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Building an interactive web mapping tool to support distributed energy resource planning using public participation GIS

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ABSTRACT

Community solar projects involve the installation of large PV systems whose net outputs are then virtually allocated to customers at other locations. They represent a relatively new model of distributed energy resource (DER) implementation that could help overcome some historical barriers to low-income, disadvantaged community, renter household participation in the ongoing renewable energy transition. Siting community solar assets is a thick and inherently geographic problem however, one which relates to historical patterns of energy infrastructure investment, local urban development, and community socio-demographic change. Creating a more equitable energy system will require planning tools which better coordinate the DER adoption decisions of individual property owners with the grid operators. Interactive decision support tools based on web maps are well suited to addressing this need for improved information sharing and coordination. However, such tools need to be designed and implemented through a process of public participation with stakeholders who explicitly focus on social and environmental justice. Here we describe the process by which one such tool was developed. We also report on several important findings derived from its use relating to current imbalances between local DER supply potential and the grid integration capacity limits which exist within Southern California's disadvantaged communities.

1. Introduction

1.1. Distributed energy resources

Distributed energy resources (DERs) are energy generation and storage systems which are located close to the end-use sources of electricity demand (Akorede et al., 2010). They are directly interconnected to the grid's distribution network and have the capability to provide supplies of power at strategic times and locations. Although the term does not denote the renewability of the primary energy resources used to generate this electricity, it is often strongly implied. Solar photovoltaic (PV) systems coupled to lithium-ion battery energy storage systems (BESS) are among the most rapidly growing of these new DER technologies due to recent rapid reductions in their manufacturing costs. These rapid cost declines are having profound implications for long-standing power dynamics among the major players within the energy system (Meneguzzo et al., 2015).

A major point of contention between utilities and DER advocates, in terms of crafting rules that govern grid interconnection, relates to the potential of distributed PV to deliver electricity back to the grid from locations which have historically only been points of consumption (Moselle et al., 2010). To date, the rules which regulate the interconnection of DERs have constrained them to function primarily in a *demand response* or *load shedding* capacity. This means that the sizing of system components that are allowed to interconnect to the grid from behind the meter have been restricted in order to limit their potential to be net suppliers of electricity.

In their public responses to regulatory proceedings pertaining to the

Abbreviations: ACS, American Community Survey; BTM, Behind the Meter; BESS, Battery Energy Storage System; CARE, California Alternate Rates for Energy; CBO, Community Based Organization; CCA, Community Choice Aggregation; CSGT, Community Solar Green Tarriff; CSOM, Community Solar Opportunities Map; DAC, Disadvantaged Community; DAC-GT, Disadvantaged Community Green Tarriff; DER, Distributed Energy Resources; FERA, Family Energy Rate Assistance; GIS, Geographic Information Systems; GSTR, Green Tarriff/Shared Renewables; ICA, Integrated Capacity Assessment; IFOM, In-Front of the Meter; IOU, Investor Owned Utility; LARIAC, Los Angeles Regional Imagery Acquisition Consortium; MVA, Megavolt-amps Reactive; MW, Megawatts; NEM, Net Energy Metering; NREL, National Renewable Energy Laboratory; PPGIS, Public Participation GIS; PV, Photovoltaic; VNM, Virtual Net Metering.

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grid integration of DERs, many utilities have voiced concerns that the creation of a true bi-directional prosumer network is likely to destabilize grid operations without the significant addition of automated hardware and software controls. This is because, as has previously been mentioned, the grid was historically architected to support only unidirectional flows of power. At the same time, proposals to actually pursue such a *high DER* future are largely being derailed by arguments that they do not reflect the least-cost pathway towards higher levels of renewable penetration on the grid – at least when compared to larger, more centralized, utility scale renewable energy generation deployments (Ramasamy et al., 2021).

1.2. Patterns of DER adoption

According to the California Public Utility Commission's (CPUCs) distributed generation statistics or *DG-Stats* portal, through the end of 2021, the state had a cumulative 10.62 GW of distributed net metered solar PV and 695.7 MW of installed BESS capacity (California DG-Stats, 2021). By comparison, the total installed capacity of utility scale solar PV and BESS were 15.92 GW and 1908.3 MW, respectively, at the same point in time (EIA, 2021). This means that ~40% of California's current solar PV capacity and ~27% of its current BESS capacity are decentralized, having been installed behind the meter in hundreds of thousands of homes and businesses throughout the state. These are impressive figures – as California alone accounts for 83% of all of the currently installed small-scale BESS capacity in the entire United States (Ibid).

Despite this, our own detailed investigations into the geographic patterns of DER adoption in Southern California revealed stark differences in the rates of participation between affluent and disadvantaged communities (Fournier et al., 2020). In California, energy system regulators have adopted a set of scoring criteria which have been developed by the state's Office of Environmental Health Hazard Assessment (OEHHA), known as CalEnviroScreen, to technically define Disadvantaged Community (DAC) status at the census tract level. Plotting levels of distributed rooftop solar PV adoption relative to these scores, aggregated to the zip code level, revealed strong negative correlations between a community's exposure to environmental pollution burdens and the installed capacity of DERs (Fournier et al., 2020).

There are numerous causal factors responsible for this outcome, many of which have been well documented in the literature. Among the most significant of these barriers include: a lack of awareness about the potential benefits and available incentive programs, structural instability of available roof areas upon which solar PV panels could otherwise be installed, and perhaps most significantly, a lack of agency due to high percentages of renter households (O'Shaughnessy et al., 2021; Scavo et al., 2016). As we shall go on to discuss, addressing many of these underlying issues would require resolving deep and long-standing issues of poverty, racism, and structural inequality within these communities.

1.3. The community solar model

One potential solution to this problem which has been put forth is the community solar model. Community solar refers to an arrangement in which a solar generating installation is owned by or leased to multiple entities that benefit from its operation. (U.S. Department of Energy, 2022) Partial owners or lessees (i.e., participants) in community solar systems typically receive credits or payments for energy generated and sold to the grid by the community solar installation. Community solar participants may be co-located with the system (the physical plant), or the system and its participants may be in separate locations.

The idea of a collectively owned solar generating system that accepts investment from a range of participants and returns benefits to them has been around since the component technologies reached commercial maturity, but the evolution of federal and state energy policy regimes has necessarily limited what kinds of system configurations can be implemented and narrowed the range of feasible community solar business models. (Asmus, 2008; Michaud, 2020). The creation of stable wholesale generation markets and new financing arrangements, diminishing DER technology costs, and California's desire to include participants who would otherwise be excluded from utility household NEM programs in the energy transition, have been influential in shaping community solar development in the state. Currently, community solar systems are implemented through utility-sponsored programs designed for the recruitment of participants, site hosts, contractors, and system operators, as well as the distribution of benefits to participants.

Within this context the key element ensuring that the community solar model will be able to provide direct benefits to low-income and renter households that are external to the project site is a mechanism known as Virtual Net Metering (VNM). VNM refers to the practice whereby individual customers, who live at locations which are physically separated from the community solar site and therefore do not host any solar assets on their properties, are permitted to receive virtual allocation of the solar output which is generated by a community solar installation.

1.4. Pilot programs in California

Contemporary community solar development efforts have been focused on recruiting participants who are excluded from household NEM programs because they are renters, own homes whose structural condition precludes the installation of solar panels or lack the financial resources to bear the upfront costs of DER installation. Community solar has come to be seen as a way to include these groups in the energy transition, and state and municipal governments have been attempting to expand access to solar through utility-sponsored community solar pilot programs.

