Modelling PV Deployment: A Tool Developed at CEEP to Explore the Delaware Market

Energy and Environmental Policy Analysis (EEPA) Program

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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 provides an update on efforts at the Center for Energy and Environmental Policy (CEEP) to construct a ‘bottom-up’ photovoltaics technologies diffusion model. 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. This report provides an overview of the different components of the bottom-up PV diffusion model. The Center for Energy and Environmental Policy (CEEP) is sole 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.
1. Introduction

Driven by its progressive renewable energy laws, regulations, programs and projects, Delaware is among the leading U.S. states that are building a clean energy economy. The State’s Renewable Energy Portfolio Standard (RPS) and its advanced solar provisions have created one of the most aggressive RPSs in the nation. Delaware’s RPS has as a solar set aside of 3.5 percent to be realized by 2025. The achievement of the state’s solar set aside target and future industry growth depends on the rate of adoption of solar PV in the residential, commercial, public and industrial sectors.

Wide adoption of PV depends on a number of technical and economic aspects. The economic viability of solar PV technology depends on many factors, including electricity prices, PV system costs, net metering rules, incentives such as investment tax credits (ITC) and other regulations. Given that electricity markets in the United States differ regionally and locally, the economics of PV and for that matter the rate of adoption of PV technologies need to be evaluated locally. In this regard, solar PV diffusion modeling focused on Delaware would allow for a clear understanding of the relationships between the state’s policies on PV economics and their impact on the diffusion of PV technology. Analysis of the adoption rate of solar PV in Delaware can be a key mechanism in evaluating the impacts of existing solar policies and incentives.
2. **Research Objectives**

The ‘bottom-up’ PV technologies diffusion model being developed by the Center for Energy and Environmental Policy (CEEP) takes into consideration current and emerging technologies, varying building types, local climate conditions, and different policy frameworks. The model helps to identify potential barriers for continued PV industry expansion and evaluates the effectiveness of policy instruments to address these problems. The purpose of building the model is to analyze the potential 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 diffusion model will link current and proposed policy impacts on future PV deployment rates and will also help to inform future policy decisions in that regard. The tool will help 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 into flexible, efficient and smart grids as PV matures into mainstream technology. To this end, the aims of this research on solar PV diffusion in Delaware are to:

a) Analyze the impact of major technological improvements (increased efficiency, reduction in material requirements, reduction in performance degradation, etc.) on the economic performance of specific PV technologies in the State of Delaware;

b) Examine the solar PV adoption rate for different policy scenarios (federal, state and local) including net metering rules, renewable portfolio standards, investment tax credit, etc. in the State of Delaware;
c) Develop economic models that evaluate the effectiveness of financial instruments to spur investment in distributed PV projects in Delaware; and
d) Evaluate the benefits and costs associated with electric energy storage systems integrated with PV.
3. CEEP’s Solar PV Diffusion Model Overview

The components of the Solar PV diffusion model are grouped into three main modules:

a) Cash Flow Module, b) Diffusion Module and c) Potential Estimation Module (see Figure 1).

![Figure 1: Overview of CEEP's Bottom-Up Solar PV Diffusion Model](image)

There modules are strongly interconnected. The Cash Flow module estimates the economic performance of PV projects for different commercial and residential customers throughout the analysis period of 2015 through 2040. The Financial performance parameters (i.e., internal rate of return and pay back) from the Cash Flow module are passed to Diffusion module. They are used in the Diffusion module to estimate the maximum market share of PV technology and to project PV adoption rate. The Potential Estimation module estimates the
technical potential of PV based on available commercial and residential roof space in the state.

The total deployment (cumulative and annual installations) of solar PV for each year is estimated by multiplication of technical potential with the maximum market share and the PV adoption rate.

The flowing subsections provide greater detail of each of the modules in question.

3.1. Cash Flow Module

The Cash Flow module is built on the PV Planner© software algorithms developed by CEEP.¹ The PV Planner© software utilizes Typical Meteorological Year 3 (TMY3) data set developed at National Renewable Energy Laboratory (NREL) which relies on over 1,000 weather stations across the U.S. to obtain temperature, insolation and other data relevant to the estimation of PV cell output. The performance of a PV system is reported using several metrics including the payback period and internal rate of return. To obtain these parameters PV Planner© analyzes revenue streams and the lifetime costs associated with PV projects. Because policy is constantly developing (particularly with the addition of new incentives to promote renewables), PV Planner© is regularly updated to reflect new policy measures. Figure 2 illustrates a sample of cash flow analysis generated by the PV Planner© software.

