contractors. During the interconnect request process, a utility provider reviews and approves the proposed generation site and asset mix, ensuring that existing circuit lines and substations can handle any changes in the flow of electricity. The CPUC regulates grid interconnection requests for IOUs, but allows each IOU to establish their own request process, rules, and tariff structure (Ricklefs et al., 2017; SCE, 2015).

Two important factors govern the size of solar systems. First, utilities designate an upper limit on the size of solar arrays (power output) that can be installed and receive favored compensation rates. Regulations typically prevent installations that would annual produce an amount of power that exceeds past average annual demand for the account. Second, for Net Energy Metering participants associated with a local circuit, utilities limit the total amount of distributed solar power allowed to be exported to the circuit. To ensure grid stability and prevent reverse flows of electricity, which could significantly affect reliability or cause outages, utilities enforce limits through a regulation called "Rule 21", which designates upper limits for installations. Screen M, which is key for projects, designates a *15% penetration capacity* upper limit on the size of distributed solar energy installations. The 15% penetration capacity represents 15% of peak historical load experienced on that circuit. The DERiM data detail the 15% limit for each circuit in IOU service areas in California. Utilities assess the limit by comparing the array size to the penetration limit, based on either the stated output (nameplate capacity) of the array or through analysis that demonstrates the peak output will not exceed the 15% penetration capacity limit. For this analysis, we assumed that solar installations would be limited based on the time-dependent peak power output that includes on-site use of solar electricity, not the stated power output of the array (nameplate capacity).

While California is a leader in requiring investor-owned utilities to publish data for current capacity for electric grid circuits, parcel to circuit relationships have not been made publicly available. Of the two utility-imposed constraints noted above, we only included the second (limits to interconnections with grid circuits from local properties) in the analysis. To accomplish this in the absence of detailed data that attributes parcels to particular grid circuits in the DERiM dataset, we used a shortest-distance estimate in GIS that assigned each property to the nearest grid circuit. All properties assigned to a circuit were aggregated to create a unique layer that attributed parcels to a "circuit group". For each circuit group, which ranged in size from 1 to approximately 100 properties, peak export potential (power) from properties was limited based on the 15% penetration capacity amount detailed by California regulations. The resultant value is the grid-constrained net solar potential. The value was aggregated across LA County to determine the countywide net rooftop solar potential from all properties. This effectively estimates rooftop solar panels of limited size according to grid

**Table 2**
Summary of findings for the study area compared to all of LA County.

| Parameter | Value | | Description |
|---|---|---|---|
| | LA County | Study Area | |
| Number of Properties | 2.4 million | 1.3 million | Number of residential, commercial, and industrial properties |
| Electric Utility | Multiple | Southern California Edison | Study region focused on one utility |
| Retail Demand | 54,000 GWh | 25,200 GWh | Building demands based on utility billing records |
| Solar Generation Potential | 47,000 GWh | 23,600 GWh | Technical potential of rooftop solar generation |
| On-site building demands met from rooftop solar | Not calculated | 7200 GWh | The total on-site building demands that can be met by solar electricity considering time-dependent supply and demand curves |
| Remaining demands from electric grid | Not calculated | 18,000 GWh | Total building demand that cannot be directly met by solar electricity generated on-site and must come from the electric grid. |
| Solar Export Potential | Not calculated | 16,400 GWh | Technical potential exports of rooftop solar generation after on-site building demands are met |
| Unutilized solar power capacity | Not calculated | 1700 MW | Rooftop solar power production that would not be installed due to current policies |

constraints, but not net energy metering limits on installation sizes.

### 2.3. Ranking and mapping net solar potential (Steps 8–9)

The final step involved mapping net solar potential to understand geographic differences across LA County, as well as analyzing results across socio-demographic indicators. We analyzed data for grid operations, Rule 21 constraints, and net solar potential, which could be higher than the building consumption, with respect to socio-demographic characteristics within the *CalEnviroScreen* (CES) scores. In particular, we examined net solar potential and grid operations data as a function of categorical bins (percentages) of *CES* rankings. For each category (0–5% of all LA County block groups, 5–10%, etc.), we calculated summary values of net solar generation and grid capacity to investigate summary relationships, including circuit export capacity, annual and peak net generation (export) potential, and unutilized power based on Rule 21 constraints. The sum and arithmetic mean of each metric was calculated for tracts within a bin. Spatial discontinuities between circuit groups and *CES* were resolved by attributing circuit groups to the block group within which they were predominantly located.

