ENGINEERING ECONOMIC ANALYSIS OF SOLAR PV INSTALLATIONS CONSIDERING POWER CONVERSION ALTERNATIVES

BY

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THESIS

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Abstract

Solar photovoltaic (PV) is increasing in capacity and availability throughout the United States each year. The value of solar, defined as the present value of future cash flows from a solar installation, is a useful metric which can help potential system owners understand the financial implications of an investment in solar in their location. A discounted cash flow model was developed and used to investigate sensitivities of various metrics across the United States showing that the geographically linked parameters of electricity price and solar radiation by far the most influential determinants of the value of solar. It is shown that systems with expected lifetimes longer than the panel warrantee can achieve significantly higher values. Additionally, the factors of panel orientation and local shading are quantified as site-specific penalty factors which can affect the value of solar. Modeling expected parameters which capture the expected range across the United States, it is shown that fixed-tilt installations can be financially feasible in nearly 50% of the United States given minimal shading and an optimal panel orientation when compared with average costs. This percentage is only expected to increase as the cost of solar decreases. Finally, state averages of radiation, electricity prices, and electricity price growth are used to determine the average value of solar for each state. Seven Southwestern states are shown to be profitable for residential installations, and over half of the states are currently profitable for businesses able to take advantage of depreciation tax benefits.

Acknowledgments

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The ultimate source of my work here and the one most worthy of acknowledgment is certainly my savior Jesus. He is the savior of all people who place their trust in his death on a cross in their place. May this thesis be for the fame of Jesus first and foremost.

Contents

1. Introduction

The state of the solar industry is constantly in a state of flux. The industry has seen exponential growth during the 2000s though it appears that solar is still many years way from being as ubiquitous as wind. Wind currently produces over 5% of U.S. generation while solar is just below 1%. There is considerable room for increased investment which will bring solar into the future it is predicted to have as a major energy source.

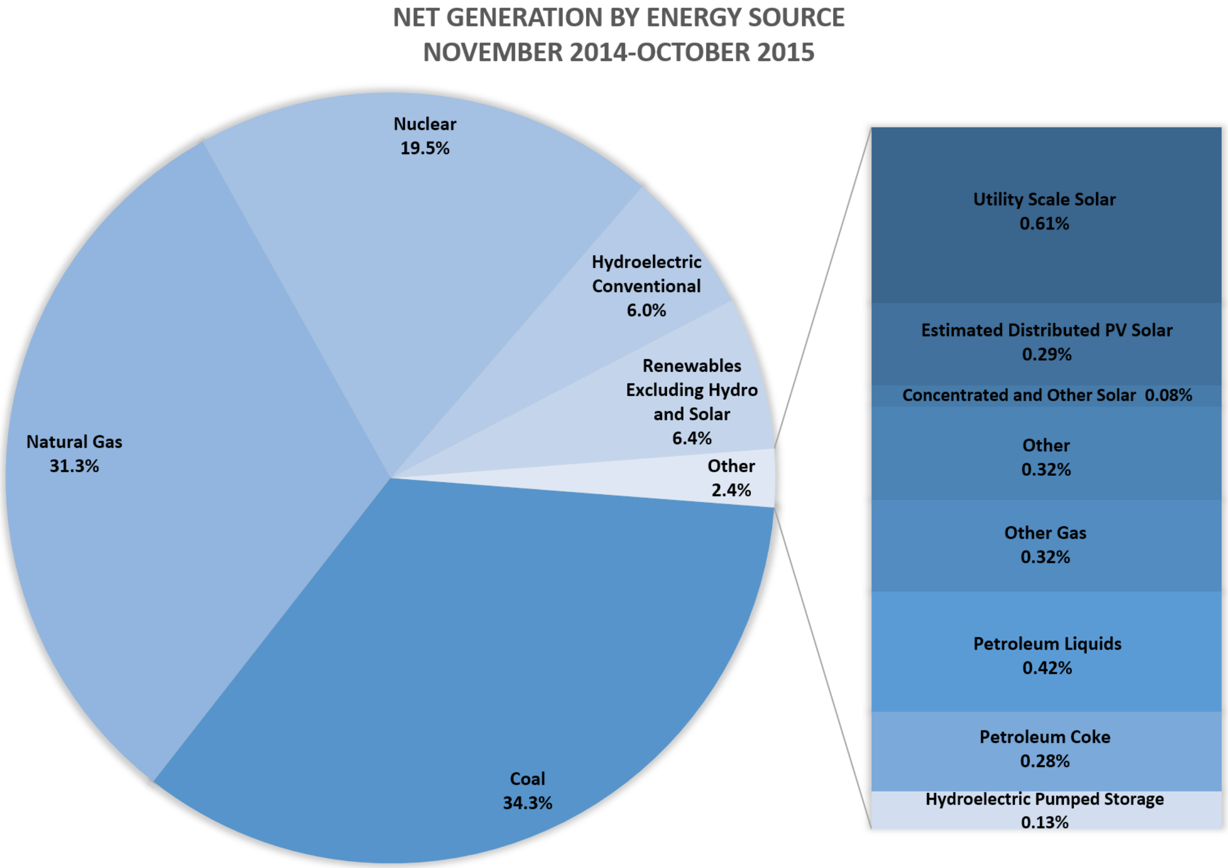


Figure 1 Sources of U.S. generation [1].

One prominent consideration potential photovoltaic (PV) system owners need to address is better understand the value that solar brings to them. In order to develop this line of inquiry, an engineering economic analysis tool called the “solar calculator” was developed. It enables users to conduct economic analysis of solar panel installations in an open and straightforward way. It does so by calculating the value of the electricity expected to be generated by the installation over its lifetime and providing that value as a single metric in dollars per installed watt. This predicted value of solar can be used to determine and installation’s financial viability.

2. Motivation

A number of tools already exist which greatly ease detailed analysis of solar installed in a particular place such as NREL's PVWatts [2] and Solar Advisor Model (SAM) [3]. These tools provide much guidance for sizing, estimating solar production, and technical considerations for a single installation with which the Solar Calculator does not compete. Instead, the tool has been developed to tackle three primary questions aimed at learning how to be more effective about commercializing advanced grid connection technology for solar PV.

1. **What design parameters and characteristics most affect the financial value of solar PV?** When users are trying to make the decision whether to install solar, they would be greatly aided in their decision-making process by knowing how their available installation options and design choices will influence their financial outcomes. For instance, perhaps solar installations are most impacted by the price of electricity, the rate at which the electricity price is changing, or by other design considerations such as reliability.
2. **How valuable are different conversion technologies? Are they worth the investment?** Should someone spend the extra money to get solar panels with an extended warranty? Does it make sense to invest in dc-to-dc optimizers or Differential Power Processing (DPP) technologies?
3. **What can be done to increase the level of solar penetration?** How do we communicate the value proposition enabled by the technologies now available such that it leads to increased solar penetration? Can we identify the stumbling blocks which keep users from pursuing more solar? What information is needed to allow potential system owners to feel confident that a solar installation will work for them?

The solar calculator is able to tackle these questions by providing a dollar value to having a new solar PV installation. With a model able to output this information, one can change inputs and investigate various alternatives in order to gain an understanding of the value of solar over a range of capacities, installed technologies, and just about any other financial or geographical input. The solar calculator considers variables such as annual electricity production, average electricity price, efficiency, financing and more to determine the expected electricity production and thus value of the installation. The ability to compare many possible configurations as enabled by the solar calculator can add a lot of value to users as they are trying to best understand economics of solar as it stands today.

3. Background

When speaking of solar installations, it is useful to aggregate them. The Solar Energy Industry Association uses three bins which capture the vast majority of installations in each of their reports: residential, non-residential, and utility installations [4], [5], [6]. Residential installations are those made by individual homeowners. Non-residential installations are the combined installations of commercial, industrial, government, and nonprofit interests and are typically larger in scale. Both of these categories of solar installations sell their power to utilities directly. Utility installations are typically much larger in scale and sell their electricity on the wholesale market.

Photovoltaic conversion technology, typically made of silicon and outputting a direct current (dc) voltage, is known as a “dc module” or “solar panel” [7]. The output from solar panels must be converted to alternating current (ac) in order to interface with the electricity grid. A standard residential installation may string together from 10 to 16 solar panels in series to achieve an output voltage around 700 V and connected them to a “string inverter” which might output on the order of 2.5 to 4 kW ac on a bright day [8], [9], [10]. When used in utility scale installations, the string inverters may be centrally located in a “central inverter” which can better handle the large power requirements [11]. One popular alternative to a string of dc panels is the “microinverter”. A microinverter is an inverter designed to convert the output of a single panel to ac power. A solar panel with a microinverter attached is referred to as an “ac module” [7], [12]. Many ac modules can be installed in the same physical configuration as a string inverter configuration but with the power being immediately converted to ac, avoiding a high voltage dc bus, and being electrically connected in parallel.

Installations of solar PV in the United States have been increasing at an exponential pace as can be seen in Figure 2, with utility scale installations taking the lion share of new capacity. This trend is expected to continue going forward [6]. This is supported in part by the fact that the installed cost is continuing an exponential downward trend as seen in Figure 3. Projecting forward, average residential costs may be below $2 per dc watt by 2019, while non-residential and utility costs may be below $1 by 2019.

These trends promise even faster adoption of solar in the future. As we will see in this analysis, we expect the value of solar to remain relatively constant assuming steady electricity prices. As the costs for solar PV installations dip below the value of solar to consumers, only some technical considerations will stand between them and choosing to invest in solar.

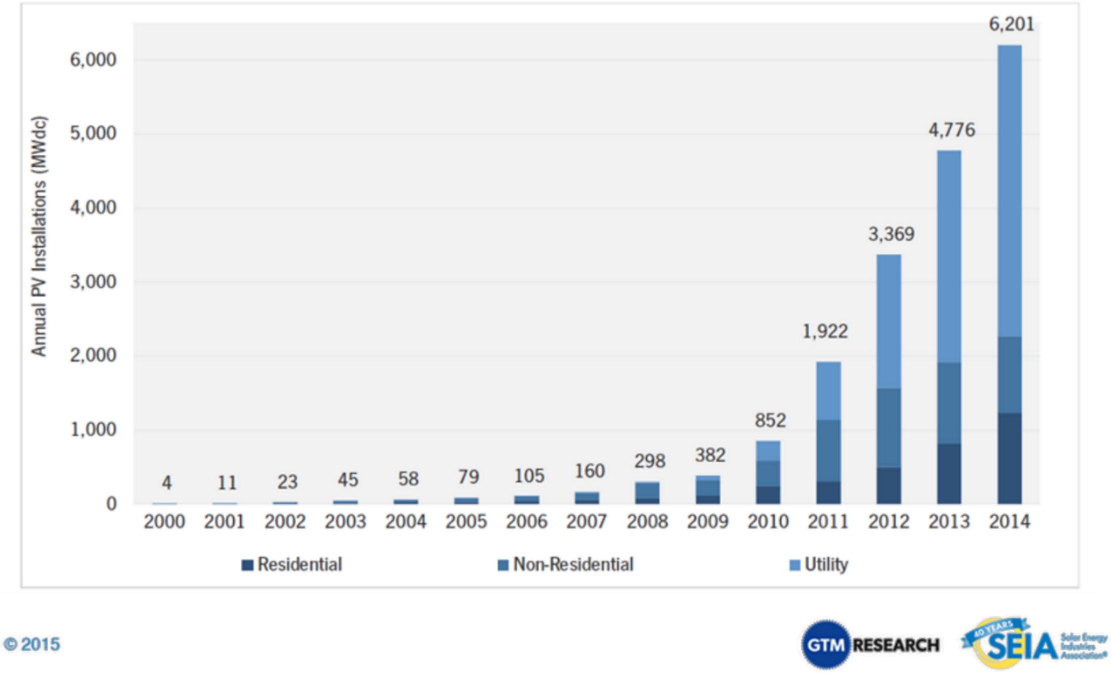


Figure 2 U.S. installations of solar PV [6].

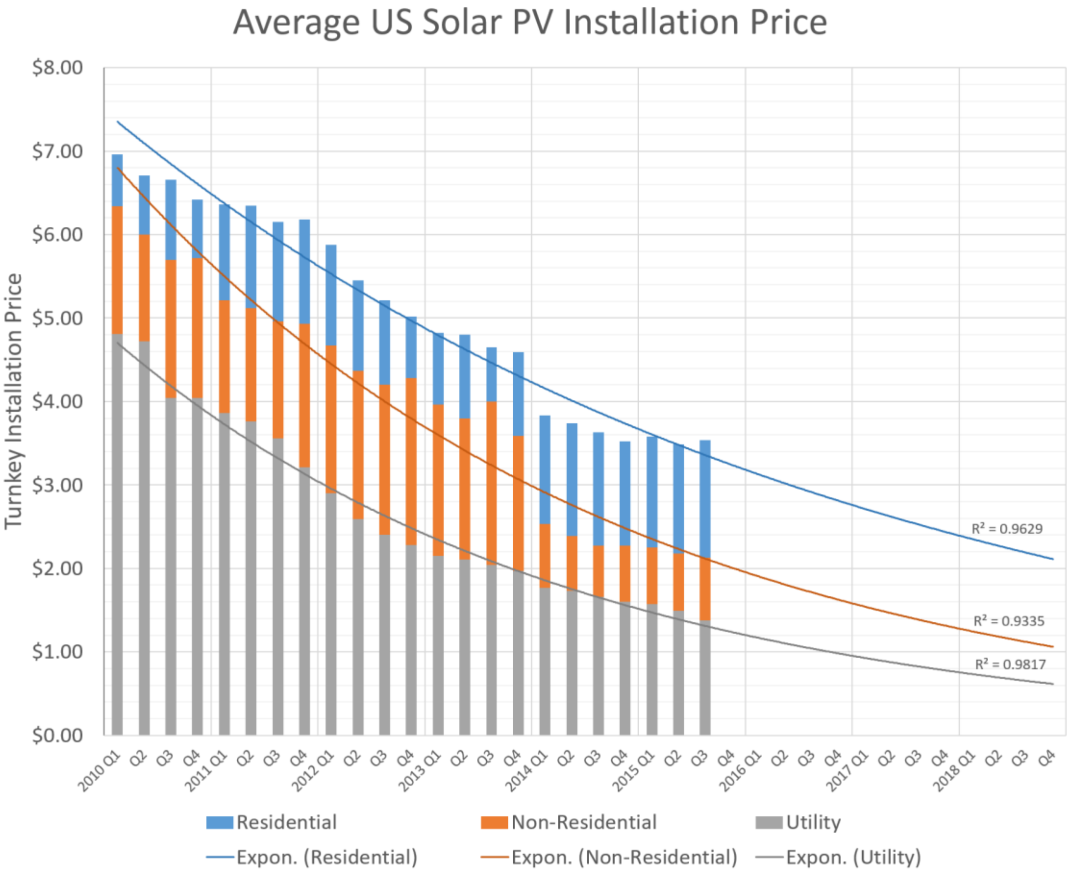


Figure 3 Cost per installed watt of U.S. solar panel systems. Exponential trend lines indicate the expected direction of these prices through the end of 2018 for each sector. Data gathered from archived SEIA quarterly Solar Market Insight reports [6].

4. Methodology

The “solar calculator” is a financial model built in Excel to determine the monetary value of electricity production from a solar PV installation. Based on technical, financial, and geographic inputs provided by the user, annual revenues and expenses for a fixed-tilt solar PV system can be calculated. By summing revenues and subtracting expenses in a period, one arrives at the net cash flow (CF) for the period. The solar calculator uses annualized cash flows calculated for future years after the installation. A discount rate can be applied to find present value of each cash flow today. The discount rate (R) is determined by the individual investor based on a complex variety of factors. In a simple model, it can be thought of as the annual interest rate of a loan used to finance a project. Summing the present value of cash flows provides the net present value (NPV) of a project,

$$NPV = \sum_{t=0}^{N} \frac{CF_t}{(1+R)^t} \tag{1}$$

The economic value of a solar PV system to its owner is defined as the present value of future cash flows to the system owner without the upfront costs (CF_0). It is the value the system would provide if the system owner was given the PV system for free.

$$V_{solar} = NPV - CF_0 = \sum_{t=1}^{N} \frac{CF_t}{(1+R)^t} \tag{2}$$

Equivalently stated, the value of solar is the cost one would pay today at time zero such that the NPV equals $0. Given that all system installation and procurement costs are paid upfront in CF_0, NPV equal to $0 implies that the installation’s future cash flows are equal to the installation price paid today. When NPV is equal to zero, we see that

$$V_{solar} = -CF_0 \tag{3}$$

The value of solar is a valuable metric for comparison and for understanding the economic implications of owning a PV installation. The value of solar can also be considered the “breakeven cost” of solar PV, indicating that if the system could be purchased at for the same price as the value of solar, then the system owner is expected to make zero profit. The higher the expected value of solar the system has over its lifetime, the more likely someone should be willing to pay to have the system installed. Almost no real-world project will ultimately have a NPV of zero. Solving for this case simply shows the point at which the project becomes profitable. If potential users could find the value of solar in their location, they can compare the value of solar with the costs required to purchase the system to see if the investment is financially feasible. If the system value over time is greater than the cost, they know installing solar is a wise financial investment.

The cash flows from a solar PV installation can be calculated using parameters input by the user into the solar calculator. Table 1 describes all input parameters used to determine the value of solar in dollars per installed dc watt for a PV system. It includes basic inputs on the irradiance of the sun, number of years the system is expected to produce electricity without unexpected maintenance cost, efficiency of the inverter system, recurring costs, and tax considerations arising from depreciation. Beyond simple depreciation, tax incentives for solar such at the ITC or other state incentives are not considered since they directly affect the costs the system owner will bear rather than the value the system will bring to the owner [13]. Government incentives are rapidly changing along with other aspects which affect the cost of a solar installation; however, the value of solar is relatively constant.

Once inputs are given for each value in Table 1, the cash flows from the PV installation the parameters describe are fully determined and can be calculated by the solar calculator. Average daily peak-sun hours is one common method for referring to the solar insulation in a given location [14]. It is found by taking the total amount of solar radiation by and dividing by the peak-sun radiation of 1 kW/m^2 to get an equivalent number of peak-sun hours as can be seen in Figure 4.

