Design and return on investment analysis of residential solar photovoltaic systems

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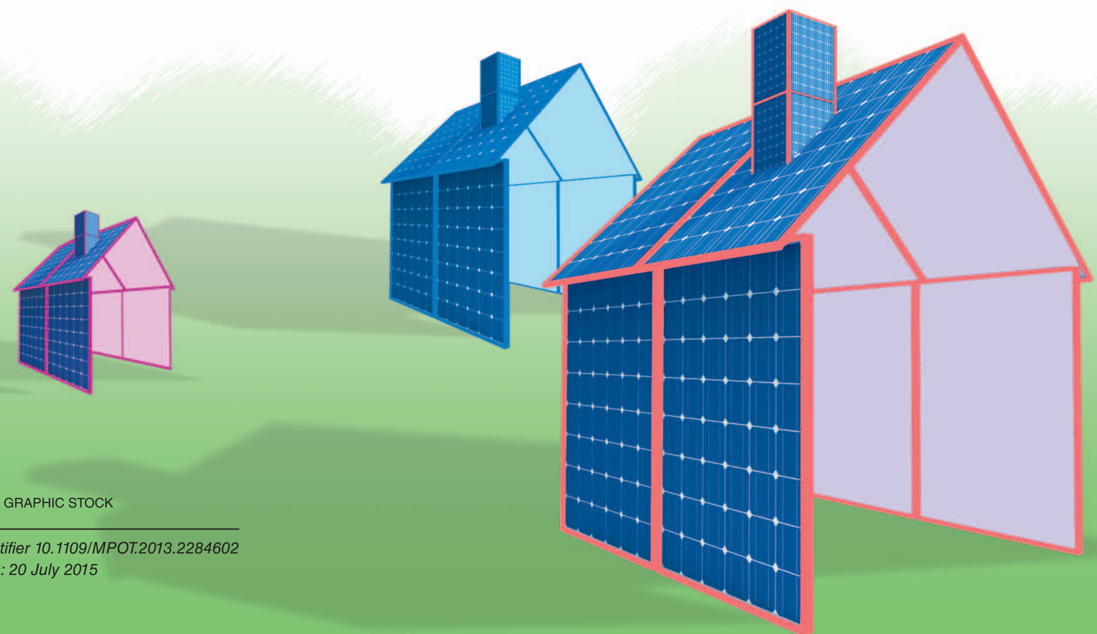
Due to the increasing cost effectiveness of solar panels, the growing demand for renewable energy sources, and the U.S. government's financial support, the adoption of solar energy has soared in the past few years. According to the *PV Market Report*, presented by the European Photovoltaic Industry Association, the cumulative installed capacity of photovoltic (PV) systems around the world rose from 4.07 GW in 2010 to 10.12 GW in 2012. As shown in this report, Europe remains the predominant leader in the global PV power market and possesses a 75% share of new installations. The report also illustrates that in the United States approximately 1.8 GW of PV systems were installed, yielding a cumulative total of 214,000 operating systems in 2011. The significant growth of solar PV installation was highly enhanced by federal energy incentives and utility rebate programs that reduced the cost of PV systems. In particular, the high average sunshine hours in California correlate to significant statewide installations of grid-tied solar PV systems.

Certainly, the key component of a PV system is the solar panel, which represents more than 50% of the overall cost of the PV system. A



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price history provided by IMS Research shows that the prices of solar module (US$/W) have dropped more than 55% from 2009 to 2012, due to increased competition and new manufacturing techniques. Moreover, the maximum power point tracking (MPPT) control strategy applied on PV inverters greatly increased the efficiency of PV system output.

As of 2011, the total capacity of PV systems reached over 67.4 GW. Consequently, PV power has become the third most important renewable energy generation technique after hydropower (970 GW) and wind generation schemes (238 GW).

The majority of solar PV projects completed thus far have been installed by licensed contractors. Moreover, O'Flaherty et. al reported that the feed-in-tariff (FIT) scheme reduces the payback period from 67 years (without FIT) to 16 years, thus improving the return on investment (ROI) of residential PV systems. However, this report did not include the scenario in which the PV system was installed by customers themselves. Furthermore, Monte Carlo simulation performed by the North Carolina Sustainable Energy Association showed that installation site preparation, electrical labor, and hardware labor contributed to more than 40% of the installed system price. Therefore, further research on the total investment difference between contractor-installed systems and do-it-yourself (DIY) systems are warranted.