## 3. Results

Results are presented below for: 1) total net solar generation potential (with and without time-dependent calculations), 2) geographic differences in net solar potential generation, 3) limitations on installed solar generation capacity, and 4) socioeconomic considerations of net generation potential. Estimated values are summarized in Table 2.

### 3.1. Total net potential solar generation

To provide context, we first summarize some overall statistics for LA County. Because our study area represents only the portion of LA County served by SCE, these values helped to understand the relative magnitudes and importance of the results in the study area. The total electricity demands across the county (retail and non-retail) are approximately 70,000 GWh, while retail demands billed directly to customers in the county based on utility billing records are 54,000 GWh. Across the entire county, total potential solar generation from rooftops is approximately 47,000 GWh according to the LA Solar Map, representing 87% of retail demand.

Within the study area, which comprises 1.2 million properties in the IOU-service territory, total retail electricity demands are approximately 25,200 GWh, while the total potential generation from rooftop solar is 23,600 GWh, which represents approximately 94% of retail demand. Notably, solar generation can supply a greater percentage of demand in the study area than across the county because the study area does not include the City of Los Angeles, the largest jurisdiction with many high-density buildings that could not satisfy on-site electricity demands through rooftop installations.

Performing the analysis at the building scale and hourly time step, however, yields critical insights into the breakdown of rooftop solar technical potential in the study area. An estimated 7200 GWh of generation would be used for on-site building demands, which is 29% of total retail demand. Remaining building demand to be met by grid sources is approximately 18,000 GWh. The potential solar output to export to the grid (not used directly on-site) is 16,400 GWh. This would be electricity available for use by neighboring properties or elsewhere.

Calculation of the technical potential of solar generation for in-building uses in terms of regional and statewide electricity generation provides additional context. In 2016, California's total electricity generation was 198,000 GWh (CEC, 2017), meaning that the technical potential for rooftop solar generation in LA County equates to 12% of current statewide generation. This does not include solar generation potential on urban land uses such as parking lots or community-owned solar assets in public right-of-way locations.

### 3.2. Net solar potential varies by geography

By using individual properties with associated electricity demand, and attributing them to one of 1700 circuits within the IOU distribution grid, the spatial variability in supply, demand, and net potential generation was revealed. The majority of grid circuits (52%) are periodically net exporters of electricity to the grid, whereby their associated buildings produce more electricity than is consumed by occupants over the course of the day. Circuits with positive net generation potentials could technically export a cumulative annual total of 16,400 GWh of electricity to the grid. This does not mean that these properties would not need grid-supplied electricity. In the absence of energy storage, the differences in the demand and potential generation curves means that properties in such areas would still require grid supplied electricity at times of the day, and at night. Without the detailed spatial and temporal calculations, these net producing circuits would not be apparent (see Fig. 3).

### 3.3. Unutilized solar generation

The regulatory potential for net solar generation is lower than the technical potential due to existing policies that limit solar generation exports to the grid for purposes of maintaining grid reliability. The average peak net export of a circuit across the study area is 5.9 MW, while the average utility-specified penetration rate limit (15%) is 12.5 MW. Thus, on average across circuits in the LA County grid, extra grid capacity exists. Areas with more solar interconnection capacity, based on penetration rate limits, include rural areas of northern LA County and dispersed communities within the interior of metropolitan Los Angeles. These are indicated as darker regions in Fig. 4a.

In some areas, the 15% penetration rate limit results in unutilized net generation potential from arrays that would be sized smaller to meet regulatory constraints (Fig. 4b). We estimate the regulatory solar potential within the study area is therefore 1700 MW less than the technical potential that would maximize energy generation (Table 2).

