Tracking Electricity Production Patterns for Residential Solar Electric Systems in Massachusetts

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Abstract

The number of residential small-scale solar electric, or photovoltaic (PV) systems installed in Massachusetts has increased over the past five years. However, expanded deployment of residential solar PV may be hindered by lack of awareness of expected electricity generation of solar PV systems, and corresponding financial return. Policymakers are also interested in using limited state resources to support the installation of well-producing solar PV systems that will help meet state greenhouse gas reduction goals. Operational residential solar PV systems may provide a key to understanding electricity production that can inform prospective system owners and policymakers.

This research utilizes monthly electricity production data for 5,400 residential solar PV systems in Massachusetts that were installed between 2010 and 2013. The analysis first focuses on understanding the aggregate dataset and distribution of systems, then explores the impact of fifteen different variables on residential solar PV system electricity production. These variables include shading, rebate eligibility, equipment type, ownership model, date in service year, system cost, selected installer, PTS reporting method, and others.

When controlling for system size, production over all systems was normally distributed. Through a multiple regression analysis, percent shading, roof inclination and azimuth, rebate eligibility and county were variables that had the greatest impact on system production, with shading being key among them, while other variables showed a more nuanced impact. Ultimately, the full regression resulted in an r^2 value of 34.2, leaving a majority of the system production variability unexplained. The data also provide insight into the impact of state policy measures surrounding system siting,

validation of production data, and forecasting as part of the production based SREC incentive. Ultimately, quantifying the impact of the variables on electricity production patterns can be an effective tool to provide guidance for both prospective system owners and policymakers.

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Abbreviations

ACP	Alternative Compliance Payment
DAS	Data Acquisition System
DOER	Department of Energy Resources
kW	Kilowatt (1,000 Watts)
kWh	Kilowatt-Hour
MassCEC	Massachusetts Clean Energy Center
PTS	Production Tracking System
REC	Renewable Energy Certificate
RPS	Renewable Portfolio Standard
PV	Solar Photovoltaic
SQA	Statement of Qualification Application
SREC	Solar Renewable Energy Certificate
TSRF	Total Solar Resource Fraction

Chapter I

Introduction

The installation rate of solar electric, or solar photovoltaic (PV) systems in Massachusetts has greatly increased over the past five years, due in part to reductions in system cost, favorable legislation and incentives, and the expansion of finance and leasing options. Correspondingly, the amount of solar PV capacity installed in the state has increased from four megawatts (MW) and 560 systems in 2006, to over 862 MW and 29,000 systems in August of 2015. Of these, small-scale residential solar PV systems represent 20 percent of total installed capacity, at 176 MW, and 90 percent of installed systems, equivalent to over 26,000 installations in the state (PTS, 2015).

Although the rate of installation of residential-scale systems has increased over the past five years, there remain several factors that hinder residents from actively pursuing installation of a solar PV system. Along with determining whether a residence has the appropriate characteristics to install a solar PV system, understanding state and federal incentives, and determining methods to finance a project, prospective system owners are often interested in gaining insight into expected electricity production of a proposed solar PV system. A commercial business or public municipality that is considering the installation of a large solar PV system may have the means to conduct an independent analysis on the expected electricity production of a solar PV system at their site, but many residents have imperfect knowledge of the tools needed to make such assessments, and often only have installer-provided electricity generation projections on which to base a financial decision that may involve an up-front payment of tens of thousands of dollars. However, the electricity production and many associated benefits are received throughout the working life of the system.

Although there may be various incentives and financing options available to defray the initial upfront capital investment, understanding how system production will ultimately offset the upfront cost and create subsequent profit, along with the projected timeframe of the break-even point, are significant decision points for prospective system owners. Under this context, and as Massachusetts follows a national trend of shifting away from upfront cash grants to production-based incentives, understanding the trends of currently operational systems, and the variables that impact system electricity production become even more important.

Additionally, state policymakers have a legislative mandate to reduce greenhouse gas emissions, while also providing guidance and financial support for expanding solar PV deployment. Through this mandate, legislatures and state program administrators have historically taken steps to provide a basic level of quality assurance, both by providing incentives for well-producing solar PV systems, and also verifying data quality. Several examples of this have included providing rebates for systems that meet minimum site and project specifications, providing production based incentives through solar renewable energy certificates (SREC), and performing validation of production data for systems receiving production based incentives. Policymakers and utilities also need a firm grasp on what to expect from systems with regards to production as they forecast both future incentive programs and electricity production added to the grid.

Because electricity production and the value proposition of a solar PV system are highly correlated, conducting an analysis of the increasing number of solar PV systems currently in operation in Massachusetts may be an effective means to provide clarity to the market. By analyzing system production data of small-scale residential solar PV systems, this analysis will seek to uncover aggregate production trends, as well as clarify the impact of specific variables on system electricity production. These variables include percent shading, rebate eligibility, ownership model, equipment manufacturer, system cost, installer, county of installation and others. Understanding the impact of these variables system production can provide clarity to the market, to utility electricity forecasters and to policymakers, ideally leading to expanded solar PV deployment, a more robust utility grid, and the continuation of targeted and impactful state incentive programs moving forward.

Background

The importance of the sun for both basic biological processes and energy production cannot be understated. From afar, the gravitational pull of the sun allows the earth to continue moving in orbit, and solar radiation energy, or solar insolation, delivers both an external source of heat for the earth and energy for photosynthesis and other natural processes critical for a living ecosystem on earth. Aside from nuclear, geothermal, and a handful of other relatively minor energy sources, most forms of energy currently consumed are connected to solar insolation from the sun or its’ gravitational pull. Coal, oil and natural gas are all largely fossilized byproducts of plant photosynthesis and decomposition that occurred hundreds of millions of years ago, while both biofuels and wood resources are byproducts of a much more recent photosynthetic conversion of solar insolation. Wind energy is directly impacted by the effects of uneven heating patterns on the earth, tidal energy is a mechanism of both the gravitational pull of the sun and the moon, while solar hot water and solar electric technologies are fully dependent on solar insolation from the sun. Without much public fanfare of its importance, solar energy is already a firmly established energy resource within human society.

Solar Insolation, Energy Demand, and the Potential of Solar Photovoltaic Technology

As part of a 2012 world population report, the United Nations Department of Economic and Social Affairs predicts that by 2050, the global human population will expand from 7.2 to 9.6 billion people (United Nations, 2014). The U.S. Energy Information Administration has projected that global energy consumption will more than double during this timeframe. These projections include both increased global human population size and increased demand for energy on a per capita basis (US Energy Information Administration, 2014). Although there is some uncertainty surrounding what the actual world population and energy consumption numbers will be in 2050, there continues to be a clear upward trend. Over time, this will put an extraordinary amount of strain on central electricity generation facilities, which in many cases are already showing signs of age and over-stress.

In upcoming decades, over the same timeframe characterized by continued growth in population and energy consumption, an increasing number of aging fossil fuel electricity generation facilities will be retired. In New England alone, by 2020 over 20 percent of all oil and coal-fired energy generation facilities will have been in operation for more than 40 years (ISO New England, 2013). These older facilities are less reliable, emit higher levels of pollution and CO_2 emissions, and are more likely to be retired from production. Although older oil and coal facilities make up 20 percent of the regional capacity of oil and coal plants, they only generate one percent of the regional energy demand, and often only at times of peak energy demand. Older plants are also under increased pressure to make potentially costly investments into meeting stringent environmental regulations (ISO New England, 2013). Correspondingly, announcements have been made of a number of major facility retirements throughout the six New England states, which will result in over 4,000 MW of generation capacity being taken out of commission over the next five years (Clarke, 2014). These facility retirements include Brayton Point coal-fired power station, Salem Harbor coal-fired power station, and Vermont Yankee nuclear power station, among others. In addition, there is strong opposition within New England to the siting of new fossil fuel facilities and natural gas pipelines in local municipalities, with a similar ethic developing nationally and internationally as citizens voice strong opinions, from arguments of ‘not-in-my-back-yard’ to demanding green alternatives, to their politicians via protests and through the ballot box. With this dynamic in place, it will be increasingly difficult to expand or even replace traditional fossil-fuel plants to meet the growing demand for energy in the coming decades.

With this juxtaposition of increased energy demand coupled with a reduced generating capacity coming to bear within a few short decades, policy-makers, industry leaders and civilians at large must consider actions to mitigate the risk of energy demand outstripping energy supply from limited fossil fuel generation facilities. In addition, during this planning process, methods that circumvent many of the negative externalities tied to the combustion of fossil fuels should also be prioritized at an equal level of importance with securing reliable energy sources. These negative externalities include negative public health impacts, environmental degradation, and global insecurity created by anthropogenic global climate change.

In the process of developing state and national policies to meet these dual goals, it is important to quantify the known availability of all potential non-renewable and renewable energy resources. Figure 1 below offers a visual representation of potential energy resource availability. Annual global consumption of energy in 2009 is seen as the orange sphere to the left, calculated as 16 terawatt-years of energy consumed per year. Situated next to it is a second orange sphere which indicates expected global energy consumption for the year 2050, projected at 28 terawatt-years per year (Tsao, 2006). The total known quantity of finite, non-renewable energy resources are shown to the right of the figure, while annual renewable energy resources are shown in the center, including annual potential capacity of wind, waves, ocean thermal energy current, biomass, hydroelectric, geothermal, tidal and solar resources. As is seen below, the potential capacity of solar insolation as a renewable means to meet global energy demand is tremendous. However, although solar insolation is generally plentiful and readily available, in order to realize this potential, a reliable, cost effective technology that harvests solar insolation must be developed and deployed.

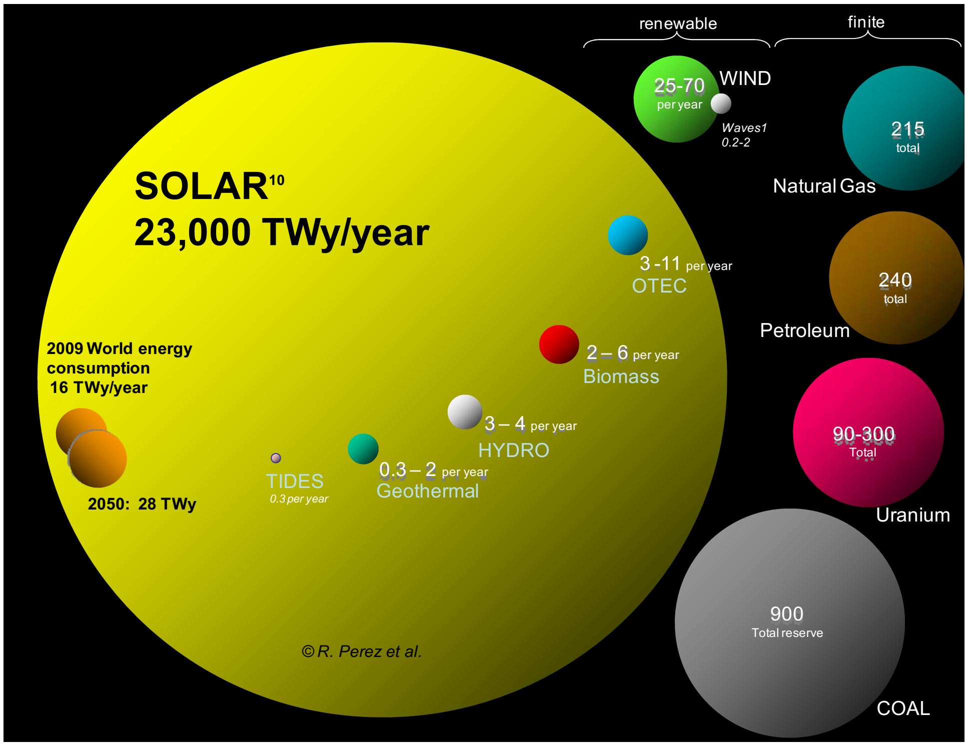


Fig. 1. Theoretical energy potential for all major energy sources vs. global annual energy consumption for 2009 and 2050 (Perez, 2009).

Commercialization of Solar PV Technology: Efficiency, Degradation, System Cost and Warrantees

Although often characterized as a new technology in popular culture, the discovery of the first photovoltaic cell was made in 1839. A young French physicist named Edmond Becquerel found that passing light over a silver chloride wafer that was linked to platinum electrodes in an acidic solution created a small current of electricity to be created (Jewell, 1988). The corresponding body of scientific knowledge continued to mature over the course of a century, including research on the quantum basis of the photoelectric effect by Albert Einstein, published in 1905, which ultimately led him to receive a Nobel Prize for his research in 1921 (NobelPrize.org, 2015). In 1954, Bell Labs developed an important breakthrough that spurred the development of modern solar photovoltaic technology. A thin positive-negative junction (p-n junction) composed of boron was placed between two crystalline silicon wafers. When the wafers were then subjected to bright light, photons from the light dislodged excess electrons in the silicon, which then passed across the junction. This resulted in a current in which the solar cell was able to convert light to electricity at six percent efficiency (NREL, 2004).

This level of cell efficiency was high enough to warrant further research and commercialization of the technology for use in remote sites, such as for offshore locations, or for use in space expeditions. As seen in Figure 2 below, continued research has led to solar PV cell efficiencies to continue to improve, with current cell efficiencies ranging from 8.6% efficiency for emerging PV technologies, to 44% efficiency for high efficiency multi-junction solar PV cells.

A standard solar PV panel, also known as a module, is an electrically connected assembly of solar cells. A solar array is a set of solar PV panels that are traditionally wired in series to a central inverter that will convert all direct current to alternating current electricity for use at the on-site facility. Some efficiency is lost between the solar cells as electricity is transported across the panel. Current standard efficiency crystalline silicon panels may range around or above 15% efficiency, while premium high efficiency panels may range up to 21% efficiency (PTS, 2015).

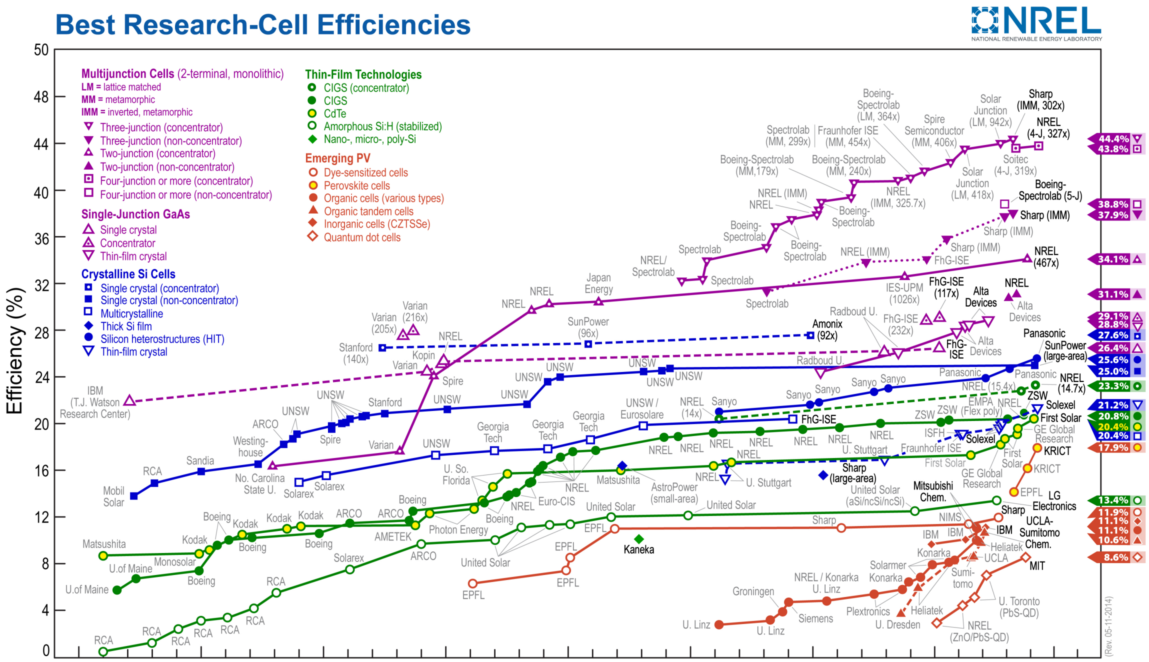


Fig. 2. Percent efficiency of lab-tested solar PV cell efficiency over time (NREL, 2014).

Prior to standardized testing methods and national electric code requirements, many early-stage research-level and commercially deployed solar PV panels were afflicted with high rates of panel power degradation, such that the power output of the solar PV system panels decreased over time. Starting in the mid-1970’s, under the auspices of the Department of Energy, two national laboratories began purchasing state-of-the art panels for accelerated lab and outdoor stress testing (Jordan, 2012). After the first four blocks of testing (Block I – Block IV), more stringent and standardized stress tests were established, and subsequent panels that were manufactured and tested when the Block V standards were implemented were found to have much lower degradation rates. Indeed, one analysis found that ‘failure rates decreased significantly from 45% for pre-Block V modules to less than 0.1% for Block V modules” (Jordan, 2012). In conjunction with national lab testing, a large number of research studies beginning in the late 1980's began to focus on the causes of higher degradation on early stage commercial panels, with the purpose of mitigating degradation where possible. As part of a 2012 report, the National Renewable Energy Lab compiled an extensive analytical literature review of historical degradation studies spanning four decades and various countries across the globe (Jordan, 2012). Of the over 90 case studies surveyed, the expected standard power degradation rate of 1% or less per year was reported in 78% of all data surveyed, with a mean of 0.8% per year and a median of 0.5% per year.

As outdoor field studies and indoor intensive studies have continued to compile real data on degradation rates for longer periods of time, product warranties have correspondingly becoming more robust over time. As Figure 3 indicates, outdoor degradation studies have kept pace with standard industry panel production warrantees. As such, a standard panel production warranty will guarantee that panel production will not degrade by more than 1% per year during the course of the warrantee. As cumulative research studies on solar PV panels in the field progress beyond standard warranty timeframes, the NREL study concludes that it is useful to continue to demonstrate that moderate degradation rates among older panels allows for continued reasonable performance even beyond 25 years of continued use.

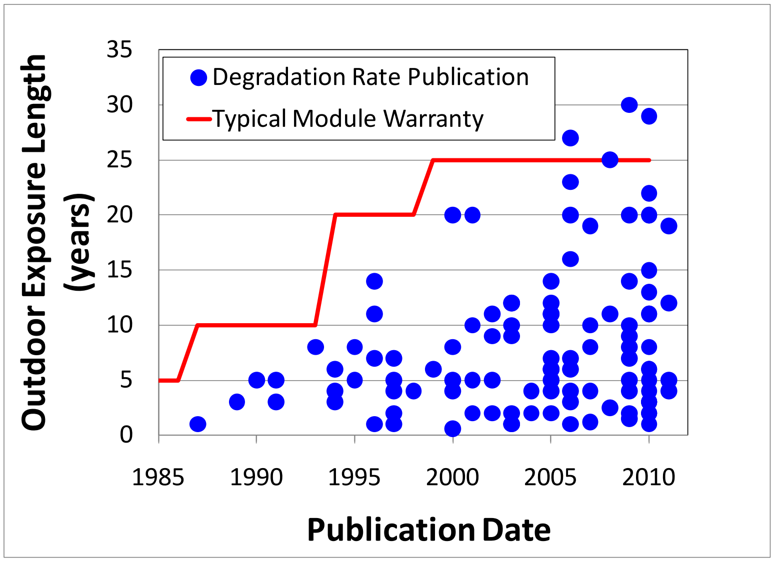


Fig. 3. Outdoor field exposure study dates vs. standard module warranty length (Jordan, 2012).

The average cost for solar PV installations between the 1950's through 1980s is not known, in large part because the cost to of the panels would have been prohibitively expensive. The cost for a one watt silicon cell alone, not including the module or installation costs, may have ranged in the hundreds of dollars, when comparatively the cost to build a coal fired power plant may have ranged around $0.50 per watt at the time (Perlin, 2013). As seen in Figure 4, in 1998 the average cost for the installation of a residential-scale solar PV system in the United States was over $12 per watt, expressed in 2014 dollars (Barbose, 2015). Therefore, for the installation of an average sized small-scale residential 5,000 watt, or 5 kW solar PV system, the up-front cost would therefore be $60,000. Due to a range of factors, including advancements in the technology, increased demand, and corresponding increased economies of scale and price reductions surrounding panel supply, the average cost for solar PV installation has consistently dropped over the past 15 years. Nationally, the 2014 median cost per watt for a small-scale residential solar PV system was $4.30/watt, while small-scale solar PV systems installed in Massachusetts in the same timeframe generally followed the national trend, with the mean cost per watt being $5.05 in 2013.

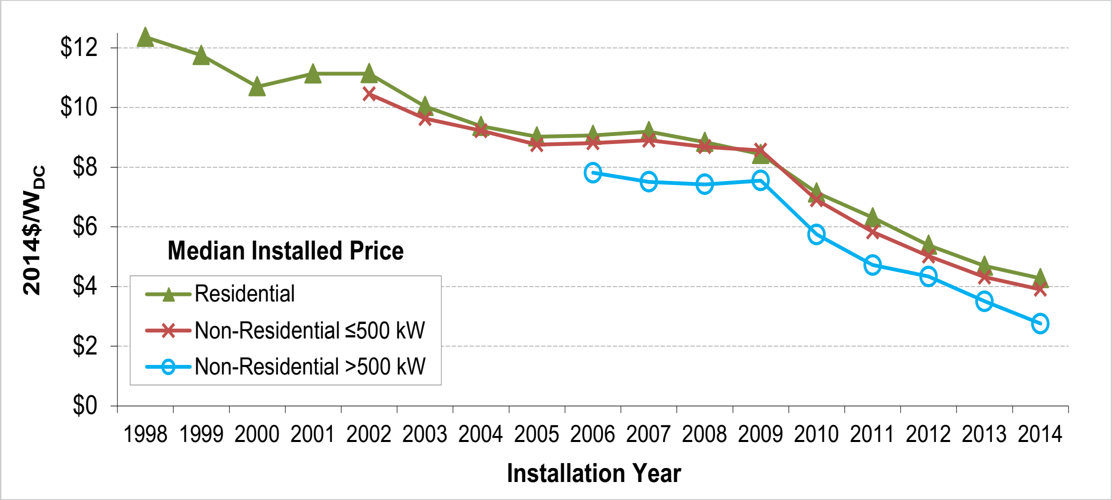


Fig. 4. Median cost of residential and commercial Solar PV systems in the United States 2998 - 2014 (Barbose, 2015).