One of the earliest programs to explicitly include these commitments was the Green Tariff/Shared Renewables (GSTR) program, developed by the CPUC in 2013. GSTR was intended to "[include] ratepayers who are currently unable to access the benefits of onsite generation" (California Public Utilities Commission, 2022a). The uneven performance of GSTR has led to the development of a number of successor community solar programs which attempt to improve on GSTR's design. Community solar programs descending from GSTR currently on offer from IOUs (and the community choice aggregators, or CCAs, within their territories) include Disadvantaged Community – Green Tariff (DAC-GT) and Community Solar Green Tariff (CSGT). CCAs are authorized by the CPUC to offer their own community solar programs based on these two programs (California Public Utilities Commission, 2022b). DAC-GT programs could potentially offer income-qualified (CARE or FERA-enrolled or eligible) participants 100% renewable power and a 20% utility bill discount, and do not have any base requirement relating to proximity or siting of the actual community solar system relative to the locations of the participants (Ibid). CSGT programs offer the same benefits as DAC-GT to CARE and FERA-enrolled or eligible participants in the San Joaquin Valley and certain pilot communities, but with the added requirement that community solar systems be located within 5mi (or 40mi, for the SJV) of the disadvantaged community where the participants reside.

One challenge associated with this situation, from a planning perspective, has been identifying and reconciling the different, and sometimes contradictory site suitability requirements associated with each different program. IOUs and CCAs can also add locational/geographic requirements to the basic community solar programs (DAC-GT and CSGT) that may limit the number of suitable sites, especially for programs based on CSGT.

1.5. Mapping community solar opportunities

There are several existing web mapping tools which allow users to either look-up pre-computed values or develop simplified physical model predictions for the technical potential of a prospective rooftop PV system at a given property or site (Castellanos et al., 2017). In the former case, some prominent examples include the Google Sunroof Project and the Los Angeles County Solar Map, while in the latter case, NREL's PV-Watts model is perhaps most representative of the approach (Dobos, 2014; Sunter et al., 2019). An important limitation of these existing tools is that they are all designed around the paradigm that a suitable candidate site is already known to the user, a-priori, and thus, their primary interest is in obtaining more information about it.

Within the context of community solar projects however, the stakeholders which tend to be most active in the pursing project development tend not to be the actual property owners themselves, but rather, interested members of local community-based organizations, non-profits, or other external parties. These individuals, therefore, seek to identify good candidate sites within a pre-defined geographic area of interest, so that they can then later approach property owners with compelling development proposals. As a result of this, within the community solar space, there is a need for a tool which facilitates the initial identification and subsequent rank prioritization of eligible sites. Our approach to the development of the tool which is reported on in this manuscript reflects this difference of concerns. It assumes that the location of eligible sites is not already known, and moreover, for candidate sites that are identified, it is important provide number technical information about attributes which are commonly used for development prioritization.

2. Methods

2.1. Public participation GIS process

The Community Solar Opportunities Map (CSOM) is an interactive geo-spatial decision support tool designed to enable the identification and prioritization of eligible institutional properties for the siting of community solar assets within Los Angeles County. When planning for the development of the CSOM tool we explicitly sought to involve representatives of target user groups to function as stakeholders in the process. We formally recruited partners from local community-based organizations (CBOs) with interests in promoting a more equitable energy transition. The intended role of these CBO partners was not only to provide input and feedback on the tool's conceptual design, underlying data sources, and various user interface components, but also to evaluate it through real-world case study applications.

We developed three guiding principles to which we adhered throughout the design and implementation of the stakeholder engagement process. These principles included (1) fair compensation (2) reciprocity and (3) accountability. To ensure fair compensation, financial resources were included in the project's budget to support the CBO's participation. This effort reflects the approach of Public Participation Geographic Information Science (PPGIS) and acknowledges critiques of previous similar GIS tool development processes for not sufficiently engaging with members of the public whose interests were ostensibly being represented (Norris, 2017; Sieber, 2006). To ensure reciprocity, as part of our three-phase stakeholder engagement process, a series of educational modules were developed by the project team and presented to the CBOs in order to provide a level-setting of knowledge around the energy system and its transitions. These *Energy 101* presentations were tightly integrated with more traditional PPGIS style, tool development charrettes and structured feedback exercises. Finally, to ensure accountability, rigorous protocols were implemented both for the collection of structured and unstructured feedback as well as for documenting and communicating the development team's responses. All of which shall be elaborated in the subsequent descriptions of the three different phases of the process.

2.2. Phase I – Convening stakeholder groups

Phase I of the project's stakeholder engagement process involved recruitment of interested CBO organizations who would be willing to formally commit to collaboration. Financial compensation was provided to members of local community-based organizations. Representatives of several additional advocacy organizations, such as the Natural Resources Defense Council (NRDC) and Grid Alternatives (a non-profit solar installer), were also invited to the phase I meetings. However, as nationally chartered non-profits, it was made clear that they would not receive the same compensation as the local CBOs.

Upon completion of the Phase I recruitment process, representatives from the following seven CBOs decided to become funded project collaborators and take part in the engagement process related to the tool's development and use.

- Asian Pacific Islander Forward Movement
- Active San Gabriel Valley
- East Yard Communities for Environmental Justice
- Pacoima Beautiful
- Redeemer Community Partnership
- Social Justice Learning Institute
- TRUST South LA (Tenemos Que Reclamar Y Unidos Salvar La Tierra)

2.3. Phase II – educational modules and structured feedback

Phase II of the stakeholder engagement process involved a series of workshops and educational sessions held with the CBO partner organizations to discuss specific challenges relating to the adoption of DERs within their constituent's communities, as well as various desired capabilities of a web-based GIS tool that might help to overcome those challenges.

The first half of each Phase II stakeholder engagement workshop was dedicated to the presentation of our *Energy 101* curriculum. This curriculum was delivered in lecture format through a series of slides and short exercises designed to reinforce key information, and also included time for questions and answers at multiple points throughout. We found this to be a critical component of the project. It enabled our CBO partners to provide more meaningful feedback to us, gave them additional vocabulary to express their energy-related goals, and served as a jumping off point for a wide range of policy discussions that allowed both the CBOs and the UCLA development team to connect the dots between community-based experiences and the technical/regulatory landscape. Our aim with this training was to provide value beyond just this project, by building our CBO partners' capacity to advocate for their communities' energy needs.

Throughout the first two phases of the stakeholder engagement process structured feedback was solicited from our CBO partners in various formats. During each meeting a professional note-taker documented CBO feedback. This in-person feedback was augmented by e-mail correspondence following each meeting, which solicited additional comments or questions that participants may not have felt comfortable voicing in-person during the meeting, or which came to mind subsequently.

All of the feedback collected both in-person and electronically for each meeting was collated into a spreadsheet of action items. Wherever possible, each item was flagged with the relevant person or organization who had initially raised the issue, so as to facilitate follow up questions from the project team in pursuit of a resolution. Extensive efforts were made to ensure that all items on this list were directly responded to, either with substantive modifications to the tool's design and functionality, or with a written justification as to why a change could not be implemented for technical or other reasons. This documentation was made available to the participating CBO groups so that they could clearly track the responses to their participation and feedback.