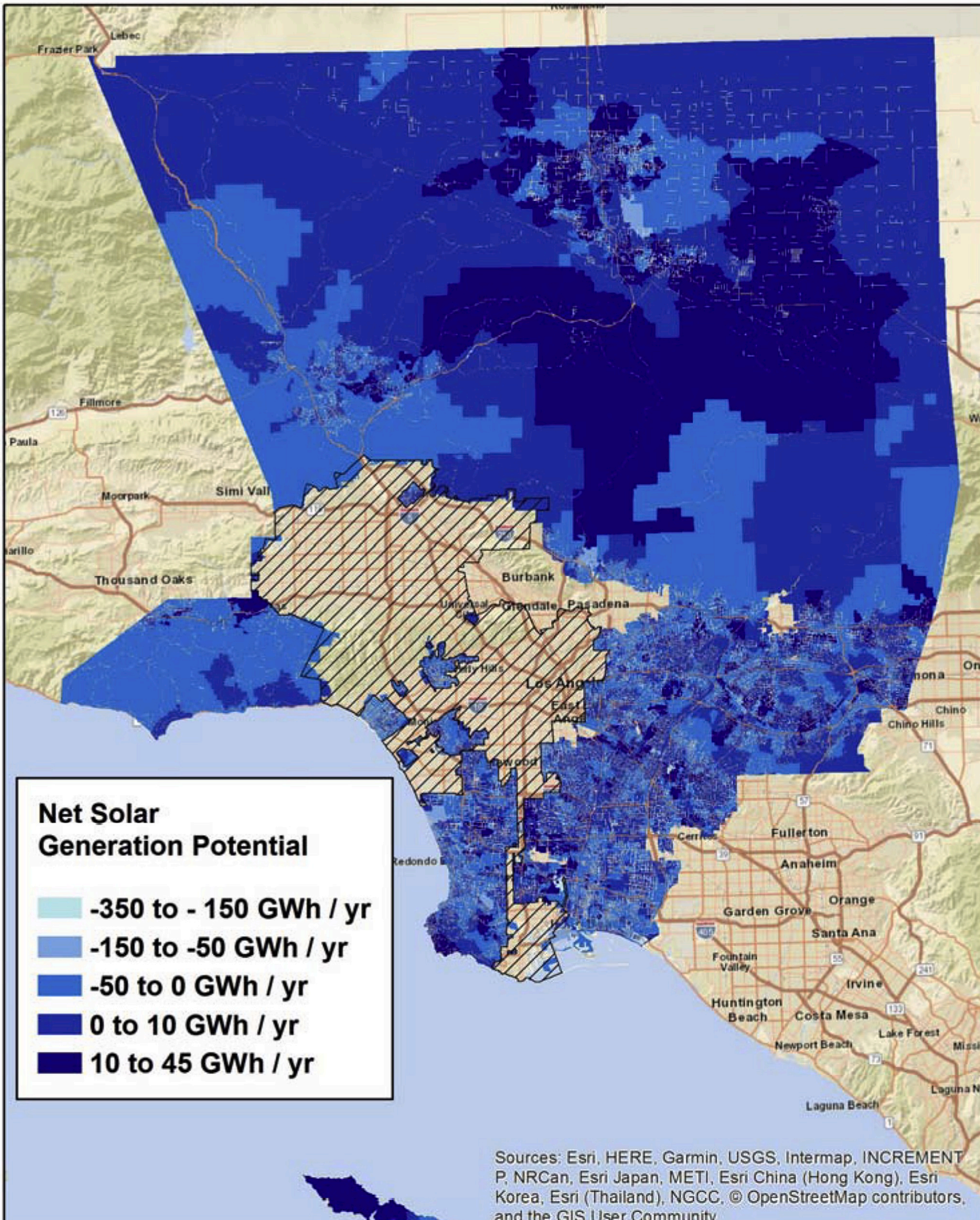


**Fig. 3.** Map of total Annual Net Supply by Circuit Sorted by Magnitude. Shading corresponds to technical potential for net generation by circuit groups, with lighter colors being net negative and darker colors being net positive (exports to grid). Unshaded areas are masked to due privacy requirements for energy consumption data, while the shaded region is the City of Los Angeles, which has a municipally-owned utility and does not publish grid capacity data.

