Title: Estimating Technical Potential for Rooftop Photovoltaics in California, Arizona and New Jersey

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Abstract: Due to the explosive growth of cumulative installed capacity of solar photovoltaic technology across the US in the last five years, industry attention has started to shift to understanding market saturation levels, at which year-over-year growth would be expected to decline significantly. On the residential and commercial scales, the saturation point in the market for distributed PV installations is directly dependent on physical roof space availability. This paper details the multi-level estimation methodology used to estimate rooftop PV potential in the commercial and residential sectors in three leading states: California, Arizona, and New Jersey, which combined account for two-thirds of the cumulative installed PV capacity in the U.S. The estimation methodology shows significant growth potential for rooftop PV in the residential and commercial sectors in these leading states, conservatively estimating that rooftop PV could provide 35 percent, 43 percent, and 61 percent of state electricity demand in New Jersey, Arizona, and California, respectively. According to the results of this analysis, these states could increase current installed distributed PV capacity by 20 times, 30 times, and 40 times, respectively.

Key Words: Photovoltaics, Solar rooftop potential, Distributed generation, Residential buildings, Commercial buildings, State solar potential

1. Introduction

1.1 Current State of PV Market in U.S.

In the last ten years, state and federal-level policies have facilitated rapid adoption of photovoltaic (PV) technologies. According to a recent Interstate Renewable Energy Council (IREC) report [1], the 30% federal Investment Tax Credit (ITC) is the “foundational” incentive for solar installations. The ITC was originally introduced in 1978 under the Energy Tax Act, initially offering a 15% tax credit. In 1986, the ITC was reduced to 10%. The Energy Policy Act of 2005 (EPAct 2005) increased the ITC to 30%. The EPAct of 2005 was shortly followed by the Energy Improvement and Extension Act (EIEA) of 2008, which extended the ITC at 30% through 2016 [2].

Historically, states and electric utilities supported PV deployment through capital rebate programs. In recent years, however, support has begun to shift towards production based incentives [1, 2].

35 Currently, 29 states and Washington D.C. have Renewable Portfolio Standards (RPS), mandating
36 Load Serving Entities (LSEs)¹ to provide a fixed portion of the electricity sold from renewable
37 energy sources. Eight more states have renewable energy goals. 21 states and Washington D.C.
38 have solar or Distributed Generation (DG) provisions, or “carveouts,” in their RPS scheme [3]. RPS
39 requirements are typically met through Renewable Energy Certificates/Credits (RECs)².
40 Consequently, RPS schemes promote the production-based incentive structure.

41 Federal and state renewable energy policies led to more than 50% annual cumulative capacity
42 growth in a five year period, guiding cumulative installed PV capacity in the U.S. from less than 1
43 GW in 2008 to more than 12 GW by the end of 2013. The states leading this growth were
44 California, Arizona and New Jersey [1, 4], which when combined, represent nearly two-thirds of
45 total cumulative installed PV capacity in the U.S. (see Figure 1). In 2013, California with 5,183 MW
46 installed capacity was a national leader, followed by Arizona with 1,563 MW and New Jersey with
47 1,184 MW of installed capacity [1].

48 Until recently, residential and commercial installations were dominating PV markets. However,
49 utility scale PV (here, installations greater than 1 MW) experienced steady growth and reached
50 46% of total installed capacity in 2013 (see Figure 2). The significant increase in utility scale PV
51 can be explained by LSEs desiring to meet their RPS obligations by developing their own PV
52 projects. In many cases, utilities prefer this approach since they stand to benefit directly from the
53 RPS and SREC market transactions in addition to the ITC [1]. Utility scale PV projects have lower
54 initial unit costs and this can transpire in lower production costs for LSEs to meet their RPS
55 obligations (through direct ownership or through SREC purchase). This might lead to conditions
56 where utility scale PV meets the entire solar carveout under the RPS. This can be avoided by
57 providing special policy provisions for small-scale PV installations.

¹ Load Serving Entity (LSE) refers to entities, such as an energy provider or a load aggregator that has been granted the authority by the state or local law to sell electricity to end-users in its service region [42].

² For solar energy RECs are referred as Solar Renewable Energy Credits (SRECs).

Figure 1. Cumulative PV Installation by Three Leading States in U.S.
Data source: [1]

Figure 2. Cumulative PV Installation by Type in U.S.
Data source: [1]

Other stimuli that have helped to facilitate the growth of utility-scale solar plants in the U.S. in recent years were the Department of Energy's Federal Loan Guarantee program and the new forms of financial structures that attract the private financing entities in funding the PV projects. The USDOE's Loan Programs Office (LPO) supports large-scale solar PV utilities by issuing federal loan guarantees to back the new PV projects, bearing some of the risks inherent in a project without any commercial operation history [5]. According to recent LPO data, the program provided

71 more than \$4.6 billion in loan guarantees to support construction of the first five utility-scale PV
72 solar facilities larger than 100 MW in the United States in 2011 [5]. Using new financial vehicles
73 and mechanisms applied to PV projects that rely on long-term Power Purchasing Agreements
74 (PPAs), such as single owner, all-equity partnership flip, leveraged partnership flip, and sale-
75 leaseback, has been essential in lowering uncertainties and distributing profits among investors,
76 which only incentivizes further investment and development [6]. These long-term PPA contracts
77 are easier to set up for a utility-scale PV project and thus benefit utility-scale projects more than the
78 residential and commercial sectors [1].

79 Due in part to the current policy environment, utility scale PV system have held the lion's share of
80 new capacity additions. However, distributed residential and commercial-scale PV systems have
81 distinct advantages over utility scale systems. Because distributed generation resources operate at
82 the back of the meter, they can sell power independently at retail prices where electricity rates are
83 higher than at bulk power supply. If the ITC reverts to 10% after 2016 and SREC prices fall,
84 revenue from electricity sales will compose a greater share of the positive cash flow, giving
85 distributed PV systems which are selling power at retail rates a noticeable advantage over utility
86 scale systems, which sell at lower, wholesale rates. Distributed generation also decreases peak
87 load, improves system reliability, minimizes transmission and distribution losses, stabilizes and
88 applies downward price pressure to retail rates, and reduces uncertainty accompanying future bulk
89 power generation [7]. More importantly, distributed PV systems make full use of existing local
90 resources, i.e. roofs and other vacant spaces, and they can avoid the tedious siting procedures as
91 applied to utility scale projects.

92 Some of the advantages of utility scale PV are also disappearing. Third Party Ownership (TPO) of
93 customer-sited systems through PPAs and leases facilitated over 67% of all PV systems installed
94 in 2013, responsible for supporting 68% of residential PV systems, and 61% of PV systems hosted
95 by for-profit commercial customers [8]. The current trends under the TPO model suggest that
96 distributed solar will continue its steady growth in the coming years. However, as federal incentives
97 such as ITC and loan guarantees are reaching their sunset terms, the incentive burden on solar PV
98 project development towards RPS goals will shift to local and state-level governments [6].

99 Even with high PV installed solar capacity growth rates, there is still vast potential for PV market
100 growth in the U.S. Yet, markets, technologies and nature experience growth patterns which are
101 normally confined by some limits [2]. To understand the potential scale of the future growth, it is
102 important to understand the technical and geographical limitations of PV growth, particularly for
103 distributed generation. Assessing the technical potential for PV installation is essential for utility
104 planning and grid capacity accommodation [9]. Moreover, such studies can aid in the development
105 of adaptive energy policies, regulations, and financing programs and further contribute to future
106 researches on the market potential for rooftop PV [9, 10, 11]. This study proposes a methodology
107 to understand the amount of electricity that can be provided from distributed PV hosted on
108 residential and commercial roofs at the state level in the U.S.

Technical potential represents the theoretical maximum amount of PV that can be deployed on the rooftops of residential and commercial buildings, which depends on the available rooftop space as well as PV module efficiency. This analysis disregards all non-engineering constraints such as costs, regulatory hurdles, and end-user participation rates. There are two main methods to conduct technical potential analysis. The following section provides short description of the major differences among these methods.

1.2 Methods for Estimating Technical Potential for Rooftop PV

Studies estimating rooftop PV potential can be grouped into two major methodological categories: the constant-value methodology and the Geographic Information Systems (GIS) based methodology [10, 12, 13]. These methodologies vary based on the data availability and the scale of focus area [12, 13].