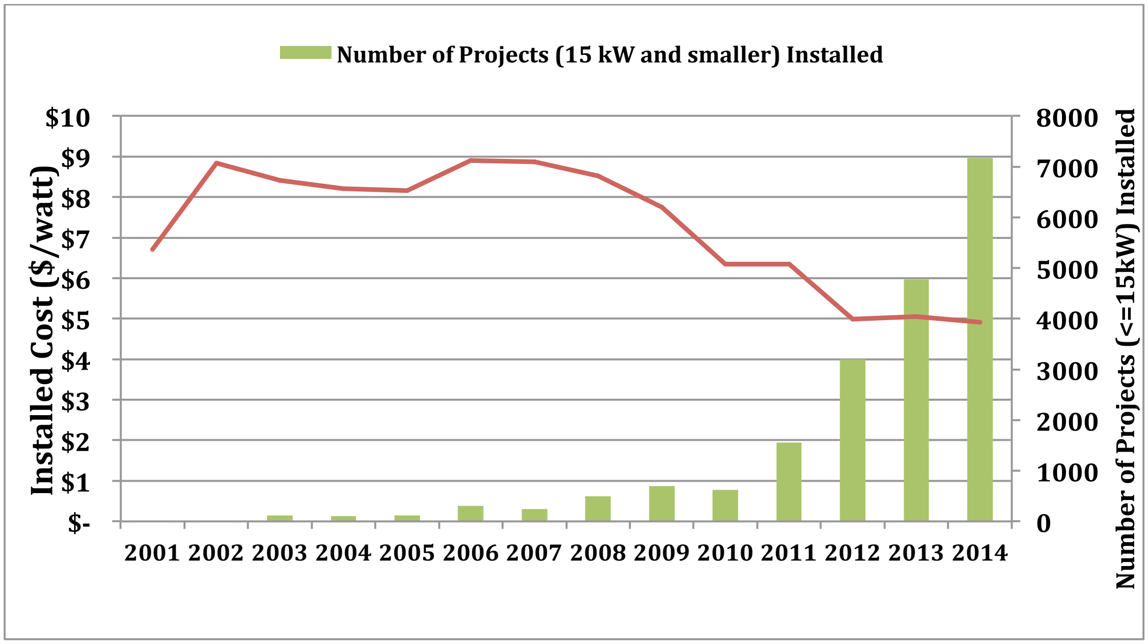


Fig. 5. Mean cost of small-scale solar PV systems in MA over time (Red), vs. number of small-scale projects installed through 2014 (PTS, 2015).

Figures 6 and 7 below shows the geographic distribution of all known solar PV installations in the year 2006 and 2014 for Massachusetts. Early dispersion patterns found more installations in the Boston metro area, the Cape Cod region, and the Pioneer Valley in Central-Western Massachusetts. Later installation patterns show a more even distribution across the state, though the Boston metro area, Cape Cod Region and Pioneer Valley still have a higher representation of solar PV systems than other regions of the state.

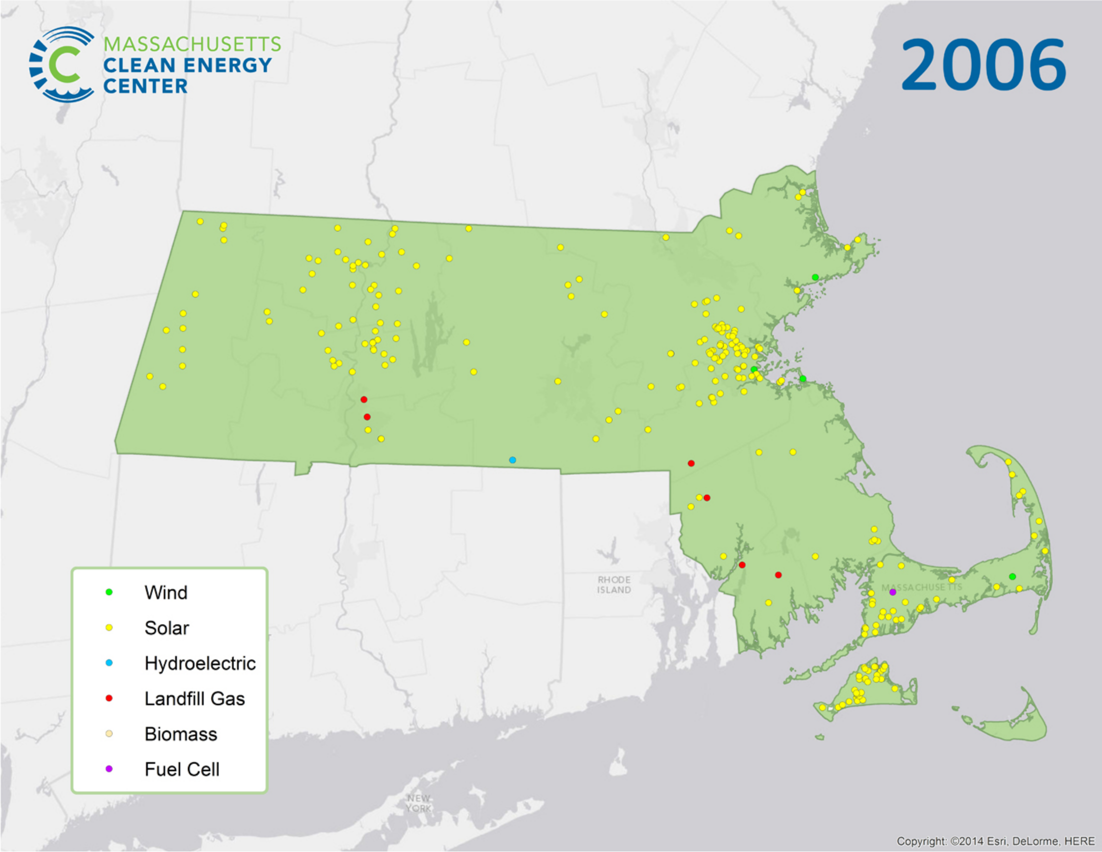


Fig. 6. Geographic distribution of solar PV installations in Massachusetts in 2006 (PTS, 2015).

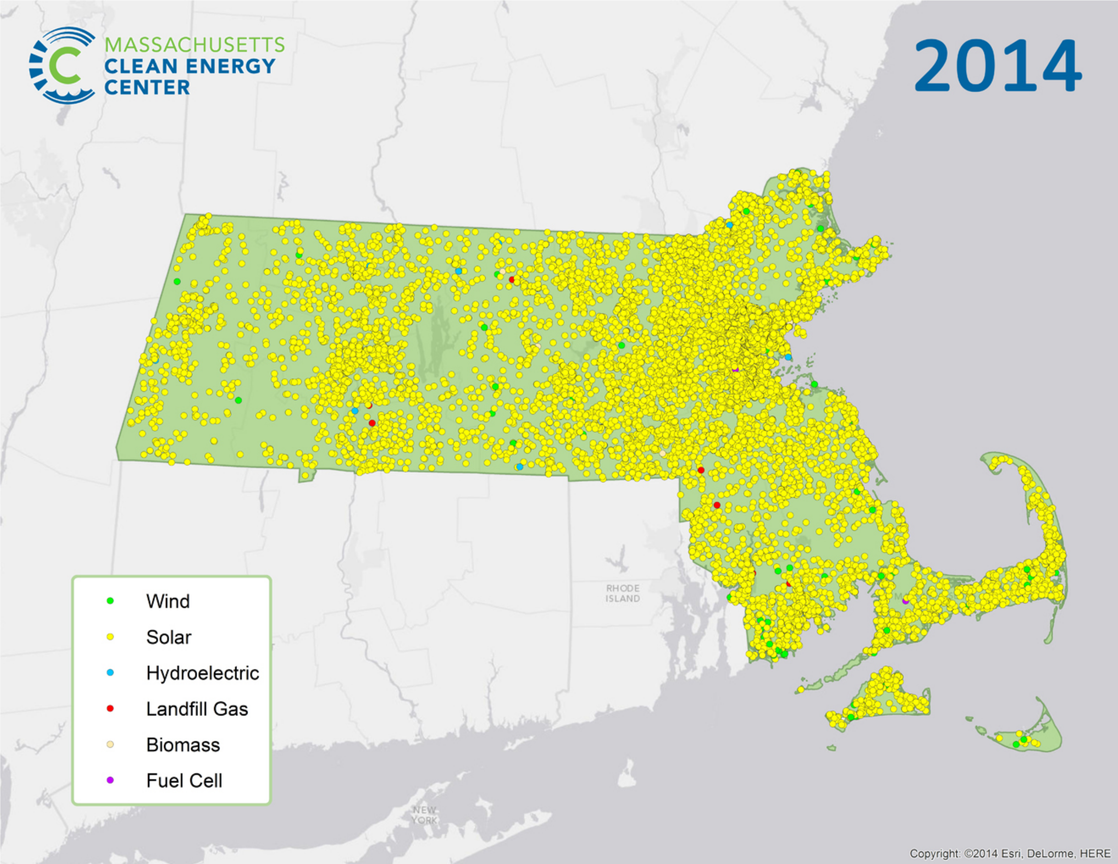


Fig. 7. Geographic distribution of solar PV installations in Massachusetts in 2014 (PTS, 2015).

Massachusetts Renewable Portfolio Standard, Green Communities Act and RPS Solar Carve-Out

In 1997, as part of a consequential legislative act that restructured the Massachusetts electric utility industry in the Commonwealth known as Chapter 164 of the 1997 session law ‘An Act Relative to the Restructuring the Electric Utility Industry In the Commonwealth, Regulating the Provision of Electricity and Other Services, and Promoting Enhanced Consumer Protections Therein’, legislators enacted two important renewable energy mechanisms, known as the Renewable Portfolio Standard (RPS) and the Renewable Energy Trust. In league with increased standardization and deployment of solar PV technology, both entities would shape the renewable energy landscape in Massachusetts for years to come.

The implementation of the Massachusetts Renewable Portfolio Standard legally obligated investor owned utilities and competitive suppliers to provide a growing fraction of their electricity generation from eligible renewable energy sources. The schedule enacted as part of the legislation mandated that starting at the end of 2003, one percent of electricity sales would be generated via renewable energy sources. Furthermore, the electricity generation fraction would continue to increase by one percent per year, with no specified end date. Utilities that did not meet their respective obligation within a given year would face a financial penalty, by paying a corresponding ‘Alternative Compliance Payment’ (ACP) for any gap between their statutory obligation and actual generation.

Under the new RPS obligations, utilities could either opt to install renewable energy systems themselves to meet their renewable energy generation obligation, pay an ACP fine, or could instead opt to purchase ‘Renewable Energy Certificates’ (RECs) from qualified private or public sources to meet their obligations. Defined by the Environmental Protection Agency as ‘the property rights to the environmental, social, or other non-power qualities of renewable energy generation,’ (EPA REC) a REC is based upon the notion that a kilowatt-hour (kWh) of electricity generated from a renewable energy technology has an additional value as compared to a kWh generated by a fossil fuel generated electricity source. Separate from the actual physical electricity generated, renewable energy systems also create what is also commonly known as a ‘green attribute.’ This green attribute can be quantified in the form of a REC, and under the auspices of the Renewable Portfolio Standard, could be subsequently monetized.

In Massachusetts, one REC is equivalent to 1,000 kWh of electricity generated by a qualified renewable energy generation system, and can then be purchased by utilities to meet their annual RPS obligations. The value of a REC is variable, and is based on market value dictated by both the annual electricity obligation of the utility and the number of available RECs in supply for that given year. In order to participate to generate RECs, a renewable energy system must first be qualified to report monthly electricity production to the Production Tracking System, or PTS. Once qualified, the Production Quality Management team will then conduct a quality assurance check for all production data reported. A REC can then be ‘minted’ and offered for sale to corresponding utilities at the market rate, with the maximum REC value being capped at the ACP rate.

As part of the 2008 Green Communities Act, the Renewable Portfolio Standard regulation was modified to include a specific carve-out for solar PV systems that would offer an increased revenue stream over the average value of a standard ‘Class I REC.’ The RPS Solar Carve-Out program, commonly referred to as the SREC program, began accepting Statement of Qualification Applications (SQA) from eligible projects in January of 2010, and has since become an important incentive program for solar PV installations in the state. Once qualified to report electricity production to the PTS, a system owner has two options on how to report their electricity production. Smaller systems 10 kW or smaller may opt to manually report production by checking their on-site electricity production meter for the accumulated electricity production number for the system on a monthly basis, and inputting that number via an online PTS webpage. A system owner may also opt to have electricity generation data automatically reported to the PTS through the purchase of an additional piece of equipment called a Data Acquisition System, or DAS. Solar PV systems that are over 10,000 watts, or 10 kW in size are obligated to purchase a DAS and automatically report production (PTS, 2015). The PTS then conducts a quality assurance check on the data. Once verified, production data from the PTS is forwarded to an entity called NEPOOL-GIS that has the authority to 'mint' the green attribute of the electricity generation into an equivalent SREC. The newly minted SREC can then be sold quarterly as part of an SREC market. In order to participate and receive incentives from the SREC program, thousands of solar PV projects are actively reporting monthly electricity production to the PTS. The emerging dataset of electricity generation for these thousands of systems can in turn provide increased clarification surrounding solar PV production patterns in Massachusetts.

The Renewable Energy Trust is a public benefits fund that is tied to a surcharge on investor owned utility ratepayer electricity bills, which amounts to an additional fee of $0.0005 per kWh of electricity consumed by ratepayers. The fund, which is separate from a similar systems benefit charge for state energy efficiency programs, generates on average around 25 million dollars per year, and has been an important vehicle for the development and financing of many renewable energy incentive programs and large renewable feasibility studies over the past ten years. For solar PV technologies, early-stage incentives included offering grants for the total cost of demonstration projects at facilities such as schools through the Green Schools Initiative, as well as relatively large upfront rebates for private and public projects through the Small Renewables Initiative, Large Renewables Initiative, Clustered PV, and followed later by the 2008 Commonwealth Solar rebate program. Feasibility studies for larger proposed renewable energy projects were meted out via competitive solicitation, and included studies that tested wind capacity for proposed on-shore wind sites, siting organics-to-energy facilities, modernizing older hydroelectric projects, and providing funding for a study conducted by the Massachusetts Audubon focused on the impacts of the proposed Cape Wind project on bird populations in Nantucket Sound (Mass Audubon, 2013). In 2009, the Massachusetts Clean Energy Center became the administrator of the Renewable Energy Trust and the Production Tracking System (PTS), a state database that tracks solar PV systems and other renewable energy technologies installed in Massachusetts from 2001 onward. The Production Quality Management team, the MassCEC division who manages the PTS, both performs quality assurance of data within the PTS, and acts as a third-party production verifier for the RPS Solar Carve-Out, or SREC program.

Solar PV Production Case Studies and Estimation Practices

Over the past several decades, a comprehensive database of scientific analyses has developed to understand and mitigate solar PV module degradation rates, as well as to develop effective modeling techniques to estimate future solar irradiation for purposes of projecting future solar PV production. The relatively recent commercial introduction of automatically reporting data acquisition systems (DAS) that can report solar PV system production in as often as 1 minute time segments has opened a window for a new series of analyses based on actual solar PV electricity production numbers. However, there are very few studies focused on analyzing actual system electricity production patterns. In

2007, the International Energy Agency, offered the most extensive review of their production database, which included 473 grid-connected systems installed between 2000 and 2007 in 17 different countries. In addition to an analysis of system cost and module efficiency, the report analyzed the range of system electricity production yields (kWh/kW) over time. This included taking latitude of the systems into consideration (IEA, 2007). In the United States, there are several state-specific white papers on solar PV system production performance (Pickrell, 2013). NREL is also in the process of analyzing solar PV production numbers for around 50,000 solar PV systems that were installed as part of the American Recovery and Reinvestment Act (ARRA), but to date NREL has only offered preliminary results in the form of a presentation that occurred at the end of February 2014 (Jordan, 2014). To date, these reports and presentations are the extent of available studies focused specifically on analyzing patterns of solar PV system electricity production using a large sample size. Under this context, the scope of this research analysis is both timely and warranted.

The aim of this thesis is to conduct an analysis to clarify what variables impact solar PV system production over a specified production year, and from this provide guidance on electricity production patterns. This thesis may assist prospective solar PV system owners in making informed decisions about installing a solar PV system. Further research into what variables impact solar PV system electricity production patterns may additionally assist financial entities in determining risk to investment, and potentially expand the market to financing options for residential solar PV systems. Understanding the impact of these variables on system production can additionally provide clarification to policymakers and incentive program administrators, which can provide guidance into the development of targeted and impactful state incentive programs moving forward.

Chapter II

Research Methodology

The research methodology section incorporates information about the dataset, a framework of the analysis and an overview of the three primary hypotheses of the analysis.

Data

This analysis utilized an extensive dataset provided by the MassCEC Production Tracking System that consisted of both system specifications and monthly production data for residential solar PV projects installed in Massachusetts between January 1, 2010 and April 30, 2013. System specifications were inputted into PTS by a system qualification application (SQA) typically submitted by an SREC aggregator or broker, prior to the system first reporting system electricity production. Systems that received a rebate through a MassCEC incentive program additionally provided system specification data via a separate application portal, which was cross-checked with data in the PTS database at time of SREC registration.

Separately, on a monthly basis electricity production data for each system is either manually reported via an online website to the Production Tracking System by the system owner, or automatically reported to PTS through a Data Acquisition System (DAS) located at the project site. Under the SREC-I and SREC-II programs, systems installed that are smaller than 10 kW are provided with the option to either manually report production on a monthly basis or to install a DAS and report automatically. As part of manual reporting, a system owner would report the meter reading shown on a revenue grade meter installed at their project site. The meter is one-directional, and production is cumulative over time. Solar PV systems over 10 kW in size however are required to install a Data Acquisition System and report production automatically. With both reporting methods, the PTS conducts a monthly validation of all reported electricity production data. PTS follows up with any system that is found to have monthly electricity production that is two standard deviations above the mean production value for the month, in order to clarify the reason for high production. This may involve direct contact with the system owner, a review of previous DAS production information, if available, or marking the project for audit by a third party inspection consultant. However, system production that was below the mean was not subject to follow-up. For systems that manually report production to PTS, aside from following up on especially high-producing systems and periodic audit inspections of projects, PTS administrators principally rely on system owners to accurately report monthly system electricity production numbers. Systems that reported production manually are allowed a monthly ‘reporting window’ of five days before to five days after the end of the month to report production. Although this range in the reporting day could lead to monthly variability, reported production numbers would ultimately even out over the course of a year. For automatically reporting systems, the on-site data acquisition system would typically report automatically on the same reporting day of each month.

Six criteria seen in Table 1 below were used to evaluate the initial dataset, and solar PV systems identified as not meeting the criteria were removed. A total of 5,400 residential Solar PV systems met the criteria and were utilized for the analysis. Further information regarding vetting of the initial dataset and systems that were removed can be found in Appendix 1.

Table 1. Required criteria for solar PV system inclusion in analysis.

	Criteria Requirement	Criteria Clarification
1.	Systems must be installed on a residential property	Commercial properties were excluded from the scope of the analysis, as solar PV systems installed on commercial properties may exhibit different production characteristics as compared to residential systems.
2.	System size must be between .1 kW and 20 kW, and have fixed, non-movable panels	A system size above 20 kW is significantly higher than the average residential solar PV installation size, and would be more likely to take on production characteristics of a commercial system. Additionally, a small number of systems with movable tracking systems were excluded, due to a lack of information about type of tracking system (single or dual sun tracking)
3.	Systems must have a Date in Service between January 1, 2010 and April, 30, 2013	An April 30, 2013 date in service was required in order to allow for the system to report during the Reporting Year used in the analysis, from July 1, 2013 to June 30, 2014. Systems with a date in service before January 1, 2010 were not eligible to participate in the SREC program.
4.	Systems must be eligible to participate in SREC program	Systems participating in the SREC program received a production-based incentive. Additionally, PTS administrators vetted production numbers from systems participating in the SREC program.
5.	Systems information with clear inaccuracies were removed	Seven systems were removed from the dataset that were found to have clearly inaccurate system specification information.
6.	System must report production to the Production Tracking System for every calendar month of the Reporting year	Systems that failed to submit production for one or more months, leading to an input of 'NULL" during production year were removed. Systems that actively reported a low monthly production number, or a production number of 0 were maintained in the dataset.

The data associated with each residential solar PV project included a broad range of system specification information, as well as monthly solar PV electricity production numbers, reported in the unit kilowatt-hours (kWh). Table 2 below lists sixteen key data-points used as variables as part of the analysis.

Table 2. Table of data variables utilized in the analysis.

	Variable Name	Variable ID	Description
1.	System Size	$Size_i$	Size of system, presented in kilowatts (kW).
2.	Percent Shading	Shd_i	(0% - 100%). Average percentage of the system that is shaded per day.
3.	Azimuth (Azimuth from 180°)	Azm_i	(0° - 360°). The ideal Azimuth for this analysis was considered 180°, or true south. System azimuth was therefore measured by degrees away from true south.
4.	Inclination (Inclination from 43°)	Inc_i	(0° - 90°). The ideal Inclination used as part of this analysis was 43°, which is associated with the geographical latitude for Massachusetts. System inclination was therefore measured by degrees away from latitude.
5.	Ownership model (Direct Purchase, Third Party Owned)	Own_i	Method of solar PV system ownership. May be directly owned by a residential system owner, or owned by a third party commercial company. If the latter, a resident would lease or enter into a Power Purchase Agreement (PPA) with the third party commercial company.
6.	Reporting method (Manual Reporting, Automatic Reporting)	Rpt_i	Method in which monthly electricity production from the solar PV system is reported to the PTS. Production can be reported manually by either the system owner via an online PTS website, or automatically reported by an on-site Data Acquisition System (DAS), by the system installer of the system or other entity on behalf of the system owner.
7.	Rebate Eligibility (Rebate, Non-Rebate)	Elg_i	Solar PV systems that were eligible and received a rebate from the Massachusetts Clean Energy Center (MassCEC) through either the Commonwealth Solar II or Solarize Mass rebate programs. Systems that qualified for a rebate were required to meet specific program and technical requirements, including using qualified equipment and meeting a percent of optimal production requirement, as determined by a tool that estimates percent shading, azimuth and inclination.
8.	Participation in Solarize Mass (Solarize, Non-Solarize)	Sol_i	Resident participation in a community outreach, education and group-purchasing program, coordinated by the Massachusetts Clean Energy Center. Participation in the program was separate than receiving a rebate.