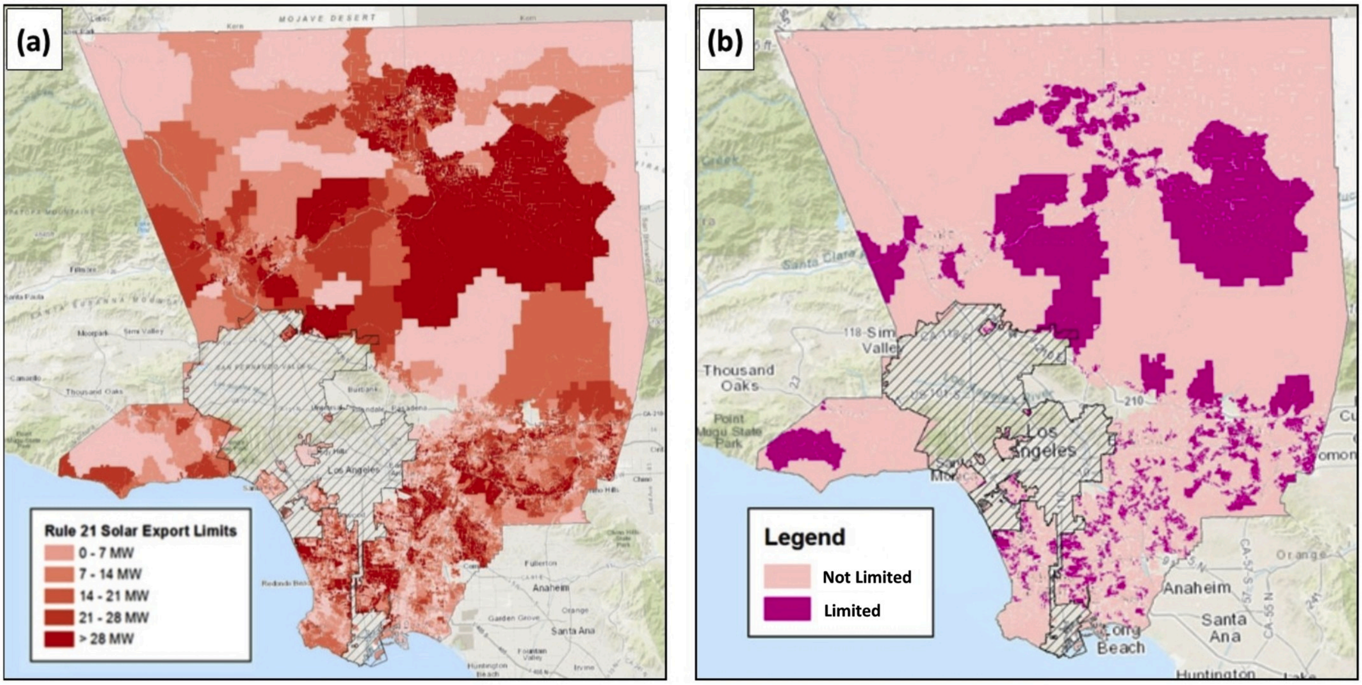


**Fig. 4.** Capacity and Rule 21 limitation trends. (a) Rule 21 limitations on peak solar exports range from 0 to over 28 MW across the study area. (b) Areas where power generation would be unutilized due to regulatory constraints are dispersed throughout the county in both urban and rural areas.

Approximately 17% of the circuits would have a regulatory potential that is less than the technical potential where policies limit potential installations. This represents inaccessible solar power generation potential in LA County based on current policies intended to maintain grid reliability. As a comparison, this value is nearly equal to the generation capacity of the Hoover Dam, which is 2000 MW. Infrastructure upgrades and more detailed assessments of net export potential based on actual conditions (i.e. Integrated Capacity Analysis procedures) would likely reduce the amount that would be limited based on the 15% penetration rate capacity. This would further help California meet aggressive renewable energy goals.

Trends in potential net electricity exports to circuits also vary across seasons (Fig. 5). Circuits that are net suppliers of electricity show fairly consistent trends across seasons, with a band of net exports during midday hours that reverses in the later afternoon and evening as the same circuits draw electricity from the grid to meet building demands. Circuits that are net consumers of grid-supplied electricity more often draw from the grid, but especially during peak hours of the summer months. The spring season has consistently lower consumption from the grid than summer and fall seasons, which show large consumption of grid electricity during the late afternoon and early evening hours.

### 3.4. Socioeconomic considerations and equity

We analyzed data for grid operations, Rule 21 constraints, and net solar potential in comparison to rankings within the *CalEnviroScreen* scores. This allowed for analyzing data for grid and renewable generation capacity in the context of communities deemed vulnerable to environmental and socioeconomic hazards. We investigated potential trends that would indicate structural inequalities in access to local grid resources, such as underserved communities having less excess grid capacity or lower net solar potential based on grid constraints, relative to their consumption. For each block group and its associated *CalEnviroScreen* score, we aggregated the circuit groups contained within the block group and calculated various statistics associated with solar generation, including grid capacity, net solar electricity generation potential, and others.