2.4. Phase III – CBO case studies

Phase III of the stakeholder engagement process involved the development of a set of case project proposals for the use of the CSOM tool. A total of 6 case study proposals were initially submitted by participating CBOs, 4 of which were seen to completion as documented case studies. Proposals were table-top exercises that utilized the CSOM tool to identify a handful of priority sites that were candidates for Community Solar or a Resilience Center within a CBO's geographic area. Case studies involved field activities related to some of the potential locations identified in the proposals, such as discussions with property owners, site assessments, development of more detailed site designs by a licensed solar installer, solicitation of community input, initiation of utility screening review, etc. Many of these activities were constrained by the COVID-19 pandemic, but the CBOs involved in this phase worked to do as much as possible under the circumstances. Information gleaned from these Case Study experiences, such as involving observed differences between the calculated solar potential available on a particular site and the assessed potential based upon a detailed on-the ground site visit by a professional solar developer, have since been incorporated into the analytical methods used to develop the CSOM tool's underlying data sets.

2.5. Technical development process

The current version of the CSOM map's interface contains eleven interactive geospatial layers. The core layer, which consists of the set of sites deemed eligible for potential community solar systems, is able to be filtered based upon a combination of attribute different attribute values. This compositional filtering is accomplished through a set of sentence prompts, presented in a "widget panel" contained on the right-hand portion of the map. These filters allow users to filter eligible solar sites based on city, use type, utility service territory, in front of and behind the meter distribution circuit capacities, solar generation potential, and number of nearby renters and residents whose average annual electricity use could be offset by a potential PV system, as well as other relevant attributes of the technical potential of each site's modeled PV system.

The additional geospatial layers are included to provide users with contextual information that may be useful to inform site selection and prioritization. These include the locations of city boundaries, disadvantaged census tracts, average annual renter household electricity consumption, distribution circuit lines, renter occupancy, electric vehicle chargers, and brownfield sites. Table 1 provides a summary description of the input datasets that were used to generate both the overlay layers and the site level attributes included within the map.

2.6. Data processing

An extensive data processing pipeline was developed to identify the set of eligible sites presented within the CSOM tool and compute the relevant attribute values necessary for their filtering and prioritization. From an implementation standpoint, the first steps in this pipeline involved a series of SQL queries, developed against a local PostgreSQL database, which contained all of the public and private data layers previously described. Subsequent attribute creation processing steps were implemented in Python using a variety of geospatial libraries and external APIs. These scripts and their associated sequence of analytical operations are described in detail within the README file of this publicly available GitHub repository:

https://github.com/ericdfournier/sgc_pt[1]

The key steps in this data processing pipeline are described in the process flow diagram contained in Fig. 1.

2.7. Selecting eligible sites

Based upon the design feedback obtained from the project's partner CBOs through the Phase II stakeholder engagement meetings, it was decided that eligible parcels would be restricted to institutional, publicly owned, and community-oriented properties. This would eliminate the need for community members to have control over, or need to influence, decisions regarding the deployment of DER technologies on residential properties or on commercial or industrial parcels. These eligible parcels were first selected on the basis of their detailed land use descriptions contained within the LA County Tax Assessor's Parcel Database. Following from this a series of geospatial filters were applied to exclude parcels that intersected with various restricted geographic features including stream and river ways, electricity transmission corridors, highway corridors, protected and sensitive habitat areas, wilderness areas, etc.

Once this set of eligible parcels was derived, groups of parcels that both shared an adjacent edge and possessed the same land use classification were then aggregated into a single composite polygon that was then assigned a unique label as an eligible site. This aggregation process was necessary as many government-owned institutional sites such as parks, education facilities, service yards, etc., were found to consist of multiple distinct tax assessor parcels that have not yet been unified in the assessor parcel database, likely due to their tax-exempt status. The boundaries between these parcels, frequently intersected the various buildings which were located on a site complicating the processes of calculating the entire site's combined technical PV system output potential as well as relating that potential to local grid distribution circuit renewable energy generation integration capacity, as discussed in the following.

2.8. Assigning sites-to-circuits

A core geospatial operation which must be completed as part of this pipeline is the association of buildings to circuits. The nature of these associations is, of-course, precisely known by the electric utility service provider. However, they are generally not made public due to concerns about the security of critical infrastructure and facilities. In order to overcome this fundamental limitation, each building is associated with the distribution feeder circuit that it is physically closed to, using a nearest-neighbor minimum distance rule. This approach involves first computing within-polygon centroids for the footprints for all buildings $\geq$400 ft^2 within the study area, Next, each centroid was assigned to its nearest neighboring circuit, using a minimum Euclidean distance rule.

Fig. 2 provides a graphical illustration of the result of this process in a localized area where two different circuits are present: (1) a high-voltage (16 kV) three-phase feeder (blue) and (2) a low-voltage (4.16 kV) single phase feeder (yellow). Within the figure circuits are shown as solid lines, building centroids are shown as points, and the computed building-to-circuit assignments are shown as broken lines, all appropriately colored. The particular area shown here has been deliberately selected to highlight some of the known limitations associated with this nearest-neighbor based building-to-circuit assignment method. For example, note the apparent misclassification of the residential building in the upper left (red). According to the nearest-neighbor rule it has been assigned to the high-voltage three phase feeder, when in reality, it is far more likely to be served by the lower-voltage single phase feeder running through the alley behind the property line (grey).

After manual visual inspection of a large number of similar site-to-circuit assignments using detailed satellite imagery, the quality of the results produced by this method for the types of eligible institutional properties were generally found to be good due to the combination of (1) the much larger average size of the buildings on institutional sites when

[1] Unfortunately, several of the data layers used in the process are private and only accessible under NDA. Thus, while these scripts are public and can be viewed by external parties, they will not be functional without access to the raw input source database.

Table 1
Summary description of key input geospatial data layers leveraged for the development of the Community Solar Opportunity Map.

Dataset	Aggregation	Access	Attributes	Source
BTM & IFOM Solar PV Integration Capacities	Distribution Circuit Level	Public, Dynamically Hosted	Information about the evolving capacity of grid distribution circuits to accommodate new DER systems.	Southern California Edison (SCE) Distribution Resource Planning External Portal (DRPEP)
Building Rooftop & Carport Solar PV Potentials	County Tax Assessor Parcel Level	Private, Statically Sourced	Information about suitable areas available to deploy rooftop and/or carport mounted solar PV systems.	Los Angeles Regional Imagery Acquisition Consortium (LARIAC) Database & Los Angeles County Solar Map
Residential Electricity Consumption	Census Tract Level	Private, Statically Sourced	Information about the average annual residential electricity consumption both per-capita and for local renter/owner households.	UCLA Southern California Energy Atlas
CalEnviroScreen 4.0 Environmental Pollution Burden	Census Tract Level	Public, Statically Sourced	Information about communities being subjected to the highest levels of environmental pollution burden throughout the state.	California Office of Environmental Health and Hazard Assessment (OEHHA) CalEnviroScreen Program
American Community Survey	Census Block Group Level	Public, Statically Sourced	Information about population density, socio-demographics, and housing occupancy characteristics.	U.S. Census Bureau American Community Survey