Furthermore, research has indicated that most PV DIY projects did not provide detailed solutions on PV system output optimization, site analysis, and roof space evaluation. Therefore, to illustrate the economics of solar energy utilization and the possibility of system installation by customers, we will present a computer-aided design process for a residential solar PV system. An ROI report is provided to demonstrate the positive economic performance of the DIY system installation.

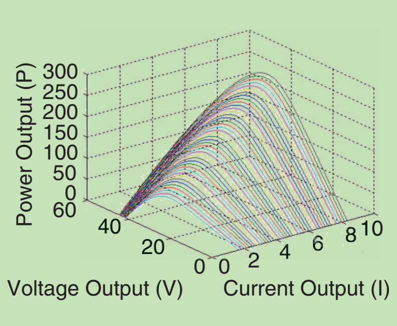

FIG1 Characteristics of the Suntech STP280-24/Vd solar panel.

Standards compliance and approval requirements

To interconnect a residential PV system to the utility grid in the state of Florida, detailed documentation of the system must be produced. At minimum, this documentation must include system specifications, parts lists, electrical schematics, mechanical drawings, and instructions for the installation, operation, and maintenance of the system. The supplied documentation is reviewed to verify that the following items are included:

1) system description and specifications (mechanical parts)
2) data sheets for all major components (modules, inverters, etc. Components should be in compliance with UL 1741 and IEEE 929 standards)
3) complete electrical schematics [electrical parts should satisfy the requirements of National Electrical Code (NEC) 90]
4) warranty information on the components and complete system
5) owners' manuals for individual major components
6) system installation and checkout procedures
7) system operation, maintenance, and troubleshooting instructions.

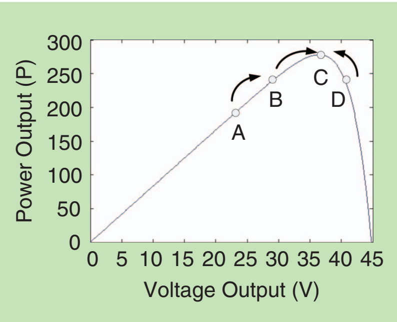

FIG2 The basic concept of the MPPT.

Choosing the key components

The PV system components (including inverters, PV panels, mounting systems, and cables) are available from a wide number of manufacturers.

PV panel

The PV panel is at the heart of a solar system, since it converts solar power to electrical energy. The PV array consists of solar panels wired together. Considering the price and efficiency of solar panels as well as the extreme temperatures in central Florida, we decided to design the PV system with Suntech's STP280-24/Vd solar panels. A simulation based on parameters in the data sheet shows the electrical characteristics of the Suntech STP280-24/Vd solar panel in Fig. 1.

PV grid-tied inverter with MPPT

Grid-tied inverters are used to convert dc produced by a PV system into the ac that is transmitted to the utility grid. A MPPT controller is used to track the continuously changing MPP of a PV array. In Fig. 2, if the power generated from the PV system increases, the voltage increases, and the system's operating point (point A) will move toward the MPP (point C). Simultaneously, to maintain the direction of the operating point, the inverter system should keep perturbing the system voltage. On the other hand, if the power drawn from the PV system decreases when the voltage increases (from point C to D), the system's operating point will move away from MPP. Consequently, the direction of system voltage perturbation by inverter system will be reversed.

Mounting system

The mounting system size is determined by the PV system's installation site. Further discussion about site analysis will be presented through a three-dimensioanl (3-D) model simulation in the next section.

PV system design

Array sizing and wiring

The amount of solar radiation incident on the solar panel is the most important parameter which affects performance of the PV system. The position and angle of a PV panel are the key factors for PV system design. Typically, PV systems installed with solar panel tracking systems have a higher performance than PV systems that have a fixed tilt angle. However, pitched-roof houses in most areas of Florida can only accommodate PV panels with a fixed tilt angle. Therefore, to maximize the system performance, a simulation was conducted to optimize the PV panel's number and the array's orientation.