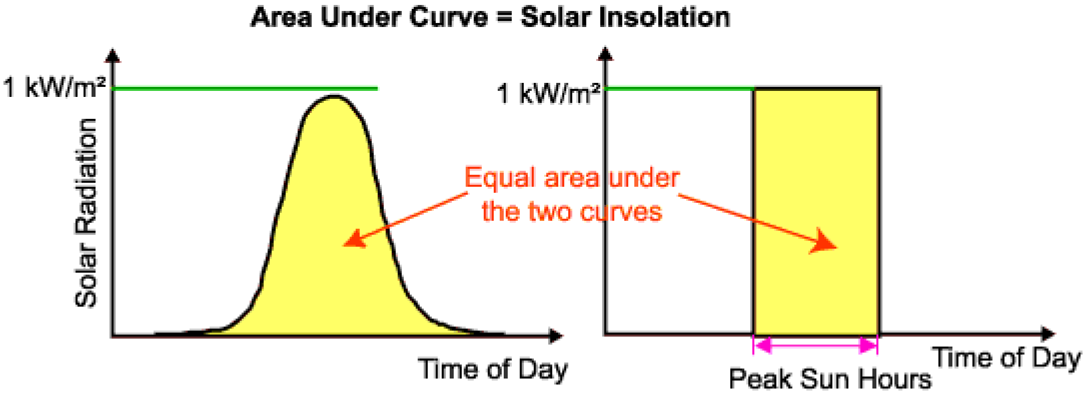


Figure 4 Peak-sun hours are equivalent way to refer to the average total amount of solar radiation in a location. Image from PVEducation.org [14].

The dc to ac derating is the overall system loss when converting dc nameplate power value from the solar panels into ac power [15]. It is used by the NREL PVWatts calculator. With version 5 of PVWatts, the derating factor was changed into a loss factor calculated as one minus the ac to dc derating [16]. The derating factor considers losses from nameplate underperformance, inverters, transformers, mismatch, diodes and connections, dc wiring, ac wiring, and soiling.

Table 1 Description of inputs used to construct the solar calculator model of PV cash flows. Parameters with "->" in front of them are the deviations which define the best-case and worst-case scenarios.

Solar Calculator Input Parameter	Description
Scenario (1=Worst-case, 2=Expected, 3=Best-case)	Input of "1", "2", or "3" indicates the set of deviations (inflation, derating, price gain) used in calculating section c output. Does not affect breakeven calculations in section D since each case is always calculated.
System Lifetime (yr)	Time until major system repair and related costs are imposed upon system owner. The model only calculates cash flows during this time period.
Discount Rate (%)	The amount by which a dollar is worth less to you in one year. For example, receiving $1.00 in one year being considered equivalent to receiving $0.94 now implies a discount rate of 6%.
Inflation Rate (%)	Annual inflation. This rate is used to increase maintenance costs each year.
-> Inflation Rate Deviation (±%)	In best-case (worst-case) scenario, *Inflation Rate* is increased (decreased) by this amount.
Annual O&M Cost (% of Install Cost)	Cash value of maintenance spent annually as function of Est. Installation Cost.
Avg. Daily Peak-Sun Hours (hr/day)	Average daily number of hours the sun would shine at peak output (1000kWh/m2) to be equivalent to the irradiance in the area. This value varies based on the location of the solar installation.
DC to AC Derating (%)	Proportion of available energy which PV system is able to convert to usable ac energy for local use or export to the grid.
-> DC to AC Derating Deviation (±%)	In best-case (worst-case) scenario, *DC to AC Derating* is increased (decreased) by this amount. Provides an envelope which actual system production will lie within.
Panel Degradation Per Year (%)	Amount by which panel output reduces from rated capacity each year.
Avg. Electricity Price ($/kWh)	Average price at which electricity can be bought (representing savings) or sold (representing income from sales of electricity) during first year of system generation.
Annual Electricity Price Gain (%/yr)	Compounding growth rate at which *Electricity Price* is modeled to increase each year forming a price trend for electricity.
-> Annual Electricity Price Gain Deviation (±%/yr)	In best-case (worst-case) scenario, *Annual Electricity Price Gain* is increased (decreased) by this amount. Provides an envelope for future electricity prices.
Depreciation (1=True, 0=False)	Toggle whether to consider depreciation. Businesses can benefit from tax advantages of depreciating their solar installation while homeowners cannot.
Depreciable Basis (% of Est. Installation Cost)	The proportion of the installation cost which is spent on fixed goods expected (by the government) to deteriorate with time and which can thus be depreciated resulting in tax savings.
Effective Corporate Tax Rate (%)	The average tax rate payed by the corporate entity.
Solar Install Cost Average ($/W) (avg install size=0.034MW)	Logarithmic relationship between *Est. Installation Cost* and *Installed Capacity* (section C table) is hinged around this average cost. See Est. Installation Cost plot in Section E.
Solar Install Discount Per Order of Magnitude (%$/W Per OoM)	Logarithmic slope is defined by this discount factor. Intuition: 10% discount means that price per watt of 100kW installation is 10% cheaper than 10kW installation.
Installation Capacity of Interest (MW)	Set this to investigate the model output for a particular size installation on the right side of section C.
Disable auto update? (0=False, 1=True)	Toggles whether VBA script enabling solver to run in the middle of Oracle Crystal Ball iterations is enabled. Keep this macro enabled (0) unless performing Monte Carlo analysis using Crystal Ball. [17], [18]

Depreciable basis is a term used in the finance world to refer to the proportion of an investment which can be depreciated by a corporate entity. Of an entire solar installation, only the cost of physical components can be depreciated. Labor, procurement, and other costs cannot be depreciated and so are not included in the depreciable basis. A percentage of the depreciable basis can be depreciated each year allowing that percentage to be considered a loss to the business resulting in no taxes being due on an equivalent amount of income [19].

One challenging aspect of modeling solar PV is ongoing operations and maintenance costs. These are often specified as a percentage of the installation cost per year and are useful for calculations over a range of capacities [20], [21]. The solar calculator performs value calculations on a per watt basis in order to easily compare installations over a wide range of capacities from a few kW to hundreds of MW. In order to easily model this, a logarithmic relationship between installation cost and capacity is defined by the user in the display assumptions (part B) of the solar calculator. The user defines a percentage of savings per watt per order of magnitude of installed capacity. This logarithmic relationship is hinged around the average install size of 34 kW [22] and with an average installed cost of \$2.89 per watt as of 2013 [4]. A 10% decrease in cost per order of magnitude capacity was chosen for use in this study because it simply and accurately describes current price trends while not implying too much accuracy. Overall, the sensitivity of the operating and maintenance cost and depreciable basis which are linked to the estimated cost is very small as shown in Chapter 5. When compared with the cost estimates updated February 2016 by NREL, this method produces estimated costs within one standard deviation of the mean over the entire range of installed capacities from less than 10 kW to over 10 MW confirming the application of this estimation method [21].

From the start, a form of sensitivity analysis is built into the model through the use of “scenarios”. The scenarios are intended to define best- and worst-case inputs, for specific factors which are external to the ongoing operation of the PV system. These include the system’s efficiency in the form of the dc to ac derating, the amount by which the electricity price increases each year, and the inflation rate. When the solar calculator is scenario input is set to 1 by the user, the results table of the solar calculator will show the financial results related to the worst-case scenario for each of these three factors. For a worst-case example, the electricity price gain used in the calculations is determined by taking the user-defined price gain and subtracting the *electricity price gain deviation* to arrive at a lower bound on the price increases each year. With a lower annual price gain, one can show that the value of the solar PV system will be smaller. The same method is used for the inflation rate and derating value. For example, the default annual electricity price gain is 3.65% per year and the electricity price gain deviation is 0.55% per year. If a worst-case scenario was requested, the value of electricity would only be increased by 3.10% (3.65% - 0.55%) per year resulting in a lower value of electricity and ultimately a lower value of solar.

Inputs into the solar calculator which are not precisely known or which contain uncertainty are best modeled as distributions. The solar calculator makes it possible to view the distribution of an output of interest when combined with risk analysis software such as Oracle's Crystal Ball to perform Monte Carlo analysis [17]. Distributions for inputs can be chosen to represent the uncertainty expected for a given parameter. Monte Carlo analysis allows the construction of output distributions by generating random inputs over a large number of trials showing the range and probability of various output parameters of interest.

Nearly any desired input distribution can be used to model uncertainty in the input. In order to model accurately, no single type of distribution should be used. The sensitivity analysis of installations across the United States in this chapter uses a combination of uniform and normal distributions to model each of the inputs. For example, the range of discount rates used by individuals is best modeled by a uniform distribution since the variety of personal circumstances and financing options lead to a relatively equal expectation of any of the discount rates within the range. Counter to this, a uniform distribution for electricity prices would not accurately reflect the prices experienced by consumers. Rather, a normal distribution centered at the average national electricity price is best suited to capture the uncertainty of such an input. The variety of input distributions and magnitudes available in Monte Carlo analysis allow it to be used to model a wide range of installations from a particular residential installation in Chicago, Illinois to the range of non-residential installations in a particular country.

Taken one step further, the solar calculator has the ability to determine the value a potential technological improvement or change made to a solar panel system may have over a wide range of systems parameters. By taking the difference of the model outputs with and without the hypothetical technology improvement, one can identify the potential financial value for technologies such as differential power processing (DPP), dc optimizers, solar tracking, etc. This allows the solar calculator to be used to test cost-benefit analysis of alternative design or energy conversion strategies. The function of comparing two different systems is built into the model and the difference can be seen in the results section of the solar calculator.

In addition to quantifying the distribution of output, Crystal Ball can be used to determine the distribution of the *change* to the value of solar due to a hypothetical technology can be modeled using Monte Carlo techniques. For example, this analysis was performed for DPP and it showed that DPP's expected added value is between $0.10 and $0.50 per installed watt across a wide range of inputs modeling the continental United States as seen in Chapter 6.

5. Solar PV Sensitivities

Two methods were used to explore the solar calculator model sensitivity to the input parameters. The first is a tornado diagram or sensitivity chart which compares the change in an output with the variation of a single input parameter with all other inputs held constant [23]. The second is the contribution to the variance of each parameter over a large number of trials during a Monte Carlo simulation [24]. Both of these sensitivity measurements require a range to be defined for each input parameter.

For the tornado sensitivity analysis, the inputs must be specified in an interval defined by a high and low value for each, with the average being considered the base. Table 2 shows conservative high and low values used for each parameter in an early iteration of the solar calculator which did not include depreciation and used energy incident per watt as the solar irradiance parameter. Energy incident per watt was later changed to peak-sun hours, a more common solar irradiance metric. The range for system lifetime is centered around 25 years, a typical period used for solar panel warranties and some system integrators. We see this is a conservative estimate since warranties generally imply a lower bound on system performance. Longer system lifetimes are examined later in this chapter. The base case inputs were determined from the University of Illinois-Bondville site (40.06° N, 88.37° W, site code 725315) with a range capturing most of the continental United States. This site has a solar irradiation level near the center of the range measured across the United States. The operating and maintenance costs were conservatively estimated at 1% of installation cost annually with a deviation of ±0.4%. Various resources for utility and residential sized installations show a range of maintenance costs that is much lower [21], [25]. This is shown in the variance analysis below. System dc to ac system derating was allowed to range from 94% to 86%. Conventional systems have an overall efficiency closer to 86% [16]. A 94% efficient conversion system would be more representative of ac panels that do not require additional connections. The discount rate was set to range across a wide range of available loan interest rates from 4% for very well-qualified borrowers up to 8%. Median annual panel degradation is set to a nominal value of 0.50% per year [26], linked to a range from 0.30% to 0.70%.

Table 2 Parameters used in initial sensitivity analysis based on single value changes to the model from the base inputs. A number of input parameters were excluded for simplicity from this preliminary analysis but are included in the variance analysis later.

Parameter	Low	Base	High
System Lifetime (yr)	20	25	30
Energy Incident Per Watt Installed (kWh/yr)	1.38	1.58	1.78
Annual O&M Cost (% of Est. Install Cost)	0.60%	1.00%	1.40%
DC to AC Derating (%)	86%	90%	94%
Discount Rate (%)	4.00%	6.00%	8.00%
Panel Degradation Per Year (%)	0.30%	0.50%	0.70%

The 80th percentile of each parameter's low and high relative to the base was used to find the average price per kWh calculated as the value of solar divided by lifetime kWh generation, keeping all other parameters constant. Since when NPV equals zero, the value of solar is equal to the cost, the price per kWh is similar to a levelized cost of electricity [27]. Recording the price per kWh for each extreme parameter and plotting relative to the baseline expected price of 9.7 cents per kWh, we can construct the tornado diagram seen in Figure 5 and use it for understanding sensitivity.

In this analysis, the amount of time the system is expected to operate before failing has a major impact on the average price per kWh, as represented by the long bars in the diagram. This is to be expected since the metric being used—average price per kWh—is calculated as the value of solar divided by the total number of kWh generated. The more years the system lasts, the more kWh produced and thus system lifetime has a large effect on the sensitivity of cost per kWh produced.

The diagram suggests that the next most impactful parameter is the energy incident on the solar panels. Since solar radiation is geography and climate dependent, we begin to see a dependence of the value of solar on location. In addition, this analysis suggests that the efficiency of the conversion system is a relatively important factor; however, we will see that the contribution to variance sensitivity analysis shows that it has a much smaller effect when more model parameters are included.

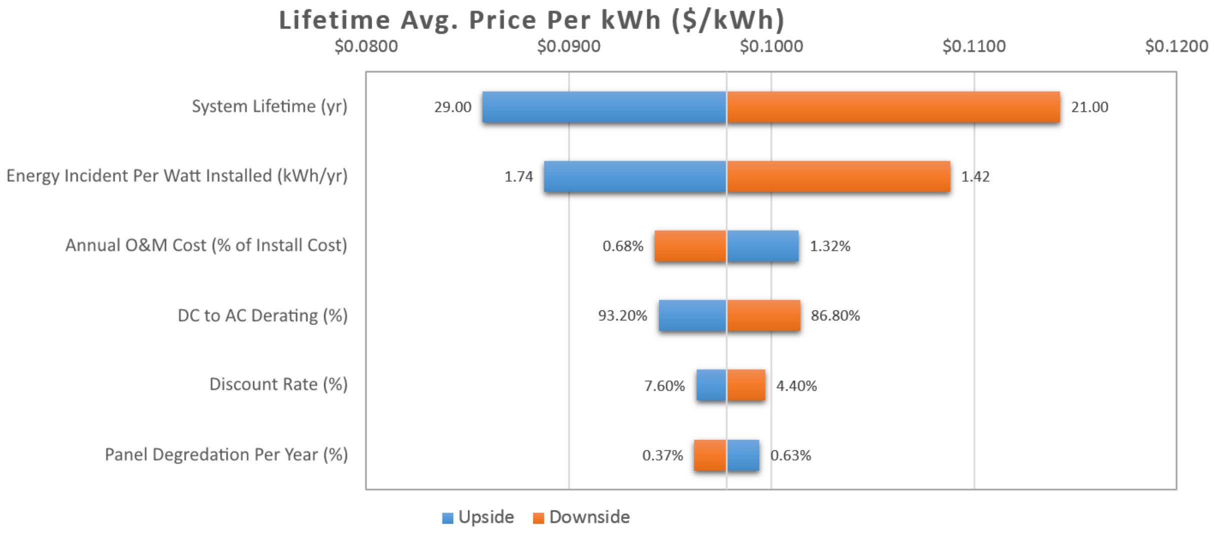


Figure 5 Tornado diagram showing the deviation of LCOE over the lifetime of the installation from the base value of 9.7 cents per kWh arising from changing a single parameter. For example, keeping all else constant, changing the system lifetime from 25 years to 29 years decreased the average price per kWh to about 8.6 cents.

One important consideration in this sensitivity analysis is that the system lifetime range of 20 to 30 years is most likely a conservative estimate. We can be sure of this given that many solar PV panel manufacturers provide a standard warranty of 25 years, and some system integrators provide a 25 year complete warranty [7]. A typical warranty may guarantee a certain percentage of the nominal panel capacity by certain years. For instance, SunPower guarantees 95% of P_{max} by year 5 and 75% of P_{max} by year 25 [7]. A manufacturer with such a standard warranty for their PV panel believes their dc panels will still provide significant generation after 25 years and historical research into PV performance bears this conclusion out.

Analysis of solar panel output over time indicates that they can be expected to perform better, if not significantly better, than their manufacturer warrantee. Skoczek et. al. found that out of 204 crystalline silicon-wafer PV modules reviewed, 65% still exceeded their warranty after 20 years and produced more than 90% of their nominal rating. They conclude that “all indications…are that the useful lifetime of solar modules is not limited to the commonly assumed 20 year” but may rather be considerably longer [28]. An NREL report by Jordan et. al. measured an average PV degradation rate of 0.8% per year for almost 2000 panels and states that “the average degradation rate still allows reasonable performance after 25 years” [26]. These authors and many others point out that solar panels do not tend to have an abrupt end of life, but rather lose generation capability at a slow and consistent rate over time. Since the earliest solar panels were created less than half a century ago, definitive understanding of the long-term trajectory of solar panel performance is not fully understood. In the context of the value of solar, the overall expectation that most solar panels will still have a significant amount of generation capacity 30, 40, or even 50 years after being manufactured. This fact has the potential to increase the valuation of solar dramatically if system owners believe they can benefit from such extended life.

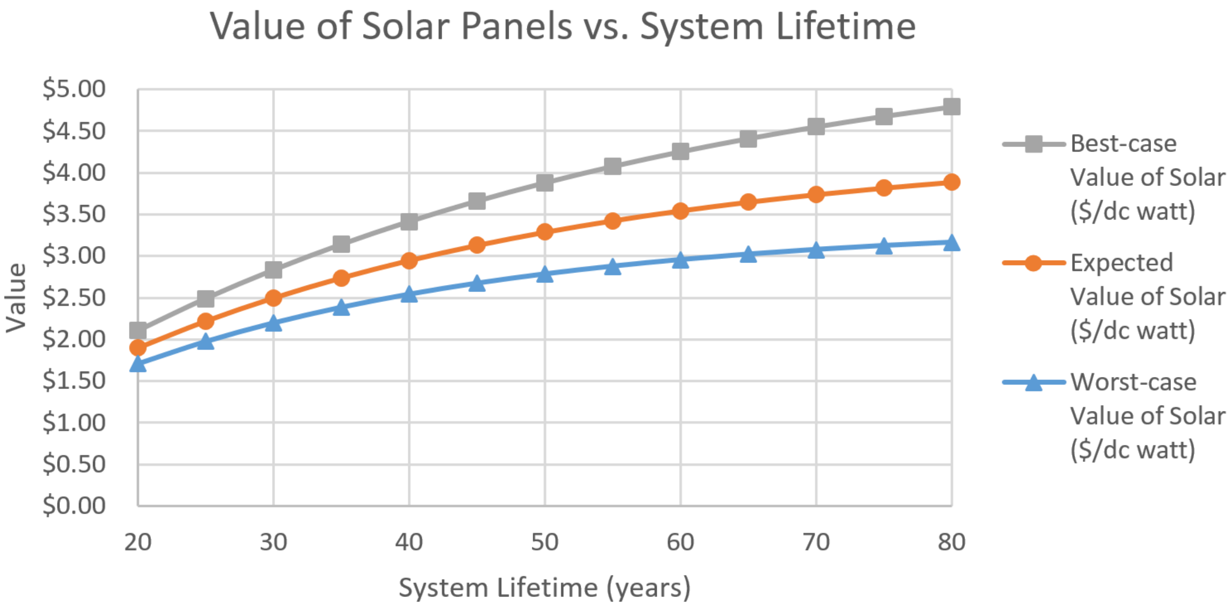


Figure 6 Comparison of system value vs. time in operation for the base installation. Many systems come with a 25 year warranty; however, there is little reason to believe the system panels will cease to function shortly after this time. The value one would be willing to pay if they believed the system would last longer could be much more if they expected generation past the period of the warranty.