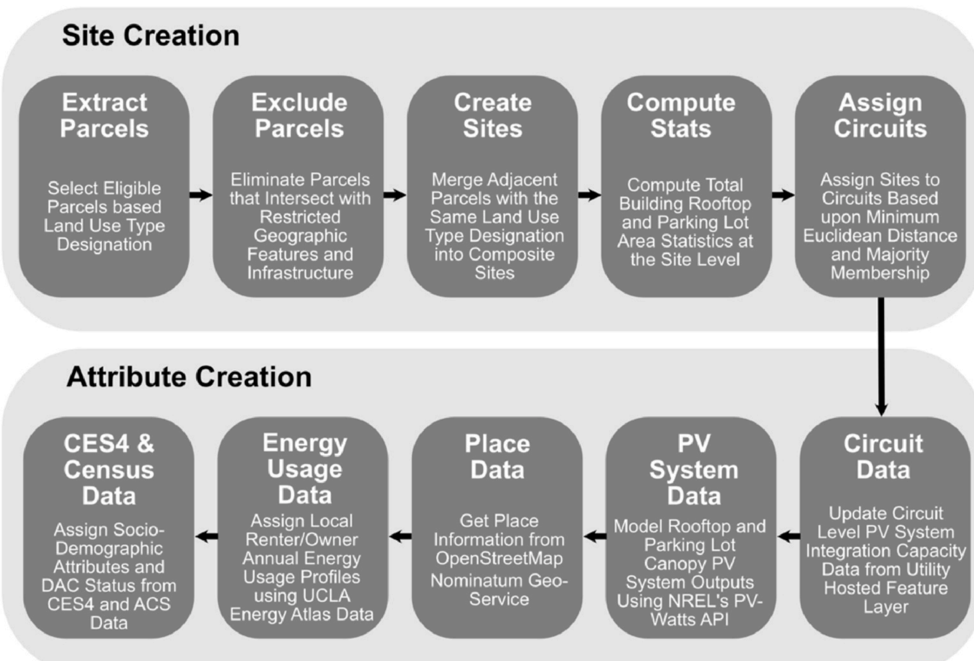

Fig. 1. Flow diagram illustrating key data processing steps used to filter eligible community solar sites and assign relevant attributes for use in their prioritization.

compared to small residential properties and (2) the more frequent occurrence of high-voltage feeders directly intersecting with the building footprint geometries, leading to less ambiguity about the location of potential interconnection points. Additionally, with circuit assignments being initially performed at the building level, and many institutional sites having multiple buildings, the final site-level circuit designation was determined based upon a majority rule, in terms of the share of the sites total buildings assigned to one circuit over another, with ties being broken on the basis of larger total cumulative building area. Unfortunately, a more systematic method for validating the quality of these building-to-circuit assignments could not be implemented in this case due to the lack of a requisite *ground-truth* training dataset.

2.9. Estimating site level technical PV system capacity and output potential

A detailed set of building rooftop and parking lot footprints were obtained from the fifth generation Los Angeles Regional Imagery Acquisition Consortium (LARIAC) database. The LARIAC program is a regional collective agencies and organizations which pool financial resources to fund the collection of primary source orthographic areal imagery and LiDAR scan data for the entirety of Los Angeles County. In each generation of the program, primary source datasets are collected, processed, and distributed to licensed consortium members by a third-party GIS data collection specialist firm (EagleView). In addition to the primary imagery products, additional derived data products, such as the building and parking lot footprints used in this analysis, are also developed using proprietary machine learning algorithms with industry leading accuracy and quality control processes similar to those described by Levinson et al. (Levinson et al., 2009).

For site level technical potentials, each square meter of parking lot and rooftop areas encompassed within a site were graded with a PV suitability score from ranging from: 1: "Unsuitable", 2: "Poor", 3: "Acceptable", 4: "Good", 5: "Excellent." These suitability scores were computed by binning the daily average solar insolation intensity values computed using a location specific solar insolation model which took into account both the three-dimensional orientation of the roof surface as well as proximate (adjacent trees, buildings, etc.) and distant (mountains, topography, etc.) shading structures. For the purpose of the analysis, as a conservative assumption, only areas in the "Good" or

Fig. 2. Example illustration of the results of an automated building-to-circuit assignment procedure based upon minimum Euclidean distance, with an evident misclassification error shown.

"Excellent" range (>4.0 kWh/day) were considered eligible for the technical potential calculations.

Once total suitable rooftop and parking lot areas were established for each site an automated workflow was used to execute a PV-Watts (Version 6.3) model to estimate annual system output potentials (kWh-DC). This was done by providing the API with each site's centroid coordinates and an input nameplate system size calculated by multiplying the total suitable rooftop area (m^2) by a characteristic power density coefficient of 160 W/m^2. For the rooftop mounted system category, additional default model parameters included the use of standard mono-crystalline modules with 19% conversion efficiencies and fixed mount racking systems installed with an average 20-degree tilt angle and 180-degree azimuth. For the parking lot system category, all of the previous assumptions remained the same, save for the use of canopy structure rack mounts with flat tilt and zero azimuth.

2.10. Measuring circuit level PV integration capacities

Assimilating the intermittent outputs of distributed renewables into the legacy architecture of the existing electric power grid presents significant engineering challenges (Cochran et al., 2015; Cohn, 2018). Within California, the process of interconnecting an intermittent renewable generation system to the electric power grid is governed by a set of regulatory guidelines known as Rule 21 (Coddington et al., 2012; Jain et al., 2019). Under the provisions of Rule 21, each local grid distribution system operator is empowered to craft a detailed set of technical requirements that projects must adhere to in order to be granted interconnection approval. For solar PV systems, these requirements often vary as a function of the size of the proposed array, whether it is associated with any on-site BESS, and whether the system is intended to be interconnected in front of or behind the meter.

In front of the meter (IFOM) systems participate in the wholesale market for energy, and thus do not benefit from subsidized net metering rates. They also must install dedicated communications infrastructure to transmit production data and receive curtailment signals issued by the independent system operator. Typically, a system is only installed IFOM when it is sufficiently large that its annualized output exceeds 150% of the recent historical usage of the customer accounts associated with the property where it is being developed. Behind the meter (BTM) systems, by comparison, tend to be much smaller in size, as they are specifically intended not to function as net-exporters of power. The difference between the interconnection of an IFOM or BTM system is significant from the perspective of the demands which are placed upon the local distribution system in terms of the ability to support *reverse flows* of power under a worst-case scenario of combined minimum on-site energy demand and maximum on-site energy production.

Within the context of the CSOM tool, two different metrics of grid integration capacity were used. Both have been developed on the basis of power system modeling undertaken the local investor-owned utility, Southern California Edison, as part of its Integrated Capacity Assessment (ICA). For BTM systems, the operative grid integration capacity metric used is something known as the *15% Penetration Limit*. This value, which reflects the cumulative capacity of intermittent renewables which can be interconnected to a given circuit (measured in MVA), is calculated 15% of the maximum historical load encountered on the circuit over the previous 18 months. Alternatively, for IFOM systems, a different capacity metric, known as the Total PV Operational Flexibility Threshold Capacity, was used. This figure is the product of detailed power flow modeling which takes into account proprietary information about the physical characteristics of the circuit conductors as well as historical load conditions to determine that maximum cumulative capacity of intermittent renewables that can be interconnected (again, measured in MVA) without encountering unacceptable thermal stress issues or exceeding voltage (min/max) threshold ranges.

