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A Photovoltaic System Payback Calculator

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Abstract

The Roof Asset Management Program (RAMP) is a DOE NNSA initiative to manage roof repairs and replacement at NNSA facilities. In some cases, installation of a photovoltaic system on new roofs may be possible and desired for financial reasons and to meet federal renewable energy goals. One method to quantify the financial benefits of PV systems is the payback period, or the length of time required for a PV system to generate energy value equivalent to the system's cost. Sandia Laboratories created a simple spreadsheet-based solar energy valuation tool for use by RAMP personnel to quickly evaluate the estimated payback period of prospective or installed photovoltaic systems.

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NOMENCLATURE

CdTe	cadmium telluride
DOE	Department of Energy
kW	kilowatt, a unit of power
kWh	kilowatt hour, a unit of energy
MWh	megawatt hour, a unit of energy
NNSA	National Nuclear Security Administration
PV	photovoltaic
RAMP	Roof Asset Management Plan
REC	Renewable Energy Credit
W	watt, a unit of power

1. INTRODUCTION

The Roof Asset Management Program (RAMP) is an initiative by the U.S. Department of Energy's (DOE) National Nuclear Security Administration (NNSA) to manage roofing repairs and replacements across several DOE NNSA sites. In some instances, it may be beneficial for RAMP to install a new photovoltaic (PV) system after replacing or repairing a roof to generate clean PV energy and offset energy purchases from a local utility and/or to meet renewable energy goals set by the U.S. federal government for governmental facilities (e.g. executive order 13693).

To aid the RAMP team in determining whether a PV system at a given site is economically feasible, personnel at Sandia National Laboratories developed a simple tool in Microsoft Excel. The tool determines the payback time of a PV system given the electrical energy generation of the system, the cost of the system, the system degradation rate, the cost of electricity at the site, the rate at which electricity costs are expected to increase, and the inflation rate. This tool is meant to provide a very simple estimate of the payback time and its goal is to be easy to use to quickly compare several "what-if" scenarios. More complex analyses should be undertaken prior to purchasing a PV system.

In section 1, we introduce the tool, show its operation, list the assumptions built into the tool, and present the underlying system of equations. In section 2, we present more detailed explanations of the inputs to the equations, and describe where to find more information. In section 3, we present a number of examples using possible PV systems at Sandia National Laboratories in Albuquerque, NM.

1.1. About the payback period tool

The PV system payback tool is a Microsoft Excel workbook. The workbook contains two worksheets titled "Data Entry" and "Calculations". All of the necessary inputs are entered on the Data Entry sheet; notes provided next to the input cells are intended as a guide to non-expert users to obtain useful estimates.

As shown in Figure 1, the cells which should be edited are highlighted blue. Calculated cells which should not be edited are highlighted red. The appropriate units are provided in parentheses next to the description of the input.