In order to investigate the effect of increased system lifetime, system value is plotted against system lifetime in Figure 6. Compounding solar degradation is still included in these factors with dc panel capacity ranging from 64 to 70% of nominal capacity at the 80 year mark. Nevertheless, as the time the system is operational increases, so does the value of solar. Based on the base installation used, an individual looking to purchase a solar PV system is expected receive a system with a 25 year present value of $2.22. If they expect the system to last at least 30 years, the present value of such a system is $2.50, a 12.5% increase. If they expect the system to last 35, 40, or 45 years, they would be willing to pay a 23%, 33%, or 41% premium over the 25-yr present value respectively. These values are given as coefficient factors of the 25 year value of solar in Table 3. If a system purchaser is confident that the panels and system being acquired are of high quality leading to a long system lifetime, they may be able to justify spending a premium over the system value expected during the warranty period.

In the battery industry, system life is coupled with degradation rate rather than a set time period. One standard is that rechargeable batteries are considered at end of life after they can achieve only 80% capacity [29]. No such standard has been accepted for solar panels and there are panels still producing many years later [30]. This is because the measured degradation of even the oldest panels to be manufactured which are still in service is very small. For now, replacement at a set time such as post-warranty or at other system component failure is the best way to model solar PV. This is how it is modeled now in the solar calculator.

Table 3 The factor change in value of solar compared to the 25 year cash flow calculation. For example, if the complete system is expected to last 35 years, one can find the value of solar by multiplying the 25 year value of solar by 1.23.

Expected Lifetime (yr)	Value Factor Worst-case	Value Factor Expected-case	Value Factor Best-case
20	0.87	0.86	0.85
25	1.00	1.00	1.00
30	1.11	1.13	1.14
35	1.21	1.23	1.26
40	1.29	1.33	1.37
45	1.35	1.41	1.47
50	1.41	1.48	1.56
55	1.46	1.54	1.64
60	1.50	1.60	1.71
65	1.53	1.64	1.77
70	1.56	1.68	1.83
75	1.58	1.72	1.88
80	1.60	1.75	1.92

The second sensitivity measure, given by the contribution to variance over a large number of Monte Carlo trials, is now considered. Distributions were selected to represent the plausible values each parameter could take for solar PV systems across the United States for both residential and utility scale systems and can be seen in Table 4. The primary modeling difference between them is the inclusion of the tax benefits due to depreciation at the utility scale. In addition, the range of annual O&M cost as a percentage of the estimated install cost was increased in keeping with the discount expected of installations of a larger size. This keeps the O&M cost on a per watt basis approximately equal.

Table 4 Parameter distributions for residential and utility scale PV installations used during Monte Carlo sensitivity analysis of the solar calculator. Each parameter was selected to represent the range expected to be seen across the continental United States.

Parameter	Distribution	Residential Mean/Min	Residential Std. Dev/Max		Utility Mean/Min	Utility Std. Dev/Max
System Lifetime (yr)	Uniform	20	30		20	30
Discount Rate (%)	Uniform	4.00%	8.00%		4.00%	8.00%
Inflation Rate (%)	Normal	2.36%	1.04%		2.36%	1.04%
Annual O&M Cost (% of Est. Install Cost)	Uniform	0.00%	0.50%		0.35%	0.85%
Avg. Daily Peak-Sun Hours (hr/day)	Uniform	3.50	6.00		3.50	6.00
DC to AC Derating (%)	Normal	86.0%	2.50%		86.0%	2.50%
Panel Degradation Per Year (%)	Normal	0.50%	0.10%		0.50%	0.10%
Electricity Price ($/kWh)	Uniform	$0.094	$0.185		$0.094	$0.185
Annual Electricity Price Gain (%/yr)	Normal	3.65%	0.38%		3.65%	0.38%
Depreciable Basis (% of Est. Install Cost)	Uniform	n/a	n/a		30%	50%
Effective Corporate Tax Rate (%)	Uniform	n/a	n/a		30%	40%

In Figure 7, the contribution to sensitivity of each parameter over the set of inputs used to model the lower 48 states is shown. These sensitivities were calculated using Oracle's Crystal Ball risk simulation software summing the contribution to variation over 10,000 trials during a Monte Carlo simulation. Utility and non-residential installations have very similar cash flow structures since they can take advantage of the same depreciation tax benefits. They are different in that utility installations sell their electricity on the wholesale market rather than on the retail market. Utility and residential installations show similar sensitivity profiles. The overall difference seen in Figure 7 is between the residential and utility model sensitivities is small indicating that the tax benefits of depreciation do not change the uncertainty of the value of solar significantly on a national scale. The sensitivity of the utility model with respect to the depreciable basis and the corporate tax rate is non-zero since both are included while they are zero for residential since neither input parameter affects the cash flows of the residential model.

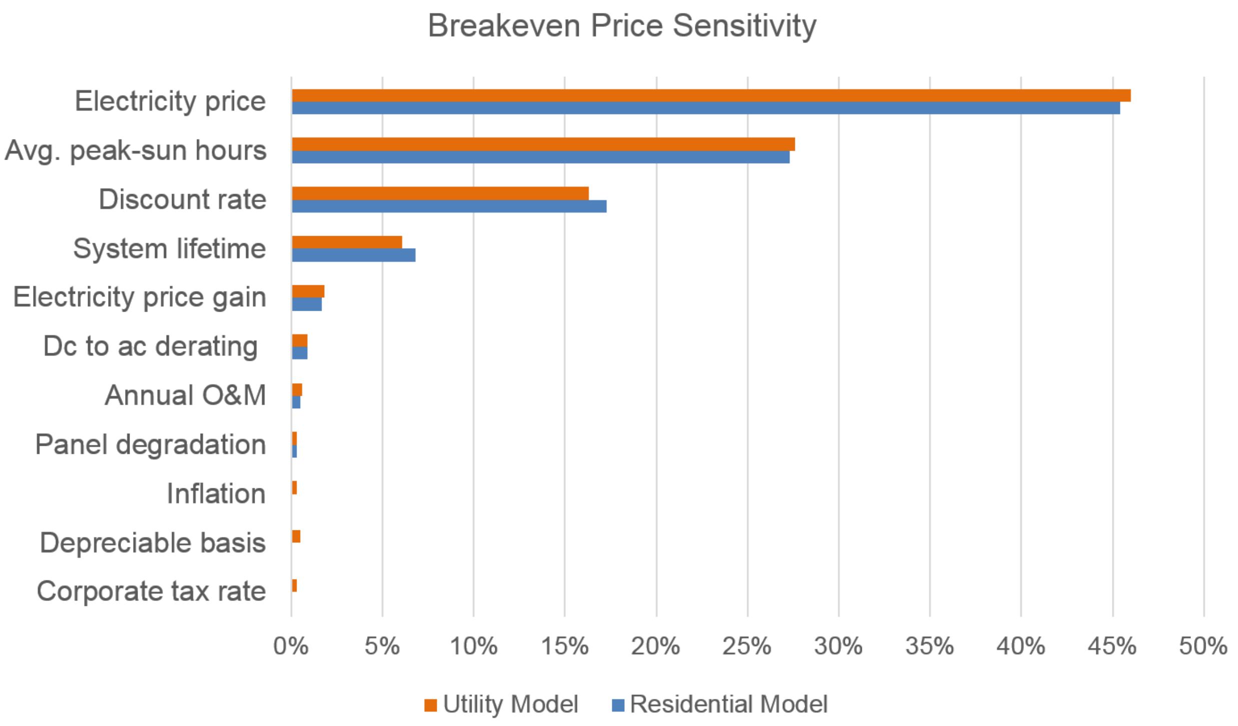


Figure 7 Sensitivity of solar calculator PV installation valuations to each of the parameters shown. The contribution to the variation was summed over 10,000 trials in a Monte Carlo simulation using the distributions shown in Table 4.

There is a clear conclusion to be drawn, though, which is that the top four most sensitive input parameters describe over 95% of the variation in system value. These parameters are the electricity price in the area (~46%), average peak-sun hours in the area (~28%), discount rate by which future cash flows are valued (~17%), and the system lifetime (~6%). These differ from the most sensitive parameters identified in Figure 5 because the metric being measured is very different. The value of solar is a more pertinent metric than the average price of electricity since it can be directly compared with PV installation costs in the market. Nevertheless, there is symmetry between the two sensitivity analyses. Both indicate that solar radiation and system lifetime play a large role. Discount rate is more sensitive in the contribution to variance analysis likely due to the fact that when it is coupled with other affects it makes all cash flows more or less valuable, while in the tornado diagram it is varied independent of other input parameters.

The electricity price is absolutely fundamental in evaluating a solar PV project. Clearly, a PV system installed in an area with high relative electricity prices across the country will be much more valuable. This is because the electricity produced by the system is valued at this price. This is a true value if the energy is used to offset a kilowatt hour purchased from the grid. In a net-metering agreement, the value remains at the electricity price. Most residential customers have a constant price contract with their electricity provider. Variable rate plans are becoming more common which can still be modeled based on an average electricity price. Utility scale installations typically sign purchase agreements which determine the terms and price paid for each kilowatt hour of production.

The solar calculator includes a tab which allows a user to enter both (1) an average hourly variable rate plan and (2) the average hourly solar irradiance for their area. With this information, the solar calculator computes an average solar electricity price used to value the PV system's energy production. In this way, variable prices can be easily included in the calculations. Figure 8 shows graphically how an average solar electricity price can be calculated. Solar PV produces electricity during times of higher demand and thus is worth more in the wholesale market. In most parts of the world, the average value of electricity for a solar PV installation under a variable pricing scheme is expected to be higher than a simple average of the electricity price across the entire day [31]. In the example of Figure 8, the average solar electricity price is 17.29 cents per kWh, an 8.4% (1.34 cent) premium over a simple average. This higher solar electricity price is used in the solar calculator computations.

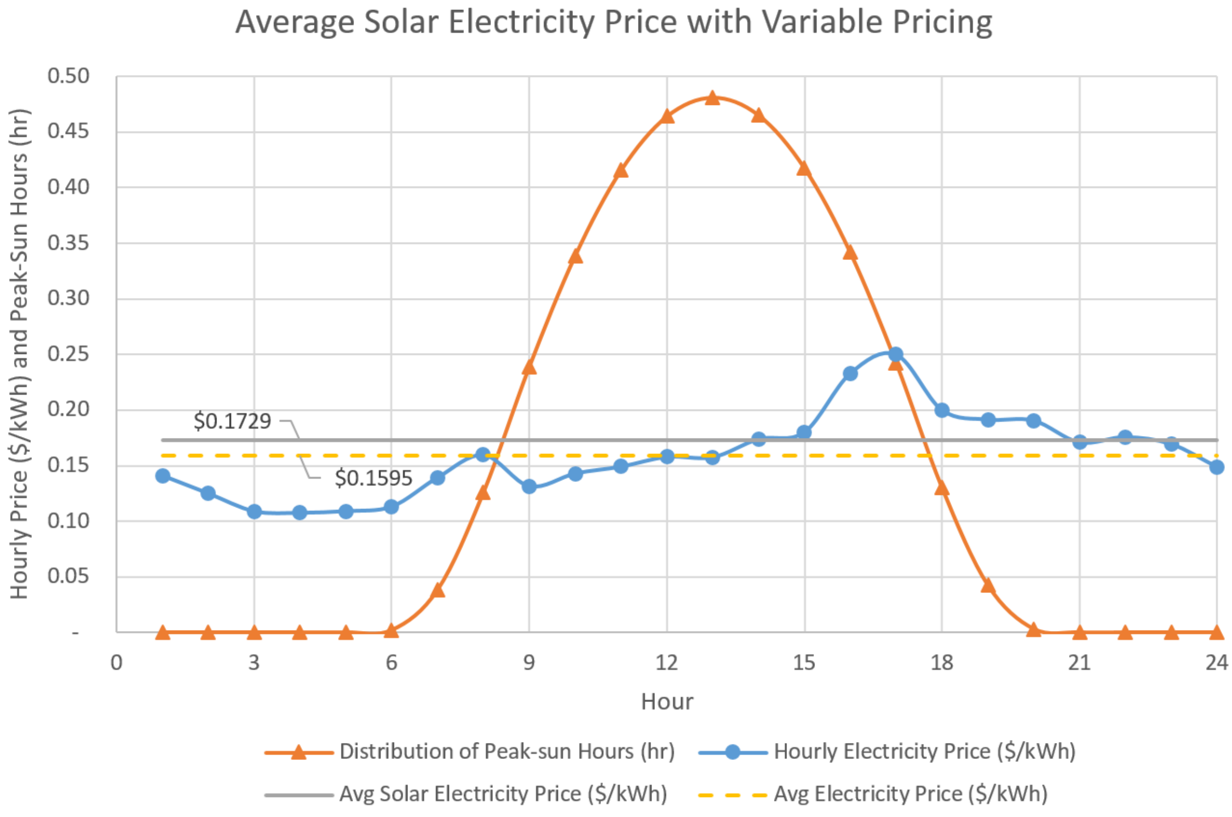


Figure 8 Example variable electricity price converted to the average received for a PV system. The amount of solar irradiance during each hour of the average day is normalized and multiplied by each hour's average variable electricity price.

Similar to electricity price, the amount of irradiation in one area is a strong determinant in how valuable a solar PV installation is expected to be since it directly affects the amount of electricity which will be produced.

This analysis clearly shows that systems installed in sunny climates can be expected to be significantly more valuable than those with less solar resource. Next, the discount rate shows the most effect on the value of solar PV. The lower a discount rate the system owner has, the more valuable the system will be. This is because the time required to recover the initial investment cost can be many number of years. Since this occurs over so much time, the way the time-value of money is considered by the system owner can have a significant effect. The time-value of money is compounding over many years, thus a high discount rate can cause future electricity savings to be worth very little today. Individuals and institutions with good credit are expected to be able to get the best rates for financing a solar installation and thus can benefit the most. For some, it may make sense to wait a year for their credit rating to improve to get better solar financing and thus maximize the value of solar to them. If waiting is considered, it may be wise to consider the age of the roof and time the PV installation with the re-roofing project.

System lifetime commands about 6% of the variation in the value of solar. Of interest, this is perhaps the first parameter which can be directly chosen by the decision of the system owner through the choice of which equipment to purchase. Figure 6 shows how the value of the solar panel system increases with increased time. A five year increase in system lifetime from the base system leads to a 12.5% increase in value. It remains for each individual to compare the savings achieved with choosing cheaper equipment to this value and weigh the additional costs that may be incurred later. Since a five-year increase in system lifetime leads to an expected 12.5% increase in system value, cost premiums below this amount for highly reliable equipment are likely to pay for themselves.

In Figure 7, annual electricity price gain, dc to ac derating, annual O&M, panel degradation, inflation, depreciable basis, and tax rate have limited impact on the value of solar PV. Perhaps most interesting is that dc to ac derating, a proxy for system efficiency, has little effect. One may seem to take it for granted that efficiency must be very high in order for a PV system to recoup its costs. In general, this sensitivity shows that the most important factor related to efficiency is not actually the last few percentage points of efficiency, but rather that the system continues to run reliably over time.

The next sensitivities investigated were pursued in order to show the ability of the solar calculator to model the value of changes made to a PV system. Figure 9 shows the sensitivity for the addition of differential power processing (DPP) to a system. DPP uses power electronics to optimize the voltage differences between cells and/or panels in the system to allow each to perform at its peak power generation potential or maximum power point (MPP) [32], [33], [34]. DPP was modeled to increase the dc to ac derating by 5%, which is conservative compared to reported results [35], as well as to decrease annual O&M by 25%. This savings is expected due to the distributed monitoring capabilities enabled by DPP.

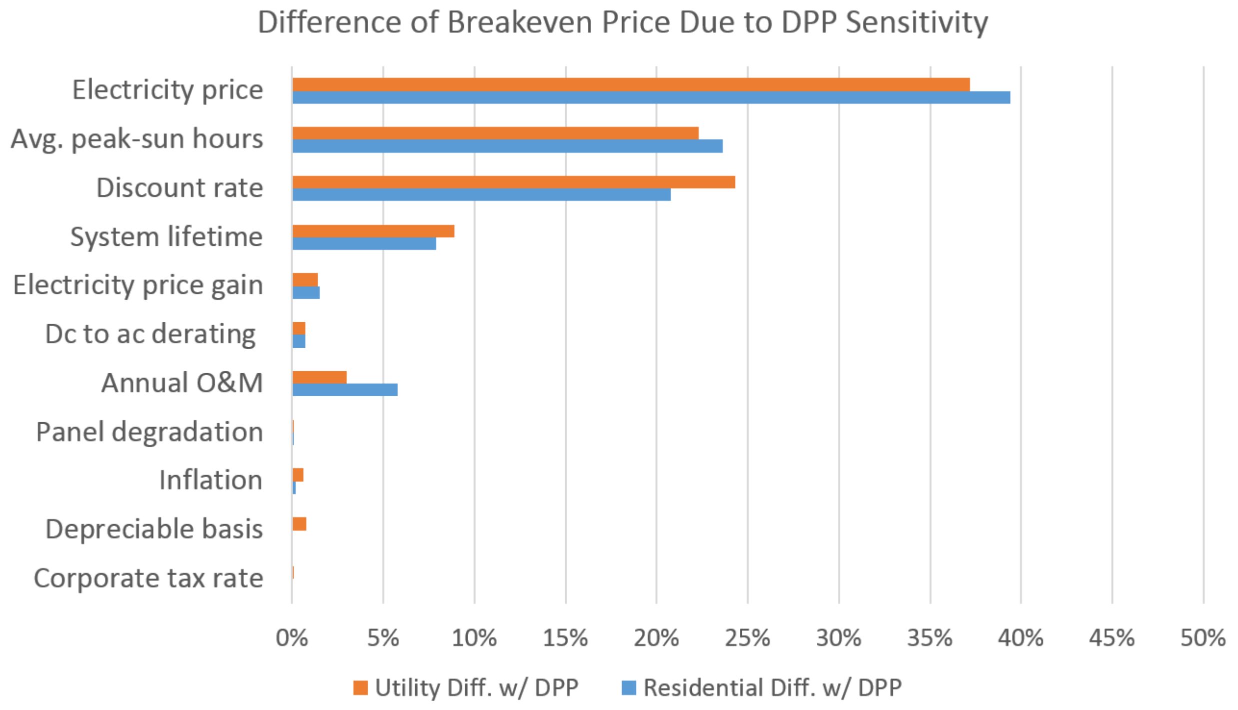


Figure 9 Sensitivity of the value of differential power processing (DPP) added to a PV system.