In bears mentioning at this point, that the CSOM tool's ability to incorporate these types of grid capacity metrics was largely contingent upon the public availability of the requisite data. Within California, a 2014 Public Utilities Commission decision mandated that all of the state's investor-owned utilities generate and make publicly accessible circuit capacity metrics, explicitly for the purpose of renewable energy integration planning (Mehr et al., 2021). In other states and regions however, where utilities have not been similarly compelled by local regulatory authorities to create and disseminate these types of data, it is likely that they will be challenging to obtain.

2.11. Assigning additional site attributes

Once the set of eligible sites have been defined and each site associated with a single local distribution circuit, a series of additional contextual attributes are computed. These attributes are assigned to individual sites based upon their geographic intersection with a corresponding set of reference geometries – (i.e., census tracts, block groups, cities, zip codes, load serving entity territories, etc.). A key source of contextual data used for the prioritization of sites is the CES-4.0 layer, which provides a census tract level composite index measure of community disadvantage that is based upon a combination of environmental pollution burden measures and other socio-economic and demographic indicators.

In addition to disadvantaged community (DAC) status, the tool also explicitly incorporates relevant housing indicators from the Census American Community Survey (ACS), such as renter/owner populations and average household sizes. These metrics are further used as a source of normalization for historical annual residential electricity consumption data sourced from the UCLA Energy Atlas (Pincetl et al., 2020). These normalized electricity consumption values provide insights into the geographic distribution of renter/owner electricity usage in the local areas that are served by the same distribution circuit that is connected to each eligible site. Within the tool, we use these normalized values to project the total number of renter/owner households that a given site's modeled annual electricity output could potentially support if it were to function as the anchor of a locally available VNM program. It should be noted that these projected *household offset* estimates are calculated without explicit consideration of the on-site electricity usage of the site itself, which cannot be disclosed for data privacy reasons.

2.11.1. Choosing a web mapping platform

Once the base dataset of eligible sites was created we then evaluated a number of different technical options for delivering a web-map application. The alternatives considered ranged from completely bespoke solutions, implemented on bare metal servers, using a complete stack of open-source web-mapping software, to fully managed product offerings from commercial software vendors. Ultimately, we decided on the use of ArcGIS Online as our web-mapping platform solution. ArcGIS is a commercial software vendor that specializes in the development of geospatial analytics software and interactive location intelligence services.

On the back end, each ArcGIS Online user is provisioned with a fully managed, cloud-based, geospatial relational database instance. The hardware performance and storage sizing of these instances is determined by the software license level of each individual user. On the front-end, users are able to interact with their individual databases through an interactive data management and analytics portal that is rendered in the browser. This portal also provides access to tooling that enables the creation of highly customizable, fully hosted, web-map applications. These user-developed applications can access both user data and data that is hosted by external third-party services and applications.

Some additional practical considerations that were important in our ultimate decision to use ArcGIS Online for this project included.

- Access to an institutional enterprise site license through the university, providing sufficient storage capacity and hardware performance capabilities to support our data requirements and anticipated user traffic.
- The stability, ease of use, and large number of customization options available for the standard user interface components. These *widgets* facilitate interactive data filtering and styling operations as part of the hosted web-maps which can be produced.
- Integrations with third-party services that perform useful functions like automatically mirroring externally hosted data layers at regular time intervals or loading customized base-map tile sets.

3. Results

3.1. User experience design

The current production version of the CSOM tool can be found at the following URL:

https://solar.energyatlas.ucla.edu/

It was developed using ArcGIS' web-app builder interface. The web map is embedded on the Solar Map page, with separate pages providing additional contextual information and user guides. All of the code that is used to host this front end-website is available at the following GitHub repository, which is hosted separately from the one previously referenced, used for the data processing scripts:

https://github.com/uclaioes/solar-tool.

Fig. 3 illustrates the structure of the various pages included in this site. Image (A) shows the "About" page which describes the design intent of the project and its funding sources. Image (B) shows the

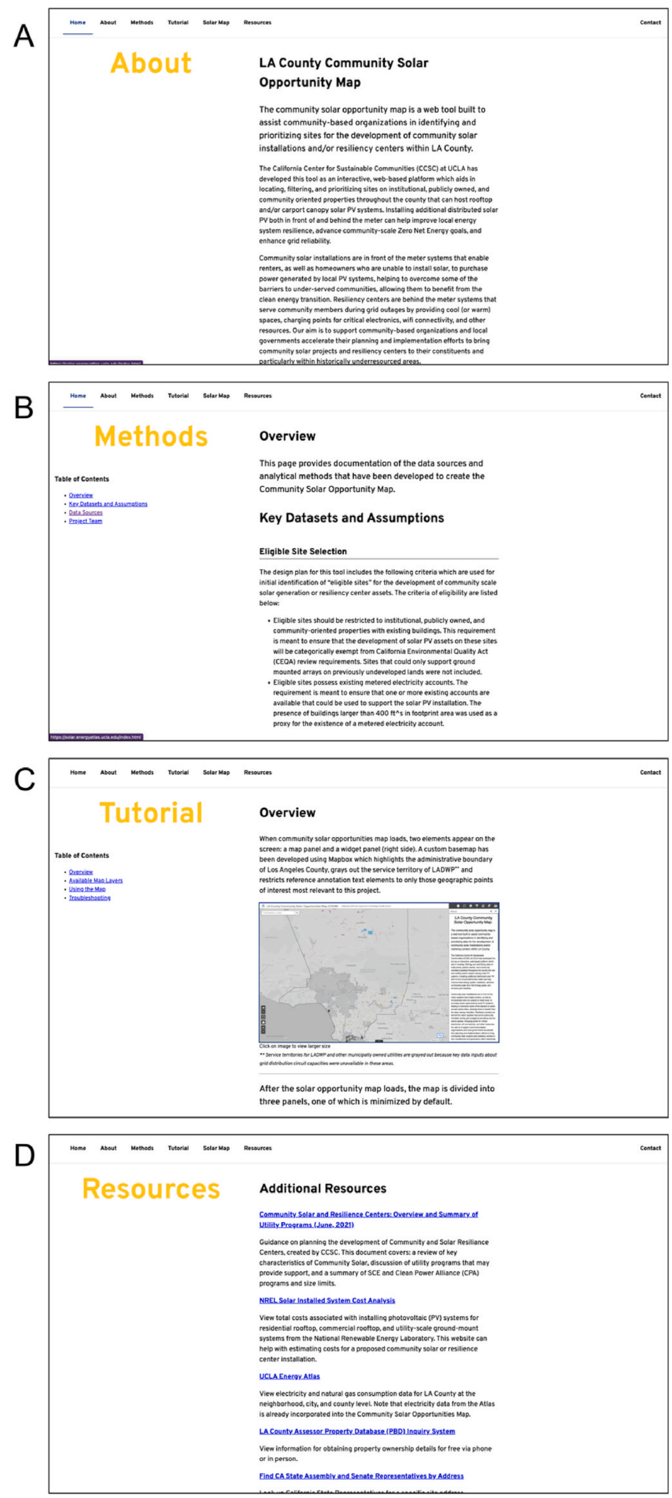

Fig. 3. Four screenshots illustrating user guides, resources, and other informational pages developed in support of the CSOM tool.

"Methods" page which details the various primary data sources, modeling assumptions, and analytical procedures used to generate the various site prioritization attributes. Image (C) shows the tutorial pages, which contains verbal and visual aids (animated GIFs) to guide users through the process of accomplish common filtering and prioritization tasks using the tool, as informed by our interactions with and feedback from the project's CBO partners during their case study experiences. And finally, image (D) provides a set of links to relevant third-party resources and tools to allow users to dive deeper into different aspects of the real-world community solar project development process.