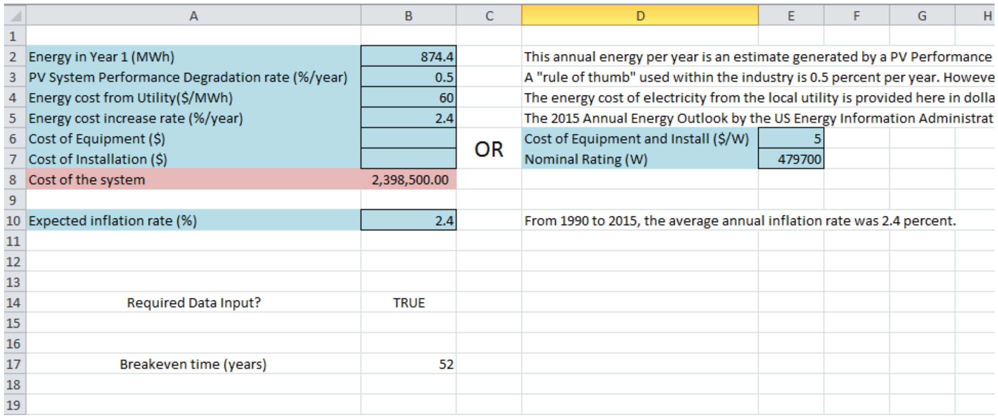

Figure 1. The Data Entry sheet

The cost of the PV system maybe calculated in two different ways. The first method requires entering the equipment and labor costs. These costs are then summed to determine the total system cost. The second method requires the input of the total cost of the system in “dollars per watt,” a common metric used in the industry to price PV systems, and the total rated power of the system in watts. If the second method is used, the product of the cost and size of the system is the total cost of the system. It should be noted that only one of the two methods should be used at a given time, if there are values entered into both methods, the tool will not calculate a payback time until only one method has data entered.

If all necessary inputs are provided (and no extra inputs are provided), the “Required Data Input” cell will say “TRUE” and a breakeven payback time will be calculated if the payback time is less than 100 years. If the payback time exceeds 100 years, the payback time will be listed as “>100 years”.

No modifications should be necessary to the Calculations sheet. This sheet provides the working calculations which the tool uses to estimate the payback period.

1.2. Assumptions Used by the Tool

It is important to list the assumptions used by the tool in its calculation of payback period in order to understand the limits of the tool. These assumptions are listed below. More complex assumptions can be used to more closely determine the payback period, but also require more complex calculations.

- The weather conditions which determine electricity production are the same from year to year. This means that a typical weather year should be used to estimate PV system energy production, such as the typical meteorological year (TMY) data set [1].
- The price of electricity does not vary with time of day.
- The rate at which the PV system performance degrades is constant, and replacement is not considered.
- The cost of electricity compounds at the same rate annually and does not change according to demand charges (i.e. electric utility rates are not set according to prior use characteristics).

- All of the cost of the PV system is incurred at installation, i.e. operations and maintenance are not included and financing is not considered
- The value of currency decreases annually at the inflation rate.
- The value of any renewable energy credits (RECs) have not been included.
- No incentives, rebates, or tax credits have been considered. Such incentives may be allowed or disallowed on federally owned buildings, and could change depending on the ownership structure for the PV system.

While the tool is quite simple, it captures the main value components for PV systems deployed at NNSA sites, namely the cost savings of reduced energy purchase from the local utility. The tool may be extended to include more complex assumptions that better reflect the nuances in effect at any given NNSA site.

1.3. Underlying Equations

The underlying set of equations can be implemented in any software. If desired, these equations can be modified to include more sophisticated assumptions or other variables not included here.

For these equations
t = the time, in years
D = degradation rate of the PV system in percent per year
R = the rate increase in electricity costs in percent per year
P = the initial cost of the PV system upon installation in $
I = the inflation rate of the US dollar in percent per year
E_t = electrical energy generated by the system in year t in megawatt hours (MWh)
C_t = the cost of the electrical energy which is offset by the PV system in year t, in $
V_t = the value of the electrical energy which is offset by the PV system in year t, in $. This is different than the cost, C_t, since the cost is in nominal year 1 dollars while the value is adjusted for inflation where, in general, future dollars are worth less than present dollars.

The electrical energy generated is a function of the weather, specifically the irradiance, a PV modeling tool (see Section 2.1.) estimates the amount of energy generated in year 1, E_1. The energy generated in subsequent years must be reduced due to system degradation as follows:

$$E_t = E_1 \cdot \left[1 - \frac{D}{100} \cdot (t - 1)\right] \tag{1}$$

The cost (amount paid to the utility provider) of electricity that is offset by PV production for any year may then be calculated as follows:

$$C_t = \left[C_1 \cdot \left(1 + \frac{R}{100}\right)^{t-1}\right] \cdot E_t \tag{2}$$

The value of the offset energy, however, may change depending on the rate of inflation. The value of the energy in year t may be calculated as follows:

$$V_t = {C_t}\Big/\left[\left(1 + \frac{I}{100}\right)^{t-1}\right] \tag{3}$$

Once the value of the energy offset in each year, V_t, is determined, the payback period can be calculated by determining the amount of time required for the *cumulative value* of the energy to exceed the initial cost of the PV system. That is, the payback year is the lowest value of n that satisfies equation (4).

$$\sum_{t=1}^{n} V_t \geq P \tag{4}$$

2. INPUT DATA DETAILS

The input variables for calculation of the payback time for a PV system can be confusing for non-expert users. This section provides additional detail about each of the possible input data fields. Within this section each input variable will be classified as either positively correlated to the payback period, indicating that increasing the input variable will increase the payback period (e.g. higher cost); or inversely correlated to the payback period, indicating that increasing the input variable will decrease the payback period.