Comparing Figure 7 and Figure 9, one can see relatively similar levels of sensitivity between the overall system and the DPP technology. The main difference is that DPP is marginally sensitive to the annual O&M since it will save more for a system with high O&M as modeled. This result is expected since the DPP technology directly affects the production of the system and so the sensitivities are closely related. Overall, because of the similar sensitivity profile, one can see that DPP will be most valuable on the most valuable solar PV installations.

6. Value Comparison of Solar PV Technologies

Monte Carlo simulation can provide distributions of the value of residential and commercial installations across the United States. One can see in Figure 10 and Figure 11 the distributions of value for residential and commercial PV installations respectively. The distributions represent the binning of 10,000 trials and indicate the expected distribution of the value of solar for each of best-, expected-, and worst-case scenarios.

The x-axis value is the price one should be willing to pay upfront to earn the cash flows provided by the particular installation modeled. As expected, the average installed PV system value is higher in the best-case scenarios where electricity prices continue to rise, inflation remains low, and the equipment has relatively high efficiency, and visa versa for worst-case scenarios. A single deviation of the expected residential installations span from \$2.53 to \$4.65 per installed dc watt. Comparing with Figure 3, one can see that many of the modeled installations will bring more value than they cost to install.

From the distribution of expected-case residential installations in Figure 10, one can integrate the area under the curve and calculate that 48.9% of installations across the United States have expected breakeven costs above \$3.48 per watt, which is the weighted average national residential system cost in Q4 of 2014 [5]. From this, one can deduce that residential solar PV is profitable in roughly half of the nation. This means the cost of solar PV installations has come down to such an extent that a reliable fixed-tilt system installed in an unshaded area can be profitable for in nearly half of the land area of the continental United States. As costs continue to fall according to Figure 3, the percentage of the United States which could have profitable fixed-tilt PV installations will only increase. Given the residential cost reduction trend and that the expected value of solar in Figure 10 remains consistent, by 2019 over 90% of locations in the United States will have the potential to host a solar PV installation which costs less than the present value it brings over its lifetime. This shows that at least in one metric, solar PV has achieved grid parity in a significant portion of the United States given average costs today.

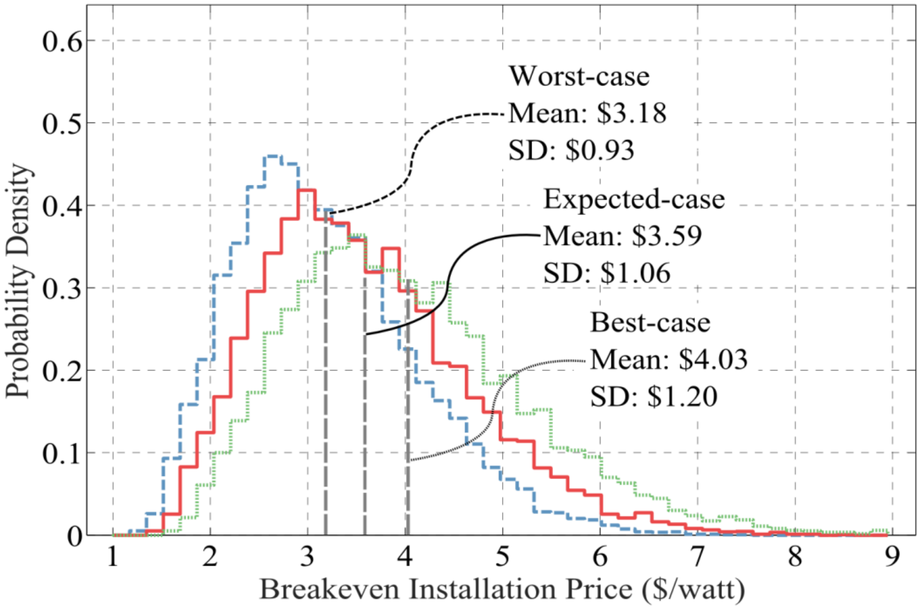


Figure 10 Distributions of 10,000 Monte Carlo simulations of U.S. residential solar PV systems in best-, expected-, and worst-case scenarios. The expected-case distribution had an average value of $3.59 per installed watt with a standard deviation of $1.06. No installations are expected to be worth less than $1.10 per installed watt while nearly 50% are valued above the 2015 Q4 weighted average residential cost of $3.48.

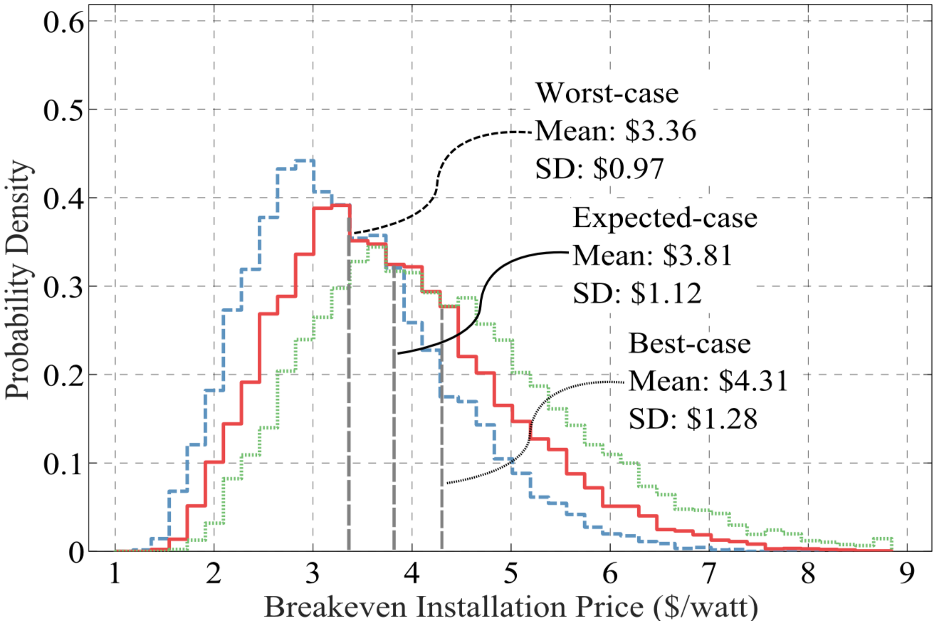


Figure 11 Monte Carlo modeled solar PV value distributions in best-, expected-, and worst-case scenarios for utility PV installations across the United States. Utility installations are more likely to have a value above that of residential, indicative of the tax advantages provided by depreciation. This does not take into account that utility-scale plants often value their electricity generated at much lower values than residential rates.

Of course, the accuracy of these value of solar statistics are dependent on the accuracy of the distributions used to model the input parameters. The true distribution of average peak-sun hours and electricity prices across the country were modeled as being evenly distributed. Such a uniform distribution is only a first order approximation of the true spread of solar irradiance across the surface area of the United States. Nevertheless, it is clear that residential solar PV can be a wise investment given a wide range of parameters expected across the country. While the average cost of solar installations is expected to decrease, the value of the future cash flows is likely to increase in the future as electricity prices increase near the rate of inflation.

In addition, using the same residential electricity prices for non-residential installations, we see that 98.0% of those modeled have an expected value above \$2.00 per watt. Utility-scale install prices per watt are already below this price point [5]. However, this does not tell the full story at the utility-scale. This is because developers of large-scale plants often sign contractual agreements for an electricity price which is low compared to present prices. Each of these agreements is taken on a case-by-case basis and so no set price is expected for utility-scale installations. Often, utility-scale developers competitively bid their designs for a unique set of plant requirements [36]. A solar bidding process completed in 2015 through Austin Energy in Texas produced 1,295 MW of solar bids priced under 4 cents per kwh [37]. Bids this low are suggestive of the cost savings possible today by implementing constantly improving solar technologies at large scales, as well as the value of tax and renewable energy credits which can be resold.

The economic value of various technologies for a PV system can be modeled and quantified using the solar calculator. The value of differential power processing (DPP) technology can be found by comparing the value of systems which include DPP to those modeled without it. DPP is modeled as a 5% improvement in the dc to ac derating factor, which is conservative compared to reported results [35], as well as a 25% reduction in maintenance costs facilitated by the distributed monitoring capabilities enabled by DPP. The effect on the value in a residential setting can be seen in Figure 12. The addition of DPP to a residential system is able to increase the amount one should be willing to pay at installation time by an average of \$0.217 per watt. Therefore, if the components and manufacturing required to implement DPP cost less than this per watt, it is likely a good value-added technology for panel manufacturers to include. Alternatively, when system owners compare two installation quotes with and without DPP, if the option with DPP is less than about \$0.15 more costly per watt, it is almost certainly a good investment for a residential system purchaser.

Another example of the value of particular technology change may be for a company which can promise a reduced panel degradation rate from 0.5% per year to 0.3%. The solar calculator can quickly show that this improvement is worth from between 7.2 to 9.5 cents per dc watt, or about $18 to $23 per 250 watt panel given the default solar calculator inputs.

The distribution of the additional value contributed by DPP is shown in Figure 13 for both utility and residential installations. The average increase for residential is $0.217 per watt matching the difference in average seen in Figure 12. In all scenarios, the utility installation is able to benefit more from the inclusion of DPP technology with an average difference of $0.295 per watt. For 250 W panels, this works out to an additional value due to DPP of $54.25 and $73.75 per panel for residential and utility installations respectively.

DPP appears to be a beneficial technology in terms of return on investment provided its costs remain lower than the expected increase in system value. Even in the poorest of modeled circumstances, DPP is shown to be worth at least $0.05 per watt, or $12.50 per 250 W panel at time of installation. If the power electronics required to implement DPP on a panel cost less than $12.50, the technology will certainly provide additional value to U.S. residential installations. If DPP were included with a panel-mounted microinverter, the synergy of the two technologies would likely lower implementation costs further than DPP implemented on panels installed in a string inverter configuration. This analysis for DPP is equally applicable for any other long-life technology that improves system output by a similar factor such as dc-dc converters.

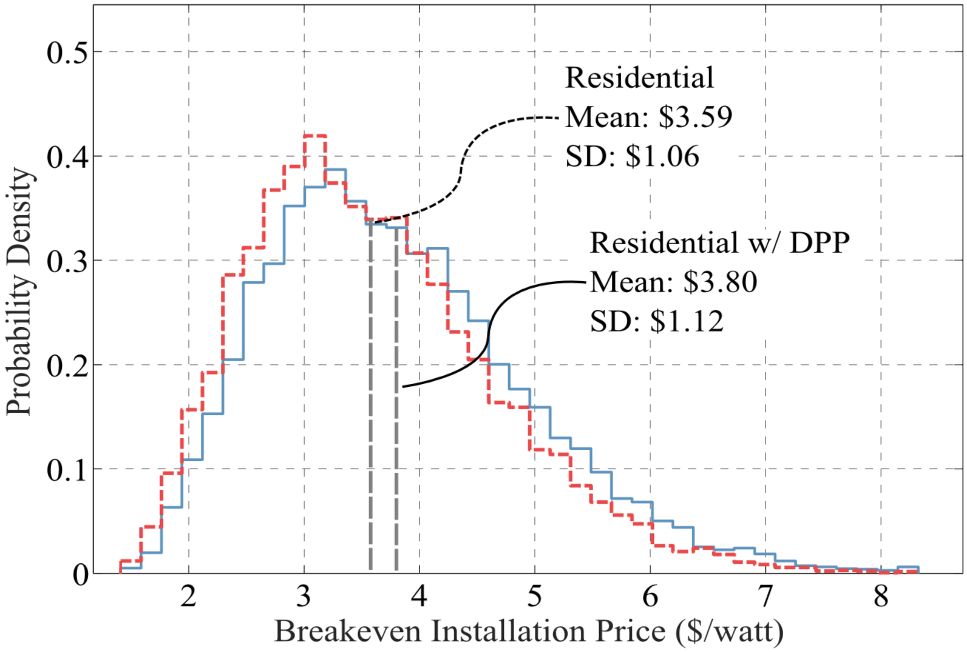


Figure 12 Comparison of the expected residential scenario with and without DPP technology for 10,000 Monte Carlo trials. DPP clearly provides an increase in the expected value of a residential PV system. The average difference in value of $0.217 is indicative of the value DPP adds per installed watt to a typical residential PV system. The distribution of the added value can be seen in Figure 13.

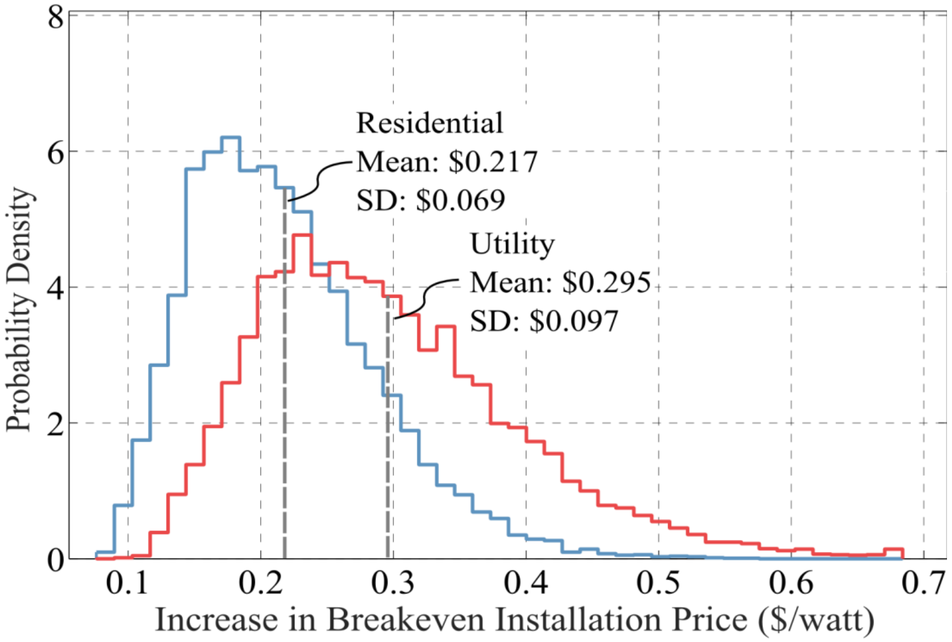


Figure 13 Distributions of the value added by DPP per installed watt for expected-case residential and utility scenarios. Utility installations are better able to take advantage of the benefits of a technology like DPP with an average benefit over residential of $0.078 per watt at residential electricity prices.

7. The Solar Choice

The growth of solar installations across the country has taken an exponential trajectory as can be seen in Figure 2; however, the trend is not guaranteed to continue in the future. For example, one can see that non-residential installations remained about constant between 2012 and 2014. The uncertainty involved in the decision to implement solar PV by a homeowner or by a business entity may be one of the greatest factors tempering the acceleration of installations across the country.

The decision to install solar is often primarily a financial one. Individuals and businesses want to know if it is a good use of their limited resources to invest in a PV system. This alone can be a daunting question to answer. In addition, a number of technical concerns must be addressed. My goal is to provide some clarity in these areas so that individuals can feel more confident in their ability to address the question of whether to further pursue solar in their situation or not.

7.1 Technical Considerations

Determining if a particular location will be able to acceptably host solar panels is the key technical consideration to being confident in the financial projections soon to follow. If an otherwise ideal location is in the shadow of a tree during half the year, the financial value of any PV system installed there will not match the valuations made in most calculators since they are based on the panels being fully exposed to the light given the latitude and climate. This full exposure is dependent on at least two parameters.

Orientation – the direction fixed-tilt panels face relative to the optimal.

Shading – shadows caused by obstacles such as trees, poles, other panels, etc.

The Solar Advisory Model (SAM) includes many options which can help users and installers quantify some of these factors on their particular system. Instead, the solar calculator lumps losses due to these factors into the ac to dc derating factor. Given a wide enough deviation in the ac to dc derating during sensitivity analysis, one would expect the solar calculator to adequately cover general scenarios for each of the factors listed above.

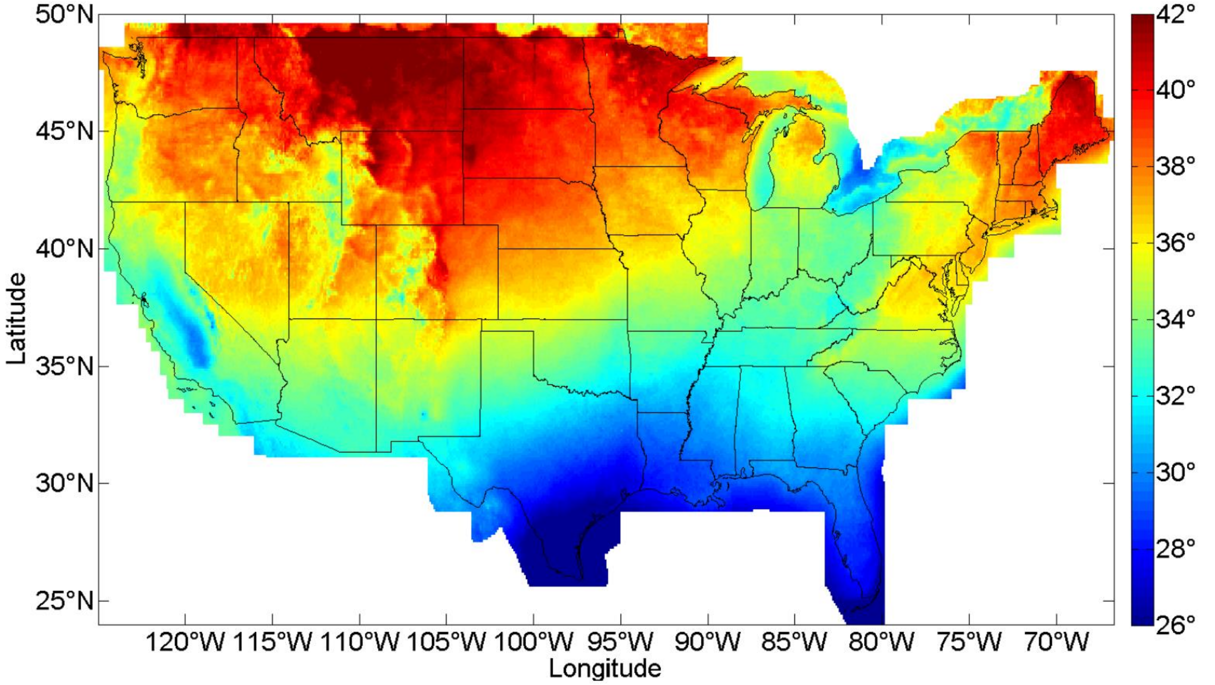
In reality, each of these factors—orientation and shading—can be addressed by someone considering a solar PV installation. By including multipliers which adjust the value of solar based on these site-specific factors, they can be confident in financial valuations from the solar calculator and other PV system models.