The constant-value methodology collects the existing building-based data such as floorspace, number of floors, and the total number of buildings [12, 13, 16, 15]. These data are used with various rule-of-thumb assumptions such as roof tilt, rooftop orientations, and shading in a “matrix” model for estimating the total roof space and the solar PV potential of the focus region [10, 13, 17, 9, 18, 19, 20]. The constant-value methodology, can also use the correlations between the roof area and the population density for estimating the total available roof space in the focus region [10, 13, 9, 21].

The second category is the GIS-based method [10]. Through setting values for ideal rooftop characteristics in the base-map data layers, this method relies on GIS software to determine the suitable region for rooftop solar installation [10]. Because this methodology is highly time- and resource-intensive [10, 12], it is rarely if ever used to the scale necessary to estimate technical potential at a country or a state level. Wiginton et al. [9] discovered the GIS data can be inconsistent and less reliable across larger regions such as a state or a country, so extant literature confines this methodology to small-scale regions such as a city or a county level zone [9, 11, 22, 23].

At the state level, conducting technical potential analysis using GIS data, due to its high resource requirements is not feasible. To estimate state level rooftop PV potential this research followed the constant-value methodology. Through extracting EIA’s comprehensive building profile data, the proposed methodology in this research is less complex and faster to conduct, and can generate relatively accurate estimation of technical PV potential for large geographical areas. In the following two sections, a detailed description of the developed methodology for estimating the technical PV rooftop potential at the state level in the commercial and residential sectors is presented. In section four, the research results for both sectors are summarized and evaluated against current electricity retail sales in each focus state. The last section provides conclusions and policy recommendations.

2. Technical Rooftop PV Potential in Commercial Buildings

2.1. Methodology

This section describes methodology used for estimation of the technical rooftop PV potential in commercial buildings. The multi-phase rooftop potential estimation includes finding data on the existing building stock and building characteristics (e.g., number of floors for different type of buildings), as well as adopting values for other parameters such as module efficiency and rooftop obstructions which might impact the estimated values. A brief summary of this process is illustrated in Figure 3.

Figure 3. Methodology for the Estimation of Technical Rooftop PV Potential in Commercial Sector

In the first step, data on number of units and the total floor area (million ft²) for different commercial building categories were obtained from Energy Information Administration's (EIA) Commercial Buildings Energy Consumption Survey (CBECS) [14]. The buildings are divided into categories by principal building use as well as size (later used to estimate available rooftop space). The EIA CBECS database organizes commercial building data into four regions, which are composed of nine smaller divisions across the United States (including Hawaii and Alaska). At this stage, the highest resolution data exists at the division level.

The original CBECS dataset was incomplete, having withheld values. As explained by the EIA, those withheld values had a Relative Standard Error (RSE) greater than 50% or a sample size smaller than 20. These missing values were extrapolated from the available data in order to build a more inclusive and complete data set. For example, in Table B4 of the EIA data set [14], the number of "Inpatient buildings" in South Atlantic Division was denoted with 'Q', however the numbers of all health care buildings and "Outpatient buildings" were given in the same table.

Therefore, the missing data on “inpatient buildings” could be estimated by subtracting the number of “outpatient” buildings in the health care category from the total values. In cases when division-level data was not available, missing numbers were extrapolated by applying the distribution ratio at the national level.

Next, state level commercial building floorspace estimates were calculated under the assumption that the total floorspace in the state is directly correlated with the population. This assumption is justified in Figure 4 below, which demonstrates that census divisions with larger population tend to have more floorspace. The combinatory analysis of these datasets allows for the justification of these state-level projections.

Figure 4. Total Commercial Building Floorspace, and Population in Each Census Davison
Data sources: [14, 15]

The estimated floorspace for each category of commercial buildings was then converted into a roof area estimation using the commercial buildings reference values developed by U.S. Department of Energy (USDOE) and its three leading national laboratories: The National Renewable Energy Laboratory, Pacific Northwest National Laboratory and Lawrence Berkeley National Laboratory [24].³ By matching the DOE reference-building types with corresponding values in the EIA’s CBECS data, the estimated ground floor area (also representing roof area) for each building category can be calculated by dividing the total building floor area by the average number of floors. The matching table between DOE’s and EIA’s commercial building category systems is shown in Table 1.

³ The U.S. Department of Energy developed 16 reference building categories. 15 of them were for commercial buildings. The last was for midrise apartment buildings.

Table 1. USDOE-CBECS Category Matching Table

EIA Category System	USDOE Category System		
Matched Building Type Names		Floor Area (ft ²)	No. of Floors
Education	Primary School	73,960	1
	Secondary School	210,887	2
Food Sales	Supermarket	45,000	1
Food Service	Quick Service Restaurant	2,500	1
	Full Service Restaurant	5,500	1
Health Care-Inpatient	Hospital	241,351	5
Health Care-Outpatient	Outpatient Health Care	40,946	3
Lodging	Small Hotel	43,200	4
	Large Hotel	122,120	6
Mercantile Retail (other than malls)	Stand-alone Retail	24,962	1
Mercantile Enclosed & Strip Malls	Strip Mall	22,500	1
Office	Large Office	498,588	12
	Medium Office	53,628	3
	Small Office	5,500	1
Warehouse & Storage	Warehouse	52,045	1

190 Data sources: [14, 24]

191

192 The USDOE categories have a higher resolution than the EIA's CBECS building category system,
 193 with two or more sub-categories for educational buildings, food service buildings, lodging
 194 accommodations, and offices, as seen in Table 1 above. In order to estimate the total roof space of
 195 the buildings in these sub-categories and therefore match them with the CBECS database, the
 196 quantity distribution of buildings under each sub-category need to be calculated. By matching the
 197 building sizes with the number of buildings and total floorspace for difference sizes of schools,
 198 restaurants, hotels and offices given in the CBECS database, the number of buildings, and
 199 therefore the floorspace, in each subcategory could be estimated [14]. For example, under the
 200 USDOE category system, the typical floorspace of quick service restaurants and full service
 201 restaurants were 2,500 ft² and 5,500 ft² respectively. Meanwhile, the CBECS database reported
 202 the numbers of restaurants with floorspace within 0-5,000 ft² and 5,000-25,000 ft². By aligning the
 203 USDOE building categories with the corresponding EIA's classification, the distribution ratio, and
 204 similarly floor space, of most building subcategories could be calculated.

205 The CBECS data for educational buildings was mostly categorized by the size, rather than the
 206 function, of school buildings [14]. Because this categorization was incongruent with the USDOE's
 207 breakdown of educational buildings between primary and secondary schools, an alternate method
 208 was used. By using relevant statistics published by the U.S. Census Bureau [25] on the numbers of
 209 public primary schools and secondary schools across U.S, and by assuming that the floorspace in
 210 a school is linearly related with its enrollment, ratios between primary and secondary schools were

estimated. This proxy estimation yielded a nearly 3:1 estimated ratio between primary schools and secondary schools. Using this distribution as well as the average enrollment data to allocate the total educational building floorspace to both subcategories, the product of the share of adjusted floorspace and the average enrollment data was divided by the combined products of both subcategories. The results of the calculation under this method, along with the original method are presented in Table 2 below.

Table 2. Floorspace Ratio for Buildings in Education Category Using Two Different Methods

Education	Share by the floorspace [14]	Share by number of schools from U.S. Census Data [25]	Average enrollment number, U.S. Census Data [25]	Share of adjusted floorspace
Primary School	55.64%	73.39%	470	64.80%
Secondary School	44.36%	26.61%	704	35.20%

After estimating the values of total roof space for commercial buildings under each category, assumptions were made to estimate the usable roof space for PV module deployment. The total area of PV arrays that could be installed on the roofs can be affected by various factors: roof pitch and orientation, structural soundness, building obstruction and shading etc. According to CBECS [14], the rooftops of commercial buildings can be divided into three categories: flat, shallow pitch and steeper pitch⁴. For states of California, Arizona and New Jersey, most of the commercial buildings are with flat roofs (over 50%). The *Access Factor* was applied in the calculation of available rooftop PV arrays. It accounts for technical potential losses due to roof pitch and orientation, structural adequacy, tree shading and other constraints. The literature on rooftop PV market penetration provides reference values for the Access Factor [17]. For states with warmer climates such as California and Arizona, the flat roofs⁵ have an Access Factor of 60% and the pitched roofs have an Access Factor of 24.3%. For states with cooler climates such as New Jersey, the Access Factor of flat roofs is 65% and that of pitched roofs is 17.55%⁶.

For buildings with flat roof, the solar panels are generally installed in parallel rows and in this case the consideration for panel-to-panel shading becomes necessary. For multi-row PV systems, this kind of shading is inevitable, but designers have the ability to choose proper array geometry to

⁴ The roofs with tilts of 14° or less are defined as shallow pitch and those with tilts greater than 14° are defined as steeper pitch. For more details, see EIA's Commercial Buildings Energy Consumption Survey (CBECS) show card A4.

