The Los Angeles 100% Renewable Energy Study

Chapter 4. Customer-Adopted Rooftop Solar and Storage

FINAL REPORT: LA100—The Los Angeles 100% Renewable Energy Study

March 2021

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Los Angeles Department of Water & Power

NREL Transforming ENERGY

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Chapter 4. Customer-Adopted Rooftop Solar and Storage

March 2021

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The Los Angeles 100% Renewable Energy Study

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Context

The Los Angeles 100% Renewable Energy Study (LA100) is presented as a collection of 12 chapters and an executive summary, each of which is available as an individual download.

- The **Executive Summary** describes the study and scenarios, explores the high-level findings that span the study, and summarizes key findings from each chapter.
- **Chapter 1: Introduction** introduces the study and acknowledges those who contributed to it.
- **Chapter 2: Study Approach** describes the LA100 study approach, including the modeling framework and scenarios.
- **Chapter 3: Electricity Demand Projections** explores how electricity is consumed by customers now, how that might change through 2045, and potential opportunities to better align electricity demand and supply.
- **Chapter 4: Customer-Adopted Rooftop Solar and Storage** (this chapter) explores the technical and economic potential for rooftop solar in LA, and how much solar and storage might be adopted by customers.
- **Chapter 5: Utility Options for Local Solar and Storage** identifies and ranks locations for utility-scale solar (ground-mount, parking canopy, and floating) and storage, and associated costs for integrating these assets into the distribution system.
- **Chapter 6: Renewable Energy Investments and Operations** explores pathways to 100% renewable electricity, describing the types of generation resources added, their costs, and how the systems maintain sufficient resources to serve customer demand, including resource adequacy and transmission reliability.
- **Chapter 7: Distribution System Analysis** summarizes the growth in distribution-connected energy resources and provides a detailed review of impacts to the distribution grid of growth in customer electricity demand, solar, and storage, as well as required distribution grid upgrades and associated costs.
- **Chapter 8: Greenhouse Gas Emissions** summarizes greenhouse gas emissions from power, buildings, and transportation sectors, along with the potential costs of those emissions.
- **Chapter 9: Air Quality and Public Health** summarizes changes to air quality (fine particulate matter and ozone) and public health (premature mortality, emergency room visits due to asthma, and hospital admissions due to cardiovascular diseases), and the potential economic value of public health benefits.
- **Chapter 10: Environmental Justice** explores implications for environmental justice, including procedural and distributional justice, with an in-depth review of how projections for customer rooftop solar and health benefits vary by census tract.
- **Chapter 11: Economic Impacts and Jobs** reviews economic impacts, including local net economic impacts and gross workforce impacts.
- **Chapter 12: Synthesis** reviews high-level findings, costs, benefits, and lessons learned from integrating this diverse suite of models and conducting a high-fidelity 100% renewable energy study.

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Key Findings

The LA100 study identifies and evaluates pathways that achieve a 100% renewable electricity supply for the city of Los Angeles while maintaining acceptable reliability for both the grid and end users. This chapter and the next focus on the role of energy resources connected to the distribution system, both customer adopted (this chapter) and procured by LADWP (Chapter 5). Customer-adopted resources complement the bulk power system in that rooftops offer many suitable locations for solar that do not compete with other urban land uses, and these resources help reduce the need for new transmission. Through simulation and analysis of the core LA100 scenarios, we evaluate distributed energy resource potential at unprecedented scale—for every building in LADWP service territory. We focus on the following questions: what is the technical potential for rooftop solar and how is it distributed spatially and by sector? How much of the potential is economic, and how is economic potential affected by the evolving power system? How much distributed solar and storage might be adopted by customers to contribute to a 100% clean energy supply?

How much potential exists for rooftop solar? Characterizing the opportunity:

1. **Rooftop solar potential in Los Angeles is significant and represents the largest in-basin generation resource.** The city has over 13 GW of solar rooftop technical potential (Figure 1), and over half is in the residential sector. Potential was measured for each building using lidar scans that assess a roof's unshaded area, tilt, and orientation.

2. **Opportunity for rooftop solar on multifamily buildings is substantial, and a potential contributor to environmental justice**. Development on multifamily buildings is currently limited due to classic owner-tenant barriers to adoption. The study identifies 2,060 MW_{DC} of technical potential for multifamily building rooftop solar and 337 MW_{DC} for ground-mount solar. Additional locations for virtual net-metering programs are identified in Chapter 5.

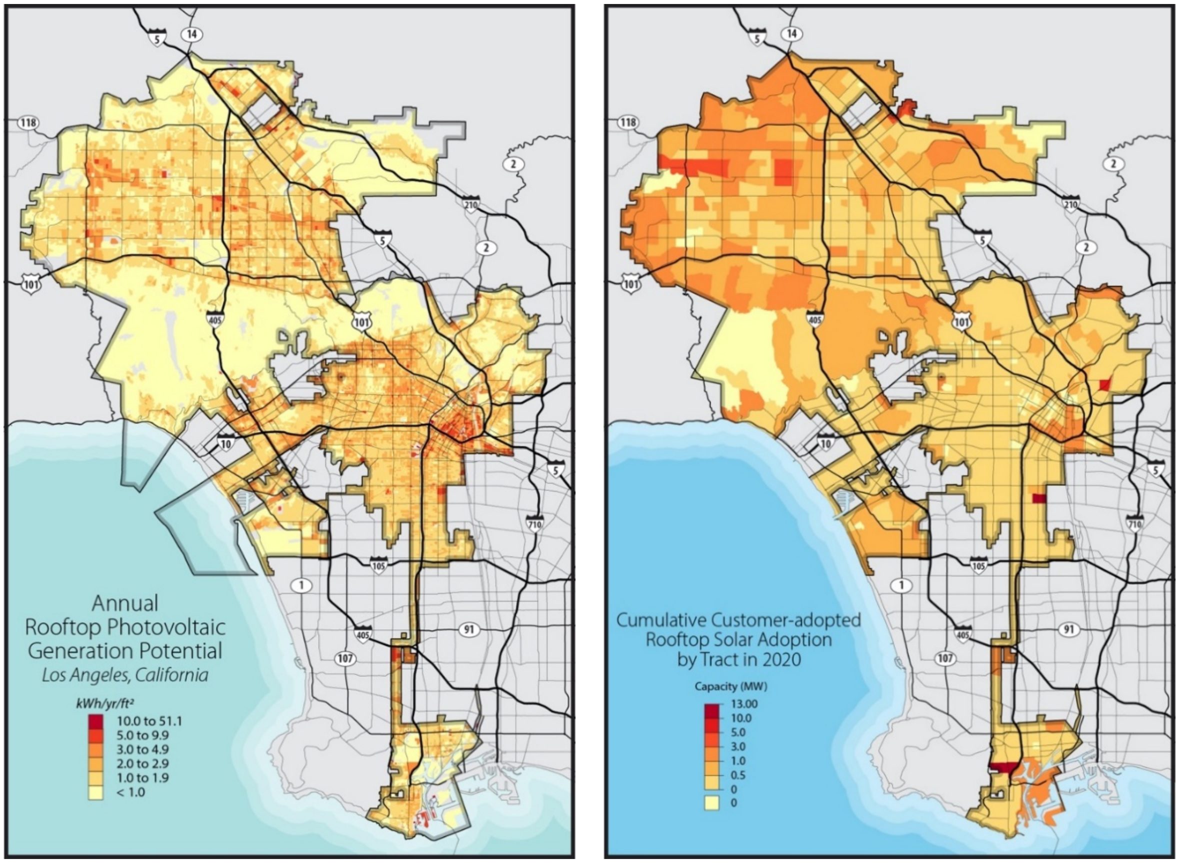

Figure 1. Annual rooftop solar generation technical potential (kWh/yr/ft^2) based on lidar scans, averaged by census tract (left)

Through 2019, over 330 MW of rooftop solar has already been deployed (right).

How much rooftop solar is economic? Interactions with load electrification

NREL conducted five projections of rooftop solar adoption, which examine the effects of customer solar compensation (High vs. Moderate) and customer electricity demand projections (Moderate, High, Stress, as covered in Chapter 3). These projections are intended to create a range of possible distributed solar adoption levels, though they are agnostic to potential policies Los Angeles might enact through 2045. In the Early & No Biofuels and Limited New Transmission scenarios, we simulate a continuation of LADWP's current compensation program for customer solar under net metering at retail electricity value (i.e., all customer solar generation is valued at the retail electricity price). In the SB100 and Transmission Focus scenarios, customer solar generation is valued using net billing starting from the year 2020. Net billing assumes that self-consumed customer solar generation offsets retail purchases, and non-self-consumed generation (i.e., exported to the grid) is valued relative to other sources of generation at that time (i.e., at wholesale rates). Net billing is evaluated due to the potential benefits of aligning customer signals with LADWP's system to help reduce total investment costs of reaching 100% renewable energy. Projected future customer solar costs are projected to decline from 2020 to 2045 for the residential ($2.3/$W_{DC}$ to $1.1/$W_{DC}$) and nonresidential ($1.6/W_{DC} to $0.9/$W_{DC}$) sectors (NREL ATB 2018).

1. **By 2045 rooftop solar would be an economic choice for nearly all households and businesses.** Fundamental drivers of rooftop solar value are strong, including projected continued declines in solar costs, increasing retail rates, and increasing electricity demand due to electrification of building end uses and vehicles. Economic potential for the twin customer solar projections of Early & No Biofuels and Limited New Transmission – High Load Electrification is 9.9 GW in 2045, followed by SB100 – Stress Load Electrification at 9.3 GW (Figure 2). To estimate customer adoption of solar, we simulate the amount of rooftop solar capacity that would be economic for LADWP customers to adopt in each year. This includes determining not only whether it is economic to adopt solar, but also the best match of solar capacity to the building's energy consumption.

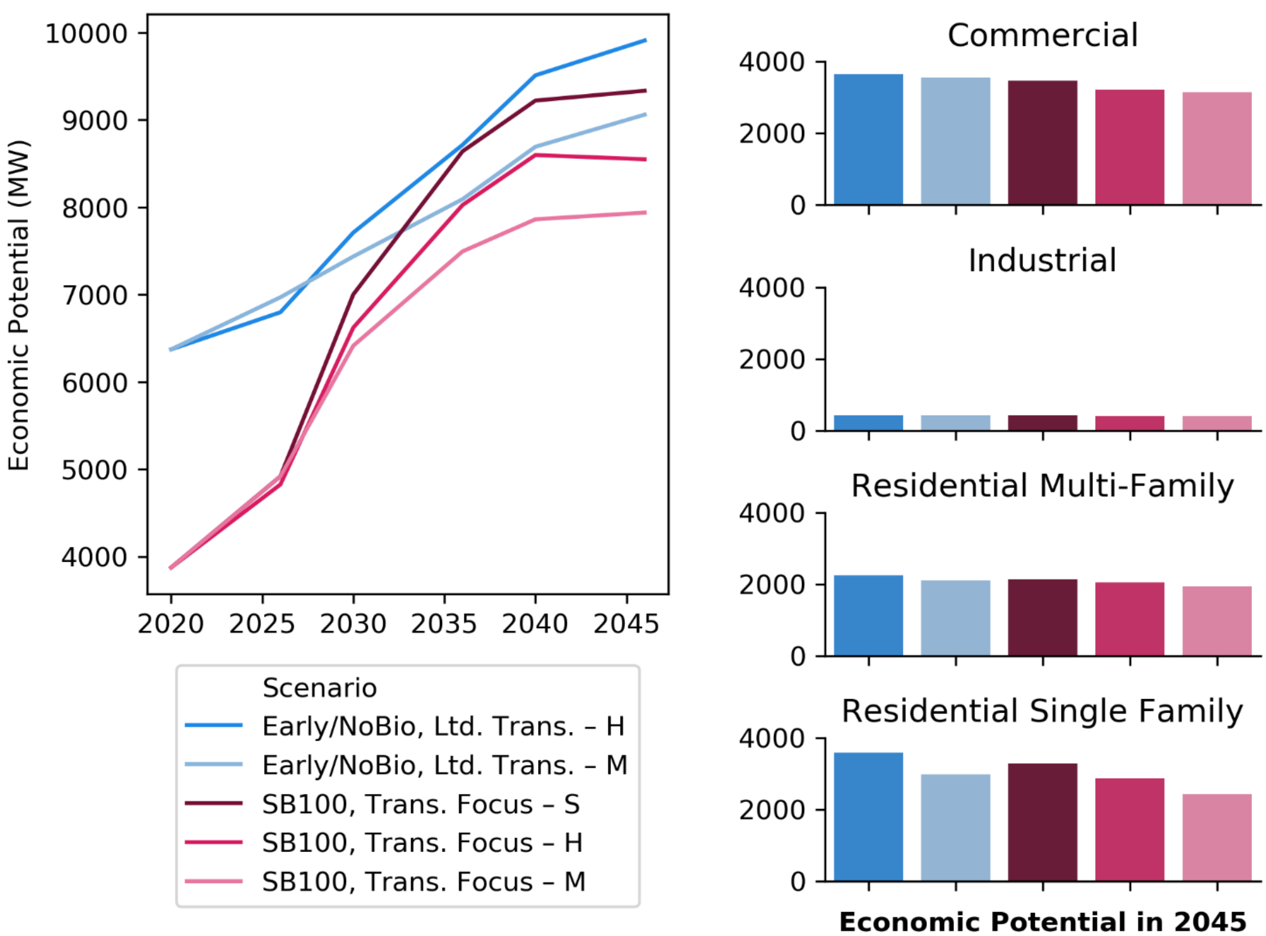

Figure 2. Total economic potential (GW) by year (left) and by sector in 2045 only (right) for the five projections

2. **Compensating non-consumed generation at wholesale rates lowers the overall economic potential**, but by 2045, results in similar amounts of overall potential as most technical potential is economic at that point. Much of the gap in what is deemed "economic" between the two compensation types is bridged by 2030, though they do result in different amounts of adoption.

3. **Increased load electrification is a significant driver of rooftop solar potential.** As demand for electricity increases with new loads, rooftop solar potential similarly increases to offset the new demand. However, the compensation mechanism for rooftop solar (net billing or net metering) is a larger driver of rooftop solar overall.

How much rooftop solar and storage is adopted?

4. **LA100 projects that customers adopt between 2.8 GW and 3.9 GW of rooftop solar by 2045, including 22%–38% of all existing single-family homes, up from 6% in 2020.** Customers are projected to adopt between 34% and 40% of the total economic potential for rooftop solar capacity. Figure 3 illustrates cumulative adoption over time. Initially scenarios with higher daytime compensation encourage earlier adoption, but over time, the scenarios begin to converge and are influenced by overall levels of customer electricity demand. Table 1. Summary of Cumulative Projected Rooftop Solar Deployment (MW_{DC}) in 2045, by Sector summarizes this potential by scenario.