Fortunately, Sketchup, developed by Google, enables amateur PV system designers' to perform simulations. Sketchup is a free three-dimensional (3-D) modeling tool featuring ease of use without input coordinates. Instead of a hiring a contractor to design the PV array layouts, Sketchup can facilitate panoramic views of the PV system for customers. In Fig. 3, a 3-D model of the target house is built based on aerial photographs from Google Maps. Further simulations in this article will be conducted using this initial Sketchup 3-D model.

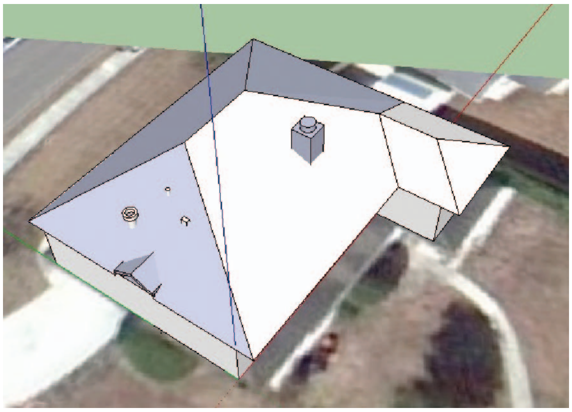

FIG3 A 3-D model for a typical Florida pitched-roof house.

The PV system scale and the number of panels were first determined through an examination of a volunteer's electric bill. For a typical pitched roof house shown in Fig. 3, the energy usage in a billing circle can be around 900 kWh. Assuming that the energy drawn from the PV system can satisfy the house appliances' power consumption, the PV system output calculation can be written as follows:

The average power required for the house is

$$P_{\text{avg\_required}} = \frac{900\text{kWh}}{\text{month}} \times \frac{\text{month}}{\text{average hours a month}} = \frac{900}{\text{month}} \times \frac{\text{month}}{730.48} = 1.232\ \text{kW}.$$

Since the peak sun hours represent the number of hours per day where solar insolation equals 1,000 W/m^2 is 5 [15], the average solar insolation can be shown as:

$$P_{\text{avg\_insolation}} = 5h \times 1000\ \text{watts}/\text{m}^2 \times \text{day} = 5\ \text{kWh}/\text{m}^2 \times \text{day}.$$

Therefore, the average panel power can be represented as

$$P_{\text{avg\_panel}} = P_{\text{avg\_insolation}} \times \frac{\text{day}}{24\ \text{hours}} \times D \times \eta_{\text{panel}} \times \eta_{\text{inverter}},$$

where D represents the dimension of the panel, η_{panel} denotes the panel efficiency, and η_{inverter} is the efficiency of the inverter. Thus, we have:

$$P_{\text{avg\_panel}} = 5\ \frac{\text{kWh}}{\text{m}^2 \times \text{day}} \times \frac{\text{day}}{24\ \text{hours}} \times \frac{1.956\ \text{m} \times 0.992\ \text{m}}{\text{panel}} \times 14.4\% \times 95.5\% = 0.056\ \text{kW/panel}.$$

The number of panels can be calculated as:

$$N = \frac{P_{\text{avg\_required}}}{P_{\text{avg\_panel}}} = \frac{1.232\ \text{kW}}{0.056\ \text{kW/panel}} = 23\ \text{panels}.$$

The SMA's Sunny Design software provides a thorough performance report for Suntech 280 W solar panels, and it details that there would be other energy loss from the dc site to the ac site, electric power generated in the dc site needs to be higher than the expected rated power. Therefore, 24 solar panels will be installed and the rated system output is

$$P_{\text{rated}} = 24 \times 280\ w = 6.7\ \text{kW}.$$

Thus, a PV system with 6.7-kW rated power output can satisfy the power consumption in this house. Based on National Electrical Code (NEC 90), the electric schematic is presented in Fig. 4, which specifically shows the 24 panels wired in two strings.

Site analysis

The tilt and azimuth angle of a PV panel are key factors that highly affect the solar radiance levels and eventually determine the electric energy output. To maximize the energy drawn from PV panels, we should understand the sun's positions relative to the site location. A climate report provided by the Florida Solar Energy Center illustrates the optimum orientation for solar panels. In Fig. 5, we can see that the best azimuth angle for PV arrays is facing south.