Estimated revenue streams in the Cash Flow module include the value of avoided electricity (savings on energy and demand charges), tax incentives (e.g., investment tax credits and accelerated depreciation) and solar renewable energy credits (SRECs). The value of

¹ For over two decades, the Center for Energy and Environmental Policy (CEEP) has investigated the technical and economic feasibility of using solar electric power (provided by commonly termed ‘photovoltaic’ (PV) technology or ‘solar cells’). CEEP has worked with the U.S. National Renewable Energy Laboratory (NREL) and others for 20 years on the development of PV Planner© software to analyze the benefits of PV technology. PV Planner© utilizes a vast quantity of data to model the physical, economic, financial and policy contexts specific to the area where the PV system is being installed.
avoided electricity depends on PV generation, the electric load profiles of buildings and electric utility rate schedules. The PV Planner© software simulates power generation and building load profiles on an hourly basis, facilitating more accurate estimation of energy and demand bill savings.

Figure 2: Sample of Cash Flow Analysis from PV Planner© Software

For the accurate estimation of demand peak shaving capability of PV systems and their impact on demand bill savings, CEEP researchers used the EnergyPlus simulation software developed by the U.S. Department of Energy (DOE).2 The load profile simulations were based on climatic conditions in the state of Delaware using TMY3 weather data files and building input data files for 15 of DOE’s reference commercial buildings (DOE, 2014). The obtained load

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2 EnergyPlus is a nationally and internationally recognized building energy simulation and load analysis tool. Over the past three decades, this program has been continually developed, upgraded, and enhanced to be one of the most trusted building energy simulation tools available.
profiles for different categories of residential and commercial buildings in Delaware were
combined with PV generation from the available roof space on these buildings. This allowed for
estimation of the peak shaving capability of PV (see Figure 3).

![August Load Profile](image)

**Figure 3: PV Planner© Simulation of PV Impact on Building Electric Load Profile**

Revenue streams from peak shaving and energy savings can be estimated based on
electric utility rate structures. After analyzing the tariff schedules for residential and
commercial buildings and their load profiles, bill savings values are estimated. This approach
allows accurate estimation of potential energy and demand charge savings. Other sources of
revenue are also analyzed. The Cash Flow module utilizes data on the different financial and
tax incentives at the federal and state level.

The Cash Flow module also estimates initial and recurring expenses associated with PV
projects. This includes initial PV system costs, inverter overhaul, and annual operation and
maintenance expenses. Initial system costs represent the main lifetime expense of any PV
Over the past decade initial PV system costs have significantly declined. The future installation cost projections can be conducted through experience curve analysis. Experience curves offer a means of projecting future cost trends based on past cost developments (Neij, 2008).

Experience curves, also referred to as learning curves, describe the link between long-term cost trends and adoption rates for new technologies. In 1936, Wright (1936) was the first to provide a mathematical representation of the experience curve (Duke and Kammen 1999, Argote and Epple 1990). Since then experience curves have become a helpful tool for analysts to assess trends in the cost competitiveness of different technologies (Neij 2008; Poponi et al, 2006; Zwaan and Rabl 2003; Colpier and Cornland 2002; IEA 2000; Reis 1991).

**Figure 4:** Schematic Representation of Learning Curves and Learning Investments
Adapted from (IEA, 2008)
Figure 4 provides a schematic representation of an experience or a learning curve on double-logarithmic scales. On the horizontal axis is the cumulative installation of the technology; on the vertical axis is unit cost of the technology. As cumulative installations grow, so do the producers’ and installers’ experiences leading to reductions in manufacturing and deployment costs.

**Figure 5: Experience Curve for Distributed PV Systems in the U.S. from 1999-2012**


Figure 5 shows historic system cost trends for distributed PV Systems in the US from 1999 through 2012. The trend helps to project future development of PV technology. It is important to provide policy support until a new technology, PV in this case becomes cost competitive with conventional sources. The point at which technology becomes cost
competitive is referred to as the break-even point (see Figures 4 and 5). Experience curve analysis can show the level of investments required to make a technology market competitive. However, experience curves do not forecast when, in time, this break-even point can be reached. Even so, experience curves can be an effective tool for policy makers to set targets and implement measures to enable new technologies to become economically viable.

Experience curve analysis is part of CEEP's bottom-up diffusion model. The system cost projections, obtained through experience curve analysis, provide key inputs in lifetime cost estimates of the Cash Flow model. After combining the revenue streams and lifetime cost estimates, values for payback and internal rate of return are determined. These values are next used in the Diffusion module as input variables for determining diffusion curve parameters and setting the maximum level of PV market share.

