

# Technical Potential for Solar Photovoltaics in Illinois

May 2013



**CENTER FOR  
RENEWABLE ENERGY**  
*Illinois State University*



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# Center for Renewable Energy



Illinois State University established the Center for Renewable Energy, and it received Illinois Board of Higher Education approval in 2008. The Center was initially funded by a \$990,000 grant from the U.S. Department of Energy to research renewable energy, to establish a major in renewable energy at Illinois State and to administer the Illinois Wind Working Group (IWWG). The Center also received a grant from the Illinois Clean Energy Community Foundation to help complete its state-of-the-art renewable energy laboratory.

The Center has three major functional areas:

- Supporting the renewable energy major at Illinois State University
- Serving the Illinois renewable energy community by providing information to the public
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## Founding Members:

Founding members include EDP Renewables, Iberdrola Renewables, State Farm Insurance, and Suzlon Wind Energy Corp.

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Many new workers will be needed in the renewable energy industry. To meet the growing demand for trained and educated workers, we have developed an interdisciplinary renewable energy major at Illinois State University. Graduates of the renewable energy program are well-positioned to compete for new and existing jobs.

The Center supports the renewable energy major through:

- Creation of an advisory board of outside experts
- Establishing a renewable energy internship program
- Bringing renewable energy experts to campus for seminars for faculty and students
- Funding scholarships to ensure high quality students in the major
- Providing ongoing financial support for the major

For more information about the Renewable Energy Undergraduate Major, please visit <http://tec.illinoisstate.edu/renewable-energy/>.

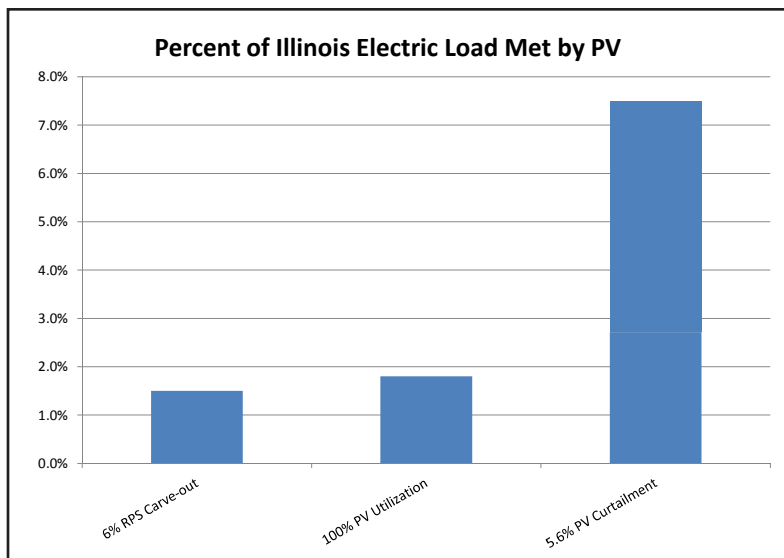


# Executive Summary

The demand for clean, renewable energy production has increased greatly over the past decade due to unstable oil prices, unprecedented peak power demand, and stricter regulations intended to protect the environment and reduce externalities from the consumption of fossil fuels. Although solar photovoltaics (PV) are recognized as a promising source of clean energy production, decision-makers need to know the optimum level of solar PV penetration into the existing generation structure so that the benefit to society can be maximized. As the level of installed PV capacity increases, it is possible that at some point the aggregated generation mix could produce electrical power exceeding electrical demand, thus requiring excessive generator curtailment. Therefore, determining the optimum penetration level of PV is becoming increasingly relevant for both power utilities and policy makers.

In this report, we investigate the optimum installed capacity of grid-connected solar PV systems in Illinois. Three scenarios are studied: a scenario in which the solar carve-out remains at 6% of the state's RPS, a scenario in which all of the PV energy that is generated must be fully utilized, and a scenario in which PV energy is allowed to be curtailed at approximately 5.6%. The conclusions are as follows:

- The level of installed PV capacity corresponding to the current 6% RPS carve-out is slightly less than the level at which 100% of the electricity produced by PV is fully utilized.
- If the optimal level of solar PV penetration is defined as the point at which 100% of the electricity produced by PV is utilized, then the state's solar carve-out could be increased to 7.3%, which would meet approximately 1.8% of Illinois' total electric load.
- If we allow some of the electricity produced by solar PV to be curtailed, the installed PV capacity could increase even more. If solar PV is allowed to be curtailed at the same rate that conventional thermal plants typically use electricity for their own internal operation (approximately 5.6%), then the solar carve-out could be increased to 29.8%, and solar PV could produce approximately 7.5% of Illinois' total electric load.



*Photo Source: Illinois Department of Commerce and Economic Opportunity*

# 1. Introduction

## 1.1 Utility-Scale Solar Photovoltaic Systems in the U.S.



*Photo Source: Illinois Department of Commerce and Economic Opportunity*

Countries across the world are beginning to reduce their dependence on fossil fuels by integrating renewable energy electricity generation sources into their electric grids. The United States, too, is increasing the amount of electrical generation it produces from renewable resources, and as one result of this shift, utility-scale solar installations in the U.S. have grown rapidly over the past few years. While a residential PV system generally comprises only a few solar panels and 5 to 20 kilowatts of capacity, utility-scale plants have capacities of 1 megawatt (MW) and above [1]. According to the National Renewable Energy Laboratory, as of April 2012 there were 42 utility-scale solar systems operating in the U.S. and another 161 systems under development [2]. Including all types of photovoltaics, the U.S. installed approximately 1,600 MW of grid-connected solar photovoltaic (PV) capacity in 2011, a 74% increase over the 918 MW installed in 2010 [1, 3], and between 2000 and 2011 the cumulative installed capacity grew from 200 MW to 3,500 MW [2]. Although this growth rate is impressive, the United States has begun to lag behind a number of other developed countries in newly installed capacity of solar photovoltaics.

There are at least four reasons for this rapid growth of utility-scale solar PV systems. First, the cost of PV systems has declined dramatically over the past decade. According to the Solar Energy Industries Association, utility system prices in the U.S. declined for the ninth consecutive quarter, dropping from \$3.20/Watt of installed capacity in the fourth quarter of 2011 to \$2.90/Watt in the first quarter of 2012, and then to \$2.60/Watt in the second quarter of 2012 [4], largely due to a decline in solar module (colloquially called solar “panel”) prices. The second reason for the rapid growth in utility-scale solar PV systems is that technological advances have led to the development of new materials and better manufacturing processes, increasing efficiency and reducing the levelized cost of energy from utility-scale solar PV systems. Third, many states in the U.S. have introduced renewable portfolio standards (RPS) where an increasing percentage of the state’s electricity must come from renewable energy. In some cases – including Illinois – the RPS includes a solar “carve-out” specifying that a portion of the renewable requirement must be provided by solar energy. This has created a demand for solar energy, especially large utility-scale solar energy systems that are typically cheaper to construct and easier to track for compliance with these renewable portfolio standards. Finally, the federal government and a number of state governments offer financial incentives to encourage the deployment of solar projects. Because the financial incentives differ between states, the growth of solar energy generation across states is unequal even among states that have similar renewable portfolio standards.



New Jersey, Arizona and California are the top three U.S. states for utility-scale solar installations. Illinois ranks eighteenth in total installed solar photovoltaic capacity (Fig. 1) and twenty-third in new installations of any type of solar PV system (not just utility-scale) [5]. As of January 2013, Illinois has three utility-scale solar farms in operation: Exelon City Solar is a 10 MW installation on the south side of Chicago, Grand Ridge Solar Farm is a 20 MW installation near Streator, IL, and the Rockford Solar Farm is a 3 MW installation near the Chicago Rockford International Airport. The question, therefore, is why New Jersey is one of the leading states for solar energy while Illinois – which has nearly identical solar resources – lags behind.