In a study performed by Asowata, it was reported that the azimuth angle is the angle clockwise from true north that the PV array faces, while the tilt angle is the angle from horizontal of the inclination of the PV array (horizontal $= 0^o$ vertical $= 90^o$). Some computer programs use default azimuth angle value (south facing) for houses in the northern hemisphere. In Fig. 6, there are three areas facing southeast (SE), northeast (NE), and northwest (NW) that we can install the PV panels. Through Google Maps street view, it can be seen that the area facing southwest is not available due to the existing pipes and chimney. To maximize the PV arrays' electric output, we should arrange the solar panels layout in these three highlighted areas (SE, NW, and NE).

The PV array on the SE area is shown in Fig. 7. Its tilt angle is fixed is and the azimuth angle for the array is 117.8°. The annual PV system output can be calculated using PV Watt calculator. Likewise, if we arrange the PV array with same number of solar panels on the NE area shown in Fig. 8, the system output

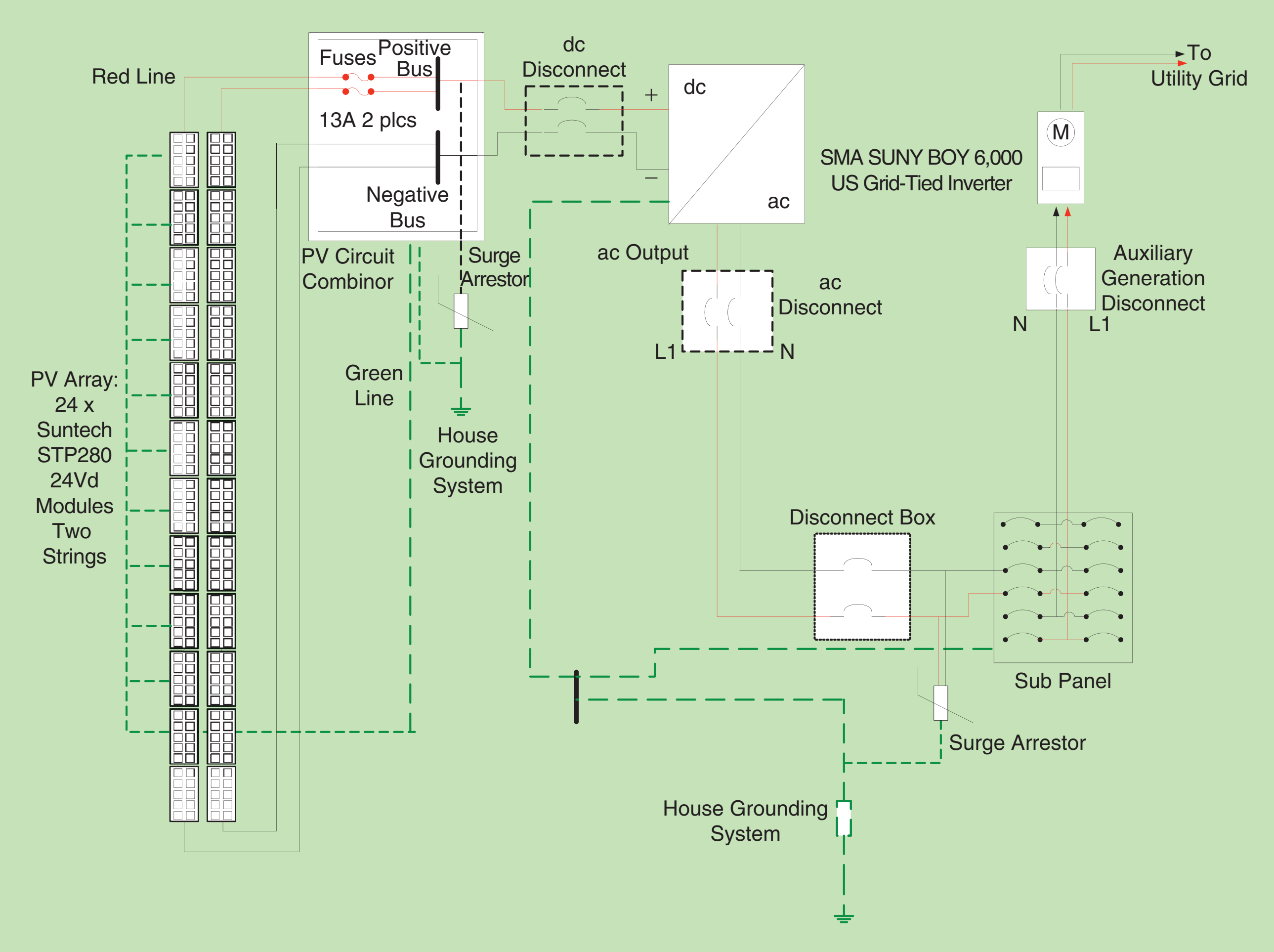

FIG4 The electrical schematic for a grid-tied PV system.

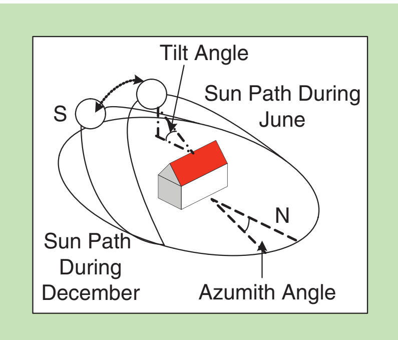

FIG5 A sun path for Florida.

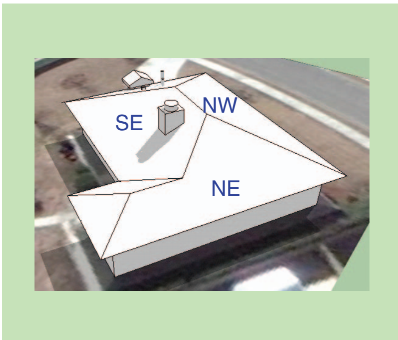

FIG6 Three roof areas for a PV array.

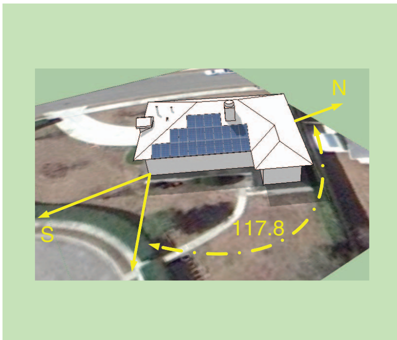

FIG7 The azimuth angle for PV arrays.

can also be obtained. Figure 9 and Table 1 illustrate the power energy drawn from PV arrays on different roof areas.

Moreover, the Sketchup simulation shown in Fig. 8 demonstrates that the number of solar panels that can be installed on the NE area is fewer than the number of panels possible on the SE area. The possible variations of array configurations (due to the available roof surface area) should be considered along with the corresponding PV watt output computations. In our case, comparing the total amount of PV system output per configuration, the SE area would be the best choice for the PV system installation.