9.	Total System Cost, Cost per Watt	Cst_i	Total system cost includes all costs associated with the installation of the solar PV system that were included as part of the turnkey contract between the system installer and the system owner. The Cost per watt is the total system cost divided by the system size in watts. A 5,000 watt, or 5 kW system that cost $25,000.00 would have a cost per watt of $5.00, or $5.00/W.
10.	Installation Year	$YrDis_i$	Systems were broken in to three separate installation years as seen in Figure 12, based on the project Date in Service (DIS). DIS is the date that the utility of the project site provided an approval to interconnect the system.
11.	Installer	Com_i	Commercial company who contracts with the resident for installation of a solar PV system. Installers with three or fewer systems installed were combined into a separate 'Other' category.
12.	County	$County_i$	Site location within one of fourteen counties in Massachusetts. A breakout of counties can be seen in Figure 11.
13.	Panel Efficiency (%)	$Peff_i$	Efficiency of solar PV panels (0% – 22.5%)
14.	Panel Manufacturer	Pmf_i	Manufacturer of the project solar PV panels
15.	Inverter Manufacturer	Imf_i	Manufacturer of the project solar PV inverter or inverters
16.	Inverter type (Micro-Inverter / Central Inverter)	$Imic_i$	Differentiation between central inverter, and micro-inverter technology. Micro-inverter technology allows for on inverter to be installed behind each solar PV panel, in lieu of installing a central inverter.

Overview of Aggregate Dataset and Selected Variables

Table 3 below provides an overview of the data, including mean, minimum, maximum and standard deviation of six variables: system size, cost per watt, azimuth, inclination, shading, and system production (kWh) per kilowatt. With regards to the cost per watt minimum pricing, there was one solar PV system that had a total system cost of $.1 and two systems that had a total system cost of $1. There is a good possibility that the total system cost for these systems was entered into the PTS incorrectly. These systems were not dropped however, because of the possibility that at lest one was associated with an installation done by an individual electrician, who may have feasibly charged themselves a low cost for the install. The legality of this possibility aside, these three systems were maintained in the dataset due to the small possibility that they are correct. These may also be outliers. However, within the dataset there are only six systems that are less than a dollar per watt, and only an additional 31 systems that are between one and three dollars per watt.

Table 3. Summary statistics of full dataset.

VARIABLES	(1) N	(2) mean	(3) sd	(4) min	(5) max
System Size (kW)	5,400	5.934	2.401	0.940	20
Cost per Watt	5,400	5.452	1.302	0.001	15.16
Azimuth	5,400	173.0	52.00	0	360
Inclination	5,400	28.80	11.11	0	90
Shading	5,400	9.250	8.078	0	59
Production kWh / kW July 13 – June 14	5,400	1,124	157.5	32.11	1,812

During the three-year installation timeframe of systems within the dataset, several variables changed over time. As seen in Table 4 below, the number of systems installed per year increased. Average system size increased over time, as did panel efficiency, percent shading, percent of systems that did not receive a rebate, and percent of systems that were owned by a third party. Third party owned systems largely utilized automatic reporting, which is often directly tied to the method in which third party companies bill their customers. For direct purchase systems, automatic reporting was utilized between 30 and 40 percent of the time. Additionally, average azimuth and inclination remained consistent over the three installation years, near 170 and 29 degrees respectively. This may be because the available building stock during each installation year was essentially static. A more extensive breakout of variables can be found in Appendix I.

Table 4. Variable summary by installation year.

Install Year	No of Systs.	% of Total	Mean Syst. Size (DC)	Mean Cost / Watt	% Third Party	% Rec'd Rebate	Mean Panel Effic.	% using Micro Inverter	% Using Auto. Report	Mean % site shaded
2010 - 2011	511	9.5	5.1	$6.44	19.0	89.8	13.8%	14.3	41.9	6.3
2011 - 2012	1369	25.4	5.9	$5.83	40.5	90.0	15.0%	28.7	57.5	8.0
2012 - 2013	3520	65.2	6.1	$5.16	68.3	72.4	15.7%	38.6	74.6%	10.2
Total	5400	100	5.9	$5.45	56.6	78.5	15.4%	33.8	67.2%	9.2

System Size. System size ranged between 0.94 kW and 20 kW, as seen in Figure 8 below. The mean for the dataset was 5.93 kW, and the median was 5 kW, with uneven distribution across the dataset. Few systems were installed with a system size below 2 kW or above 15 kW, and there was a visible reduction in the number of solar PV systems sized greater than 10 kW.

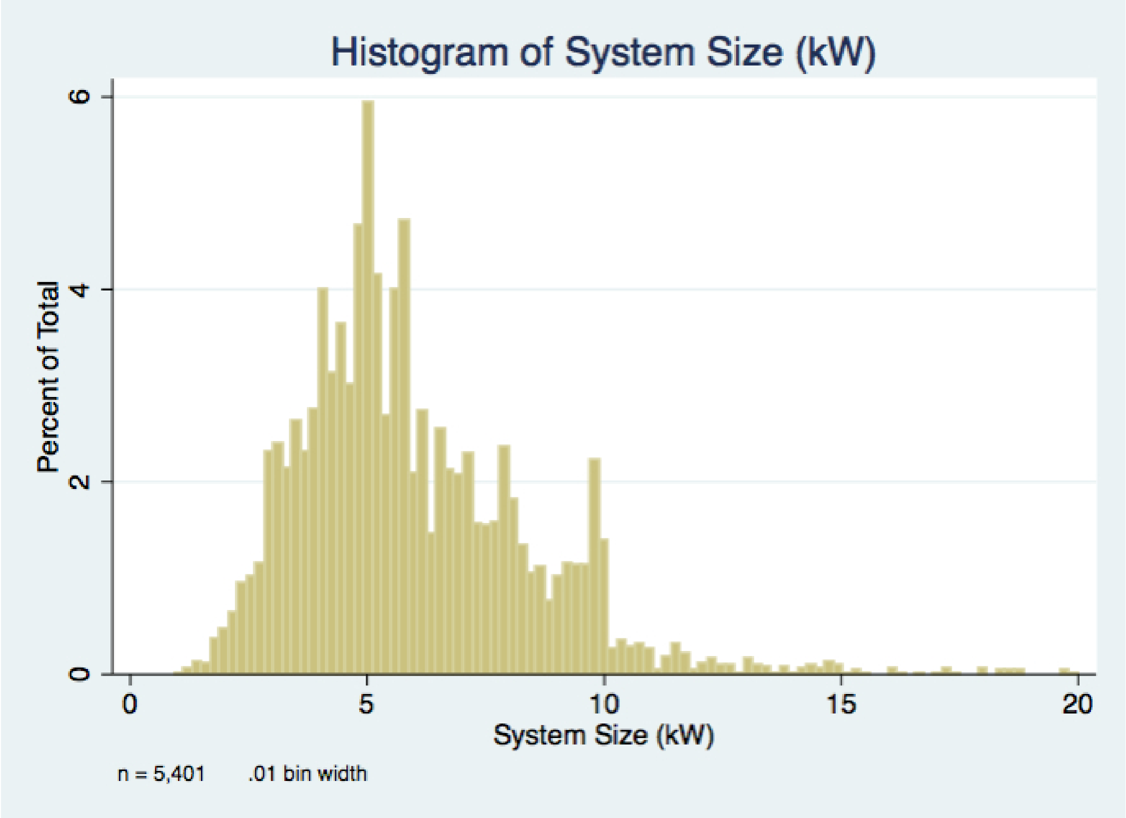


Fig. 8. Histogram of projects by system size (kW).

Several different factors may have impacted this distribution. Massachusetts investor owned utilities, including National Grid, Eversource and WMECO generally enforce additional fees and restrictions for systems sized over 10 kW. Additionally, for projects sized over 10 kW, a Data Acquisition System was required to be installed for purposes of automatic SREC production reporting, which imposed an additional cost to the project (PTS, 1). Larger system sizes may have also been less common due to roof space constraints, or because the electricity demands of the average residence would not require the installation of a larger solar PV system. A 2012 report from the US Energy Information Administration found that the average New England residence consumed

7,500 kWh in electricity per year (EIA, 1). A Massachusetts Department of Energy Resources report found that the average electricity production per kW of solar PV capacity was 1,156 kWh / kW (Department of Energy Resources, 2014). Using this as a standard, a residence would need (7,500 kWh / 1,156 kWh/kW), or around a 6 kW system to fully meet their electricity needs.

Additionally, a residence may have opted to install a system that only met a portion of their electricity needs. Systems sized less than 2 kW would most likely cover a relatively small portion of a resident's electric bill, and may have a reduced value as compared to the cost of installation.

Solar PV System Distribution by County. Figure 9 and Table 5 below provide clarification on the distribution of solar PV systems across Massachusetts. Counties with the largest population centers had the highest aggregate number of solar PV systems installed, as was the case in Middlesex and Worcester County. However counties that had the highest percentage of systems installed over number of owner occupied residences were Franklin, Hampshire and Dukes, located in Western Massachusetts and on Cape Cod, respectively.

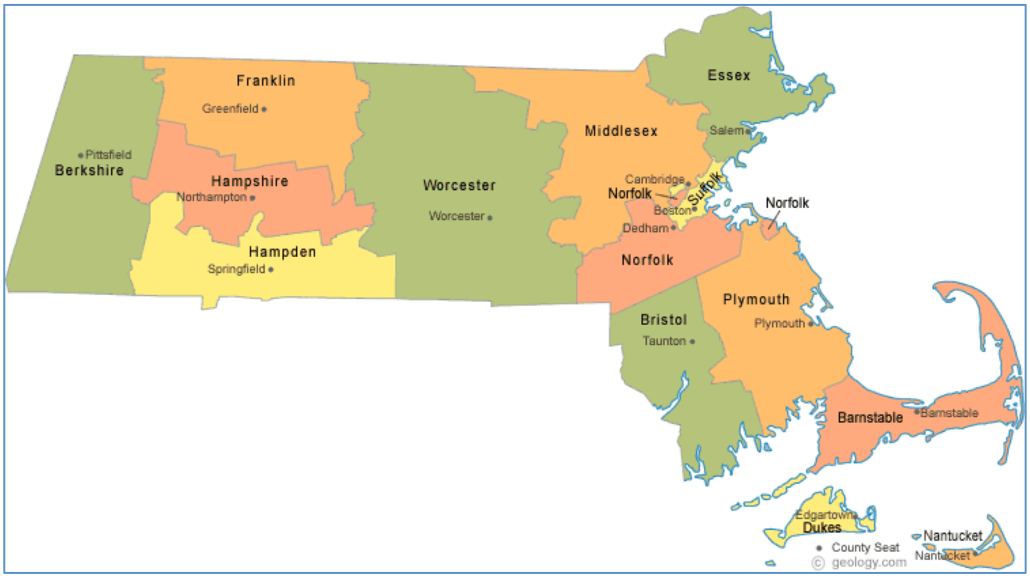


Fig. 9. Map of Massachusetts by county (Geology.com, 2015).

Table 5. Solar PV systems by county.

County	Systems Installed	% of Total	Population	Owner Occupied Housing Units	Percent Owner Occupied Housing Units with Solar PV System
Barnstable	438	8.10%	215,888	74,110	0.59%
Berkshire	163	3.00%	131,219	37,770	0.43%
Bristol	348	6.40%	548,285	132,793	0.26%
Dukes	68	1.30%	16,535	7,368	0.92%
Essex	454	8.40%	743,159	182,572	0.25%
Franklin	211	3.90%	71,372	20,987	1.01%
Hampden	133	2.50%	463,490	111,719	0.12%
Hampshire	279	5.20%	158,080	39,001	0.72%
Middlesex	1,589	29.40%	1,503,085	361,089	0.44%
Nantucket	3	0.10%	10,172	2,475	0.12%
Norfolk	369	6.80%	670,850	178,369	0.21%
Plymouth	322	6.00%	494,919	181,126	0.18%
Suffolk	345	6.40%	722,023	103,220	0.33%
Worcester	679	12.60%	798,552	200,322	0.34%
Total	5,401	100.00 %	6,547,629	1,632,921	0.33%

Overview of Solar PV Installers. A total of 211 companies or individual electricians installed the 5,400 solar PV systems included in the dataset. Table 6 below shows that the number of companies and individual electricians who actively installed solar PV systems over a given year increased over the course of the three installation years.

Table 6. Number of companies or individual electricians actively installing by installation year.

System Installation Year	Number of Companies or Individual Electricians Actively Installing
2010 - 2011	72
2011 - 2012	114
2012 - 2013	144

The 211 companies were broken into six different categories, including individual electricians, electrical contractors, construction or engineering companies, and solar energy installation firms. Table 7 below shows that individual electricians, electrical contractors, construction and engineering companies made up 98 of the 211 companies, or 46 percent of all installation companies. These companies installed an average of 2.8 systems per company, accounted for 4.4 percent of all solar PV installations, and 0.5 percent of all solar PV installations owned by a third party company. Additionally, 19 of the 24 individual electricians installed a single system. It may be that these electricians were installing a solar PV system on their own residence, or may have elected to pursue further installations as part of a separate firm. Eight companies were flagged for being mischaracterized. The term mischaracterized means that a company name in the dataset was misspelled, an acronym was used in lieu of the full name, or the installer name was listed as ‘See PowerClerk,’ NULL, or None. Additionally, five organizations were found to have changed their name, or to have undergone a company merger. As an example, the company Alteris Renewables Inc. installed a number of solar PV systems, then went through a merger to become Real Goods Solar in 2011, and subsequently began installing systems under their new name. In these instances, each organization was treated as separate company, as a change of leadership, ownership or company structure may have led to different installation practices.

Table 7. Summary of installations by company type.

Type of Company	No. of Companies	%of All Companies	Total No. of Installations	Average of Number of Installations	% of All Installs	% of All Installations (Third Party Owned)
Construction or Engineering Company	13	6.2%	30	2.3	0.6%	0.1%
Electrical Contractor	47	22.3%	105	2.2	1.9%	0.1%
Individual Electrician	24	11.4%	42	1.8	0.8%	0.0%
Other - Null, None, Mischaracterized	8	3.8%	47	5.9	0.9%	0.2%
Other Company or LLC	6	2.8%	11	1.8	0.2%	0.1%
Solar Installer or Energy Company	113	53.6%	5165	45.7	95.6%	99.5%
Total	211	100.0%	5400	25.6	100.0%	100.0%

An additional breakout of the 113 solar installer and energy firms can be seen in Table 8 below, and provides a useful snapshot of the solar PV installation industry, in which a relatively small number of solar PV and energy companies accounted for a large percentage of residential solar PV systems installed. Solar installation or energy companies made up 113 of the 211 companies, and accounted for the installation of 95.6 percent of all systems, and 99.5 percent of all systems that were owned by a third party company.

Table 8. Number of installations by solar PV or energy company.

No. of Solar PV Installations by Solar / Energy company	No. of Companies	% of All Solar Energy Companies	Total No. of Installs	Mean No. of Installs	% of All Installs by Solar / Energy company	% of all Installations (Third Party Owned)
Installed 1 system	29	25.7%	29	1.0	0.6%	0.2%
Installed 2 - 3 systems	14	12.4%	33	2.4	0.6%	0.1%
Installed 4 - 10 systems	22	19.5%	157	7.1	3.0%	0.6%
Installed 11 - 30 systems	16	14.2%	313	19.6	6.1%	0.8%
Installed 31 - 100 systems	19	16.8%	1239	65.2	24.0%	15.4%
Installed 100 - 200 systems	6	5.3%	817	136.2	15.8%	5.8%
Installed 200+ systems	7	6.2%	2578	368.3	49.9%	77.1%
Total	**113**	**100.0%**	**5166**	**45.7**	**100.0%**	**100.0%**

Sixty-five companies, equaling 57 percent of all solar installer and energy companies, installed 10 or fewer solar PV systems. The combined number of installations of this subset of solar installers is equivalent to 4.2 percent of all solar PV systems installed by solar installer and energy companies. Thirty-two companies accounted for 89 percent of solar PV systems installed by solar PV and energy companies. Of these, thirteen companies accounted for 65 percent of all systems installed by solar PV and energy companies, and 82 percent of systems were owned by a third party company. Of the seven companies with over 200 systems installed, three companies installed third party owned systems 100 percent of the time, two companies installed third party owned systems 90 to 99 percent of the time, and two companies installed third party owned systems 51 to 89 percent of the time. Very few of the smaller-scale installers sold third party owned systems. A more extensive chart can be found in Appendix 1.

Overview of Inverter Manufacturers. The inverter of the solar PV system is responsible for converting electricity from the solar PV panels from direct current electricity (DC) to alternating current electricity (AC), which can then be used in the residence. Twenty-two inverter manufacturers were utilized within the dataset, though as seen in Figure 10, five inverter manufacturers serviced 85% of all solar PV systems.

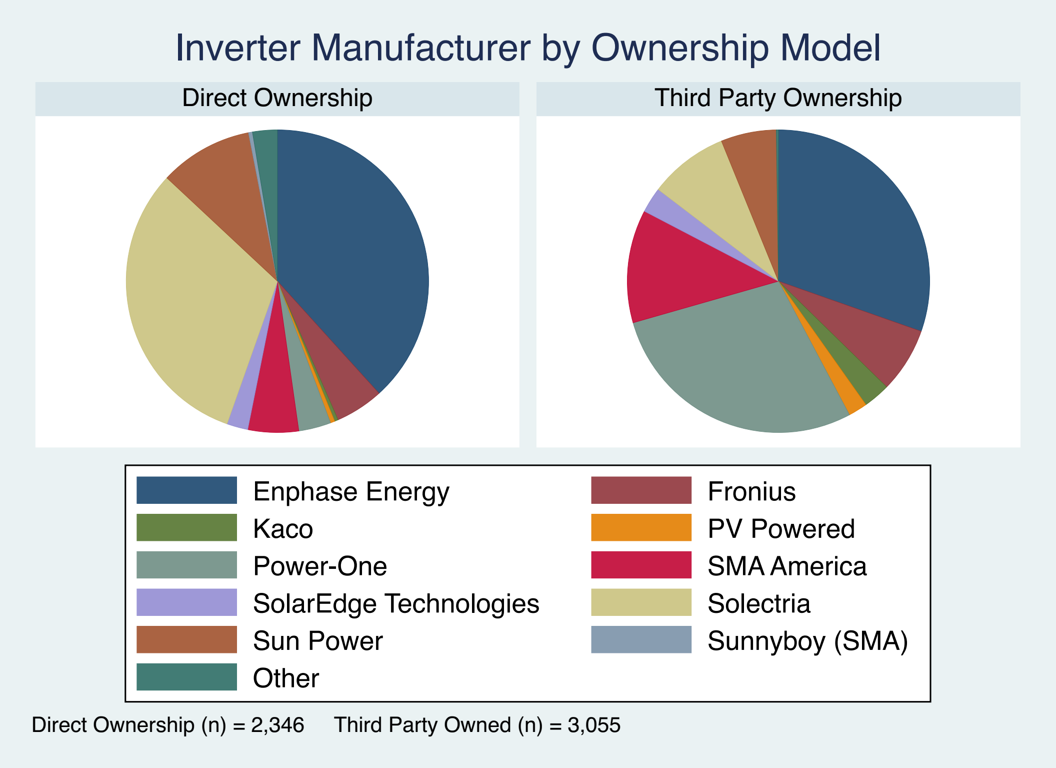


Fig. 10. Pie chart of inverter manufacturers by ownership model.

As part of the Massachusetts Commonwealth Solar II rebate program, an additional 'Massachusetts Manufactured Components' rebate incentive was offered, equivalent to between $250 and $500 dollars of additional rebate incentive if major system components were used that were manufactured by a Massachusetts-based company. During the installation timeframe of this analysis, the only major piece of equipment eligible for this incentive and was actually installed was the Solectria inverter product. Solectria inverters were utilized for 18 percent of all systems. They were selected more often as part of direct ownership systems, as compared to third party owned systems. This may be because residential system owners may have a greater interest in purchasing equipment from a local manufacturer, or may be more likely to respond to small additional rebate incentives, as compared to a third party owned company.

The company Enphase was the primary manufacturer of micro-inverter technology. Micro-inverters are typically individually placed under each solar PV panel, and allow each panel to produce electricity independently from other solar PV panels. This can be especially useful for sites with partial shading. With a standard central inverter system, panels are wired in series, such that if one solar PV panel is shaded, other panels connected in series may be impacted similarly to the shaded panel, even if other panels are in full sun. In addition, although not yet widely used during the installation timeframe of the dataset, a separate inverter manufacturer called SolarEdge Technologies utilizes a central inverter coupled with DC-optimizer technology. For purposes of this analysis, SolarEdge Technologies inverters were considered to be equivalent to micro-inverter technology and labeled as micro-inverters. A full list of solar inverter and PV panel manufacturers can be found in Appendix 2.

Overview of Solar PV Panel Manufacturers. Fifty-five solar PV panel manufacturers were utilized within the dataset, though as was found with inverter manufacturers, eight solar PV panel manufacturers serviced 75% of all solar PV systems. Also similar to the inverter manufacturers, third party companies often utilized a subset of solar PV panel manufacturers as compared to direct purchase systems.

Percent Shading. As seen in Figure 11 below, there was likely a correlation between shading and production (kWh/kW), though there can be seen a lot of remaining production variability not accounted for by shading. It is also clear that there are fewer systems built at higher shading percentages. This is likely due to installer and public awareness around the likely negative correlation between shading and production. This leads to a dataset that shows clear signs of heteroscedasticity, which may mean that the relationship between shading and production cannot be as precisely estimated, as may have been the case for a normally distributed dataset for the percent shading variable.

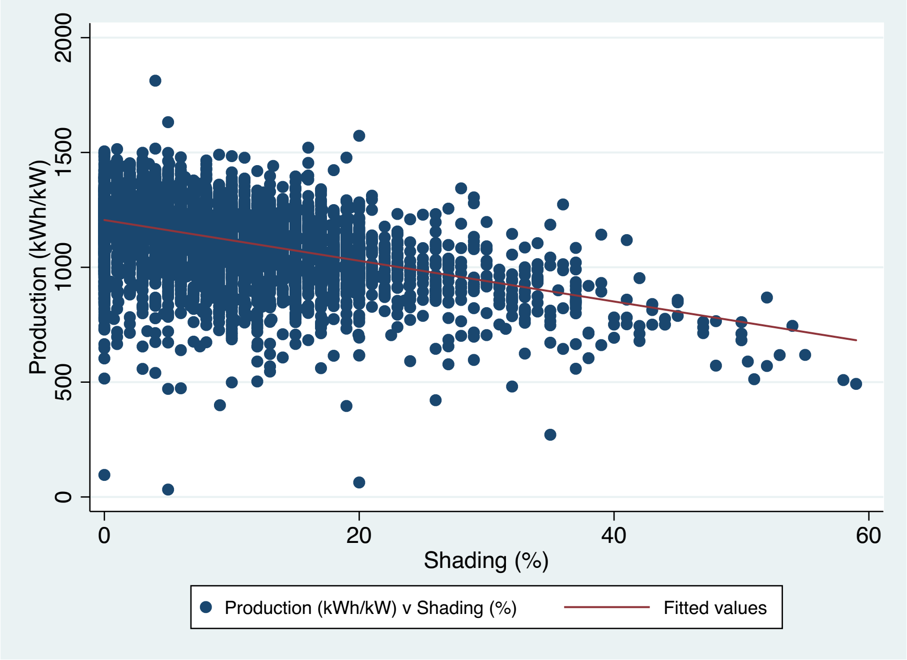


Fig. 11. Production (kWh / kW) of dataset by percent shading.