7.1.1 Orientation

The direction a solar panel faces plays a large role in determining annual electricity production. The traditional rule of thumb has been that the optimal fixed direction for a solar panel in the northern hemisphere is at latitude tilt angle and pointed due south. This provides a good first approximation for the energy maximizing orientation; however, the best orientation is ultimately dependent on many factors this method does not consider such as cloud formation patterns and atmospheric diffusion. Lave and Kleissl report a better optimal angle for all locations in the continental United States in their paper [38] with their key maps reproduced in Figure 14. They note that the calculated optimal orientations are always within 10° of the rule of thumb.

Many solar installations, particularly residential ones, have less flexibility in the elevation angle at which they can be installed. Even if one knows the ideal fixed direction for installation, perhaps one's roof angle will not permit it in a visually appealing way. One must look deeper at how much difference being oriented away from the ideal can affect total system output. Figure 15 shows the relative generation of the default 4 KW fixed-tilt solar PV system from PVWatts in five different cities over a wide range of tilt and azimuthal angles. These cities are widespread and are meant to capture some of the common extremes experienced in the continental United States. The cities are Seattle, WA; Phoenix, AZ; Topeka, KS; Portland, ME; and Tampa, FL.

Looking into each of the charts in Figure 15, one can see very similar patterns overall. The PVWatts model agrees with the Lave and Kleissl paper that the optimal fixed tilt orientation of a solar panel in Seattle should be oriented slightly west of due south and at about 35° tilt angle. The most likely explanation for an optimal azimuthal angle deviating from due south is because of local weather patterns. For example, Seattle's cloudy weather means an optimal orientation must maximize direct and diffuse radiation as well as morning maritime cloud cover which skews the time panels can collect direct radiation to times when the sun is in the west. Nevertheless, it should be noted that Figure 15 shows that even if a system was oriented due south in Seattle, the panel would still produce over 99% of the generation at the optimal. This is very little loss due to a non-optimal orientation. Tampa, FL has an even more forgiving tolerance for non-optimality of orientation with its 95% of annual generation being much more spread than the other four cities.


Optimal Tilt Angle

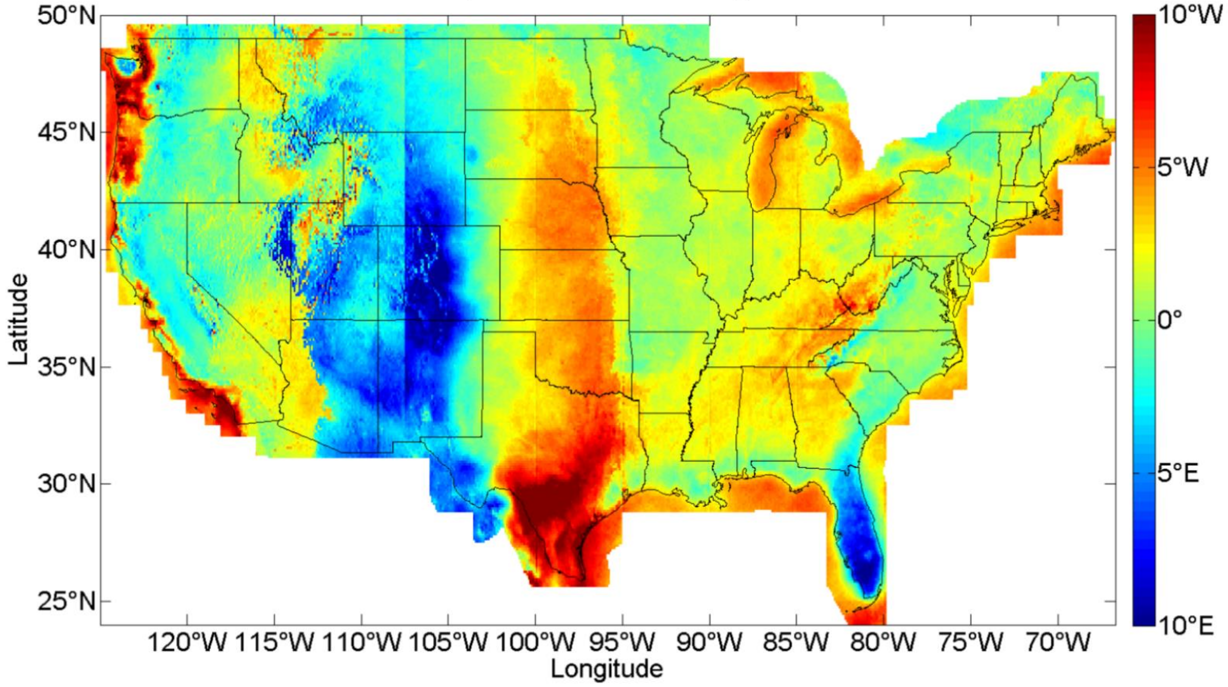

Optimal Azimuthal Angle

Figure 14 Optimal tilt and azimuth angles for continental United States as shown by Lave and Kleissl [38]. Tilt angles are given as degrees from horizontal. Azimuthal angles are given east or west of due south at 0°.

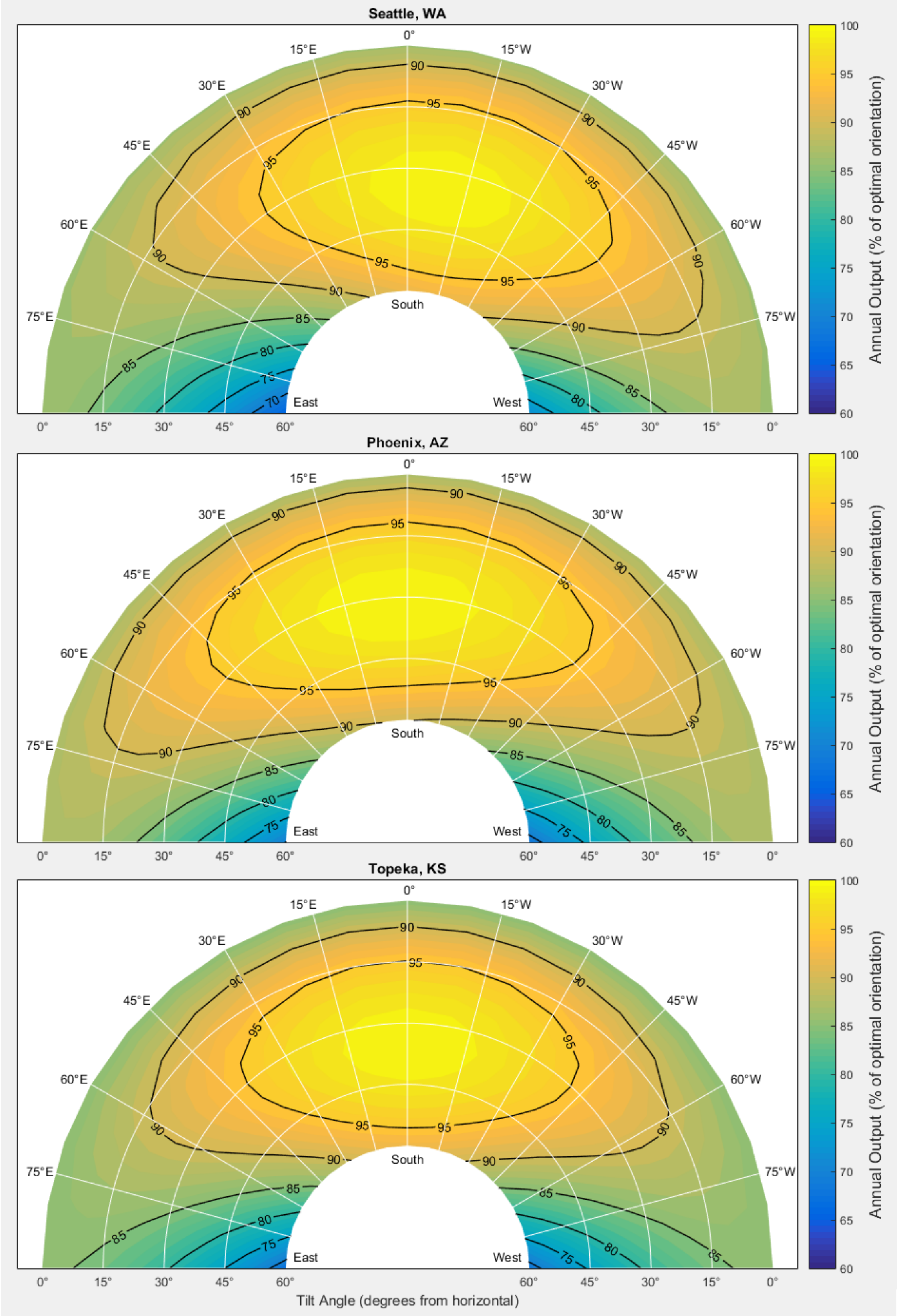


Figure 15 Percentage of peak generation at various tilt and azimuth angles for five cities.

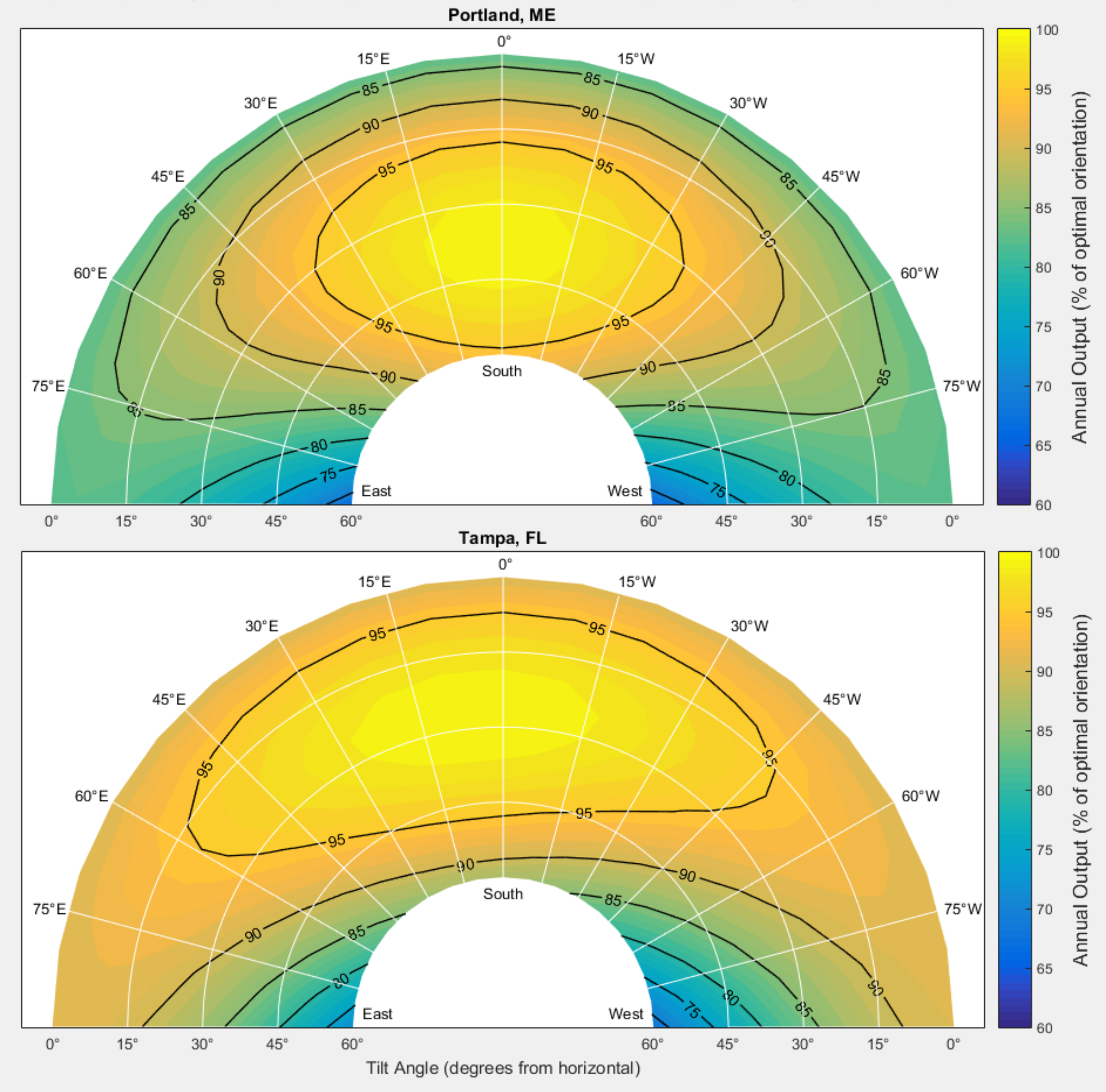


Figure 15 (cont.) Percentage of peak generation at various tilt and azimuth angles for five cities.

Taking all the graphs of Figure 15 into consideration, we can draw some conclusions regarding the expected amount of lost generation due to non-ideal orientation. One can plot the angular distance in degrees away from the optimal orientation in a graph like those in Figure 15, and while they do not perfectly match the annual generation contours, they are a close approximation, and certainly more easy to conceptualize. One can summarize that within about 20° from the optimal orientation, one can expect to get at least 95% of the best output possible. For each 10° further away, one can expect to lose an additional 5% of output. This result is summarized in Table 5.

Table 5 Approximate loss in annual generation output of a fixed-tilt solar panel if installed at a non-optimal orientation for the continental United States.

Orientation Deviation (Degrees from Optimal)	Annual Output (% of Optimal)
0°-10°	99%-100%
10°-20°	96%-99%
20°-30°	90%-96%
30°-40°	85%-90%
40°-50°	80%-85%

7.1.2 Shading

Calculating losses due to shading is one of the most challenging aspects of determining the viability of solar PV. The effect of shading is ultimately a complicated interaction between the incoming radiation for each cell in a solar panel array and the electrical configuration and conversion process of the array.

Since the shading for each installation is completely dependent on individual location characteristics, the best estimates of the cumulative effects require a site-specific evaluation. Many paid and free apps exist for both iPhone and Android phones which use device sensors to allow the user to trace the outline of obstacles such as buildings and trees along the horizon. While these apps are not as accurate as a professional system, they can give relatively accurate shading loss estimates with low effort and low cost. These tools tend to capture the effects of faraway shading, such as a tree line or hill near the horizon. When the shading object is far away, it is more likely to affect all the panels in the array roughly equivalently making it easier to determine the amount of direct and diffuse irradiance being blocked.

Obstructing object nearby the array will cause shadows to be cast on the array which will move throughout the day. The negative effects of this kind of nearby shading can be minimized by using smaller maximum power point tracking (MPPT) zones. A string inverter without localized technologies will perform MPPT over all of the panels in the string. Even if a portion of a single panel is shaded, the entire string’s output could be severely affected. A localized technology such as DPP, dc-dc converters, or microinverters perform MPPT on each panel individually, so that panels affected by a daily moving shadow do not affect the output of others. It is possible to use these technologies on the substring level, particularly DPP, such that each third of the solar panel performs its own MPPT. The smallest MPPT zones possible is certainly the preferred case when considering a site with significant shading from nearby obstructions. As MPPT zones become smaller, the effect of nearby shading can be thought of as the fraction of the panel area being shaded each day on average. As localized MPPT technologies become more common, many sites that are infeasible for the string topologies due to nearby shading could become feasible. In the case of significant nearby shading, the most accurate assessment of electricity generation can be made by a professional installer using 360° imaging technology and a full 3D model.

One common shading scenario to consider is self-shading. This is shading caused by shadows from other solar panels in an array. Typically, non-residential and utility-scale fixed-tilt PV installations panels are arranged on a flat surface in southward facing parallel rows which could cast shadows on rows behind them particularly when the sun is close to the horizon. Self-shading in this type of area-constrained installation (such as a commercial building rooftop) can lead to system owners needing to make design decisions trading off between individual panel annual output and the overall system energy output.

Galtieri presents a systematic evaluation of self-shading in the centralized case which uses maximum power point tracking (MPPT) over an entire PV panel [39] and decentralized utilizing DPP technology for MPPT on each of three modeled substrings in a panel [40]. Utilizing DPP enables MPPT on each third of the panel rather than the whole. This allows the DPP panel to continue production even while large sections are shaded.

Spacing factor, D, is defined as the row width (distance from front edge of one row to front edge of the next) divided by panel width allowing it to be generalized for different geometries. This factor is dependent on tilt angle since row width will change while panel width will not with changing tilt angle. We see in Figure 16 the trade-off between row spacing, tilt angles, and power output.

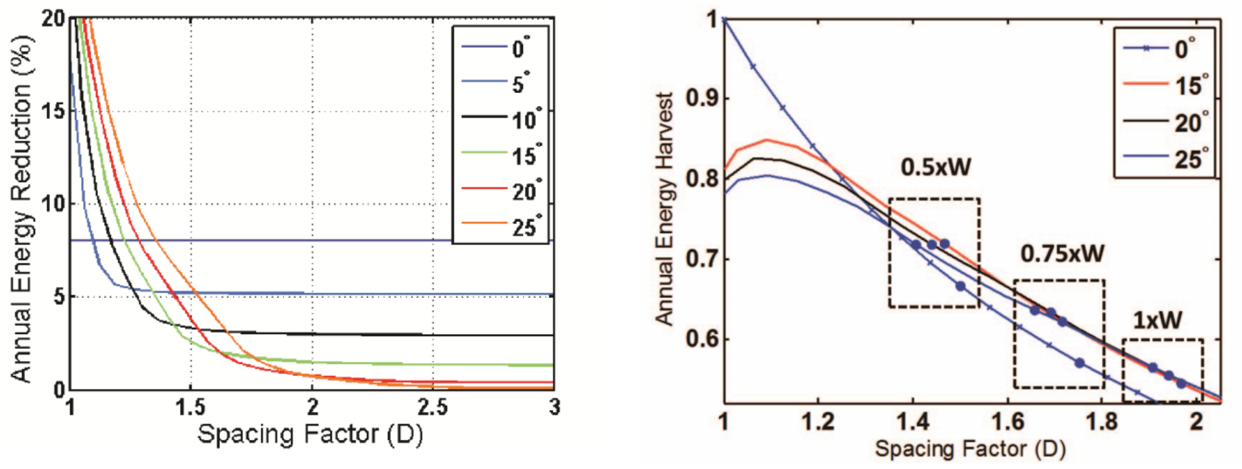


Figure 16 Galtieri shows the above two plots for modeled PV installation near Urbana-Champaign, IL in [39]. On the left, the reduction of annual output as percentage of maximum, showing that more horizontal tilt angles allow PV panels to be closer spaced due to less self-shading. On the right, total normalized energy harvest for an area constrained PV installation given various tilt angles. The three boxes represent system parameters if a certain space required for maintenance is imposed on the space between rows.