ROI

ROI is an economic performance measure for evaluating the efficiency of an investment. Certainly, an investment with a high ROI will be more attractive. In this section, a ROI report is developed to illustrate the advantages of investing in solar PV systems and to compare the ROI between PV systems installed by customers versus those installed by licensed contractors. The formulas for calculating ROI can be simplified as

$$\mathrm{ROI} = \frac{\text{Net profit}}{\text{Total Investment}}.$$

Since the estimated payback periods are fewer than ten years, we would not consider the effect of inflation. Also, we assume that the annual electric output of PV system and the incentives policies do not change.

Cost of the solar PV system

The rough price for the whole system is illustrated in Table 2.

The total expenditure of the PV system $C = \text{US\$}12,717.52$.

The electricity consumption of the aforementioned residence is assumed to be 900 kWh per month. As stated in the Gainesville Regional Utilities (GRU) residential electricity bill calculation methods, the retail price is US$0.115/kWh, which consists of the electric retail price and electric fuel adjustment. Supposing that the solar PV system has started to generate electricity and all of the power drawn from the PV system is consumed by the customer, the annual net profit can be represented as

$$\text{Net profit} = P \times (r + w) + \text{Tax} - C_{OM},$$

where P is the system's total annual output that equals 8,628 kWh, r is the electric retail price, and w is the electric fuel adjustment. $r + w = 0.064 + 0.051 = \text{US\$}0.115/\text{kWh}$. C_{OM} represents the cost of operation and maintenance, which equals $6.72\text{kW} \times \text{US\$}25/\text{kW}-\text{yr} = \text{US\$}168/\text{yr}$. The tax calculation is shown as follows.