2.1. Performance of the PV System

The performance of the PV system is an estimation of how much electrical energy the PV system will generate in each year. The electrical energy generation of a PV system is usually measured in megawatt hours (MWh). PV system performance for a given PV system is affected primarily by the amount of solar radiation available to the PV modules over time, and to a lesser extent by temperature and solar spectra. These three primary inputs to a PV system are affected by many other factors such as soiling level, mounting configuration, wind speed, time of day, location, and many others. For a more in-depth primer of PV modeling, the PV Performance Modeling Collaborative (PVPMC) [2] should be consulted.

Determining the expected performance of a PV system is quite complicated due to the large number of inputs and their varying effects on different PV systems. Software programs such as PVSYST [3], System Advisor Model (SAM) [4], PVWATTS [5], and Helioscope [6] among others are available to model PV system performance with varying degrees of detail. Some of these programs are easy for novice users (e.g. PVWATTS) while others are more complex and may require more in-depth knowledge about PV system design and operation.

A PV system installation contractor *should* be familiar with these modeling tools and could provide an estimate of the annual energy generation for any proposed PV system. However, installation contractors may provide a "warranted" energy production which is typically much lower than the expected energy generation due to annual variations in weather. For this economic analysis it is very important to use the expected production and not the warranted production.

Ultimately, the tool requires the expected annual production in the first year of operation in MWh. Some conversions may be necessary if the modeling software presents the energy generation in units other than MWh. For reference, 1 MWh = 1,000 kWh = 1,000,000 Wh.

The PV system performance is inversely correlated to the payback period. This is obvious since one would expect that a higher performance rate (more energy) requires fewer years before the PV system produces energy value in excess of its initial cost.

2.2. PV System Performance Degradation

The photovoltaic materials in PV modules typically degrade as the modules are exposed to sunlight. There are many mechanisms for this degradation, but the net effect is usually the same: a reduction in the energy generated by the PV modules. The PV degradation is usually expressed as a percentage reduction per year. Typically, degradation rates are assumed to be 0.5 percent per year. However, measured degradation rates and the degradation of any particular system may be something other than 0.5 percent per year, but empirical data shows that 0.5 percent per year is a good median value. See [7] for more information. Thus, for most calculations, a degradation rate of 0.5 percent per year is probably acceptable.

The PV system performance degradation rate is positively correlated with the payback period, indicating that a PV system with a higher degradation rate (degrades faster) will produce less energy over time and will extend the time required for the electrical energy value to exceed the installation cost.

2.3. Energy Cost from the Utility

The primary financial benefit of a PV system comes from producing electrical energy which offsets electrical energy that would normally be purchased from a local electric utility. As noted earlier, the reasons for installing a PV system may include motivations other than financial benefits, but this tool only assesses the financial value of a PV system.

Electrical energy is purchased from the local utility at a cost per unit energy. Other cost elements such as demand charges are not considered. The tool requires the input energy cost to be in units of dollars per megawatt hour, $/MWh. Users may be more familiar with prices in cents per kilowatt hour, ¢/kWh; the conversion is 1 ¢/kWh = 10 $/MWh.

It is important to input the actual cost of electricity paid by the organization which will have its electricity offset by the PV system. Residential and commercial utility rates may vary greatly, for example in Albuquerque the residential rate is approximately 10 ¢/kWh (100 $/MWh), while the rate for Sandia National Laboratories is approximately 6 ¢/kWh (60 $/MWh). The cost of the electricity is highly location-dependent, we therefore do not recommend a “typical” value for this variable; rather, it should be determined on a site by site basis.