A straightforward analysis of socio-demographic characteristics with net solar potential and grid operations yielded trends of interest. LA County has many Census tracts deemed as "high-risk" based on the rankings within *CalEnviroScreen* (CES). Large sections of LA are of low-to-moderate income and subject to environmental hazards that range from flooding to industrialized wastes and air pollution. The distribution of census tracts across LA is weighted towards high-risk categories.

Examining solar generation statistics against these CES scores reveals important insights. The largest unutilized capacity occurs in areas assessed as higher-risk of economic insecurity and environmental hazard by *CalEnviroScreen* (Fig. 6). This is primarily due to the prevalence of communities in LA that rank high on the *CalEnvironScreen* scoring index. In addition, such communities have more capacity in local grid circuits to accept net solar generation beyond rooftops, such as from ground-mounted or canopy parking lot arrays (Fig. 6 and Table S5).

## 4. Discussion

To date, utilities and grid managers have been primarily responsible for maintaining reliability of the electric grid. For the most part, they have succeeded. The increasing use of distributed technologies for generation, storage, and efficiency, however, is dispersing these technologies to many smaller and uncoordinated parties. Such trends, varyingly promoted by regulators and private sector entities, are posing significant management issues in the complex electric grid infrastructure. Traditional planning processes are inadequate. In particular, third-party verification of energy planning analyses by traditional Investor-Owned Utilities (IOUs) is highly useful as it may provide insights that IOUs are not equipped to undertake. Access to data for energy use, generation, and distribution allows third parties such as researchers to present innovative and alternative analysis in the public domain on a topic that has traditionally been the purview of regulated utilities.

While the results highlight the opportunities and challenges for integrating renewable energy sources into existing grid operations, technological and policy innovations do offer potential solutions. In particular, energy storage technologies, which store electricity generated during a period of time for later deployment in times of higher