3.2. Web map capabilities

The CSOM tool's web-map application was designed to enable the following three core capabilities.

- Exploration of a predetermined suite of eligible sites, initially selected on the basis of their feasibility of hosting a Community Solar PV system.
- Filtering of these eligible sites based upon their incidence to various reference geographies of interest as well as by other numerical and categorical attribute values.
- Prioritization of a narrowed set of eligible sites on the basis of, potentially, multiple simultaneous constraints/considerations.

This functionality is enabled through the compositional use of multiple geospatial overlays which providing relevant contextual information about regional characteristics. In addition to this, a widget panel is provided which exposes multiple customizable filters which operate on site level attributes. Finally, when viewing an individual site within the map, a customized base map has been provided which transitions from a vector to a raster tile set at high resolutions. The raster tiles provide high resolution satellite imagery of the site which enables the user to explore potential obstacles or opportunities for the placement of solar on the site.

Fig. 4 provides screenshot overviews of several key contextual overlay layers which have been included within the tool. Image (A) shows the base layer of eligible sites which, by default, are colored according to their general land use designation. Image (B) shows the activation of the layer showing the centerlines of local grid distribution circuits colored according to their BTM grid integration capacity. Image (C) shows the average annual electricity consumption of renter households for collections of census block groups served by the same local distribution circuits. Finally, Image (D) shows the location of census tracts identified as "Disadvantaged Communities" according to the CES-4.0 program, which is an important determinant of eligibility for various incentive programs and funding sources.

In addition to the interactive map overlays, dynamic filtering widget, and customized base map, there are two additional map components which help support the tool's core capabilities The first of these is an interactive attribute table, which can be toggled in and out of view, that provides a detailed view of the attributes of selected sites and allows for finer grained, sorting and manipulation of values, or even the export of data to a file which can be used for external processing. A second is a dynamic infographic, which plots salient attribute summaries for the set of currently selected sites.

3.3. Distributed solar potential and grid capacity limits

By querying the underlying database of sites exposed within the CSOM tool we were able to develop a high-level characterization of the technical potential for solar PV on eligible properties as well as anticipated limitations on realization of that potential based upon grid distribution circuit interconnection capacity figures. We note that these findings depict a single snapshot in time. While our methodology is based upon the best data available, there are still unavoidable

Fig. 4. Four screenshots illustrating various key contextual geographic overlay layers included in the CSOM tool.

uncertainties, all of which have been documented in the tool's GitHub repository and the Tool website's *Methods* page. We have sought to make conservative assumptions wherever possible and feel that this work represents the most logical and defensible approach to assessing current conditions and identifying needed policy changes.

There are 8091 institutional properties within LA County SCE territory with a combined potential of just under 3.5 GW. We estimate that the combined output of these systems, if developed under Community Solar programs with support from virtual net metering tariffs, would be sufficient to offset the energy use of between 460K and 2.5M households. This represents a tremendous opportunity to provide benefits of renewable energy to members of low-income and disadvantaged communities who would otherwise be prohibited from installing solar on their own homes due to their being renters, having unsuitable rooftops, having insufficient funds, etc.

Under current CPUC regulations and IOU program offerings, sites that are used for Community Solar projects must be developed IFOM. When the solar potential of each eligible site presented within the CSOM tool were compared to the ICA capacity of its nearest adjacent circuit segment, it was found that one-third (33%) of the total identified solar potential would likely be constrained from development due to current insufficient circuit capacities.

Community solar sites that might additionally incorporate BESS, such as resilience centers, must be interconnected to the grid from behind the customer meter and are subject to Net-Metering tariffs and interconnection rules. Rule-21, which governs the interconnection of these types of BTM DER systems within California, references the circuit's 15% Penetration Limit. According to this capacity metric, over 85% of the total solar potential identified across all of the CSOM tool's eligible sites would likely be constrained from development as Resilience Centers. BTM resilience centers offer access to electricity in times of outage due to their hosting storage batteries. These findings as well as relevant demographic statistics for the population of the LA County SCE service territory covered by the tool are summarized in Table 2.

4. Discussion

4.1. Energy democracy and decentralization

By making possible the radical decentralization of the generation and storage of electrical energy, DER technologies also enable accompanying (and potentially equally radical) democratization of the ownership and control over energy infrastructure (Bridge et al., 2013). This eventuality is far from assured, as the political war over what role DER will play in the renewable energy transition is still in a nascent stage (Szulecki, 2018). For example, one struggle which has recently concluded, involved California state energy regulators' decision to revise incentives available for grid interconnected rooftop solar PV systems. The CPUC's recently proposed net-metering rules would drastically reduce the compensation provided to homeowners for any electricity sold back to the grid, likely stemming the growth in distributed rooftop solar adoption.

Table 2
Summary statistics on Community Solar potential, grid limitations, and associated contextual information for LA County SCE Territory.

LA County SCE Territory, Total Potential	Value	Percent
Number of potential institutional sites	8091	
TOTAL Community Solar Potential on Institutional Properties (MW)	3466	100%
CIRCUIT ICA CONSTRAINED[a] Community Solar Potential on Institutional Properties (MW)	1136	33%
LA County SCE Territory, Household Energy Offset Potential	**Min**	**Max**
Households Whose Energy Could be Offset by TOTAL Community Solar Potential	460K	2.5M
Range of Households Whose Energy Would Not be Offset Due to CIRCUIT ICA CONSTRAINED[a] Community Solar Potential	150K	829K
LA County SCE Territory, Demographic Statistics	**Households**	**Percent**
TOTAL Households	1.7M	100%
TOTAL Households in DAC Census Tracts	635K	42%
RENTAL Households	807K	100%
RENTAL Households in DAC Census Tracts	362K	52%

[a] Each distribution circuit has a technical photovoltaic integration capacity that is measured in MVA. This metric is the result of an integrated capacity assessment (ICA) conducted by the local electric utility provider. When the combined solar potential of a group of sites that are assumed to be interconnected to the same circuit exceeds its ICA potential, we describe any remaining excess potential as being "ICA Constrained."

A great deal is at stake in this and other related policy debates: who benefits from DER systems, and who will be positioned to profit from knock-on effects of the energy transition? (Burke & Stephens, 2018) Ironically, the Rule 21 limitations that apply most stringently to larger solar arrays, curb community solar, yet the argument for revising the NEM incentives is that they most favor higher-income homeowners. Thus, communities are caught in a kind of catch 22. Community solar projects, which might help bring their ability to participate in a distributed energy transition, are constrained by the utilities, yet the utilities wish for NEM tariffs to reflect higher adoption by wealthier neighborhoods. Battery storage for community solar facilities is even further constrained and thus the most vulnerable communities have even more limited options for resilience centers.

Utilities, fossil fuel purveyors, and other groups with vested interests in minimizing disruption of the status quo, support a market-driven approach where decentralization is limited, the extent of DER adoption is greatest among higher-income cohorts, and where DERs serve to mitigate grid vulnerabilities by slowing the growth in demand for grid-supplied energy in certain locations (Porse et al., 2020; Brockway et al., 2021). Under this *market-based* adoption paradigm, DER functions primarily as a means to slow the growth in energy consumption among the most prolific users and to defer grid upgrades and operational changes. Utilities concerned about the grid management and challenges to their business models are aligned in this instance with those who wish to limit public (i.e., state) support for widespread DER adoption and investment in distributed renewable energy systems.