⁵ In this study, the roofs with a shallow pitch are applied with an approximate Access Factor equal to that of flat roofs.

⁶ The parameters used in calculating the Access factor for pitched rooftops were adopted from [17, p. 5]. For warmer climates, the tree shading factor is 90%, "other" shading factor is 90%, and the orientation factor is 30%. The Access factor can then be calculated by multiplying these three parameters together (90%*90%*30%=24.3%). For cooler climates, the tree shading is 65%, the "other" shading is 90%, and the orientation is 30%. The Access factor is then 65%*90%*30%=17.55%.

satisfactorily minimize this type of shading loss [26]. Figure 5 illustrates how panel shading affects design geometry for multi-row arrays.

Figure 5. Multi-row PV Arrays Geometry

Source: [26]

The setback ratio (SBR) is defined as the horizontal distance, or gap, between rows, divided by the vertical distance between the highest edge of the panel and the ground. The SBR is at least 2:1 in sunny, lower latitude regions and at least 3:1 in cloudier higher latitude regions [26]. For the purposes of this methodology, the SBR was assumed to be 3:1 for all locations. The influence on available PV array area from panel-to-panel shading can be estimated using the Ground Cover Ratio (GCR). GCR is defined as the array area divided by the ground area [26]. In multi-row systems, Tilt angle, SBR and GCR are related, which can be explained by Equation 1:

$$GCR = (\cos(\beta) + SBR \cdot \sin(\beta))^{-1} \quad (\text{Equation 1})$$

Empirically, PV arrays tilted at the appropriate angle (β in Equation 1), to minimize panel to panel shading. Higher tilts require more roof space, which results in lower GCR. For flat commercial building rooftops, the tilt angle of solar panels is usually set at 5 to 10° to maximize economic performance of the available roof space [27]. Higher tilt angles increase wind load on the panels and increases weight requirements for blasted mounts. Majority of commercially available racking structures are sold at fixed 5°, 10°, 15° and 20° tilt angles [28]. For this study the tilt angle for flat roofs was assumed at 10°. Under these assumptions, applying Equation 1, the GCR was calculated at 66.4%.

For commercial buildings with pitched roofs, the solar panels are installed along the surface of the roofs and the issues of row-to-row shading will not occur. For the purpose of this study, the roofs with shallow pitches are assumed to have an average tilt of 10° and those with steeper pitches are assumed as 30°. In order to accurately estimate the available PV array area for pitched roofs, a Geometric Factor is applied in the calculation. The geometric factor can be calculated as follows:

$$\text{Geometric Factor} = 1/\cos(\text{Tilt}) \quad (\text{Equation 2})$$

For example, for the assumed 30° tilt, the geometric factor value is $2/\sqrt{3}$. After considering all the introduced factors that will influence the available space for PV installation, the total area for PV arrays that can be mounted on commercial rooftops can be calculated by the equations below.

Calculation for flat roofs:

$$\begin{aligned} \text{Total PV Array Area} = & \\ \text{Estimated Gross Horizontal Roof Space} \times & \\ \text{Access Factor} \times \text{Ground Cover Ratio (GCR)} & \end{aligned} \quad (\text{Equation 3.1})$$

Calculation for pitched roofs:

$$\begin{aligned} \text{Total PV Array Area} = & \\ \text{Total Estimated Pitched Roof Space} \times \text{Access Factor} & \end{aligned} \quad (\text{Equation 3.2})$$

Where

$$\begin{aligned} \text{Total Estimated Pitched Roof Space} = & \\ \sum_i^2 \text{Estimated Gross Horizontal Roof Space}_i \times \text{Geometric Factor}_i^7 & \end{aligned}$$

The technical power potential can be calculated by multiplying the estimated total PV array area with the assumed solar system power density (W/m^2). The estimation process is shown in the equation below.

$$\begin{aligned} \text{Power Density (W/m}^2\text{) under Standard Test Condition} &= 1000\text{W/m}^2 \times \text{Panel Efficiency} \\ \text{Technical PV Potential (MW)} &= \text{Total PV Array Area} \times \text{Power Density} \div 10^6 \end{aligned} \quad (\text{Equation 4})$$

The solar power density is determined by the efficiency of selected solar panels. In this study, the average panel efficiency was assumed at a conservative 16%. This is a quite reasonable estimate in the current market, but a highly conservative estimate in the context of the study. Because this methodology is static using government data and does not account for the future module efficiency innovations or additional building development and the subsequent additional rooftop space that will arise in the next 15-20 years, the final technical potential estimation represents a restrained *ceteris paribus* result. NREL's most recent Tracking the Sun VIII Report shows the trend of market median PV module efficiency has increased at a steady rate from 14% to 16% from 2010 to 2014 [29], and current market-leading module manufacturers SunPower, SolarCity, and Panasonic have reported module-level efficiencies pushing 22% [30, 31]. Additional confidence in this conservative nature of this assumption arises from previous work demonstrating the high value of high efficiency PV modules [29, 32].

2.2. Analysis

Based on the methodology described above, rooftop potential analyses for the commercial buildings in the states of California, Arizona and New Jersey were conducted. This section explains in depth how the data was collected, organized, and analyzed.

⁷ In this methodology, pitched commercial building roofs are divided into two categories: shallow pitch and steeper pitch. The average tilts of 10° and 30° are assumed for each category correspondingly.

2.2.1. Commercial Building Portfolios

As introduced in the methodology section, the building counts and total floorspace of commercial buildings at a state level are estimated using division-level building statistics and the population data from the U.S. Census Bureau, DOE, and EIA. Using California as an exemplar, this section at first details the applied methodology and then displays the results for all three states in summary tables.

According to CBECS [14], California is within the West Region and more specifically, the Pacific Division. The number of commercial buildings in the Pacific Division is 929,000, with a total floorspace of 13,379 million square feet [14]. Under the assumption that the number and total floorspace of commercial buildings within a state are correlated with its population scale, these building statistics can be estimated by applying population ratio on the Division-level building data in California.

According to U.S. Census data, the state of California has a population of 38 million, which accounts for 74.56% of the population of the Pacific Division [33]. By multiplying this population ratio by the commercial building statistics of West Division region, it is estimated that there are 693,473 commercial buildings in California, with a total floorspace of 9,987 million square feet.

A similar analysis was conducted for Arizona and New Jersey. The estimation results for building counts and floorspace totals of commercial buildings in California, Arizona and New Jersey is summarized in Table 3.

Table 3. Number of Commercial Building and Aggregate Floorspace in Three States		
States	Estimated Number of Commercial Buildings	Estimated Floorspace of Commercial Buildings (Million ft ²)
California	693,473	9,987
Arizona	97,931	1,443
New Jersey	108,445	2,416

Using the EIA's CEBES database, Table 4 (below) was created. The table presents an overview of the building portfolios in Pacific Division, which provides information on how the number of buildings and floorspace are distributed under different categories of building usage. The first ten categories of buildings are the commercial building types that were matched between USDOE's building categories and EIA's commercial building categories in Table 1. Other building categories listed in the EIA's database (i.e., Public Assembly, Public Order and Safety, Religious Worship, and Service) were not included in the rooftop analysis study.

Table 4. Building Statistics in Pacific Division

Principal Building Activity	Number of Buildings (Thousands)	Percentage of Building Count	Total Floorspace (Million ft ²)	Percentage of Floor Space
Education	94	10.12%	1,065	7.96%
Food Sales	24	2.58%	304	2.27%
Food Service	59	6.35%	282	2.11%
Health Care (Inpatient)	1	0.11%	315	2.35%
Health Care(Outpatient)	18	1.94%	182	1.36%
Lodging	26	2.80%	940	7.03%
Mercantile Retail (Other Than Mall)	61	6.57%	1,030	7.70%
Mercantile (Enclosed and Strip Malls)	30	3.23%	1,058	7.91%
Office	179	19.27%	2,562	19.15%
Warehouse and Storage	173	18.62%	2,938	21.96%
Total for Building Types Included in Study	665	71.58%	10,676	79.80%
Public Assembly	61	6.57%	697	5.21%
Public Order and Safety	12	1.29%	176	1.32%
Religious Worship	52	5.60%	511	3.82%
Service	78	8.40%	578	4.32%
Other	27	2.91%	345	2.58%
Vacant	34	3.66%	396	2.96%
Total for building types not Included in study	264	28.42%	2,703	20.20%
All Buildings	929	100.00%	13,379	100.00%

328 Source: [14]

329 To project the building portfolio in California, the estimated number of commercial buildings (i.e.,
330 693,473) and the total floorspace (9,987 million square feet) [See Table 3] were multiplied by the
331 percentage values of different categories of buildings at division level (i.e., Pacific Division). The
332 resulting building portfolio for California is presented in Table 5.

