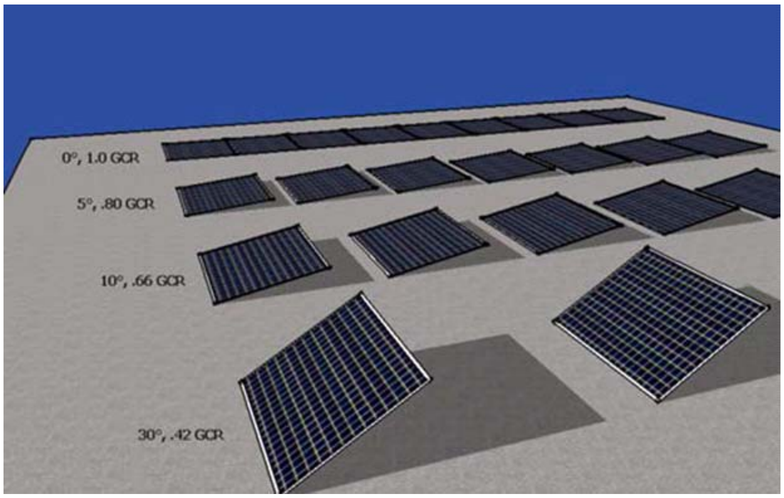
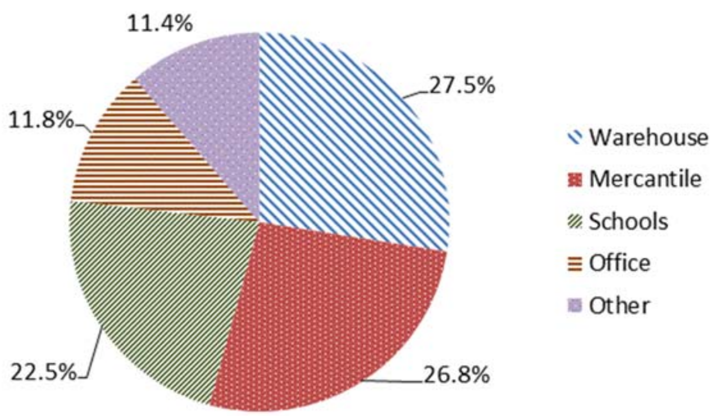
Estimating the Technical Rooftop PV Potential in the State of Delaware





The Energy and Environmental Policy Analysis (EEPA) Program

Center for Energy and Environmental Policy

University of Delaware

March 2016

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March 2016

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Preface

It is a pleasure to provide the Delaware General Assembly and the citizens of Delaware with this report. As part of the Energy and Environmental Policy Analysis (EEPA) Program, this report applies the efforts at the Center for Energy and Environmental Policy (CEEP) to construct a 'bottom-up' photovoltaics technologies diffusion model to the state of Delaware. The purpose of the model is to analyze the future market penetration of solar PV technologies in Delaware under a variety of policy scenarios for different market segments (at the residential, commercial, and utility scale). The model will help policy makers to identify pathways for fostering self-sustained PV markets with the gradual phase-out of economic incentives, and investigate new technologies and strategies to integrate large amounts of PV in flexible, efficient and smart grids as PV matures into mainstream technology.

In the previous report, we provided an overview of the different components of the bottom-up PV diffusion model. In this report, results of estimating the technical rooftop PV potential in the state of Delaware are presented. The technical potential represents the theoretical maximum amount of PV that can be deployed on residential and commercial buildings. Findings from this report will be used for building future market penetration scenarios of solar PV technologies in Delaware. The Center for Energy and Environmental Policy (CEEP) is solely responsible for the findings and recommendations in this report.

We hope this report and the model under development will be helpful to Delaware in building a more sustainable energy future.

Executive Summary

In the past ten years, solar Photovoltaic (PV) deployment has experienced significant growth. In the U.S., by end of 2013, cumulative PV capacity surpassed 12 GW. This was significant increase, from 2005, when cumulative capacity was less than half GW. Similar trend was followed by Delaware, where cumulative capacity at the end of 2013 stood at 63 MW. On per capita bases with 68 Watt per person installed, Delaware was ranked eighth in the nation.

Until recently, residential and commercial PV installations were dominating PV markets. However, utility scale PV (i.e., installations with more than 1 MW) experienced steady growth and reached 46% of total installed capacity in 2013. Similar trend was observed in Delaware where utility scale PV represented 49% of the cumulative installed capacity. Several factors led to the increasing share of utility scale PV with respect to overall PV deployment, including the Department of Energy's Federal Loan Guarantee program, innovations in project financing that attracted more private equity, and declining initial capital costs.

Due to current policy environment, the utility scale PV systems gained dominant share in new PV installations. However, distributed residential and commercial PV systems have distinct advantages over utility scale systems. Distributed PV generation operate at retail level where electricity rates are higher than at bulk power supply. Once federal Investment Tax Credit (ITC) reverts from current 30% to 10%, revenue from electricity sales will have higher weight in the total project cash flow. Therefore, PV systems selling power at retail rate will have noticeable advantage over utility scale systems, which are selling at lower wholesale rates.

Distributed generation may provide additional benefits such as decreasing peak loads, enhancing system reliability, reducing transmission and distribution losses, stabilizing and lowering retail electricity prices, and reducing uncertainty accompanying bulk power generation. More importantly, distributed PV systems make full use of local resources, i.e. roofs and other vacant spaces and save land that might otherwise be used for utility-scale energy generation for other commercial uses or environmental protection. Distributed PV also avoids the tedious siting procedures applied to utility scale PV programs, and also enhances local energy security.

Delaware's PV deployment increased significant in the past decade. Yet, even with the former success, there is still a vast potential for PV market growth in the state. Important question in this regard is:

- How much of electricity can be provided from the distributed PV hosted on residential and commercial roofs in Delaware?

In order to answer this question, assessment of technical PV potential for the state was conducted. Technical potential represents the theoretical maximum amount of PV capacity that could be deployed from an engineering perspective, and does not take into account cost, regulatory constraints, or end user participation. The methodology presented here is a step-by-step technical potential estimation process developed at the Center for Energy & Environmental Policy (CEEP). Because no national or state-level database exists containing residential or commercial rooftop space, an essential input in calculating technical potential, this methodology was developed to extrapolate residential and commercial roof space from building characteristics that align with a recent Energy Information Administration (EIA) survey effort.

For the commercial building sector, the CEEP team obtained and analyzed the commercial buildings statistics from the U.S. Energy Information Administration's 2012 Commercial Building Energy Consumption Survey (CBECS), which was released in 2015. This data was used to estimate the number and total floor space of different categories of buildings in Delaware. The commercial buildings were divided into 15 categories by principle activity functions. Total rooftop space for each category was extrapolated through regional building portfolios and averaged building characteristics. These categories were created based on commercial buildings representation developed by U.S. Department of Energy (U.S. DOE) and its three leading national laboratories: (National Renewable Energy Laboratory, Pacific Northwest National Laboratory and Lawrence Berkeley National Laboratory).

Table ES1 provides summary results for the commercial PV rooftop potential for Delaware. Based on this estimation, 1,063 MW of PV can be deployed in the state. The nominal capacity of rooftop PV system was determined by applying assumed PV module efficiency value at 16%. Most of the commercial building rooftops for PV installation can be provided by mercantile buildings, schools, warehouses and offices.

Table ES1. Technical PV Potential for Commercial Rooftops in Delaware

	Principal Building Activity	Total PV Array Area (m^2)	Technical PV Potential (MW)	Share of PV Potential (%)
1	Primary Schools	1,152,460	184	17.35%
2	Secondary Schools	343,688	55	5.17%
3	Supermarket	121,792	19	1.83%
4	Quick-service restaurant	84,376	14	1.27%
5	Full-service restaurant	172,164	28	2.59%
6	Hospital	52,474	8	0.79%
7	Outpatient Health Care	166,492	27	2.51%
8	Small Hotel	81,746	13	1.23%
9	Large Hotel	76,904	12	1.16%
10	Stand-alone retail	681,517	109	10.26%
11	Strip mall	1,097,424	176	16.52%
12	Small Office	391,869	63	5.90%
13	Medium Office	339,507	54	5.11%
14	Large Office	54,304	9	0.82%
15	Warehouse	1,826,880	292	27.50%
Total		**6,643,599**	**1,063**	**100%**

For residential buildings, data was obtained from the EIA's Residential Energy Consumption Survey (RECS) of 2009 (released in 2013). The roof space was estimated separately for single-family homes, small apartments and multi-floor apartments. Specifically, CEEP researchers classified the single-family houses and small apartments by their architecture design, for instance by presence of attic, garage and basement. Based on the properties of different categories of residential houses and building portfolios in Delaware, the available roof space for residential buildings was estimated.

For area-constrained rooftops, the factors that limit the installation of PV panels were evaluated in the technical potential estimation, including tilt angle, building orientation, structural obstacles, and panel shading. After the total available panel area was calculated, the nominal capacity of rooftop PV system was estimated assuming 16% for PV module efficiency. The technical rooftop potential in the residential sector of Delaware was estimated to be 888 MW, representing an average per household solar potential of 2.65kW. The results of the residential sector analysis are presented in Table ES2.

Table ES2. Residential Technical PV Potential for Delaware

	Total Housing Space (million ft²)	Total Horizontal Rooftop Space (million ft²)	Total Horizontal Rooftop Space (million m²)	Rooftop Potential, MW
Single-Family detached, attached and apartment buildings with 2 to 4 units	586	260.2	24.2	784
Apartment buildings with more than 5 units	63	16.3	1.5	104
Total	**649**	**276.5**	**25.7**	**888**

In total, technical rooftop potential in Delaware is estimated at 1,948 MW, slightly biased towards the commercial sector. This value represents a 30-fold increase in current cumulative installed rooftop capacity in the state, and could satisfy 22.02% of Delaware's electricity demand[1]. Electricity generation from PV depends on installed capacity, solar radiation, tilt angle and the energy conversion efficiency of the PV system components. Using PV Planner©, a software program developed at CEEP for estimating output from PV systems based on design parameters, geography, and Typical Meteorological Year (TMY) weather data, annual electricity generation from the estimated technical rooftop potential was also calculated. Based on the local solar radiation and assumed tilt angles this capacity can generate 2,462.03 million kWh per year.

Table ES3. The Result Table for PV Potential and the Ratio to Total Annual Electricity Consumption

State	PV Capacity (MW)			Potential PV Generation (GWh)	Total State Electricity Consumption (GWh)	Ratio of PV Generation to Total Electricity Consumption
	Comm.	Res.	Total			
Delaware	1,060	888	1,948	2,462.03	11,179	22.02%

[1] The annual electricity consumption for Delaware was 11,179 GWh in 2014 (EIA, 2015b)

1. Introduction

As the landscape of the distributed electricity generation market has continued to swell, state and federal level policies have been at the center of facilitating rapid adoption of photovoltaic (PV) technologies. Led by the 30% federal Investment Tax Credit (ITC), federal and state level incentive policies for renewable energy have been impacting the distributed generation landscape since the ITC's introduction in 1978 at 15% under the Energy Tax Act. In 1986, ITC was reduced to 10%, and remained at that level until President Bush signed the Energy Policy Act of 2005 (EPAct 2005), which increased the ITC to 30%. President Obama extended the ITC through 2016 in 2008 and to 2021 in 2016, and also removed the previous cap for residential installations (USD $2,000) (Byrne and Kurdgelashvili, 2011; DSIRE, 2016).