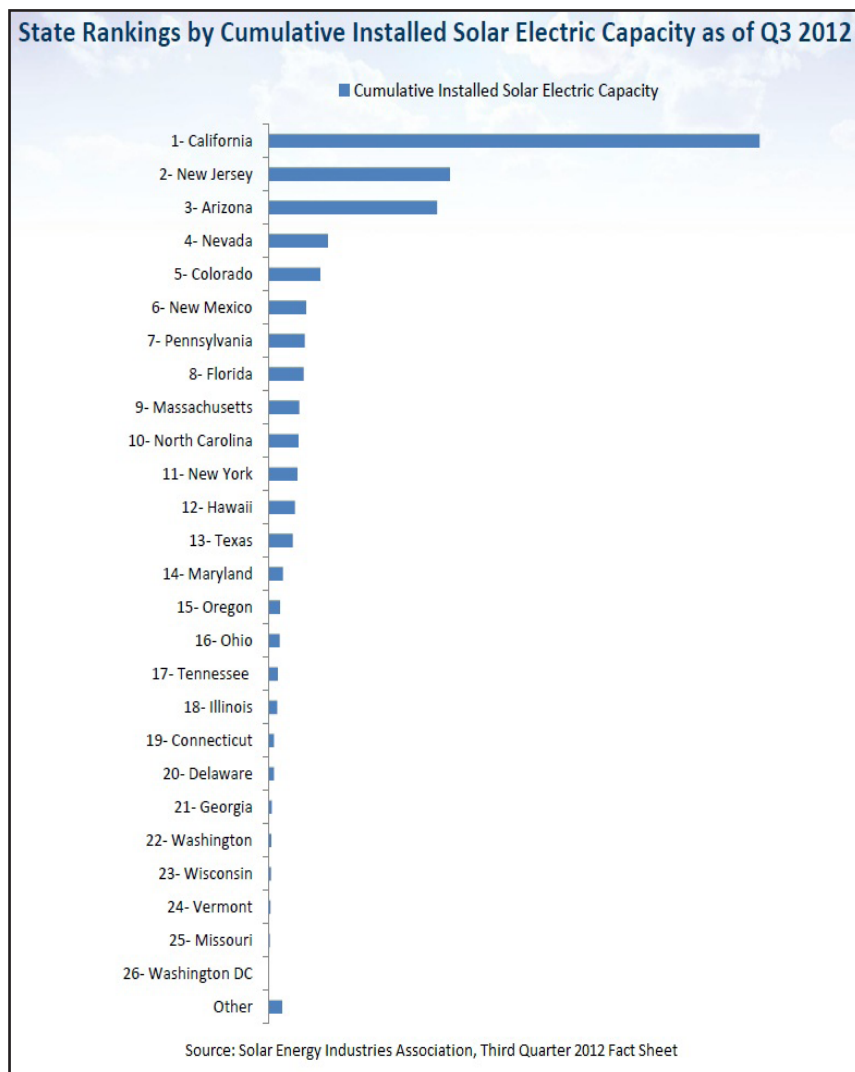


Figure 1.— State Rankings by Cumulative Installed Solar Electric Capacity



Photo Source: NREL, Jamie L. Keller



*Photo Source: Illinois Department of Commerce and Economic Opportunity*

The simplest reason why New Jersey is more advanced in solar installations than Illinois is because of differences in state policy. Beginning in 1999, New Jersey implemented a set of stable policies that incentivized the building of solar systems, and this led to a rapid growth in solar PV systems in the state. Illinois policy is catching up, however: in August 2007 the state passed an RPS requiring 25% of Illinois' eligible electricity consumption to be sourced from renewable resources by the year 2025. The RPS was created as part of the Illinois Power Agency Act (IPAA), which also designated the Illinois Power Agency (IPA) as the organization responsible for meeting these goals [6]. The RPS was later amended to include a solar carve-out requiring that 6% of the renewable energy procured under the RPS must be produced from solar energy. This is equivalent to 1.5% of the state's total annual eligible retail electricity sales by the year 2025. The role of the IPA and the procurement of renewable electricity continue to evolve, however, due to the recent move by some communities towards municipal aggregation. Communities that choose to procure electricity through municipal aggregation are free to purchase electricity from any source they desire – including solar photovoltaics. However, these purchases are not bound by the RPS, and the procurement of the electricity does not involve the IPA. As a result of this reduced load seen by the IPA, the IPA does not currently have plans to procure additional renewable energy until at least 2018.

Given the state's new regulations requiring electricity production from solar sources and the increasing installed capacity of solar PV systems, both researchers and local policy makers are now asking whether there is an optimum level of solar PV capacity penetration into the state's existing generation structure under the current fuel mix for the region. As the level of PV generation capacity increases beyond a certain point, the electricity generated from solar PV systems may be wasted if the energy being generated by PV and other sources exceeds the electrical demand at the time, unless energy storage systems can support the solar PV system. For the purpose of this report, we will neglect energy storage, and instead assume that any power generated in excess of what the system demands at a particular moment will be wasted, or "curtailed."

## 1.2 Previous Research

A variety of research has been completed regarding the effects of increasing photovoltaic penetration. For example, previous research has analyzed the potential for solar PV to be deployed on a very large scale to examine how the hourly availability of PV interacts with the limited flexibility of traditional electricity generation plants. Other research has combined the effects of additional solar energy with the effects of additional energy from other renewable resources such as wind and wave power. Still others have assessed the impact of large-scale solar development in the state of Wisconsin. For more information on this previous research, see Denholm and Margolis [7], Lund [8], and Myers et al. [9].

Although previous research studies and collaborative reports presented at industry solar conferences have attempted to address the limitation of large-scale PV deployment, few have assessed the optimum level of PV penetration into existing electrical power systems in the near and long terms. Additionally, none have evaluated large scale PV applications to provide an



approach that should be used to determine the optimum level for seamlessly integrating PV systems into the current generating structure. Finally, a suitable method for evaluating the effectiveness of state RPS plans has not been suggested.

Given the limited applicability of previous studies to the current situation in Illinois, the objectives of this paper are to first examine the feasibility of the solar carve-out specified in the current Illinois RPS plan and second, to determine the optimal level of PV energy generation in Illinois. The 6% carve-out specified in Illinois' RPS represents a political compromise rather than a carefully considered view based on technical feasibility. Therefore, this investigation of the optimal solar penetration rate based on the state's solar radiation and hourly electrical demand is both timely and necessary. However, there are multiple ways to define the optimal level of PV generation. One possible criterion for determining the optimal level is to aim for a level of solar capacity such that no solar energy is generated that would be wasted at any time. This is a very stringent criterion, however, because the total amount of PV installed would be limited by only a few time periods during the year during which PV irradiance is high and electrical demand is low. It is possible that the benefit of additional PV capacity during times of high electrical demand would outweigh the possibility of having to curtail output during occasional periods of low electrical demand. Thus, an alternative criterion for optimal PV generation level is to allow some hours with excess solar power (which will be curtailed), but to limit the percentage of time during which output is curtailed to some small percentage. The exact rate at which PV energy is allowed to be curtailed is somewhat arbitrary, and in actuality will vary depending on economic factors beyond the scope of this report. For the sake of a convenient reference point, we will allow PV energy to be curtailed at the same rate that energy is typically consumed internally by thermal plants (e.g. coal, nuclear) to maintain their own operation.

A summary of the three research questions that guided our evaluation is:

- Given the current solar carve-out of 6% specified in the state's RPS, how many Megawatts of capacity must be installed by 2025?
- Can Illinois fully utilize all of the solar energy that will be produced as a result of the 6% carve-out without wasting a portion of the generated electrical energy? If so, how much PV could be installed in Illinois while maintaining 100% utilization of the energy that is produced by the systems?
- How much of Illinois' electrical energy could PV supply if curtailment of the PV output is occasionally permitted? For this analysis, curtailment will be allowed at a rate equal to the typical internal energy consumption at thermal generation facilities.

## 1.3 Research Questions

## 2. Data Collection

### 2.1 Illinois Electricity Demand

The electric grid in Illinois consists of two regional transmission organizations (RTOs): PJM Interconnection (PJM), which covers the northern part of Illinois including the greater Chicago area, and Midwest ISO (MISO), which covers the rest of the state. Although PJM and MISO coordinate the transmission of wholesale electricity in many states, only the Illinois portion of their data was gathered and analyzed in this study. The hourly electrical demand data used for analysis in this study is based on 2010 load data collected from PJM and MISO. The hourly electrical demand may also be interpreted as the hourly average electric power consumption. For the purposes of this analysis, all references to power production or consumption refer to hourly average power production or consumption.

Power demand fluctuates over the course of a day. Many variables affect electrical power demand, such as the time of day, day of the week, and outside temperature. Generally speaking, however, electrical power consumption follows a relatively predictable daily trend. Electrical power demand is lowest in the early morning, climbs throughout the day, peaks in the late afternoon and early evening hours, and then declines through the evening. A graph of Illinois' total electrical power demand on an average day is shown in Fig. 2.