There are two taxes that would be charged on electricity bills when residents are living inside the city of Gainesville. The Florida Gross Receipts Tax, represented as Tax1, is the tax on GRU's nontax revenue received for electric energy, which is 2.5%.

$$\begin{aligned} \text{Tax1} &= [P \times (r + w) \times 2.5\%] \\ &= 8,628 \times 0.115 \times 0.025 \\ &= \text{US\$}24.8. \end{aligned}$$

In addition, the Gainesville Electric Utility Tax Electric Surcharge, represented as Tax2, will charge the sum of the electricity charge and the Florida Gross Receipts at the rate of 10%.

$$\begin{aligned} \text{Tax1} &= [P \times r + \text{Tax1}] \times 0.1 \\ &= [8,628 \times 0.064 + 24.8] \times 0.1 \\ &= \text{US\$}57.7. \end{aligned}$$

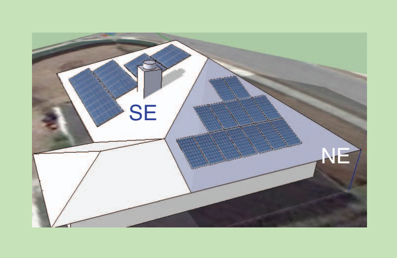

FIG8 PV arrays on both areas SE and NE.

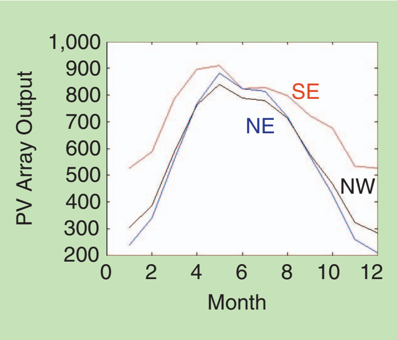

FIG9 An annual PV array output.

TABLE 1. Enery drawn from the PV system.

AREAS	AC ENERGY (kWh/YEAR)	ENERGY VALUE (US$0.115/kWh)
SE	8,628	992.22
NW	6,612	760.38
NE	6,812	783.38

Therefore, the total Tax charge will be

$$\begin{aligned} \text{Tax} &= \text{Tax1} + \text{Tax2} \\ &= 24.8 + 57.7 \\ &= \text{US\$}82.5. \end{aligned}$$

We can have the annual net profit as

$$\begin{aligned} \text{Net profit} &= P \times (r + w) + \text{Tax} \\ &\quad - C_{OM} = \text{US\$}906.72. \end{aligned}$$

Solar PV system incentives and rebates

In Gainesville, GRU provides the Solar Electric System FIT program to PV system owners. According to the Solar Energy Purchase Agreement, this is a contract between the PV system owner and GRU. It was designed to encourage investment in renewable energy by requiring utilities to buy renewable electricity from customers at fixed prices. In Gainesville, customers sell 100% of the power drawn from the solar system to GRU at the price of US$0.21/kWh when the system capacity is equal or less than 10 kW.

Customers can also apply for the Solar Electric System Rebate Program from GRU. Participants will be reimbursed a rate per watt based on the amount of direct or diffused sunlight available based on a PV system's location. However, the purchase agreement shows that customers who receive the Solar Electric System Rebate are not eligible to apply for the FIT program.

The rebate rates are shown as follows.

1) US$1/W for a solar window of 80% or greater
2) a rebate would be available for solar windows 79% or lower

Before applying the rebate program, the capacity of the system needs to be calculated. The system

TABLE 2. The cost of the whole system.