Historically, states and electric utilities had supported PV deployment through capital rebate programs. In recent years however, support has begun to shift towards production-based incentives (Byrne and Kurdgelashvili, 2011; IREC 2014). Additionally, 29 states and Washington D.C. have Renewable Portfolio Standard (RPS) mandating load serving entities (LSEs) to provide a certain portion of electricity from renewable energy sources, and eight more states have renewable energy goals (Wiser et al., 2016). 21 of these states and Washington D.C. have solar or distributed generation (DG) "carve-out" provisions in their RPS scheme (DSIRE, 2015). RPS requirements are typically met through Renewable Energy Certificates/Credits (RECs)[2].

Federal and state renewable energy policies led to rapid growth of PV installations in the U.S. These policies resulted in more than 50% annual cumulative capacity growth during 2005 -2013 period (IREC, 2014). By the end of 2013, cumulative PV capacity in the U.S. was more than 12 GW (IREC, 2014). The national trend was followed by Delaware, where PV capacity reached 63 MW by the end of 2013 and landed Delaware in the top 10 states of installed capacity on a per capita basis (See Table 1) (IREC, 2014). In 2013, on a per capita basis with 68 Watt per person, Delaware ranked number eight in terms of PV installations in the nation (See Table 1). Compared with national average value of 38 Watts per person, Delaware had 80% more capacity per capita. Consequently, Delaware is one of the leading states in terms of PV deployment.

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

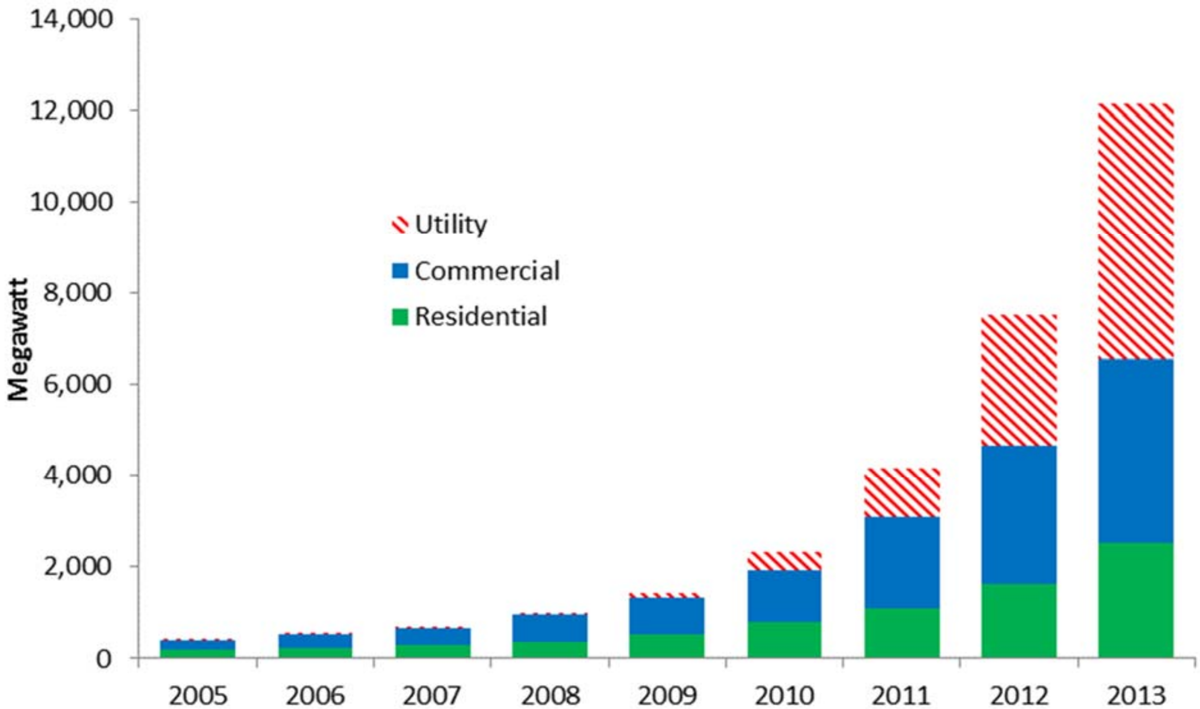

Figure 1. Cumulative PV Installation in the U.S. 2005-2013

Data Source: IREC, 2009-2014 reports

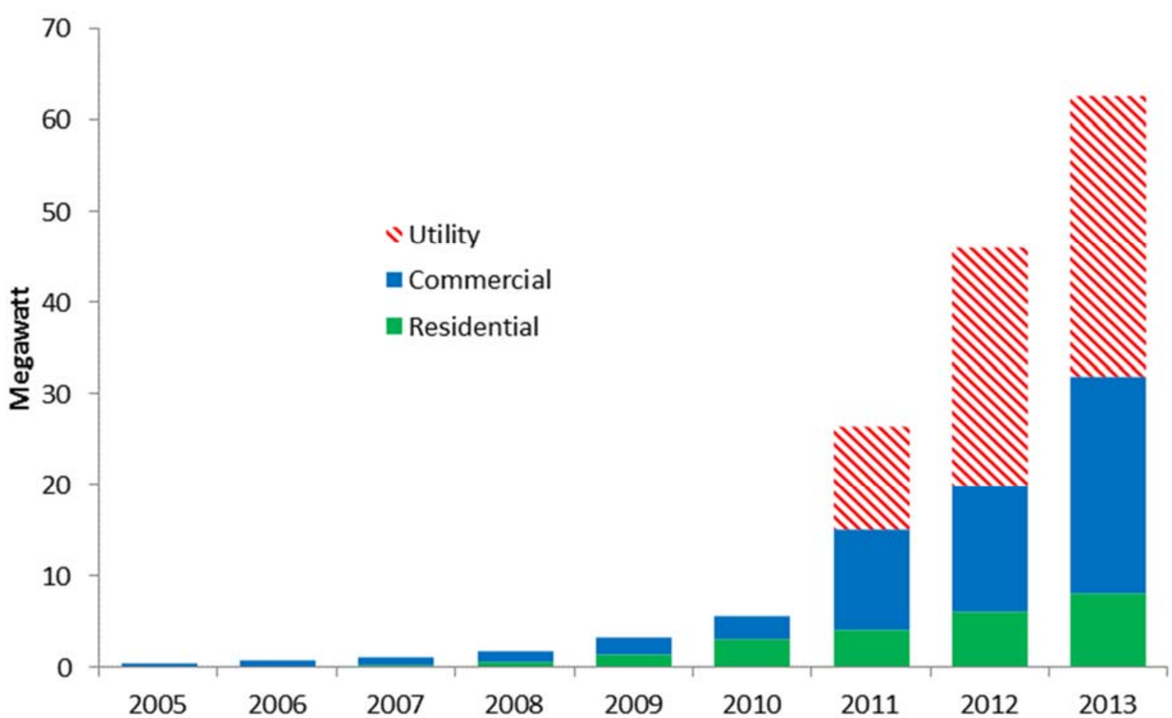

Figure 2. Cumulative PV Installation in Delaware 2005-2013

Data Source: IREC, 2009-2014 reports

Table 1. Leading Ten States with Cumulative PV Installation on per Capita Basis

		Cumulative PV Installation Per person by 2013 (Watt/person)	PV Installations in 2013 (Watt/person)	Cumulative PV Capacity by 2013 (MW)
1	Hawaii	255.1	108.9	358.2
2	Arizona	235.9	63.9	1,563.1
3	Nevada	152.0	16.8	424.0
4	California	135.2	68.0	5,183.4
5	New Jersey	133.1	22.7	1,184.6
6	New Mexico	123.1	23.5	256.6
7	Colorado	68.4	11.0	360.4
8	**Delaware**	**67.8**	**18.0**	**62.8**
9	Massachusetts	66.5	33.3	445
10	Vermont	66.2	21.6	41.5
	U.S.	**37.9**	**14.4**	**12,120.1**

Data source: IREC, 2014

In recent years, utility-scale PV installations (capacity greater than 1 MW) have been the dominant category in both the U.S. and Delaware markets, capturing 46% of the total cumulative installed capacity in 2013 (see Figure 1). Similarly, utility-scale PV represented 49% of the cumulative installed capacity in the same year (see Figure 2). This significant increase in utility-scale PV installed capacity is due to the benefits load-serving entities (LSEs) stand to gain by meeting their RPS obligations through developing their own PV projects and reaping the SREC sale revenues and the tax benefits from the ITC (IREC, 2014). Utility-scale PV projects also have lower initial unit costs, which can manifest themselves in lower costs for LSEs to meet their RPS obligations, either through direct ownership or by proxy through SREC buys.

Additionally, renewable incentive policies in the U.S. largely favor utility-scale plants. Notably, the Department of Energy's Federal Loan Guarantee program supports large-scale solar PV utilities by issuing federal loan guarantees to back new PV projects from developers without an extensive commercial operation history (U.S. DOE, 2015). According to the Loan Program Office (LPO), the program provided more than $4.6 billion in loan guarantees to support construction of the first five utility-scale PV solar facilities larger than 100 MW in the United States in 2011 (U.S. DOE, 2015). Due to the long-term power purchase agreements (PPA) used in utility-scale, the program also spawned the creation of many new project financing structures, such as the single owner structure, all-equity partnership flip structure, leveraged partnership flip structure, and sale-leaseback structure, which play critical roles in lowering uncertainties and distributing profits among investors and therefore further promoting the development of the photovoltaic (PV) utility-scale projects (Feldman and Lowder, 2014).

With the support from current policy environment, the utility scale PV systems gained dominant share in new PV installations. However, distributed residential and commercial PV systems have distinct advantages over utility scale systems. Distributed PV generation operate at retail level where electricity rates are higher than at bulk power supply. Once ITC reverts to 10% and SREC prices will be reduced, revenue from electricity sales will have higher share in the total project cash flow. Thus, PV systems selling power at retail rate will have noticeable advantage over utility scale systems, which are selling generated power at lower, wholesale rates.

Distributed generation can provide additional benefits such as peak load shaving, system reliability enhancements, avoid transmission and distribution losses, stabilizing and lowering retail electricity prices, and reducing uncertainty accompanying bulk power generation (Byrne et al., 2005). More importantly, distributed PV systems make full use of local resources, i.e. roofs and other vacant local spaces. Distributed PV development also avoids costly siting procedures, and enhances local energy security, and economies.