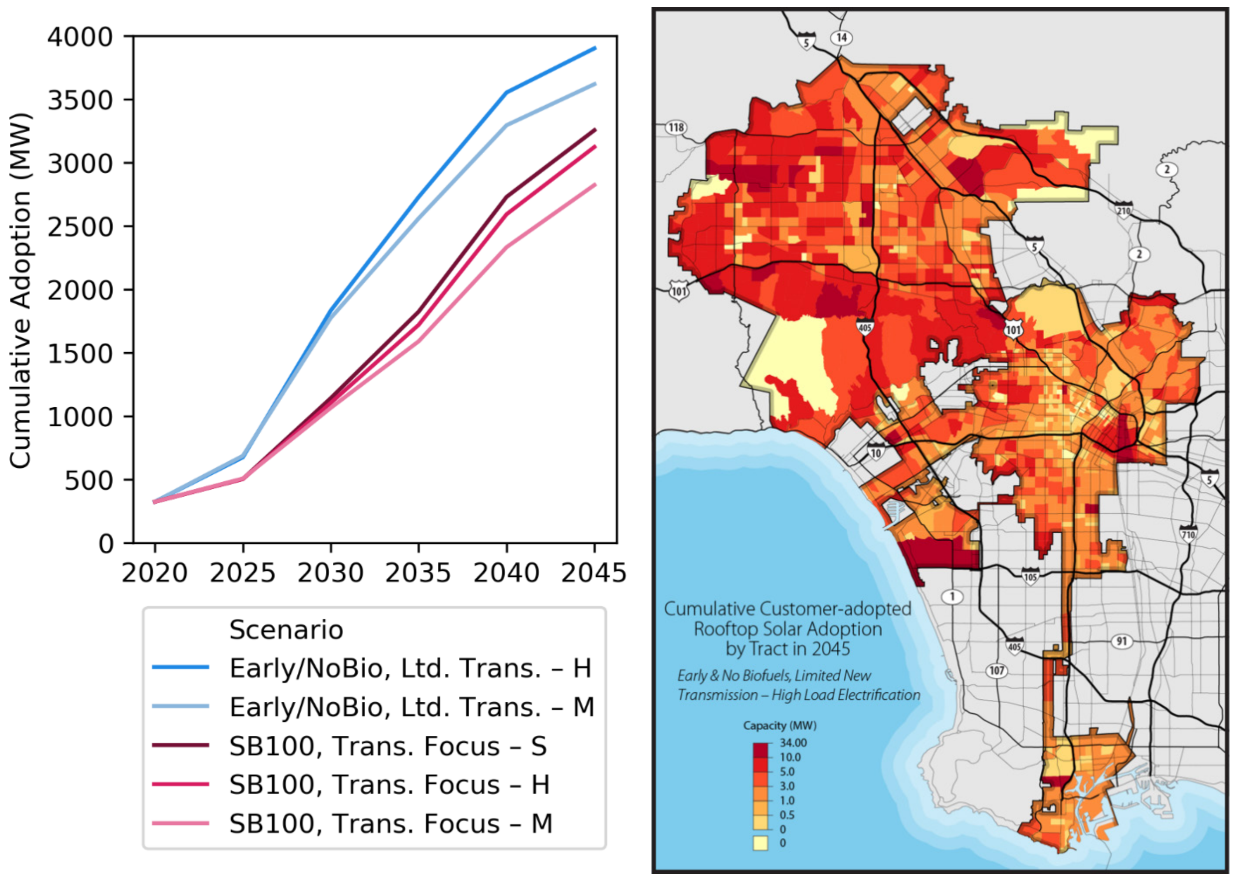

Figure 3. Rooftop solar adoption projection by scenario (left); Adoption by tract in the Early & No Biofuels – High and Limited New Transmission – High scenario in 2045 (right)

Table 1. Summary of Cumulative Projected Rooftop Solar Deployment (MW_{DC}) in 2045, by Sector

	Total	Residential – Single-Family	Residential – Multifamily	Commercial	Industrial
Early & No Biofuels, Limited New Transmission – High Load Electrification	3,899	2,394	867	575	63
Early & No Biofuels, Limited New Transmission – Moderate Load Electrification	3,617	2,159	833	564	62
SB100 – Stress Load Electrification	3,254	2,057	755	408	35
SB100, Transmission Focus – High Load Electrification	3,122	1,964	721	403	34
SB100, Transmission Focus – Moderate Load Electrification	2,822	1,709	693	385	35

5. **LA100 also projects customer-adopted storage based on historical trends of adoption** within LADWP and California. Using a linear trend, NREL projects that in 2045, 91% of residential solar systems purchased that year are co-adopted with storage and 64% of nonresidential systems, resulting in 1.1–1.5 GW adopted (4-hour duration).

Important Caveats

1. **The potential role of evolving electricity prices has not been explored.** This analysis starts from existing LADWP tariffs and does not consider changes to their structure or design. For instance, at high levels of renewable deployment, retail prices might evolve to better communicate needs of the overall power system during periods of scarcity to ratepayers.
2. **This study assumes strong uptake from low-income households.** Existing solar adoption in Los Angeles is currently skewed to mid- to-high-income single-family homes. Research indicates that economic factors, specifically, savings on electricity bills, are a significant factor in solar adoption for all sectors. This study presumes that, when it is economic to do so, low-income households adopt solar at equal measures as high-income ones and have equal access to financing. However, we do assume a lower rate of adoption among multifamily and renter-occupied buildings. The analysis is agnostic to the types of policies that Los Angeles could enact to encourage low-income solar adoption.
3. **Customer adoption of distributed storage is in an early stage**. As such, well-calibrated customer adoption models are currently not widely available. Among other factors to be further understood by further research are how customers respond to utility and/or price signals to charge and discharge from the grid, and the degree to which distributed solar is coupled with storage.

1 Introduction

The future electricity system in Los Angeles will likely be shaped by increased adoption of customer-owned solar and storage. This study uses NREL's dGen™ model (NREL 2021a, NREL 2021b) to represent decision-making of potential adopters of rooftop solar and storage. Such a model is needed because the capacity expansion model (CEM) used in this study, the Resource Planning Model (RPM), like most CEMs, does not inherently include customer adoption of distributed resources. Utility-side investment decisions in RPM are based on least-cost investment decisions, subject to meeting load, reliability requirements, transmission constraints, and environmental and policy regulations. Rooftop solar investment decisions, however, are typically independent of these considerations. Adoption decisions are still often cost driven, but they typically do not consider the impacts of the rooftop system beyond one's own home or office building. Also, costs for the rooftop systems are typically compared against retail rates, which are considerably higher than the wholesale rates considered in utility-side decisions. Per discussions with LADWP and the LA100 Advisory Group, projected rooftop solar adoption is based off customer electricity bill savings and does not consider adoption that could occur under LADWP's feed-in tariff or other possible future programs.

This combined modeling framework (Figure 4) allows us to consider the interplay between rooftop solar deployment and bulk power system evolution. The interactions are many, including the contribution of demand-side generators to generation surplus, ramping requirements, and the effect of increased demand-side penetration on wholesale rates. These interaction effects will eventually impact retail rates, net metering, and other mechanisms for valuing demand-side generation. It is especially important to understand these interactions in high solar scenarios because at high levels of solar photovoltaic (PV) penetration, new PV generators tend to have decreasing value.

Context within LA100

This chapter is part of the Los Angeles 100% Renewable Energy Study (LA100), a first-of-its-kind power systems analysis to determine what investments could be made to achieve LA's 100% renewable energy goals. Figure 5 provides a high-level view of how the analysis presented here relates to other components of the study. See Chapter 1 for additional background on LA100, and Chapter 1, Section 1.9, for more detail on the report structure.

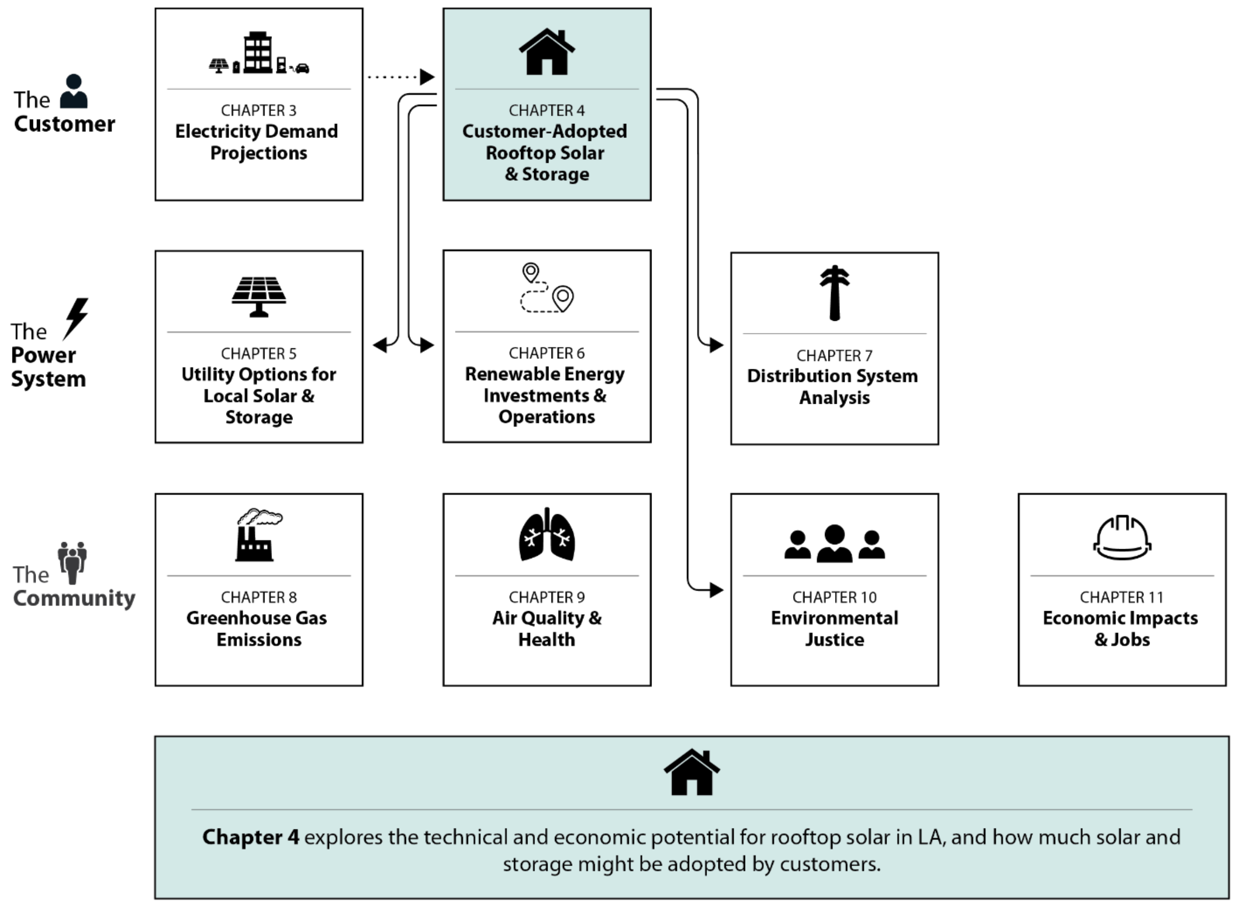

Figure 5. Overview of how this chapter, Chapter 4, relates to other components of LA100

Chapter 3 (Electricity Demand Projections) provides data that serve as inputs to this chapter. The results from this chapter provides inputs to the power system analyses in Chapters 5, 6, and 7, and the environmental justice analysis in Chapter 10.

In particular, the analysis in this chapter focuses on customer adoption of solar and storage, which is based on economic analysis associated with customer bill savings. Because this analysis is from the customer perspective, the study assumes that this solar and storage is built regardless of the value to LADWP relative to other sources of generation. Furthermore, the analysis does not consider changes of retail rate design. The locations for customer-procured solar in this study are limited to the customers' rooftops.

Additional locations within the city could also be suitable for solar and storage, on both public and private property. This type of solar includes ground-mount, parking canopy, and floating. The study assumes that these types of solar connected to the distribution grid would be procured by LADWP, such as through feed-in tariffs, power purchase agreements, or direct ownership, though does not consider utility-procured rooftop solar. Chapter 5 presents analysis for possible locations and associated distribution-grid-integration costs. The analysis that determines how much additional solar and storage would be of value for each scenario is addressed through system-wide planning, covered in Chapter 6. Chapter 7 evaluates the combined impacts of these installations, along with changes to customer electricity demand, to assess upgrades needed for the distribution grid.

2 Methodology

The dGen model used in this study is a bottom-up agent-based model that simulates the potential adoption of rooftop solar systems in the residential, commercial, and industrial sectors in Los Angeles from 2020 to 2045. Rooftop solar adoption is modeled through an agent-based approach that includes four overarching steps (Figure 6):

1. *Identifying agents (i.e., potential customers) and their attributes.* For this project, agents are defined at the at the level of individual residents or firms using LADWP-provided data
2. *Establishing measures of technical potential* including resource quality, unshaded roof area, and building and load constraints for each agent
3. *Conducting financial calculations* using cash flow analysis incorporating project costs, prevailing retail rates, incentives, and net metering considerations
4. *Estimating rooftop solar adoption* based on the Bass diffusion model and other considerations of consumer behavior and calibrated to historical adoption trends.

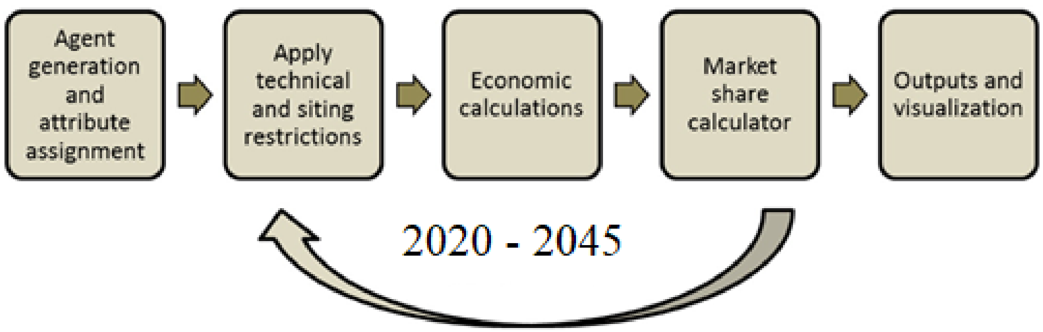

Figure 6. Flow diagram for dGen model

Diffusion of rooftop solar in dGen had traditionally been based on the payback period as the primary metric for determining the maximum market share of rooftop solar, though for this study adoption decisions were calibrated using historical data and incorporating economic and non-economic factors. The primary non-economic factors used are proximity to previous adopters, income, and building type (e.g., single-family vs. multifamily). To improve the precision of adoption forecasts, dGen uses a premise-level algorithm to estimate a probability of adoption in each model year. The technical suitability of individual roofs for solar was assessed using established NREL methods and 2013 lidar (light detecting and ranging) scans of Los Angeles.[1] Then, the rooftop technical potential estimates were paired with other premise-level attributes (e.g., hourly load profile, retail tariff) and neighborhood-level attributes (e.g., average income

[1] Data from 2013 were deemed the best-available complete scan of LAWDP territory; Pieter Gagnon, Robert Margolis, Jennifer Melius, Caleb Phillips, and Ryan Elmore. *Rooftop Solar Photovoltaic Technical Potential in the United States: A Detailed Assessment* (NREL, 2016), NREL/TP-6A20-65298. https://www.nrel.gov/docs/fy16osti/65298.pdf; Ben Sigrin and Meghan Mooney. *Rooftop Solar Technical Potential for Low-to-Moderate Income Households in the United States* (NREL, 2018), NREL/TP-6A20-70901. https://www.nrel.gov/docs/fy18osti/70901.pdf.

and other demographics, existing PV penetration rate) to construct the dGen input agents. Finally, NREL trained a predictive model of existing rooftop solar interconnection records for each census tract and load sector to estimate probabilities of rooftop solar adoption at the premise level. The premise-level probabilities incorporated solar price elasticity (i.e., the responsiveness of consumers to different prices, as well as other fixed effects such as the influence of income or social interaction on consumers' decisions). The simulations do not consider the introduction of any new policies enacted by Los Angeles relating to distributed generation. Also, because agents are not created corresponding to future new construction, the simulations do not consider the influence of the California Energy Commission Title 24 building efficiency standards (i.e., that rooftop solar is default for new construction).

In the LA100 study, dGen is run first based on current rate structures and parameters, with results (rooftop solar and distributed storage capacity and performance by location) passed to RPM. RPM uses the rooftop solar capacity and capacity factors to determine the amount of generation supplied by rooftop solar. Once RPM receives the dGen inputs, it solves the capacity expansion and dispatch optimization over the study period. dGen uses the results of RPM to 1) assign cost increases over time to all electricity rate components, and 2) assign a time-specific value to customer generation to evaluate the impact of PV value (including curtailment) on potential adoption using scenario-year specific energy and capacity prices. The feedback cycle is repeated, as seen in Figure 7.