Framework of Analysis

System electricity production data utilized for the analysis was taken from a single reporting year, from July 1, 2013 until June 30, 2014 for all systems. This reporting year included one winter cycle, and was selected in order to allow for the largest number of solar PV systems to be included in the analysis.

Weather and solar irradiance background on reporting year. The reporting year showed typical weather patterns. As seen in Figure 11 and 12, temperature and dew point data during the 2013 – 2014 reporting year were within historical norms at Boston Logan Airport, Worcester Municipal Airport.

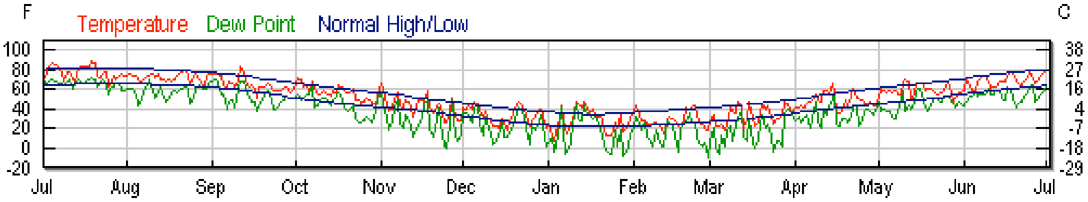


Fig. 12. Chart of temperature and dew point for Boston Logan Airport July 1, 2013 through June 30, 2014 (Weather Underground, 2015).

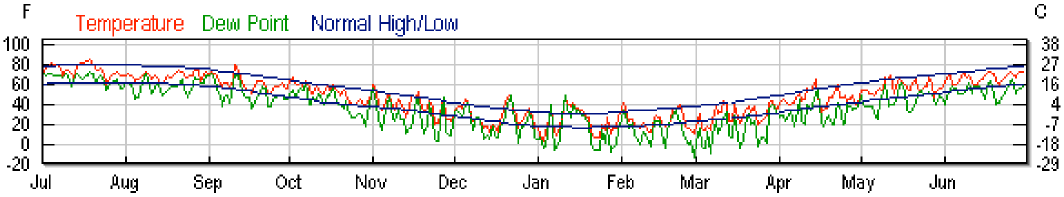


Fig. 13. Chart of temperature and dew point for Worcester Regional Airport July 1, 2013 through June 30, 2014 (Weather Underground, 2015).

Table 9 presents solar irradiance data for the reporting year compared to historical norms for Boston Logan Airport, Worcester Municipal Airport Westfield Regional Airport, and Barnstable Regional Airport. Global horizontal irradiance (GHI), direct normal irradiance (DNI), and diffuse horizontal irradiance (DHI) are three factors utilized in determining how much solar radiation is reaching the earth’s surface for a given location. The amount of solar irradiance varied across the four sites over the reporting year, but was generally higher or equivalent to the 1991 – 2005 Typical Meteorological Year (TMY3) averages. (National Solar Radiation Database, 2009) GHI, DNI, and DHI solar radiation numbers for the July 1, 2013 – June 30, 2014 timeframe were compiled using the resource tool SolarAnywhere® with permission from the company Clean Power Research®.

Table 9. Typical meteorological year vs. reporting year annual irradiance for four sites.

	Barnstable Municipal Airport			Boston Logan Airport		
	GHI	DNI	DHI	GHI	DNI	DHI
1991 - 2005 Average	1317809	1207756	619107	1407838	1336042	651843
July 1, 2013 - June 30, 2014	1462866	1443169	624592	1446568	1460657	637355
Percent Difference	9.9%	16.3%	0.9%	2.7%	8.5%	-2.3%
	Westfield Municipal Airport			Worcester Regional Airport		
	GHI	DNI	DHI	GHI	DNI	DHI
1991 - 2005 Average	1225092	1034108	648922	1394729	1276221	677955
July 1, 2013 - June 30, 2014	1417135	1378177	652104	1410213	1397542	637594
Percent Difference	13.6%	25.0%	0.5%	1.1%	8.7%	-6.3%

Installation year. Many solar PV systems did not begin reporting production until several months after the official project Date in Service (DIS). The DIS is the date the utility provided authority for the system owner to turn on their system. This delay is likely tied to the time needed to formalize a relationship with an aggregator or broker after installation, and have that entity submit a Statement of Qualification Application (SQA) to the Department of Energy Resources. With this in mind, in order to minimize the number of systems with missing reporting months in the dataset, when determining the parameters for how systems would be broken into installation years, a two month buffer was added after the last included project DIS and the start of the July 1, 2013 – June 30 reporting year. Therefore, for a system to be included in the 2012 – 2013 installation year, it would need to have a DIS of April 30, 2013 or earlier. Systems with a DIS that was later than April 30, 2015 were removed from the dataset. Systems with a DIS from previous years were assigned to an installation year according to Table 10 below.

Note that mid-way through the analysis, systems with a reported number of ‘Null’ during one or more months during the reporting year were removed. A production number of ‘Null’ meant that the system owner did not actively report a production number. However, systems where the reporter actively reported a ‘0’ for a given month were maintained in the dataset. If this decision had been implemented at the onset of the analysis, then the two month timeframe between the last solar PV system DIS and the start of the July 1, 2013 – June 30 reporting year could have been removed. This was kept in place however, because to remove the two-month timeframe later in the analysis would have required re-adjusting the installation years, and would have included adding new systems into the dataset. Since much of the analysis was completed at that stage, the two-month timeframe between the last system DIS and the start of the reporting year was kept in place.

Table 10. Installation Year Breakout.

Installation Year	Timeline
2010 - 2011	Systems installed and with a DIS between January 1, 2010 and April 30, 2011
2011 - 2012	Systems installed and with a DIS between May1, 2011 and April 30, 2012
2012 - 2013	Systems installed and with a DIS between May 1, 2012 and April 30, 2013

Overview of variable analysis. Sixteen variables in the dataset were identified as having a potential impact on system electricity production. Of these, the variable system size was analyzed separately. System production was then normalized by system size as part of the analysis of the remaining 15 variables. We hypothesize that system size would be one of the most important variables that impact system electricity production. We expected that as a solar PV system increased in size, the amount of production would increase correspondingly.

The additional fifteen variables were seen as impacting system production independently from system size. This meant that variables such as county, system shading, receipt of a rebate, ownership model, reporting method, system azimuth and inclination, and other variables would impact the entire solar PV system, regardless of whether the system size was 1 kW or 15 kW. Additionally, as noted previously in Figure 8, project system size was unevenly distributed over the dataset. As a result of these two factors, production was normalized by system size and a standard unit of measurement, production per kilowatt of installed capacity (kWh / kW), was used to quantity the impact of the remaining 15 variables. The new outcome variable production per kW also offers a standard measurement unit, which makes the impact of the 15 predictor variables easier to compare over systems of different sizes. Production per kilowatt was created by dividing total system size by total annual production over the reporting year. As an example, a 5 kW system that produced 5,000 kWh over the course of the reporting year would be shown as having produced 1,000 kWh / kW.

Correspondingly, production per kW may be more readily converted to a system ‘Capacity Factor,’ an internationally recognized measurement that can be used to compare system output over time across both conventional and renewable energy technologies. The Capacity Factor of an electricity generating system is defined as the percentage of time that a system is actively producing electricity, as compared to if the system were to produce electricity 100 percent of the time. For example, a conventional coal fired power plant may have a capacity factor of close to 100 percent, as the system generating electricity can be turned on and off at will, though may only be turned off periodically for system maintenance. The capacity factor for a renewable energy system is likely more variable, as it is dependent on when the sun is shining, and local weather patterns. The Capacity Factor (%) equals annual electricity production from solar PV system divided by system size (kW) and then divided by total hours per year (8,760 hr). This may also be defined as the Ratio of Generation. Table 17 in the Results section shows the coefficient of determination of variables found to be statistically significant, as well as their relative impact on system capacity factor.

Figure 14 below provides some clarification on the relative range of capacity factors by technology type, based on utility-scale systems installed across the United States. The vertical lines represent the range, while the whiskers represent (+/-) one standard deviation beyond the interquartile range (National Renewable Energy Lab, 2015). The capacity factor for the 69 utility-scale solar PV systems tested had a mean capacity factor of 20%, as compared to onshore wind at 38% and natural gas combustion, at around 80%. Solar PV technology also had a relatively small capacity factor range in comparison to several other technologies.

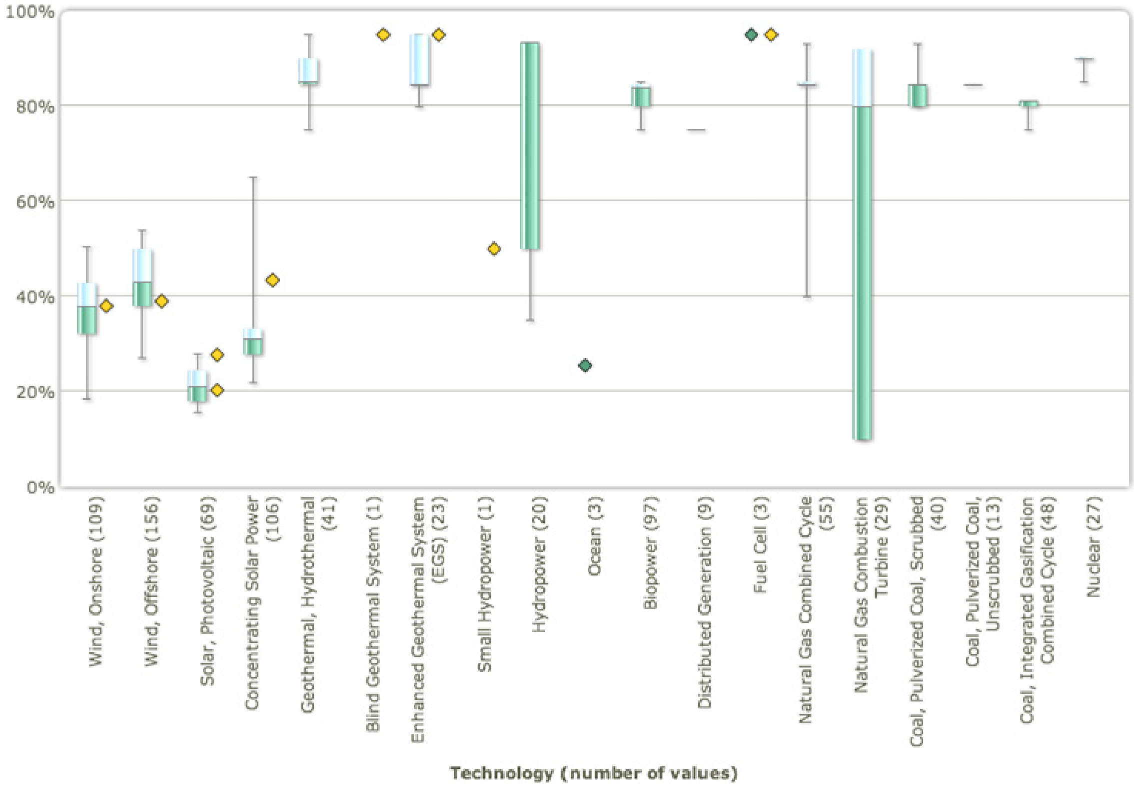


Fig. 14. Capacity factor of utility scale electricity generation units, by technology (NREL, 2015).

Hypothesis I, II, and III Scope

The following hypotheses were examined by this methodology:

I. As part of the preliminary analysis, system size will account for a majority of electricity production (kWh) variability as part of the 2013 – 2014 reporting year.

II. When electricity production is normalized by system size, I hypothesize that the distribution of residential solar PV electricity production per kilowatt (kWh / kW) over all measured solar PV systems will exhibit a normal distribution pattern.

III. Using a multiple regression analysis, I hypothesize that fifteen variables will elicit a measurable, statistically significant impact on the production of solar PV systems (kWh / kW) and will account for the greatest percentage of production variability. These variables include percent shading, azimuth, inclination, receipt of a rebate, county and others. The below empirical specification further clarifies the proposed analysis.

Hypothesis III Empirical Specification

Below is the full formula used for the outcome variable production per kilowatt (kWh / kW) and the variables that are predicted to influence solar PV system production.

Production per kilowatt is denoted as P_i for installation i. A description of each of the below variables can be found in Table 2 above.

$$\begin{gathered} P_i = \beta 0 + \boldsymbol{\beta 1}\text{Shd}_i + \boldsymbol{\beta 2}\text{Azm}_i + \boldsymbol{\beta 3}\text{Inc}_i \\ + \boldsymbol{\beta 4}\text{Elg}_i + \boldsymbol{\beta 5}\text{Imic}_i + \boldsymbol{\beta 6}\text{Own}_i + \boldsymbol{\beta 7}\text{Rpt}_i + \boldsymbol{\beta 8}\text{Sol}_i + \boldsymbol{\beta 9}\text{Cst}_i + \boldsymbol{\beta 10}\text{YrDis}_i\ \boldsymbol{\beta 11}\text{Peff}_i \\ + \boldsymbol{\beta 12}\text{County}_i + \boldsymbol{\beta 13}\text{Pmf}_i + \boldsymbol{\beta 14}\text{Imf}_i + \boldsymbol{\beta 15}\text{Com}_i + \varepsilon_i \end{gathered}$$

Variables were tested as part of eight different multiple regression models, broken down as follows:

Table 11. Eight multiple regression models.

Model	Empirical Specification
1.	$P_i = \beta 0 + \boldsymbol{\beta 1}\text{Shd}_i + \varepsilon_i$
2.	$P_i = \beta 0 + \boldsymbol{\beta 1}\text{Shd}_i + \boldsymbol{\beta 2}\text{Azm}_i + \boldsymbol{\beta 3}\text{Inc}_i + \varepsilon_i$
3.	$P_i = \beta 0 + \boldsymbol{\beta 1}\text{Shd}_i + \boldsymbol{\beta 2}\text{Azm}_i + \boldsymbol{\beta 3}\text{Inc}_i + \boldsymbol{\beta 4}\text{Elg}_i + \boldsymbol{\beta 5}\text{Imic}_i + \varepsilon_i$
4.	$P_i = \beta 0 + \boldsymbol{\beta 1}\text{Shd}_i + \boldsymbol{\beta 2}\text{Azm}_i + \boldsymbol{\beta 3}\text{Inc}_i + \boldsymbol{\beta 4}\text{Elg}_i + \boldsymbol{\beta 5}\text{Imic}_i + \boldsymbol{\beta 6}\text{Own}_i + \boldsymbol{\beta 7}\text{Rpt}_i + \varepsilon_i$
5.	$P_i = \beta 0 + \boldsymbol{\beta 1}\text{Shd}_i + \boldsymbol{\beta 2}\text{Azm}_i + \boldsymbol{\beta 3}\text{Inc}_i$ $+ \boldsymbol{\beta 4}\text{Elg}_i + \boldsymbol{\beta 5}\text{Imic}_i + \boldsymbol{\beta 6}\text{Own}_i + \boldsymbol{\beta 7}\text{Rpt}_i + \boldsymbol{\beta 8}\text{Sol}_i + \boldsymbol{\beta 9}\text{Cst}_i + \boldsymbol{\beta 10}\text{YrDis}_i + \boldsymbol{\beta 11}\text{Peff}_i + \varepsilon_i$
6.	$P_i = \beta 0 + \boldsymbol{\beta 1}\text{Shd}_i + \boldsymbol{\beta 2}\text{Azm}_i + \boldsymbol{\beta 3}\text{Inc}_i$ $+ \boldsymbol{\beta 4}\text{Elg}_i + \boldsymbol{\beta 5}\text{Imic}_i + \boldsymbol{\beta 6}\text{Own}_i + \boldsymbol{\beta 7}\text{Rpt}_i + \boldsymbol{\beta 8}\text{Sol}_i + \boldsymbol{\beta 9}\text{Cst}_i + \boldsymbol{\beta 10}\text{YrDis}_i + \boldsymbol{\beta 11}\text{Peff}_i$ $+ \boldsymbol{\beta 12}\text{County}_i + \varepsilon_i$
7.	$P_i = \beta 0 + \boldsymbol{\beta 1}\text{Shd}_i + \boldsymbol{\beta 2}\text{Azm}_i + \boldsymbol{\beta 3}\text{Inc}_i$ $+ \boldsymbol{\beta 4}\text{Elg}_i + \boldsymbol{\beta 5}\text{Imic}_i + \boldsymbol{\beta 6}\text{Own}_i + \boldsymbol{\beta 7}\text{Rpt}_i + \boldsymbol{\beta 8}\text{Sol}_i + \boldsymbol{\beta 9}\text{Cst}_i + \boldsymbol{\beta 10}\text{YrDis}_i + \boldsymbol{\beta 11}\text{Peff}_i$ $+ \boldsymbol{\beta 12}\text{County}_i + \boldsymbol{\beta 13}\text{Pmf}_i + \boldsymbol{\beta 14}\text{Imf}_i + \varepsilon_i$
8.	$P_i = \beta 0 + \boldsymbol{\beta 1}\text{Shd}_i + \boldsymbol{\beta 2}\text{Azm}_i + \boldsymbol{\beta 3}\text{Inc}_i$ $+ \boldsymbol{\beta 4}\text{Elg}_i + \boldsymbol{\beta 5}\text{Imic}_i + \boldsymbol{\beta 6}\text{Own}_i + \boldsymbol{\beta 7}\text{Rpt}_i + \boldsymbol{\beta 8}\text{Sol}_i + \boldsymbol{\beta 9}\text{Cst}_i + \boldsymbol{\beta 10}\text{YrDis}_i + \boldsymbol{\beta 11}\text{Peff}_i$ $+ \boldsymbol{\beta 12}\text{County}_i + \boldsymbol{\beta 13}\text{Pmf}_i + \boldsymbol{\beta 14}\text{Imf}_i + \boldsymbol{\beta 15}\text{Com}_i + \varepsilon_i$

I hypothesize that these fifteen variables will be statistically significant, and will explain the majority of the variability of the production data (kWh / kW). Since the production from solar PV panels can be greatly impacted by the effects of shading, I hypothesize that shading will have the largest impact on system production, in which each additional percentage of shade on the system will be correlated with an additional loss in system electricity production. It is also expected that as the azimuth and inclination of solar PV systems move further from optimal conditions (180 degrees true south, and 43 degrees respectively), the system production will correspondingly decrease. Correspondingly, I expect that systems that received a MassCEC rebate will be positively correlated to greater electricity production, as compared to systems that did not , because eligibility for a rebate was contingent on having favorable site specifications with regards to shading, azimuth and inclination. Additionally, I expect that the county where the system is installed will impact system production. The impact may be the result of regional weather variability, closeness to large bodies of water, or density of area tree cover.

I hypothesize that solar PV systems that are owned by a third party company will have higher electricity production as compared to solar PV systems directly owned by residential property owners. The postulation is that commercial companies have a good return on investment as a primary end-goal of their system ownership, which is tied to a well producing system. For a residential system owner, a good return on investment may only be one of multiple motivations to purchase a system. Additionally, I hypothesize that production which is reported manually to PTS will have a higher standard deviation, versus automatic reporting of production. This may be caused by human errors in manual reporting, or potential human manipulation of the production numbers. I hypothesize that use of micro inverter technology will be positively correlated to system production, especially for systems with higher levels of site shading.

I hypothesize that system cost per watt will be positively correlated to system production, in which an additional unit dollar per watt cost would result in higher production. The historical drop in system cost over the past several years may lead to the expansion of sites that were once considered to be non-feasible, to subsequently become feasible. This may be because as projects become less expensive, sites with lower levels of expected production may increasingly result in an acceptable return on investment for system owners. Correspondingly, I hypothesize that systems installed in later installation years will be negatively correlated to system production, in which every additional year after the first installation year of 2011 would result in lower mean production. I hypothesize solar PV systems installed as a result of the community outreach and education campaign known as Solarize Massachusetts would be positively correlated with production. Selection of a specific installer, panel manufacturer, and inverter manufacturer will be statistically significant, and specific manufacturers and installers will correspondingly positively and negatively impact system production.

An additional variable, weather, is not taken into consideration directly. Rather, county may act as a correlating covariate to control for differences in weather across counties. All solar PV systems are compared over the same one-year timeframe of July 1, 2013 through June 30, 2014, therefore controlling for solar resource availability at the state-level.

Chapter 3

Results

The Results section incorporates the results of the three hypotheses, including a summary of the regression by variable and overall summary of the results of the analysis.

Hypothesis I: Impact of System Size on Overall System Production

The first hypothesis asserted that as part of an initial analysis, system size would account for a majority of electricity production (kWh) variability as part of the 2013 – 2014 reporting year. As a means of visualizing the dataset, Figure 15 below shows total system production (kWh) as compared to system size, and also includes a best-fit line. As previously seen as part of Figure 7, there are fewer systems that are larger than 10 kW, and fewer still that are larger than 15 kW. Additionally, as system size gets larger, the variance of system production grows wider, which is an indication of heteroscedasticity in the dataset. This means that the standard errors would be biased and cannot be assumed to be uniform within the dataset. As a result of this, as part of the below regression analysis, a robust regression was used in which the regression formula included robust standard errors.