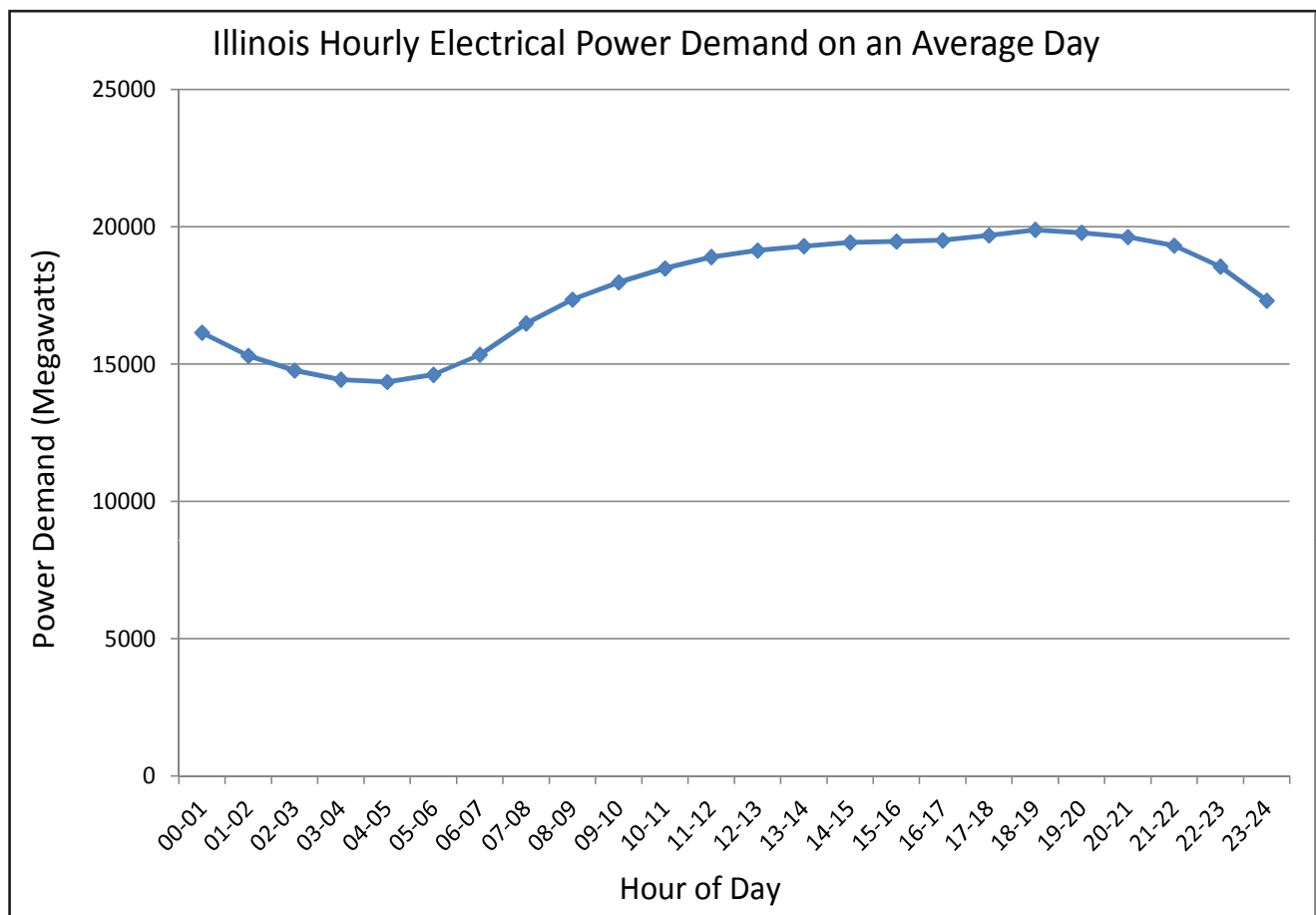


Figure 2.—Average Hourly Illinois Electrical Power Demand (aggregate Illinois load)



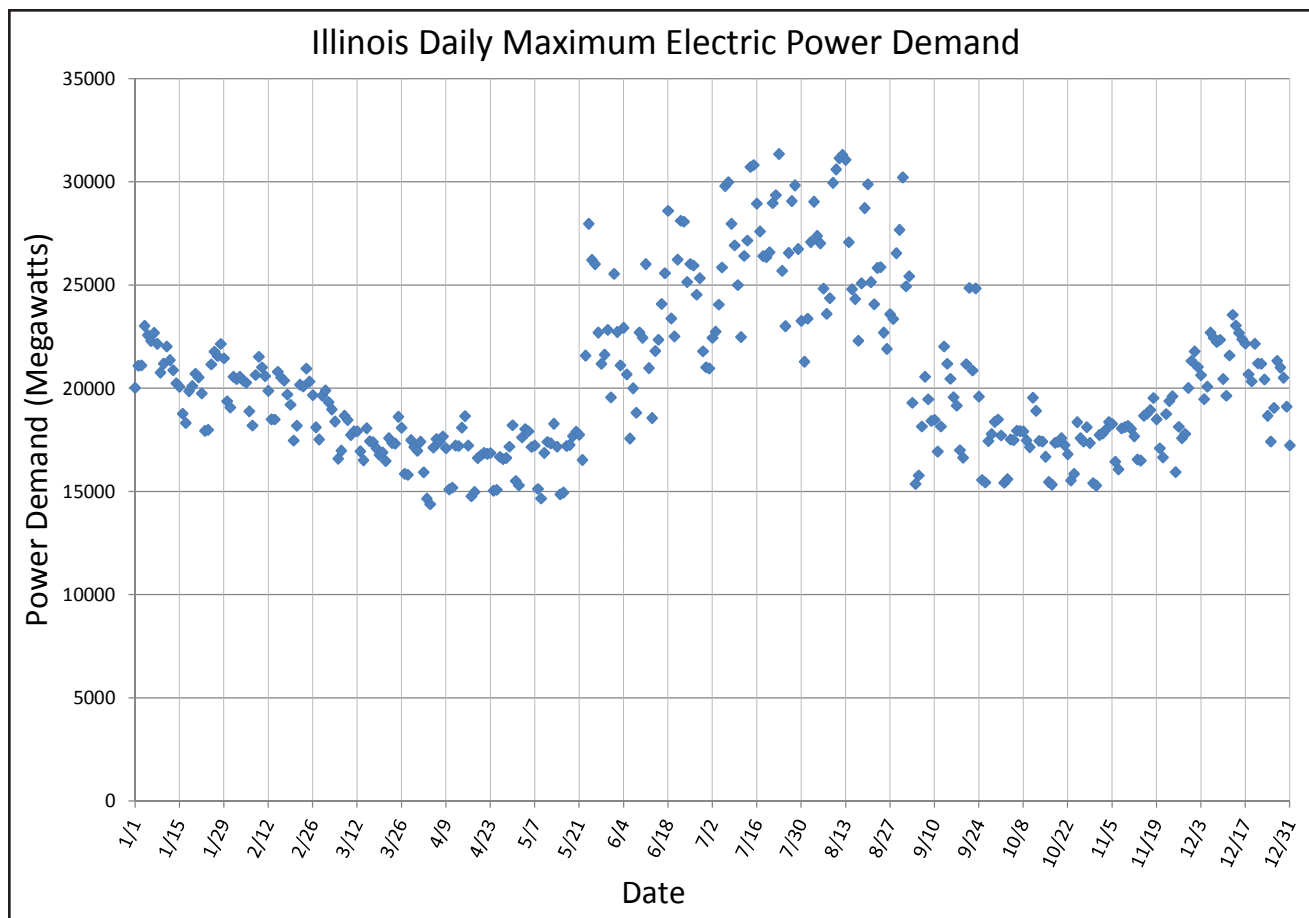


Figure 3.—Daily Peak Electrical Power Demand (aggregate Illinois load)

The general daily power demand trend shown in Figure 2 holds true throughout the year, but the actual power demand (the scale of the vertical axis) varies from day to day. For example, the peak electric power demand is much higher during hot summer months, when homes and businesses run air conditioners to keep buildings cool. Conversely, the peak electric demand is lower than average during the spring and fall, when outside temperatures are moderate. A graph of peak daily electric load for the state of Illinois over the course of a year is shown in Figure 3.