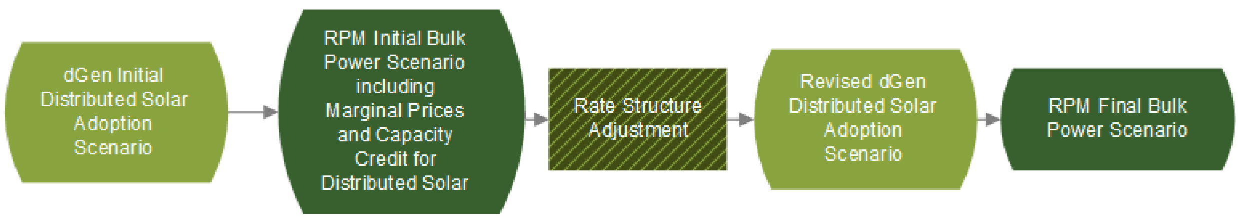

Figure 7. Schematic of the RPM-dGen linkage

Model Calibration

To understand the drivers of historical adoption, we performed a screening analysis to identify features correlated with solar adoption in LADWP territory. From there, a logistic regression model was developed with a training data set composed of selected features to predict whether or not an agent would install PV, based on historical adoption. The features for the logistic regression were identified based on the correlation of installed capacity and the specific attribute or feature. The following are the list of attributes or features that were selected and that are important drivers of adoption for premises in LA:

- Developable rooftop (ft^2) or kW: assessed through lidar analysis and unique for each premise
- Property area (ft^2) and assessed property area (ft^2): unique for each premise
- Land value: unique for each premise
- Historical annual energy consumption: unique for each premise
- Vintage (home age): unique for each premise
- Payback period: calculated by dGen, unique for each premise
- Median income: median value by tract

- Climate Zone: unique for tract
- Historical adoption: unique for tract

Due to lack of premise-scale data on household income, the land value of the premise (unique for each premise) was used as a proxy for income. The correlation of installed PV capacity with land value in the LADWP data set is 0.098, independent of sector. Correlation values above 0.5 are considered to show positive correlation while those closer to zero indicate that there is no or low correlation between the attributes considered. Therefore, in the case of premises in LA, the land value has a moderate correlation with the PV capacity (i.e., higher land value is not positively correlated with higher PV capacity). The correlation between assessed property area (ft^2) and installed PV capacity was also calculated and is found to be 0.35. Therefore, the assessed area of a premise, which would determine the available rooftop area for PV is a good indicator of the amount of installed PV capacity. Historical production data (i.e., hourly generation profiles) and grid exports were not available to the study.

Summary of Assumptions—Distributed Generation Adoption

- The study uses the dGen model to identify customer-driven adoption of distributed energy resources (e.g., rooftop solar).
- Adoption of distributed storage is not explicitly modeled in dGen and is based on an assumption of a fixed fraction of storage attachment to new rooftop solar systems, similar to the approach for EV adoption. The fraction is based off historical trends of co-adoption of storage with solar in LADWP and increase linearly through 2045, again following trends in historical attachment rate. By 2045, 91% of residential solar adopters co-adopt storage and 64% of nonresidential adopters. The storage is randomly assigned to solar adopters in each model year. The study assumes that all distributed storage is dispatched by LADWP.
- dGen uses lidar data to assess roof suitability for PV based on roof shading, fire code compliance, tilt, orientation, and minimum area but does not consider roof structural suitability or roof age. 100% of the roof area that meet the shading, tilt, orientation, fire code, and area requirements are assumed to be developable. NREL assumes that roofs can be replaced between now and 2045 and we do not evaluate implementation options such as third party services to offer roof replacements together with PV systems.
- The value of purchasing distributed energy resources is from the customer perspective, based primarily on electricity bill savings. This basis for adoption is applied to all communities, including disadvantaged, and for multifamily buildings. For multifamily buildings, compensation is based on the retail rate from the building owner's perspective. While we model the potential for adoption from disadvantaged communities and multifamily buildings, the explicit policy changes needed to enable adoption in these sectors are not considered.
- dGen evaluates two adoption projections that differ by how the customer is remunerated for its generation. The SB100 and Transmission Focus scenarios include new buildings and use net billing as the basis for compensation, in which only the net electricity exported (electricity generation minus self-consumption in that hour) is compensated at RPM hourly wholesale prices; the value of self-consumption is equal to the retail tariff. In the Early & No Biofuels and Limited New Transmission scenarios we extend LADWP's current practice of using net energy metering, in which all generation (not to exceed the building's annual energy consumption) is compensated at retail tariffs. Note that these rate structures were selected only as a basis to project differentiated levels of adoption. Proposed rate structures, incentives, or other policies are not specified or evaluated.

- The dGen model does not consider potential curtailment of customer-sited generation in projecting rooftop solar adoption. Curtailment is allowed to occur from use of smart inverters, but this amount is assumed to be small enough to not affect decisions to adopt PV. dGen also assumes that two-way power flow is allowed from individual customers.

3 Results

Over the five projections modeled, NREL projects between 2.8 and 3.9 GW of rooftop solar and 1.1 and 1.4 GW of distributed storage could be adopted in LADWP through 2045. These estimates are based on household-level models, including use of lidar data to assess rooftop solar technical potential (13.4 GW).

The following subsections provide details on each component of our analysis, which build to the high-level results. Section 3.1 provides context on the historical trends and drivers of solar adoption in Los Angeles to date. Next, Section 3.2 assesses how much of the technical potential would be economic to pursue, Section 3.3 summarizes the customers' economic potential, and Section 3.4 presents how much of that potential customers might ultimately adopt under each of the LA100 scenarios.

3.1 Historical Trends and Drivers of Customer Solar Deployment for LADWP

Historical PV adoption data provided by LADWP were used to analyze the drivers and trends in adoption. Two sets of information were provided, one in 2019 that contained 31,640 PV net energy metering (NEM) interconnections and a 2020 update with 38,461 PV NEM interconnections. These data sets were cleaned, homogenized to a single data set, geocoded, and matched to premises and agents in the LADWP service area. The information provided included installed capacity, installation date, and address. Additional information at the tract scale was sourced from the 2015 U.S. Census American Community Survey (U.S. Census Bureau 2015), and the LA County Tax Assessor's Database (LA County 2017). Information on technical potential and economic potential from dGen simulations was also included in the data set. After the merging and cleaning process, the data set of NEM PV installations accounts for 300 MW by 2019 and 330 MW by 2020. The mean installed capacity per agent was 180 kW for the commercial sector, 560 kW for the industrial sector, and 8 kW for the residential sector (single-family and multifamily).

The average penetration of customer-adopted PV in the LADWP service area was 5.4% as of January 2020 (Figure 8), defined as the cumulative number of agents adopted PV divided by the total number of premises. We also calculate the average penetration, weighted by the tract population, which better accounts for tracts of different population. Most of the tracts have a weighted penetration between 0% and 2.5%, indicating that the tracts that have higher adoption tend to be smaller tracts with fewer agents or households.

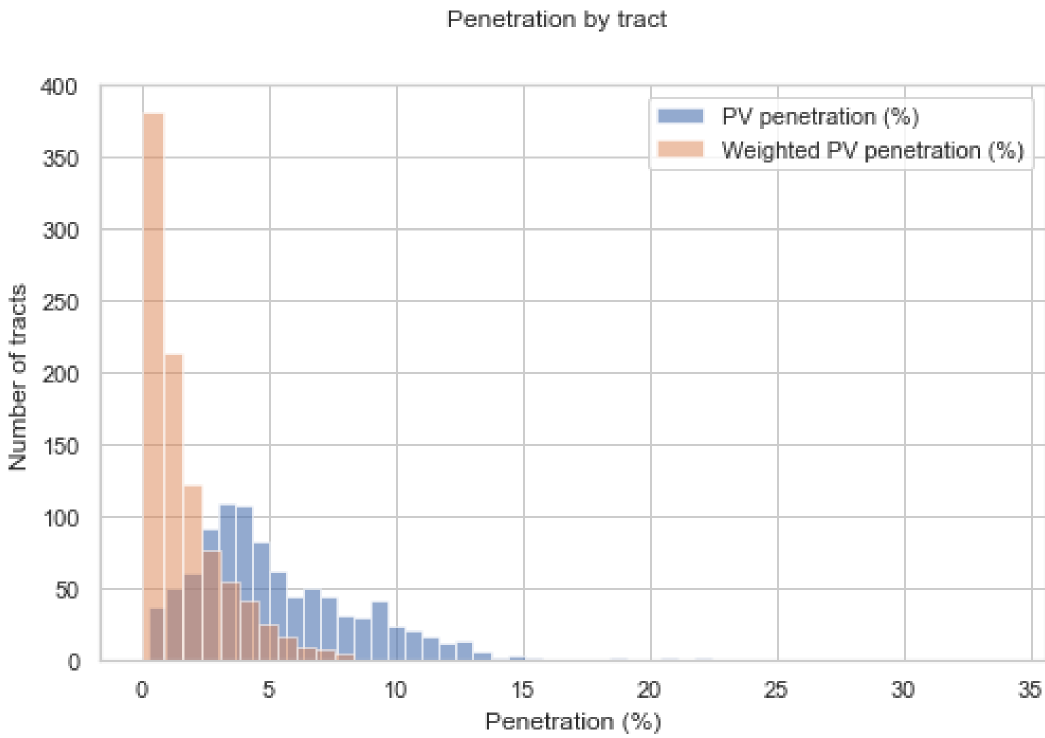

Figure 8. PV penetration and weighted penetration for tracts in LADWP service territory

Nearly every neighborhood in Los Angeles has adopted some rooftop PV, but at varying proportions. For instance, we see that neighborhoods with lower urban density or with more single-family homes in the northwest have higher penetration (Figure 9, left). The highest adoption in a single tract is approximately 33%.

In terms of absolute amount of deployment (i.e., MW), deployment patterns somewhat to downtown Los Angeles (Figure 9, right). Taken together, solar adoption in Los Angeles reflects many factors including urban density, income, land use, and the building stock.

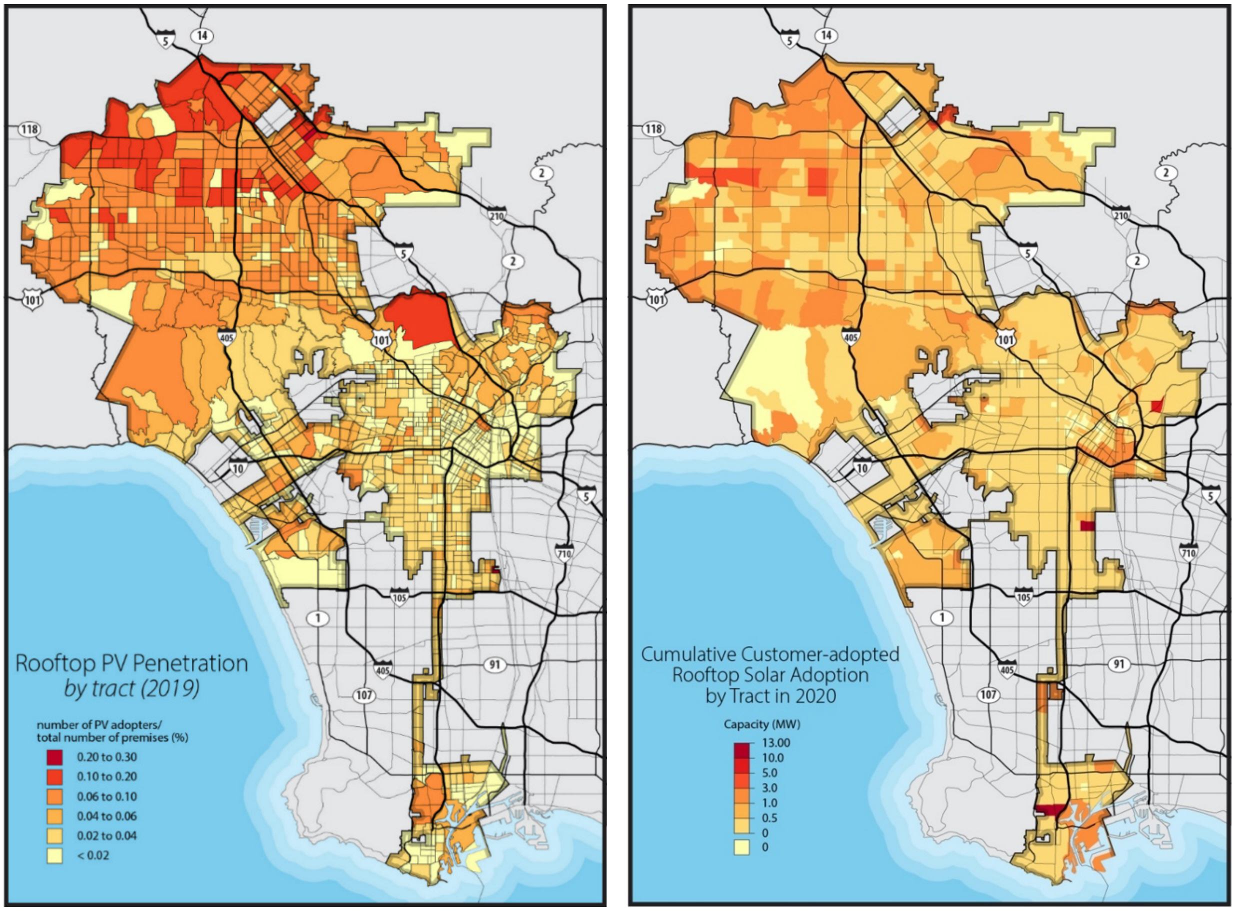

Figure 9. PV penetration by tract in LA in 2019 (%) (left) and total adopted (MW) in 2020 (right)

3.2 Technical Potential for Rooftop Solar

Spatial-analysis methods were used to assess potential for siting solar on building rooftops. Technical potential is a metric that evaluates the theoretical upper bound on deployment potential and is not a reflection of the amount of distributed solar capacity that is economic, or that is likely to occur. Over the full territory, we identified approximately 13.4 GW_{DC} of rooftop solar technical potential (Table 2) using PV technologies currently available to customers.

Table 2. Summary of Technical Potential of Customer-Adopted Rooftop Solar by Customer Type

Use	Developable Sites	Developable Roof Area (thousands of m^2)	Annual Generation Potential (TWh)	Capacity Potential (GW_{DC})
Airport	477	930	0.13	0.09
Commercial	46,731	25,581	2.89	2.04
Industrial	1,640	1,429	0.20	0.14
Manufacturing	24,658	24,093	3.48	2.45
Open Space	2,644	1,196	0.11	0.08
Other	12,018	7,605	0.88	0.62
Residential	746,935	158,157	11.28	7.96
Total	**835,103**	**218,991**	**18.97**	**13.39**

3.2.1 Rooftop Technical Potential—All Sectors

NREL assessed rooftop potential using lidar scans for buildings in the service territory (Figure 10). The lidar method incorporates factors including roof shading, tilt, azimuth, and minimum project size (10 m^2). Significantly, the assessment incorporates LA County fire codes, which require a 1-meter setback from the roof edge and roof ridge; using these setbacks removed about 21% of flat roof area and 37% of tilted-roof area. However, lidar data are unable to assess several practical aspects of building solar suitability and are not considered in this study, including roof age, building structural suitability, and electrical code compliance. A recent NREL study of solar on low- and moderate-income homes in California estimated between 11% and 19% of residential structures may be limited in solar suitability based on at least one of the above factors (Sigrin and Mooney 2018). However, NREL did not derate the technical potential estimates by these percentages in the study, given the long time horizon for the analysis. A detailed methodology of the rooftop technical potential assessment is covered in Appendix C.