Some of the advantages of utility scale PV are also disappearing. Third party ownership (TPO) of customer-sited PV systems through PPAs and leases has become increasingly common for PV systems of all sizes, as 67% of all PV systems installed in 2013 fall under this ownership structure, including 68% of residential PV systems and 61% of PV systems hosted by for-profit commercial customers (Barbose et al., 2014). As residential and small commercial markets continue to open up with additional state-level incentives, favorable net metering decisions, and utility cooperation, it is a likely expectation that distributed solar will continue its steady growth. It is therefore important to estimate how much electricity can be provided from distributed PV hosted on residential and commercial roofs in Delaware.

In order to estimate how much electricity can be produced from rooftop PV, CEEP conducted a technical PV potential assessment for the state. Technical potential represents the theoretical maximum amount of PV that can be deployed on the rooftops of residential and commercial buildings, taking into account only the engineering potential of the specific technology such as module efficiency and rooftop area and disregarding all non-engineering constraints such as economic costs, regulatory constraints, and end user participation rates. Rooftop PV potential studies can be grouped into the constant-value methodology or Geographic Information Systems (GIS) based methodology.

The constant-value methodology uses existing building characteristics data on floorspace area, number of floors, and the total number of buildings. The data is combined with various rule-of-thumb assumptions such as rooftop orientations and tilt angle, shading and building obstructions to estimate the total roof space available for PV deployment. 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 (Schallenberg-Rodrıguez 2013; Byrne, et al. 2015; Melius, et al. 2013; Wiginton, et al. 2010).

The GIS-based methodology relies on GIS software to determine the suitable area for rooftop solar installation (Melius, et al. 2013). This methodology is commonly used for small-scale regions such as a city or a county (Wiginton, et al. 2010; Izquierdo, et al. 2008; Bergamasco and Asinari 2011; Ko, et al. 2015). Because this methodology is highly time and resource-intensive, it is rarely if ever used to the scale necessary to estimate technical potential at a country or a state level (Schallenberg-Rodrıguez 2013). In addition, Wiginton et al. (2010) reported that the GIS data can be inconsistent and less reliable across larger regions such as a state or a country.

Using GIS for rooftop PV technical potential analysis at the state level, would have required significant data and computational resources. Therefore, at this scale conducting PV potential studies using GIS data for state of Delaware was deemed not feasible. To estimate the state rooftop PV potential this research followed the constant-value methodology. Even though the proposed methodology in this research is less complex, it is faster to conduct, and can generate relatively accurate estimation of technical PV potential for large geographical areas.

In chapter two, we present a detailed description of the applied methodology and findings for commercial buildings in Delaware. In Chapter 3, the methodology used for residential building potential estimation and relevant findings are presented. In Chapter 4, the research results for both sectors are summarized and evaluated against electricity consumption in Delaware. The last chapter concludes the report.

2. Estimation of Technical Rooftop PV Potential in Commercial Sector

2.1 Methodology

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

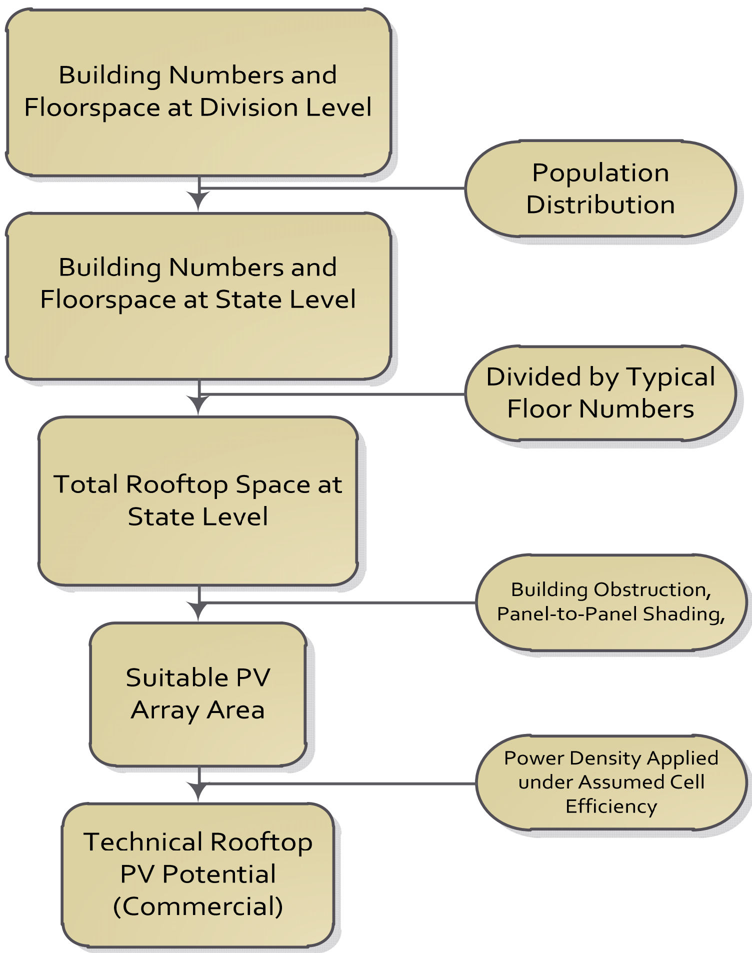

Figure 3. Methodology for Estimation of Technical Rooftop PV Potential in Commercial Sector

In the first step, data on number of units and the total floor area (million ft^2) for different commercial building categories were obtained from Energy Information Administration's (EIA) Commercial Buildings Energy Consumption Survey (CBECS) (EIA, 2015a). The building categories were divided by principle building activities or building sizes. In the EIA's CBECS database, the information on commercial buildings was collected from four regions consisting with nine divisions across the United States (including Hawaii and Alaska). They are shown in Figure 4. At this stage, the most accurate data on building numbers and total floor space could be obtained at the division level.

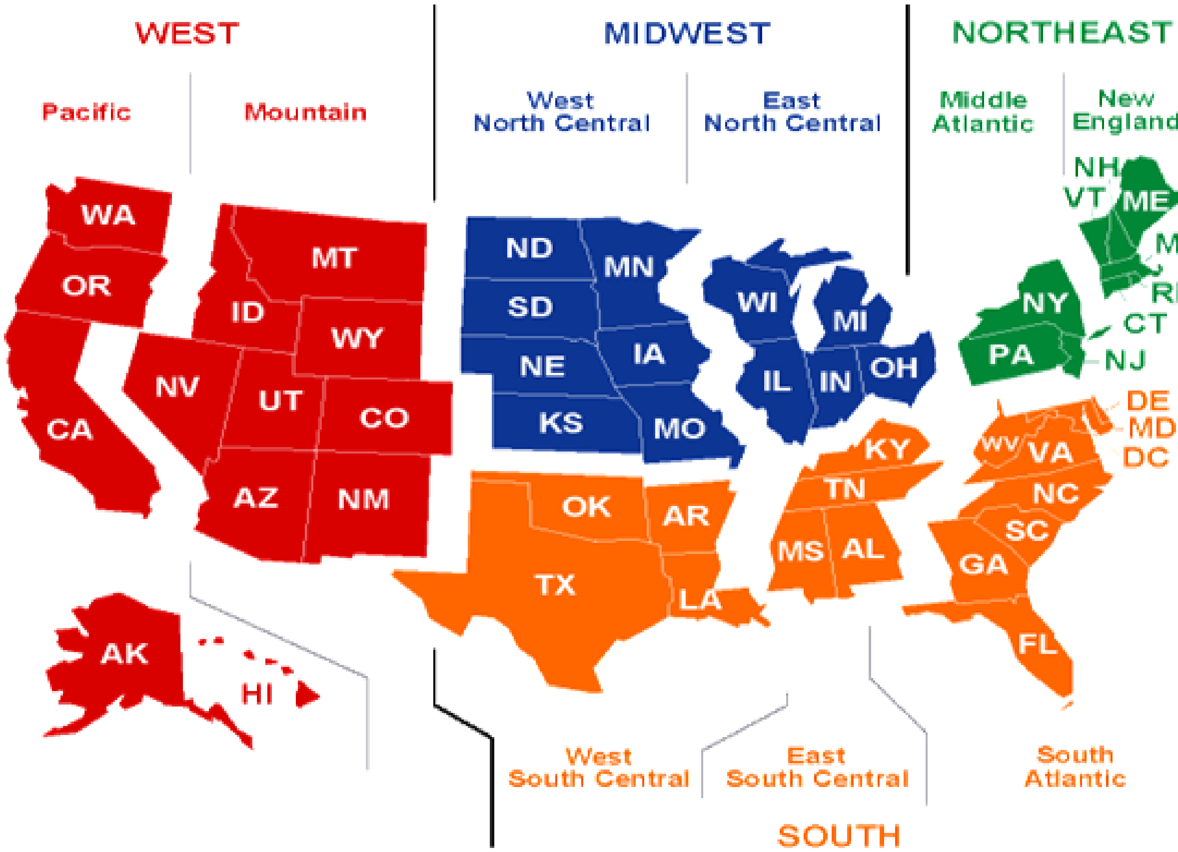

Figure 4. U.S. Census Regions and Divisions

Sources: EIA, 2015b

In the original CBECS datasets, some of the cells were denoted with letter ‘Q’, which means the data was withheld. As explained by EIA, the reason of doing so was that the Relative Standard Error (RSE) for those data was greater than 50 percent, or fewer than 20 buildings were sampled. In order to better analyze the roof space of buildings corresponding to those blanked data, the missing values were extrapolated from the available data (EIA, 2015a).