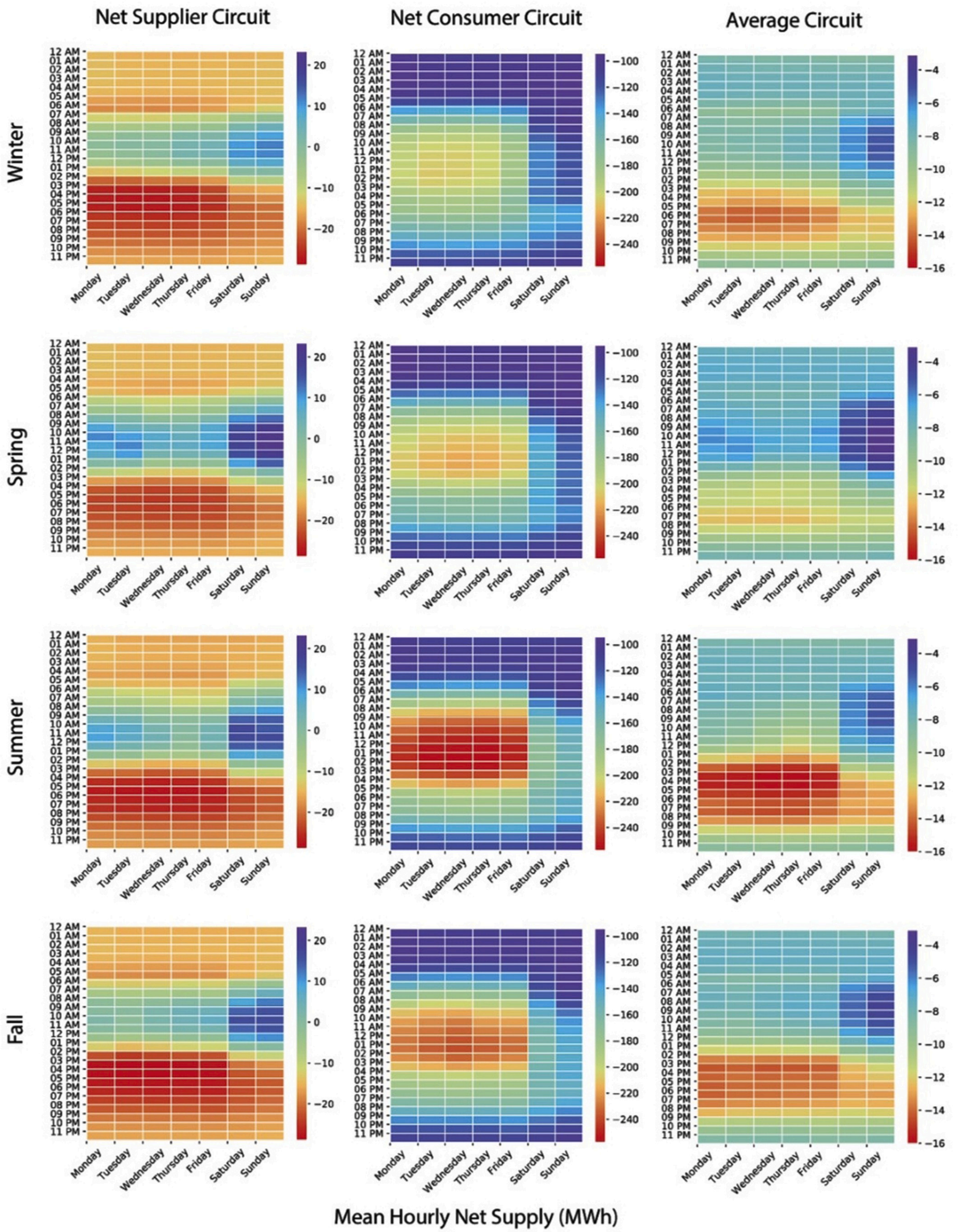


**Fig. 5.** Changes in grid operations at multiple time scales. The first two columns show average hourly net trends for individual representative net exporter and net importer circuits. The third column shows the average hourly supply across all circuits in the study area.