333 Table 5. Projected Building Portfolios in California

Principal Building Activity	Number of Buildings (Thousands)	Percentage of Building Count	Total Floorspace (Million ft ²)	Percentage of Floor Space
Education	70.168	10.12%	794.994	7.96%
Food Sales	17.915	2.58%	226.929	2.27%
Food Service	44.042	6.35%	210.505	2.11%
Health Care (Inpatient)	0.746	0.11%	235.139	2.35%
Health Care (Outpatient)	13.437	1.94%	135.858	1.36%

Lodging	19.408	2.80%	701.685	7.03%
Mercantile Retail (Other Than Mall)	45.535	6.57%	768.867	7.70%
Mercantile (Enclosed and Strip Malls)	22.394	3.23%	789.769	7.91%
Office	133.619	19.27%	1,912.464	19.15%
Warehouse and Storage	129.140	18.62%	2,193.138	21.96%
Total for Building Types Included in Study	496.404	71.58%	7,969.347	79.80%
Public Assembly	45.535	6.57%	520.292	5.21%
Public Order and Safety	8.958	1.29%	131.379	1.32%
Religious Worship	38.817	5.60%	381.448	3.82%
Service	58.225	8.40%	431.461	4.32%
Other	20.155	2.91%	257.533	2.58%
Vacant	25.380	3.66%	295.603	2.96%
Total for Building Types not Included in Study	197.069	28.42%	2,017.717	20.20%
All Buildings	693.473	100.00%	9,987.063	100.00%

334

335 Using the subcategory-matching methodology explained in section 2.1, the percentage and
336 quantitative data for the Education, Food Service, Lodging, and Office subcategories of buildings
337 were estimated. The results are presented in Table 6.

338 Table 6. Building Portfolios for Education, Food Service, Lodging and Office

Principal Building Activity (based on IEA's building category system)	Subcategories of Buildings (based on U.S.DOE's building category system)	Share by Number of Buildings	Share by Floorspace
Education	School Primary	73.4%	64.8%
	School Secondary	26.6%	35.2%
Food Service	Quick Service Restaurant	70.3%	64.8%
	Full-Service Restaurant	29.7%	35.2%
Lodging	Hotel Small	41.3%	86.7%
	Hotel Large	58.7%	13.3%
Office	Office Small	75.3%	20.0%
	Office Medium	23.8%	53.9%
	Office Large	0.9%	26.1%

339

Date sources: [14, 24]

340 The matching procedure resulted in 15 commercial building categories. Table 7 below shows the
341 estimated number and floorspace for each category of buildings as well as their corresponding
342 ratios in California.

Table 7. Final Summary of Commercial Building Portfolios in California

NO.	Principal Building Activity	Number of Buildings	Share	Floorspace (ft ²)	Share
1	Primary Schools	51,497	10.37%	515,191,432	6.46%
2	Secondary Schools	18,672	3.76%	279,802,390	3.51%
3	Supermarket	17,915	3.61%	226,927,814	2.85%
4	Quick-service restaurant	30,945	6.23%	91,192,007	1.14%
5	Full-service restaurant	13,097	2.64%	119,313,400	1.50%
6	Hospital	746	0.15%	235,139,018	2.95%
7	Outpatient Health Care	13,437	2.71%	135,858,099	1.70%
8	Small Hotel	16,829	3.39%	289,417,835	3.63%
9	Large Hotel	2,580	0.52%	412,266,853	5.17%
10	Stand-alone retail	45,535	9.17%	768,867,264	9.65%
11	Strip mall	22,394	4.51%	789,768,510	9.91%
12	Small Office	100,610	20.27%	381,605,626	4.79%
13	Medium Office	31,820	6.41%	1,031,282,310	12.94%
14	Large Office	1,188	0.24%	499,576,074	6.27%
15	Warehouse	129,140	26.02%	2,193,137,885	27.52%
Total		496,405	100.00%	7,969,346,515	100.00%

344

345 The commercial building portfolios for Arizona and New Jersey were calculated in a similar manner
 346 to California's commercial building portfolio. Table 8 summarizes the estimation result for all three
 347 states.

348

Table 8. Commercial Building Portfolios in California, Arizona and New Jersey

Principal Building Activity	Total Floorspace(million ft ²)			Floorspace Percentage		
	California	Arizona	New Jersey	California	Arizona	New Jersey
Primary Schools	515	147	197	6.46%	12.88%	10.52%
Secondary Schools	280	80	107	3.51%	7.01%	5.72%
Supermarket	227	21	30	2.85%	1.84%	1.60%
Quick-service restaurant	91	13	15	1.14%	1.14%	0.80%
Full-service restaurant	119	17	20	1.49%	1.49%	1.07%
Hospital	235	38	79	2.95%	3.33%	4.22%
Outpatient Health Care	136	45	91	1.71%	3.94%	4.86%
Small Hotel	289	62	71	3.63%	5.43%	3.79%
Large Hotel	412	88	101	5.17%	7.71%	5.40%
Stand-alone retail	769	89	145	9.65%	7.80%	7.75%
Strip mall	790	122	111	9.91%	10.69%	5.93%
Small Office	382	49	127	4.79%	4.29%	6.78%
Medium Office	1,031	133	344	12.94%	11.66%	18.38%

Large Office	500	64	167	6.27%	5.61%	8.92%
Warehouse	2,193	171	267	27.52%	14.99%	14.26%
Total	7,969	1,141	1,872	100.00%	100.00%	100.00%

349

350 2.2.2. Rooftop Space Estimation for Commercial Buildings

351 In the previous section, the total floor spaces for each type of building in California, Arizona and
352 New Jersey were estimated. As detailed in Equations 3.1, 3.2 and 4 above, an estimate of total
353 rooftop space is needed to calculate technical rooftop solar potential.

354 Firstly, the gross horizontal area of the commercial buildings should be estimated.

355 Table 9 shows the calculated result of total floor space divided by profiled floor numbers to yield
356 total horizontal roof space for each building category in California.

357 Table 9. Rooftop Space of Commercial Buildings in California

NO.	Principal Building Activity	Floorspace (million ft ²)	Typical Number of Floors	Horizontal Rooftop Space (million ft ²)
1	Primary Schools	515.191	1	515.191
2	Secondary Schools	279.802	2	139.901
3	Supermarket	226.928	1	226.928
4	Quick-service restaurant	91.192	1	91.192
5	Full-service restaurant	119.313	1	119.313
6	Hospital	235.139	5	47.028
7	Outpatient Health Care	135.858	1	135.858
8	Small Hotel	289.418	4	72.354
9	Large Hotel	412.267	6	68.711
10	Stand-alone retail	768.867	1	768.867
11	Strip mall	789.768	1	789.769
12	Small Office	381.606	1	381.606
13	Medium Office	1,031.282	3	343.761
14	Large Office	499.576	12	41.631
15	Warehouse	2,193.138	1	2,193.138
Total		7,969.347		5,935.249

358

359 According to CBECS, for the Pacific division where the State of California belong, 60.5% of the
360 commercial building roofs are flat (by floorspace) and the percentages for shallow pitch and
361 steeper pitch are 27.7% and 11.7%. By applying geometric factors as shown in Equation 3.2 for the
362 pitched roofs and adding up the total rooftop space (flat and pitched), the aggregated rooftop space
363 of commercial buildings in California was calculated (see Table 10)

Table 10. Rooftop Space on Commercial Buildings in California			
Total Horizontal Rooftop Space (million ft ²)	5,935.25		
Roof Type	Flat	Shallow Pitch (10°)	Steeper Pitch (30°)
Ratio	60.5%	27.7%	11.7%
Horizontal Space (million ft ²)	3,592.91	1,645.40	697.38
Rooftop Space (million ft ²)	3,592.91	1,670.79	805.26
Total Rooftop Space (million ft ²)	6,068.96		

Applying the same method, the rooftop space of commercial buildings in Arizona and New Jersey were also calculated (see Table 11).