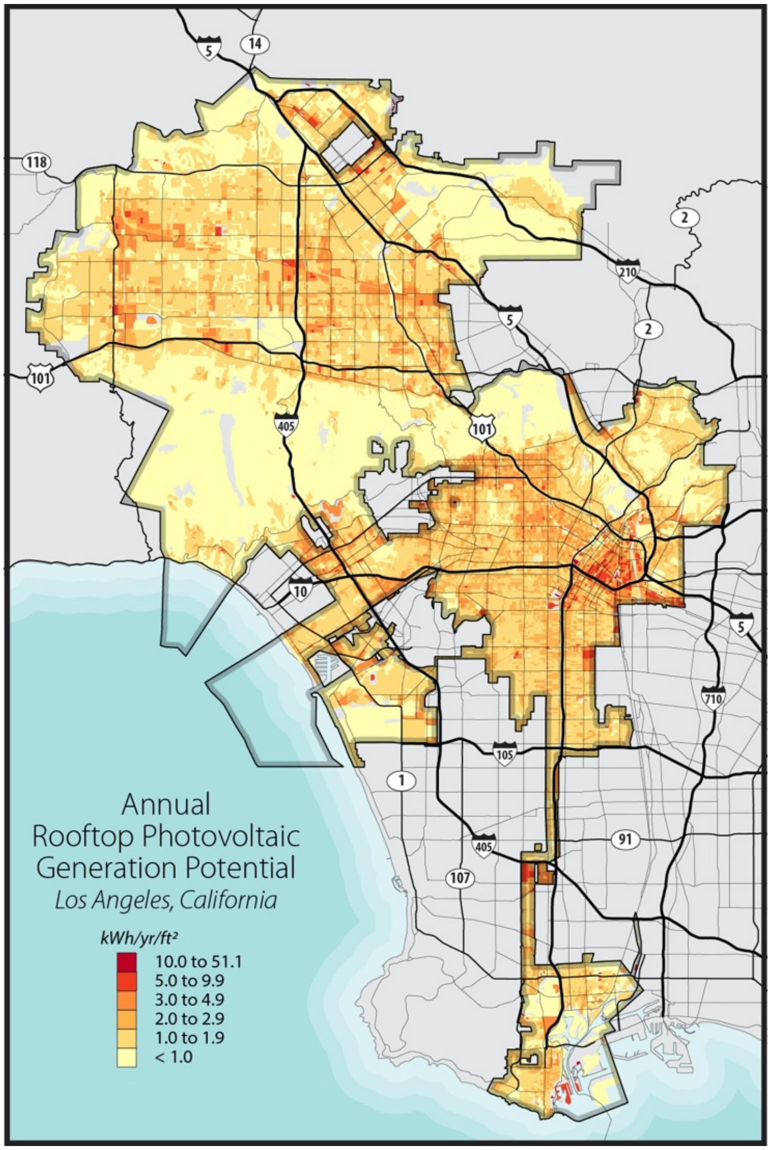

Figure 10. Annual rooftop solar PV generation potential (kWh/yr/ft^2) in 2019 based on lidar scans, averaged by census tract

3.2.2 Multifamily Building Technical Potential

Despite its potential, solar deployment on multifamily buildings remains limited due to a misalignment of landlord-tenant incentives to adopt, which is not unique to Los Angeles. In addition to its potential as a resource, multifamily solar might be considered as a tool for addressing environmental justice (e.g., allowing multifamily buildings to participate in a virtual net energy metering [VNEM] program). In such a program, onsite generation could hypothetically be used to virtually credit other tenants in the same building or neighborhood. Alternatively, deployment of solar on multifamily buildings might also be spurred by a feed-in tariff, which could incentivize building owners to invest in solar to receive revenue.

Most residents of multifamily buildings live in large buildings in which the total electricity demand is smaller than what could be generated from the building's rooftop (see Table 3).

Table 3. Multifamily Rooftop Solar Technical Potential Versus Annual Consumption

	Number of Premises	Total Electricity Consumption (MWh/yr)	Total Solar Potential Generation (MWh/yr)	Mean Developable Project (kW)	Mean Percentage Production to Metered Load
50+ Units	1,807	796	487	248.8	61%
20 to 49 Units	5,956	624	717	98.6	114%
10 to 19 Units	8,985	392	559	58.6	142%
5 to 9 Units	15,979	326	524	31.8	161%
3 or 4 Units	14,550	139	271	17.2	196%
2 Units	43,087	246	591	14.4	240%
Total	**90,364**	**2,523**	**3,149**		

We estimate 2,060 MW of technical potential for rooftop solar on multifamily buildings within LADWP (Table 3). Through a complementary geographic information system (GIS) analysis (covered in the next chapter, Chapter 5) we estimate that only 1.4% of multifamily buildings have available land area for ground-mounted solar (337 MW, or 155 MW when excluding multifamily land near public transit). This assessment of potential is independent of costs, incentives, or other motivations for building owners to adopt.

Expanding LADWP's current feed-in tariff is one mechanism that could be used to enable solar deployment on multifamily buildings. Feed-in tariffs provide a fixed price guarantee for generation, thereby incentivizing a building owner to install solar even if the solar generation is consumed by the building occupants. Expanding LADWP's feed-in tariff program to multifamily buildings is part of the LA pLAn 2019 goals. LADWP's current minimum interconnection limit (kW) for feed-in tariff projects is 30 kW, which may limit multifamily building potential. This floor to participation would exclude many 2- to 4-unit buildings; 76% of multifamily buildings have <30 kW of potential, and these buildings contain 36% of multifamily tenants (Figure 11).

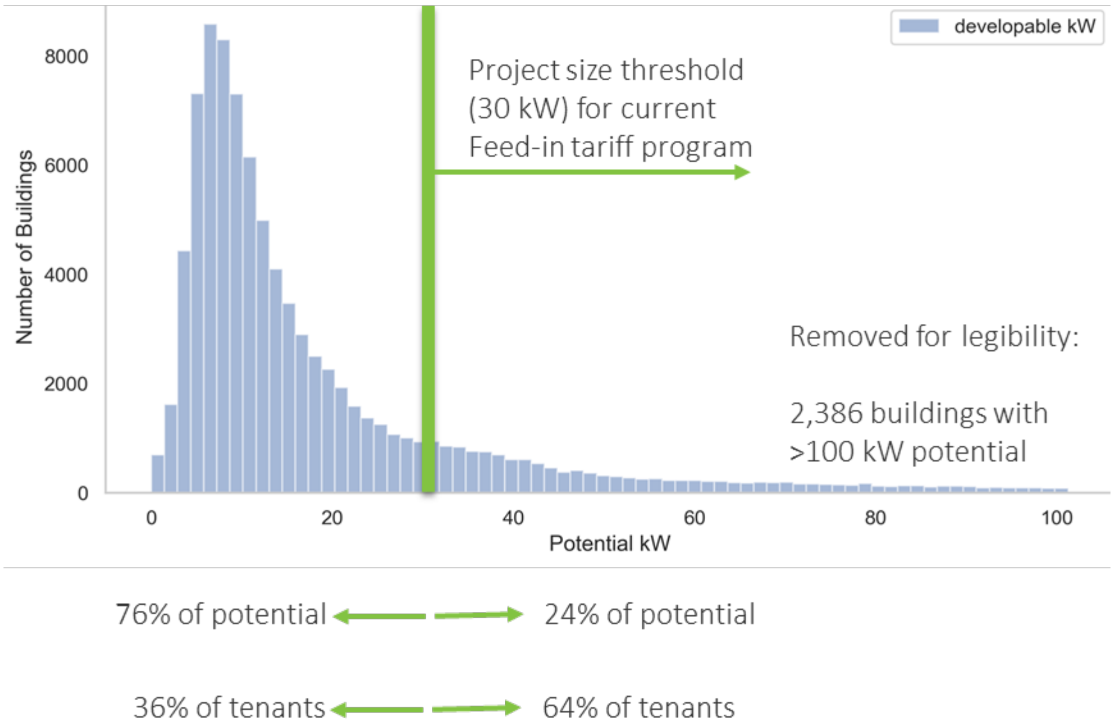

Figure 11. Histogram of rooftop solar potential for multifamily buildings with technical potentials >100 kW

3.3 Economic Potential for Rooftop Solar

NREL conducted five projections of rooftop solar adoption, which examine the effects of customer solar compensation (High vs. Moderate) and customer electricity demand projections (Moderate, High, Stress, as covered in Chapter 3) (Table 4). In the Early & No Biofuels and Limited New Transmission scenarios, we simulate a continuation of current LADWP compensation for customer solar under net metering at retail electricity value (i.e., all customer solar generation is valued at the retail electricity price, a continuation of LADWP's current solar program). In the SB100 and Transmission Focus scenarios, customer solar generation is valued using net billing starting from the year 2020. Net billing assumes that customer rooftop solar generation instantaneously offsets the consumer's electrical consumption ("self-consumption"), valued based on current LADWP retail electricity tariffs. However, any non-self-consumed generation (i.e., exported to the grid) is valued at RPM-derived hourly locational marginal prices (LMP) for energy and capacity at each transmission node in LADWP service territory (i.e., Figure 12). The Moderate, High, and Stress load electrification projections correspond to evolution of building loads, driven by electrification. These load projections are modeled by the ResStock™ and ComStock™ models, as discussed in Chapter 3. Consistent with the rest of the LA100 study, projected future technology costs are exogenous to the model. Specifically, the capital costs of customer rooftop solar are projected to decline from 2020 to 2045 for the residential ($2.3/W to $1.1/W) and nonresidential ($1.6/W to $0.9/W) sectors (NREL ATB 2018).

Table 4. Description of Solar Adoption Projections

Scenarios	Compensation for Rooftop Solar	Consumer Demand Projection
Early & No Biofuels, Limited New Transmission – Moderate Load Electrification	Net metering (i.e., compensation at retail rate)	Moderate
Early & No Biofuels, Limited New Transmission – High Load Electrification	Net metering (i.e., compensation at retail rate)	High
SB100, Transmission Focus – Moderate Load Electrification	Net billing (i.e., compensation of exported generation at wholesale rate)	Moderate
SB100, Transmission Focus – High Load Electrification	Net billing (i.e., compensation of exported generation at wholesale rate)	High
SB100 – Stress Load Electrification	Net billing (i.e., compensation of exported generation at wholesale rate)	Stress

3.3.1 Retail Tariffs and Projections for Rooftop Solar

Each agent in dGen was assigned a retail tariff based on the tariffs currently offered by LADWP, corresponding to the sector, annual electricity consumption, and its peak demand. dGen simulates the full tariff structure using an hourly generation and consumption profile and does not use the average cost of electricity per kWh. Table 5 shows the retail rates used to map to the dGen agent type or sector based on their consumption and the tariff structure.

Table 5. Summary of LADWP Tariffs Used in the dGen Model

Tariff Details	Assignment to Sector
Residential Service (R1A): Zone 1 Tier 1: 350 kWh, Tier 2: 1,050 kWh, Tier 3: >1,050 kWh	Residential
A1A - Small Commercial (applicable to general service customers with recent demand below 30 kW)	Commercial
A2B - Medium Commercial (medium commercial customers of LADWP's 4.8kV system with recent demand of at least 30 kW)	Commercial
A3A - Large Commercial (large commercial and industrial customers of LADWP's 34.5kV system with recent demand of at least 30 kW)	Commercial
A3A - Industrial (large commercial and industrial customers of LADWP's 34.5kV system with recent demand of at least 30 kW)	Industrial

Projections in the retail electricity price (Figure 13) start from existing LADWP tariffs and their current structure, and are escalated by an annual scalar from RPM. The scalar from RPM is based on projected total system cost by scenario, via the dGen-RPM linkage. Escalations were averaged across all RPM scenarios but result in slight differences in effective prices due to changes in load shapes. The retail electricity price increases from an average of $0.19/kWh in 2020 to $0.30/kWh in 2045 for the residential sector. For the commercial sector, the retail electricity price increases from an average of $0.18/kWh in 2020 to $0.24/kWh in 2045.

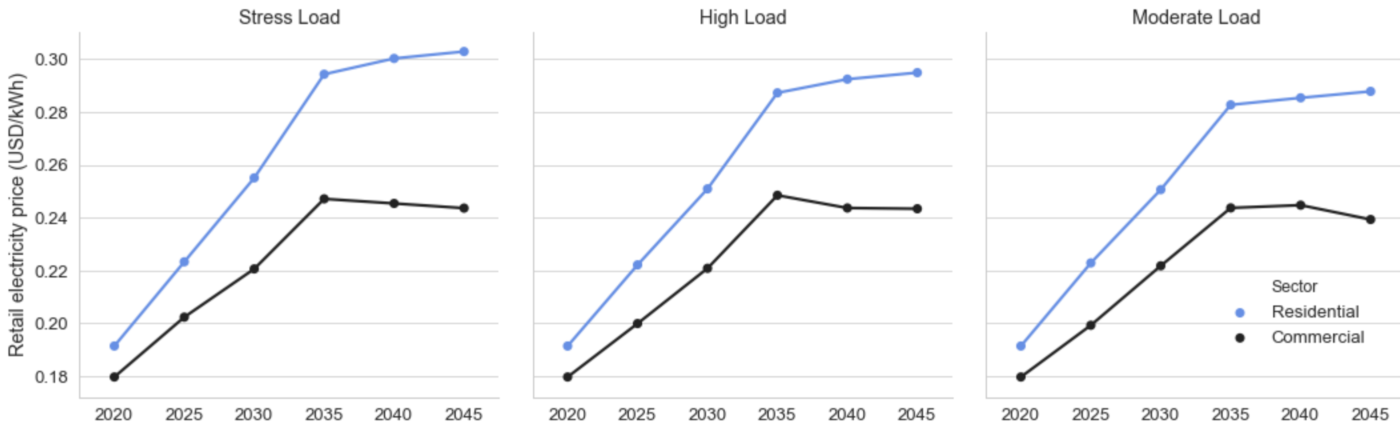

Figure 13. Average retail electricity price (USD/kWh) by load projection and year (2019$)

Note that the y-axis starts at current prices.

3.3.2 Wholesale Electricity Prices for Net Billing Projections

Wholesale prices used in dGen are hourly locational marginal prices (LMPs) at nodes, simulated by NREL's Resource Planning Model (RPM) model in 5-year increments. The hourly projected energy-only LMPs and capacity value) are used as inputs to dGen bill savings calculations in the SB100 and Transmission Focus scenarios to simulate a net billing program. Diurnal and seasonal trends in the value of excess solar generation help to explore how rooftop solar adoption is impacted if non-self-consumed generation is compensated at wholesale rates, as opposed to retail rates.

Several RPM scenarios are used to derive the LMP prices at transmission nodes. Prices are modeled hourly for five representative grid conditions, as discussed in Chapter 6, and are determined as the marginal value of reduced demand for each LADWP transmission node. Nodal-specific prices for each agent are used because there could be substantial inter-nodal variance in price due to transmission or distribution congestion. Each agent is mapped to a location on the 4.8kV and 34.5kV distribution system and uses the corresponding LMP (methods for mapping agents to the electrical grid are described in Chapter 3, Appendix K). Table 6 shows the matrix that maps RPM scenarios to the respective dGen projections.

Table 6. Mapping of dGen Model Projections to RPM Model Scenarios

Scenario	RPM Scenarios
Early & No Biofuels, Limited New Transmission – Moderate Load Electrification	N/A – LMP prices not applicable
Early & No Biofuels, Limited New Transmission – High Load Electrification	N/A – LMP prices not applicable
SB100 & Transmission Focus – Moderate Load Electrification	Hourly prices, averaged from the SB100 and Transmission Focus – Moderate scenarios
SB100 & Transmission Focus – High Load Electrification	Hourly prices, averaged from the SB100 and Transmission Focus – Moderate scenarios
SB100 – Stress Load Electrification	Hourly prices from the SB100 – Stress scenario

Hourly wholesale prices from RPM (Figure 14) are used to value non-self-consumed generation in each 5-year increment. Trends in these prices reflect evolution in the diurnal energy value (e.g. low energy values at noon) and broader trends in the LADWP power system. For sake of visualization, Figure 13 shows the modeled wholesale price averaged over all transmission nodes and all times of the year. The trend for the average prices indicates a near-term decline in the value of solar generation in the High and Moderate load projections, followed by a long-term increase. In contrast, the Stress load projection indicates a continued increase in solar value. Trends in the RPM wholesale price are influenced by the amount of distributed PV adopted via dGen-RPM as well as the broader least-cost portfolio.