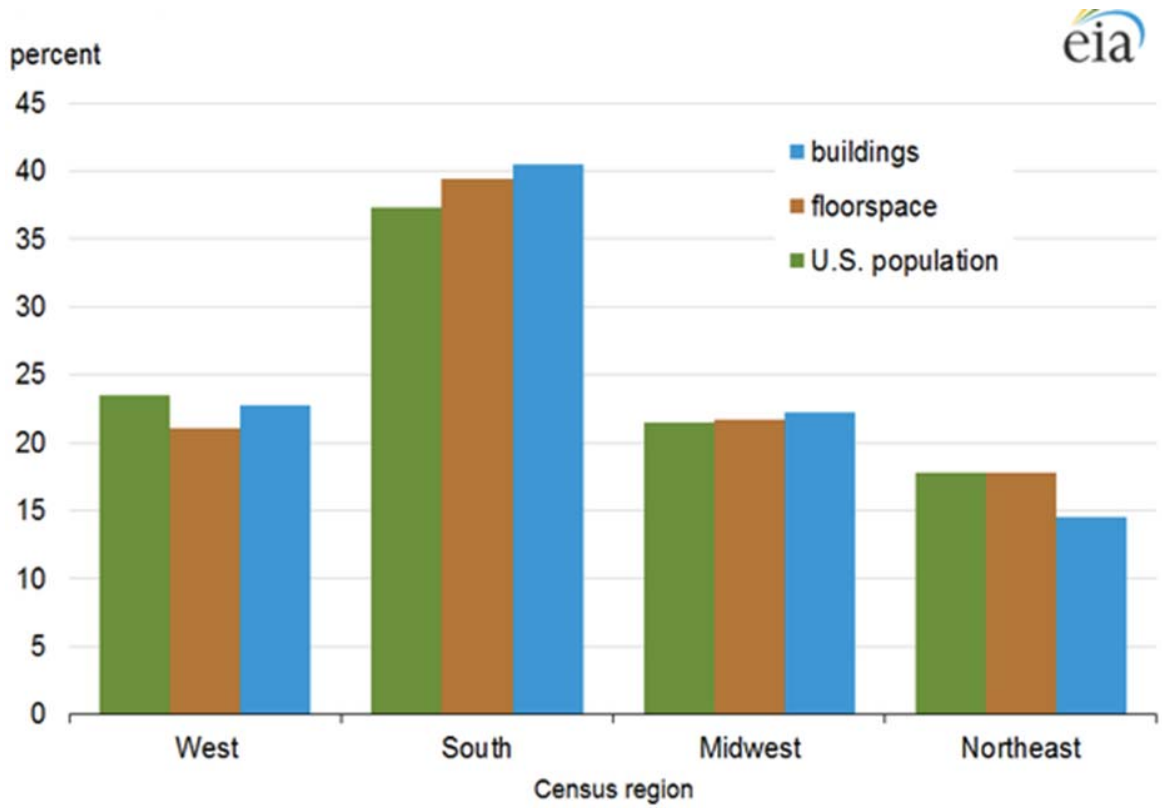

Figure 5. Number of Building, Floor space, and Population in Each Census Region

Sources: EIA, 2015a

In the second step, building numbers and floor space at the state level were estimated with the assumption that the number of commercial buildings and floor space in the state was correlated with the population. Figure 5 shows that the regions with larger population tend to have more commercial buildings and hence floor space, from which the assumed relationship can be justified. The population data for different states were collected from U.S. Census Bureau (2015). The population values for the South Atlantic division combined with the building characteristics at the division level were used to project the building information for the state of Delaware.

The next step involved converting estimated floor space for different categories of commercial buildings into the roof area. To achieve this task, CEEP team used commercial buildings representation developed by U.S. Department of Energy (U.S. DOE) and its three leading national laboratories (National Renewable Energy Laboratory, Pacific Northwest National Laboratory and Lawrence Berkeley National Laboratory). As shown in Table 2, U.S. DOE developed 16 reference building types that represent most commercial buildings across all U.S. climate zones. Each building type was reported with total building floor space and average number of floors (U.S. DOE, 2014).

Table 2. U.S. DOE Commercial Buildings Reference Table

Building Type Name	Floor Area (ft^2)	Number of Floors
Large Office	498,588	12
Medium Office	53,628	3
Small Office	5,500	1
Warehouse	52,045	1
Stand-alone Retail	24,962	1
Strip Mall	22,500	1
Primary School	73,960	1
Secondary School	210,887	2
Supermarket	45,000	1
Quick Service Restaurant	2,500	1
Full Service Restaurant	5,500	1
Hospital	241,351	5
Outpatient Health Care	40,946	3
Small Hotel	43,200	4
Large Hotel	122,120	6
Midrise Apartment	33,740	4

Sources: U.S. DOE, 2014

By referring to Table 1 and matching the building types of U.S. DOE with corresponding values obtained from the EIA's CBECS (2015a) data, the estimated ground floor area (representing roof area) for different building categories were calculated by dividing the total floor area by the average number of floors. The resulting matching table between U.S. DOE's and EIA's commercial building category systems is shown in Table 3.

Table 3. Category Matching Table

EIA Category System	U.S. DOE Category System		
Building Type Names		Floor Area (ft^2)	Number 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 Impatient	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 and Strip Malls	Strip Mall	22,500	1
Office	Large Office	498,588	12
	Medium Office	53,628	3
	Small Office	5,500	1
Warehouse and Storage	Warehouse	52,045	1

Compared with EIA's building category system, U.S. DOE's categorization is more specific. It lists the separate categories for education with two sub-types of school function (primary and secondary); food service with two sub-types of restaurants (quick service and full service); lodging with two different hotel scales (large and small), and office category with three different sizes (small, medium, and large). U.S.DOE provides the average floor numbers of these sub-categories of buildings; therefore, in order to find out the total roof space of these buildings, the number of buildings under each sub-category must be determined. In Table B6 and Table B7 of the EIA's CBECS database (EIA, 2015a), the number of buildings and total floor space for difference sizes of school, restaurant, hotel and office were provided. Therefore, the number of buildings and the floor space for the subcategories could be estimated by matching the building sizes with these data. For example, under the U.S. DOE category system the typical floor space of quick service restaurants and full service restaurants were 2,500 ft^2 and 5,500 ft^2 respectively. Meanwhile, EIA's Table B6 reported the numbers of restaurants with floor space within 0-5,000 ft^2 and 5,000-25,000 ft^2. By matching the reference restaurant types of U.S. DOE with the corresponding sizes of restaurants in EIA's Table B6, numbers ratio of quick service restaurants and full service restaurants in different regions could be obtained. The total floor space of restaurants was estimated by similar method using EIA's Table B7.

Following U.S. DOE category system, education category floor space can be divided between primary and secondary schools. To split education floor space, reported by EIA as a whole, into these two sub-categories, a different method was used. This was due to fact that the data from the EIA's (2015a) Table B7 was reported by the size and not by the function of schools. The U.S. Census Bureau (2012) published relevant statistics on the numbers of public primary schools and second schools across the U.S. Under the assumption that floor space is linearly related with its enrollment, ratios between primary and secondary schools were estimated at about 3:1, allowing the allocation of total education building floor space to both subcategories by multiplying the share of adjusted floor space and average enrollment data and dividing by the combined products of both subcategories. See Table 4 for results.

Table 4. Floor space Ratio for Buildings in Education Category Using Two Different Methods

Education	Floor space ratio calculated from EIA data (first method)	Number ratio calculated from U.S. Census Data	Average enrollment number, U.S. Census Data	Adjusted floor space ratio calculated from U.S. Census data (second method)
Primary School	55.64%	73.39%	470	64.80%
Secondary School	44.36%	26.61%	704	35.20%

Next, under assumptions about roof pitch, orientation, structural soundness, and building obstruction and shading, the usable rooftop space for module deployment was estimated. Building obstruction accounts for the other equipment installed on the building's rooftop and the shade cast by surrounding buildings and vegetation. The impact from building obstruction can be calculated by applying a building obstruction reduction coefficient (BORC). Panel-to-panel shading results in the necessity for allowing reasonable space between solar panels. This reserved space between solar panels not only avoids shading within the solar panel system but also provides space for access between modules, wiring and inverters. The influence of panel-to-panel shading can be estimated using the Ground Cover Ratio (GCR). GCR is defined as the PV module area divided by the system area (Culligan and Botkin, 2007).

The CBECS database classifies commercial building rooftops in three categories: flat, shallow pitch and steeper pitch[3]. In Delaware, over 50% of commercial buildings have flat roofs (EIA, 2015a). Using the Access Factor to account for technical potential losses due to roof pitch and orientation, structural adequacy, tree shading, and other constraints, available area for rooftop PV arrays was estimated. These Access Factor values are sourced directly from the literature and are based on climate and geography, among other factors (Paidipati, Frantzis, Sawyer, & Kurrasch, 2008). In Delaware, the access factor for flat roofs is 65% the access factor for pitched roofs is 17.55%[4]. On flat roofs with space-efficient arrays, panel-to-panel shading is also an inevitable reality and therefore a necessary consideration in the analysis. Certain system layouts can minimize panel-to-panel shading based on the setback ratio (SBR), which 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, as seen in Figure 6 below (Whitaker, 2011).

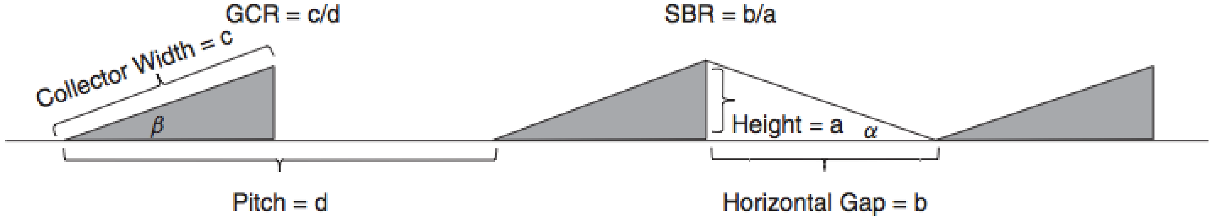

Figure 6. Multi-row PV Arrays Geometry

Source: Whitaker, 2011

In sunny, lower latitudes, the SBR is generally 2:1, and often 3:1 in cloudier, higher latitude regions, including the mid-Atlantic and specifically Delaware (Whitaker et al., 2011). Therefore, for Delaware, we assume a 3:1 SBR. Using the SBR, we can calculate the Ground Cover Ratio (GCR), which is related to tilt angle and SBR in multi-row arrays by Equation 1. GCR represents the available PV area accounting for panel-to-panel shading (Whitaker et al., 2011).

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

Empirically, arrays tilted to angle β in Equation 1 will minimize panel-to-panel shading. Tilts at greater angles require more roof space, resulting in a lower GCR and placing the array under

[3] See CBECS show card A4. "Shallow pitch" rooftops have tilts of 14° or less. "Steeper pitch" rooftops have tilts greater than 14°.

[4] See (Paidipati, Frantizs, Sawyer, & Kurrasch, 2008, p. 5) for further reading on Access Factor parameters. Access factors are based on assumptions of tree shading, other shading, and orientation factors multiplied together. In warm climates, the tree shading factor is 90%, "other" shading factor is 90%, and the orientation factor is 30%, yielding an access factor of (90%*90%*30%=24.3%). In cool climates, the tree shading factor is 65%, the "other" shading factor is 90%, and the orientation factor is 30%, yielding an access factor of (65%*90%*30%=17.55%).

greater stresses for rooftop mounts and wind load resistance. For this reason, β is usually between 5-10° for flat rooftops in order to maximize rooftop real estate (Culligan & Botkin, 2007). This is reflected in most commercially available fixed racking systems for commercial-scale systems (Mayfield, 2009). For this study, the tilt angle for flat roofs was assumed at 10° and the pitch angle for commercial buildings with pitched roofs to be 30° (on pitched roofs, there is no panel-to-panel shading.

Under these assumptions, applying Equation 1, the GCR was calculated at 66.4%. For pitched roofs, a geometric factor is necessary to accurately estimate the available PV array area for pitched roofs, calculated as follows in Equation 2:

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

Under the 30° tilt assumption, the geometric factor is 2/ √ 3. All of these factors influencing the available rooftop real estate for PV systems, total available rooftop space can be calculated by the equations below.

Calculation for flat roofs:

Total PV Array Area=
Estimated Gross Horizontal Roof Space × (Equation 3.1)
Access Factor × *Ground Cover Ratio (GCR)*

Calculation for pitched roofs:

Total PV Array Area=
Total Estimated Pitched Roof Space × *Access Factor* (Equation 3.2)

Where *Total Estimated Pitched Roof Space=*
$\sum_i^2 Estimated\ Gross\ Horizontal\ Roof\ Space_i \times\ Geometric\ Factor_i$[5]

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) (see Equation 4).