Aspects such as demand charges, where a utility charges a rate or fee based upon a customer’s highest consumption period, or time of use rates, where a utility charges a different rate based on time of day, are currently not considered in the tool. If demand charges and time of use rates are in effect for a particular site, the long-term average cost of electricity to the site should be input into the tool. Furthermore, the tool assumes that net metering is in effect and the value of energy generated by PV at the site is equivalent to the value of energy which would have otherwise been purchased from the utility.

The cost of electricity from a utility is inversely correlated with the payback time. As the cost of the energy offset by the PV system increases, the shorter the payback period will be.

2.4. Increase in Energy Cost per Year

The cost of energy may not remain fixed from year to year, the rate at which the utility energy costs change must be provided to the tool as the year-over-year percent change in costs. A positive value indicates that energy prices are increasing, and a negative value indicates that energy prices are decreasing. The change in energy costs may be location dependent, and we suggest that, if possible, values be based on historical trends. However, in the event that it is not possible to determine the change in energy cost per year, the US Energy Information Administration's 2015 Annual Energy Outlook [8, table A8] provides a value (in nominal dollars) of 2.4 percent per year that can be used as a typical value. It is important to use the cost increase of energy in nominal dollars (rather than inflation-adjusted dollars) as we consider inflation separately.

The change in cost for utility energy is inversely correlated with payback time.

2.5. Initial Cost of the PV System

PV system initial costs may include costs of PV modules, inverters, wiring, disconnect switches, combiner boxes, racking, design costs, interconnect fees, and installation labor costs, among others. This total cost of installation can be entered into the tool in one of two ways, either by 1) the cost of the system per rated watt ($/W) and a desired system size or 2) by the total cost of the system.

Frequently, a PV system contractor will provide a system price in terms of dollars per watt, $/W. The total cost of the system can then be determined by multiplying the cost per watt by the size of the system. For example, if the cost is $5/W for a 10 kilowatt system, then the total cost is $50,000.

While $/W is a common way to express the cost of a system, it is not a detailed cost breakdown. When the system size is increased while estimating the system cost with a $/W metric, the cost increases linearly. However, the energy generation of such a system will probably increase nearly linearly as well. For these reasons, when using a $/W cost basis, changes in the system size (and by extension the cost) do not greatly change the payback time unless a change in system size also changes the $/W cost basis.

In cases where the materials and labor costs are known, the total cost is the sum of the material costs (modules, inverters, etc.) and labor costs (installation, fees, design, permitting, etc.). In order to receive a detailed cost breakdown for a PV installation project, the project will most likely be nearly completely designed with little opportunity to make design changes.

The total cost or cost per watt are positively correlated with the payback period.

2.6. Inflation Rate of Currency

The tool assumes that the cost of the PV system is incurred at the system's installation; however, PV systems generate energy well into the future. Due to inflation, the present value of future dollars is lower than present dollars. Thus, assuming the electricity cost remains the same, the value of the energy generated in the future is lower than the value of the same amount of energy generated in the present. This reduction in future value causes a longer payback period, thus the inflation rate and the payback period are positively correlated.

It is difficult to predict future inflation rates, but the user may want to use the average annual inflation rate from 1990 to 2015, which was 2.4 percent [9].

3. CASE STUDIES

In order to show how to operate the PV system payback tool, we provide in this section a small example set based on roofs at the Sandia National Laboratories campus in Albuquerque, NM. For these examples we have chosen two buildings at Sandia National Laboratories, building 880 and 890, which will soon need to be re-roofed.

Unless otherwise specified, we use the electricity cost of $60 per MWh of energy, an energy cost escalation of 2.4 % per year, an inflation rate of 2.4 % per year, and a PV degradation rate of 0.5 % per year. All systems in these examples are tilted from horizontal with the direction of tilt toward the south. Two PV module technologies were considered: a thin-film module (FirstSolar) and crystalline silicon modules (SunPower).

Initial costs of the PV systems are estimates. While most of the other factors (energy costs, system performance, etc.) are close to the values which may be expected at the SNL-Albuquerque site, system pricing may be considerably different than the estimates we have made, depending on the design and other factors. For this reason, these analyses should not be used to determine the suitability of SNL in Albuquerque as a potential site for PV systems.