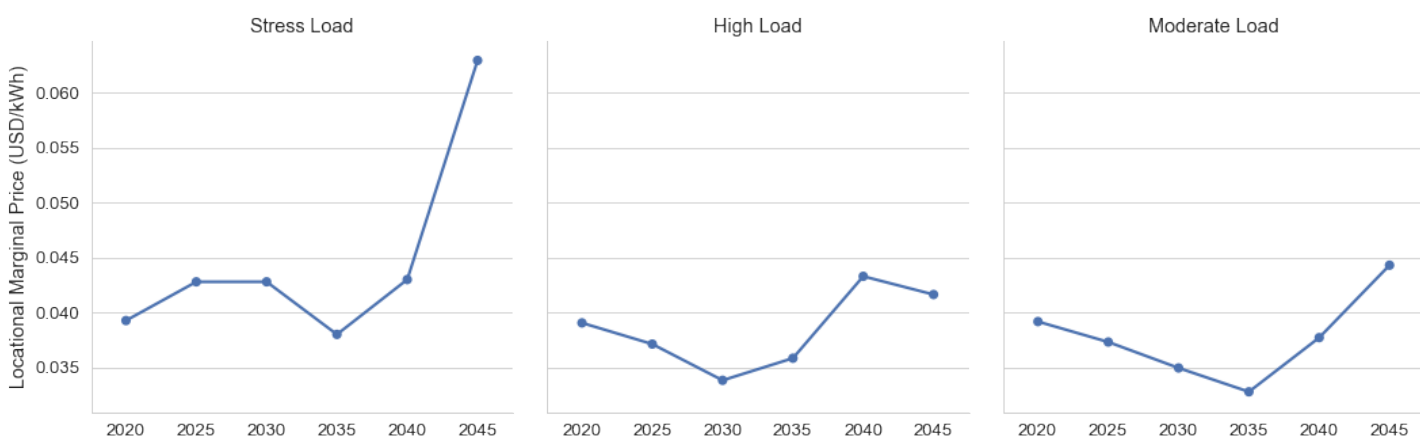

Figure 14. Average LMP price (USD/kWh) by load projection and year (2019$)

3.3.3 Load Profiles and Projections

The dGen model simulates potential adopters or agents using a premise-level database of LADWP ratepayers. A premise is any contiguous parcel that is interpretable as a decision-maker. For instance, a university campus would be categorized as a single premise, though it is composed of multiple buildings. Likewise, a single-family home is also a premise. More than 600,000 agents corresponding to premises, which spans the entirety of LADWP's service territory, are assigned load profiles and annual load for all years that are simulated in dGen.

Details behind the dGen agent generation process are described in Chapter 3, Appendix I. The load profiles used in dGen are outputs of the dsgrid load model (Chapter 3), mapped to their corresponding load growth projections: Moderate, High, and Stress. The hourly load profiles and peak loads from representative building models in dsgrid (e.g., ResStock and ComStock) are assigned to dGen agents based on information available at each premise about the sector, building type, or subsector (for industrial and commercial agents) and the number of units (for residential agents). This agent-load allocation is discussed in more detail in Chapter 3, Appendix J. Figure 15 shows the growth of total annual load and the peak load by projection and Figure 16 by sector.

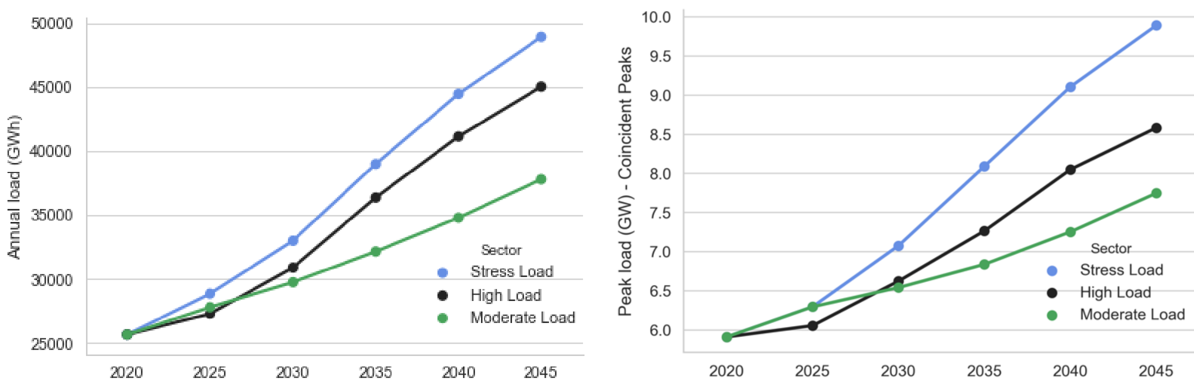

Figure 15. Growth in annual consumption (GWh) and peak load (GW) for the three load projections

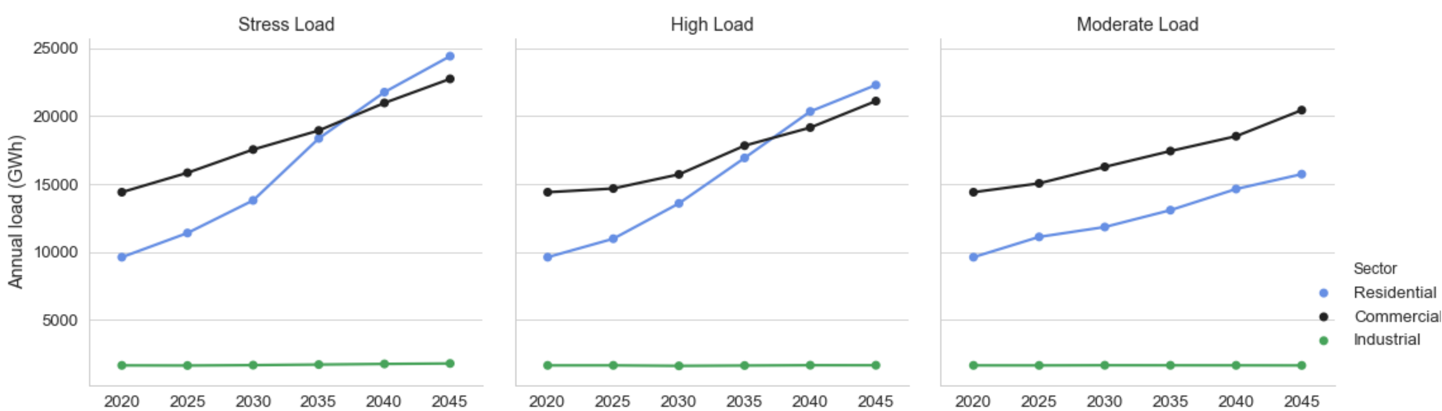

Figure 16. Total annual load (GWh) by sector and year for the three load projections

3.3.4 Rooftop Solar Economic Potential

Before assessing adoption, the dGen model first calculates the amount of rooftop PV capacity that would be economic for LADWP customers to adopt in each year (Figure 17). The economic potential is principally affected by capital cost and prevailing retail rates, followed by incentives and cost of financing. Economic potential is influenced by both the type of compensation (i.e., "is it economic to adopt?") and load growth (i.e., "what is the optimal PV system size?"). Finally, economic potential is a discrete metric—either the project exceeds the required rate of return or not—and does not distinguish gradations in economic attractiveness, e.g. payback period.

Economic potential increased in all scenarios through 2045, driven by continuing declines in distributed solar prices, increased load growth, and increases in retail electricity prices.

Economic potential under the Early & No Biofuels and Limited New Transmission scenarios was larger than that of the SB100 and Transmission Focus scenarios, though they largely converge by 2035. By 2045 nearly all rooftop technical potential is considered economic. However, as noted earlier, the economic potential metric does not distinguish gradations of economic attractiveness. For example, though the economic potential of the two compensation styles converges by 2045, they result in different amounts of overall adoption because the net metering compensation type results in more favorable customer economics.

Economic potential is similar for the Early & No Biofuels and Limited New Transmission – High scenarios in 2045 (9.9 GW) as compared to SB100 – Stress in 2045 (9.3 GW). This indicates that while the compensation mechanism for rooftop solar (net billing or net metering) is an important factor to predicting adoption, the electricity demand and load profile also impact solar economics for the customer. For instance, a higher electricity demand can result in greater bill savings from the PV system to the extent that increases in load are correlated with diurnal solar generation, thus minimizing non-self-consumed generation.

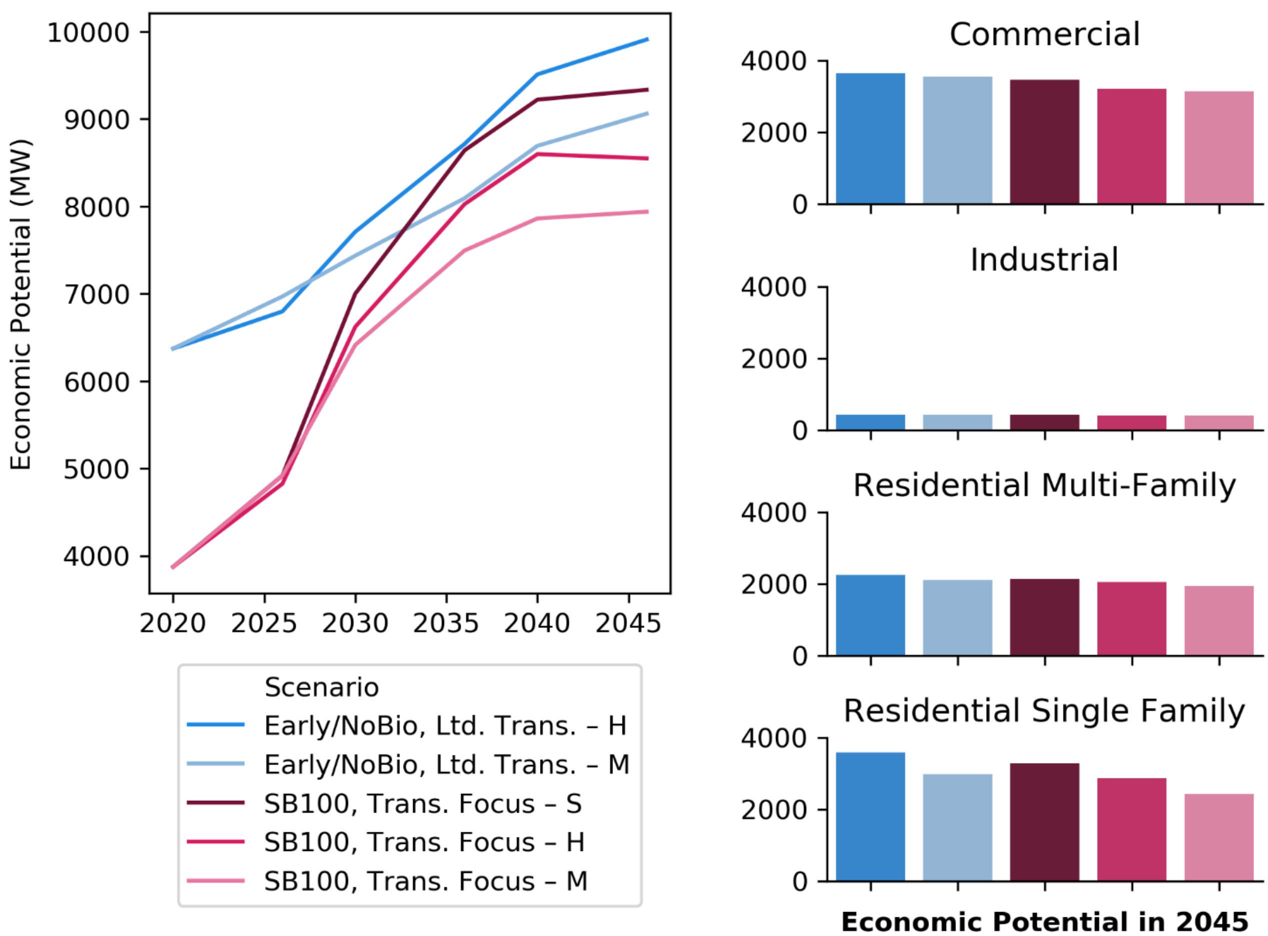

Figure 17. Total economic potential (GW) by year (left) and sector in 2045 only (right) for the five projections

The highest economic potential was in the residential sector with 5.8 GW, followed by the commercial sector with 3.6 GW and industrial sector 0.4 GW by 2045 for the Early & No

Biofuels and Limited New Transmission – High scenarios. The quantity of economic potential starts to saturate or slightly decrease after 2040 in the SB100 and Transmission Focus scenarios.

Figure 18 shows projected spatial trends in rooftop solar economic potential in 2045 by census tract for the Early & No Biofuels and Limited New Transmission – High scenarios. Generally, economic potential in 2045 is high throughout the city, though highest pockets follow a similar spatial distribution as current historical rooftop adoption, with a few notable differences in high-potential areas near downtown, the airport, and ports.

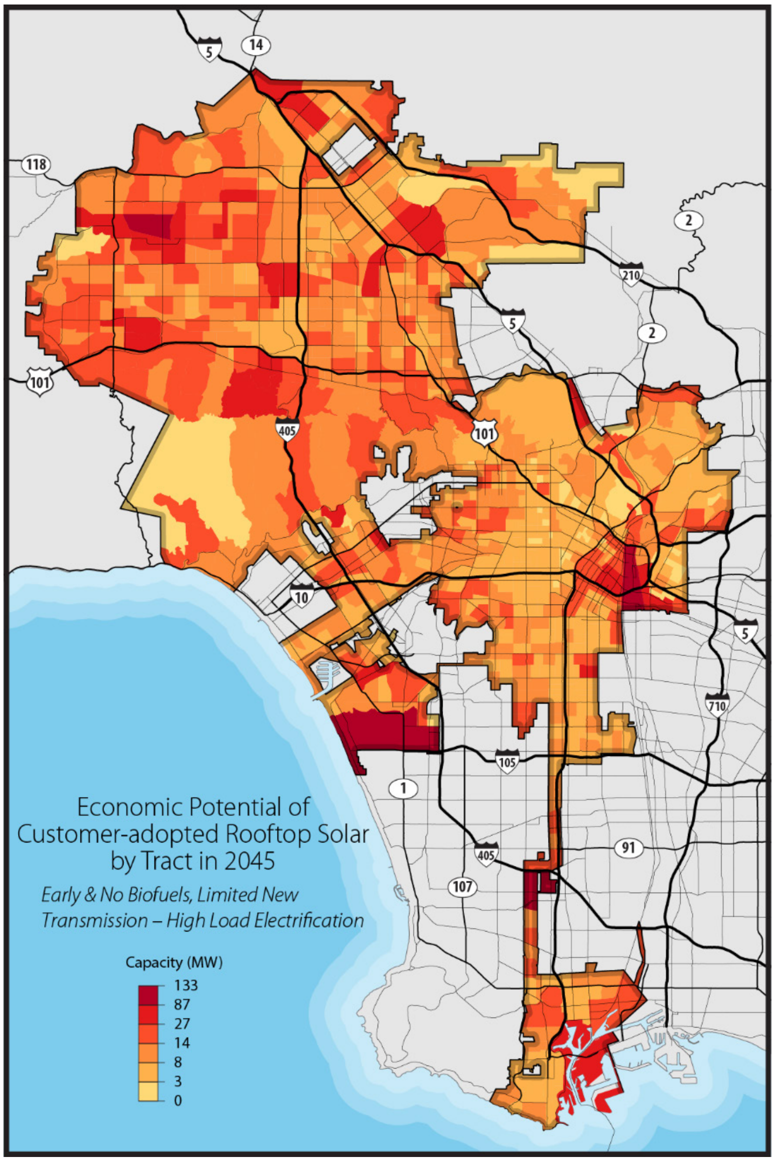

Figure 18. Economic potential by tract for Early & No Biofuels, Limited New Transmission – High scenario in 2045

3.4 Deployment Projection for Rooftop Solar

The deployment projection for rooftop solar is an output of the dGen model. Consumer demand is modeled through an agent-based approach that uses individual customer data and technical and economic calculations for each customer to identify the economic potential (rooftop PV systems that have positive net present value). This potential is then used within the Bass diffusion model to develop the projection of PV adoption in future years. The total amount of future adoption is largely driven by the PV system payback period, and the timing of adoption determined by regressing historical growth in the Bass diffusion model.