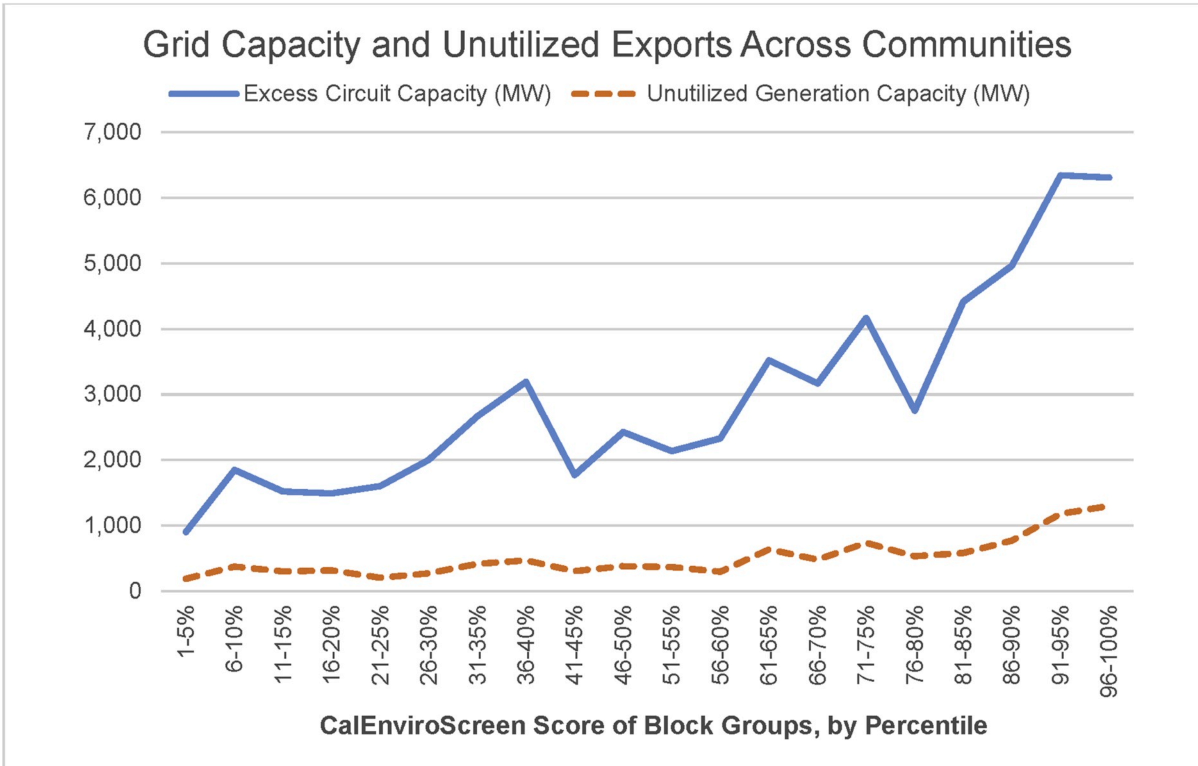


**Fig. 6.** Grid Capacity and unutilized potential exports across communities, ranked by *CalEnviroScreen* percentile.

need, could significantly address the issues of latency in demand and solar electricity production in California. Vehicles, household batteries, and grid-scale energy storage operations are all being tested in the state. Most assessments render energy storage as a promising but still expensive technology option.

The analysis also highlights the needs and difficulties of working with large data sets in obtaining accurate assessments of renewable energy generation potential. Without incorporating high-detail spatial and temporal resolution, spatial differences in net potential generation are not apparent. Yet, creating information technology platforms and gaining access to all the relevant data sets is a time-consuming endeavor. Evaluating the potential for rooftop solar as a large-scale electricity source adds further complexity to an energy management system in California that is already very data-intensive.

Data access is an important issue. California has made strides in opening access to energy data, but further changes are necessary in the state and elsewhere. We should note that in California, universities may request individual consumption data, and such data is critical to evaluating solar potential and underpin this analysis. This analysis and presentation of the publicly available tool – where consumption data is aggregated to protect customer privacy according to Public Utility Commission aggregation rules – is highly novel as a policy-relevant instrument for a large metropolitan region. As part of developing the tool, we identify key policy recommendations for localities and policymakers to pursue, which would broaden access to quality data for planning California's energy future and support its energy transition. These are intended to provide guidance to creating smarter statewide energy policies that look to a future of a transitioned energy grid that supports distributed generation. The recommendations provide a framework for replicating the procedures in other communities.

### 4.1. Developing tools for multiple audiences

When creating energy planning tools, researchers and developers should consider the multiple potential users, each with slightly different information needs. In developing the tool that supported this analysis, we considered multiple types of users:

- *Local governments* with interest in investing in local generation assets, participating in emerging Community Choice Aggregation authorities and other activities to reduce local greenhouse gas emissions and fulfill Climate Action Plans.
- *Local government energy planners* responsible for managing local government assets. For instance, local governments investing in electric utility fleets need to understand net export potential and grid capacity in identifying good sites to install charging stations.
- *State energy planners* that work with investor-owned utilities to increase renewable energy generation in urban areas throughout the state.
- *Investor-Owned and Municipally-Owned Utility staff* involved in operating and upgrading transmission and distribution grids, as well as interconnecting new generation assets.
- *Non-profits* involved in promoting greater access to renewable energy, especially within underserved communities throughout California.
- *State policy makers* concerned about equity implications of distributed generation.

### 4.2. Equity considerations

Results indicate the need for further investments in lower-income neighborhoods to stimulate solar generation capacity. Communities deemed at risk to economic insecurity and environmental hazards in LA comprise a significant portion of census block groups (Table S5). The distribution of CES scores across LA County is skewed towards "at-risk" communities. Thus, as an aggregate contribution, these communities would be critical participants to achieving greater self-sufficiency for meeting electricity demands through rooftop solar. Such communities have circuits with slightly greater available excess capacity to accept net generation exports (Fig. 6). At the same time, these communities have less access to capital to pay for rooftop solar installation. Infrastructure upgrades, coupled with solar installation incentives, could help address this opportunity to engage low-income communities as a critical contributor to meeting renewable energy goals, which is a noted equity issue for energy and other infrastructure sectors (Bouzarovski, 2014; Gnansounou, 2008; Sovacool, 2012).

### 4.3. Opening access to data

Discussions with stakeholders revealed that data and resources for developing the tools are often inaccessible. In particular, tax assessor data, parcel boundaries, and high-detail electricity consumption are essential for developing spatial prioritization tools for distributed energy resources. Such data requires resources and expertise to collect, process, and interpret. Public regulatory agencies should continue to broaden access to high-detail energy consumption data, especially for the public sector. Local governments in California, which are mandated to reduce energy use and greenhouse gas emissions, often need highly disaggregated data for planning.