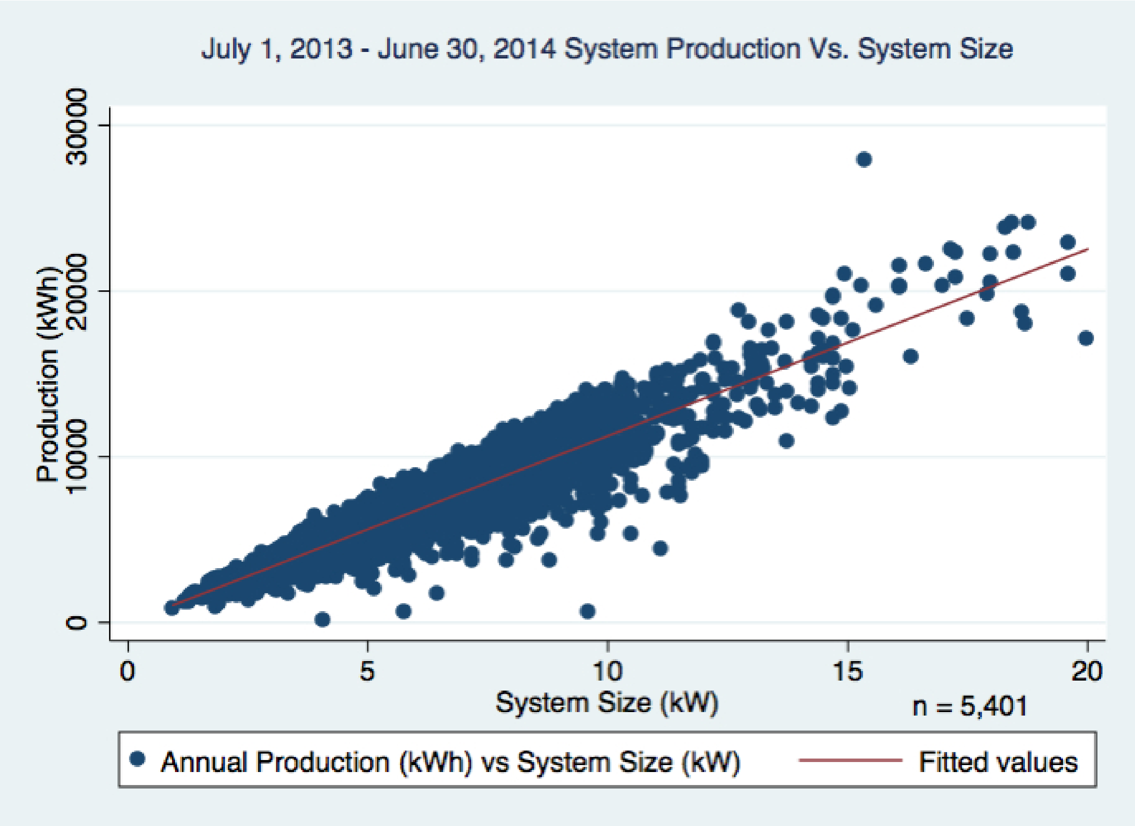


Fig. 15. Scatterplot and best fit line of 2013 – 2014 production (kWh) compared to system size (kW).

Although there is variability in system production relative to the best-fit line, there is only one extreme outlier that is above the line of best fit, while there are over ten outliers that are below the line of best fit. The lack of outliers above the line of best fit may be the result of the monthly PTS production validation process. As noted previously, the PTS administrators flagged systems for follow-up that in a given month produced electricity at a level that was more than two standard deviations above the mean. Over the course of a year, this validation process may have limited any errors or false reporting of production at levels well above the average system in the state for manual reporting systems. Systems with an automatically reporting Data Acquisition System which directly provided information to the PTS, would likely be much more resistant to tampering.

Figure 15 above shows that solar PV systems are likely not over-reporting their monthly production, at least not at a level that would be flagged for further review by the PTS. This may be a positive finding for the PTS and administrators of the production based SREC program.

A regression analysis was conducted to determine the slope of the best-fit line for the variable system size as it relates to total system production. As seen in Table 12 below, system size was found to be a statistically significant predictor variable, and as expected, was positively correlated with electricity production. An increase in system size of 1 kW resulted in an average annual increase in production of 1,127 kWh (slope 1,127kWh / kW).

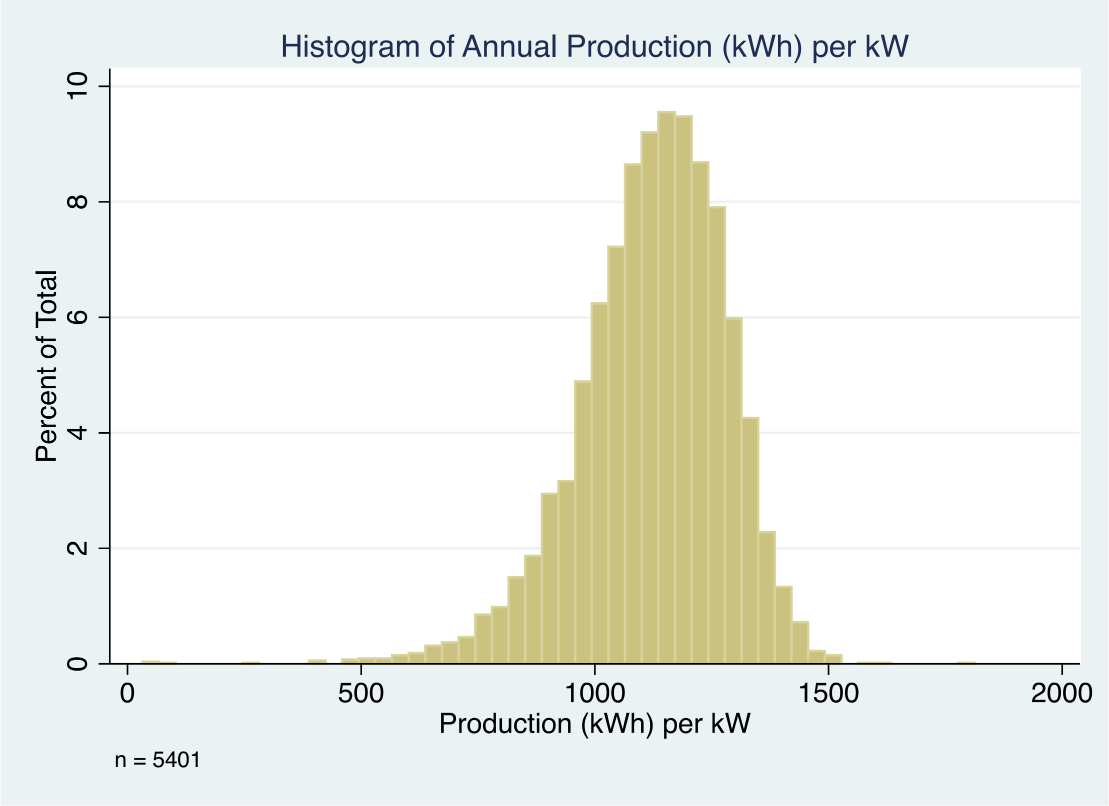
Table 12. Regression of production (kWh) by system size (kW).

VARIABLES	(1) Production
System Size DC	1,127***
	(9.610)
Constant	-14.12
	(49.97)
Observations	5,401
R-squared	0.872

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Hypothesis II: Distribution of Production when System Size is Normalized

The second hypothesis asserts that when production is normalized by system size, residential solar PV electricity production per kilowatt (kWh / kW) of all systems will exhibit a normal distribution pattern. Figure 16 below shows two histograms showing production (kWh) per kW, as segmented into 50 distinct bins. The second histogram shows a normal-density plot superimposed over the original histogram. The mean of the dataset is 1,123.8 kWh/kW.



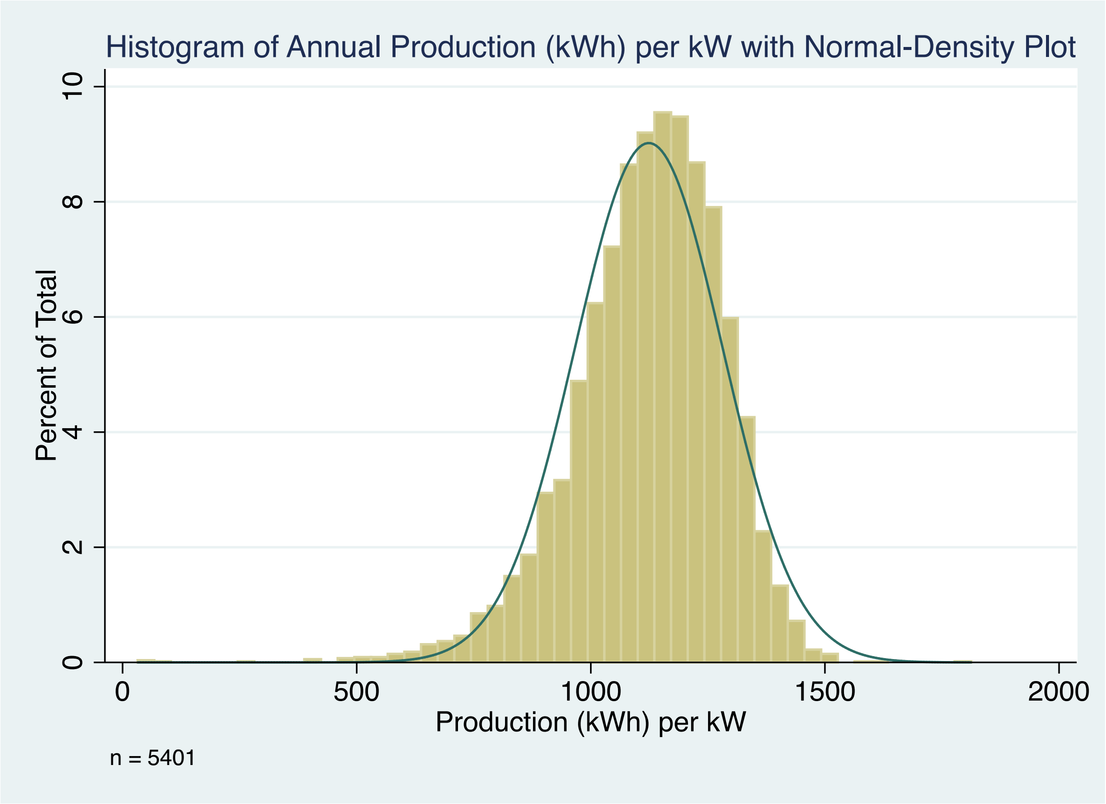


Fig. 16. Histogram of production (kWh) per kW and normal-density plot.

Although the histogram shows a bell shaped distribution, when comparing to the normal-density plot, the data set show a slightly longer left tail. Additionally, there is a higher peak in the center right of the production curve than the normal distribution curve. This dynamic can also be found as part of Table 13 below. A skewness of -0.78 demonstrates that there is a slightly longer tail to the left of the histogram shown in Figure 15, in comparison to the normal distribution shown in red. A kurtosis of 4.99 (or 1.99) is positive, showing that the kernel density curve has a slightly higher peak than the normal distribution curve. However, the production per kW appears to closely trend toward a normal distribution. In addition, the standard deviation of the dataset was 157 kWh/kW, meaning that the majority of systems (67%) reported production within (+/-) 7% of the mean.

Table 13. Percentiles of 2013 - 2014 production (kWh / kW).

	Percentiles	Smallest		
1%	671.525	32.10784		
5%	848.519	62.86183		
10%	922.2178	95.77954	Observations	5400
25%	1033.681	270.7029	Sum of Weight	5400
50%	1137.765	Largest	Mean	1123.805
75%	1233.933	1520.855	Standard Deviation	157.4732
90%	1305.802	1572.538	Variance	24797.8
95%	1346.755	1631.794	Skewness	-0.7865343
99%	1424.466	1812.413	Kurtosis	4.99629

To better see this, the Normal Probability Plot seen in Figure 17 below is a graphical technique for assessing whether or not a data set is approximately normally distributed. If the data lie close to the green line, then the data can be considered normally distributed, as is largely the case in the figure above.

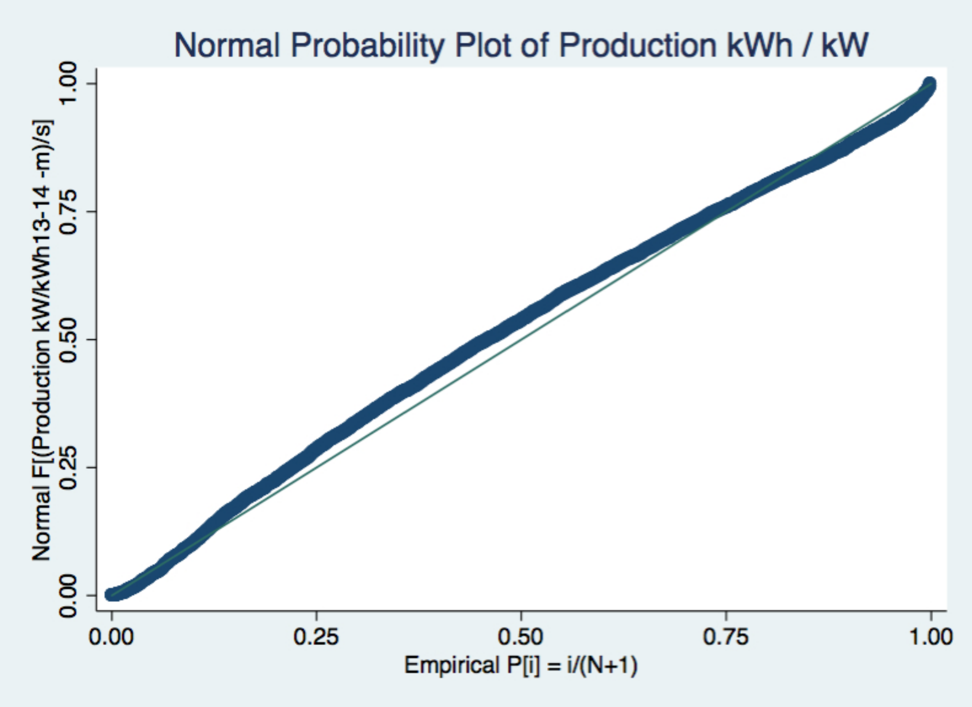


Fig. 17. Normal probability plot of production kWh / kW.

Hypothesis III: Multiple Regression Analysis

The third hypothesis stipulated that fifteen variables would elicit a measurable, statistically significant impact on the production of solar PV systems per kW (kWh /

kW), and would account for the greatest percentage of production variability. By building out eight separate multiple regression models shown in Tables 14 and 15 below, a series of patterns emerged. To address the possibility that heteroscedasticity is biasing the standard errors, the regressions were run with robust standard errors.

Table 14. Multiple regression analysis models 1 through 4.

VARIABLES	(1) Model 1	(2) Model 2	(3) Model 3	(4) Model 4
Percent Shading	-8.872***	-8.972***	-8.889***	-8.964***
	(0.240)	(0.237)	(0.242)	(0.243)
Azimuth from 180		-0.424***	-0.409***	-0.425***
		(0.0598)	(0.0595)	(0.0600)
Inclination from 43		-1.082***	-1.168***	-1.161***
		(0.212)	(0.209)	(0.209)
Rebate Eligibility			28.00***	30.66***
			(4.816)	(4.986)
Micro Inverter			41.46***	43.77***
			(4.079)	(4.125)
Ownership (Third Party)				21.65***
				(5.064)
Reporter (Automatic)				-6.819
				(5.257)
Constant	1,206***	1,237***	1,200***	1,191***
	(3.042)	(4.057)	(6.360)	(7.356)
Observations	5,400	5,400	5,400	5,400
R-squared	0.207	0.232	0.248	0.251

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table15. Multiple regression analysis models 5 through 8.

VARIABLES	(5) Model 5	(6) Model 6	(7) Model 7	(8) Model 8
Percent Shading	-8.912***	-8.949***	-8.961***	-9.482***
	(0.249)	(0.250)	(0.269)	(0.289)
Azimuth from 180	-0.438***	-0.404***	-0.390***	-0.370***
	(0.0608)	(0.0603)	(0.0596)	(0.0584)
Inclination from 43	-1.161***	-1.223***	-1.163***	-1.165***

	(0.209)	(0.207)	(0.206)	(0.203)
Rebate Eligibility	37.04***	29.10***	36.08***	50.79***
	(5.299)	(5.485)	(5.666)	(6.375)
Micro Inverter	41.61***	41.86***	6.387	17.29
	(4.261)	(4.312)	(14.91)	(14.99)
Ownership (Third Party)	20.75***	24.60***	17.25***	8.902
	(5.250)	(5.193)	(5.674)	(6.662)
Reporter (Automatic)	-5.000	-2.413	-5.163	0.869
	(5.289)	(5.294)	(5.473)	(6.487)
Cost per Watt	7.683***	7.275***	7.687***	7.226***
	(1.764)	(1.758)	(1.809)	(2.302)
Solarize Mass	9.584	21.30***	12.98**	7.053
	(5.868)	(6.092)	(6.461)	(7.597)
Date in Service Year	6.039	8.849**	9.387**	12.62***
	(3.757)	(3.715)	(4.224)	(4.890)
Panel Efficiency	-0.0941	-0.667	-1.900	-2.083
	(0.977)	(0.955)	(1.875)	(1.967)
1. Barnstable County		92.86***	99.17***	103.6***
		(12.46)	(13.14)	(14.52)
3. Bristol County		80.88***	85.82***	91.87***
		(12.75)	(13.33)	(13.81)
4. Dukes County		136.0***	140.5***	158.3***
		(17.79)	(18.31)	(23.63)
5. Essex County		40.68***	40.23***	60.97***
		(12.56)	(13.09)	(13.60)
6. Franklin County		38.30***	45.15***	38.82**
		(14.83)	(15.01)	(15.61)
7. Hampden County		58.46***	55.70***	62.91***
		(15.30)	(15.43)	(15.73)
8. Hampshire County		50.71***	51.73***	49.81***
		(13.99)	(14.25)	(14.70)
9. Middlesex County		33.83***	29.08**	40.59***
		(11.28)	(11.70)	(12.35)
10. Nantucket County		111.9**	106.7**	80.57*
		(45.94)	(50.88)	(46.35)
11. Norfolk County		33.63***	33.64**	42.68***
		(12.61)	(13.16)	(13.54)
12. Plymouth County		59.39***	65.03***	79.65***
		(12.94)	(13.34)	(14.03)
13. Suffolk County		27.97**	27.68**	49.16***
		(13.16)	(13.81)	(14.43)
14. Worcester County		57.15***	53.54***	52.26***
		(11.84)	(12.22)	(12.76)
Inverter Manufacturer Dummies			(Y)	(Y)
Panel Manufacturer Dummies			(Y)	(Y)
Installer Dummies				(Y)
Constant	1,129***	1,086***	1,108***	1,073***
	(21.08)	(23.15)	(35.45)	(38.31)
Observations	5,399	5,399	5,399	5,399
R-squared	0.255	0.275	0.299	0.342

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table16. Capacity factor and percent of the constant.

Variable	(Model 8) Covariate (kWh/kW)	Percent of Constant	Capacity Factor
Percent Shading (per percent)	-9.482	-0.88%	-0.108%
Azimuth from 180 (per degree)	-0.37	-0.03%	-0.004%
Inclination from 43 (per degree)	-1.165	-0.11%	-0.013%
Rebate Eligibility (eligible, not eligible)	50.79	4.73%	0.580%
Ownership (Third Party) *Model 7	17.25*	1.61%	0.197%
Cost per Watt (dollar per watt)	7.226	0.67%	0.082%
Date in Service Year (2011, 2012, 2013)	12.62	1.18%	0.144%
Constant	1073	100.00%	12.249%

Table 16 above shows the impact of 7 of the variables on kWh per kW, percent of constant, and capacity factor. Although each variable has its own respective bearing on production, it is interesting to understand the relative impact based both on the constant, and on Capacity Factor. It is instructive to understand the relatively small impact these variables have on overall system capacity factor. As compared to the range of capacity factors for electricity generators seen previously in Figure 14, small-scale residential solar PV systems have a relatively low capacity factor. The 1,073 kWh / kW constant, prior to the addition of the 15 variables, provides a capacity factor of 12.25%, which is slightly below the 13.21% ‘average capacity factor’ developed by the Department of Energy Resources as part of a three year 2010 – 2013 analysis of residential, commercial and utility-scale solar PV systems in Massachusetts, used to forecast future production under the production based SREC-II program (Department of Energy Resources, 2014). Note that the 2014 DOER analysis removed systems with a capacity factor lower than 10% from the analysis, which is equivalent to removing any system that produced less than 870 kWh/kW in a given production year (Department of Energy Resources, 2014). If applied to the dataset used as part of this thesis, this requirement would remove 6% of the dataset. The relative impact of rebate eligibility, at + 0.58% or -0.1 for each percent shading, have a relatively minor impact on overall system capacity factor. Larger impacts are likely state solar irradiance, local weather patterns, and latitude. However, the current cost point, coupled with incentives for solar PV systems is such that even a system with the current average capacity factor can provide a good value proposition for a system owner. However, it is the role of program administrators at the state and national level to weigh these benefits with the associated cost for incentives, and also potentially to continue to develop initiatives that lead to better producing systems with progressively greater capacity factors. This could be through advocating for better-sited systems, providing resources for innovative technologies, and offering informational resources to potential system owners. State agencies may also take on the role of requiring installers to meet minimum permitting and installation requirements, and incorporating certain standards of quality assurance as part of the growing solar industry. These tactics would likely lead to better producing solar PV systems in the long run, both for systems installed in the future, and for the longevity of systems currently being installed.

Regression Analysis Findings by Variable

Certain variables were found to be statistically significant for all regression models, some were significant for some models, while others were not statistically significant in any regression model. All variables in the first four models were statistically significant, except the reporting method, which was not statistically significant in any model. System owner type was significant until the variable of installer was introduced in Model 8. Further analysis of this can be seen in the System Owner section below. The variable of micro-inverter was statistically significant until the variables of panel and inverter manufacturer were introduced in Model 7 and 8. Date in Service year became statistically significant when panel, inverter and installer were added. The Solarize Mass variable was only statistically significant in Model 6 and 7. An overview of each of the specific variables can be found below.

Rebate. The rebate variable is positively correlated with production, such that when a system received a rebate, it had a higher average production than a non-rebated system. The relative impact of receiving a rebate on production increased with each successive model. As is seen in Model 3, a system that received a rebate corresponded to an average system that produced an additional 28 kWh per kW during the reporting year, while in Model 8, a system that received a rebate corresponded to an average system that produced an additional 50 kWh per kW during the reporting year, or an additional 5% increase in system production. This dynamic can be further understood as part of the below box plot and kernel density plot.