Table 11. Rooftop Space on Commercial Buildings in Arizona and New Jersey						
State	Arizona			New Jersey		
Total Horizontal Rooftop Space (million ft ²)	802.58			1235.42		
Roof Type	Flat	Shallow Pitch (10°)	Steeper Pitch (30°)	Flat	Shallow Pitch (10°)	Steeper Pitch (30°)
Ratio	55.6%	31.9%	12.5%	70.4%	13.6%	16.0%
Horizontal Space (million ft ²)	445.84	256.03	100.71	869.32	168.36	197.85
Rooftop Space (million ft ²)	445.84	259.98	116.28	869.32	170.96	228.46
Total Rooftop Space (million ft ²)	822.11			1,268.74		

2.2.3. Determining the Technical PV Potential on Commercial Rooftops

In this section, the technical PV potential on commercial rooftops in California, Arizona and New Jersey are estimated based on the previously estimated rooftop space. As introduced in Section 2.1, Access Factors will be applied to all types of roofs considering the influence of roof pitch, orientation, structural soundness and shading on available rooftop space for PV installation. In order to calculate the total PV array area that could be installed on the flat roofs, a factor of GCR should be further taken into account due to the row-to row shading effect of the solar PV systems. Taking California as an exemplar, the total PV array area for all roofs is calculated as below:

Table 12. Feasible PV Array Area in California				
Roof Type	Rooftop Space (million ft ²)	Access Factor (%)	GCR (%)	Feasible PV Array Area (million ft ²)
Flat	3,592.91	60.0%	66.4%	1,431.67
Shallow Pitch (10°)	1,670.79	60.0%	N.A.	1,002.47
Steeper Pitch (30°)	805.26	24.3%	N.A.	195.68
Total PV Array Area (million ft ²)	2,629.82			

378

379 In the table above, as the state of California is located in warm climate zones, the *Access Factor* of
 380 the roofs is assumed at 60%⁸. The Access Factor of 60% is also applicable to Arizona. In case of
 381 New Jersey, which is located in a colder climate, the *Access Factor* is assumed at 65%. Again,
 382 with a 10° tilt angle and assumed SBR of 3, the Ground Coverage Ratio (GCR) was calculated at
 383 66.4% (see Section 2.1) for all states.

384 Applying the same method, the potential PV array area on commercial building rooftops in Arizona
 385 and New Jersey were also estimated. The summarized table is shown below.

386 Table 13. Feasible PV Array Area in Arizona and New Jersey

State	Roof Type	Rooftop Space (million ft ²)	Access Factor (%)	GCR (%)	Feasible PV Array Area (million ft ²)	Total PV Array Area (million ft ²)
Arizona	Flat	445.84	60.0%	66.4%	177.66	361.90
	Shallow Pitch (10°)	259.98	60.0%	N.A.	155.99	
	Steeper Pitch (30°)	116.28	24.3%	N.A.	28.26	
New Jersey	Flat	869.32	65.0%	66.4%	375.26	526.48
	Shallow Pitch (10°)	170.96	65.0%	N.A.	111.12	
	Steeper Pitch (30°)	228.46	17.55%	N.A.	40.09	

387

388 For all scenarios, module efficiency is assumed at 16%, yielding the power density of the PV arrays
 389 under standard test conditions at 160 W/m². Using the Equation 4, technical potential PV potential
 390 for commercial buildings were estimated. The results are presented in Table 14.

391 Table 14. Technical Rooftop PV Potential Calculation for Commercial Buildings

State	Total PV Array Area (million ft ²)	Total PV Array Area (million m ²)	Power Density (W/m ²)	Technical PV Potential (MW)
California	2,629.82	244.31	160	39,090
Arizona	361.90	33.62	160	5,379
New Jersey	526.48	48.91	160	7,826

392

⁸ The parameters used in calculating the Access factor for flat rooftops were adopted from [17, pp. 5-6]. For warmer climates, the structural adequacy factor is 80%, shading factor is 75%, and the orientation factor is 100%. The Access factor can then be calculated by multiplying these three parameters together (80%*75%*100%=60%). For cooler climates, the structural adequacy factor is 100%, the shading is 65%, and the orientation is 100%. The Access factor is then 100%*65%*100%=65%.

3. Technical Rooftop PV Potential in the Residential Buildings

3.1 Methodology

In the residential sector, a different methodology was used to estimate technical PV rooftop potential. To evaluate this potential, a buildings characteristics matrix was developed. Inputs for the matrix were obtained from the most recent published data from the US Energy Information Administration's Residential Energy Consumption Survey (RECS) [15].

In the RECS dataset [15], house space is broken into four distinct sections: attic, basement, garage, and the rest of the house. The purpose of this breakdown is to capture the heating and cooling needs of different types of housing units. In the survey, attics are measured if they are heated or cooled, and garages are measured if they are heated, cooled, or directly attached to the housing units [16].

Applying the classifications used in the survey, housing unit types can be categorized as: single-family detached, single-family attached, apartment buildings of two to four units, and large apartments with more than five units. All housing unit types are assumed to have pitched roofs, except for the large apartments category, which is assumed to have flat roofs and was assessed separately. The housing units also can be classified as having basement, attic or both. In addition, this residential matrix also accounts for the number of floors in each housing unit category⁹.

The RECS survey data [15] also provides total housing unit square footage. In order to calculate building roof space the housing square footage need to be divided by the number of floors including attic and basement in a similar fashion to the commercial buildings sector. Based on the RECS data, a housing characteristics matrix to capture key differences in the housing categories was developed. Housing units can be captured by four characteristics: 1) absence or presence of attic 2) absence or presence of basement 3) type of house and 4) number of floors.

The survey data [15] reveals the percentage shares for each separate characteristic. Assuming these characteristics are independent from each other, the characteristics matrix can be used to build joint probability (JP) values for each of combinations. There are two combinations for attic, two combinations for basement, three combinations for housing type, and three combinations for number of floors yielding 36 combinations in total. Table 15 demonstrates the structure of the residential buildings characteristics matrix. In this matrix, the presence or absence of an attic or a basement is denoted with binary code of 1 or 0, respectively. Excluding large apartments, each type of house could be classified as single family detached (type 1), single family attached (type 2) and apartments in 2 to 4 unit buildings (type 3).

⁹ Due to difficulty of assessing share of garages with separate roof space and their feasibility for solar PV installation, garage roof space was not included in the PV technical potential estimation calculations.

426

Table 15. Residential Buildings Characteristics Matrix

	Attic	Basement	Building Type	# of Floors
1	0	0	1	1
2	0	0	1	2
3	0	0	1	3
4	1	0	1	1
5	1	0	1	2
6	1	0	1	3
.....				
.....				
35	1	1	3	2
36	1	1	3	3

427

428 The total gross roof space of the residential buildings can be calculated from the following
 429 equation:

430
$$Gross\ RoofSpace = N_1 * \sum_{n=1}^{36} JP * \frac{HUS_n}{NF_n + A_n + B_n} + \sum_j^4 N_{2j} * HUS_{Lj} \quad (Equation\ 5)$$

431 Where, N_1 is a total number of single family housing units and small apartments, HUS_n is average
 432 housing unit size; N_{2j} is total number of apartments in large apartment buildings and HUS_{Lj} is
 433 average size of the large apartments with specific floor numbers (e.g., 1-2 floors, or 5-10 floors).
 434 NF_n is number of floors for small units, A_n equals one if attic is present and zero otherwise.
 435 Likewise, B_n equals one if basement is present and zero otherwise. JP is the joint probability
 436 function built based on the selected housing unit's combined characteristics.¹⁰

437 Residential rooftops can be divided into two categories: pitched roofs and flat roofs. It was
 438 assumed that all residential housing units, except large apartments, have pitched roofs, namely
 439 single-family houses and small apartments (with 2-4 units). It was also assumed that the average
 440 tilt angle of tilted roofs was 30 degree (similar to assumptions in [17]). Only for the large
 441 apartments, flat roofs were assumed. The available space for PV installation on these residential
 442 flat roofs can be estimated by the same methodology that was used for commercial rooftops (see
 443 Section 2.1).

444 Calculations for Pitched Roofs

¹⁰ For example, if 40% of surveyed housing units do not have an attic, 60% do not have a basement, 50% of housing units are single family detached houses, and 30% of housing units have only one floor, then the first category of the housing units (i.e., single detached housing units with one floor and no attic and basement) will have joint probability equal to: $JP_1 = 0.4 * 0.6 * 0.5 * 0.3 = 0.036 = 3.6\%$, meaning that only 3.6% of housing stock meets these criteria.

Under the residential gross roof space estimation methodology illustrated above, the results were calculated by assuming flat roof space for all the buildings. For more accurate roof space estimation for tilted roofs, a geometric factor needs to be applied (see Equation 2).