While reading this section, we suggest that the reader use the PV system payback tool to follow the examples in order to more fully understand how to use the tool.

The system performance estimations for this section are obtained for two different tools, Helioscope by Folsom Labs; and PVWatts, a free tool provided by the National Renewable Energy Lab (NREL). These two tools span a range of user profiles. Helioscope is a detailed tool designed for users with experience in designing and modeling PV systems; a detailed model simulation may take hours to create. PVWatts is a simple tool designed for inexperienced users to get a rough idea of a PV system's expected performance. A PVWatts simulation requires very few inputs and results can usually be obtained in just a few minutes. For all PVWatts simulations for First Solar PV modules, the "Thin Film" option for PVWatts was selected. For PVWatts simulations for SunPower modules the "Premium" module type was selected. In both cases for PVWatts, the default system loss of 14% was used.

The two PV performance tools provide results that are slightly different due to variations in the PV modeling algorithms and assumptions within each tool. For example, the tools may use different performance parameters for their PV modules or inverters or may model the sunlight into the plane of the PV modules differently. Typically, the more advanced performance models allow the user to more carefully control the algorithms and more accurately predict system performance, but the knowledge of which algorithms to use is a specialized field that requires significant expertise.

Example reports from the Helioscope modeling software will be provided as PDF attachments to this report.

3.1. Building 880

Building 880 is a large building with a membrane roof. The roof has four equipment rooms which rise above the main level. Building 880 would be a good site for a larger commercial-scale PV system installation of perhaps several hundred kilowatts (kW).

3.1.1. High Performance Silicon-based PV with 10 Degree Tilt

The first PV system example on Building 880 is based on a high-performance crystalline silicon module with a low tilt angle. The low tilt angle allows for low wind loading and consequently less ballast (weight) for systems which are simply weighted to the roof, which removes the need to penetrate the roof for structural support. However, the low tilt angle is not optimal for energy generation.

The selected PV system would utilize 363.6 kW of SunPower PV modules. These high performance crystalline PV modules will maximize the amount of power (and energy) per unit of roof area, but generally come at a premium price. For this example, the estimated initial cost is $3/W, for a total system price of $1.09 million.

The Helioscope modeling tool, using TMY3 weather data, estimates that this PV system will generate 665.8 MWh of electricity in the first year. When all of the aforementioned variables are entered into the spreadsheet tool, we obtain a payback time of approximately 30 years.

If we use the PVWatts modeling tool for 363.6 kW of "Premium" PV modules, PVWatts estimates that a similar system would produce 606.6 MWh of electricity in the first year, with a resulting payback of approximately 33 years.

3.1.2. High Performance Silicon-based PV with 30 Degree Tilt

In order to show the effect of tilt angle on a PV system, we have modeled a system similar to the one in section 3.1.1. with a 30 degree tilt from horizontal rather than a 10 degree tilt from horizontal. The additional tilt will cause longer shadows from each row of PV modules, and we have thus spaced each of the rows further apart to avoid shading. This increased row spacing reduces the overall power rating of the system, but each PV module will generate more energy annually.

The increased row spacing means that this system will only be 270 kW of PV modules. The increased tilt angle will increase wind loading and subsequent racking costs, thus we estimate the cost to be slightly higher than before at $3.2/W. Thus the resultant total cost of the system is $864,000

The Helioscope modeling tool estimates that the system's annual energy generation will be 525.3 MWh. Once all of these factors are entered into the payback period tool, we find an estimated payback period of 30 years. Thus, it seems that the increased cost per watt of PV was offset by the increased energy generation of each watt of PV and we arrive with a similar payback period.

The PVWatts modeling tool estimates 485.1 MWh of energy generation in the first year, with a resultant payback of 33 years.

3.1.3. Thin-film Cadmium Telluride PV with 10 Degree Tilt

For comparison, we have provided an example from a lower-cost thin-film PV technology. Note that the term "thin-film" does not imply a form factor for a PV module, that is, a thin-film module is structurally similar to a crystalline module.