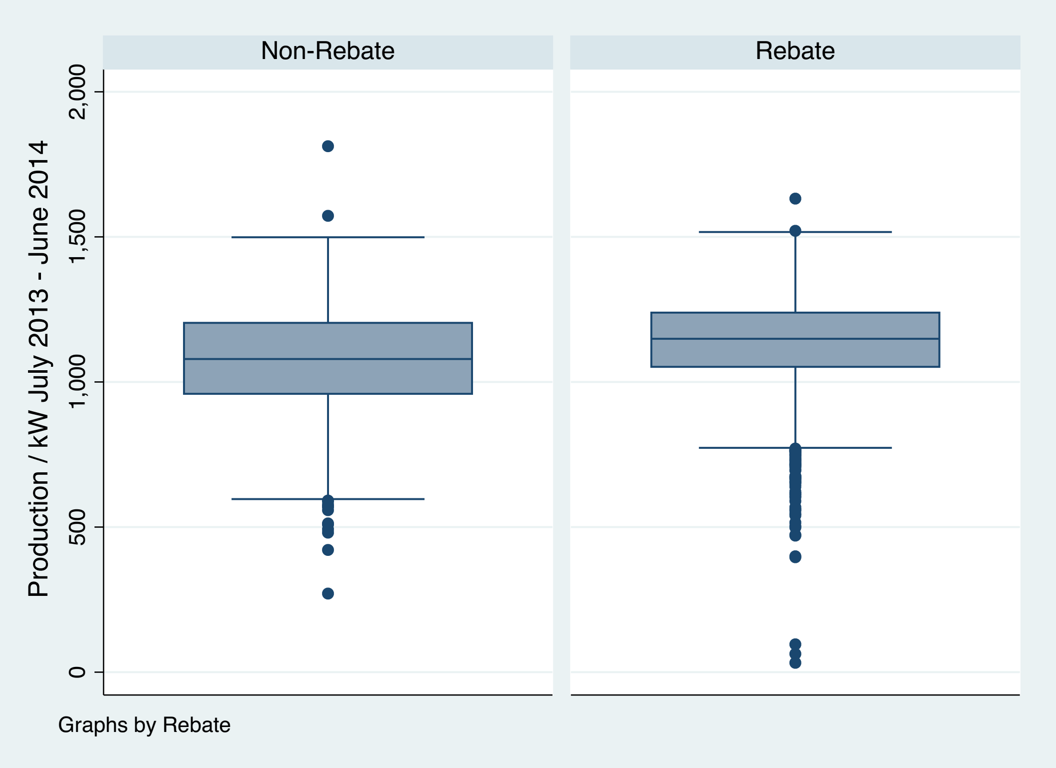


Fig. 18. Box Plot system production (kWh / kW) by rebate.

Figure 18 above shows a box plot of system production (kWh/kW) broken out by rebate. The center of the box plot shows the mean production, followed by the middle two quartiles. The whiskers of the boxplot show 1.5 times the interquartile range. From the boxplot, it can be seen that the mean production of rebated systems is higher than non-rebated systems, and that the production of these systems falls within a tighter range. However there are more outliers found below the lower interquartile range for rebated systems, as compared to non-rebated systems.

The different profiles found between rebated and non-rebated system can be further seen as part of the below Kernel Density plot. Rebated systems also had a narrower band of production than non-rebated systems, which tended to have a broader range of system production. As seen in Figure 19 below, non-rebated systems show a broader range of production over the sub-dataset, and have a lower mean production value.

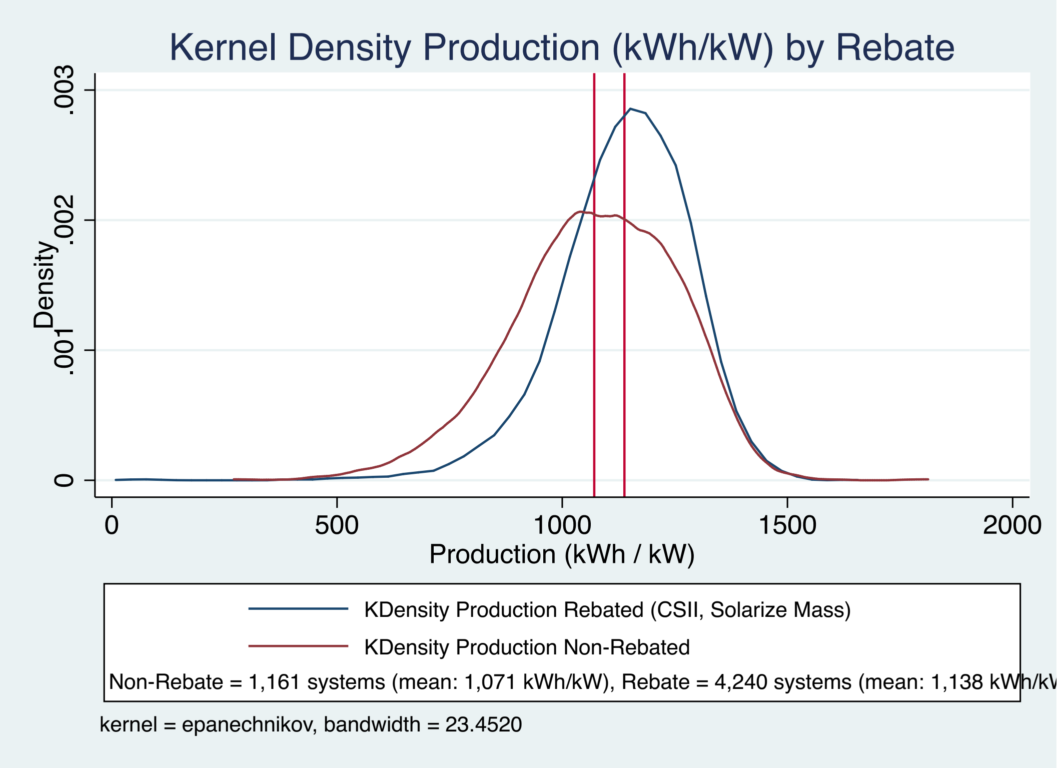


Fig. 19. Kernel density plot of production (kWh per kW) by rebate.

This difference may be correlated with the program requirements associated with receiving a rebate, including meeting a minimum production requirement requirements in which the project is anticipated to produce at least 80% of an optimally sited system, as compiled via site shading, azimuth and inclination. Additionally, systems met several equipment standards including being UL listed and being on the California Energy Commission’s list of approved equipment, included standard warranties, and is subject to inspection. This is a useful finding. Although the MassCEC included these as minimum technical requirements under their rebate programs, they not take additional steps to compare actual to expected system production, as is the case with at least one other state rebate program. This result may be an indicator that requiring certain system specifications may be a sufficient method to lead to the installation of higher performing systems.

Surprisingly, as seen in Model 3 of the regression analysis above, the addition of the rebate variable, although it was statistically significant and positively correlated with higher production, explained very little of the variability in the dataset. In seeking to explain this further, rebated and non-rebated systems were separated into two different datasets. Model 8 of the regression analysis was then administered with the non-rebated systems alone (Model 8a), and then a separate regression analysis was conducted with just the rebated systems (Model 8b). The rebate variable became a dummy variable in the Model 8a and Model 8b regression. The R squared values of Model 8a and Model 8b are seen in table 17 below.

Table 17. R squared value for model 8 regression, broken out by rebate.

Model	Number of Systems	Average Production (kWh / kW)	Standard Dev. Production (kWh/kW)	**Regression R-squared**	Average Shading	Std. Dev. Shading
Model 8a Non-Rebate	1,161	1,071	182	**0.585**	13.9	11.9
Model 8b Rebate	4,238	1,138	147	**0.243**	8.0	6.1

As part of Model 8a, the regression analysis that only included systems that did not receive a rebate, the 15 variables in the regression accounted for 58.5% of variability of the dataset. As part of Model 8b, the regression analysis that only included systems that did receive a rebate, the 15 variables accounted for only 24.3% of variability in the dataset. A potential reason for this could be that there was less variability found overall for systems that received a rebate. As seen both in the box plot and density plots above, a larger number of systems fell within a narrower band of production, such that the standard deviation of systems that received a rebate was 20% smaller then that of non-rebated systems. With less variability overall, and with some variables, such as shading, relatively controlled by rebate program parameters, the variables in Model 8b may account for a lower percentage of remaining production variability.

As seen in the Table 17 above, both the average and standard deviation for percent shading were lower for rebated systems, while average and standard deviation for both azimuth and inclination were essentially equivalent for both rebated and non-rebated systems. As part of the regression analysis Model 8a and Model 8b, in both regressions, shading was a statistically significant factor that was negatively correlated with production. However, as seen in the below scatter-plot, there is a clearer line of best fit between shading and production for non-rebated systems, while for rebated systems, there is not a clear linear line of best fit. Although there are some systems that received a rebate that had a shading percent above 20%, it is surprising that for rebated systems, there is no clear line of best fit for shading percentage. As noted previously, in order to qualify for a rebate, a project needed to provide proof that it was sited at a location that was at least 80% of an optimally sited system. Therefore any one component, including shading percentage, could not reduce the production of the system by more than 20%. The fact that there are projects in the below figure that are more than the 20% shaded is interesting given this rebate requirement.

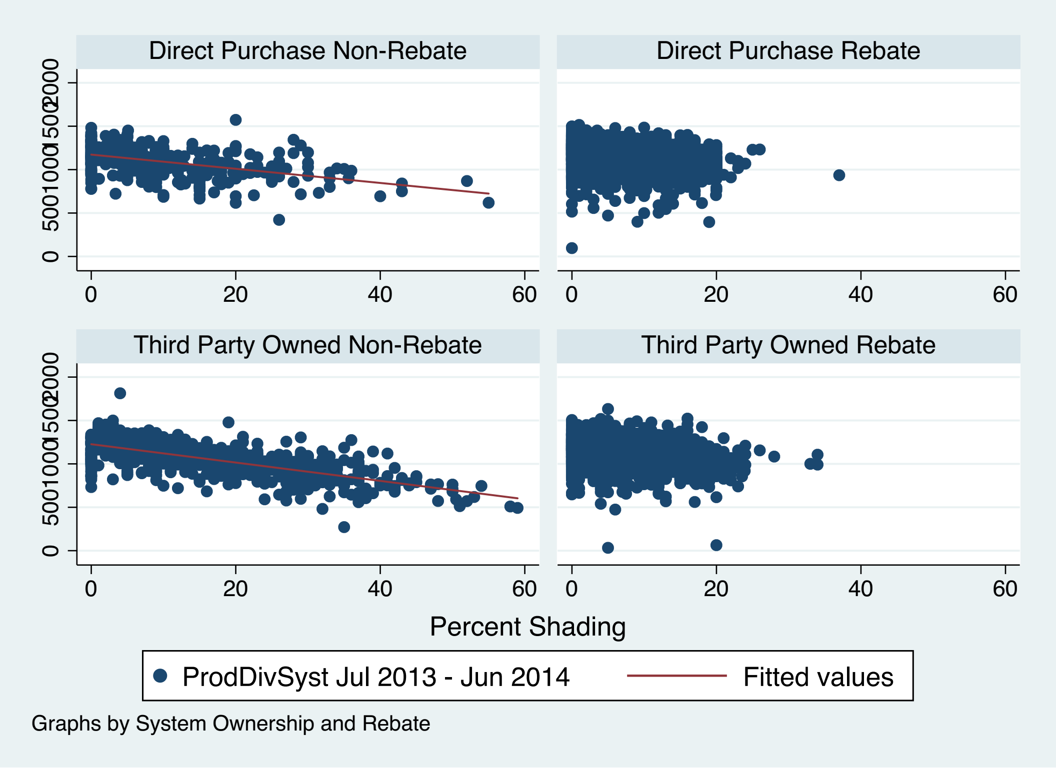


Fig. 20. Production by shading percentage, broken out by rebate, system owner.

The reason for this dynamic is unclear. Although there was almost four times the number of rebated systems as compared to non-rebated systems, this should not directly impact their dispersion. A second, though unlikely, cause of this dynamic may be tied the different processes by which rebated versus non-rebated systems are inputted into PTS. Although the monthly PTS production reporting process is the same between rebated and non-rebated systems, such that systems may manually report on the PTS platform, or a

Data Acquisition System map report production automatically, the process for an aggregator to submit system specification data is different between rebated and non-rebated projects. For a non-rebated system, once the system has been installed and interconnected, an aggregator submits all system specifications as part of a long-form System Qualification Application (SQA). For a system that receives a rebate, some system specifications already reside in the PTS from a data export from the rebate application portal, prior to project completion. Then at the time of PTS system registration, the aggregator searches for the system in PTS and submits a short-form SQA, where they input certain fields, such as shading percentage, azimuth and inclination, and others, while simply verifying other system specifications. These different processes could potentially lead to differences in system data quality in PTS. If this dynamic were the case however, one would expect that the data that was entirely inputted by the aggregator for non-rebated systems would be less accurate than for rebated systems. This is because as part of the rebate program the installer initially provides the system specification data in a rebate application portal, which is then verified by again the installer at project completion, and finally verified a third time by the system aggregator. As part of a future study, it may be useful to do further analysis into whether one method of PTS registration, PTS System Qualification Application long-form or short-form, leads to greater system specification variability over the other.

Percent shading. The percent shading variable was statistically significant in all models, and was negatively correlated with system production. Using Model 8 as a reference, for every percent shading increase, the production per kW would reduce by 9.48 kWh (slope = -9.48 kWh/kW). With a production constant of 1,073 kWh per kW, this is equivalent to losing 0.88% of production per percent shading. Therefore, when considering that the mean shading percent of the dataset was 9.25%, an average project would lose 87.7 kWh per kW, or about 8% of potential production per year due to shading. This can significantly impact total electricity generation, and corresponding return on investment from the system over time. The model cannot be extrapolated to a 100% shading scenario however, as there are no data points beyond 60% shading.

Additionally, it is likely that percent shading variable accounts for the largest percentage of variability in the dataset. As part of the Model 1 regression, percent shading initially accounts for 20.7% of the variability, prior to other variables being added. As part of Model 8, all 15 variables account for 34.2% of variability in the dataset. Although this method cannot be used to determine the exact percentage of variability accounted for by percent shading, it is a clear indication that this variable plays an important role in clarifying the variability of the production data.

Azimuth and inclination. Both azimuth and inclination variables are statistically significant for all regression models. System production is negatively correlated with systems with an azimuth and inclination that is further away from the optimal azimuth and inclination of 180 degrees and 43 degrees, respectively. For azimuth, using Model 8 as a reference, for every degree away from 180 degrees, or true south, system production was reduced by.37 kWh/kW. For inclination, using Model 8 as a reference, for every degree away from an optimal roof angle of 43 degrees, system production was reduced by 1.17 kWh/kW. Both variables are directly tied to access to solar irradiance, so it is not surprising that systems with an azimuth and inclination that is further away from optimal conditions would result in reduced production.

Ownership model. The ownership model variable is statistically significant until the Installer variable is included; at which point the relative impact of the ownership model variable is reduced by half and is no longer statistically significant. Prior to inclusion of the Installer variable, in Model 8, third party ownership had a positive correlation with system production, equating to a 1.6% increase in mean production, or 17.25 kWh/kW. This may be an indication that third party owner companies may be targeting and funding higher quality project sites that have less shading, and more favorable azimuth and inclination numbers that will in turn lead to a better producing site, and a quicker return on investment. Many third party ownership contracts are structured such that potential customer sites with less advantageous attributes may either not receive a contract at all, or pay a higher per-unit cost for the electricity generated, which would mitigate the risk to the third party company of a lower producing system. Through Model 7, there is merit to the possibility that third party ownership companies place a greater priority on higher performing solar PV systems than do residential system owners.

With the inclusion of the variable Installer in Model 8, the loss of statistical significance may be tied to the different site assessment and installation methods of the installer vendors who sell the third party owner's lease or PPA products to customers. Since many third party owner companies, such as SunRun, Sungevity, NRG and others may engage with multiple installer vendors who sell their products, the quality of the site assessment lies in the hands of the installer vendor, or more specifically, the individual salespeople of that installer. This may in turn lead to projects owned by one commercial system owner having different production profiles. Each installer vendor may sign an agreement to uphold the site assessment and sales guidelines of the commercial system owner. However, one installer may uphold stricter site assessment processes than others, as ultimately the installer is incentivized to sell projects. Under this model, the risk of a poorly performing system does not fall on the installer or even the host customer, but on the commercial system owner. This dynamic may be different for companies that are vertically integrated, such that the sales, installation, operations and maintenance teams all work within the same company. Companies such as SolarCity, Vivint and Sungevity fall into this category, which are three of the ten installers with most installations in Massachusetts. The variability in the third party owner – installer dynamic may be a cause for the loss of statistical significance of the system owner variable as part of the full regression.

Cost per watt. Although there is a statistically significant positive correlation between system cost and increased production, the increase in production is relatively modest as compared to the increase in expense. As an example, a one-dollar per watt increase in cost for a 1 kW system would equate to a $1,000 increase in total system cost, with the relative benefit being 7 kWh / kW. There may be several reasons for this small increase in production. First, this result may be tied to a system owner's expected return on investment. If the cost for a solar PV system is higher, system owners may be less likely to proceed with a proposed installation unless the expected electricity production is high enough for them to receive a sufficient return on investment. Correspondingly, if a system owner were presented with a proposal for a solar PV system that was less expensive, but with a lower level of expected electricity production, they may be more willing to proceed, as the overall return on investment for the lower producing system may be similar to the more expensive, higher producing system. Secondly, a more expensive system may have unique attributes that are not captured in this analysis. It may be that the installer of a more expensive system may have used higher quality balance of system components including wiring, junction boxes, and other system components that are not the solar PV panels or inverter, offered production guarantees, used inverter optimizers not captured in the dataset, or incorporated other features that increased the production. There may also be some truth to the argument that increased price may equate to increased quality of installation.

It is also important to note that the variable Cost per Watt did not differentiate between direct purchase and third party owned systems. As part of a future analysis, it may be valuable to either analyze direct-purchase systems only for this variable, or analyze direct purchase and third party owned systems separately. For third party owned systems, the fee paid by the host customer may not be directly tied to the cost of the system, which is paid for by the commercial system owner. Additionally, the system cost data for some third party owned systems may be based on the appraised value of the system, which may be higher or lower than the actual physical cost of the system to the company. This may lead Cost per Watt to be a less accurate predictor variable in its current form.

Panel efficiency. Panel Efficiency was not statistically significant in models 5 through 8. This is likely because panel efficiency is directly represented in the wattage of a panel, such that a highly efficient panel, such as, for example, a 21% efficient panel, would have a wattage rating of 350W per panel, while a standard 15% efficient panel may have a wattage rating of 260W per panel. By normalizing production by system size, panel efficiency may also have been partly normalized, making this variable statistically insignificant in the regression analysis.

Use of micro-inverter. Use of Micro-Inverter is statistically significant until Model 7 and 8, when panel and inverter manufacturer, and installer are added to the regression analysis. The reason for this pattern is unknown. However, it is interesting to note that when inverter manufacturer was added to the regression analysis as part of Model 7 and 8, of the two micro-inverter options, SolarEdge and Enphase, SolarEdge was dropped from the dataset for due to perfect collinearity. Whether SolarEdge was dropped because systems with SolarEdge inverters had a similar profile to Enphase inverters or to a central inverter is unknown, but it is the only inverter out of 22, and out of any variable that was dropped.

Figure 21 below shows a simple scatterplot of percent shading as compared to kWh/kW production. There is also a linear line of best fit for both the central inverter (green) and micro-inverter (orange). The line of best fit for systems with microinverters diverges as percentage shading increases. Because there are many more systems in the dataset with lower shading percentages, it is difficult to determine whether a linear line of best fit is an accurate representation of the impact of micro-inverters.

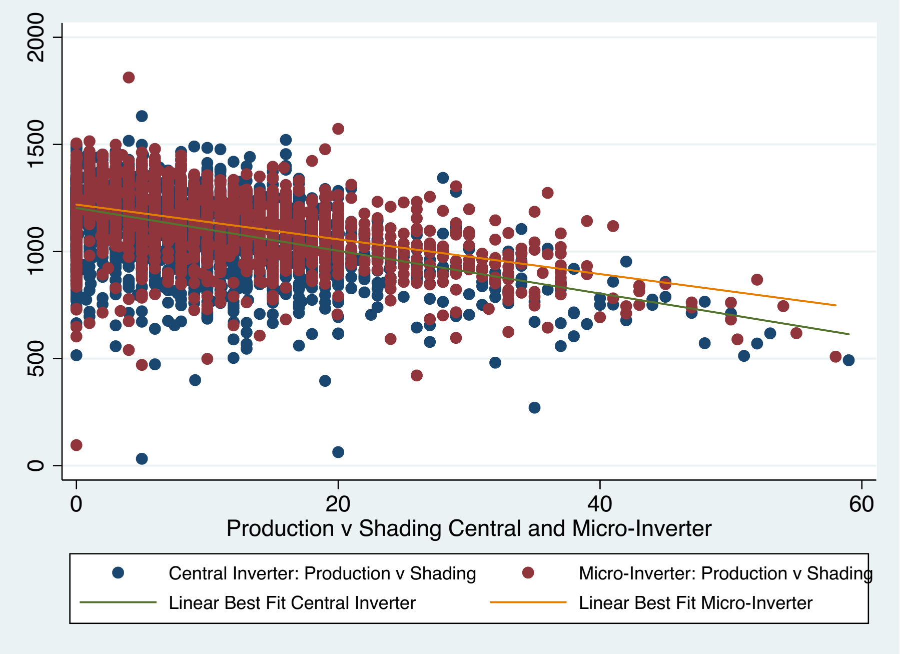


Fig. 21. Production by shading percentage, broken out by inverter type.

Production reporting method. Production reporting method was not statistically significant in any of the eight models. This is somewhat surprising, as one would expect that there would be some differentiation between an automatic reporting system and a system where production data is self-reported manually by system owners via an online webpage. However, as seen in the regression analysis, this does not seem to be the case. In some ways, this can be seen as a positive finding. Likely there is some human error in the manual reporting process, however, system owners who are manually reporting are not behaving in a manner that is substantially different than an automated instrument. The reason for this may be in part because residential system owners who are manually reporting are likely aware that the reported data is validated by the Production Tracking System management team, and production that is seen as being an outlier would lead to follow-up by an administrator. Additionally, the system owners who are manually reporting production are actually reporting a one-directional revenue grade meter reading. Therefore, if they were going to attempt to cheat the system, they would need to devise a new number based on the calculated number from the previous month, leading to the reported number being further and further apart from the actual meter reading. With this in mind, an individual would likely need to actively track both their own calculated monthly meter reading and the actual monthly meter readying in order to determine what actual production per month was, add the production amount to their previously calculated meter reading, and then add an additional percent of production onto that. In this way, being truthful in submitting the actual meter reading is a much easier task than developing a calculated metric.