The available area of pitched roofs for PV installation can also be reduced by shading from trees and other obstructions as well as roof orientation [17]. Following the previously cited methodology, the *Access Factor* for residential roofs was estimated at 17.55% in cool climates (New Jersey) and at 24.3% for warm climates (Arizona and California) [17]. In a similar methodology to the commercial building sector, the total area for PV arrays that can be installed on tilted residential rooftops can be calculated by Equation 6:

$$\text{Total PV Array Area (Tilted Residential Roof)} = \text{Gross Horizontal Roof Space} \times \text{Access Factor} \times \text{Geometric Factor}$$

(Equation 6)

Calculations for Flat Roofs

The large apartments, which are classified in the RECS data set as buildings containing more than five family units, can have up to 20 floors and are assumed to have flat roofs. Therefore, in this case, the potential PV array area can be calculated by using the same methodology as was used for commercial buildings (see section 2.1). Equation 7 below illustrates this methodology.

$$\text{Total PV Array Area (Flat Residential Roof)} = \text{Gross Horizontal Roof Space} \times \text{Access Factor} \times \text{Ground Cover Ratio (GCR)}$$

(Equation 7)

After calculating PV array areas for both tilted and flat rooftops, the total residential PV potential can be easily estimated by converting the roof space values from square footage to square meters and multiplying estimated total PV array area in square meters with the assumed solar system power density (W/m^2), which is determined by panel efficiency (here, assumed at 16%). This calculation is demonstrated in the Equation 8 below.

$$\text{Power Density (W/m}^2\text{) under Standard Test Condition} = \frac{1000\text{W/m}^2 \times \text{Panel Efficiency}}{10^6}$$

$$\text{Technical PV Potential (MW)} = \text{Total PV Array Area} \times \text{Power Density} \div 10^6$$

(Equation 8)

Reporting total residential PV potential against total housing units is also a useful metric to help the households and local communities to better understand the PV potential in their state.

3.2 Analysis

3.2.1 Housing Unit Characteristics

478 Distribution of housing unit types for selected three states can also be easily obtained from the
 479 survey data [15]. Table 16 shows the distribution of each housing characteristic across the three
 480 states under analysis.

481 Table 16. Characteristics of Residential Buildings in Three States

	California	Arizona	New Jersey
With Attic			
Yes	17.98%	18.75%	53.85%
No	82.02%	81.25%	46.15%
With Basement			
Yes	6.74%	6.25%	57.69%
No	93.26%	93.75%	46.31%
Housing Type			
Detached	78.89%	93.75%	77.78%
Attached	10.00%	6.25%	7.41%
Appt. 2-4 units	11.11%	0.00%	14.81%
Number of Floors			
1	78.51%	86.96%	53.33%
2	19.83%	13.04%	43.33%
3	1.65%	0.00%	3.33%

482 Data source: [15]

483 By using the percentage values presented in Table 16, distribution of housing types in California
 484 were constructed (see Table 17). Since each category of building characteristics is independent of
 485 the others, the joint probability for each of the 36 combinations can be calculated by multiplying the
 486 independent probabilities together.

487 Table 17. Distribution of Housing Categories in California

	Attic	Basement	Building Type	# of Floors	Attic	Basement	Building Type	# of Floors	Joint Probability
1	0	0	1	1	82.0%	93.3%	78.9%	78.5%	47.4%
2	0	0	1	2	82.0%	93.3%	78.9%	19.8%	12.0%
3	0	0	1	3	82.0%	93.3%	78.9%	1.7%	1.0%
4	1	0	1	1	18.0%	93.3%	78.9%	78.5%	10.4%
5	1	0	1	2	18.0%	93.3%	78.9%	19.8%	2.6%
6	1	0	1	3	18.0%	93.3%	78.9%	1.7%	0.2%
7	0	1	1	1	82.0%	6.7%	78.9%	78.5%	3.4%
8	0	1	1	2	82.0%	6.7%	78.9%	19.8%	0.9%
9	0	1	1	3	82.0%	6.7%	78.9%	1.7%	0.1%
10	0	0	2	1	82.0%	93.3%	10.0%	78.5%	6.0%
11	0	0	2	2	82.0%	93.3%	10.0%	19.8%	1.5%
12	0	0	2	3	82.0%	93.3%	10.0%	1.7%	0.1%
13	1	1	1	1	18.0%	6.7%	78.9%	78.5%	0.8%
14	1	1	1	2	18.0%	6.7%	78.9%	19.8%	0.2%

15	1	1	1	3	18.0%	6.7%	78.9%	1.7%	0.0%
16	0	1	2	1	82.0%	6.7%	10.0%	78.5%	0.4%
17	0	1	2	2	82.0%	6.7%	10.0%	19.8%	0.1%
18	0	1	2	3	82.0%	6.7%	10.0%	1.7%	0.0%
19	1	0	2	1	18.0%	93.3%	10.0%	78.5%	1.3%
20	1	0	2	2	18.0%	93.3%	10.0%	19.8%	0.3%
21	1	0	2	3	18.0%	93.3%	10.0%	1.7%	0.0%
22	1	1	2	1	18.0%	6.7%	10.0%	78.5%	0.1%
23	1	1	2	2	18.0%	6.7%	10.0%	19.8%	0.0%
24	1	1	2	3	18.0%	6.7%	10.0%	1.7%	0.0%
25	0	0	3	1	82.0%	93.3%	11.1%	78.5%	6.7%
26	0	0	3	2	82.0%	93.3%	11.1%	19.8%	1.7%
27	0	0	3	3	82.0%	93.3%	11.1%	1.7%	0.1%
28	0	1	3	1	82.0%	6.7%	11.1%	78.5%	0.5%
29	0	1	3	2	82.0%	6.7%	11.1%	19.8%	0.1%
30	0	1	3	3	82.0%	6.7%	11.1%	1.7%	0.0%
31	1	0	3	1	18.0%	93.3%	11.1%	78.5%	1.5%
32	1	0	3	2	18.0%	93.3%	11.1%	19.8%	0.4%
33	1	0	3	3	18.0%	93.3%	11.1%	1.7%	0.0%
34	1	1	3	1	18.0%	6.7%	11.1%	78.5%	0.1%
35	1	1	3	2	18.0%	6.7%	11.1%	19.8%	0.0%
36	1	1	3	3	18.0%	6.7%	11.1%	1.7%	0.0%

According to Table 17, the distribution of housing units in California favors type 1 homes (47.4%), type 2 homes (12.0%), and type 4 homes (10.4%). Similar calculations were conducted for Arizona and New Jersey, though the tables were omitted for brevity. In Arizona, type 1 homes comprise 62.1% of the housing distribution, type 2 homes comprise 9.3%, and type 4 homes comprise 14.3%. In New Jersey, type 13 homes held the highest share of the distribution (12.9%), type 7 homes held 11.0%, and type 14 homes held 10.5% of the distribution. These distribution data are used in the following section to estimate the total rooftop space of residential buildings in each state.

3.2.2 Rooftop Space Estimation for Residential Buildings

The U.S. Census Bureau reports that the average number of households in California between 2009 and 2013 was 12,542,460 [33]. The RECS data [15] groups California within the West Census Region. California's census data, which is separately reported as a part of the Pacific Census Division, indicates that single family detached, single family attached and apartments in 2 to 4 unit buildings represent about 73.17% of the households in the state, resulting in an estimated 9,177,400 housing units of these types for this analysis.

Before calculating the total rooftop area for residential buildings, it is necessary to calculate the average square footage for each of the different house types in California. The RECS survey reports that the average square footage per residential housing unit in California is 1,583 ft². Unfortunately, a more detailed breakdown by building type at the state level is not available from

this data set, but a West Census Region level breakdown is available. Average size of a housing unit in this region was reported at 1,708 ft² [15], it can be concluded that before using West Census Region data for California, the data need to be adjusted by factor of 0.93. This value is obtained through dividing the average square feet size for all housing types in California by the average square feet size of the housing units in West Census Region. The adjusted factor is used to estimate the average size different housing types. The results of calculating the adjusted average square footage for different house type in California are presented in Table 18 below.

Table 18. Adjusted Average Square Footage for Different House Type in California

	West Census Region Average Home Size (ft ²)	Adjusted Average Home Size (ft ²) in California
Single-Family Detached	2,163	2,005
Single-Family Attached	1,465	1,358
Apartments in 2-4 Unit Buildings	930	862
Apartments More than 5 Units Buildings	811	752
Mobile Homes	995	922
All types of home	1,708	1,583

Similar to California, values for Arizona need to be adjusted given the available data. In Arizona, it was estimated that there were 1,648,900 units that were classified as either single family detached, single family attached, or apartments in 2 to 4 unit buildings. The RECS survey reports an average square footage per housing unit in Arizona at 1,793 ft² [15], which results in an adjustment factor (to align with the West Census region data) of 1.05. The calculated adjusted average square footage results for different house type in Arizona are presented in Table 19 below.