Power Density (W/m^2) under Standard Test Condition = =1000W/m^2×Panel Efficiency

*Technical PV Potential (MW) = Total PV Array Area*Power Density÷10^6* (Equation 4)

[5] 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.

The solar power density is determined by the efficiency of selected solar panels. Here, we assume an average panel efficiency of 16%. This is in fact quite a reasonable estimate given the state of module technology today, but a highly conservative estimate in the context of the study. Because this methodology is based on static data, it does not account for future innovations in module efficiency, additional building development in Delaware, and therefore represents a *ceteris paribus* result. NREL has recently demonstrated the rapid upward trend of median market PV module efficiency, from 14% to 16% from 2010 to 2014 (Barbose & Darghouth, 2015). Recently, current market-leading module manufacturers SunPower, SolarCity, and Panasonic have reported module-level efficiencies upwards of 22% under standard test conditions (Wesoff, 2015; Clover, 2015). Additionally, previous work demonstrating the high value of high efficiency PV modules contributes to the conservative nature of this assumption (Barbose & Darghouth, 2015; Wang et al., 2011).

2.2 Analysis

Based on the methodology described above, CEEP conducted a technical rooftop potential analysis for the commercial buildings sector in the State of Delaware. This section explains in depth how the data was collected, constructed, and analyzed.

2.2.1 Commercial Building Portfolio in Delaware

As introduced in the methodology section, the number and total floor space of commercial buildings at the state level are estimated using division-level building statistics and the population data. According to the U.S. Census Regions and Divisions map, Delaware falls under the South Atlantic Division within the South Region. According to the CBECS (2015a) data, the number and floor space of commercial buildings in South Atlantic division is 1,091,000, with a total floor space of 17,969 million square feet. Under the assumption that the number and total floor space of commercial buildings within a state are correlated with its population scale, these building statistics can be estimated by applying the population ratio to the division-level building data in Delaware.

EIA's CBECS (2015a) provides building data statistics only at the division level. The Table 5 shows the South Atlantic division, including Delaware, seven other states, and the District of Columbia. According to U.S. Census data (U.S. Census Bureau, 2015), in 2012 (at the time of survey) the state of Delaware had a population of 917,000, which accounted for 1.50% of the population in the whole division. By multiplying this population ratio with commercial building statistics of the South Atlantic Division, it was estimated that there are 16,352 commercial buildings in Delaware, the total floor space of which is 269 million square feet.

Table 5. Estimation of Commercial Building Statistics in Each State of South Atlantic Division

	Region: South	Division: South Atlantic		
	Population (as of 2012)	Population Ratio	Estimated Number of Commercial Buildings	Estimated Floor space of Commercial Buildings (Million ft^2)
DELAWARE	917,092	1.50%	**16,352**	**269**
GEORGIA	9,919,945	16.21%	176,874	2,913
FLORIDA	19,317,568	31.57%	344,435	5,673
WASHINGTON D.C.	632,323	1.03%	11,274	186
VIRGINIA	8,185,867	13.38%	145,955	2,404
MARYLAND	5,884,563	9.62%	104,923	1,728
NORTH CAROLINA	9,752,073	15.94%	173,881	2,864
SOUTH CAROLINA	4,723,723	7.72%	84,225	1,387
WEST VIRGINIA	1,855,413	3.03%	33,082	545
TOTAL	61,188,567	100.00%	≈1,091,000	17,969

As introduced in the methodology section, the building category system is constructed upon principal use of the commercial buildings. In EIA's (2015a) CBECS database, building statistics has been collected for different categories of buildings. Using this data (specifically Table B4 and B5 in EIA's CEBES database), Table 6 was created. The table presents an overview of the building portfolios in South Atlantic Division, which provides information on how the number of buildings and floor space are distributed under different categories of building usage. The first ten categories of buildings are the commercial building types that where matched between U.S. DOE's building categories and EIA's commercial building categories (see Table 2). 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 6. Building Statistics in South Atlantic Division

Principal Building Activity	Number of Buildings (Thousands)	Percentage of Building Amount	Total Floor space (Million ft^2)	Percentage of Floor space
Education	87	7.97%	2,840	15.80%
Food Sales	40	3.67%	188	1.05%
Food Service	78	7.15%	396	2.20%
Health Care (Inpatient)	2	0.18%	405	2.25%
Health Care (Outpatient)	21	1.92%	257	1.43%
Lodging	33	3.02%	1,217	6.77%
Mercantile Retail (Other Than Mall)	92	8.39%	1,052	5.85%
Mercantile (Enclosed and Strip Malls)	51	4.63%	1,694	9.43%
Office	198	18.15%	3,183	17.71%
Warehouse and Storage	177	16.22%	2,820	15.69%
Total for Building Types Included in Study	**779**	**71.31%**	**14,052**	**78.20%**
Public Assembly	45	4.12%	904	5.03%
Public Order and Safety	13	1.19%	301	1.68%
Religious Worship	80	7.33%	857	4.77%
Service	100	9.17%	741	4.12%
Other	17	1.56%	568	3.16%
Vacant	58	5.32%	546	3.04%
Total for Building Types not Included in Study	**313**	**28.69%**	**3,917**	**21.80%**
All Buildings	**≈1,091**	**100.00%**	**17,969**	**100.00%**

Sources: EIA CBECS, 2015a

To project the building portfolio in Delaware, the estimated number of commercial buildings (i.e., 16,352) and the total floor space (269 million square feet) were multiplied by the percentage values of different categories of buildings at division level (i.e., South Atlantic Division). The resulted building portfolio for Delaware is presented in Table 7.

Table 7. Projected Building Portfolios in Delaware

Principal Building Activity	Number of Buildings	Total Floor space (ft^2)
Education	1,304	42,565,816
Food Sales	600	2,817,737
Food Service	1,169	5,935,233
Health Care (Inpatient)	30	6,070,125
Health Care (Outpatient)	315	3,851,907
Lodging	495	18,240,351
Mercantile Retail (Other Than Mall)	1,371	15,767,337
Mercantile (Enclosed and Strip Malls)	757	25,389,610
Office	2,968	47,706,687
Warehouse and Storage	2,653	42,266,057
Total for Building Types Included in Study	**11,661**	**210,610,861**
Public Assembly	674	13,549,119
Public Order and Safety	195	4,511,377
Religious Worship	1,199	12,844,685
Service	1,499	11,106,081
Other	255	8,544,261
Vacant	869	8,213,321
Total for Building Types not Included in Study	**4,691**	**58,707,852**
All Buildings	**≈16,352**	**269,318,714**

The first 10 categories of buildings presented in the Table 7 were taken from the EIA's CBECS (2015a) database. These EIA's building categories correspond well with U.S. DOE's building categories listed in Table 1. However, U.S. DOE's building classification has subcategories for Education, Food Service, Lodging and Office categories. To better evaluate the typical floor numbers of each building category, EIA's CBECS list of categories was expanded based on the U.S. DOE's subcategories. Using the methodology explained in section 2.1, the percentage and quantitative data for these subcategories of buildings were estimated. The results are presented in Table 8.

Table 8. Building Portfolios for Subcategories of Education, Food Service, Lodging and Office

Principal Building Activity			Secondary Building Activity				
	Number of Buildings	Floor space (ft^2)		Number Percentage	Floor space Percentage	Number of Buildings	Floor space (ft^2)
Education	1,304	42,565,816	School Primary	73.39%	55.64%	957	26,662,910
			School Secondary	26.61%	44.36%	347	15,902,906
Food Service	1,169	5,935,233	Quick Service Restaurant	68.01%	32.89%	795	1,952,096
			Full-Service Restaurant	31.99%	67.11%	374	3,983,137
Lodging	495	18,240,351	Hotel Small	88.38%	41.47%	437	7,564,950
			Hotel Large	11.62%	58.53%	57	10,675,402
Office	2,978	47,706,687	Office Small	76.46%	19.00%	2,269	9,066,146
			Office Medium	22.69%	49.39%	673	23,564,165
			Office Large	0.85%	31.60%	25	15,5076,376

Date sources: EIA CBECS, 2015a; DOE, 2014

To better illustrate the building portfolios in Delaware, the building category systems of EIA CBECS and DOE was merged and rearranged. The summary table resulted in 15 commercial building categories. In Table 9, the estimated number and floor space for each category of buildings is presented as well as their corresponding ratios.

Table 9. Final Summary of Commercial Building Portfolios in Delaware

	Principal Building Activity	Number of Buildings	Number Percentage	Floor space (ft^2)	Floor space Percentage
1	Primary Schools	957	5.85%	26,662,910	9.90%
2	Secondary Schools	347	2.12%	15,902,906	5.90%
3	Supermarket	600	3.67%	2,817,737	1.05%
4	Quick-service restaurant	795	4.86%	1,952,096	0.72%
5	Full-service restaurant	374	2.29%	3,983,137	1.48%
6	Hospital	30	0.18%	6,070,125	2.25%
7	Outpatient Health Care	315	1.92%	3,851,907	1.43%
8	Small Hotel	437	2.62%	7,564,950	2.81%
9	Large Hotel	57	0.35%	10,675,402	3.96%
10	Stand-alone retail	1,371	8.39%	15,767,337	5.85%
11	Strip mall	757	4.63%	25,389,610	9.43%
12	Small Office	2,269	13.88%	9,066,146	3.37%
13	Medium Office	673	4.12%	23,564,165	8.75%
14	Large Office	25	0.15%	15,076,376	5.60%
15	Warehouse	2,653	16.22%	42,266,057	15.69%
Total		**11,661**	**71.34%**	**210,610,861**	**78.20%**

2.2.2 Calculating the Rooftop Space of Commercial Buildings in Delaware

In the previous section, the total floor space for each type of buildings in Delaware was estimated. As detailed in Equations 3.1, 3.2 and 4 above, for estimating technical rooftop solar potential total rooftop space needs to be calculated.

The Table 10 shows the calculated result of total floor space divided by profiled floor numbers to yield total horizontal roof space for each building category in in Delaware.