Extending this work, Galtieri went on to include the effect of DPP in a similar analysis. With more localized MPPT, shading is shown to have less effect on power output and allows more energy capture. Tilt angles can vary beyond the 5° increments shown and if plotted would show a smooth curve of optimal points for with and without DPP. The increase due to DPP is between 0.5 to 1% for the same spacing simply due to the sections being shaded being able to output more as the shadow moves throughout the day. Alternatively, for the same energy output the spacing factor can be decreased between 0.05 and 0.2 depending on the original spacing factor which is equivalent to a decrease in required area of about 5 to 10%. This can be highly beneficial to finite area arrays which may want to maximize the value per area of a limited space. For example, the Electrical and Computer Engineering Building at the University of Illinois roof coverage was roughly doubled when a local converter analysis was used as compared to the typical rule of thumb, allowing significantly higher production over the same area while remaining practical financially.

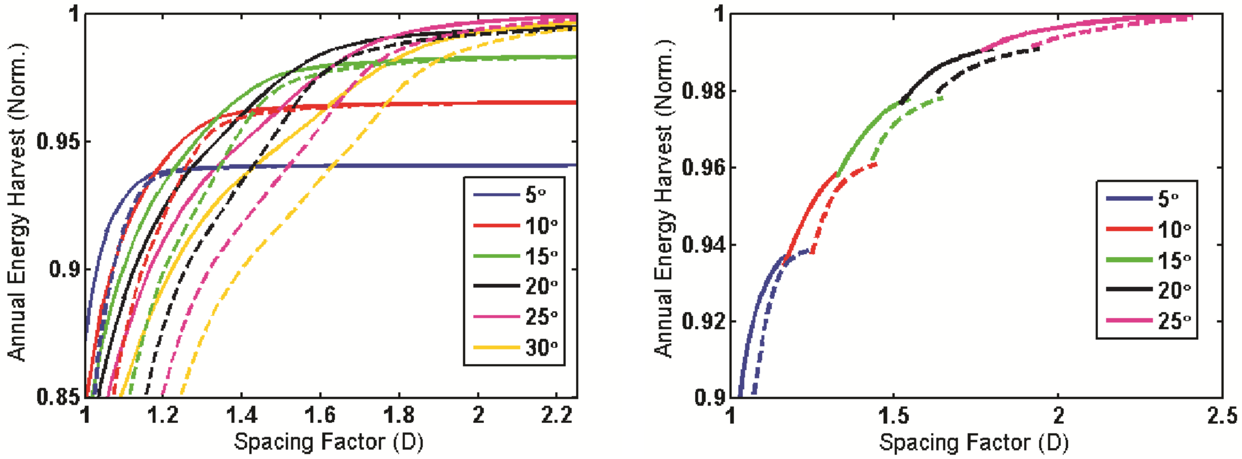


Figure 17 Comparison of row spacing effects with and without DPP from [40]. On the left, total normalized annual output for a given tilt angle and spacing factor with (solid) and without (dashed) DPP. On the right, only optimal sections are shown.

7.2 Financial Considerations

The financial decision of whether to install solar PV is dependent on the technical considerations covered. However, most of the value of solar comes from the value of electricity and the solar resource available as was seen in the sensitivity analysis in Figure 7. These are location-dependent variables and thus one can get a gauge of the cost-effectiveness of solar PV in each state by simply using the solar calculator to determine the value of solar in each state given their unique solar resource and average electricity price. In addition, one can calculate the average rate of growth in electricity prices to include this in each state's value analysis.

The annual growth rate for each state was determined using a weighted average of the national average electricity price growth rate of 3.65% and the state's average in a 10%/90% ratio. The state compound average growth rate (CAGR) was taken over the years 2004 to 2014. Due to the variability in average electricity prices, the three years from 2004 to 2006 and the three years from 2012 to 2014 were averaged and set as the 2005 and 2013 year prices. Then the compound growth was calculated during the intervening 8 years to find the CAGR which was then weighted with the national average. Finally, the weighted CAGR was used to calculate each state's value of solar.

Taking the three input values of peak-sun hours, the 2014 average price, the weighted compounded average growth rate of the electricity prices for each state, and the remaining default inputs shown in Table 6, one can use the solar calculator to get worst-case, expected-case, and best-case values for solar in each state. Table 7 and Table 8 show the variable inputs used for these results as well as worst-, expected-, and best-case values of solar for each state. We expect that if the expected-case value of solar is higher than the cost of solar in that location, that solar PV is a good investment. The residential average cost of solar in Q3 of 2015 was $3.54 and we can compare our value of solar calculation with this price to identify states in which residential investment in solar PV is already financially advantageous. These states are shown in green in Figure 18. Similarly, the 2015 Q3 non-residential average price for installed solar PV was $2.15 and the financially advantageous states are shown in green in Figure 19.

Table 6 Inputs used for each state. Location independent variables were kept constant while calculating the value of solar for each state of the United States.

	Residential	Non-Residential
System Lifetime (yr)	25	25
Discount Rate (%)	6%	6%
Inflation Rate (%)	2.36%	2.36%
->Inflation Rate Deviation (±%)	1.00%	1.00%
Annual O&M Cost (% of Install Cost)	0.25%	0.40%
Avg. Daily Peak-Sun Hours (hr/day)	*Variable*	*Variable*
DC to AC Derating [setup dependent] (%)	86.00%	86.00%
->DC to AC Derating Deviation (±%)	5.00%	5.00%
Panel Degradation Per Year (%)	0.50%	0.50%
Avg. Electricity Price ($/kWh)	*Variable*	*Variable*
Annual Electricity Price Gain (%/yr)	*Variable*	*Variable*
->Annual Electricity Price Gain Deviation (±%/yr)	0.55%	0.55%
Depreciation (1=True, 0=False)	0	1
Depreciable Basis (% of Est. Installation Cost)	N/A	40%
Effective Corporate Tax Rate (%)	N/A	30%

Figure 18 and Figure 19 clearly show that the highest value of solar can be found among the Southwestern states. This is to be expected because of the high amounts of solar radiation. In combination, the Southwest also experiences relatively high electricity prices, particularly California with an impressive value of solar of about $5 per dc watt. With residential install prices around $3.50 per dc watt, an investment in California residential solar PV is well worth it in most cases. Washington suffers from a very low value of solar due to its cloudy conditions and affordable electricity from ample hydroelectric resources. Since the average cost of non-residential solar PV is substantially lower than residential, many more states can achieve a value of solar higher than the cost to install PV. Outside the Southwest, the Midwest and Northeastern states show promise for solar PV. The Northeast becomes an unlikely place for profitable solar due to the high cost of electricity despite lower solar radiation. States such as Illinois, Ohio, Louisiana, and Texas are shown to have relatively low values of solar because of their extremely low expected growth in electricity price. Ultimately, low electricity prices and low price growth is a good scenario for consumers; however, it makes the case for solar less appealing since future electricity will still be cheap.

Table 7 Value of solar for residential installations across the United States including location-dependent inputs.

Residential Value of Solar						
State	Peak-Sun Hours	2014 Average Price (cents/kWh)	Elec. Price Weighted CAGR	Value of Solar Worst-case ($/Wdc)	Value of Solar Expected-case ($/Wdc)	Value of Solar Best-case ($/Wdc)
Hawaii	4.50	37.3	7.6%	$ 13.75	$ 15.58	$ 17.60
California	6.25	16.3	2.6%	$ 4.45	$ 4.99	$ 5.59
Arizona	7.50	12.0	3.4%	$ 4.34	$ 4.88	$ 5.47
New Mexico	6.50	12.3	3.5%	$ 3.91	$ 4.39	$ 4.93
Utah	6.50	10.7	4.2%	$ 3.70	$ 4.16	$ 4.68
Nevada	6.75	12.9	2.1%	$ 3.61	$ 4.04	$ 4.52
Colorado	5.75	12.2	3.7%	$ 3.52	$ 3.95	$ 4.44
Kansas	4.75	12.1	4.9%	$ 3.33	$ 3.75	$ 4.21
Wyoming	5.75	10.5	3.9%	$ 3.11	$ 3.49	$ 3.92
Michigan	3.00	14.5	6.3%	$ 3.00	$ 3.39	$ 3.82
Maryland	3.50	13.6	5.5%	$ 2.95	$ 3.33	$ 3.75
New Jersey	3.75	15.8	3.5%	$ 2.90	$ 3.26	$ 3.66
Connecticut	3.00	19.6	3.3%	$ 2.79	$ 3.13	$ 3.51
South Carolina	4.25	12.3	4.3%	$ 2.78	$ 3.13	$ 3.52
Vermont	3.25	17.5	3.5%	$ 2.77	$ 3.11	$ 3.48
Nebraska	4.75	10.4	4.6%	$ 2.76	$ 3.10	$ 3.49
New York	3.25	20.1	2.3%	$ 2.76	$ 3.09	$ 3.45
Delaware	4.00	13.4	3.8%	$ 2.70	$ 3.03	$ 3.40
Minnesota	4.00	12.1	4.5%	$ 2.66	$ 2.99	$ 3.36
Idaho	4.50	9.8	5.1%	$ 2.61	$ 2.94	$ 3.31
Missouri	4.25	10.6	4.8%	$ 2.58	$ 2.91	$ 3.27
Wisconsin	3.50	13.9	4.2%	$ 2.58	$ 2.90	$ 3.26
Rhode Island	3.50	17.6	2.0%	$ 2.51	$ 2.81	$ 3.14
New Hampshire	3.25	17.5	2.6%	$ 2.50	$ 2.80	$ 3.14
Alaska	2.50	19.3	4.0%	$ 2.48	$ 2.79	$ 3.14
Georgia	4.25	11.6	3.8%	$ 2.48	$ 2.79	$ 3.13
South Dakota	4.75	10.5	3.6%	$ 2.46	$ 2.77	$ 3.10
Alabama	3.75	11.5	4.3%	$ 2.33	$ 2.62	$ 2.94
Tennessee	4.00	10.3	4.4%	$ 2.23	$ 2.51	$ 2.82
Oregon	4.00	10.5	4.1%	$ 2.19	$ 2.46	$ 2.76
North Carolina	4.25	11.1	2.9%	$ 2.15	$ 2.41	$ 2.70
Montana	4.50	10.3	3.0%	$ 2.12	$ 2.38	$ 2.66
Oklahoma	5.00	10.0	2.3%	$ 2.12	$ 2.38	$ 2.66
Virginia	3.75	11.2	3.8%	$ 2.11	$ 2.37	$ 2.66
Mississippi	4.25	11.4	2.5%	$ 2.10	$ 2.35	$ 2.63
Kentucky	3.50	10.1	5.1%	$ 2.08	$ 2.34	$ 2.63
Massachusetts	3.00	17.4	1.8%	$ 2.09	$ 2.34	$ 2.61
Texas	5.25	11.8	0.2%	$ 2.09	$ 2.33	$ 2.60
District Of Columbia	3.00	12.8	4.2%	$ 2.05	$ 2.30	$ 2.58
Florida	4.25	12.0	1.9%	$ 2.05	$ 2.30	$ 2.57
Indiana	3.25	11.3	4.5%	$ 2.02	$ 2.27	$ 2.55
Illinois	3.50	11.4	3.6%	$ 1.98	$ 2.22	$ 2.49
Ohio	3.00	12.4	4.1%	$ 1.94	$ 2.18	$ 2.44
Maine	3.25	15.3	1.6%	$ 1.94	$ 2.17	$ 2.42
Pennsylvania	3.00	13.3	3.4%	$ 1.93	$ 2.16	$ 2.42
Iowa	4.00	11.4	2.2%	$ 1.91	$ 2.14	$ 2.39
North Dakota	4.25	9.3	3.4%	$ 1.90	$ 2.14	$ 2.40
West Virginia	3.00	9.3	5.4%	$ 1.73	$ 1.95	$ 2.20
Washington	3.75	8.7	3.5%	$ 1.59	$ 1.79	$ 2.00
Arkansas	3.75	9.5	2.0%	$ 1.46	$ 1.63	$ 1.83
Louisiana	4.25	9.5	0.6%	$ 1.41	$ 1.58	$ 1.76

Table 8 Value of solar for non-residential installations across the United States including location-dependent inputs.

Non-Residential Value of Solar						
State	Peak-Sun Hours	2014 Average Price (cents/kWh)	Elec. Price Weighted CAGR	Value of Solar Worst-case ($/Wdc)	Value of Solar Expected-case ($/Wdc)	Value of Solar Best-case ($/Wdc)
Hawaii	4.50	34.3	7.8%	$ 13.96	$ 15.87	$ 17.99
California	6.25	15.7	2.2%	$ 4.41	$ 4.96	$ 5.56
Arizona	7.50	10.1	3.3%	$ 3.87	$ 4.36	$ 4.90
New Mexico	6.50	10.4	3.2%	$ 3.42	$ 3.86	$ 4.33
Utah	6.50	8.6	4.1%	$ 3.17	$ 3.57	$ 4.02
Colorado	5.75	10.2	3.7%	$ 3.16	$ 3.56	$ 4.01
Wyoming	5.75	8.9	4.2%	$ 2.94	$ 3.32	$ 3.74
Kansas	4.75	10.0	4.7%	$ 2.90	$ 3.28	$ 3.70
Nebraska	4.75	8.7	4.6%	$ 2.48	$ 2.80	$ 3.15
Alaska	2.50	17.2	4.1%	$ 2.44	$ 2.75	$ 3.10
South Carolina	4.25	10.2	3.9%	$ 2.38	$ 2.69	$ 3.02
Alabama	3.75	10.8	4.3%	$ 2.36	$ 2.66	$ 3.00
Vermont	3.25	14.6	3.0%	$ 2.35	$ 2.65	$ 2.97
Tennessee	4.00	10.4	4.1%	$ 2.35	$ 2.65	$ 2.98
Georgia	4.25	10.3	3.7%	$ 2.34	$ 2.64	$ 2.97
Connecticut	3.00	15.5	3.0%	$ 2.30	$ 2.59	$ 2.91
Missouri	4.25	8.8	4.8%	$ 2.29	$ 2.59	$ 2.92
New Jersey	3.75	13.2	2.3%	$ 2.27	$ 2.55	$ 2.86
South Dakota	4.75	8.7	3.8%	$ 2.25	$ 2.54	$ 2.86
Minnesota	4.00	9.6	4.3%	$ 2.22	$ 2.51	$ 2.82
Nevada	6.75	9.7	-0.5%	$ 2.19	$ 2.44	$ 2.73
Wisconsin	3.50	10.9	4.1%	$ 2.16	$ 2.44	$ 2.74
Montana	4.50	9.6	3.0%	$ 2.14	$ 2.41	$ 2.71
New York	3.25	16.1	1.0%	$ 2.07	$ 2.33	$ 2.60
Kentucky	3.50	9.3	5.0%	$ 2.06	$ 2.32	$ 2.62
Rhode Island	3.50	14.6	1.2%	$ 2.06	$ 2.31	$ 2.59
Mississippi	4.25	10.9	2.0%	$ 2.05	$ 2.30	$ 2.58
North Dakota	4.25	8.5	4.0%	$ 2.01	$ 2.27	$ 2.55
Delaware	4.00	10.6	2.6%	$ 2.00	$ 2.25	$ 2.52
Idaho	4.50	7.8	4.1%	$ 1.98	$ 2.24	$ 2.52
New Hampshire	3.25	14.4	1.3%	$ 1.92	$ 2.15	$ 2.41
District Of Columbia	3.00	12.2	3.4%	$ 1.90	$ 2.14	$ 2.40
Indiana	3.25	9.8	4.5%	$ 1.89	$ 2.14	$ 2.41
Michigan	3.00	10.9	4.1%	$ 1.85	$ 2.09	$ 2.35
North Carolina	4.25	8.8	3.0%	$ 1.84	$ 2.07	$ 2.33
Oregon	4.00	8.8	3.4%	$ 1.83	$ 2.06	$ 2.32
Maryland	3.50	11.2	2.2%	$ 1.78	$ 2.00	$ 2.24
Florida	4.25	10.0	1.5%	$ 1.78	$ 1.99	$ 2.23
Massachusetts	3.00	14.7	1.2%	$ 1.77	$ 1.98	$ 2.22
Virginia	3.75	8.2	3.7%	$ 1.66	$ 1.88	$ 2.11
Oklahoma	5.00	8.0	1.3%	$ 1.63	$ 1.83	$ 2.05
Iowa	4.00	8.7	2.3%	$ 1.60	$ 1.80	$ 2.02
West Virginia	3.00	8.0	5.0%	$ 1.52	$ 1.72	$ 1.94
Arkansas	3.75	8.0	3.0%	$ 1.49	$ 1.68	$ 1.88
Maine	3.25	11.7	0.7%	$ 1.46	$ 1.64	$ 1.83
Louisiana	4.25	9.1	0.3%	$ 1.42	$ 1.59	$ 1.77
Washington	3.75	7.9	2.5%	$ 1.40	$ 1.57	$ 1.76
Texas	5.25	8.1	-1.1%	$ 1.35	$ 1.50	$ 1.67
Ohio	3.00	9.8	2.2%	$ 1.32	$ 1.49	$ 1.67
Illinois	3.50	8.7	0.8%	$ 1.19	$ 1.33	$ 1.49
Pennsylvania	3.00	9.7	1.1%	$ 1.17	$ 1.31	$ 1.47