3.4.1 Model Calibration

The dGen model is calibrated based on historical adoption in LADWP (see Section 3.1). The historical adoption in a tract was found to be correlated with adoption in a specific tract in future years, based on an analysis of historical PV adoption data from 2012–2019. Several information attributes of the agents are directly or indirectly co-related with their location, address, or neighborhood—e.g., income, assessed area of the parcel, and land value of the parcel—and these attributes were also found to be correlated to adoption. To capture the influence of location, neighborhoods were assumed to follow tract boundaries (which was the next aggregation scale after parcel location).

The historical adoption in a tract by sector and year was used to increase the propensity of adoption in the same tract and sector for future years. This inclusion of historical adoption in the model aims to provide higher precision in the spatial prediction of adoption, which is important for modeling distribution system upgrades. The projection is not influenced by inter-tract peer effects nor does it include projection of evolution in neighborhood demographics, building stock, or gentrification. Adoption among multifamily buildings is based on the same adoption methodology (i.e., evaluating the payback period, but are derated by 30% to account for landlord-tenant barriers).[2] Finally, adoption projections are used as inputs to determine distribution system impacts and required investments.

3.4.2 Rooftop Solar Adoption Projection

Distributed generation is projected to constitute a significant fraction of the 2045 energy mix for LADWP. Its ultimate levels depend on future tariffs for compensating distributed generation and the demand-side loads served.

From Table 7, the amount adopted ranges from 34% to 40% of the economic potential. Scenarios that have a higher compensation of customer rooftop solar through net metering have a higher potential of cumulative adoption compared to those that have lower compensation for this generation. However, the influence of compensation mechanisms is more limited in future years when the annual demand and load profiles of the individual agents have a greater influence on the value of rooftop solar and thus its adoption (Figure 19 and Table 7).

[2] The derate of 30% is considered engineering judgment and was informed by historical trends in single- vs multifamily adoption rates.

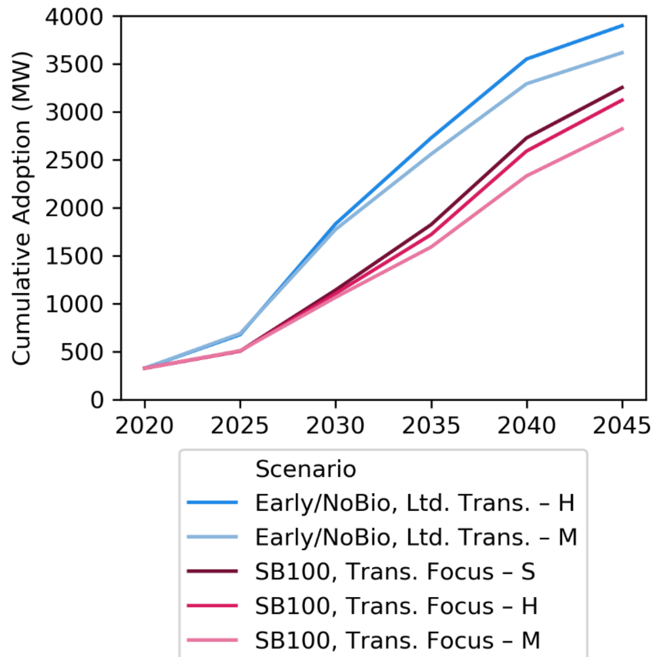

Figure 19. Projected cumulative solar adoption by projection (MW), 2020–2045

Table 7. Summary of Projected Customer-Adopted Solar Deployment in 2045 (MW), By Sector

	Total	**Residential - Single-Family**	**Residential - Multifamily**	**Commercial**	**Industrial**
Early & No Biofuels, Limited New Transmission – High Load Electrification	3,899	2,394	867	575	63
Early & No Biofuels, Limited New Transmission – Moderate Load Electrification	3,617	2,159	833	564	62
SB100 – Stress Load Electrification	3,254	2,057	755	408	35
SB100, Transmission Focus – High Load Electrification	3,122	1,964	721	403	34
SB100, Transmission Focus – Moderate Load Electrification	2,822	1,709	693	385	35

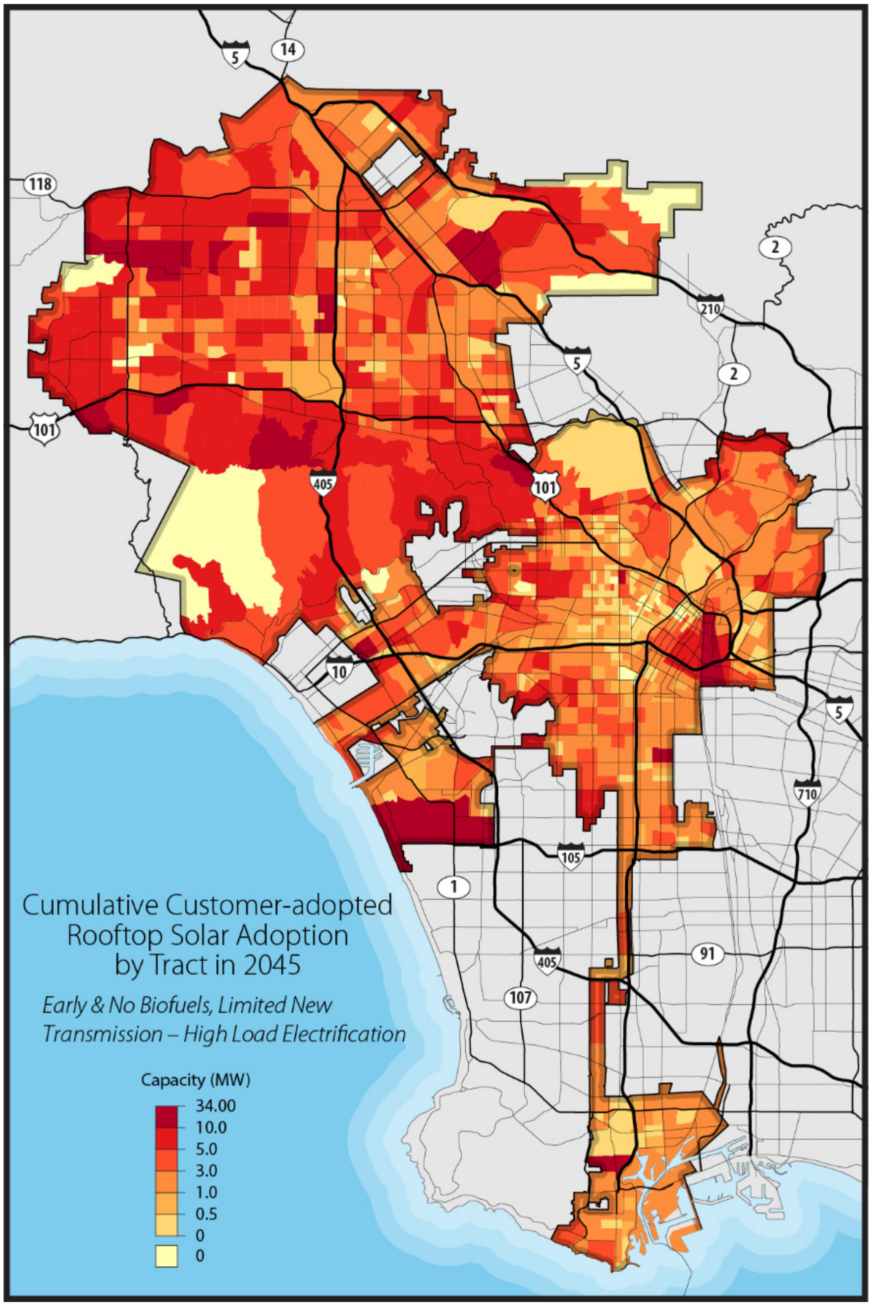

Figure 20. Cumulative rooftop adoption by tract in 2045 Early & No Biofuels, Limited New Transmission – High scenario

Figure 20 shows the projected cumulative adoption by tract for 2045. Because the model is calibrated based on historical adoption in each tract, the projection for cumulative adoption is influenced by the spatial patterns of historical adoption, as well as spatial patterns in changes in load profiles and payback period. When comparing this cumulative adoption in 2045 (Figure 20) with the economic potential in 2045 (Figure 18) for the Early & No Biofuels and Limited New Transmission – High scenarios, we find that economic potential significantly influences the cumulative adoption projection. In addition, the spatial patterns of the simulated economic potential are correlated with patterns of empirical adoption in 2020, reinforcing that the economic viability of the PV system has significantly influenced historical adoption.

We also note different analytical conclusions when comparing adoption by tract in terms of capacity (MW) adopted, versus penetration rate (% of agents adopting). Capacity adopted is mainly reflective of the number of agents (i.e., populations) in the tract and is highly dependent on the type of agents (e.g., commercial and industrial agents have higher mean system sizes).

3.4.3 Deployment Projection for Customer Storage

Distributed storage adoption remains limited in LADWP, with 10.8 MW adopted to date. However, customer-adopted storage could be a valuable grid resource if operated to minimize overall system costs and provide local system benefits. While significant research exists regarding the drivers of consumer adoption and operation of customer rooftop solar, research on distributed storage adoption is limited. Some significant outstanding questions include i) What is the relationship between the degree of consumer benefits (i.e., bill savings and back-up power) and adoption of distributed storage?; ii) How will consumers with storage operate their system and respond to price signals, and in conjunction with demand response and energy efficiency? These uncertainties also affect utility strategy in operating an electric grid with high levels of customer-sited storage.

Due to a lack of research on distributed storage adoption and complexity of how storage dispatches optimally to price signals, NREL did not directly develop a distributed storage adoption projection within the dGen model. Instead, we develop a projection based on historical trends of distributed storage adoption within LADWP and California. The projection uses i) historical co-adoption, or attachment rates, of distributed storage paired with customer rooftop solar; and ii) historical ratios of storage capacity with customer rooftop solar capacity. The outcome is a projection of which dGen agents co-adopt storage, by projection and year. However, the dGen model does not calculate the direct bill savings of the solar plus storage system, nor how it would be optimally dispatched to reduce customer costs. Instead, the distributed storage is optimally dispatched within the PLEXOS production cost model. This approach could create misalignment between the true flexibility needs of the bulk power system and the amount adopted by customers, and it should be revisited in future planning studies as new data and methods emerge.

In California in 2019, 9.6% of residential PV adopters co-adopted distributed storage, and the average ratio of storage-to-PV capacity was 0.92 (7.5 kW) (Figure 21, left). In the nonresidential sector, 4.0% of adopters co-adopted storage and the average ratio was 0.60 (18.7 kW). Data were not available on storage duration, but we assume all batteries will have a 4-hour storage duration. Using a linear trend, NREL projects that 91% of residential PV systems are co-adopted with storage and 64% of nonresidential systems in 2045. Though residential co-adoption rates are currently higher than those of commercial, they might eventually converge or cross due higher perceived value of backup power by commercial and industrial customers.[3] When paired with

[3] For example, "ICE Calculator Documentation," https://www.icecalculator.com/documentation.

the customer PV adoption projections, we project 1.1–1.5 GW of distributed storage could be deployed in LADWP by 2045 (Figure 21, right), depending on the projection.

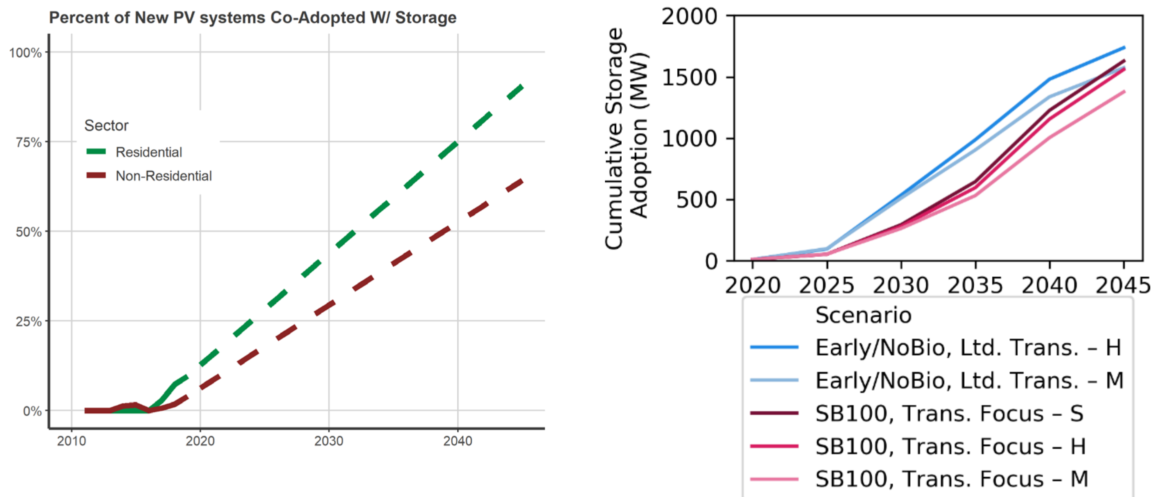

Figure 21. Projected distributed storage co-adoption rates (left) and deployment (right)

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Appendix A. Renewable Resource Performance

Renewable resource analysis underpins multiple models in this study (dGen, RPM, PLEXOS, and PRAS) and consists of two major steps. The first is evaluating the location and capacity (MW) of developable renewable resources. The second is generating power output profiles for these resources. For this study, NREL uses the Renewable Energy Potential (reV) model to perform renewable resource assessment. Figure 22 shows the process flow for the reV model.

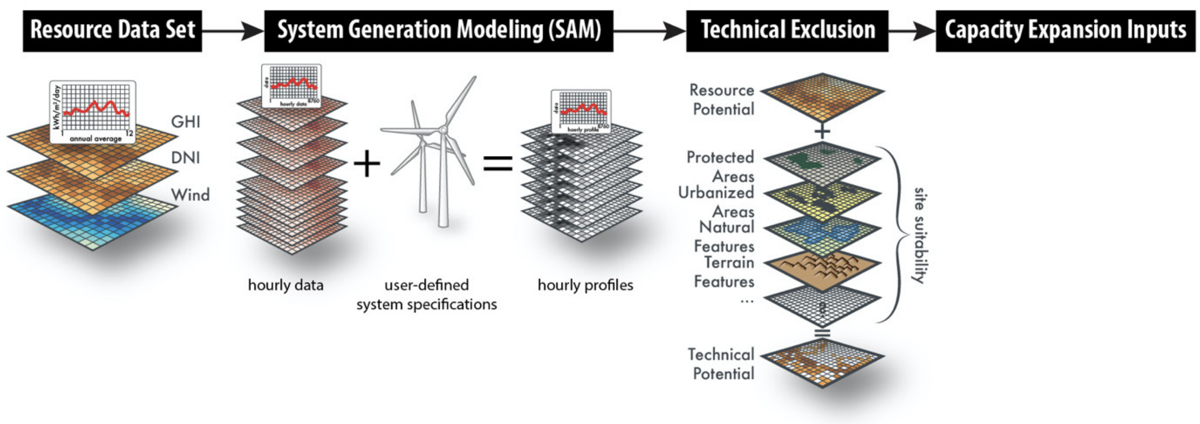

Figure 22. Process flow of the Renewable Energy Potential (reV) model

reV uses solar and wind resource data and available sites for both photovoltaics (PV) and wind by incorporating system performance and geographic constraints such as topographic limitations and environmental or other land-use restrictions to development (Brown et al. 2016). The base meteorological year used for the study is 2012 (i.e., the study applies the weather patterns of 2012 to the stock of renewable generators representing future growth to produce renewable generation profiles). We also apply weather data for 2007–2016 to the projected stock as a sensitivity.

Development constraints considered by reV include:

- Protected areas
- Terrain features (e.g., elevation, slope, etc.)
- Land-use and/or land-cover, including rivers, lakes, wetlands, and other water bodies
- Major landmarks, and parks
- Urbanized areas / population density
- Other known exclusions, constraints, and stakeholder concerns
- Land ownership
- Soil and vegetation characteristics (for hydro resource assessments).

reV also produces the output profiles for renewable resources at each site location. It uses the System Advisor Model (SAM) to determine the hourly or subhourly generation output for a given site.