Table 10. Rooftop Space for Commercial Buildings in Delaware

	Principal Building Activity	Floor space (ft^2)	Typical Number of Floors	Rooftop Space (ft^2)
1	Primary Schools	26,662,910	1	26,662,910
2	Secondary Schools	15,902,906	2	7,951,453
3	Supermarket	2,817,737	1	2,817,737
4	Quick-service restaurant	1,952,096	1	1,952,096
5	Full-service restaurant	3,983,137	1	3,983,137
6	Hospital	6,070,125	5	1,214,025
7	Outpatient Health Care	3,851,907	1	3,851,907
8	Small Hotel	7,564,950	4	1,891,237
9	Large Hotel	10,675,402	6	1,779,234
10	Stand-alone retail	15,767,337	1	15,767,337
11	Strip mall	25,389,610	1	25,389,610
12	Small Office	9,066,146	1	9,066,146
13	Medium Office	23,564,165	3	7,854,722
14	Large Office	15,076,376	12	1,256,365
15	Warehouse	42,266,057	1	42,266,057
Total		**210,610,861**		**153,703,973**

According to CBECS, 55.96% of the commercial building roofs are flat (by floor space) and the percentages for shallow pitch and steeper pitch are 29.39% and 14.64% in the South Atlantic Division. By applying geometric factors as shown in Equation 3.2 for the pitched roofs and adding up the total rooftop space (flat and pitched), the aggregated rooftop space of commercial buildings in Delaware was calculated (see Table 11)

Table 11. Rooftop Space on Commercial Buildings in Delaware

Total Horizontal Rooftop Space (million ft²)			153.70
Roof Type	Flat	Shallow Pitch (10°)	Steeper Pitch (30°)
Ratio	55.96%	29.39%	14.64%
Horizontal Space (million ft²)	86.02	45.18	22.50
Rooftop Space (million ft²)	86.02	45.88	25.98
Total Rooftop Space (million ft²)			**157.88**

2.2.3 Determine the Technical PV Potential on Commercial Rooftops in Delaware

In this section, the technical PV potential for commercial rooftops in Delaware is estimated based on the previously estimated rooftop space. As described above, the influence of roof pitch, orientation, structural soundness, and shading on available rooftop space is captured in access factors applied to the total rooftop calculations detailed above. Additionally, the GCR on flat roofs will further adjust the estimation. See Table 12 for results.

Table 12. Feasible PV Array Area in Delaware

Roof Type	Rooftop Space (million ft²)	Access Factor (%)	GCR (%)	Feasible PV Array Area (million ft²)
Flat	86.02	65.0%	66.4%	37.13
Shallow Pitch (10°)	45.88	65.0%	N.A.	29.82
Steeper Pitch (30°)	25.98	17.55%	N.A.	4.56
Total PV Array Area (million ft²)				**71.51**

According NREL (Paidipati, Frantzis, Sawyer, & Kurrasch, 2008) Delaware is located in colder climate zone, the *Access Factor* of the roofs is assumed at 65%[6]. Again, with a 10° tilt angle and

[6] See Paidipati, Frantizs, Sawyer, & Kurrasch, 2008, pp. 5-6 for details regarding the sources of the parameters. In warm climates, the structural adequacy factor is 80%, shading factor is 75%, and the orientation factor is 100%, yielding an access factor of (80%*75%*100%=60%). In cool climates, the structural adequacy factor is 100%, the shading is 65%, and the orientation is 100%, yielding an access factor of (100%*65%*100%=65%).

assumed SBR of 3, the Ground Coverage Ratio (GCR) was calculated at 66.4% (see Section 2.1) for Delaware.

For this study, module efficiency was assumed at 16%, yielding the power density of the PV arrays under standard test conditions at 160 W/m^2. Using the Equation 4, technical potential PV potential for commercial buildings were estimated. The results are presented in Table 13.

Table 13. 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)
Delaware	71.51	6.64	160	1,063

As the result indicates, there is 1,063 MW of PV potential for commercial rooftops in Delaware. The detailed calculation process and potential breakup for each type of buildings in Delaware are summarized in Table 14.

Table 14. Technical PV Potential for Commercial Rooftops in Delaware

	Principal Building Activity	Total PV Array Area (m^2)	Technical PV Potential (MW)	Share of PV Potential (%)
1	Primary Schools	1,152,460	184	17.35%
2	Secondary Schools	343,688	55	5.17%
3	Supermarket	121,792	19	1.83%
4	Quick-service restaurant	84,376	14	1.27%
5	Full-service restaurant	172,164	28	2.59%
6	Hospital	52,474	8	0.79%
7	Outpatient Health Care	166,492	27	2.51%
8	Small Hotel	81,746	13	1.23%
9	Large Hotel	76,904	12	1.16%
10	Stand-alone retail	681,517	109	10.26%
11	Strip mall	1,097,424	176	16.52%
12	Small Office	391,869	63	5.90%
13	Medium Office	339,507	54	5.11%
14	Large Office	54,304	9	0.82%
15	Warehouse	1,826,880	292	27.50%
Total		**6,643,599**	**1,063**	**100%**

Based on data presented in Table 14, the Figure 7 shows the ratio of PV potentials distributed by major building types. In Delaware, most of the commercial building rooftops for PV installation can be provided by mercantile buildings, schools, warehouses and offices.

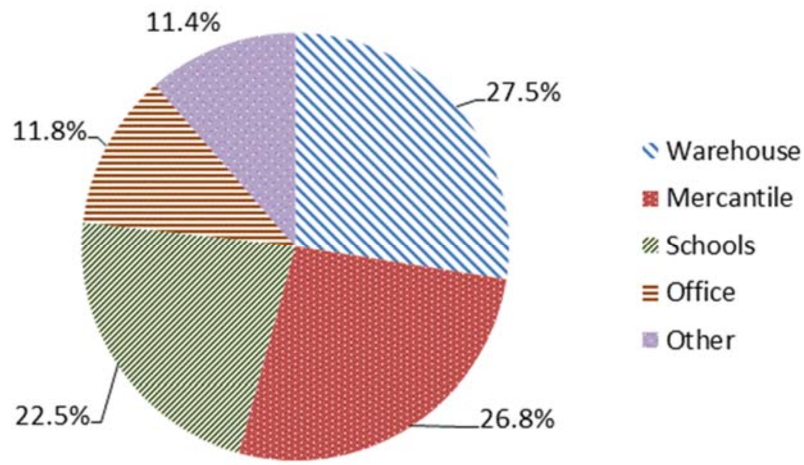

Figure 7. Major Rooftop PV Potential Sources in Commercial Sector (Delaware)

3. Estimation the Rooftop Technology PV Potential in Residential Sector

3.1 Methodology

As discussed in the previous chapters, technical potential represents the theoretical maximum amount of PV that can be deployed on the building rooftops. The CEEP team developed a matrix for estimating the rooftop PV technical potential in the residential sector in Delaware. To build the matrix, the CEEP team retrieved the most recent data from the U.S. Energy Information Administration (EIA) Residential Energy Consumption Survey (RECS) of 2009 (released in 2012).

In the EIA's RECS (2012) data set, housing space was broken in four distinguished parts. These were: attic, basement, garage, and the rest of house. These four areas were measured separately to capture the heating and cooling needs of different housing units. In the survey, attics were measured if they were heated or cooled, and garages were measured if they were heated, cooled, or directly attached to the housing units. Figure 6 illustrates the measurement of floor space for a residential sector according to EIA's RECS.

Figure 8. EIA RECS Measurement of Floor space in Residential Households

Source: EIA RECS, 2012

Appling EIA RECS's (2012) classification, the housing unit types can be classified as the single-family detached, attached, and the apartment building of two to four units. The fourth category covering the large apartments with more than five units was assessed separately. The housing units also can be classified as having basement, attic or both. In adding, residential matrix also accounts for the number of floors.[7]

EIA RECS data (2012) provides aggregate square footage values for different types of housing units. In order to calculate building roof space the housing square footage need to be divided by the number of floors including attic and basement. This is why it is important to evaluate share of the different hosing categories in the total housing stock in Delaware. Based on the EIA RECS (2012) housing data CEEP team developed housing characteristics matrix to capturing key differences in the housing categories. Housing units can be captured by four characteristics:

- Albescence or presence of attic
- Albescence or presence of basement
- The type of house
- Number of floors

Table 15 demonstrates how residential buildings characteristics matrix can be constructed. In this matrix absence of attic is denoted as 0 and its presence is denoted with 1. Similarly, absence of basement is denoted with 0, and its presence is denoted with 1. Excluding large apartments, which are evaluated separately, the housing type could be classified as single family detached (type 1), single family attached (type 2) and apartments in 2 to 4 unit buildings (type 3).

From EIA RECS (2012) data it is possible to extract the percentage shares for each separate characteristic. Assuming these characteristics are independent from each other, the characteristics matrix can be used to build the 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: 2x2x3x3=36 combinations in total.

[7] Because available data does not represent the share of garages with separate roof space versus included roof space, this analysis does not include garage roof space in the technical potential estimation calculations.

Table 15. Residential Buildings Characteristics Matrix

Category	Attic	Basement	Housing 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

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

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

Where

- N_1 = total number of single family housing units and small apartments
- HUS_n = average housing unit size
- N_{2j} = total number of apartments in large apartment buildings
- HUS_{Lj} = average size of large apartment buildings with specific floor numbers (e.g., 1-2 floors, or 5-10 floors)
- NF_n = number of floors for small units
- A_n = 1 if the residence contains an attic and 0 otherwise
- B_n = 1 if the residence contains a basement and 0 otherwise.
- JP = the joint probability function built based on the selected housing units combined characteristics.[8]

Dividing residential rooftops into the categories of pitched and flat roofs, it was assumed that all residential housing units except for large apartment buildings had pitched roofs at tilt of 30°

[8] This joint probability is based on the proportions of households with each characteristic in the analysis. 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 facility detached houses, and 30% of housing units have a 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.

(Paidipati, Frantzis, Sawyer, & Kurrasch, 2008). For the large apartment buildings, previously detailed methodology for flat commercial rooftops was used.

Estimation for Pitched Roofs

The estimation for residential gross roof space above assumes flat roof space for all buildings, so they need to be adjusted by a geometric factor and a region-specific access factor (see Equation 2). The total area for PV arrays installed on tilted residential rooftops can then be estimated by Equation 6:

Total PV Array Area (Tilted Residential Roof) =
Gross Horizontal Roof Space × Access Factor × Geometric Factor (Equation 6)

Estimation for Flat Roofs

Large apartment buildings (containing more than five family units) can have up to 20 floors and are assumed to have flat roofs, so we estimate their rooftop potential using the commercial building methodology, illustrated in Equation 7:

Total PV Array Area (Flat Residential Roof) =
Gross Horizontal Roof Space × (Equation 7)
Access Factor × Ground Cover Ratio (GCR)

Technical potential can be estimated by multiplying the power density and assumed panel efficiency by the total rooftop area in square meters, as demonstrated in Equation 8 below.

Power Density (W/m^2) under Standard Test Condition=
$1000 W/m^2 \times$ Panel Efficiency (Equation 8)
*Technical PV Potential (MW) = Total PV Array Area*Power Density$\div 10^6$*

3.2 Analysis

3.2.1 Housing Unit Characteristics in Delaware

The RECS (2012) data set also groups Delaware within the South Atlantic Census Division, which is further broken into subdivisions for some components of the dataset. For the housing unit types, Delaware is grouped with Maryland, District of Columbia and West Virginia. According to these data 69.23% of single family detached, single family attached and apartments in 2 to 4 unit buildings have basement, 32.00% have attic. For the full characteristics of these buildings, see Table 16, below.

Table 16. Characteristics of Residential Buildings

Percentage, share by housing units			
	Yes	no	
Attic	32.00%	68.00%	
Basement	69.23%	30.77%	
Type	**Detached**	**Attached**	**Appt. 2-4 units**
	1	2	3
Ratio	69.23%	23.08%	7.69%
Number of Floors	1	2	3
Ratio	45.71%	48.57%	5.75%

To estimate available residential roof space, the housing units were classified by several characteristics. Combination of these characteristics leads to unique 36 housing types. By using the percentage values presented in Table 16, distributions of the different housing types in Delaware were constructed (see Table 15) for the different categories.