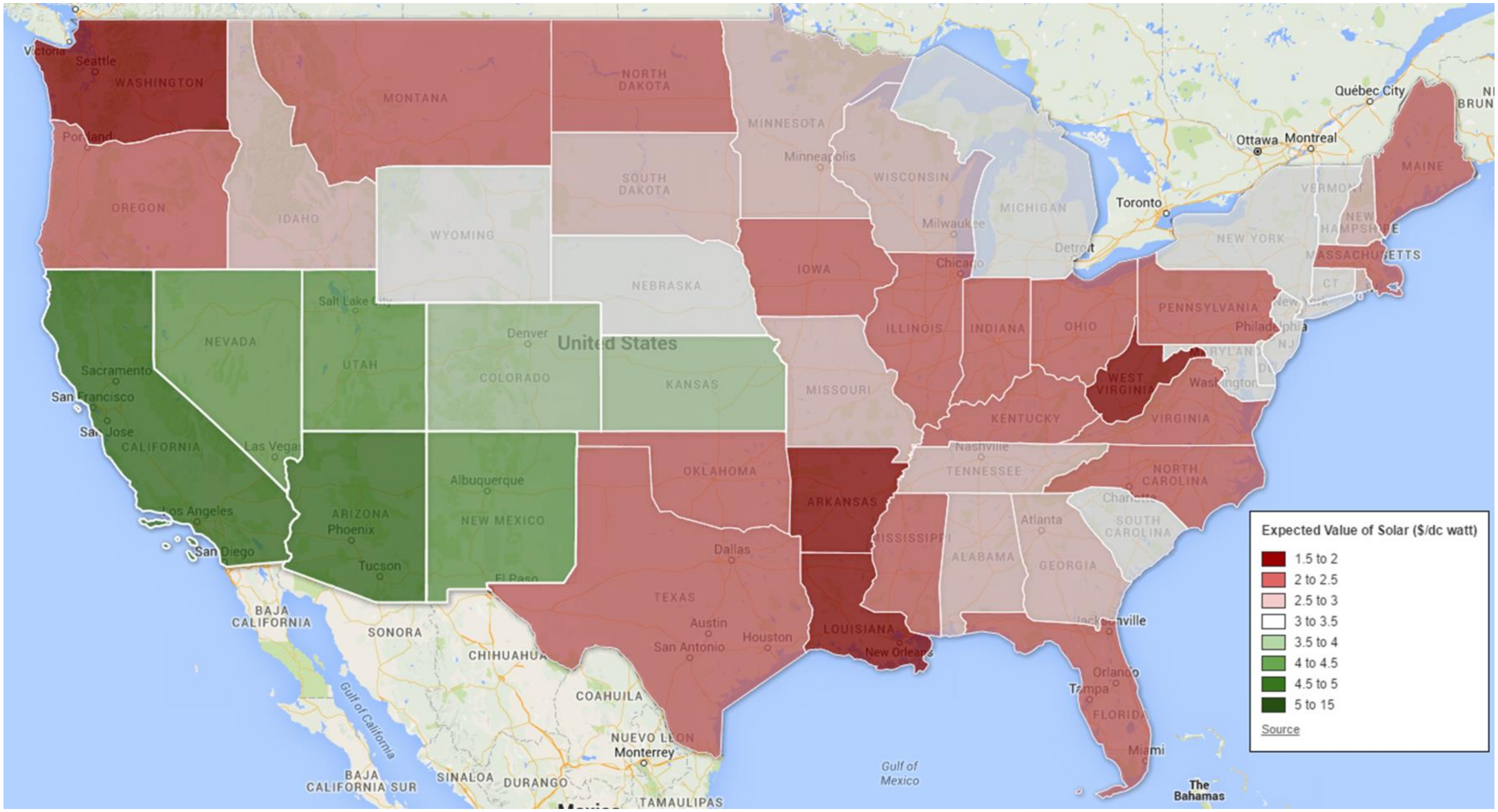


Figure 18 Expected value of residential solar for each state of the continental United States colored with respect to the average cost of residential installed solar PV in Q3 2015 of $3.54.

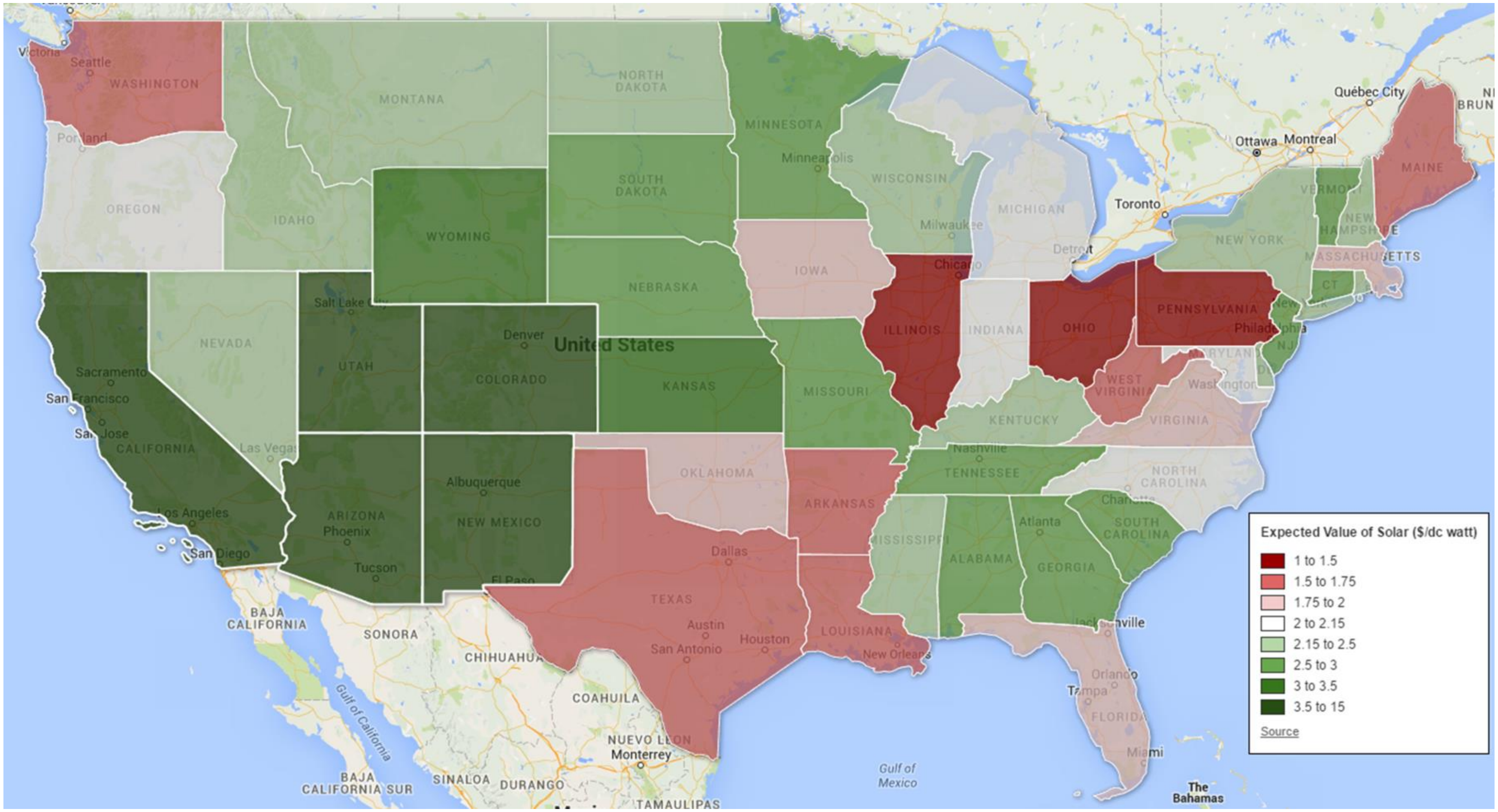


Figure 19 Expected value of non-residential solar for each state of the continental United States colored with respect to the average non-residential cost of installed solar PV in Q3 2015 of $2.15.

8. Discussion

The solar calculator developed from which these results were derived is intended to enable anyone to perform a valuation of an intended solar PV installation. Additionally, it is intended to allow users to understand the economic impact some added technology may provide. In this analysis, the model was provided inputs canvassing the inputs expected across the continental United States.

The calculator provides results which are only as good as the inputs provided. A number of simplifications were used in the sensitivity modeling performed here such as uniform distributions of average peak-sun hours across the United States making the results somewhat less dependable than a more thorough investigation. Nevertheless, technology manufacturers can assess the value they are adding to solar PV by modeling the effects their technology has. A study such as the one included for DPP (see Figure 9) could provide the motivation for continued development. It may also help developers to understand under what circumstances their technology is most valuable, and thus who their target market should be. The model can also evaluate the impact of alternative technologies through appropriate inputs, such as different circuit arrangements. It can also be used to test the financial impact of other performance parameters. For example, some PV system MPPT controls are more effective than others at delivering maximum power at all times [41].

The model developed was able to clearly identify the most important parameters that determine profitability of an installation assuming shading and orientation were ideal. These parameters are the local electricity price, the amount of sunlight available, the discount rate used for financing the project, and system lifetime. The model is also able to determine factors which only play a minor role in the economic considerations of an installation. Future electricity price growth and O&M costs are relatively insensitive; however, it should be noted that within a particular area (where the two dominating factors of electricity price and peak-sun hours are well-defined), a sensitivity study for that area would show that the dominating factors are discount rate and system lifetime. Since geographic location may be outside of one’s immediate control, particularly for residential installations, it would behoove the system owner to consider maximizing value through inexpensive financing and purchasing a high-quality system which will last as long as possible. Corporations and utilities who can take advantage of depreciation will find that spending more at the time of installation in order to reduce O&M costs will provide additional benefits due to tax advantages and lower running costs.

Utility scale installations demand special attention during the design and construction phases of the project due to their size and financial impact. Such large projects often sign particular agreements with municipalities or service providers which are difficult to generalize. Residential and non-residential installations are often much simpler. These installations are most likely implemented with a net-metering agreement between the system owner and a utility, making it easy to determine the average value of a kWh of electricity provided and thus easy to use the solar calculator with confidence. In these cases, the potential system owner can determine if a solar panel system is likely to be a good financial decision for them by determining the value of solar in their location and comparing it with installation quotes from local installers on a per dc watt basis.

The value of solar, V_{ref}, for an ideally oriented, non-shaded solar PV installation for each state of the United States is given for residential and non-residential installations in Table 7 and Table 8, respectively. These values assume a 25 year lifetime which is conservative given panels have been shown to not catastrophically fail over much longer periods [26] and many microinverter manufacturers provide a warranted life of 25 years [7]. The thesis results suggest that equipment sold without such reliability expectations are unlikely to be financially profitable due to replacement and repair costs. In addition, the most reliable equipment will allow the system owner to avoid untimely system outages and the associated time and resources required to restore the system.

With the value of solar in hand, three factors must be considered which will alter the value for each installation: expected system life, orientation, and shading. With a long warranted life, it is reasonable to expect a lifetime longer than the warrantee and this is likely to mean the value of the panels is higher. The appropriate factor for the longer expected life, $f_{lifetime}$, can be determined from Table 3.

Next, any losses due to non-ideal orientation must be considered. The optimal orientation can be determined from Figure 14, and if the installed angle will be different, the correction for total energy capture, $f_{orientation}$, and thus value of solar, is given in Table 5. Finally, a judgment must be made of the expected losses due to shading, $f_{shading}$, at the installation location. Since this is very site-specific, specialized tools are recommended for a very accurate assessment; however, conservative estimates can be used in a preliminary economic analysis. Taking these numbers together, we get an estimated value of solar for a site, V_{site}.

$$V_{site} = V_{ref} \times f_{lifetime} \times f_{orientation} \times f_{shading}$$

The financial decision whether to invest or not, can then be made by comparing the estimated value for a site with quotes from installers. If the value of solar at the site is greater than the quote on a per watt basis, one can be confident that the investment is a wise choice. If not, then further pursuing solar is unlikely to lead to a positive economic outcome from the installation of fixed-tilt solar PV.

As was discussed in section 7.2, quite a few states are capable of benefiting from the installation of solar PV given a good site and that they can purchase solar PV equipment at the national average price. The number of states which will be included in this category will only increase as equipment and balance of plant costs continue to decrease.

For many installations, radiation and electricity prices will have little uncertainty in the model since the proposed installation location will be well-defined. Therefore, the most important factor an owner can impact through purchasing decisions is system reliability. A high-quality system is more likely to result in a positive overall NPV due to its extended system lifetime and lack of downtime and the associated repair costs.

In addition, it is possible for an increase in system efficiency to provide a large financial benefit. For example, differential power processing (DPP) technology is estimated to increase total panel output by 5% in most cases and decrease maintenance cost by 25%. By modeling installations with and without DPP, one can calculate that this technology is worth \$24.12 (worst-case), \$44.65 (expected), and \$121.28 (best-case) per 250 W panel.

9. Conclusions and Future Directions

The economics of solar PV can be a challenging problem to get a handle on; however, the value of solar is a useful metric for gaining insight. By its nature, the value of solar should remain relatively constant while the costs of solar are expected to continue their steady decline. The range of values a solar PV installation is expected to provide is a valuable benchmark for determining if and when solar PV may become economically feasible. This analysis was carried out for each state in the United States for fixed-tilt PV. As the market and technology continues to mature, there is little reason to believe that the sensitivities affecting the value of solar will change dramatically. The expected value of solar will continue to be dominated by the radiation and the cost of electricity in a particular region. Should a potential system owner find these factors in favor of solar PV, once they have incorporated the site-specific factors of panel orientation and shading, they have most of the information needed for an estimation of the value of solar. Between these four factors, most of the uncertainty in the value of solar has been eliminated.

The solar calculator can be used to quickly estimate the value of solar and other economic factors for one or more solar PV installations through providing distributions for input variables using Monte Carlo techniques. In addition, the solar calculator can easily determine the change that a technological improvement may bring to the value of solar. The analysis of individual technology changes can be useful for system installers wishing to show the value of a given improvement, potential owners evaluating the costs and benefits of a change, and technology developers as they determine the value they can bring to users. This type of quantification of financial value for solar and related technologies should play a vital role in the decisions made by businesses and homeowners alike.

The regions where solar PV shows economic feasibility is expanding and this analysis predicts that about half the United States is currently able to host a profitable residential installation. This is one way of showing that solar is reaching economic parity with other technologies in the market given the incentives currently available.

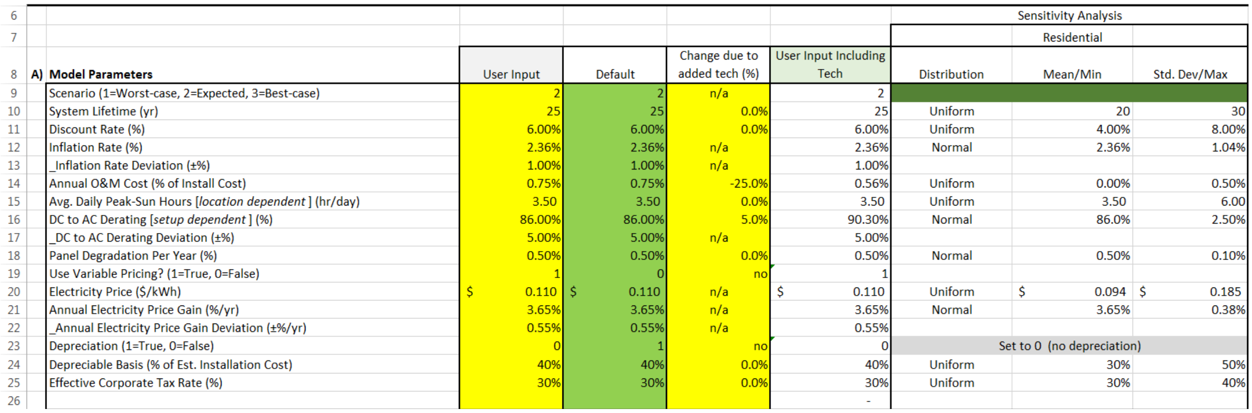
In this analysis, only the national average of solar PV costs was used to compare with calculated values of solar. SEIA includes state averages for solar panel equipment costs in its paid reports. These state average costs could be combined with the calculated average state values of solar to determine the expected profitability of solar in each state.

An additional area of exploration may be the economics of extremely long-life solar installations. One can evaluate a few models for panel degradation and determine at what point it may be cost effective to replace the panels. Even with only half of the nominal power production, it may not be worth the investment to replace panels. It would be a tradeoff between future costs of panels, advances in technology efficiency, and the rate of degradation of the old panels.

Appendix A: Using the Solar Calculator

Section A of the solar calculator spreadsheet contains inputs for model parameters. When not using the model for Monte Carlo analysis, the user needs only change values with a yellow background. All remaining cells are locked to protect the sheet from unintentional modification. The model outputs seen in sections C and D of the spreadsheet are dependent on the inputs provided by the user in section A. The column in green represents default values which can help the user identify reasonable inputs to the model for each parameter. The second yellow column allows the user to input changes caused by any type of change to the system as percentage changes from the user inputs column. Anytime a yellow cells is changed, a script is run which recalculates the breakeven prices for best-, worst-, and expected-case scenarios which can be seen in section D. The percentage change inputs can used to model the difference caused by a technology being implemented on the solar installation such as DPP which is expected to decrease maintenance costs by about 25% and increase the system output by 5% as can be seen modeled in Figure 20. By defining the values in the two yellow columns as desired, the user has almost completely defined the attributes of two solar panel installations. Various financial and production results are shown in sections C and D. Information about each parameter can be seen in a description column located just to the right of each row.

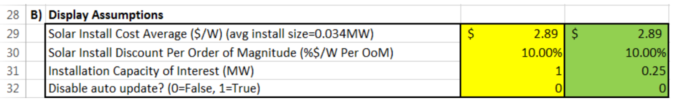
The three columns labeled "Sensitivity Analysis" at the far right of section A are there for convenience when performing Monte Carlo analysis. It shows what distribution is intended to be used by a risk analysis software such as Oracle's Crystal Ball which can automate performing the Monte Carlo simulations. When running a Monte Carlo analysis on the model, the user can reference these cells and the output will be the distributions of the results as selected by the user in the risk analysis software used. The Solar Calculator is configured to run with Crystal Ball and includes macros which Crystal Ball references to solve for the breakeven cost between each iteration.