3.2. Diffusion Module

A prominent view regarding evolution of new technology holds that technology evolves in three phases, invention, innovation and diffusion (OECD, 2003). Invention refers to the initial development of a scientifically or technologically innovative process or product. Innovation refers to the point when the new product or process reaches the market. Diffusion is the final stage in this evolution, and is the focus of our research. It refers to the process of broad dissemination through which successful innovations come to be widely available through the adoption by individuals and/or firms (Schumpeter, 1942, quoted in [OECD, 2013]).

Nature, markets and technologies experience growth patterns which are usually confined by some limits. These limits could be the size of the potential market, as in the case of technological innovations, or an ecosystem’s carrying capacity, as in the case of animal and
plant populations. The graphical representation of this type of growth resembles an 'S-shaped curve' (Meyer, Yung and Ausubel 1999). The diffusion of innovations, i.e. growth in the market for innovations, such as photovoltaics, computers or cellular phones have also been found to follow an S-shaped or logistic growth curve (Byrne, et al. 2005; Byrne, et al. 2004). Figure 6 depicts this curve.

![Figure 6: Representation of Technology Diffusion by an 'S-Shaped Curve' and its Linear Form](image)

Source: Byrne and Kurdgelashvili, 2011

Logistic growth models have proven to be accurate tools for forecasting a wide range of phenomena, from human population growth (used by Belgian mathematician Pierre Verhulst in 1838) to oil development (Hubbert, 1962; Laherrère, 2000). Often, technologies (e.g. computers or cell phones) grow exponentially during an initial phase. However, as a device eventually reaches saturation in the potential market, the rate of growth slows down and finally tapers off. This methodology is commonly used to anticipate the entry of new technology.
(Fisher and Pry, 1971; Meyer et al., 1999; Woodall, 2000) including new energy technologies such as PVs (EWEA, 1999; Collantes, 2007).

The logistic growth model is a variation of Bass diffusion model. CEEP’s bottom-up diffusion model uses parameters obtained from the Bass diffusion model (Bass, 1969). PV market share for a specific year is projected from these parameters. PV market share for a given year depends on the technical potential of PV (evaluated in the Potential Estimation module), the maximum PV market share and the adoption rate (set by the S-Curve). The maximum market share is a function of the payback time, while the technical potential is a function of PV system performance and available roof space of residential and commercial buildings. The relationship between market share, maximum market share, adoption rate and technical potential is shown below:

\[ PV \text{ Installations} = (Max. \text{ Market Share}) \times (Adoption \text{ Rate}) \times (PV \text{ Technical Potential}) \]

3.3. Potential Estimation Module

Technical potential represents the theoretical maximum amount of PV that can be deployed on residential and commercial buildings. It takes into account only this engineering potential, (hence disregarding all non-engineering constraints such as costs, regulatory constraints, and end user participation). PV technical potential of PV depends on the available commercial and residential roof space and the PV module efficiency assumptions. The technical potential is not fixed, however. It can dynamically change based on roof space additions due to new construction and advances in PV model efficiency. Therefore, the CEEP research team forecast the technical potential for the analysis period of 2015 to 2040 on a
yearly basis taking into consideration the projected available roof space and the PV module efficiency for new projects.

The technical potential estimation methodology consists of a step-by-step process; the first phase of which is estimating roof space available for PV in Delaware for both residential and commercial buildings. In order to estimate technical potential, CEEP research team obtained the most recent data from the US Census Bureau, the Residential Energy Consumption Survey (RECS) and Commercial Building Energy Consumption Survey (CBECS) databases of the Energy Information Administration (EIA) (EIA, 2014a; 2014b).

For example, to estimate the available roof space for different building types in the State of Delaware, buildings are grouped according to 16 commercial building types in the EIA’s CBECS database. These 16 EIA’s building types are then matched with the DOE’s 15 representative commercial building categories (similar breakdowns and groups exist for residential units). The roof space area for each of these 15 building categories is then adjusted using ‘availability coefficients’, which account for building obstructions and panel-to-panel shading.

In area-constrained rooftops, the main factors that limit the nominal capacity and the output of a PV system are structural obstacles on the ground, near-field shading from surrounding equipment, and shading from adjacent rows of PV panels (row shading) (Whitaker et al, 2011). Structural obstacles and near-field shading will determine the total available area for PV installation. After accounting for row shading, the remaining area available for modules can be estimated. Once the available module area is known, the nominal capacity of the PV
system can be determined assuming a value for PV module efficiency. The common approach used for estimating nominal capacity is to avoid near-field and row shading.