In Table 17, the columns two through five reflect the characteristics of the residential buildings. These include the presence of attic, basement, the number of floors, and three types of houses. The presence or absence of attic and basement in the housing units is denoted by binary code (1 means presence and 0 means absence). The types of households, were classify in three numerical values: single-family detached household as 1, single-family attached household as 2, and the apartment with two to four units as 3. The number of floors in the Table reflects number of floors in a house unit. Since each of the percentage of attic, basement, type of houses, and number of floors is independent with each other, their probabilities can be multiplied to find the joint probability for each of the 36 housing categories.

Table 17. Distribution of Housing Categories in Delaware

	Attic	Basement	Building Type	# of Floors	Attic	Basement	Building Type	# of Floors	Joined Probability
1	0	0	1	1	68.0%	30.8%	69.2%	45.7%	6.6%
2	0	0	1	2	68.0%	30.8%	69.2%	48.6%	7.0%
3	0	0	1	3	68.0%	30.8%	69.2%	5.7%	0.8%
4	1	0	1	1	32.0%	30.8%	69.2%	45.7%	3.1%
5	1	0	1	2	32.0%	30.8%	69.2%	48.6%	3.3%
6	1	0	1	3	32.0%	30.8%	69.2%	5.7%	0.4%
7	0	1	1	1	68.0%	69.2%	69.2%	45.7%	14.9%
8	0	1	1	2	68.0%	69.2%	69.2%	48.6%	15.8%
9	0	1	1	3	68.0%	69.2%	69.2%	5.7%	1.9%
10	0	0	2	1	68.0%	30.8%	23.1%	45.7%	2.2%
11	0	0	2	2	68.0%	30.8%	23.1%	48.6%	2.3%
12	0	0	2	3	68.0%	30.8%	23.1%	5.7%	0.3%
13	1	1	1	1	32.0%	69.2%	69.2%	45.7%	7.0%
14	1	1	1	2	32.0%	69.2%	69.2%	48.6%	7.4%
15	1	1	1	3	32.0%	69.2%	69.2%	5.7%	0.9%
16	0	1	2	1	68.0%	69.2%	23.1%	45.7%	5.0%
17	0	1	2	2	68.0%	69.2%	23.1%	48.6%	5.3%
18	0	1	2	3	68.0%	69.2%	23.1%	5.7%	0.6%
19	1	0	2	1	32.0%	30.8%	23.1%	45.7%	1.0%
20	1	0	2	2	32.0%	30.8%	23.1%	48.6%	1.1%
21	1	0	2	3	32.0%	30.8%	23.1%	5.7%	0.1%
22	1	1	2	1	32.0%	69.2%	23.1%	45.7%	2.3%
23	1	1	2	2	32.0%	69.2%	23.1%	48.6%	2.5%
24	1	1	2	3	32.0%	69.2%	23.1%	5.7%	0.3%
25	0	0	3	1	68.0%	30.8%	7.7%	45.7%	0.7%
26	0	0	3	2	68.0%	30.8%	7.7%	48.6%	0.8%
27	0	0	3	3	68.0%	30.8%	7.7%	5.7%	0.1%
28	0	1	3	1	68.0%	69.2%	7.7%	45.7%	1.7%
29	0	1	3	2	68.0%	69.2%	7.7%	48.6%	1.8%
30	0	1	3	3	68.0%	69.2%	7.7%	5.7%	0.2%
31	1	0	3	1	32.0%	30.8%	7.7%	45.7%	0.3%
32	1	0	3	2	68.0%	30.8%	69.2%	45.7%	0.4%
33	1	0	3	3	68.0%	30.8%	69.2%	48.6%	0.0%
34	1	1	3	1	68.0%	30.8%	69.2%	5.7%	0.8%
35	1	1	3	2	32.0%	30.8%	69.2%	45.7%	0.8%
36	1	1	3	3	32.0%	30.8%	69.2%	48.6%	0.1%

According to the Table 17, the most common housing units in Delaware are: type number eight (no attic, single-family detached with two floors and basement), type number seven (no attic, single-family detached with basement and one floor), and type number fourteen (single-family detached with two floors, attic, and basement). Using this data, the total rooftop area of the residential buildings in Delaware is calculated in the following section.

3.2.2 Calculating the Rooftop Space of Residential Buildings in Delaware

The total number of house units for the specific house category can be calculated by multiplying the total number of house units in a state to the join probability of each house category obtained in the previous section. Once the number of house units for each of 36 categories is obtained, these values should be multiplied by the average roof space of corresponding category. This method allows calculating total roof space of residential buildings in the state.

The total number of households in Delaware was obtained from the U.S. Census Bureau (2015). According to this data average number of Delaware households between 2009 and 2013 was 335,707 units. As noted above, The RECS data set (2012) groups Delaware within South Atlantic Census Division, which for some data is further broken into subdivisions. For the housing unit types Delaware is grouped with Maryland, District of Columbia and West Virginia. According to the subdivision data single family detached, single family attached and apartments in 2 to 4 unit buildings represent about 74.3% of the households. Based on these data, it was calculated that Delaware had 243,161 units of these types.

Before calculating the total rooftop area for residential buildings in Delaware, the average square footage for different house types was to be calculated. In EIA's RECS (2012) reports average square footage per housing unit for Delaware, Maryland, District of Columbia and West Virginia at 2,218 square feet. More detailed breakdown by building type at the state level is not available from this data set. EIA's RECS (2012) has these data at the South Atlantic Census Division level, which Delaware is part of. Average size of housing unit in South Atlantic was reported at 1,867 square feet. Based on this data it can be concluded that prior of using South Atlantic data for Delaware, the housing unit size values need to be adjusted by factor of 1.19. This value is obtained through dividing the average square feet number for all housing types in Delaware by the average square feet number of the South Census region. The adjusted factor is used to estimate the average size for different housing types. The results of calculating the adjusted average square footage for different house type in Delaware are presented in the Table 18 below.

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

	South Atlantic Division Average Home Size (ft^2)	Adjusted Average Home Size (ft^2) in Delaware
Single-Family Detached	2,278	2,706
Single-Family Attached	1,641	1,950
Apartments in 2-4 Unit Buildings	945	1,123
Apartments More than 5 Units Buildings	916	1,088
Mobile Homes	1,128	1,340
All types of home	1,867	2,218

For the calculation of the horizontal roof space the total number units of each house type need to be multiplied with the adjusted average square footage from the Table 18. The product of this operation will be the total building square footage for 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 divide the total square footage for each housing type by number of floors.

The resulting Table 19 shows estimated horizontal roofs space for single family detached, single family attached and apartments in Delaware. The remaining housing in the state comprises with the apartment with five or more units and mobile homes. For this study it was assumed that the mobile homes were not suitable for distributed PV installation (e.g., net metering would be difficult for these homes and the life of a mobile home could be shorter than the lifetime of the solar panels) and they were excluded from the residential solar potential estimation.

Table 19. Number of House Units and Their Horizontal Roof Space

	Number of house units in DE (thousand)	Average Unit Size (ft^2 per unit)	Calculated Total square footage (million ft^2)	Number of Floors	Horizontal Roof Footage (million ft^2)
1	16.102	2706	43.575	1	43.58
2	17.108	2706	46.299	2	23.15
3	2.013	2706	5.447	3	1.82
4	7.577	2706	20.506	1	10.25
5	8.051	2706	21.788	2	7.26
6	0.947	2706	2.563	3	0.64
7	36.229	2706	98.045	1	49.02
8	38.493	2706	104.173	2	34.72
9	4.529	2706	12.256	3	3.06
10	5.367	1950	10.463	1	10.46
11	5.703	1950	11.117	2	5.56
12	0.671	1950	1.308	3	0.44
13	17.049	2706	46.139	1	15.38
14	18.114	2706	49.022	2	12.26
15	2.131	2706	5.767	3	1.15
16	12.076	1950	23.543	1	11.77
17	12.831	1950	25.014	2	8.34
18	1.510	1950	2.943	3	0.74
19	2.526	1950	4.924	1	2.46
20	2.684	1950	5.232	2	1.74
21	0.316	1950	0.615	3	0.15
22	5.683	1950	11.079	1	3.69
23	6.038	1950	11.771	2	2.94
24	0.710	1950	1.385	3	0.28
25	1.789	1123	2.009	1	2.01
26	1.901	1123	2.134	2	1.07
27	0.224	1123	0.251	3	0.08
28	4.025	1123	4.519	1	2.26
29	4.277	1123	4.802	2	1.60
30	0.503	1123	0.565	3	0.14
31	0.842	1123	0.945	1	0.47
32	0.895	1123	1.004	2	0.33
33	0.105	1123	0.118	3	0.03
34	1.894	1123	2.127	1	0.71
35	2.013	1123	2.260	2	0.56
36	0.237	1123	0.266	3	0.05
Total	**243.161**				**260.20**

According to EIA's RECS (2012) data, 17.1% of housing units in Delaware, Maryland, District of Columbia and West Virginia are apartments with more than five units. As mentioned above, based on U.S. Census Data (2015) the total housing units in Delaware at the time of the EIA's survey were 335,707 units. Appling this percentage to the total housing units gives 57,550 housing units of this type. The total horizontal rooftop area for each category (categories are grouped according to number of floors) can be calculated by multiplying average unit floor space by the number of apartment for each category and dividing the result of multiplication by average number of floors. Therefore, for roof top potential estimation it is also important to take into the account the number of the floors in the apartments these units are housed in.

Using EIA's RECS's data adjusted for Delaware, it can be seen that majority of residential apartments have 3 to 4 floors (see Table 20). In Table 18, it was shown that average floor space for the "apartment units in buildings with more than five units" was 1,088 square feet. From Table 20 it can be seen that there are 38,367 units, which are in 3 to 4 floor apartment buildings (average of 3.5 floors for our purposes).Based on these data to estimate roof space for these category following calculations can be performed:

*Horizontal Roof Footage for 3-4 Floor Apartments= 38,367*1,088*3.5=11.93 Million* ft^2

After conducting similar calculations for apartments with 1-2 floors and apartments with 5 to 10 floors, results can be summed yielding the total square footage for the large apartment building is Delaware. Table 20 shows this process. Based on this method, the total roof space for the large apartments was calculated at 20.3 million square feet.

Table 20. Average Number of Floors in Apartment with More than 5 Units

Number of Floors	Number of Apartment Units in EIA's RECS Subdivision for DC, DE, MD and WV	Share	Calculated Number of Apartment Units in Delaware	Average Unit Size (ft^2 per unit)	Horizontal Roof Footage (million ft^2)
1 or 2 Floors	100,000	16.67%	9,592	1,088	6.96
3 or 4 Floors	400,000	66.67%	38,367	1,088	11.93
5 to 10 Floors	100,000	16.67%	9,592	1,088	1.39
Total	**600,000**	**100.00%**	**57,550**		**20.28**

3.2.3 Determining the Technical PV Potential on Residential Rooftops in Delaware

Like the commercial sector, the residential estimates must be adjusted by an access factor (Denholm & Margolis, 2008). As mentioned in Section 2.1, Delaware, which is located in a colder climate zone, the *Access Factor* was assumed at 65% (Paidipati, Frantzis, Sawyer, & Kurrasch, 2008). For large apartments, the GCR was calculated at 66.4% for 10^o tilt installations in the same manner as was calculated in the commercial buildings sector. Using Equations 6 and 7, the access factors were accounted for, as seen in Table 21. Technical rooftop potential in the residential sector of Delaware was estimated to total 887.97 MW, representing average solar potential per household to be 2.65kW.