Figure 3 shows the daily peak electric load over the course of a year, but it still does not tell the full story. In order to understand how photovoltaics could integrate into the existing electric infrastructure, we need to know how much time the grid is loaded at various “load fractions.” Load fraction is equal to the electric load at a particular time divided by the maximum annual electrical load during the entire year. For example, if the peak electric load for the year (likely occurring during a hot summer afternoon) is 1,000 MW, and the load at a particular time is 500 MW, then the load fraction at that time is 50%.

In order to better visualize the characteristics of the Illinois electric load, a histogram of the total Illinois load fraction vs. time is shown in Figure 4. The histogram in Figure 4 plots the aggregate Illinois load for 2010 divided into 5% load fraction bins (e.g. 95-100% of peak load, 90-95% of peak load, etc.). The plot illustrates the fraction of the year that the system was operating within each range of aggregated electric load. As shown in Figure 4, the system operated for the greatest number of hours at a load between 50 and 55% of peak load. This loading condition accounted for 23.3% of the time during the year (2038 hours out of 8760 hours). The system was loaded below 70% of peak load for 88.3% of the year. It is also worth noting that the system operated at 95-100% of peak load for only 0.56% of the year (49 hours). These hours generally occurred in the afternoons of hot summer days.

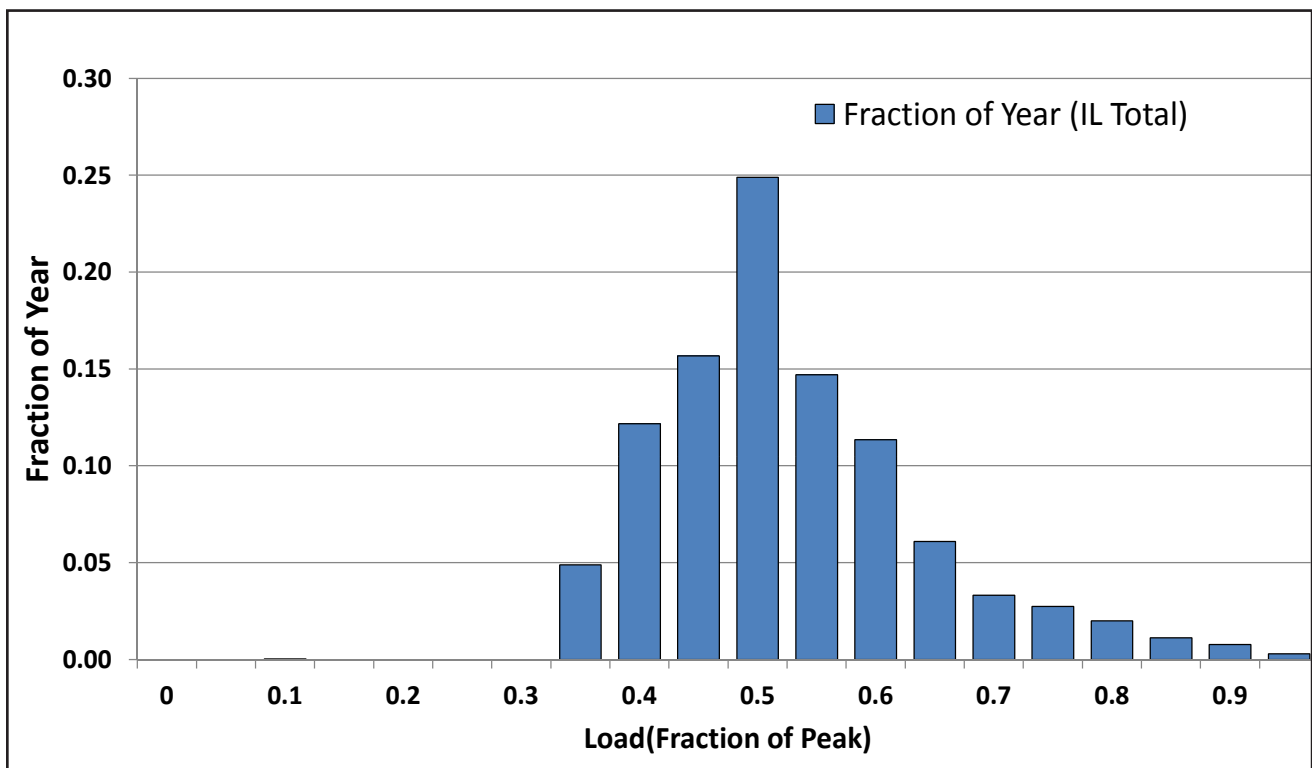


Figure 4.—Histogram of the system load fraction for 2010 (aggregate Illinois load)



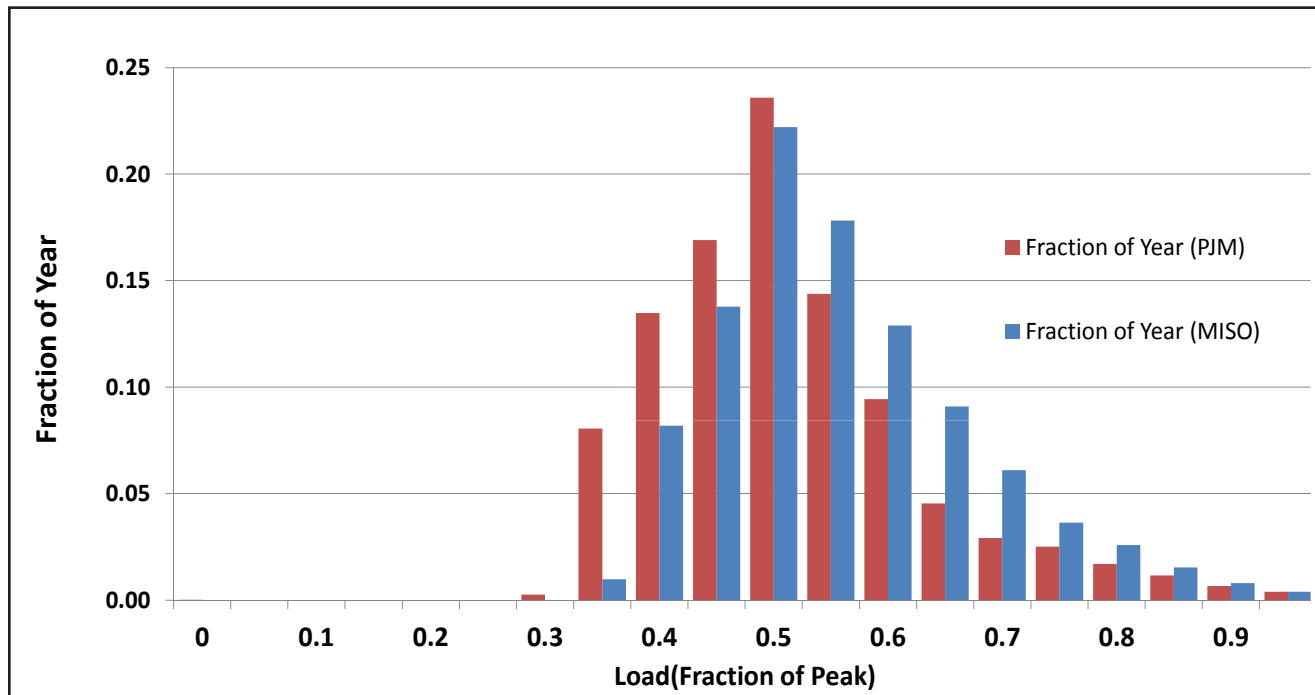


Figure 5.—Histogram of system load fraction for 2010 (PJM and MISO load)

In Figure 5, a similar histogram shows the differences in load fractions between Illinois PJM loads and Illinois MISO loads. This histogram is useful because it shows the differences in load fractions between the two systems. As we will see, these differences will affect the way that solar photovoltaic systems complement the existing system.

As you can see in Figure 5, the load fraction of peak demand above 0.5 in the MISO region was considerably higher than in the PJM region (6749 hours compared to 5368 hours). In other words, the MISO region typically operated closer to its peak power demand, whereas it was more common for the PJM region to operate farther from its peak power demand. The higher peak load fractions, especially load fractions above 0.7, occurred mostly in the summer months. This effect can be explained by the impact of climate differences between the two regions – specifically, the impact of summer air-conditioning loads, as most Illinois customers rely on electricity for air-conditioning. To measure the difference in air-conditioning load between the two zones, we can use the difference in cooling degree days between the two regions. A cooling degree day is a convenient proxy to relate daily temperatures to the energy demands of air conditioning.<sup>1</sup> The normal cooling degree days in Chicago (representative of PJM load) and Springfield (representative of MISO load) were 835 and 1,165, respectively [10]. The MISO region's higher value for cooling degree days indicates that it is likely to consume a greater percentage of its annual electric energy demand during the summer months due to this increased cooling demand, which is reflected in the higher load fractions for the MISO region shown in Fig. 5.