In addition, the added financial incentive may not be worth the risk of detection. If a resident with a 5 kW system decided to calculate a production number that was consistently 10% above actual system production, they may net the minting of an additional SREC every two years. Over the 10-year span of the SREC incentive program, although the individual may net an additional 5 SRECs, for a potential $1,000 benefit, they would need to consistently calculate new fabricated meter readings, and would also be at risk of detection. These factors may lead system owners that are manually reporting to opt to play by the rules of the program, thereby leading to system electricity production values that are not dissimilar to automatically reported production numbers. This scenario assumes an average production of 1,124 kWh/kW and that the resident is adding 112 kWh to this number (10%), and assuming the average SREC-II (equivalent to 1,000 kWh of production) sells for $200 / SREC, though the SREC value is subject to market valuation.

Solarize Mass. The variable 'Solarize Mass' was statistically significant in Models 6 and 7, and had a mild positive correlation with production. The Solarize Mass sub-dataset includes eight installers, and 525 systems installed within 21 communities. Since the Solarize Mass program occurs in rounds, this dataset includes systems installed as part of the 2011 pilot program, and the 2012 program.

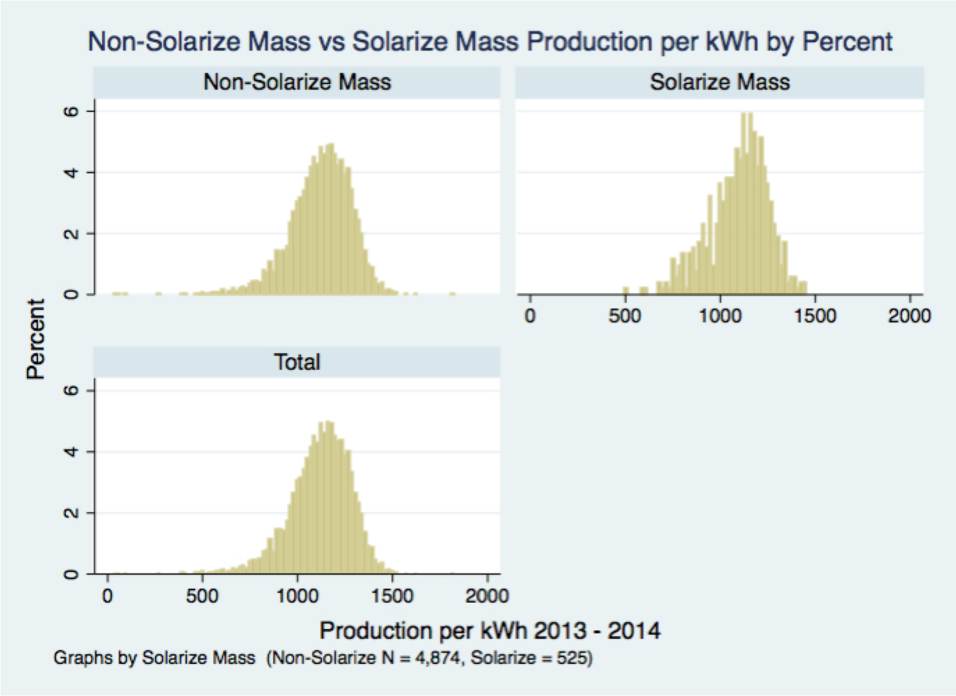


Fig. 22. Histogram of Solarize Mass systems, non-Solarize Mass systems and all systems (100 Bin).

In reviewing Figure 22 above, it is not surprising that projects that contracted under the Solarize Mass projects would have similar production patterns as compared to non-Solarize projects. It is useful to note however that although the average production per kWh was essentially equivalent for systems that received a rebate, irrespective of whether they contracted under a Solarize Mass program, specifically1,138 kWh/kW

Commonwealth Solar II and 1,135 kWh/kW Solarize Mass (PTS, 2015), the subset of 79 Solarize Mass projects that did not receive a rebate behaved differently compared to non-Solarize counterparts. For non-rebated projects that contracted under the Solarize Mass program, average production was 17% lower than average production for other non-rebated projects that did not contract as part of a Solarize Mass program, specifically1,138 kWh/kW Commonwealth Solar II and 1,135 kWh/kW Solarize Mass (PTS,2015). 72% of the non-rebated systems that contracted under Solarize Mass were third party owned. The reason for this dynamic is not fully understood.

Date in service year. Date in Service Year (2010-11, 2011-2012, 2012-13), was statistically significant for models 6, 7, and 8. Later years of installation had a mild positive correlation to system production that ranged between 8 and 12 kWh / kW. This variable is somewhat in opposition to cost per watt, as systems installed in the 2013 installation year generally had a lower cost per watt, as compared to previous years. It is also in opposition to the initial hypothesis set out in the methods section, which posited that later date in service year would be negatively correlated with production. One potential reason for this small drop in production in earlier installation years may be tied to degradation rate. A loss in 12 kWh / kW is equivalent to a 1% loss in production per year. Under many solar PV panel production warranties, systems may lose up to 1% of their rated power output due to degradation in a given year. There are likely other factors in play for this variable as well. However, certainly this theory should be tested, especially as more years of solar PV system electricity production data becomes available.

County. All counties were statistically significant in models 6, 7, and 8, including Nantucket County, which had three systems installed. The relative value of all counties was compared against Berkshire County, which for the purposes of the regression analysis would have a value of '0.' When compared to Berkshire County as a constant, County was correlated with production, and lead to an increase in production from 27 kWh/kW to 111 kWh/kW. Several counties, including Barnstable, Bristol, Dukes and Nantucket, were located along Cape Cod, and exhibited higher production numbers than counties that were further inland. This could lead to different weather patterns, different foliage, and higher rates of solar PV system that are close to sources of water and potentially favorably affected by water glare. Also of interest, as seen in the regression analysis, as more variables were introduced, such as inverter and panel manufacturer and installer, the relative impact of the county variable became greater for most counties. Certainly county is an important variable, and likely is accounting for some of the weather variability across the state.

Inverter and solar PV panel manufacturer. Inverter and solar PV manufacturers used by three or fewer projects were combined with systems with an inverter manufacturer listed as NULL or TBD in a separate category titled 'Other.' As part of Model 7 and 8, very few inverter and solar PV panel manufacturers were found to be statistically significant. For all intents and purposes, these variables were essentially controls for the dataset.

Installer. For purposes of the multiple regression analysis, companies that were mischaracterized, listed as Null or None, or had 10 or fewer installations were combined into a group called 'Other.' Additionally, a single installation company was selected as the base company for which all other installers were compared. Out of a total of 211 installers, 16 installers were found to have a statistically significant impact on the production on the systems that they installed. Firms associated with a larger number of projects were more likely to result in being statistically significant. Of the sixteen firms found to be statistically significant, fourteen had installed 25 or more solar PV systems, and of these, five companies were some of the largest installers of residential systems, Second, third, fourth, seventh and tenth largest installers, respectively. Seven firms were positively correlated with system production, while nine firms were negatively correlated with system production. Note that further analysis may be needed to clarify the impact of different variables on production before specific installers are marked as having higher or lower producing systems.

Summary of Regression Analysis Findings

As seen in Model 8, the regression of the fifteen variables led to an R^2 value of 0.34, such that 34 percent of kWh / kW production variability was explained by the 15 variables, leaving 63 percent of the production variability unexplained. This is unexpected, given the solar industry's general focus in the siting and development of solar PV systems on the importance of quantifying percent shading, azimuth, inclination, and other variables. There may be several different reasons for this relatively low R^2 value. First, there may be additional variables that impacted system electricity production that were not included in the regression analysis. Several examples could include short periods of time when a system may have been turned off such as during an outage, manual shut-off or snow coverage over the panels, weather variability within counties, and taking into consideration that some installers may have contracted out part or all of the solar PV installation to a subcontractor entity, all which may have impacted system production. Additionally, although only impacting eighteen systems, the number of months where 0 production was reported could have been added as an additional variable. Lastly, the system aggregator was not considered as a variable, even though aggregators are responsible for initially reporting system specifications, and are ultimately responsible for the data quality of system specifications.

Along with clarifying whether there may be additional variables that were not taken into consideration as part of the regression analysis, there may also be value in considering some of the limitations of the system specification data. As part of this, there are three potential factors that could have impacted the accuracy of the system specification data submitted in PTS; the impact of the system aggregator, the limitations of some of the system specification fields used to input projects into PTS, and the different system specification submittal processes for projects receiving a rebate, as compared to non-rebated systems, noted previously in Section I above.

A third-party aggregator or broker is often the entity who inputs solar PV specification data into PTS via an online registration form. With this in mind, it may be valuable to understand how aggregators receive project specifications, such as whether from the installer or system owner; via a database export, PDF, excel datasheet, or other method, how they take steps to clarify missing or inaccurate information, or alternatively, whether they input dummy system specifications. These are important factors to clarify, as they would certainly affect the overall quality of the data. The possibility of system specification data manipulation is concerning, and is something that the PTS administrators have likely considered. As part of a future analysis, system specification data submitted by aggregators could be analyzed via a regression analysis in order to uncover any statistically significant patterns in the dataset that are unique to a specific aggregator. Additionally, certain data fields in PTS could be verified through other external processes. As an example of this, as aerial roof analysis tools become more commonplace, such as commercial products such as Aurora, MapdWell and Google Project SunRoof, an analysis could be conducted to use these online tools to determine whether a system azimuth found in PTS matches the azimuth of the site found through the aerial tool.

Second, several required system specification fields that are part of the PTS registration form likely did not offer enough flexibility to fully capture certain system specifications, which may lead to the submittal of inaccurate information. This is specifically applicable to the variables of azimuth, inclination and percent shading for solar PV projects where a solar system is installed on more than one roof. Although a solar PV system could have two or three sub-arrays installed on different roofs, each potentially with a different azimuth and inclination, the online PTS registration form only allows for one azimuth, inclination and shading percentage number to be entered for each project application. Although a blended shading percent may be possible to calculate for a project with multiple sub-arrays,[1] the blending of two or three azimuths or inclinations may lead to an incorrect system specification. For example, creating a combined azimuth

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[1] One method to calculate the total percent shading for a solar PV system with multiple roofs would be to take the percent shading number for each roof and multiply it by the number of solar PV panels on a roof, and add the corresponding numbers. If a site had two sub-arrays, one with 10 percent shading and ten panels, and the other with 30 percent shading and ten panels, the average for the site would be 20 percent shading.

of 180° for a system with both 90° east facing and 270° west facing sub-arrays would not be equivalent to a project with a single 180° south facing array. If an aggregator submitted 180° as the azimuth for the project with two sub-arrays, it would be inaccurate. Additionally, there may not be a standard method for installers and aggregators to develop a blended number, leading to variability in how system specifications for these systems are submitted.

Chapter 4

Conclusions and Implications

The three hypotheses posed in this analysis centered on defining the dataset and system electricity production patterns, while also clarifying the variables that impacted system production. Through this analysis, the first two hypotheses were validated. System size is directly correlated to system production, whereby greater system size is positively correlated with higher overall system production. When electricity production was normalized by system size, production (kWh / kW) over the dataset followed a normal distribution pattern. Additionally, the standard deviation of the dataset showed that the majority of systems reported production within (+/-)7% of the mean of the dataset.

The regression analysis partially supported the predictions of Hypothesis 3. The variables of percent shading, system azimuth and inclination, rebate eligibility, cost per watt and county were found to be statistically significant in all models. Variables such as reporting method and panel efficiency were never statistically significant, while other variables, such as ownership model; micro-inverter; Solarize Mass; and date in service year were statistically significant for earlier models, but not for others. Systems with less shading, and azimuth and inclinations that were closer to those of an ideal site were positively correlated with higher production, which is in line with our expectations and standard industry knowledge. Ultimately, the 15 variables explained 34% percent of production variability within the dataset, leaving a majority of the variability unexplained. As noted earlier, this may be due to additional variables not be accounted for in the analysis, or separately, could be associated with the quality of the system specification data. A future analysis could expand on these findings by conducting new regressions that include additional variables, such as system aggregator, include data for multiple reporting years, and also potentially break out the data on a monthly basis in order to understand system fixed effects over time. This could clarify additional electricity production patterns, including better defining production in winter months. A multi-year analysis could also smooth out some out some variability found in the dataset within a single year. A future analysis could also focus more attention on the impact of micro-inverters on system production, as the technology may have a non-linear impact on system production at different site shading percentages. This analysis also did not analyze commercial systems, though in reviewing the DOER Capacity Factor analysis, it is likely that commercial systems will have higher capacity factors than residential systems, likely due to more standardized siting and less shading. Lastly, a future analysis could seek to clarify if the method that system specification data is inputted into PTS has an impact on overall system specification data quality. Since electricity production data is received and validated through a separate process than system specification data, it is possible that one dataset could suffer from issues of data quality, while the other may not, especially for production data that is automatically reported.

Overall, the three hypotheses provided a tremendous array of insightful information, while also leading to additional questions and implications for policymakers. As noted previously, there were almost no systems that were dramatically overproducing electricity in the dataset. This is likely a result of the Production Tracking System monthly data validation process. This is corroborated by the regression analysis, which did not find that the production numbers of manually reporting systems were inherently different than automatically reporting systems. This is a helpful window into how system owners report their production, and demonstrates that the PTS may be meeting their production validation goals. Additionally, giving system owners with systems 10 kW and smaller the option to manually report[2] may not lead to an abuse of the system.

With this in mind, there may be an additional role for the PTS in following up with under-performing systems. At the onset of the analysis, 88 systems were removed from the dataset for missing one or more reporting months. Fifteen of these systems had never reported, although they were qualified to report production. Additionally, as noted previously, six percent of systems in the dataset had a capacity factor of 10% or less, demonstrating that these systems are generally underperforming. Although not in their mandate, PTS administrators may be able to provide additional guidance to these system owners and their aggregators. This could entail either following up with specific systems which are underperforming, or potentially offering an open resource via a document or website that provides average monthly production metrics, such as showing mean monthly production, standard deviation, minimum and maximum for the entire system fleet. This could help solar PV system owners that are actively reporting monthly production and those considering installing to have a greater understanding of production patterns of solar fleet as a whole. For those who have systems that are under-producing, they may be able to compare aggregate numbers to their own, and potentially take steps to engage their installer to clarify reasons for having lower production, or potentially take

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[2] Allowing small-scale systems to manually report is effectively allowing system owners to take a cost-cutting measure. The installation of a Data Acquisition System, and the fee for automatic reporting may add an additional $2,000 or more to the total system cost, leading to a longer payback for the system. Additionally, there are some areas of Massachusetts that are currently without broadband, and therefore a separate dedicated phone line would likely need to be added to a residence for the DAS, which would be an additional cost to the system owner.

action themselves to remove some impediments, such as trim back tree branches, visually check the panels for damage, or check if the site revenue grade meter or DAS has a similar total production number as the production number often shown on the front of the system inverter.

An additional finding was that systems that received a rebate had a higher average production and a narrower standard deviation than non-rebated systems. This is an interesting finding, as a primary goal of the rebate program was to provide a small additional incentive for well-producing systems. However, because the rebate was paid at project completion, but before the system was producing electricity, proof of good project siting was accepted in lieu of production numbers. This process is in contrast to other incentive programs, such of that of New York State, which requires verification of certain production levels prior to payout of a portion of the incentive. However, the results of the analysis indicate that requiring adequate project siting may be an effective tool for consumers and installers to select sites for higher electricity production. Future initiatives where an incentive is paid upfront may benefit participating consumers by including a siting requirement, or seeking to provide potential system owners with access to educational resources that clarify specific variables that can ultimately lead to better site production.

Average system costs dropped throughout the installation timeframe of the dataset, while panel efficiency and average system size increased. Residential adoption of solar PV systems has also continued to increase, from a few hundred in 2006 to well over 5,000 systems through the course of the dataset, to over 20,000 residential-scale systems installed through August 2015. Within a short timeframe, there will be multiple years of production data available for thousands of systems throughout the Commonwealth. By analyzing the impact of system specifications and other variables on production trends, the data for the current fleet of projects can become a valuable tool for policymakers, program administrators, and electric utilities, and current and prospective solar PV system owners.

Appendix 1.

Methods for Vetting the Dataset

The MassCEC Production Tracking System managers provided a report on November 5th, 2014 that included data for 13,989 solar PV systems installed between January 1, 2010 and August 30, 2014. The data was compiled using the PTS data-field ‘Pk_Facility Type, in which the facility type was categorized as a 1, 2, or 3, as seen in the below table.

Table 18. Residential Pk_Facility types.

pk_FacilityType	**FacilityType**
1	Residential (3 or fewer dwelling units per building)
2	Multi-family residential (4 or more dwelling units per building)
3	Mixed use (commercial & residential)

An additional data-field used to verify residential systems was ‘Facility Type,’ which includes 20 different descriptions of a facility, and is an additional check of Pk_Facility. For both Pk_Facility Type and Facility Type, clarification of facility type is provided at the time of SREC registration, often by the system SREC aggregator. Solar PV projects needed to conform to specific requirement in order to be utilized as part of the final data-set. Table 20 below provides further clarification regarding systems that were removed from the dataset.

Table 19. Overview of solar PV systems removed from dataset by category.

	Requirement	**Notes**	**Number of Systems removed from original data set**
1.	System must be eligible to participate in the SREC program	Projects that are not eligible to participate in the SREC program do not receive an incentive to consistently provide electricity production numbers. The reported production numbers for these projects may non-existent or of lower quality, both because monthly reporting would be voluntary, and because the data is not vetted by PTS team. Projects with a date in service before 1/1/2010, and projects that participated in early-stage state incentive programs and so were not eligible for the SREC program were excluded.	No systems with DIS prior to 1/1/2010 were included in the initial dataset. 301 systems were removed that were not eligible for the SREC program
2.	System must be installed on a residential property	Systems that could not be confirmed as residential were removed. This was done via the following method: Systems with a Residential facility type were maintained. Projects with a Commercial facility type and a sub-sector type as 'Residential solar lease' were also maintained. Any other systems were could not be verified as residential, and were removed	1,393 systems removed
3.	Systems must report production during every month of the reporting year.	Residential system listed as 'Non-Reporter,' systems that never reported production, did not report in the July 1 2013 – June 30, 2014, or missed at least 1 months of reporting were removed.	Systems removed from dataset: Listed as Non-reporter: 41 Qualified to report but never reported: 15 Qualified to report, reported in previous years, but not reporting in 2013 – 2014 timeframe: 10, Qualified to report but missed 1 or more months of reporting: 63 (See Table 21 for breakout by month) Total: 129
4.	Systems with a date in service that after April 30, 2013	Systems needed to have a date in service that is two months prior to the reporting year.	Systems interconnected after April 30 2013: 6,705 systems removed
5.	Non-fixed array	Systems with a single or dual tracking system were removed from the dataset.	19 systems removed
6.	System size must be between .1 kW and 20 kW	All systems excluded were over 20 kW in size	35 systems removed
7.	Systems must	Systems Removed:	7 systems removed

	not have any obvious inaccuracies	1 system with cost of $0.00 1 system with cost of over $4.9 million, or $798/watt 1 system with 96% shading, reporting typical system production 2 systems with azimuth of over 360 degrees 2 systems with inclination of more than 90 degrees (facing away from sun)	

Table 20. Number of systems that did not report production, by month.

Number of Months Solar PV System Did Not Report Production	**Number of Systems**
12	10
11	1
10	1
8	1
7	2
6	2
5	1
4	3
3	20
2	10
1	22
Total	**73**

Appendix 2.

Additional Charts and Graphs

Tables in this Appendix include the following:

1. Dataset by Installation Year, Rebate, Ownership and Reporting Method
2. Solar PV Installers by Installer Type, Number of Systems Installed, and Percent Third Party Systems Installed
3. Expanded list of Inverter and Solar PV Panel Manufacturers

	No. of Systems	Average Shading	Average Azimuth	Average Inclination	Cost Per Watt	Average Size (kW)
Date In Service Jan 1 2010 - Apr 30 2011	**511**	**6.33**	**165.56**	**27.26**	**$6.44**	**5.11**
Non-Rebate	**52**	**7.95**	**182.17**	**29.96**	**$6.72**	**4.95**
Direct Own	50	8.27	182.90	30.14	$6.81	5.02
Manual Reporting	25	6.37	183.56	33.08	$6.88	4.43
Automatic Reporting	25	10.18	182.24	27.20	$6.74	5.61
Third Party Own	2	0.00	164.00	25.50	$4.50	3.29
Automatic Reporting	2	0.00	164.00	25.50	$4.50	3.29
Rebate	**459**	**6.14**	**163.68**	**26.96**	**$6.41**	**5.13**
Direct Own	364	7.10	162.37	27.04	$6.62	5.10
Manual Reporting	270	7.17	167.11	28.31	$6.63	5.03
Automatic Reporting	94	6.89	148.72	23.40	$6.62	5.30
Third Party Own	95	2.48	168.73	26.62	$5.58	5.28
Manual Reporting	2	11.00	195.00	34.00	$7.15	3.64
Automatic Reporting	93	2.30	168.16	26.46	$5.54	5.31
Date In Service May 1 2011 - Apr 30 2012	**1369**	**7.95**	**163.16**	**27.93**	**$5.83**	**5.86**
Non-Rebate	**137**	**10.66**	**181.26**	**31.53**	**$6.18**	**5.94**
Direct Own	99	7.21	181.41	32.04	$6.03	6.01
Manual Reporting	58	8.33	182.19	32.38	$6.04	4.88
Automatic Reporting	41	5.64	180.32	31.56	$6.01	7.60
Third Party Own	38	19.63	180.87	30.18	$6.58	5.79
Automatic Reporting	38	19.63	180.87	30.18	$6.58	5.79
Rebate	**1232**	**7.65**	**161.15**	**27.53**	**$5.79**	**5.85**
Direct Own	716	7.90	171.23	29.41	$5.81	5.71
Manual Reporting	438	7.97	173.16	29.61	$5.93	5.29
Automatic Reporting	278	7.79	168.18	29.09	$5.64	6.37
Third Party Own	516	7.31	147.17	24.92	$5.76	6.06
Manual Reporting	86	7.49	181.34	29.55	$5.27	6.16
Automatic Reporting	430	7.27	140.33	23.99	$5.86	6.04
Date In Service May 1 2012 - Apr 30 2013	**3521**	**10.18**	**177.85**	**29.36**	**$5.16**	**6.08**
Non-Rebate	**972**	**14.61**	**183.99**	**29.04**	**$5.89**	**6.01**
Direct Own	190	12.79	181.08	30.65	$4.71	7.30
Manual Reporting	84	10.46	175.85	31.08	$4.87	5.84
Automatic Reporting	106	14.63	185.24	30.31	$4.58	8.46
Third Party Own	782	15.05	184.70	28.65	$6.17	5.69
Manual Reporting	4	21.50	169.50	24.25	$4.06	4.58
Automatic Reporting	778	15.02	184.78	28.68	$6.19	5.70
Rebate	**2548**	**8.49**	**175.51**	**29.47**	**$4.89**	**6.11**
Direct Own	927	8.41	172.32	29.56	$4.98	6.12

Manual Reporting	635	8.43	173.90	29.77	$5.06	5.77
Automatic Reporting	292	8.37	168.89	29.09	$4.81	6.87
Third Party Own	1622	8.54	177.34	29.43	$4.83	6.10
Manual Reporting	171	8.87	177.36	30.48	$4.98	6.14
Automatic Reporting	1450	8.50	177.33	29.30	$4.81	6.10
Total	**5400**	**9.25**	**172.97**	**28.80**	**$5.45**	**5.93**

Table 21. Solar PV installers by installer type, number of systems installed, and percent third party systems installed.