Table 21. Residential Technical PV Potential for Delaware

	Total Housing Space (million ft²)	**Total Horizontal Rooftop Space (million ft²)**	**Total Horizontal Rooftop Space (million m²)**	**Rooftop Potential, MW**
Single-Family detached, attached and Apartments with 2 to 4 units	586	260.2	24.2	784
Apartments with more than 5 units	63	16.3	1.5	104
Total	**649**	**276.5**	**25.7**	**888**

4. Estimation of Potential Electricity Generation from Rooftop PV in Delaware

Using these rooftop PV technical potential estimations, theoretical amount of electricity produced from this potential can be calculated. Retail electricity sales in Delaware have not changed significantly in the last fourteen years (EIA, 2015b). Electricity sales peaked in 2003 at 12,600 million kWh, and have since declined to 11,179 Million kWh in 2014 (see Figure 7). This reduction was mainly due to a significant decline in industrial sector sales (more than 40% decline from 2001 to 2014). In 2014 residential sector consumed 41.5%, followed by commercial sector with 37.6% and the industrial sector with 20.9%.

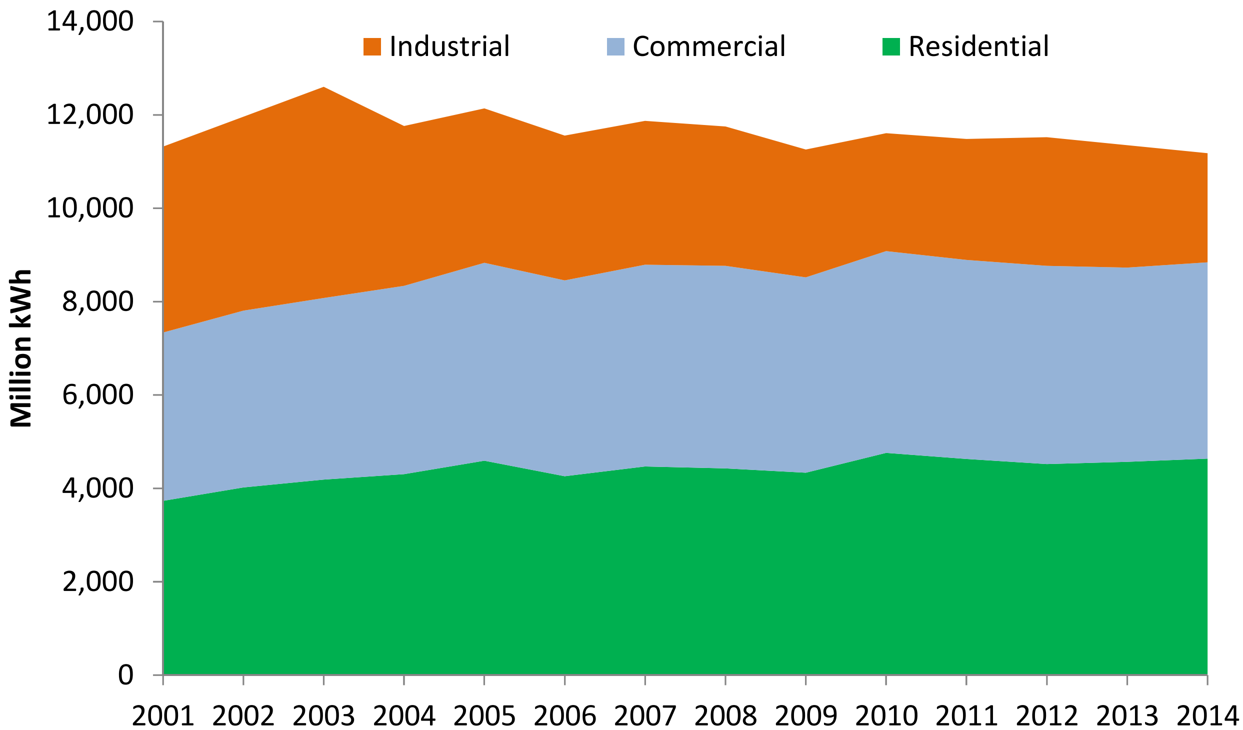

Figure 9. Retail Electricity Sales in Delaware by Sector, 2001-2014

Date source: EIA, 2015b

For electricity generation calculations, to be more conservative this study did not account for future increases in module efficiency. Therefore, conservative value of 16% was used for the module efficiency. For the inverter efficiency 95% was used and the power derating factor was assumed at 90%[9]. For radiation data, NREL's Typical Meteorological Year (TMY[10]) weather data

[9] Other power derating factor accounts for losses in wires, connectors, module mismatch, soiling and other factors.

was used. Using this data, PV capacity factors can be estimated using PV Planner© software[11] with the base assumptions for the PV arrays detailed above. By assuming a positive correlation with the number of buildings and the number of households (as a proxy for population), weighted average capacity factors, adjusted by state population distribution, can be calculated (see Table 22).

Table 22. Power Generation Yield in Delaware

County	# Households	Share	TMY3 Location	Capacity Factor (flat roof)[12]	Capacity Factor (shallow pitch)[13]	Capacity Factor (steeper pitch)[14]
New Castle	200,739	59.8%	724089	14.55%	13.52%	15.19%
Kent	58,524	17.4%	724088	14.04%	12.99%	14.78%
Sussex	76,444	22.8%	724088	14.04%	12.99%	14.78%
Total	**335,707**	**100.00%**	**Weighted Average**	**14.34%**	**13.31%**	**15.03%**

Data Sources: NREL, 2008; PV Planner software

In order to calculate how much electricity can be generated in Delaware from rooftop PV, the production levels need to be adjusted based on the population distribution. From the Table 22 it can be see that around 60% of Delaware's households are located in the Northern Delaware (New Castle County), where Wilmington weather station (724089 TMY3) can be used to calculate electricity generation from PV. Kent and Sussex counties representing around 40% of Delaware's households, the closest weather station with TMY 3 data for both counties is located in Dover (724088 TMY3), and this data is used for electricity generation calculations in these counties.

These weighted average capacity factors were used to estimate Delaware's total potential electricity generation from rooftop PV and compared with total statewide annual electricity

[10] 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 (Wilcox & Marion,2008).
[11] PV Planner© software was developed at the Center for Energy and Environmental Policy at the University of Delaware (Byrne, Kurdgelashvili, & Couey, 2011).
[12] For flat roofs, multi-row PV systems are installed and the tilt is assumed to 10° facing South.
[13] 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.
[14] The tilt of PV systems installed on steeper pitched roofs is assumed to be 30° facing South.

consumption[15] (Energy Information Administration (EIA), 2015). Table 23 shows that rooftop PV can meet significant portion of electricity demand in Delaware.

Table 23. 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			
Delaware	1.06	0.888	1.948	2,462	11,179	22.02%

The results from the previous chapters yield the estimate of total rooftop PV potential in Delaware of 1,948 MW. Based on the local solar radiation and assumed tilt angles this capacity can generate 2,462 Million kWh per year. With the annual state electricity consumption in 2014 (11,179 Million kWh) rooftop PV can provide 22.02% of Delaware's retail electricity demand.

This is significantly higher than current highest solar curve out objective for Delaware targeting 3.5% of electricity from PV by 2025-2026 (includes also utility scale PV). Theoretically, rooftop PV can meet not just the solar carve out, but also a tremendous portion of the eligible renewable target of 25% (see Table 24).

[15] Total electricity consumption includes residential, commercial, industrial, and transportation sectors.

Table 24. Compliance schedule for Renewables Portfolio Standard in Delaware

Compliance Year	Eligible Renewables	PV
2007-2008	2.00%	--
2008-2009	3.00%	0.01%
2009-2010	4.00%	0.01%
2010-2011	5.00%	0.02%
2011-2012	7.00%	0.20%
2012-2013	8.50%	0.40%
2013-2014	10.00%	0.60%
2014-2015	11.50%	0.80%
2015-2016	13.00%	1.00%
2016-2017	14.50%	1.25%
2017-2018	16.00%	1.50%
2018-2019	17.50%	1.75%
2019-2020	19.00%	2.00%
2020-2021	20.00%	2.25%
2021-2022	21.00%	2.50%
2022-2023	22.00%	2.75%
2023-2024	23.00%	3.00%
2024-2025	24.00%	3.25%
2025-2026	25.00%	3.50%

Source: DSIRE, 2015

As was demonstrated in Chapter 1, over the last decade Delaware's PV installation have steadily increased reaching 63 MW of cumulative installation by the end of 2013 (IREC, 2014). This number includes utility scale PV installations (see Figure 1). If only counting residential and commercial PV installations, then the total cumulative installation is just 32 MW, which is around 1.6% of calculated technical rooftop PV potential in Delaware. Using average yield values for rooftop PV (1,264 kWh per installed kW) it was calculated that in 2013 install rooftop PV could generate 40 Million kWh of electricity, which was only 0.4 % of retail electricity sales in the state. Therefore, a significant potential exists for future PV growth on residential and commercial rooftops.

5. Conclusion

Despite the fact that the U.S. PV market has seen 50% year-over-year growth since 2010, PV (rooftop or otherwise) still generates less than 1% of total U.S. electricity needs (IEA, 2014). Following the national trend, Delaware has made significant progress in PV deployment, notably in the utility-scale sector. Although utility scale PV has its merits, distributed PV can provide higher benefits in terms peak load reduction, enhancing system reliability, avoiding transmission and distribution losses, stabilizing and lowering retail electricity prices, and enhance local energy security and economies among others.

In this study, technical rooftop potential in the state was estimated at 1,948 MW, from which 54.4% was attributed to commercial buildings and remaining 45.6% was attributed to residential buildings. The results presented in the report indicate that vast rooftop technical potential exists in Delaware for future PV growth. Delaware can increase its current PV capacity more than 30 times to reach the estimated technical potential. Electricity generation from this potential can be affected by solar resources, building orientation, roof pitch, architectural obstructions, population distribution, and other factors explored in this report. Based on technical potential and other factors impacting PV generation it was calculated that full utilization of the technical rooftop PV potential could theoretically provide 22.02% of the State's current electricity demand.

It is recognized that although the benefits of distributed generation are many, large-scale penetration of distributed PV systems can 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 addressed through innovative smart grid technologies, including customer sited electric storage (Kezunovic, McCalley, & Overbye, 2012). Hence, further research needs to be conducted for evaluating the economic feasibility and timeframe of larger adoption of distributed PV in Delaware.

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