<sup>1</sup>The number of cooling degree days are calculated by subtracting 65°F (approximate room temperature) from each day's average temperature, and then summing the results over the year to give a value for annual cooling degree days [10].



*Photo Source: Illinois Department of Commerce and Economic Opportunity*

Another useful way of visualizing the electric system utilization is to sort the hourly load fractions from highest to lowest, and then plot the data points. The result will be 8,760 data points – one for each of the 8,760 hours of the year. We would expect a very few points to have very high load fractions (e.g. corresponding to hot summer afternoons), a few data points to have very low load fractions (e.g. the middle of a night with pleasant temperatures), and the vast majority of points to have load fractions that are somewhere between the two extremes. The total Illinois load fraction vs. time is plotted in Figure 6, and the resulting “load duration curve” looks much as we would expect. This turns out to be a very useful plot.

As the level of PV generation capacity increases, power generation from PV can begin to offset other forms of power generation. Electricity generated from PV may offset variable, or “peaking” load without significant negative consequences. However, traditional thermal baseload power generation equipment – for example, nuclear or coal power generation plants – cannot reduce their power output below a minimum threshold without significant economic penalty. Therefore, a minimum loading condition must be maintained on the thermal baseload generators [7, 9]. The value of this aggregated minimum loading condition is dependent upon the particular fuel mix being used within a region. It is therefore necessary to identify the minimum loading condition in Illinois in order to establish how much of the net load could potentially be replaced by alternative power sources. By inspection of the load duration curve in Figure 6, we can see that the minimum load fraction that actually occurred during the year was approximately 35%. Therefore, for the purposes of this study, we will require that a minimum loading condition of 35% of the 2010 peak load be maintained on thermal generation plants at all times. Any load fraction above 35% may potentially be produced by an alternative generation source such as photovoltaics.

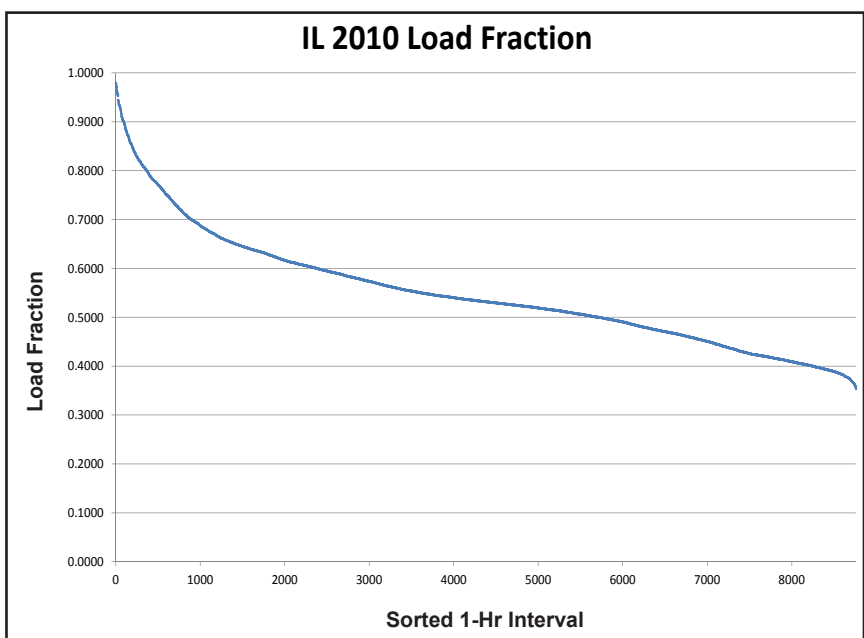


Figure 6.—Load duration curve normalized by peak system load

## 2.2 Illinois Electricity Subject to RPS Requirements

Illinois' RPS requires that 25% of the state's eligible retail electricity sales must come from renewable sources by 2025 [6]. Three quarters of the RPS requirement must come from wind power generation, and 6% of the requirement must come from solar power generation. However, not all electricity that is consumed in Illinois is subject to the requirements of the RPS. Most notably, rural electric cooperatives and municipal electric utilities are not subject to the RPS [6]. Therefore, the electrical load from rural electric cooperatives and municipal electric utilities was excluded from our analysis.

The total load for all of Illinois' rural electric cooperatives was 6,291,867 MWh in 2010 [11]. The total load for all of the municipal electric utilities in Illinois in 2010 was 4,211,874 MWh [12]. As the total annual Illinois load was 187,875,624 MWh, the Illinois load subject to the RPS requirements was therefore 177,371,883 MWh after excluding the net load from the state's rural electric cooperatives and municipal electric utilities. All references in this report to total Illinois power or energy refer only to the retail electricity sales eligible under the state's RPS.

Electricity that is procured by communities through municipal aggregation is also not subject to the RPS. However, some communities may elect to purchase electricity that is supplied – at least in part – by renewable energy sources. Thus, the long-term effects of municipal aggregation on the supply and demand of solar photovoltaics in Illinois are unknown. For the purpose of calculations in this report, the decline of electricity purchased by the IPA and the rise of renewable energy purchased directly by communities are assumed to cancel each other out, and the net effect on solar photovoltaic installations in Illinois is assumed to be negligible.

Climate data from the 1991-2005 National Solar Radiation Database (NSRDB) known as TMY3 (Typical Meteorological Year 3) and including hourly temperature, humidity, wind, and solar radiation was utilized to run photovoltaic simulation models for the study [13,14]. The selected TMY3 weather stations in Illinois are Chicago O'Hare Airport and Springfield Regional Airport. These stations represent the solar radiation available for the PJM and MISO regions, respectively. Both data sets are categorized as Class I, indicating sites with the lowest uncertainty data [14].

## 2.3 Illinois Weather Data



Photo Source: NREL, Dennis Schroeder



## 3. Methodology

### 3.1 Optimization Matrix for Large-Scale PV System Applications

Because a high level of PV installed capacity could occasionally produce more power than is needed at the time, some of the electricity generated from a PV system could be wasted under certain circumstances. For example, excess electricity could be generated during times of high solar irradiance and low electricity demand. To identify the optimum level of PV penetration that minimizes this wasted electricity and to determine the level of PV capacity that meets the RPS requirement, we developed the Renewable Energy Optimization Matrix (REOM) based on 8,760 load data points and simulated PV generation potential at each hourly time segment based on the NSRDB climate data for the region.

The first step in the analysis is to calculate the total electric energy consumed in the year 2010. This is done by summing the data points for each of the 8,760 hours in 2010. This can be written as a succinct equation by using the summation symbol  $\Sigma$ , as in Equation 1. The next step is to calculate the total Illinois electric load for the year 2025. The year 2025 was targeted to assess the 6% solar carve-out goal because 2025 is the year when the Illinois RPS reaches its maximum of 25% renewable energy. The total Illinois electric load in 2025 was calculated by applying a growth rate “ $\alpha$ ” to the recorded 2010 data (Eq. 2). The growth rate “ $\alpha$ ” was calculated from PJM and MISO energy demand projections for 2025; annual growth rates of 1.7% and 1.125% were calculated for the PJM and MISO regions, respectively.

$$E_{T2010} = \sum_{i=1}^{8760} (P_i \times 1 \text{ hr}) \quad \text{Eq. 1}$$

$$E_{T2025} = E_{T2010} \times (1 + \alpha)^{15} \quad \text{Eq. 2}$$

As discussed previously, the baseload power from thermal electric generation units cannot be replaced with alternative power sources. This required minimum baseload from thermal generation,  $P_B$ , is equal to the peak power demand multiplied by the minimum load fraction of 35%, as shown in Section 2.1 (Eq. 3).

$$P_B = (\text{Peak power}) \times 35\% \quad \text{Eq. 3}$$

Therefore, the electric power that is replaceable ( $P_R$ ) by alternative generation sources at a particular point in time is equal to the power demanded by the electric grid system at that point in time, minus the required minimum baseload  $P_B$  (Eq. 4). Note that the subscript  $i$  denotes that the quantity is time-dependent, where  $i$  represents the particular point in time.

$$P_{R_i} = P_i - P_B \quad \text{Eq. 4}$$

The power that could be replaced by alternative generation sources at a point in time ( $P_{R_i}$ ) was then compared to the modeled PV power production at that point in time under various PV installation scenarios ( $P_{PV_i}$ ). When  $P_{R_i}$  is greater than or equal to the power generated from PV ( $P_{PV_i}$ ), then the PV power utilized ( $P_{PV \text{ utilized}_i}$ ) by the electric grid is equal to  $P_{PV_i}$  (Eq. 5), and no PV power is rejected (Eq. 6). During those times when  $P_{R_i}$  is less than  $P_{PV_i}$ , however, the electric grid cannot utilize all of the power that is produced by PV, so  $P_{PV \text{ utilized}_i}$  is equal to  $P_{R_i}$  (Eq. 7), and the PV power that is rejected ( $P_{PV \text{ rejected}_i}$ ) is equal to  $P_{PV_i}$  minus  $P_{R_i}$  (Eq. 8).