The output from reV is a database of available sites, available power capacity at each site (MW), with system performance at site in terms of subhourly and annual generation (MWh). Time-series power profiles includes forecasts for use in grid simulations.

Availability of other, nonvariable resources is also processed by the reV tool and generates availability of hydro, biomass, and geothermal resources using a variety of GIS data sets that consider resource availability and environmental restrictions.

Summary of Assumptions—Renewable Resource

- The study produces generation profiles for renewable generation technologies (Table 8).
- The renewable resource availability is generated from high-resolution temporal and spatial resource data from the meteorological year of 2012. These data will not be adjusted based on expected changes to temperature.
    - Solar: National Solar Radiation Database (NSRDB) 2012 weather year at 4 km^2 spatial resolution and 5-minute, half-hourly, and hourly temporal resolution
    - Wind: Wind Integration National Dataset (WIND) Toolkit 2012 weather year at 2 km^2 spatial resolution at 5-minute, half-hourly, and hourly temporal resolution
    - Biomass: 2011 U.S. Billion-Ton Update, including all non-food energy crops and forest residues available within a 50-mile radius of any transmission node
    - Geothermal: U.S. Department of Energy’s GeoVision study data on geothermal potential by balancing authority
- For analysis of generation under multiple weather years (2007–2016), the source remains the same for solar. The WIND Toolkit is available for only 8 years (2007–2014). As a result, we create wind generation profiles from this data set for the available 8 years as well for all 10 years using a less accurate reanalysis data set.
- The study excludes areas currently unavailable for utility-scale solar and wind development (e.g., developed lands, steep terrains, etc.). Aside from standard technical exclusions, the exclusions are based on current policies and land ownership, and do not consider future policies that may increase or decrease land availability.
- Plant-specific capacity factors are an output of the modeling, determined by site-specific renewable resource data and technology selection
    - Development of generation profiles for wind facilities assume a 100-m hub height for all turbines
    - Assumed power density at wind and utility-scale solar (ground mount, single axis tracking) facilities is 3 MW/km^2 and 32 $MW/km,^2$ respectively.

Table 8. Renewable Resource Performance Data

Name	Values	Source
Wind turbine hub height (new)	100 m	NREL ATB
Wind plant power density (new)	3 MW/km^2	NREL ATB
PV plant power density (new)	32 MW/km^2	NREL ATB
Potentially Deployable Wind (So Cal)	31 GW	reV
Potentially Deployable Solar (So Cal)	420 GW	reV
Wind Plant Output	Forecast and actual plant output at 2x2 km resolution (5-min time steps)	SAM using wind speed data from the WIND Toolkit [4,5]
Solar Plant Output	Forecast and actual plant output at 4x4 km resolution (5-min time steps)	SAM[6] using solar resource data from the NSRDB [7,8,9,10]
Land Availability	Many exclusion layers are applied to eliminate certain types of land from potential development	reV

[4] Caroline Draxl and Bri-Mathias Hodge, *The Wind Integration National Dataset (WIND) Toolkit*. (NREL, 2015). NREL/PR-5000-64691. https://www.nrel.gov/docs/fy15osti/64691.pdf.
[5] Caroline Draxl, Andrew Clifton, Bri-Mathias Hodge, and Jim McCaa, "The Wind Integration National Dataset (WIND) Toolkit," *Applied Energy* (151): 355–366 (August 2015), https://doi.org/10.1016/j.apenergy.2015.03.121.
[6] "System Advisor Model (SAM)," NREL, https://sam.nrel.gov/.
[7] Yu Xie, Manajit Sengupta, and Jimy Dudhia, "A Fast All-Sky Radiation Model for Solar Applications (FARMS): Algorithm and Performance Evaluation," *Solar Energy* (135): 435–445 (October 2016), https://doi.org/10.1016/j.solener.2016.06.003.
[8] Aron Habte, Manajit Sengupta, and Anthony Lopez, *Evaluation of the National Solar Radiation Database (NSRDB): 1998-2015* (NREL, 2017), NREL/TP-5D00-67722. https://www.nrel.gov/docs/fy17osti/67722.pdf.
[9] Yu Xie, Manajit Sengupta, and Jimy Dudhia. "A Fast All-Sky Radiation Model for Solar Applications (FARMS): Algorithm and Performance Evaluation," *Solar Energy* (135): 435–445 (October 2016), https://doi.org/10.1016/j.solener.2016.06.003.
[10] Aron Habte, Manajit Sengupta, and Anthony Lopez, *Evaluation of the National Solar Radiation Database (NSRDB): 1998-2015* (NREL, 2017), NREL/TP-5D00-67722. https://www.nrel.gov/docs/fy17osti/67722.pdf.

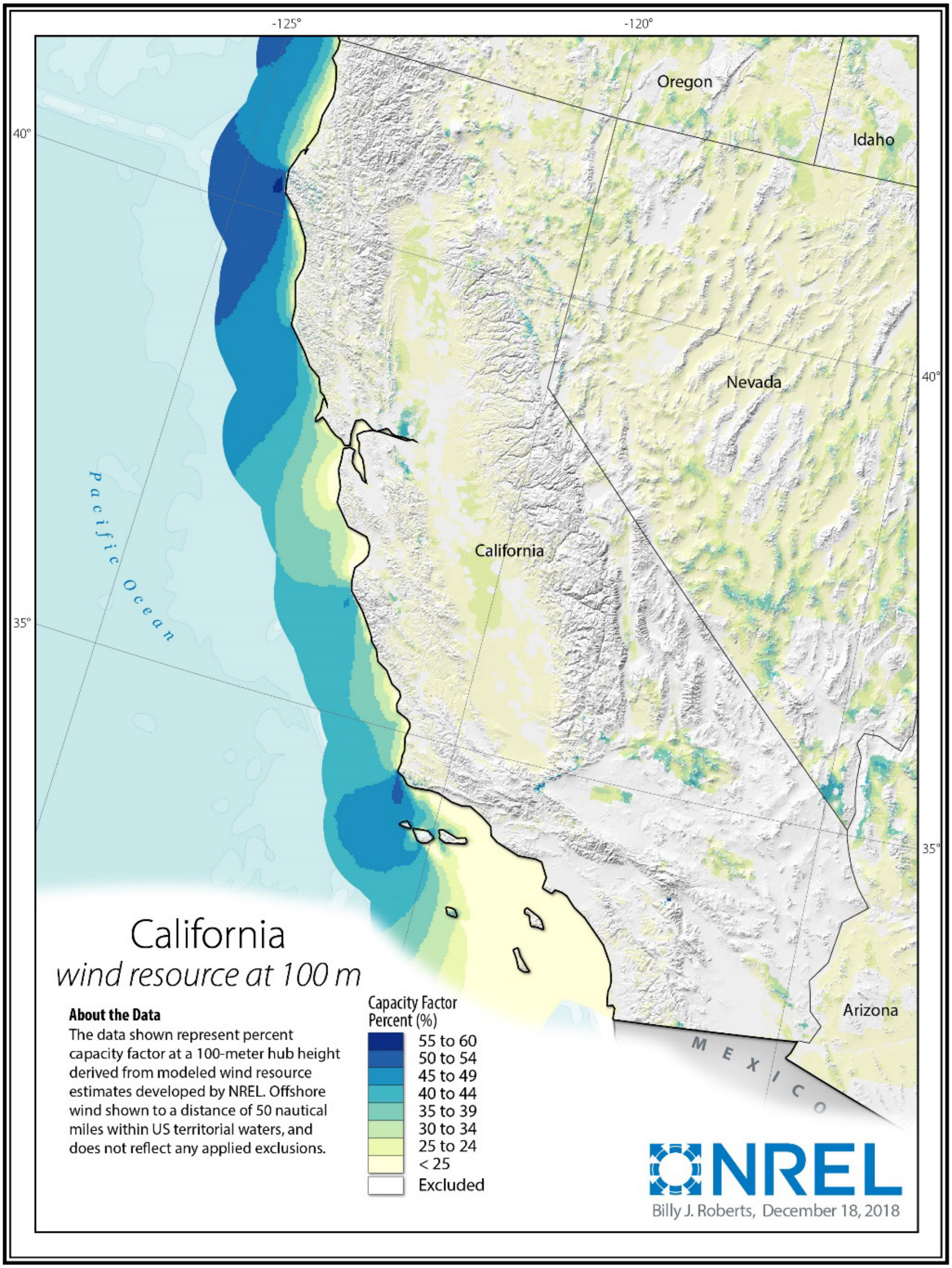

Figure 23. Capacity factor for potential wind sites in California, with land exclusions applied

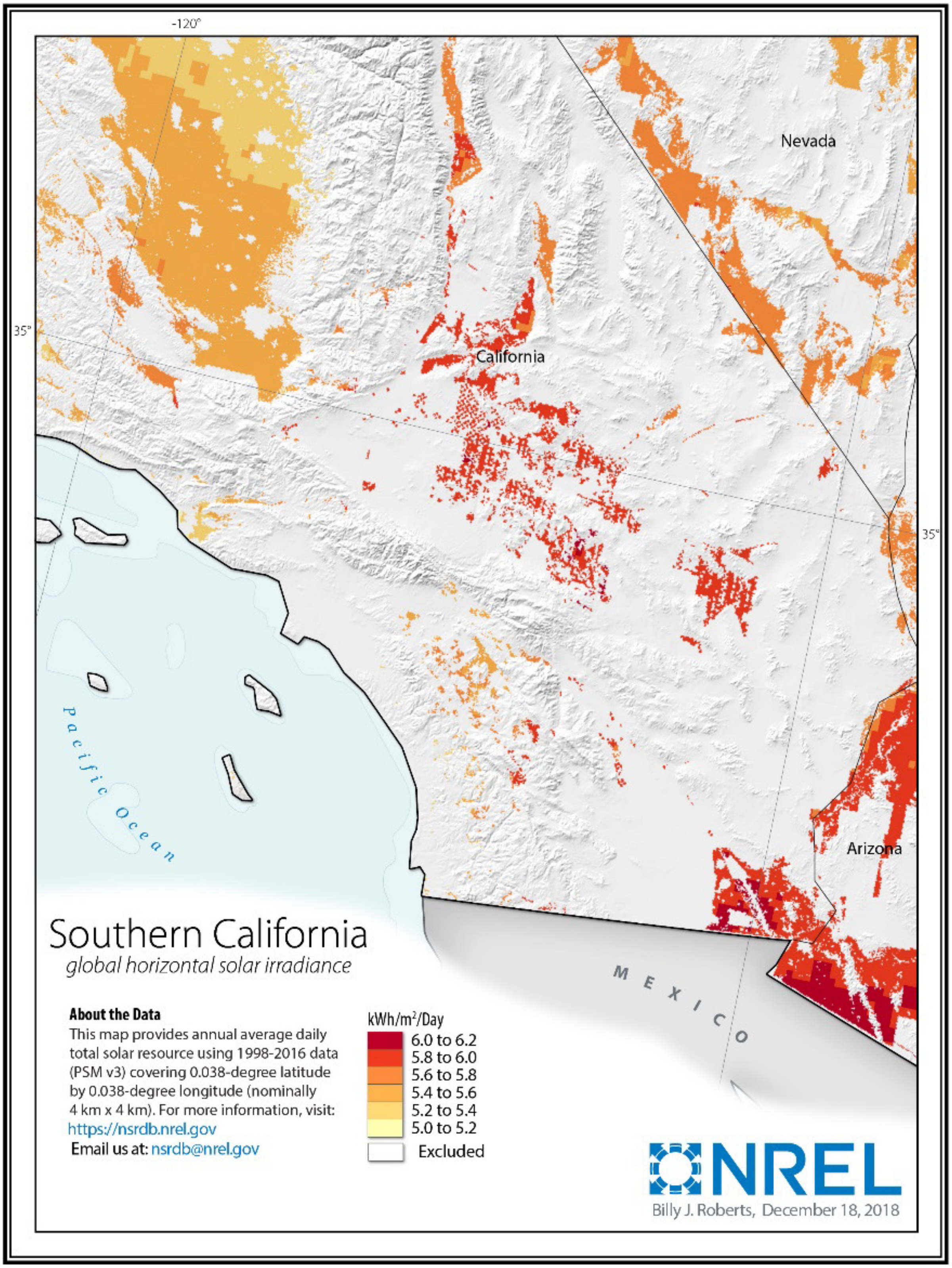

Figure 24. Solar resource for southern California; white represents excluded areas

Appendix B. Model and Data Sources for Distributed Generation Adoption (dGen)

The dGen model is a geospatially rich, bottom-up, market-penetration model that simulates the potential adoption of distributed energy resources (DERs) for residential, commercial, and industrial entities ("agents") in the continental United States through 2050. In this analysis, dGen is used to project the potential adoption of distributed PV systems by end-use customers; adoption of other distributed technologies is not considered. The model used in this analysis was the v2018 version as described in (Cole et al. 2018).

NREL adapted the dGen model for fidelity with the LADWP power system, most notably, to develop a premise-level database of LADWP ratepayers. A premise is the atomic unit of the database; a premise is any contiguous parcel that is interpretable as a decision-maker. For instance, a university campus would be categorized as a single premise, though it is composed of multiple buildings. Likewise, a single-family home is also a premise. This database, which spans the entirety of LADWP's service territory, allows us to populate agents' characteristics in dGen for each unique premise in LADWP. The premise-level database ensures that model represents the diversity of LADWP ratepayers, for instance, by identifying disadvantaged communities. The spatial granularity of the database also permits NREL to model the interaction between solar adoption and distribution hosting capacity and other infrastructure needs. Categories of agent attributes includes (agent locations, end use (sector), premise characteristics, retail electricity tariff, electricity consumption, rooftop technical potential (if applicable), parking lot characteristics (if applicable), neighborhood characteristics, and details of whether solar exists at the premise).

In dGen, market diffusion of DER technologies is simulated in 5-year intervals from 2020 through 2050 based on various market factors for each agent in the model. The consumer demand is modeled through an agent-based approach that includes the following steps:

1. Agents (i.e., potential customers) are assigned attributes (e.g., building area, building value, zoning type) based on data provided by LADWP, LA County tax assessor records, and other building-level fields.
2. Solar resource potential or technical potential is identified using lidar scans of the LADWP service territory. The suitability of each occupied building for hosting roof-mounted customer PV is identified, including the developable surface area and the roof tilt and azimuth.
3. Load Profiles: Hourly electrical demand profiles for each agent are assigned based on data provided by the LA100 Loads team using the ResStock and ComStock models. These profiles are scenario based, allowing projections of how electrical consumption could change (e.g., under a high electrification future).
4. Economic calculations incorporating, among other things, project costs, prevailing retail rates, incentives (e.g., net metering), and cost of financing, are performed to evaluate the value of investment in a distributed PV system to each agent.

5. Ultimate adoption or market share of distributed PV technologies is determined by simulating adoption based on Bass-style adoption and other considerations of consumer behavior.

Following the outlined information above, five projections are simulated in the dGen model, and results are produced for random seeds, which are used to introduce stochasticity and to provide a range of adoption values for year and projection.

The dGen model generates four results for each agent: the technical, economic, and market solar potential, and the amount of distributed solar adopted. Each of these metrics is available by agent or at various aggregations, for instance, by sector, transmission node, or the territory as a whole. Model users can customize numerous parameters related to current and future DER performance improvements and cost reductions, customer financing structures, market projections (e.g., load and rate growth), siting criteria, and incentive and net metering policies. With these inputs, model users can investigate the effects of a diverse set of scenarios on market potential and identify the critical market factors that drive end-use demand.

Table 9 lists the parameters that define spatial and temporal components of dGen. Note that dGen operates with 2-year solve periods, while RPM, and LA100 more generally, operates with 5-year solve periods. Data are translated between dGen and other LA100 models using interpolation.