To avoid further shading, designers leave some space between PV panels. The size of this space depends on the tilt angle. The linkage of tilt angle and the recommended distance between PV panel rows can be established through Ground Coverage Ratio (GCR) and the related Setback Ratio (SBR). GCR is defined as the PV module area divided by the system area (Culligan and Botkin, 2007). For example, a GCR of 1.0 is realized by a system where the PV modules are laying horizontally on the plane (no tilt) and without space between the PV module rows (see Figure 7 – top Rows of PV Modules). A GCR of 0.5 is realized in a PV system where the module area occupies half of the roof area. The remaining roof area accounts for row shading.

Figure 7: Visual of Ground Coverage Ratio and Tilt Angle
The GCR can also be obtained by the formula:

\[ \text{GCR} = (\cos(\beta) + \text{SBR} \cdot \sin(\beta))^{-1} \]

The variable ‘\( \beta \)’ is the tilt angle. The SBR, or the Setback Ratio is set at around 3 for northern climates (Whitaker et al, 2011).

The PV technical potential for commercial buildings in Delaware will be calculated by multiplying the available roof space by the calculated power density. The power density is proportional to module efficiency and its value reflects improvements in module efficiency for new PV projects.

A similar approach will be used by CEEP researchers in estimating PV technical potential for residential units in the state. In the case of residential units, data on residential buildings stock for attached and detached single-family homes was obtained from the U.S. Census Bureau and EIA’s RECS database. This methodology will be used in finalizing the estimation of PV technical potential for Delaware.
4. Comparison of the CEEP’s Solar PV Diffusion Model with Other Models

This section reviews the analytical tools developed by the National Renewable Energy Laboratory (NREL) and compares their features with CEEP’s bottom-up PV diffusion model. Review of these tools helps to highlight the advantages of developing the new PV diffusion modeling tool.

One of the widely used tools for PV performance estimation is NREL's PVWatts (NREL, 2014a). PVWatts uses TMY2 or TMY3 weather data sets, and conducts hourly simulations over a period of one year. The tool is a web-based, allowing it to be easy accessible. While PVWatts is a useful tool for preliminary estimation of PV system performance, it does not have the robust cash flow analysis capability which is required for a detailed financial performance evaluation. For this task NREL’s Systems Analysis Model (SAM) is more suitable.

SAM is a desktop application that can be downloaded free of charge on personal computers. For the performance evaluation of PV projects, SAM uses various technical, financial and policy related input variables. Users can choose different system sizes, locations, utility rate structures and financial parameters (NREL, 2014b). SAM is an advanced tool for estimating financial performance of individual PV projects. Currently, however, the software does not have the capability to evaluate the impact of PV generation on hourly building load profiles and consequently cannot estimate demand charge reductions due to PV.

Capability to estimate the impact of PV generation on monthly peak demand is a useful feature for more accurate estimation of economic benefits of building integrated PV. Specifically, many commercial customers in addition to energy charges ($/kWh) also pay demand charges ($/kW). These demand charges can be a significant portion of the final utility
bill for commercial customers. Demand charges can potentially be reduced when PV generation coincides with peak demand. These features are an integral part of CEEP’s PV Planner© software which serves as the basis for CEEP’s bottom-up PV diffusion model.

SAM provides economic performance evaluation at the individual project level and it does not model PV adoption at the local or national level. For that task NREL developed the Solar Deployment System (SolarDS) Model. SolarDS is a bottom-up PV deployment model for residential and commercial rooftops in the U.S. (Denholm et al, 2009). The model is comprehensive and is capable of projecting PV deployment under different policy scenarios. However, unlike PVWatts and SAM, SolarDS is not easily accessible to independent scholars. SolarDS is proprietary software developed by NREL and it cannot be accessed or modified by outside researchers. To address these limitations CEEP is developing its own bottom-up diffusion model.

The bottom-up diffusion model developed by CEEP researchers will be able to model the impact of major technological improvements (increased efficiency, reduction in material requirements, reduction in performance degradation, etc.) on the economic performance of specific PV technologies (e.g., CdTe, c-Si, a-Si, multi-junction, etc.) in the State of Delaware. This feature of the PV diffusion model allows for identifying PV market penetration pathways in Delaware based on technology improvements and different policy scenarios (e.g., changing state and federal policies, including net metering rules, RPS, ITC etc.). We believe this will be a significant contribution to the state and it residents as Delaware continues to be a national leader in promoting a sustainable energy future.
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