Property-level information is critical for understanding energy use trends. It is also useful for many other resource management sectors in the public domain, such as water management. Local and state agencies should pursue opportunities for creating openly available tax assessor and parcel data to ensure higher accuracy and consistency across the state. As part of developing the *LA Energy Atlas*, we discovered and documented many inconsistencies with parcel data. Data quality and attributes vary widely by planning area and some areas charge significant amounts of money for their data.

Evaluating the potential for net solar or other renewable energy sources requires high-detail data for electric grid operations and capacity. In California, the Public Utilities Commission has pursued policies to openly publish grid capacity data with increasing details for IOU service areas. This has opened many opportunities for analysis. It also highlights opportunities for technological investments and policy changes. As the results demonstrate, capacity constraints imposed on grid circuits should be based on feasibility studies of potential renewable energy generation. The utility developed 15% peak load penetration limit for grid circuits likely reflects historical trends of the grid and an excess caution relative to new technologies and policies for renewable penetration.

Regulators can work with energy utilities to improve the availability of data that attributes properties to individual circuits. Accessible data would improve knowledge of on-site consumption and grid constraints. In this analysis, we assumed that properties were associated with local circuits based on a shortest distance proximity based calculation. Improving this assumption with actual data that aligns properties and circuits would require compiling and perhaps digitizing multiple existing data sources as well as integrating new sources such as imagery.

## 5. Conclusions and policy implications

In this analysis, we presented an algorithm for prioritizing the location of distributed solar energy generation capacity across a county, given on-site electricity requirements, solar generation capacity, and nearby electric grid circuit capacity.

Using the case study of a utility territory in the county of Los Angeles, California, we showed how to conduct a comprehensive analysis of net potential of solar electricity generation in a megacity region using integrated data sources. Results demonstrated several key points. First, net solar generation potential in metropolitan Los Angeles County is significant. Second, in nearly 20% of communities, current policies would reduce the technical potential of net solar generation by limiting the size of arrays that can be installed. Third, disadvantaged communities in Los Angeles generally have greater potential to contribute peak solar generation exports to the electric grid, along with greater excess capacity in local circuits to accept solar from sources other than rooftops. The research demonstrates the importance of third-party verification in energy planning, based on openly-available data for energy consumption and electric grid capacity.

The analysis can help renewable energy planning and policy-making (Table 3). Improved access to data, along with better community engagement and communication in planning are critical tasks if California and similar regions are to meet aggressive greenhouse gas emissions reduction targets.

**Table 3**
Summarizing policy recommendations for advanced energy planning.

| Recommendation | Description |
|---|---|
| *Develop tools for multiple audiences* | Regulators and researchers must consider the many audiences, including developers, researchers, consultants, local government officials, and regulators, that will benefit from easily accessible tools for energy planning. |
| *Opening access to data* | Distributed energy planning disperses planning responsibilities. To be successful it requires more openly available data, which participants throughout the system can access in responding to personal and policy incentives for installing new renewable energy generation capacity. |
| *Equity Considerations* | The analysis demonstrated that communities in Los Angeles deemed at risk for economic insecurity and environmental hazards are important, even critical, contributors to achieving greater energy self-sufficiency. Municipal and investor-owned utilities should more closely embrace the planning opportunities available in such communities through thoughtfully-tailored programs that respond to the needs of such communities. |
| *Installing solar to reduce energy consumption* | Reducing greenhouse gas emissions requires reducing energy consumption, especially energy produced from GHG-intensive sources. Combined with energy storage, using distributed solar resources to meet on-site demands can potentially limit use of GHG-intensive fossil fuels such as natural gas by reducing peak load requirements. Understanding and mapping electricity demand data at high geographic resolution can help to identify where local generation capacity can reduce GHG-intensive energy production |

## Data repository

Summary data is available for viewing at the LA Solar Prioritization Tool website: https://solar.energyatlas.ucla.edu. Due to privacy requirements mandated by California state regulations, disaggregated calculations are not available.

## Author contribution statement

All authors contributed equally to the manuscript.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enpol.2020.111461.

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