Table 9. dGen Spatial and Data Definition

Name	Values	Information	Source
Agent	All parcels containing electricity-consuming buildings	This is the target resolution of dGen for the LA100 project	dsgrid (see Chapter 3, Appendix I–Appendix J)
Tract	All tracts in LADWP territory	Tract-level demographic variables are used to define some agent attributes undefined at the individual level	U.S. Census Bureau (2015) American Community Survey
Sector	Residential, commercial, industrial	Sector category names for each agent. These are the categories by which dGen will need all data for all data sets marked with ‘sector’	dsgrid (see Chapter 3, Appendix I)
Tenure	Owner-occupied and renter-occupied	dGen considers potential on both owner-occupied and renter-occupied buildings	dsgrid (see Chapter 3, Appendix I)
Building type	Single-family and multifamily	dGen considers potential on both single-family and multifamily buildings	dsgrid (see Chapter 3, Appendix I)
Rooftop availability	Area available (m^2/kW)	Customer-level rooftop availability data	LA-specific lidar data (DHS 2013 and 2017)

Table 10. dGen Load and Existing Capacity Data

Name	Units	Resolution	Information	Source
Load shape	kWh per hour	Premise	An hourly load shape defined at the agent level as output from the loads models for each scenario and year	dsgrid
Load growth	%/yr	Tract or parcel	The percent at which per-capita consumption changes per year, as output from the loads models	dsgrid
Existing capacity	Counts, MW	Location, date of installation, quantity	The capacity of historically adopted rooftop solar. dGen uses historical system deployment data to train and validate the model.	LADWP (request ID = dist_2)

Table 11 lists input data for the cost and performance for new distributed resources.

Table 11. dGen Financial Data

Name	Units	Resolution	Source
Capital costs	$/MW	Technology, sector, year, and scaling factor	ATB (2018)
Fixed operation and maintenance (O&M)	$/MW-yr	Technology, sector, year	ATB
Variable O&M	$/MWh	Technology, sector, year	ATB
Financing parameters	%	Technology, sector, year Debt rate, equity rate, debt fraction, tax rate	ATB
Solar capacity factor profiles	%	Representative solar generation profiles for each location, tilt, and azimuth	NREL (PVWATTS v5 using NSRDB TMY3)

Table 12 specifies all information regarding local, state, or national policies that impact capacity expansion and operation. Most of these data involve what the actual policies are, but they also include how the policies are enacted in these models. Table 13 shows other model values.

Table 12. Policy Data

Name	Value	Information	Source
State, federal, and local financial incentives	varies	Any financial incentives that affect the system cost or value of the generation	DSIRE (and LADWP for utility-specific information)
Retail tariff	varies	Tariffs defined at the agent level based on current LADWP retail tariffs	OpenEI Utility Rate Database, LADWP/once-through cooling (OTC) data (OTC rate name to tariff in req. dist_8)
Wholesale prices	Hourly	Forecasted wholesale prices are output from RPM. Wholesale prices are used in the Moderate scenario for non-self-consumed generation	RPM
Carbon price	0	Carbon prices are not currently considered in the scenarios	N/A

Table 13. dGen Internal Model Parameters

Name	Units	Columns	Information	Source
Maximum market share	% of market	Payback (year), sector	dGen uses the system payback to establish the maximum number of customers who adopt the technology. The exact relationship is subject to change based on model calibration.	Sigrin 2015[a]
Bass parameters	N/A	Sector	The shape and pace of technology adoption is derived from fitting a Bass model to historical growth. The parameters are calibrated by Census tract.	Regression
American Community Survey (ACS) demographics	Varies	Tract	Average demographic characteristics of the tract's population	Census ACS

[a] Sigrin et al. 2016

Appendix C. Rooftop PV Technical Potential Methods

To assess the rooftop technical potential of distributed solar in the city of Los Angeles, NREL used lidar scans to determine the developable area, tilt, and azimuth of each building's roof planes in the service territory. Lidar is a remote-sensing method that uses pulsed laser beams to measure distances to the ground. The lidar sensing algorithms can be used to infer (1) the presence of individual buildings and their footprint, and (2) the area, tilt, azimuth, and shading of each distinct geometric roof plane on a building's roof. Based on these roof characteristics, the NREL PVWatts tool (NREL 2017) was used to estimate the technical performance for panels on individual buildings and thus the collective tract-level building stock.

Rooftop Technical Potential Data

This work relies on lidar data sets provided by the U.S. Department of Homeland Security's Homeland Security Infrastructure program for the larger Los Angeles Metropolitan Area collected in 2007 and 2013. This data set consists of lidar data in raster format at 1-m by 1-m resolution and a corresponding polygon shapefile for 701,013 building footprints (of the 837,083 buildings modeled in LADWP). The raster data are based on the reflective surface return (first return) of the lidar data, which correlates to the elevation of the first object detected and creates a digital surface model for each building. Approximately 16% of buildings are not included in the lidar scans, and their developable area is imputed using a Random Forest model trained and validated on the empirical data.

The technical potential estimates are supplemented by parcel-level tax assessor data for Los Angeles County (Los Angeles County 2017). This data set provides additional attributes for the parcel, including the building's year of construction, the tax-assessed value of the building and land, and the zoning (e.g., residential). We use additional data to supplement and give context to the results. These include census tract-level characteristics, particularly, the CalEnviroScreen score[11] and whether the building resides in an environmental justice (i.e., disadvantaged) community. We also use the National Land Cover Database (Jin et al. 2011) to assess shading (i.e., whether they are unsuitable for solar) from tree canopy for parking lots in LADWP and the buildings without lidar extent.

Methods for Estimating Rooftop Technical Potential using Lidar Data

This analysis builds upon previous work pioneered by NREL (Gagnon et al. 2016; Sigrin and Mooney 2018) using lidar data to model rooftop suitability for solar PV. This chapter summarizes the method used, but interested readers should read Gagnon et al. (2016) and Sigrin and Mooney (2018) for a complete description of the method.

Using the lidar scans of LADWP, NREL developed a geospatial predictive model to identify rooftop planes suitable for rooftop-mounted solar PV given the roof's orientation (tilt and azimuth) and shading characteristics. To account for potential shading from adjacent buildings, trees, or other obstacles, NREL researchers generated hourly hillshades that identify roof square-

[11] CalEnviroScreen is a metric that evaluates the exposure of California communities (Census Tracts) to many sources of pollution. The overall score uses environmental, health, and socioeconomic information to evaluate communities' pollution burden ("CalEnviroScreen," California Office of Environmental Health Hazard Assessment, https://oehha.ca.gov/calenviroscreen).

pixel areas with sufficient sunlight illumination. Because rooftop shading can vary by time of day and season, we run the simulation for four days—March 21, June 21, September 21, and December 21—resulting in the number of hours of sunlight each square meter of roof area received on the simulated days. The hours of sunlight for the four representative days were used to determine the daily sunlight for each square meter, and we used this metric to exclude roof area that is excessively shaded (Figure 25).

Azimuth \ Tilt	0	10	20	30	40	50
North	1,472	1,329	1,150	957	781	621
Northeast	1,472	1,373	1,245	1,102	960	832
East	1,472	1,469	1,437	1,385	1,318	1,239
Southeast	1,472	1,557	1,602	1,610	1,581	1,522
South	1,472	1,588	1,660	1,689	1,674	1,617
Southwest	1,472	1,549	1,588	1,591	1,558	1,493
West	1,472	1,459	1,423	1,365	1,292	1,206
Northwest	1,472	1,367	1,237	1,095	954	824

Figure 25. Simulated annual generation (kWh/kW-yr) for rooftop solar in Los Angeles for different tilt and azimuth combinations

The tilt and orientation (azimuth) of a roof plane is important for determining its suitability for PV, the amount of annual generation (Figure 24), and the generation profile. Using the first returns, or reflections, of the lidar data we determine the average tilt and azimuth of each square meter of roof area. Each square meter was categorized into one of nine azimuth classes, shown in Figure 25, where tilted roof areas were assigned one of the eight cardinal and primary intercardinal directions; area with a tilt less than 9.5 degrees was classified as flat. We then used the tilt-azimuth values of the roof square meter to identify distinct roof planes, assuming contiguous areas of identical tilt-azimuth class were a unique plane, aggregating each of the individual square meters of roof area into polygons representing contiguous roof planes. This results in a classification of tilt and azimuth for each unique roof plane.

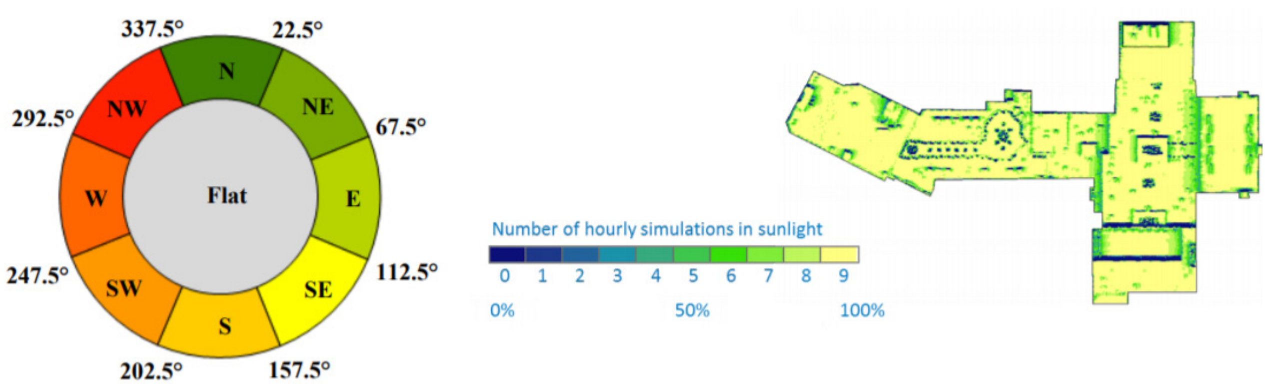

Figure 26. Categorization of roof plane orientations (left) and visualization of roof plane irradiance based on plane tilt, azimuth, and shading (right)

Replicated from Gagnon et al. 2016.

To identify developable surfaces for PV installment, a zonal mean neighborhood function was used to identify and remove data noise and complex features on roofs (e.g., peaks, edges, chimneys, steeples, facades). Finally, roofs were filtered for developable rooftop surfaces that met basic PV suitability requirements, such as being south-facing and having a minimum area of 10 m^2 (see Table 14). The end result is a database of rooftop plane-level data with detailed attribution regarding the slope, tilt, azimuth, and developable area of all suitable rooftops in the service territory.

Table 14. Criteria Used to Determine Roof Suitability for Solar

Roofing Characteristic Criteria	Suitability Criteria
Shading	Seasonal requirements: March requires 60% illumination, June requires 70% illumination, September requires 60% illumination, and December requires 50% illumination[12]
Azimuth	All azimuths considered[13]
Tilt	≤ 60°
Minimum Area[14]	≥ 10 m^2

Given the developable roof area, solar generation profiles were simulated for each distinct tilt-azimuth observed using the NREL reV tool and current PV technology (see Table 15). The reV model's generation module is a complex wrapper that enables distributed generator performance modeling using NREL's PVWatts model with large renewable resource databases in a parallel computing environment. To simulate PV productivity, reV uses multiple historical solar irradiance time-series data from the NSRDB, producing generation and capacity factor profiles for the 2012 meteorological year. Generation profiles based on the 2012 meteorological year are congruent with the remainder of the LA100 study; using historical data, as opposed to typical meteorological year (TMY) data, is preferable for grid integration studies as it captures the true correlation of load and variable renewable resources (e.g., due to weather events).

[12] In cases where a plane is developable, but partly shaded, the generation potential estimates are accordingly derated to account for partial shading

[13] North, Northwest, and Northeast-facing planes are traditionally not commercially developed due to their lower irradiance than South-facing planes. Here we estimate developable area for these unconventional azimuths, though ultimately the capacity expansion modeling selects which planes to develop

[14] At the assumed panel density 10 m^2 provides sufficient area to install a 1.8 kW system. This minimum area threshold was chosen to represent a conservative lower-end estimate of viable PV system sizes based on 2018 PV performance and historical patterns in reported PV sizing.

Table 15. Photovoltaic Configuration Parameters

PV System Characteristic	Previous Value
Ratio of module area to roof area[15]	0.7 for flat roofs 0.98 for tilted roofs
Module power density	183 W/m^2
Total system losses	14.08%
Inverter efficiency	96%
DC-to-AC ratio	1.2

Accounting for Effects of Fire Department Requirements

The Los Angeles city fire department requires that permitted solar arrays installed in LADWP comply with Regulation 96, which specifies the minimum requirements for fire-compliant PV systems. In short, this regulation affects the configuration of a PV array on a rooftop for safe firefighting operation, typically, a 3-foot setback from the roof ridge and edges of the roof. These setbacks are intended to allow safe vertical ventilation techniques during a firefighting operation. Though NREL did not explicitly model the effect of this policy, NREL conducted a literature review and determined that the compliance with the policy is likely to reduce the amount of solar-developable roof area by 26%. Thus, a uniform derate fraction of 26% was applied to the developable area, generation potential, and capacity potential for all solar-suitable roofs. The derate factor was not applied to parking lot solar canopies.

Methods for Imputing Rooftop Technical Potential using Predictive Model

The lidar data set used for this analysis spans 84% of the buildings in LADWP, thus a Random Forest statistical model was developed to impute the generation potential for the missing buildings. We explored a suite of candidate variables representing building and land use attributes, solar resources, and key environmental characteristics to identify those with the greatest relevance to generation potential.

The statistical model was trained on a random subset (80%) of buildings with observed lidar data using a five-fold cross validation procedure. Various permutations of the Random Forest model were assessed against withheld subsets of training data to inform optimal hyper-parameterization. We evaluated the performance of the best trained model (as determined via cross-validation) against the remaining buildings (20%) that were not used in model training. Against this test set the model was found to have a high degree of accuracy, $R^2 = 0.94$ (see Figure 27). We explain the goodness-of-fit largely because the building footprint area—which was populated for all buildings via the Los Angeles County's tax assessor LARIAC building data set (Los Angeles County 2017)—was found to be highly correlated with rooftop developable area and generation potential ($r^2 = 0.9$). Through model interrogation we determined the five most important predictors of generation potential were, in order of decreasing relative

[15] For flat roofs, the ratio of module area to roof area was assumed to 0.7 to reflect the row spacing necessary to incur only approximately 2.5% losses from self-shading for south-facing modules at a 15-degree tilt. For tilted roofs, the value was assumed to be 0.98 to reflect the 1.27 cm spacing between each module for racking clamps.

importance: building footprint area, shading from buildings (as approximated using a topographic position index), elevation, building height, and canopy cover.

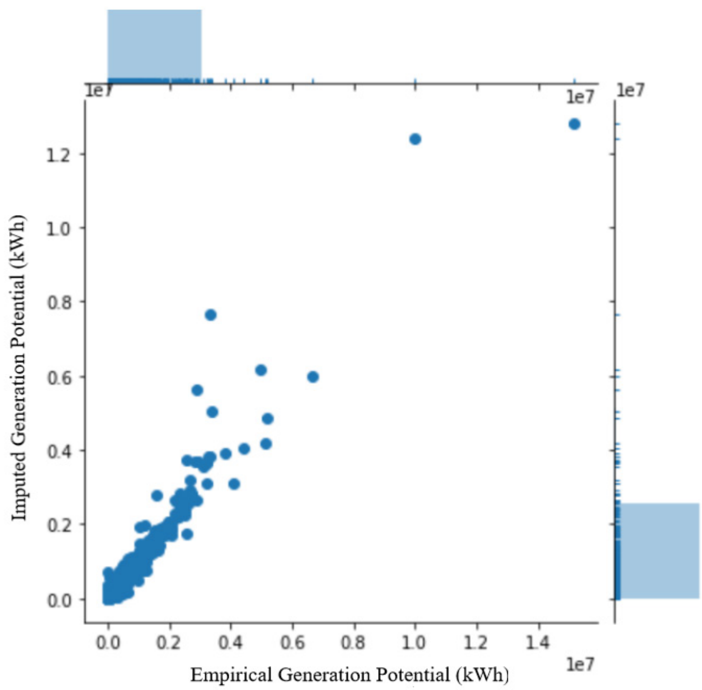

Figure 27. Scatter plot of empirical rooftop generation potential (x-axis) to imputed value (y-axis)

The Los Angeles 100% Renewable Energy Study

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