Table 22. Data by installation year, rebate, ownership and reporting method.

Installer	**No. of Companies**	**% of All Companies**	**Total No. of Installs**	**Mean No. of Installs**	**% of All Installs**	**% of all Third Party Owned Installs**
Construction or Engineering Company	**13**	**6.2%**	**30**	**2.3**	**0.6%**	**0.1%**
Installed 1 system	**8**	**3.8%**	**8**	**1.0**	**0.1%**	**0.0%**
0% Third Party	7	3.3%	7	1.0	0.1%	0.0%
100% Third Party	1	0.5%	1	1.0	0.0%	0.0%
Installed 2 - 3 systems	**1**	**0.5%**	**3**	**3.0**	**0.1%**	**0.0%**
0% Third Party	1	0.5%	3	3.0	0.1%	0.0%
Installed 4 - 10 systems	**4**	**1.9%**	**19**	**4.8**	**0.4%**	**0.0%**
0% Third Party	3	1.4%	14	4.7	0.3%	0.0%
11 - 50% Third Party	1	0.5%	5	5.0	0.1%	0.0%
Electrical Contractor	**47**	**22.3%**	**105**	**2.2**	**1.9%**	**0.1%**
Installed 1 system	**29**	**13.7%**	**29**	**1.0**	**0.5%**	**0.0%**
0% Third Party	28	13.3%	28	1.0	0.5%	0.0%
100% Third Party	1	0.5%	1	1.0	0.0%	0.0%
Installed 2 - 3 systems	**13**	**6.2%**	**30**	**2.3**	**0.6%**	**0.0%**
0% Third Party	12	5.7%	28	2.3	0.5%	0.0%
11 - 50% Third Party	1	0.5%	2	2.0	0.0%	0.0%
Installed 4 - 10 systems	**3**	**1.4%**	**16**	**5.3**	**0.3%**	**0.1%**
0% Third Party	2	0.9%	11	5.5	0.2%	0.0%
11 - 50% Third Party	1	0.5%	5	5.0	0.1%	0.1%
Installed 11 - 30 systems	**2**	**0.9%**	**30**	**15.0**	**0.6%**	**0.0%**
0% Third Party	2	0.9%	30	15.0	0.6%	0.0%
Individual Electrician	**24**	**11.4%**	**42**	**1.8**	**0.8%**	**0.0%**
Installed 1 system	**19**	**9.0%**	**19**	**1.0**	**0.4%**	**0.0%**
0% Third Party	19	9.0%	19	1.0	0.4%	0.0%
Installed 2 - 3 systems	**4**	**1.9%**	**10**	**2.5**	**0.2%**	**0.0%**
0% Third Party	4	1.9%	10	2.5	0.2%	0.0%
Installed 11 - 30 systems	**1**	**0.5%**	**13**	**13.0**	**0.2%**	**0.0%**

0% Third Party	1	0.5%	13	13.0	0.2%	0.0%
Other - Null, None, See PowerClerk, Miscategorized	**8**	**3.8%**	**47**	**5.9**	**0.9%**	**0.2%**
Installed 1 system	**5**	**2.4%**	**5**	**1.0**	**0.1%**	**0.0%**
0% Third Party	5	2.4%	5	1.0	0.1%	0.0%
Installed 4 - 10 systems	**2**	**0.9%**	**9**	**4.5**	**0.2%**	**0.1%**
11 - 50% Third Party	2	0.9%	9	4.5	0.2%	0.1%
Installed 31 - 100 systems	**1**	**0.5%**	**33**	**33.0**	**0.6%**	**0.1%**
1 - 10% Third Party	1	0.5%	33	33.0	0.6%	0.1%
Other Company or LLC	**6**	**2.8%**	**11**	**1.8**	**0.2%**	**0.1%**
Installed 1 system	**3**	**1.4%**	**3**	**1.0**	**0.1%**	**0.0%**
0% Third Party	3	1.4%	3	1.0	0.1%	0.0%
Installed 2 - 3 systems	**2**	**0.9%**	**4**	**2.0**	**0.1%**	**0.1%**
0% Third Party	1	0.5%	2	2.0	0.0%	0.0%
100% Third Party	1	0.5%	2	2.0	0.0%	0.1%
Installed 4 - 10 systems	**1**	**0.5%**	**4**	**4.0**	**0.1%**	**0.0%**
0% Third Party	1	0.5%	4	4.0	0.1%	0.0%
Solar Installer or Energy Company	**113**	**53.6%**	**5166**	**45.7**	**95.6%**	**99.5%**
Installed 1 system	**29**	**13.7%**	**29**	**1.0**	**0.5%**	**0.2%**
0% Third Party	24	11.4%	24	1.0	0.4%	0.0%
100% Third Party	5	2.4%	5	1.0	0.1%	0.2%
Installed 2 - 3 systems	**14**	**6.6%**	**33**	**2.4**	**0.6%**	**0.1%**
0% Third Party	12	5.7%	29	2.4	0.5%	0.0%
100% Third Party	2	0.9%	4	2.0	0.1%	0.1%
Installed 4 - 10 systems	**22**	**10.4%**	**157**	**7.1**	**2.9%**	**0.6%**
0% Third Party	17	8.1%	121	7.1	2.2%	0.0%
11 - 50% Third Party	3	1.4%	22	7.3	0.4%	0.2%
51 - 89% Third Party	1	0.5%	9	9.0	0.2%	0.3%
100% Third Party	1	0.5%	5	5.0	0.1%	0.2%
Installed 11 - 30 systems	**16**	**7.6%**	**313**	**19.6**	**5.8%**	**0.8%**
0% Third Party	12	5.7%	224	18.7	4.1%	0.0%
1 - 10% Third Party	1	0.5%	27	27.0	0.5%	0.0%
11 - 50% Third Party	2	0.9%	43	21.5	0.8%	0.2%
90 - 99% Third Party	1	0.5%	19	19.0	0.4%	0.6%
Installed 31 - 100 systems	**19**	**9.0%**	**1239**	**65.2**	**22.9%**	**15.3%**
0% Third Party	5	2.4%	361	72.2	6.7%	0.0%
11 - 50% Third Party	8	3.8%	512	64.0	9.5%	5.5%
51 - 89% Third Party	2	0.9%	146	73.0	2.7%	2.6%
90 - 99% Third Party	2	0.9%	93	46.5	1.7%	3.0%
100% Third Party	2	0.9%	127	63.5	2.4%	4.2%
Installed 100 - 200 systems	**6**	**2.8%**	**817**	**136.2**	**15.1%**	**5.8%**
1 - 10% Third Party	4	1.9%	506	126.5	9.4%	0.5%

11 - 50% Third Party	1	0.5%	130	130.0	2.4%	1.1%
51 - 89% Third Party	1	0.5%	181	181.0	3.4%	4.2%
Installed 200+ systems	**7**	**3.3%**	**2578**	**368.3**	**47.7%**	**76.8%**
51 - 89% Third Party	2	0.9%	683	341.5	12.6%	15.4%
90 - 99% Third Party	2	0.9%	854	427.0	15.8%	27.3%
100% Third Party	3	1.4%	1040	347.0	19.3%	34.1%
Total	**211**	**100.0%**	**5400**	**25.6**	**100.0%**	**100.0%**

Table 23. Solar PV systems by inverter manufacturer.

Inverter Manufacturers	**No. of Systems with Inverter**	**Percent of Total**	**Percent of Inverters Tied to Third Party Owned Systems**
AUO	1	0.02%	0.0%
Aurora	2	0.04%	0.0%
Chint Power	1	0.02%	0.0%
Enecsys	5	0.09%	0.0%
Enphase Energy	1826	33.81%	50.8%
Fronius	333	6.17%	63.7%
Growatt	1	0.02%	0.0%
Kaco	97	1.80%	90.7%
NULL	37	0.69%	10.8%
Outback Power	3	0.06%	0.0%
Power-One	947	17.53%	91.4%
PV Powered	73	1.35%	84.9%
Schneider	1	0.02%	0.0%
Schuco	4	0.07%	75.0%
Siemens	2	0.04%	0.0%
SMA America	496	9.18%	74.4%
Solarbridge Pantheon	3	0.06%	0.0%
SolarEdge Technologies	136	2.52%	61.0%
Solectria	998	18.50%	25.9%
Sun Power	415	7.68%	43.6%
Sunnyboy (SMA)	10	0.19%	0.0%
TBD	2	0.04%	0.0%
Westinghouse Solar	1	0.02%	0.0%
Xantrex	6	0.11%	0.0%
Total	**5400**	**100.00%**	**56.6%**

Table 24. Solar PV systems by solar PV panel manufacturer.

Solar PV Panel Manufacturers	No. of Systems with Panel	% of Total	Average Efficiency	% of Solar PV Panels Tied to Third Party Owned Systems
Advanced Solar Photonics	1	0.02%	15.0%	0.0%
Aleo	9	0.17%	13.5%	11.1%
American Choice	25	0.46%	15.2%	0.0%
Astronergy	1	0.02%	14.0%	0.0%
AUO	2	0.04%	19.0%	0.0%
axitec	3	0.06%	14.9%	0.0%
Bosch Solar	13	0.24%	14.9%	0.0%
BP Solar	80	1.48%	13.3%	91.3%
Canadian Solar	427	7.91%	14.7%	39.1%
CertainTeed	1	0.02%	13.2%	0.0%
Chint Solar (Astronergy)	5	0.09%	14.3%	0.0%
Conergy	8	0.15%	14.7%	0.0%
Del Solar	22	0.41%	14.0%	72.7%
Eclipsall	4	0.07%	15.7%	0.0%
ET Solar	21	0.39%	14.9%	71.4%
Evergreen Solar	129	2.39%	13.2%	3.9%
Fluitecnik	4	0.07%	14.5%	0.0%
Grape Solar	2	0.04%	15.3%	0.0%
Hanwha SolarOne	27	0.50%	14.1%	63.0%
Helios	17	0.31%	15.2%	0.0%
Hyundai Heavy Industries	42	0.78%	15.2%	95.2%
Jinko Solar	6	0.11%	14.4%	0.0%
Kyocera	103	1.91%	14.7%	66.0%
LDK Solar	1	0.02%	15.3%	0.0%
LG - Life's Good	353	6.54%	15.6%	93.2%
Lumos	4	0.07%	15.7%	0.0%
MAGE	75	1.39%	14.7%	0.0%
MEMC Singapore	20	0.37%	14.8%	95.0%
Mitsubishi Electric	3	0.06%	14.8%	33.3%
Motech Americas	71	1.31%	15.3%	43.7%
MX Solar USA	2	0.04%	13.9%	0.0%
NULL	37	0.69%	0.4%	10.8%
Perlight	5	0.09%	15.7%	0.0%
Phono Solar	2	0.04%	14.9%	0.0%
Ready Solar	1	0.02%	14.0%	0.0%
REC Solar	106	1.96%	14.8%	0.9%

Samsung	4	0.07%	15.0%	0.0%
Sanyo	62	1.15%	17.2%	3.2%
Schott Solar	42	0.78%	13.8%	7.1%
Schuco	216	4.00%	14.5%	32.9%
Schueten Solar Technology	1	0.02%	13.3%	100.0%
Sharp Corporation	241	4.46%	14.3%	4.6%
Siliken	36	0.67%	15.2%	2.8%
Solar World	240	4.44%	14.8%	33.8%
Solon	1	0.02%	14.3%	0.0%
SolTech	5	0.09%	15.2%	0.0%
Sun Power	595	11.02%	20.1%	34.8%
Sun-Earth	1	0.02%	14.3%	0.0%
Suniva	60	1.11%	15.6%	61.7%
Sunslate	1	0.02%	15.0%	0.0%
Suntech	710	13.15%	14.7%	60.0%
TBD	7	0.13%	4.6%	0.0%
Trina Solar	1004	18.61%	15.7%	93.2%
Uni Solar	4	0.07%	5.7%	0.0%
Upsolar	3	0.06%	14.0%	0.0%
Westinghouse	3	0.06%	14.4%	0.0%
Yingli	532	9.85%	14.5%	92.3%
Total	**5400**	**100.00%**	**15.4%**	**56.6%**

Bibliography

Barbose, G., Darghouth, N., Millstein, D., Spears, M., Wiser, R. (2015). Tracking the sun VIII: The Installed Price of Residential and Non-Residential Photovoltaic Systems in the United States. *Lawrence Berkley National Lab Report, LBNL-188238/August 2015*

Bird, L., Heeter, J., Kreycik, C., & National Renewable, E. L. (2011). *Solar renewable energy certificate (SREC) markets*. Golden, CO: National Renewable Energy Laboratory, U.S.Dept. of Energy, Office of Energy Efficiency and Renewable Energy.

Brown, S., Kennedy, E., & Ramras, E. (2012). 'What's behind your SREC?' Retreived on 4/22/2014 from *Http://www.Cadmusgroup.com/wp-content/uploads/2013/10/Whats-Behind-Your-SREC.Pdf*,

Burns, J. E., & Kang, J. (2012). Comparative economic analysis of supporting policies for residential solar PV in the united states: Solar renewable energy credit (SREC) potential. *Energy Policy, 44*, 217-225. doi:10.1016/j.enpol.2012.01.045

Clarke, S. (2014). *New England Governors Regional Energy Infrastructure Initiative*. Restructuring Roundtable Presentation. Boston, MA. Retrieved on 11/4/2014 from http://www.raabassociates.org/main/roundtable.asp?sel=128;

Clavadetscher, L., & Nordmann, T. (2007). Cost and performance trends in grid-connected photovoltaic systems and case studies. *Report IEA-PVPS T2-06:2007,*

Dereli, Z., Yücedag, C., & Pearce, J. M. (2013). Simple and low-cost method of planning for tree growth and lifetime effects on solar photovoltaic systems performance. *Solar Energy, 95*, 300-307. doi:10.1016/j.solener.2013.06.019

Department of Energy Resources. (2014). 'Determination of Average Solar PV Capacity Factor Analysis." Retrieved on 2/1/2015 from https://www.google.com/webhp?sourceid=chrome-instant&ion=1&espv=2&ie=UTF-8#q=DOER+capacity+factor

Department of Energy Resources. (2015). 'Interconnection guidance.' Retrieved on 3/9/2014 from https://sites.google.com/site/massdgic/home/interconnection

Drury, E., Jenkin, T., Jordan, D., & Margolis, R. (2014). Photovoltaic investment risk and uncertainty for residential customers. *Photovoltaics, IEEE Journal of, 4*(1), 278-284. doi:10.1109/JPHOTOV.2013.2280469

EIA. (2009). 2009 Consumption Report. Retrieved on 2/1/2016from http://www.eia.gov/consumption/residential/reports/2009/state_briefs/pdf/ma.pdf

Fagiani, R., Barquín, J., & Hakvoort, R. (2013). Risk-based assessment of the cost-efficiency and the effectivity of renewable energy support schemes: Certificate markets versus feed-in tariffs. *Energy Policy, 55*(0), 648-661.

Geology.com (2015). County Map of Massachusetts. Retrieved on 3/16/2015 from http://geology.com/county-map/massachusetts.shtml

Gillingham, K. (2012). Barriers to implementing low-carbon technologies. *Climate Change Economics, 3*(4), 1-21.

Halasah, S. A., Pearlmutter, D., & Feuermann, D. (2013). Field installation versus local integration of photovoltaic systems and their effect on energy evaluation metrics. *Energy Policy, 52*(0), 462-471. Retrieved on 10/22/2014 from

Hsu, C. (2012). Using a system dynamics model to assess the effects of capital subsidies and feed-in tariffs on solar PV installations. *Applied Energy, 100*, 205-217. doi:10.1016/j.apenergy.2012.02.039

ISO New England 2013 Regional Electricity Outlook. (2013) Retrieved on 11/1/2014 from http://www.iso-ne.com/aboutiso/fin/annl_reports/2000/2013_reo.pdf.

Jewell, W. T., & Ramakumar, R. (1988). The history of utility-interactive photovoltaic generation. *Energy Conversion, IEEE Transactions on, 3*(3), 583-588. doi:10.1109/60.8071

Jordan, D., & Kurtz, S. (2012). *Photovoltaic degradation rates - an analytical review*. (No. NREL/JA-5200-51664). National Renewable Energy Lab.

Jordan, D., & Kurtz, S. (2014). Recent photovoltaic performance data in the USA. Presentation, National Renewable Energy Lab. Retrieved on 11/1/2014 from http://www.nrel.gov/docs/fy14osti/61446.pdf

Kurtz, S., Newmiller, J., Kimber, A., Flottemesch, R., Riley, R., Dierauf, T., McKee, J., Krishnani, R. (2013). Analysis of photovoltaic system energy performance evaluation method. (No. NREL/TP-5200-60628).National Renewable Energy Laboratory.

Kwan, C. L. (2012). Influence of local environmental, social, economic and political variables on the spatial distribution of residential solar PV arrays across the United States. *Energy Policy, 47*, 332-344. doi:10.1016/j.enpol.2012.04.074

Madaeni, S. H., Sioshansi, R., & Denholm, P. (2013). Comparing capacity value estimation techniques for photovoltaic solar power. *Photovoltaics, IEEE Journal of, 3*(1), 407-415. doi:10.1109/JPHOTOV.2012.2217114

Marion, B., Anderberg, M., George, R., Gray-Hann, P., & Heimiller, D. (2001). PVWATTS version 2 – enhanced spatial resolution for calculating grid-connected PV performance. *National Renewable Energy Laboratory*.

Massachusetts Audubon. (2013) ‘Avian Research on Nantucket Sound.’ Retrieved on 4/22/2014 from http://www.massaudubon.org/our-conservation-work/climate-change/climate-change-policy/wind/avian-research

NobelPrize.org. (2014). ‘The Nobel Prize in Physics, 1921.’ Retrieved on 11/1/2014 from http://www.nobelprize.org/nobel_prizes/physics/laureates/1921/

National Renewable Energy Lab. (2004). *‘The Silicon Solar Cell Turns 50.’* Retrieved on 2/1/2015 from http://www.nrel.gov/education/pdfs/educational_resources/high_school/solar_cell_history.pdf

National Renewable Energy Lab. (2014). Research Cell Efficiency Records. Retrieved on 10/27/2014 from http://www.nrel.gov/ncpv/

National Renewable Energy Lab. (2015). Energy Analysis: Utility-Scale energy Technlogy Capacity Factors. Retrieved on 7/10/2015 from http://www.nrel.gov/analysis/tech_cap_factor.html

Oliva H., S., MacGill, I., & Passey, R. (2014). Estimating the net societal value of distributed household PV systems. *Solar Energy, 100*, 9-22. doi:10.1016/j.solener.2013.11.027

Perez, R. (2009). Solar Power Generation in the US: Too expensive, or a bargain? Retrieved on 10/30/2014 from http://www.asrc.cestm.albany.edu/perez/2011/solval.pdf

Perez, R., Ineichen, P., Seals, R., Michalsky, J., & Stewart, R. (1990). Modeling Daylight Availability and Irradiance Components from Direct and Global Irradiance. *Solar Energy, 44*(5), 271-289.

Perlin, J. (2013) University of California, A History of Solar Photovoltaics. Retrieved on 11/4/2014 from http://www.usc.edu/org/edisonchallenge/2008/ws1/A%20History%20of%20Photovoltaics.pdf

Production Tracking System, ‘PTS Reporting Guide.’ Retrieved on 11/14/2014 from http://images.masscec.com/uploads/programdocs/PTS%20Reporting%20Guide%20v1_0.pdf

Pickrell, K., DeBenedictis, A., Mahone, A., & Price, S. (2014, May). *Cost-effectiveness of rooftop photovoltaic systems for consideration in California's building energy efficiency standards*. (No. CEC-400-2013-005-D). California Energy Commission: Energy and Environmental Economics, Inc.

Rahim, M., Yoshino, J., & Yasuda, T. (2012). Evaluation of solar radiation abundance and electricity production capacity for application and development of solar energy. *International Journal of Energy & Environment, 3*(5), 687-700.

Rosenthal, A. L., Thomas, M. G., & Durand, S. J. (1993). A ten-year review of performance of photovoltaic systems. *Photovoltaic Specialists Conference, 1993., Conference Record of the Twenty Third IEEE,* 1289-1291. doi:10.1109/PVSC.1993.346934

Ryan Wiser, G. B. (October 2010). Supporting solar power in renewables portfolio standards: Experience from the United States. *Ernest Orlando Lawrence Berkeley National Laboratory, LBNL- 3984E*

Sarzynski, A., Larrieu, J., & Shrimali, G. (2012). The impact of state financial incentives on market deployment of solar technology. *Energy Policy, 46*(0), 550-557.

Tsao, J., Lewis, N. & Crabtree, G. (2006). Solar frequently asked questions, Sandia National Lab. Retrieved on 10/15/2014 from http://www.sandia.gov/~jytsao/Solar%20FAQs.pdf

United Nations, Department of Economic and Social Affairs. (2012) "World Population Prospects: the 2012 Revision; Volume I: Comprehensive Tables." Retrieved on 2/1/2015 from http://esa.un.org/unpd/wpp/Documentation/pdf/WPP2012_Volume-I_Comprehensive-Tables.pdf.

US Energy Information Administration. (2013) "International Energy Outlook 2013." Retrieved on 3/10/2015 from http://www.eia.gov/forecasts/ieo/.

Weather Underground. "Weather History of Boston MA." (n.d.) Retrieved on 8/22/2015 from http://www.wunderground.com/history/airport/KBOS/2013/7/1/CustomHistory.html?dayend=30&monthend=6&yearend=2014&req_city=&req_state=&req_statename=&reqdb.zip=&reqdb.magic=&reqdb.wmo=&MR=1