Table 19. Adjusted Average Square Footage for Different House Type in Arizona

	West Census Region Average Home Size (ft ²)	Adjusted Average Home Size (ft ²) in Arizona
Single-Family Detached	2,163	2,277
Single-Family Attached	1,465	1,542
Apartments in 2-4 Unit Buildings	930	979
Apartments (more than 5 units)	811	854
Mobile Homes	995	1,047
All types of home	1,708	1,798

Again, values for New Jersey need to be adjusted similarly, given the available data. In New Jersey, it was estimated that there were 3,186,418 housing units that were classified as single family detached, single family attached and apartments in 2 to 4 unit buildings. The RECS survey reported average square footage per unit at 2,339 ft² which results in an adjustment factor of 1.13.

The calculated adjusted average square footage results for different house type in New Jersey is presented in the Table 20 below.

Table 20. Adjusted Average Square Footage for Different House Type in New Jersey

	Northeast Census Region Average Home Size (ft ²)	Adjusted Average Home Size (ft ²) in New Jersey
Single-Family Detached	2,977	3,367
Single-Family Attached	2,038	2,305
Apartments in 2-4 Unit Buildings	1,191	1,347
Apartments (more than 5 units)	849	960
Mobile Homes	1,030	1,165
All types of home	2,121	2,399

The total number of housing units held within each of the 36 categories can be estimated by multiplying the total number of housing units in the state by the joint probability of each of the 36 categories. This value multiplied by the average roof space of the corresponding category yields total roof space in each category, which can be easily summed to yield the state level total. In order to calculate horizontal roof space, the total number of units of each of the 36 categories needs to be multiplied by the adjusted average square footage (the values found in Table 18, Table 19, and Table 20). The product of this operation will be the total building square footage for each of the selected housing types. After obtaining the total building square footage, the horizontal rooftop for each housing type can be calculated. This can be achieved by dividing the total square footage for each housing type by number of floors.

The results of this operation, shown in Table 21, shows estimated horizontal rooftop for each of the 36 housing type categories. The remaining housing in the state is comprised of large apartment buildings (those with five or more units) and mobile homes. Since it would be difficult to have for net metering and the life of a mobile home could be shorter than the lifetime of the solar panels, it was determined that mobile homes are not suitable for PV, and they were therefore excluded from the residential solar potential estimation in this study.

For California aggregate horizontal roof footage for single family detached, single family attached and apartments in 2 to 4 unit buildings was calculated at 13,105.45 million ft². Similar calculations were conducted for Arizona and New Jersey, yielding 3,031.96 million ft² and 3,590.90 million ft² of gross roof space respectively.

Table 21. Number of House Units and Their Horizontal Roof Space (CA)

	Number of housing units (million)	Average Unit Size (Ft ² per unit)	Calculated Total square footage (million)	Number of Floors	Horizontal Roof Footage (million)
1	4.3481	2005	8,716.552	1	8,716.55

2	1.0985	2005	2,202.076	2	1.101.04
3	0.0915	2005	183.506	3	61.17
4	0.9530	2005	1,910.477	1	955.24
5	0.2408	2005	482.647	2	160.88
6	0.0201	2005	40.221	3	10.06
7	0.3143	2005	630.112	1	315.06
8	0.0794	2005	159.186	2	53.06
9	0.0066	2005	13.266	3	3.32
10	0.5512	1358	748.359	1	748.36
11	0.1392	1358	189.059	2	94.53
12	0.0116	1358	15.755	3	5.25
13	0.0689	2005	138.107	1	46.04
14	0.0174	2005	34.890	2	8.72
15	0.0015	2005	2.908	3	0.58
16	0.0398	1358	54.098	1	27.05
17	0.0101	1358	13.667	2	4.56
18	0.0008	1358	1.139	3	0.28
19	0.1208	1358	164.024	1	82.01
20	0.0305	1358	41.438	2	13.81
21	0.0025	1358	3.453	3	0.86
22	0.0087	1358	11.857	1	3.95
23	0.0022	1358	2.995	2	0.75
24	0.0002	1358	0.250	3	0.05
25	0.6124	862	527.853	1	527.85
26	0.1547	862	133.352	2	66.68
27	0.0129	862	11.113	3	3.70
28	0.0443	862	38.158	1	19.08
29	0.0112	862	9.640	2	3.21
30	0.0009	862	0.803	3	0.20
31	0.1342	862	115.694	1	57.85
32	0.0339	862	29.228	2	9.74
33	0.0028	862	2.436	3	0.61
34	0.0097	862	8.363	1	2.79
35	0.0025	862	2.113	2	0.53
36	0.0002	862	0.176	3	0.04
All	9.1774				13,105.45

554

555 According to the RECS data, 23.58% of housing units in California are large apartments (with more
556 than five units) [15]. As mentioned above, based on U.S. Census Data the total housing units in
557 California were 12,542,460 units [33]. Applying this percentage to the total housing units gives
558 2,957,200 housing units of this type for California. Using a similar methodology, the total numbers
559 of housing units in large apartments were calculated at 412,224 in Arizona and at 497,878 in New
560 Jersey. See Table 22.

561 Table 22. Number of Housing Units in Large Apartments

	Total Number of Housing Units	Share of Large Apartments in Total Units	Number of Housing Units in Large Apartments
California	12,542,460	23.58%	2,957,200
Arizona	2,370,289	17.39%	412,224
New Jersey	3,186,418	15.63%	497,878

562 Data sources: [15, 33, 34, 35]

563 RECS data groups Large Apartments based on number of floors. The total horizontal rooftop area
 564 for each group can be estimated by multiplying the average unit floor space by the number of
 565 apartments in each group, and then dividing the result by the group's average number of floors.
 566 Therefore, for roof top potential estimation it is also important to take into the account the number
 567 of the floors in the apartments these units are housed. Table 23 shows that the distribution of floor
 568 counts in the residential sector is heavily skewed towards apartments with 1-2 floors.

569 Table 23. Distribution of Number of Floors in the Large Apartments

Group	California		Arizona		New Jersey	
1 or 2 Floors	2.0 million	69.0%	0.3 million	75.0%	0.3 million	60.0%
3 or 4 Floors	0.6 million	20.7%	0.1 million	25.0%	0.2 million	40.0%
5 to 10 Floors	0.2 million	6.9%	-	-	-	
11 to 20 Floors	0.1 million	3.4%	-	-	-	
Total	2.9 million	100.0%	0.4 million	100.0%	0.5 million	100.0%

570 Data source: [15]

571 The average square footage of apartment units in each state and floor number group can be used
 572 to estimate horizontal roof space for large apartments using the following equation:

573 *Horizontal Roof Footage for Multi Floor Apartments= number of housing units*proportion of total*
 574 *units in group * average square footage/average number of floors* (Equation 9)

575

576 The results of these calculations are presented in Table 24 below.

577 Table 24. Total Horizontal Roof Footage of Large Apartments

	California (Million ft ²)	Arizona (Million ft ²)	New Jersey (Million ft ²)
1 or 2 Floors	1,022.44	176.02	191.19
3 or 4 Floors	131.46	25.15	54.62
5 to 10 Floors	20.45	0.00	0.00
11 to 20 Floors	4.95	0.00	0.00
Total	1,179.30	201.17	245.81

578

579 3.2.3 Determining the Technical PV Potential on Residential Rooftops

In a similar fashion to the technical potential estimation in the commercial sector performed above, the residential sector estimates for technical rooftop PV potential must be adjusted for building obstructions, vegetation shading and other constraints [18]. As mentioned in Section 2.1, California and Arizona are located in the warm climate zone, therefore like in case of commercial buildings, the *Access Factor* was assumed at 60%. In New Jersey, which is located in a colder climate zone, the *Access Factor* was assumed at 65% [17]. For large apartments, the GCR was calculated at 66.4% for 10° tilt installations in the same manner as was calculated in the commercial buildings sector.

Following the methodology of Paidipati, et al [17], for single-family detached, single-family attached and apartments with 2 to 4 units, the *Access Factors* of 24.3% (for Arizona and California) and 17.55% (for New Jersey) were used (see Sections 2.1 and 3.1 for details). The total horizontal rooftop spaces for these categories were estimated using equation 6 described in section 3.1. For large apartments equation 7 was used. Calculation results are reported in Table 25.