In these particular examples, we have selected a thin-film module with a rigid construction and Cadmium Telluride (CdTe) chemistry from First Solar. The thin-film modules generally have a lower efficiency per unit of area, but also generally cost less than crystalline silicon PV systems.

The 10 degree tilt is the same as in the example in section 3.1.1. This example uses the same footprint as example 3.1.1, but due to the lower efficiency of the PV modules the rated power of the system is 248.5 kW. If we assume the installed system cost to be $2.7/W, the total system cost is $671,000.

In this example, the Helioscope models estimate that the annual energy production is 460.2 MWh, which provides a payback period of 26 years.

The PVWatts calculator with the module type selected as "thin-film" generates an estimated energy of 420 MWh. These results calculate a payback period of 29 years.

3.2. Building 890

Building 890 is a smaller building with a two-level membrane roof. The roof has a single equipment room near the center of the roof which rises above both levels. Due to the equipment on the roof, the available area for a PV system is relatively small, and building 890 would be a good site for a smaller PV system installation of less than 50 kW.

3.2.1. High Performance Silicon-based PV with 30 Degree Tilt

Similar to the example in section 3.1.2, the first example for building 890 is a high performance crystalline PV system with modules from SunPower at a 30 degree tilt from the horizontal. Building 890 only has space for two rows of these modules, and thus only 21.6 kW of PV are available for placement. If we assume a slight price premium for a smaller PV system (compared to example 3.1.2) of $3.4/W, then the total system cost is $73,400.

The Helioscope modeling tool estimates the first year energy production to be 43.12 MWh. When provided with the cost assumption and the energy estimate, the payback tool determines an approximate payback period of 31 years.

The PVWatts modeling tool estimates the first year energy production to be 38.81 MWh, with which the PV system payback tool estimates a payback period of 35 years.

3.2.2. Thin-film Cadmium Telluride PV with 30 Degree Tilt

This example for building 890 is a lower efficiency thin-film CdTe PV system with First Solar modules. As with the example provided in section 3.2.1, the modules are tilted 30 degrees from horizontal. Using the same footprint as in the example for section 3.2.1, the CdTe modules can create a PV system of 13.2 kW. Since the CdTe PV modules are less expensive than the high performance silicon modules, we assume an installed cost of $3.1/W. Thus the total system cost is $41,000.

The Helioscope modeling tool estimates the energy production of the first year to be 27.03 MWh. The PV system payback tool then estimates a payback time of 27 years.

If PVWatts is used to estimate the energy production for a similar sized thin film system, it estimates 24.05 MWh of energy per year, which results in a payback period of 31 years.

4. CONCLUSIONS

Sandia National Laboratories has developed a tool for determining the simple payback period of a PV system when given system cost, system annual energy production, inflation rate, system degradation rate, utility energy cost, and expected utility energy cost escalation rate. The tool is created within an Excel workbook with a data entry sheet and a calculations sheet. The tool can be used to approximate the payback period under the given set of assumptions. It is designed to provide a quick "what-if" estimation, and we suggest using a more robust tool with sophisticated assumptions prior to selecting and installing a system.

The underlying equations which are implemented by the tool to determine the payback time are presented and may be implemented in any computer package or program. Likewise, the equations may be expanded to include more complex assumptions and additional input factors.

Each of the input factors; PV system performance, PV system degradation, utility energy cost, energy cost increase, installation cost of the PV system, and the inflation rate are described and typical values are provided for those factors which do not vary greatly from PV system to PV system.

Finally, we have provided a set of examples for a pair of buildings on the Sandia National Laboratories campus in Albuquerque, NM. Building 880 and 890 were selected as a pair of buildings in need of new roofs and which might also be suitable for PV systems. A number of systems were modeled on each roof including PV systems including modules made of high performance silicon and inexpensive cadmium telluride, PV systems with varying angles of tilt from the horizontal, and various PV system sizes. In each example, the performance modeling was performed by the Folsom Labs Helioscope tool to show a more robust modeling tool and the much simpler to use PVWatts modeling tool.

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