On the opposite side are those who see the potential of DER and decentralized generation to reduce economic inequality and involve communities more directly in decisions regarding energy policy (Bridge Gavin, BegümÖzkaynak, & Ethemcan, 2018). Subsidized DER adoption and a decentralized approach to generation are key to a more equitable energy transition. The movement for *energy democracy*, consisting of community groups, local governments, activist organizations, labor groups etc., is attempting to capitalize politically on the renewable energy transition in order to ensure that historically disadvantaged communities receive and benefit from DER systems, and that the renewable transition reduces economic inequality and improves local environmental conditions, in addition to abating carbon emissions (Burke & Stephens, 2018; Hess & Gentry, 2019; Williams et al., 2012). Community solar, a means to provide access to DER, is a means to level the playing field. Groups agitating for energy democracy point to the disproportionate adoption of DER among wealthier cohorts, legacies of environmental racism, and the potential for the exploitation of low-income DER adopters via predatory contracting as justifications for aggressive public intervention and investment in distributed renewable energy systems (Bullard, 1999).

4.2. Promoting a more equitable energy transition

Among the major questions which must be resolved in this ongoing energy transition is the scale of the new systems that are to be built, what tradeoffs exist between different choices for their siting and design, and their suitability to people's needs and existing built infrastructure (Calvert, 2016). Under the modernist paradigm, the electricity grid evolved in response to the suburbanization of cities and the increasing reliance on fossil fuels in all sectors of the economy and daily life. The energy transition offers an opportunity for the reassessment of this paradigm which has been both very successful and enormously polluting and damaging (Geels et al., 2017).

Distributed electricity systems depart from the top-down modernist approach by matching local conditions and local stakeholder input to that energy system (Graham & Marvin, 2002). Yet, as we have shown, the design of distributed systems requires expert knowledge to enable the assessment of local capacity, constraints, and options, from which stakeholders can then make informed decisions. Utilizing a PPGIS approach can help break down the silo between the experts and the stakeholder communities, but it does not overcome the types of embedded expert knowledge that GIS maps and analysis are built upon and transmit. Making that expert knowledge more transparent and accessible is a challenging task for the tool builders, and also requires stakeholders to have the time and interest to delve into the assumptions and programs utilized. Indeed, technologies such as GIS come with a history and a genealogy that themselves determine pathways of mapping, choices for the display of the data, and more. While researchers and experts can work to make their knowledge more accessible and indeed responsive, it is important to acknowledge the embedded structures within any knowledge system (Pincetl et al., 2020).

Beyond those facts, such tools are still enormously useful and can be transformative, providing new insights and understandings of what is possible to communities committed to a just energy transition that moves away from fossil energy generation. Just as the centralized energy system relied on centralized knowledge, a distributed energy system can grow many centers of expertise and knowledge, enabling communities to assert their own choices for their future.

5. Conclusions

5.1. Lessons from the CSOM tool

As this project has clearly demonstrated, geospatial decision support systems can play a valuable role in the pursuit of a more equitable renewable energy transition through the identification and prioritization of suitable candidate sites for the development of community solar assets. At present, the successful realization of these types of projects is often contingent upon the receipt of subsidized funding through state or federally sponsored programs seeking to prioritize grid infrastructure improvement and renewable energy investments within under-resourced and disadvantaged communities. The difficulties associated with simply defining what constitutes a disadvantaged community, however, means that these programs can have complicated eligibility criteria, something which these tools can be designed to specifically address. In addition to this, the site prioritization concerns of different stakeholders, such as between community-based organizations and local distribution grid operators, for example, tend to compete with one another. Within this type of environment, tools such as the CSOM are able to function (at the very least) as a clearing house of information where the requirements associated with building and maintaining a reliable power system can be transparently communicated to, and hopefully, suitably reconciled with the needs and preferences of local community members.

From a technical development standpoint, we were pleasantly surprised by the relative ease with which sophisticated and performant prototype web-maps were able to be spun-up and iterated upon using *off the shelf* geospatial software solutions. In the not-so-distant past, custom solutions that required significant cost and technical expertise to develop will be much facilitated by these tools. Much of this improvement is a result of the rapid pace of recent innovation in the geospatial software ecosystem, particularly among commercial service providers with fully managed cloud-based hosting platforms. This reduction in prototyping effort allowed for a significant increase in project resources to be allocated to the engagement with our stakeholders through the PPGIS process. Not only were we able to explore more alternative directions in terms of the design and features of the tool, but we were also able to allocate more time to developing formal responses to their feedback, guiding them through practical use-cases of the tool within the context of their specific interest and geographic areas of focus. The learning from these experiences was then later able to be generalized in the form of an extensive of user guides and tutorials that are now permanent features of the final version of the tool.

5.2. Policy recommendations

Relative to the California specific context that was the focus of the tool development process discussed in this manuscript, we suggest that in order to further unlock the tremendous potential which exists for increased distributed solar on institutional, publicly owned, and community-oriented properties state Public Utility Commissions must consider the following regulatory changes. Community Solar programs should be greatly expanded, and the rules regarding both site and enrollee eligibility should be standardized and simplified across all of the IOU service territories. Relevant tariffs must be created which both allow for VNM, especially for projects which include BESS which can provide local communities with enhanced energy resilience services.

More broadly, nationwide, PUCs should also revise regulations and make financing available, through rate payer funds, to facilitate the development of these types of Community Solar projects. Other, more innovative, but perhaps less consistently available sources of funding, such as from cap-and-trade programs, can and should be used to support local governments and CBOs in the development of these types of projects as well.

From a technical standpoint, PUCs in other states should follow California's lead in mandating that local distribution system operators analyze the capacity of the grid to support the interconnection of greater DER capacity. Moreover, these grid integration capacity constraints must be made publicly available for use in assessing the feasibility of planned DER projects. And finally, the detailed methodologies used to estimate these constraints should be evaluated through a public process, using open source/access datasets and models.

Author statement

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References

Akorede, M. F., Hizam, H., & Pouresmaeil, E. (2010). Distributed energy resources and benefits to the environment. *Renewable and Sustainable Energy Reviews, 14*(2), 724–734. https://doi.org/10.1016/j.rser.2009.10.025

Asmus, P. (2008). Exploring new models of solar energy development. *The Electricity Journal, 21*(3), 61–70. https://doi.org/10.1016/j.tej.2008.03.005

Bridge, Gavin, Özkaynak, Begüm, & Ethemcan, T. (2018). "Energy infrastructure and the fate of the nation: Introduction to special issue.". *Energy Research & Social Science*. https://doi.org/10.1016/j.erss.2018.04.029

Bridge, G., Bouzarovski, S., Bradshaw, M., & Eyre, N. (2013). "Geographies of energy transition: Space, place and the low-carbon economy.". *Energy Policy*. https://doi.org/10.1016/j.enpol.2012.10.066

Brockway, A. M., Conde, J., & Callaway, D. (2021). Inequitable access to distributed energy resources due to grid infrastructure limits in California. *Nature Energy, 6*(9), 892–903. https://doi.org/10.1038/s41560-021-00887-6