When  $P_{R_i} \geq P_{PV_i}$  :

$$P_{PV \text{ utilized}_i} = P_{PV_i} \quad \text{Eq. 5}$$

$$P_{PV \text{ rejected}_i} = 0 \quad \text{Eq. 6}$$

When  $P_{R_i} < P_{PV_i}$  :

$$P_{PV \text{ utilized}_i} = P_{R_i} \quad \text{Eq. 7}$$

$$P_{PV \text{ rejected}_i} = P_{PV_i} - P_{R_i} \quad \text{Eq. 8}$$

These equations were applied to all 8,760 hours of the year and summed to quantify the annual energy produced by PV (Eq. 9), the total utilized energy from PV generation (Eq. 10), and the total rejected energy from PV generation (Eq. 11).

$$E_{PV} = \sum_{i=1}^{8760} (P_{PV_i} \times 1 \text{ hr}) \quad \text{Eq. 9}$$

$$E_{PV \text{ utilized}} = \sum_{i=1}^{8760} (P_{PV \text{ utilized}_i} \times 1 \text{ hr}) \quad \text{Eq. 10}$$

$$E_{PV \text{ rejected}} = \sum_{i=1}^{8760} (P_{PV \text{ rejected}_i} \times 1 \text{ hr}) \quad \text{Eq. 11}$$



Photo Source: Illinois Department of Commerce and Economic Opportunity



Photo Source: NREL, Dennis Schroeder

To calculate the PV utilization rate (the percentage of PV energy that is actually used) the total utilized PV energy is divided by the total energy generated by PV over the year (Eq. 12). Then, the percentage of Illinois load that is met by PV in the year 2025 is calculated by dividing the total utilized PV energy by the Illinois 2025 load (Eq. 13). Finally, the percent of the RPS met by PV energy is calculated by dividing the total utilized PV energy by the RPS energy requirement, which is equal to 25% of eligible retail electricity sales in the year 2025 (Eq. 14).

$$PV \text{ Utilization Rate} = \frac{E_{PV \text{ utilized}}}{E_{PV}} \quad \text{Eq. 12}$$

$$IL \text{ Load from PV} = \frac{E_{PV \text{ utilized}}}{E_{T 2025}} \quad \text{Eq. 13}$$

$$IL \text{ RPS from PV} = \frac{E_{PV \text{ utilized}}}{0.25 \times E_{T 2025}} \quad \text{Eq. 14}$$

Three scenarios were examined using the preceding analysis, corresponding to each of the three research questions posed in Section 1.3. Scenario 1 considers the amount of PV capacity that will be required to meet the RPS requirement, specifically, the 6% solar carve-out. Scenario 2 was designed to determine the level of PV capacity where all of the energy generated from PV is utilized 100% of the time. Finally, Scenario 3 represents the case where electricity generated from PV is allowed to be curtailed at the same rate that energy is typically “wasted” due to internal energy consumption at thermal generation plants. Annual electricity consumption for internal thermal plant operation averages 5.58% of the gross generation of electricity in the US [15]. Therefore, Scenario 3 requires that the PV energy be utilized at a rate greater than 94.42%.

To accurately determine the amount of installed PV capacity that will result in a given level of PV energy under all three scenarios, the efficiency of the solar modules and associated equipment (inverter, transformer, connections, etc.) were considered and accounted for in the simulation software. In addition, because the majority of the generation is assumed to come from large solar farms, the electric energy will be transmitted over the transmission grid. Therefore, transmission and distribution losses were considered. According to the U.S. Energy Information Administration (EIA), average electricity transmission and distribution losses in the U.S. are approximately 7% of the generated electrical energy [15]. We applied this average loss to the PV generation power outputs to reflect the difference between generated and delivered electrical energy.



## 3.2 Photovoltaic Performance Model

The System Advisor Model (SAM) software developed by the National Renewable Energy Laboratory (NREL) was selected as the platform to perform the simulations and calculations in this study. SAM is based on an hourly simulation engine that interacts with performance and finance models to calculate energy output, energy costs, and cash flows [16]. We used SAM software to model a 100 kW reference system that will simulate PV system performance in the two solar radiation regimes in this study, and then scaled the output to replicate the regional solar PV applications in Illinois.

The amount of energy generated by any PV system is dependent on the amount of solar radiation that is received. To reflect the different solar radiation levels available in the PJM and MISO regions, we simulated two reference PV systems: one located in the PJM region, and one located in the MISO region. Fig. 7 represents the projected monthly outputs from reference systems in the PJM and MISO regions. Overall, the MISO region will have higher monthly outputs due to more plentiful solar radiation compared to the PJM region.

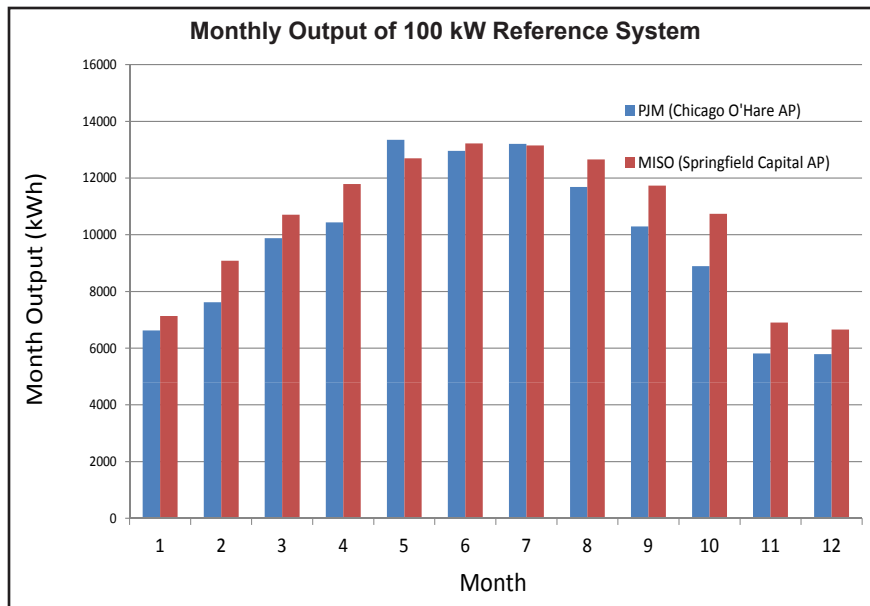


Figure 7.—Monthly AC Output per 100kW of installed system capacity in PJM and MISO regions in Illinois

Although this study focused primarily on determining the optimum level of PV system capacity, the indirect benefits of regional-scale PV installations such as lower GHG emissions and reduced water use were also evaluated. This analysis was based on our PV system simulation results and data associated with reduced electricity generation from conventional fossil fuel plants replaced by solar PV systems [17]. Based on actual figures for electricity generation by energy sources in Illinois [18] and a study of power plants and their respective water consumption in the US [19], the indirect benefits for each of the case scenarios were quantified.

## 3.3 Evaluating Indirect Benefits

## 4. Results

### 4.1 Analysis

The PV capacity and electrical generation potential were estimated for each of the three case scenarios. To reflect differences in the solar radiation levels between the PJM and MISO regions, the simulation models were performed individually based on geographical weather information for each of the two regions. The results of the simulations are shown in Figure 8 for the PJM region and Figure 9 for the MISO region. The solid line in each figure shows the percent of PV energy that is actually utilized on the left vertical axis vs. the amount of PV installed capacity as a percent of peak demand on the horizontal axis. For convenience, the right vertical axis shows the total amount of installed PV capacity in Megawatts (MW), and the dotted line shows the relationship between installed capacity in MW and installed capacity as a percent of peak demand. The intersection of the dotted and solid lines is not meaningful.