Similar to the estimation methodology for commercial rooftop potential conducted above, which assumed module efficiency at 16%, technical rooftop potential in the residential sector of California was estimated to total 61.67GW, representing average solar potential per household to be 4.91kW. In Arizona, estimated total technical rooftop potential in the residential sector totals 13.83GW, representing 5.83kW per household. In New Jersey, the estimated total residential potential was 12.38GW, representing 3.89kW per household. See Table 25 below.

Table 25. Residential Technical PV Potential

	Horizontal Rooftop Space (million ft ²)	PV Array Area (million ft ²)	PV Array Area (million m ²)	Technical PV Potential (GW)
California				
Single-Family Detached, Attached & 2-4 Unit Apts.	13,105.45	3,677.29	341.63	54.66
Large Apartments	1,179.30	467.00	43.39	6.94
Total	14,284.75	4,144.29	385.02	61.60
Arizona				
Single-Family Detached, Attached & 2-4 Unit Apts.	3,031.96	850.74	79.04	12.65
Large Apartments	201.17	79.66	7.40	1.18
Total	3,233.13	930.41	86.44	13.83
New Jersey				
Single-Family Detached, Attached & 2-4 Unit Apts.	3,590.90	727.70	67.61	10.82
Large Apartments	245.81	105.45	9.8	1.57
Total	3,836.71	833.15	77.40	12.38

4. Potential Electricity Generation from Rooftop PV

An important question regarding state-level technical potential estimates for distributed renewable energy revolves around comparison with the current electricity consumption in these states. Using EIA annual electric power report data [36] and estimate of PV capacity factors across each of these states, potential electricity generation from distributed PV in each of these states can be calculated. Because solar resources and population in these states are not evenly distributed, capacity factors were estimated using PV Planner® software¹¹ with the base assumptions for the PV arrays detailed above. PV Planner® uses Typical Meteorological Year (TMY) data published by NREL.¹² Capacity factors were calculated for most populous counties in each of the states, which accounts for over 70% of the population of the target states. Population distributions for each state are presented in Figure 7.

Figure 6. Population Distribution in California, Arizona and New Jersey

Assuming that the number of buildings is positively correlated with the population, weighted average capacity factors adjusted by country level population distribution were calculated for different types of solar PV systems categorized by roof tilts. The calculation results for California are presented in Table 26.

¹¹ PV Planner® software was developed at the Center for Energy and Environmental Policy at the University of Delaware [41].

¹² The TMY data set provides hourly meteorological values that represent typical weather conditions at a specific location for one year. The hourly profiles are built based on a longer period of meteorological observations (typically 30 years). The most up-to-date version of the data set is denoted as TMY 3 [40].

616

Table 26. Capacity Factor Calculation for California

County	Population Ratio	TMY number	Capacity Factor (flat roof) ¹³	Capacity Factor (shallow pitch) ¹⁴	Capacity Factor (steeper pitch) ¹⁵
Los Angeles County	26.4%	722880	17.88%	16.63%	18.60%
San Diego County	8.3%	722930	17.87%	16.66%	18.55%
Orange County	8.1%	722977	17.64%	16.38%	18.43%
Riverside County	5.9%	747187	18.93%	17.49%	19.87%
San Bernardino County	5.5%	23161	19.30%	17.80%	20.31%
Santa Clara County	4.8%	724945	17.44%	16.20%	18.20%
Alameda County	4.1%	724927	17.49%	16.25%	18.23%
Sacramento County	3.8%	724830	17.02%	15.85%	17.63%
Contra Costa County	2.8%	724936	14.01%	12.94%	14.80%
Fresno County	2.5%	93193	17.49%	16.32%	18.11%
Total	72.1%	Weighted Average	17.78%	16.52%	18.54%

617

618 These weighted average capacity factors were used to calculate the electricity generation from the
619 estimated rooftop PV potential. The detailed calculation results for potential rooftop PV electricity
620 generation in California are presented in Table 27. The feasible PV array areas for commercial and
621 residential buildings were reported in Table 12 and Table 25, respectively. After converting ft²
622 values to m² and assuming module efficiency of 16% (see Section 2.1), total technical potential
623 was calculated (see Equations 4 and 8). The weighted capacity factors reported in Table 26 were
624 then applied to different building categories. Specific tilt angle and array orientation assumptions
625 are detailed in the footnotes. Based on Equations 4 and 8, California's total technical potential was
626 estimated at 100.7 GW and potential annual PV generation was estimated at 159,046.70 GWh.
627 See Table 27.

628

629

Table 27. Potential PV Generation Calculation for California

	Feasible PV Array Area (million ft ²)	Feasible PV Array Area (million m ²)	Technical PV Potential (GW)	Weighted Average Capacity Factor	Potential PV Generation (GWh)
Commercial Sector					

¹³ For flat roofs, multi-row PV systems are installed and the tilt is assumed to 10° facing South.

¹⁴ The average tilt of shallow pitch roofs is assumed to be 10°. Capacity factor under this case is estimated by taking an average of capacity factors at 10° at all orientations, namely South, East, North and West.

¹⁵ The tilt of PV systems installed on steeper pitched roofs is assumed to be 30° facing South.

Flat (10°)	1,431.67	133.00	21.28	17.78%	33,151.63
Shallow Pitch (10°)	1,002.47	93.13	14.90	16.52%	21,561.55
Steeper Pitch (30°)	195.68	18.18	2.91	18.54%	4,724.84
Total Commercial	2,629.82	244.31	39.09		59,438.02
Residential Sector					
Single-Family Detached, Attached & 2-4 Unit Apts. (30°)	3,677.29	341.63	54.66	18.54%	88,794.48
Large Apartments (10°)	467.00	43.39	6.94	17.78%	10,814.19
Total Residential	4,144.29	385.02	61.60		99,608.68
Total					
Total	6,774.11	629.33	100.70		159,046.70

630

631 This methodology was duplicated for Arizona and New Jersey below, and the results for all three
632 states were compared with total annual electricity consumption¹⁶ (obtained from EIA [36]) in these
633 states. The results in Table 28 show that rooftop PV can meet significant portion of electricity
634 demand in the selected states.

635 Table 28. The Result Table for PV Potential and the Ratio to Total Annual Electricity Consumption

State	PV Capacity (GW)			Potential PV Generation (GWh)	Total State Electricity Consumption (GWh)	Ratio of PV Generation to Total Electricity Consumption
	Comm.	Res.	Total			
California	39.10	61.60	100.70	159,046.70	261,524.91	60.82%
Arizona	5.38	13.83	19.21	32,301.01	75,668.22	42.69%
New Jersey	7.83	12.38	20.21	26,363.76	74,642.40	35.32%

636

637 These ratios show that, even in the leading states, there is significant space for future PV growth.
638 In 2013, California, Arizona, and New Jersey had 2.5, 1.0 and 0.6 GW of distributed PV installed
639 capacity respectively [1]. These results indicate that theoretically California can increase its
640 distributed PV installations by 40 times from the 2013 level. Similarly, Arizona and New Jersey can
641 increase their distributed PV installations by 30 and 20 times respectively.

642 5. Conclusions

643 Despite the fact that the U.S. PV market has seen 50% year-over-year growth since 2010, PV still
644 provides less than 1% of the U.S.'s electricity needs [37]. The results presented above for the three
645 target states in this analysis indicate that vast rooftop technical potential exists for these states for

¹⁶ Total electricity consumption includes residential, commercial, industrial, and transportation sectors.

future PV growth. These states can increase their current PV capacity 20 to 40 times, and PV theoretically can provide 35.3% to 60.8% of total state electricity demand. The difference in PV generation potential can be explained by solar resources (higher in Arizona and California) as well as building characteristics and distribution. For example, in California and Arizona one-floor single-family detached housing units without attic and basement, predominate the housing types. This type of housing units, due to their design (e.g., compared to two or more floor houses) have large roof areas, thus providing higher space for PV installations. In New Jersey housing units are more evenly spread. Therefore, New Jersey's comparatively lower solar potential can be explained not only by the state's lower solar resource base but also by the housing characteristics.

The analysis results also revealed that for all reviewed states the residential sector has a predominant share of the total technical rooftop potential (from 61.2% to 72.0% in the target states), which has significant energy policy implications for promoting small-scale rooftop energy systems. Though the benefits of distributed generation are many, large-scale penetration of distributed PV systems will pose a problem for grid operators due to their intermittency and the maintenance costs of the grid as they exist today. However, these technical challenges can be address through innovative smart grid technologies, including customer sited electric storage [38].

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