Bullard, R. D. (1999). Dismantling environmental racism in the USA. *Local Environment, 4*(1), 5–19. https://doi.org/10.1080/13549839908725577

Burke, M. J., & Stephens, J. C. (2018). "Corrigendum to 'energy democracy: Goals and policy instruments for sociotechnical transitions' [energy res. Soc. Sci. 33 (2017)

35–48].". *Energy Research & Social Science*. https://doi.org/10.1016/j.erss.2018.03.030
California Public Utilities Commission. (2022a). Green tariff/shared renewables program (GTSR). Retrieved February 2, 2022, from https://www.cpuc.ca.gov/industries-and-topics/electrical-energy/electric-rates/green-tariff-shared-renewables-program.
California Public Utilities Commission. (2022b). *Solar in disadvantaged communities*. Retrieved. from https://www.cpuc.ca.gov/industries-and-topics/electrical-energy/solar-in-disadvantaged-communities. (Accessed 2 February 2022).
Calvert, K. (2016). "From 'energy Geography' to 'energy Geographies.'". *Progress in Human Geography*. https://doi.org/10.1177/0309132514566343
Castellanos, S., Sunter, D. A., & Kammen, D. M. (2017). Rooftop solar photovoltaic potential in cities: how scalable are assessment approaches? *Environmental Research Letters, 12*(12), 125005.
Cochran, J., Denholm, P., Speer, B., & Miller, M. (2015). *Grid integration and the carrying capacity of the US grid to incorporate variable renewable energy*. Golden, CO (United States): National Renewable Energy Lab. (NREL). https://doi.org/10.2172/1215010. No. NREL/TP-6A20-62607).
Coddington, M., Mather, B., Kroposki, B., Lynn, K., Razon, A., Ellis, A., & Smith, J. (2012). *Updating interconnection screens for PV system integration (No. NREL/TP-5500-54063)*. Golden, CO (United States): National Renewable Energy Lab.(NREL).
Cohn, J. (2018). When the grid was the grid: The history of north America's brief coast-to-coast interconnected machine [scanning our past]. *Proceedings of the IEEE, 107*(1), 232–243. https://doi.org/10.1109/JPROC.2018.2880938
Dg-Stats. (2021). California DG-Stats. Retrieved from https://www.californiadgstats.ca.gov/. (Accessed 30 January 2022).
Dobos, A. P. (2014). *PV-Watts version 5 manual (No. NREL/TP-6A20-62641)*. Golden, CO (United States): National Renewable Energy Lab. (NREL).
Energy Information Administration (EIA). (2021). *Battery storage in the United States: An update on market trends*. www.eia.gov.
Fournier, E. D., Cudd, R., Federico, F., & Pincetl, S. (2020). "On energy sufficiency and the need for new policies to combat growing inequities in the residential energy sector.". *Elem Sci Anth*. https://doi.org/10.1525/elementa.419
Geels, F. W., Sovacool, B. K., Schwanen, T., & Steve, S. (2017). "Sociotechnical transitions for deep decarbonization.", 6357 *Science, 357*, 1242. https://doi.org/10.1126/science.aao3760, 44.
Graham, S., & Marvin, S. (2002). Splintering urbanism: Networked infrastructures, technological mobilities and the urban condition. *Routledge*. https://doi.org/10.1111/1467-8306.93121
Hess, D. J., & Gentry, H. (2019). 100% renewable energy policies in US cities: strategies, recommendations, and implementation challenges. *Sustainability: Science, Practice and Policy, 15*(1), 45–61.
Jain, A. K., Nagarajan, A., Chernyakhovskiy, I., Bowen, T., Mather, B., & Cochran, J. (2019). Evolution of distributed energy resource grid interconnection standards for integrating emerging storage technologies. In *2019 North American power Symposium (NAPS)* (pp. 1–6). IEEE.
Levinson, R., Akbari, H., Pomerantz, M., & Gupta, S. (2009). Solar access of residential rooftops in four California cities. *Solar Energy, 83*(12), 2120–2135. https://doi.org/10.1016/j.solener.2009.07.016
Mehr, V., Kahrobaee, S., & Avendano, M. (2021). Harnessing the full potential of clean energy: The role of Southern California's utility distributed energy resource pilots. *IEEE Power and Energy Magazine, 19*(4), 28–40.
Meneguzzo, F., Ciriminna, R., Albanese, L., & Pagliaro, M. (2015). The great solar boom: A global perspective into the far-reaching impact of an unexpected energy revolution. *Energy Science & Engineering, 3*(6), 499–509. https://doi.org/10.1002/ese3.98
Michaud, G. (2020). Perspectives on community solar policy adoption across the United States. *Renewable Energy Focus, 33*(June), 1–15. https://doi.org/10.1016/j.ref.2020.01.001
Moselle, B., Padilla, J., & Schmalensee, R. (2010). *Harnessing Renewable Energy in Electric Power Systems: Theory, Practice, Policy*. https://doi.org/10.4324/9781936331864
Norris, T. B. (2017). "Public participation GIS, participatory GIS, and participatory mapping.". *Geography*. https://doi.org/10.1093/obo/9780199874002-0160
O'Shaughnessy, E., Barbose, G., Wiser, R., Forrester, S., & Darghouth, N. (2021). The impact of policies and business models on income equity in rooftop solar adoption. *Nature Energy, 6*(1), 84–91. https://doi.org/10.1038/s41560-020-00724-2
Pincetl, S., Gustafson, H., Federico, F., Fournier, E. D., Cudd, R., & Porse, E. (2020). Energy use in cities. In *Energy use in cities*. Springer International Publishing. https://doi.org/10.1007/978-3-030-55601-3.
Porse, E., Fournier, E. D., Cheng, D., Hirashiki, C., Gustafson, H., Federico, F., & Pincetl, S. (2020). Net solar generation potential from urban rooftops in Los Angeles. *Energy Policy, 142*, Article 111461. https://doi.org/10.1016/j.enpol.2020.111461
Ramasamy, V., Feldman, D., Desai, J., & Margolis, R. (2021). *U.S. Solar photovoltaic system and energy storage cost benchmarks: Q1 2021*. www.nrel.gov/publications.
Scavo, J., Korosec, S., Guerrero, E., Pennington, B., & Doughman, P. (2016). Low-income barriers study, Part A: Overcoming barriers to energy efficiency and renewables for low-income customers and small business contracting opportunities in disadvantaged communities. In *CEC (issue CEC-300-2016-009-CMF)*. https://efiling.energy.ca.gov/getdocument.aspx?tn=214605.
Sieber, R. (2006). "Public participation geographic information systems: A literature review and framework.". *Annals of the Association of American Geographers*. https://doi.org/10.1111/j.1467-8306.2006.00702.x
Sunter, D. A., Castellanos, S., & Kammen, D. M. (2019). Disparities in rooftop photovoltaics deployment in the United States by race and ethnicity. *Nature Sustainability, 2*(1), 71–76.
Szulecki, K. (2018). "Conceptualizing energy democracy.". *Environmental Politics*. https://doi.org/10.1080/09644016.2017.1387294
Williams, J. H., DeBenedictis, A., Ghanadan, R., Mahone, A., Moore, J., Morrow 3rd, W. R., Price, S., & Torn, M. S. (2012). "The technology path to deep greenhouse gas emissions cuts by 2050: The pivotal role of electricity.". *Science, 335*, 53–59. https://doi.org/10.1126/science.1208365, 6064.