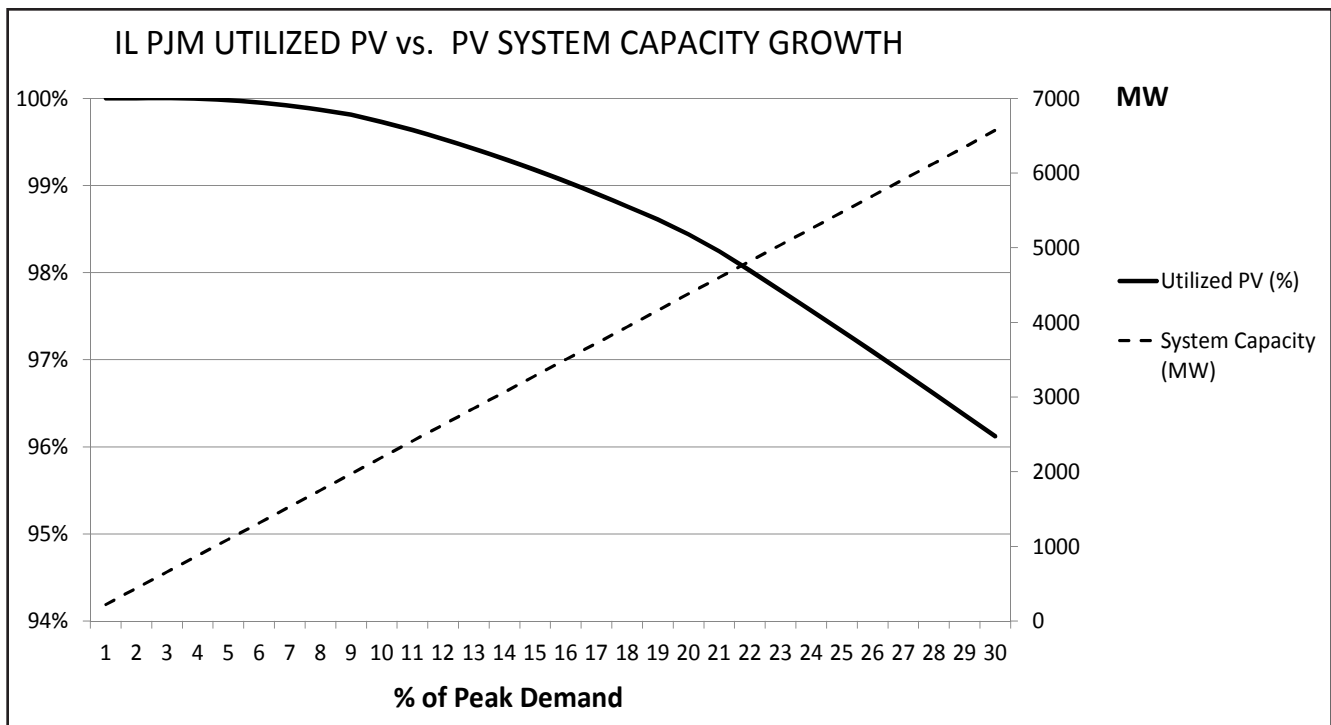
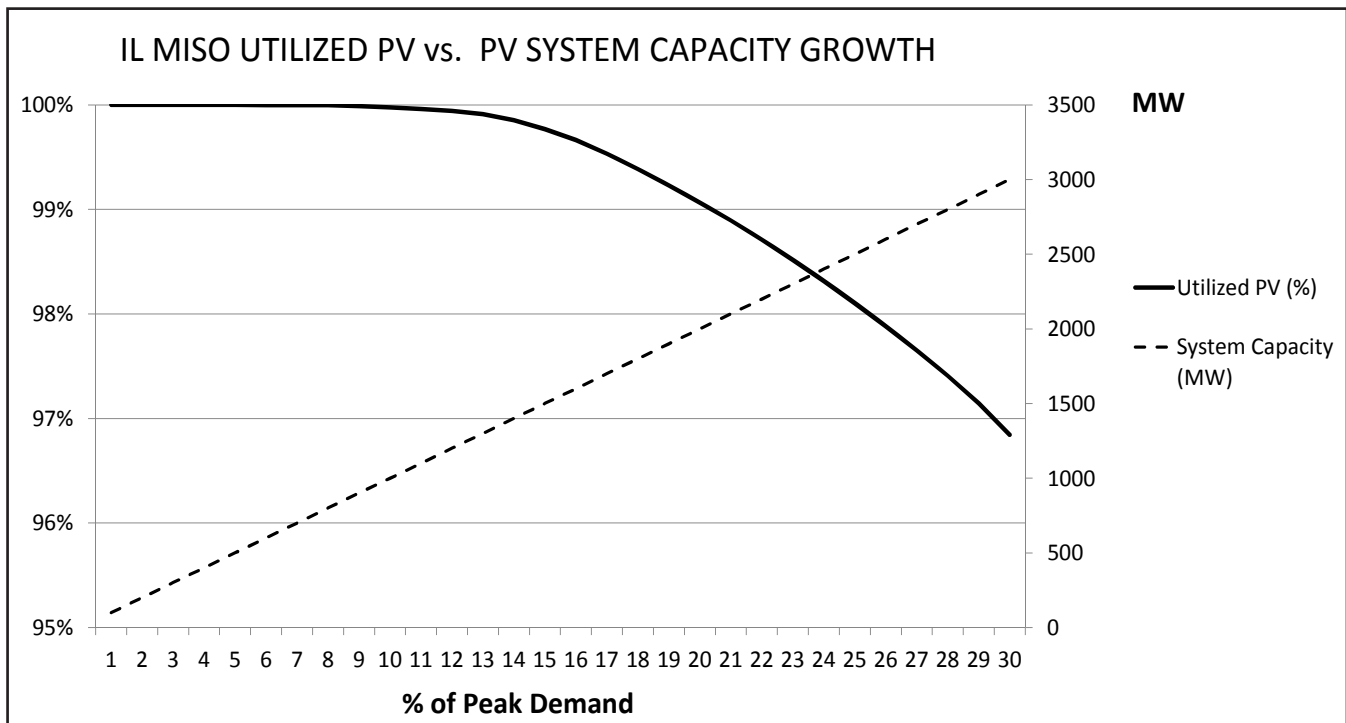


Figure 8.—Utilized Solar Generation vs. Nameplate Capacity in the PJM Region

When installed PV capacity is small, 100% of the PV energy will be utilized. This is because small amounts of PV energy added to the system do not ever exceed the replaceable power  $P_{R_i}$  that was calculated in Eq. 4. As installed PV capacity increases beyond a certain point, however, the amount of power produced by the PV systems  $P_{PV_i}$  will occasionally exceed the replaceable power  $P_{R_i}$ , in which case the excess PV power will be curtailed, and the overall PV utilization rate will drop.



**Figure 9.— Utilized Solar Generation vs. Nameplate Capacity in the MISO Region**

As Fig. 8 and Fig. 9 reveal, the rate of PV utilization starts to drop off at about 6% of the peak demand (1300MW) in the PJM region and about 12% (1,400MW) in the MISO region. The utilization rate therefore starts falling at different capacity levels for the two different regions in Illinois. This is mainly due to the higher fraction of peak demand above 0.5 in the MISO regions, as shown in Fig. 5. The majority of these higher fractions of peak demand in the MISO region occur in the summer months during periods of higher cooling demand. These time periods also frequently correspond to periods of high solar irradiance. This explains the ability for PV capacity in the MISO region to provide a greater utilization rate than in the PJM region, for a given level of installed PV capacity as a percent of peak demand. As the MISO region has more cooling degree days, this suggests that it can accommodate a higher solar PV penetration rate since the higher cooling demand can be leveraged by the increased electrical generation from solar. Therefore, a 100% PV utilization rate can be maintained at a higher PV system penetration rate in the MISO region as compared to the PJM region, as shown in Fig. 8 and Fig. 9.

Although the qualitative effects can easily be seen in Figures 8 and Figure 9, the specific quantitative answers to the research questions are not easily discerned. For this purpose, Table 1 presents the three scenarios and their results from the analysis and the SAM simulation model.