6								Sensitivity Analysis	
7								Residential	
8	A)	**Model Parameters**	User Input	Default	Change due to added tech (%)	User Input Including Tech	Distribution	Mean/Min	Std. Dev/Max
9		Scenario (1=Worst-case, 2=Expected, 3=Best-case)	2	2	n/a	2			
10		System Lifetime (yr)	25	25	0.0%	25	Uniform	20	30
11		Discount Rate (%)	6.00%	6.00%	0.0%	6.00%	Uniform	4.00%	8.00%
12		Inflation Rate (%)	2.36%	2.36%	n/a	2.36%	Normal	2.36%	1.04%
13		_Inflation Rate Deviation (±%)	1.00%	1.00%	n/a	1.00%			
14		Annual O&M Cost (% of Install Cost)	0.75%	0.75%	-25.0%	0.56%	Uniform	0.00%	0.50%
15		Avg. Daily Peak-Sun Hours [*location dependent*] (hr/day)	3.50	3.50	0.0%	3.50	Uniform	3.50	6.00
16		DC to AC Derating [*setup dependent*] (%)	86.00%	86.00%	5.0%	90.30%	Normal	86.0%	2.50%
17		_DC to AC Derating Deviation (±%)	5.00%	5.00%	n/a	5.00%			
18		Panel Degradation Per Year (%)	0.50%	0.50%	0.0%	0.50%	Normal	0.50%	0.10%
19		Use Variable Pricing? (1=True, 0=False)	1	0	no	1			
20		Electricity Price ($/kWh)	$ 0.110	$ 0.110	n/a	$ 0.110	Uniform	$ 0.094	$ 0.185
21		Annual Electricity Price Gain (%/yr)	3.65%	3.65%	n/a	3.65%	Normal	3.65%	0.38%
22		_Annual Electricity Price Gain Deviation (±%/yr)	0.55%	0.55%	n/a	0.55%			
23		Depreciation (1=True, 0=False)	0	1	no	0	Set to 0 (no depreciation)		
24		Depreciable Basis (% of Est. Installation Cost)	40%	40%	0.0%	40%	Uniform	30%	50%
25		Effective Corporate Tax Rate (%)	30%	30%	0.0%	30%	Uniform	30%	40%
26						-			

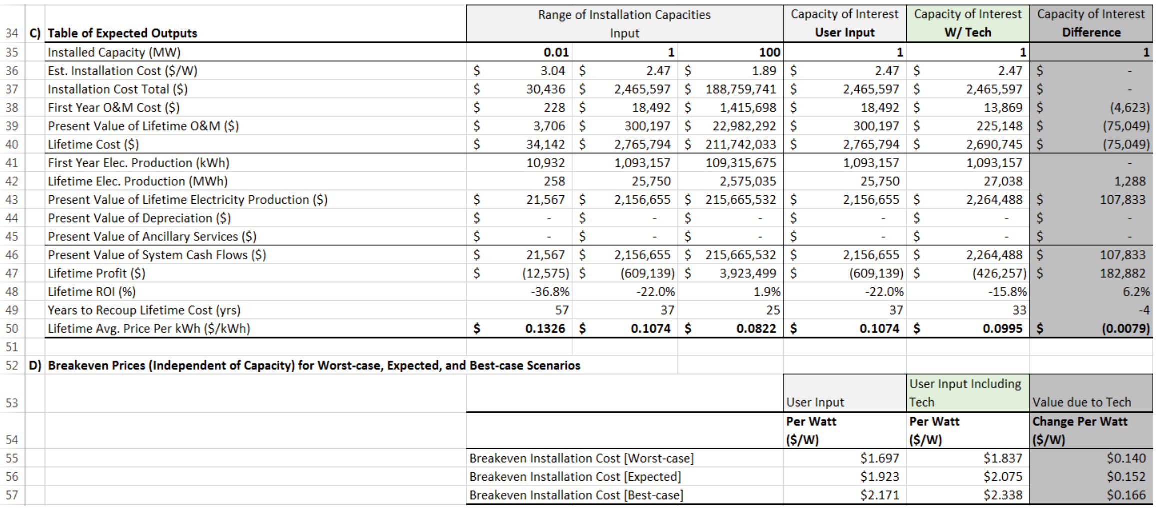
Figure 20 Solar calculator screenshot of section A used for model inputs.

Section B Display Assumptions shown in Figure 21 defines a few more parameters which predominately affect the results as seen in sections C and D of the spreadsheet. The final parameter related to auto update controls whether a VBA script runs which solves for the breakeven cost runs after any change to a yellow input cell. Auto update should only be disabled if the user wants to run a Monte Carlo analysis in order to save processing time and prevent unintended errors.



28	B)	**Display Assumptions**		
29		Solar Install Cost Average ($/W) (avg install size=0.034MW)	$ 2.89	$ 2.89
30		Solar Install Discount Per Order of Magnitude (%$/W Per OoM)	10.00%	10.00%
31		Installation Capacity of Interest (MW)	1	0.25
32		Disable auto update? (0=False, 1=True)	0	0

Figure 21 Solar calculator section B used for additional inputs predominantly related to display of results.



			Range of Installation Capacities Input			Capacity of Interest **User Input**	Capacity of Interest **W/ Tech**	Capacity of Interest **Difference**
34	C)	**Table of Expected Outputs**						
35		Installed Capacity (MW)	**0.01**	**1**	**100**	**1**	**1**	**1**
36		Est. Installation Cost ($/W)	$ 3.04	$ 2.47	$ 1.89	$ 2.47	$ 2.47	$ -
37		Installation Cost Total ($)	$ 30,436	$ 2,465,597	$ 188,759,741	$ 2,465,597	$ 2,465,597	$ -
38		First Year O&M Cost ($)	$ 228	$ 18,492	$ 1,415,698	$ 18,492	$ 13,869	$ (4,623)
39		Present Value of Lifetime O&M ($)	$ 3,706	$ 300,197	$ 22,982,292	$ 300,197	$ 225,148	$ (75,049)
40		Lifetime Cost ($)	$ 34,142	$ 2,765,794	$ 211,742,033	$ 2,765,794	$ 2,690,745	$ (75,049)
41		First Year Elec. Production (kWh)	10,932	1,093,157	109,315,675	1,093,157	1,093,157	-
42		Lifetime Elec. Production (MWh)	258	25,750	2,575,035	25,750	27,038	1,288
43		Present Value of Lifetime Electricity Production ($)	$ 21,567	$ 2,156,655	$ 215,665,532	$ 2,156,655	$ 2,264,488	$ 107,833
44		Present Value of Depreciation ($)	$ -	$ -	$ -	$ -	$ -	$ -
45		Present Value of Ancillary Services ($)	$ -	$ -	$ -	$ -	$ -	$ -
46		Present Value of System Cash Flows ($)	$ 21,567	$ 2,156,655	$ 215,665,532	$ 2,156,655	$ 2,264,488	$ 107,833
47		Lifetime Profit ($)	$ (12,575)	$ (609,139)	$ 3,923,499	$ (609,139)	$ (426,257)	$ 182,882
48		Lifetime ROI (%)	-36.8%	-22.0%	1.9%	-22.0%	-15.8%	6.2%
49		Years to Recoup Lifetime Cost (yrs)	57	37	25	37	33	-4
50		Lifetime Avg. Price Per kWh ($/kWh)	**$ 0.1326**	**$ 0.1074**	**$ 0.0822**	**$ 0.1074**	**$ 0.0995**	**$ (0.0079)**
51								
52	D)	**Breakeven Prices (Independent of Capacity) for Worst-case, Expected, and Best-case Scenarios**						
53						User Input	User Input Including Tech	Value due to Tech
54						**Per Watt ($/W)**	**Per Watt ($/W)**	**Change Per Watt ($/W)**
55			Breakeven Installation Cost [Worst-case]			$1.697	$1.837	$0.140
56			Breakeven Installation Cost [Expected]			$1.923	$2.075	$0.152
57			Breakeven Installation Cost [Best-case]			$2.171	$2.338	$0.166

Figure 22 Solar calculator sections C and D display outputs of the model inputs provided in sections A and B.

Sections C and D shown in Figure 22 display a variety of calculated values resulting from inputs in section B such as profit and return on investment. These are calculated using an estimated installation price which is modeled as having a logarithmic relationship with capacity. The default relationship of a 10% discount per order of magnitude was empirically estimated based on market prices for a range of installed capacities during 2014.

Section C contains the first set of model results. The first three columns show outputs for a range of installation sizes using the user input parameters for systems ranging from 10 kW up to 100 MW. This is intended to give users a sense for the economic effects of installation size.

The next three columns are based on the installation capacity of interest defined in section B. The user input column shows the results for exactly the user inputs at the capacity of interest. The next column, “W/ Tech,” includes changes due to the technological change defined by the user. The final column shows the difference attributable to the technological change. Descriptions of each output can be found just to the right of each row.

The breakeven price matrix, equivalent to the value of solar, shown in section D shows the price per watt at which the given solar installation (user input or user input including technology) would cost exactly as much as the expected cash flows to be gained over the system lifetime. A higher breakeven price indicates that the system will generate more value for the system owner over time. The last column in gray shows the change in breakeven price attributable to the technological change thus giving an indication of how valuable the technological change is.

The final section shown in Figure 23, E, graphs best-, worst-, and expected-case return on investment over a wide range of installed capacities clearly showing the benefit to the system owner of a lower installation cost per watt.

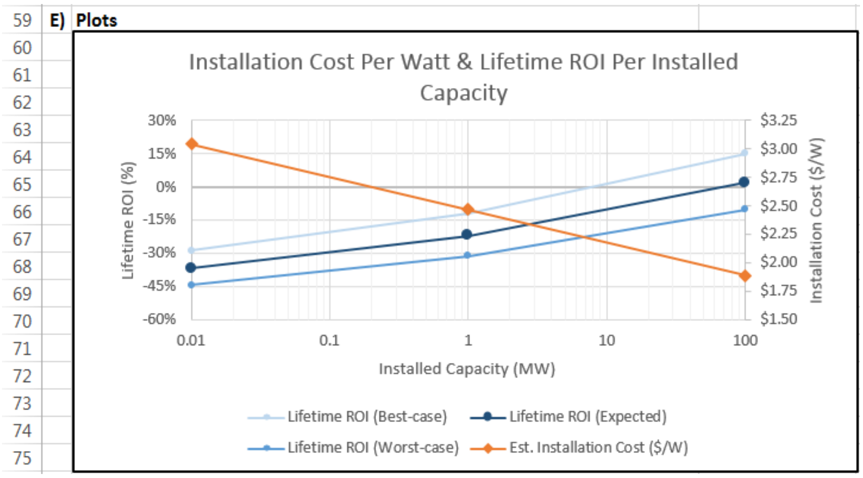


Figure 23 Solar calculator section E shows a plot of the estimated installation cost for a given capacity as well as the return on investment based on the value of solar and the estimated cost.

References

[1] U.S. Energy Information Administration, "Net generation by energy source: total (all sectors)," 2005-2015. [Online]. Available: https://www.eia.gov/electricity/monthly/epm_table_grapher.cfm?t=epmt_1_1. [Accessed December 2015].

[2] National Renewable Energy Labs, "PVWatts Calculator," [Online]. Available: http://pvwatts.nrel.gov/. [Accessed January 2016].

[3] National Renewable Energy Labs, "System Advisor Model (SAM)," [Online]. Available: http://sam.nrel.gov/. [Accessed January 2016].

[4] Solar Energy Industries Association, "Solar Market Insight Report 2013 Year in Review," 2014. [Online]. Available: http://www.seia.org/research-resources/solar-market-insight-report-2013-year-review.

[5] Solar Energy Industries Association, "Solar Market Insight Report 2014 Q4," 2015. [Online]. Available: http://www.seia.org/research-resources/solar-market-insight-report-2014-q4.

[6] Solar Energy Industries Association, "Solar Market Insight Report 2014 Year in Review Executive Summary," 2015. [Online]. Available: http://www.seia.org/sites/default/files/HOlFT6ym3i.pdf.

[7] SunPower, "SunPower limited product and power warranty for PV modules," July 2012. [Online]. Available: http://us.sunpower.com/sites/sunpower/files/media-library/warranties/wr-sunpower-limited-product-and-power-warranty-pv-modules.pdf.

[8] P. Nightingale, "Microinverters - A history and explanation," Solar Power Portal, October 2012. [Online]. Available: http://www.solarpowerportal.co.uk/guest_blog/microinverters_a_history_and_explanation_2356.

[9] SMA, "Basic residential systems," [Online]. Available: http://www.sma-uk.com/residential-systems/solar-system-basic.html. [Accessed January 2016].

[10] The Green Age, "How many solar panels can I fit on my roof?," July 2014. [Online]. Available: http://www.thegreenage.co.uk/how-many-solar-panels-can-i-fit-on-my-roof/.

[11] Cenergy Power, "String vs. central inverters: Choosing the right inverter for your solar system," January 2014. [Online]. Available: http://cenergypower.com/blog/string-vs-central-inverters-choosing-right-inverter/.

[12] R. Dana, "Solar modules: The future of PV panels?," Solar Tribune, November 2014. [Online]. Available: http://solartribune.com/ac-solar-panels/.

[13] United States Department of Energy, "Business energy investment tax credit," 2015. [Online]. Available: http://energy.gov/savings/business-energy-investment-tax-credit-itc.

[14] C. Honsberg and S. Bowden, "PVEducation.org," [Online]. Available: http://www.pveducation.org/pvcdrom/properties-of-sunlight/average-solar-radiation. [Accessed January 2016].

[15] National Renewable Energy Labs, "Changing system parameters," [Online]. Available: http://rredc.nrel.gov/solar/calculators/pvwatts/system.html. [Accessed October 2015].

[16] A. P. Dobos, "PVWatts version 5 manual," September 2014. [Online]. Available: www.nrel.gov/docs/fy14osti/62641.pdf.

[17] Oracle, "Oracle Crystal Ball product page," [Online]. Available: http://www.oracle.com/us/products/applications/crystalball/overview/index.html. [Accessed January 2016].

[18] Oracle Crystal Ball, "Running user-defined macros," [Online]. Available: https://docs.oracle.com/cd/e12825_01/epm.111/cb_user/frameset.htm?ch05s09.html. [Accessed January 2016].

[19] IRS, "A brief overview of depreciation," Internal Revenue Service, October 2015. [Online]. Available: https://www.irs.gov/businesses/small-businesses-&-self-employed/a-brief-overview-of-depreciation.

[20] T. Keating, A. Walker and K. Ardani, "SAPC best practices in PV operations and maintenance," National Renewable Energy Laboratory, 2015.

[21] National Renewable Energy Labs, "Distributed generation renewable energy estimate of costs," February 2016. [Online]. Available: http://www.nrel.gov/analysis/tech_lcoe_re_cost_est.html.

[22] J. Farrell, "Average size of U.S. solar installations: Small," Institute for Local Self-Reliance, July 2012. [Online]. Available: https://ilsr.org/average-size-u-s-solar-installations-small/.

[23] J. Mao-Jones, "Decision & risk analysis," Merrick Consultancy, 2012. [Online]. Available: http://www.merrick.com/merrickandcompany/media/resources/energy/whitepapers/merrick-decision-risk-analysis-white-paper.pdf?ext=.pdf.

[24] Oracle, "The crystal ball charts: Sensitivity," 2008. [Online]. Available: http://www.oracle.com/technetwork/middleware/crystalball/overview/sensitivity-chart-128074.pdf. [Accessed January 2016].

[25] Electric Power Research Institute, "Addressing solar photovoltaic operations and maintenance challenges: A survey of current knowledge and practices," 2010. [Online]. Available: http://www.epri.com/abstracts/pages/productabstract.aspx?productid=000000000001021496.

[26] D. C. Jordan and S. R. Kurtz, "Photovoltaic degradation - An analytical review," *Progress in Photovoltaics: Research and Applications,* June 2011.

[27] Renewable Energy Advisors, "What is LCOE?," 2016. [Online]. Available: http://www.renewable-energy-advisors.com/learn-more-2/levelized-cost-of-electricity/. [Accessed January 2016].

[28] A. Skoczek, T. Sample and E. D. Dunlop, "The results of performance measurements of field-aged crystalline silicon photovoltaic modules," *Progress in Photovoltaics: Research and Applications,* vol. 17, no. 4, pp. 227-240, 2009.

[29] Power Thru, "Lead acid battery working-lifetime study," [Online]. Available: http://www.power-thru.com/documents/the%20truth%20about%20batteries%20-%20POWERTHRU%20White%20Paper.pdf. [Accessed March 2016].

[30] Z. Shahan, "Solar panels creating electricity for much longer than 20 years," Clean Technica, December 2011. [Online]. Available: http://cleantechnica.com/2011/12/27/solar-panels-creating-electricity-for-much-longer-than-20-years/.

[31] L. Hirth, "The market value of solar power: Is PV cost-competitive?," *IET Renewable Power Generation,* 2014.

[32] S. Qin, S. T. Cady, A. D. Dominguez-Garcia and R. C. N. Pilawa-Podgurski, "A distributed approach to MPPT for PV sub-module differential power processing," *IEEE Trans. Power Electronics,* vol. 30, no. 4, pp. 2024-2040, 2015.

[33] S. Qin, C. Barth and R. C. N. Pilawa-Podgurski, "Enhancing microinverter energy capture with submodule differential power processing," *IEEE Transactions on Power Electronics,* vol. 31, no. 5, pp. 3575-3585, 2016.

[34] P. S. Shenoy, K. A. Kim, B. B. Johnson and P. T. Krein, "Differential power processing for increased energy production and reliability of photovoltaic systems," *IEEE Transactions on Power Electronics,* vol. 28, no. 6, pp. 2968-2979, 2013.

[35] P. Krein, R. Pilawa-Podgurski, A. Dominguez-Garcia, P. L. Chapman and J. Ehlmann, "The differential power processing architecture: Enhancing energy production, cost effectiveness, and reliability in photovoltaic energy systems," in *ARPA-E Energy Innovation Technology Showcase*, Washington, DC, 2015.

[36] International Finance Corporation, "Utility-scale solar photovoltaic power plants: A project developer's guide," 2015. [Online]. Available: http://www.ifc.org/wps/wcm/connect/topics_ext_content/ifc_external_corporate_site/ifc+sustainability/learning+and+adapting/knowledge+products/publications/publications_utility-scale+solar+photovoltaic+power+plantsJPERES.

[37] Z. Shahan, "World's cheapest solar power lands in Austin, Texas," Clean Technica, July 2015. [Online]. Available: http://cleantechnica.com/2015/07/02/worlds-cheapest-solar-power-lands-in-austin-texas-under-4%C2%A2kwh-sort-of/.

[38] M. Lave and J. Kleissl, "Optimum fixed orientations and benefits of tracking for capturing solar radiation in the continental United States," *Renew Energy,* no. 36, pp. 1145-1152, 2011.

[39] J. Galtieri and P. Krein, "Designing solar arrays to account for reduced performance from self-shading," in *Power and Energy Conference at Illinois*, Urbana-Champaign, IL, 2015.

[40] J. Galtieri and P. Krein, "Impact of differential power processing on inter-row shading in solar arrays," in *Control and Modeling for Power Electronics (COMPEL)*, Vancouver, BC, 2015.

[41] T. Esram and P. Chapman, "Comparison of photovoltaic array maximum power point tracking techniques," *IEEE Transactions on Power Electronics,* vol. 22, no. 2, pp. 439-449, 2007.