**Table 1.—Solar PV installations and generation potentials under three scenarios**

		6% Carve-Out	100% Utilization (None Wasted)	94.4% Utilization (Thermal Plant Use Match)
PJM Region	System Capacity (MW)	1,577	1,314	7,665
	Electricity Delivered (MWh)	1,800,190	1,500,158	8,750,924
	Load Demand met in PJM (%)	1.5	1.3	6.9
MISO Region	System Capacity (MW)	715	1400	3600
	Electricity Delivered (MWh)	885,573	1,733,989	4,458,830
	Load Demand met in MISO (%)	1.5	3.0	7.2
Total	System Capacity (MW)	2,292	2,714	11,265
	Electricity Delivered (MWh)	2,685,763	3,234,147	13,209,754
	Load Demand met in IL (%)	1.5	1.8	7.5
	RPS met in IL (%)	6.0	7.3	29.8

## 4.2 Research Question #1

**Given the current solar carve-out of 6% specified in the state's RPS, how many Megawatts of capacity must be installed by 2025?**

For the first scenario, Table 1 shows that in order to achieve the solar carve-out at the rate of 6% of the state's RPS, a total of 2,292 MWs of PV need to be installed by the year 2025. If allocated proportionally based on electric load, this equates to approximately 1,577 MW for the PJM region and 715 MW for the MISO region. This will generate a combined 2,686 GWhs of electricity per year, and will meet 1.5% of the electrical load demand in Illinois from PV sources, thus satisfying the state's solar carve-out requirement.

## 4.3 Research Question #2

**Can Illinois fully utilize all of the solar energy that will be produced as a result of the 6% carve-out without wasting a portion of the generated electrical energy? If so, how much PV could be installed in Illinois while maintaining 100% utilization of the energy that is produced by the systems?**

The second scenario in Table 1 represents the maximum PV penetration level that avoids wasting any of the electricity generated by the installed PV. This is the maximum installed PV capacity where all the energy generated

from PV sources will be utilized 100% of the time. This is a very stringent requirement because it means that rare instances during the year (e.g. mid-morning on a particularly bright but cool day), when the PV could produce more than the replaceable load calculated in Equation 5, will be the limiting factor for the system's size. As shown in Table 1, the maximum PV capacity that could be installed without wasting any electricity is 2,714 MW across the state of Illinois, which will generate 3,234 GWhs of electricity per year, thus meeting 7.3% of the state's RPS and 1.8% of the state's total electrical load demand.

These output potentials show that the state can indeed utilize 100% of the energy generated by the 6% carve-out for solar energy in the RPS. In the PJM region the 6% solar carve-out is slightly more than the level at which 100% of the power generation can be utilized, but in the MISO region there is room to nearly double the solar carve-out and still fully utilize all the electricity generated. As discussed earlier, the reason for this higher potential PV system capacity in the MISO region is that the peak power production from the PV system closely matches the region's peak demand hours, most of which occur during the summer months. On a statewide level, the solar carve-out could be increased from 6% to 7.3%, and the state would still utilize 100% of the PV electricity generated.

**How much of Illinois' electrical energy could PV supply if curtailment of the PV output is occasionally permitted? For this analysis, curtailment will be allowed at a rate equal to the typical internal energy consumption at thermal generation facilities.**

As mentioned earlier, the requirement that none of the energy generated by PV be wasted is a very stringent requirement. The limiting condition would be a time when there is high solar irradiance but relatively low electricity demand. Instead of limiting the installed PV capacity by requiring that no energy be wasted, it may actually be preferable to allow some small amount of electricity to be wasted (connected to a dump load or simply disconnected from the electric grid), because the PV systems still offer significant benefits during times of high electricity demand. The practice of limiting the power output of a generation facility below what it would otherwise produce is called curtailment, and it is a common mechanism for controlling the flow of power onto the electric grid. However, the question of how much electricity is allowed to be curtailed is somewhat arbitrary in this analysis. For the purpose of comparison, we will allow electricity generated from the PV systems to be curtailed at the same rate as what is typically used by thermal generation plants for their own internal use, which is approximately 5.58% according to the U.S. Energy Information Administration [15]. Examples of internal electricity use include pumps, blowers, and conveyers that are used internally to sustain the operation of the generation facility. As shown in Table 1, the installed PV capacity at which 5.58% of the generated electricity is expected to be curtailed is a state-wide total of 11,265 MW. This level of installed PV capacity will produce approximately 13,210 GWhs of electricity annually. This is equivalent to 29.8% of the state's RPS and 7.5% of the state's total electrical load.



*Photo Source: NREL, Jim Yost*

## 4.4 Research Question #3

## 4.5 Indirect Benefits

The potential reductions in greenhouse gas (GHG) emissions and fresh water savings due to the deployment of large scale PV systems were estimated based on the modeling results. The Intergovernmental Panel on Climate Change (IPCC) has developed the concept of Global Warming Potential (GWP) to compare the ability of each greenhouse gas to trap heat in the atmosphere relative to another gas [20]. As shown in Table 2, implementing the three case scenarios in Illinois would result in reductions of 1,713.5 kilotons, 2,063.4 kilotons, and 8,427.8 kilotons of carbon dioxide (CO<sub>2</sub>), respectively. Table 2 also shows the potential reductions in methane (CH<sub>4</sub>) and nitrous oxide (N<sub>2</sub>O) emissions.

In thermal electricity generation plants, an average of 0.47 gal (1.8 L) of fresh water evaporates per kWh of electricity consumed at the point of use [22]. Based on the fuel mix in Illinois, implementing the PV systems in the three case scenarios would result in annual savings of 1,262 million gallons (4,777 million L), 1,520 million gallons (5,754 million L), and 6,208 million gallons (23,499 million L) of fresh water, respectively.

**Table 2.—Annual environmental benefits from GHG reductions<sup>a</sup> and fresh water savings**

	6% Carve-Out	100% Utilization	94.4% Utilization (Thermal Plant Use Match)
Annual Generation (MWh) from PV	2,685,763	3,234,147	13,209,754
Nitrous Oxide (N <sub>2</sub> O) Reduction (Tons)	28,146	33,894	138,438
Methane(CH <sub>4</sub> ) Reduction (Tons)	33,062	39,812	162,612
Carbon Dioxide (CO <sub>2</sub> ) Reduction (Tons)	1,713,517	2,063,386	8,427,823
Fresh Water Saving (Gallons)	1,262,308,610	1,520,049,090	6,208,584,380

<sup>a</sup> Domestic Electricity Emission Factors in Illinois and Wisconsin [21]

## 5. Discussion and Conclusions

The primary purpose of this study was to evaluate the solar carve-out portion of the current RPS plan and to determine the optimum amount of solar PV energy generation for the state of Illinois. We found that the electrical generation from the installed PV systems at the level of the current solar carve-out (6% of the state's RPS) will be fully utilized and none will be wasted. By dividing the state into two regions based on the existing regional transmission organizations in the state and taking into account data on their respective weather patterns, we were able to estimate the regional potential more accurately. The solar carve-out of 6% for the PJM region was found to be close to the level at which the generated electricity can be fully utilized. For the MISO region, however, there is room for the solar capacity to expand further without wasting any of the electricity generated. The solar carve-out in the Illinois RPS could therefore be modified by raising it to 7.3% to reflect a 100% utilization potential of the solar PV systems. If PV system curtailment at a rate equal to the internal electricity consumption of traditional thermal generation facilities is acceptable, then the solar carve-out could be as high as 29.8%.

The economic impact of renewable energy projects in Illinois is not limited to the benefits gained during operation but includes the construction phase of the development. For example, the 10MW solar PV project in West Pullman, IL created approximately 200 construction jobs, with at least half of all work hours filled by Chicago residents [23]. This project utilized steel tubing and other construction materials manufactured on Chicago's South Side and thus had a significant impact on the supply chain. Future studies could examine further economic and supply chain impacts through meeting the near term solar carve-out RPS requirement and by addressing long term goals for greater solar PV deployment in Illinois.

Determining the optimum penetration of large-scale PV is a growing concern for both power utilities and policy makers. We believe the new methodology developed for this study to assess the optimum PV capacity for the future, as well as the questions addressed by this study's analyses, combine to support the construction of more grid-connected large scale solar PV installations in Illinois. This methodology can also be applied to other regions in the U.S. and around the world to support the decision-making process for those charged with developing near and long term energy plans for their communities.



*Photo Source: Illinois Department of Commerce and Economic Opportunity*



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