QUANTITY	COMPONENTS	PRICE (US$)	TOTAL PRICE (US$)
24	Suntech 280 W	308	7,392
2	Solar panel cable	43.86	87.72
2	Fuse holder	5.4	10.8
1	Grid-tied inverter SMA	2,647	2,647
2	Lightning arrestor	40	80
1	Combiner box	330	330
1	dc disconnect	170	170
1	Mounting system	2,000	2,000
	Total		12,717.52

Research has indicated that most PV DIY projects did not provide detailed solutions on PV system output optimization, site analysis, and roof space evaluation.

output on the ac side can be represented as

$$P_{AC}(w) = PTC(w) \times N(\text{panels\#}) \times I(\text{inverter efficiency}),$$

where PTC is the solar panel performance under Photovoltaics for Utility Scale Applications test conditions. In our case, $P_{AC}(w) = 280 \times 24 \times 95.5\% = 6417.6\ w$.

Besides the FIT and GRU rebate programs, the federal energy investment tax credit (ITC) incentive authorized under 26 USC 48 provides a 30% tax credit on the installed cost of off-grid or grid-tied solar power systems. Typically, an energy ITC program reduces federal income taxes by offering a 30% tax credit to owners or long-term lessees for qualified property including panels, mounting, and inverters that meets the performance and quality standards. For instance, if equipment costs US$100,000, the energy ITC would be 30% of the cost basis of US$100,000, or US$30,000. Moreover, the cap on solar electric property expenditures (US$2,000) was removed in 2008. The full value of the energy ITC is earned immediately when a project is placed in service. The tax credits can be applied to the federal income tax for individual taxpayers to offset the alternative minimum tax liability. The tax credit incentive has been proven to be popular with investors for both residential and utility solar PV systems, since banks could choose to invest in energy ITC facilities for earning attractive rates of return, and thus all the rebates aforementioned would highly reduce the investment more than we expected.

ROI calculation

Suppose the solar PV system is sponsored by the FIT program and the residents sell their electric power to the grid at the rate of US$0.21/kWh. Accordingly, the net profit from the PV system can be denoted as

$$\text{Net profit} = P \times f + \text{Tax} - C_{OM},$$

where f is the rate of the FIT program which equals US$0.21 and P is the annual system output, which equals 8,628 kWh. C_{OM} represents the annual operation and maintenance cost. The payment for tax is saved through applying to the FIT program. Hence, the tax can be recognized as part of the net profit. According to Table 2, the cost for the whole system is US$12,717 and the federal tax credit can be represented as

$$\text{Tax credit} = 0.3 \times \text{cost} = \text{US\$}3{,}815.$$

Consequently, the return on investment of the installed system with the FIT program and the federal credits can be written as

$$\begin{aligned}\text{Net profit} &= P \times f + \text{Tax} - C_{OM}\\ &= 8{,}628 \times 0.21 + 82.5 - 168\\ &= \text{US\$}1{,}726.4.\\ \text{ROI} &= \frac{\text{Netprofit}}{\text{Cost} - \text{Taxcredit}}\\ &= \frac{1726.4}{12717 - 3815} = 0.19.\end{aligned}$$

For systems with solar electric rebate and federal credits, the rebates are denoted as

$$\begin{aligned}\text{Rebate} &= \text{Solar Rebate} + \text{Tax credit}\\ &= \text{US\$}1 \times P_{AC}(W) + \text{US\$}3815\\ &= 6{,}417.6 + 3{,}815\\ &= \text{US\$}10{,}232.\end{aligned}$$

$P_{AC}(w)$ is the system output on the ac side of the inverter.

The net profit of the PV system is the payment to the tax and the electric retail price, which is saved if all of the power generated from the system is sold to the utility company.

$$\begin{aligned}\text{Net profit} &= P \times f + \text{Tax} - C_{OM}\\ &= \text{US\$}906.72.\end{aligned}$$

TABLE 3. The ROI for a PV system with different rebate programs.

	FIT AND FEDERAL CREDITS	SOLAR ELECTRIC REBATE AND FEDERAL CREDITS	INSTALLED BY CONTRACTOR WITH FIT AND FEDERAL CREDITS	INSTALLED BY CONTRACTOR WITH SOLAR ELECTRIC REBATE AND FEDERAL CREDITS
PV system output P	8,628 kWh/year	8,628 kWh/year	8,628 kWh/year	8,628 kWh/year
Net profit	US$1,726.4/year with FIT	US$906.72/year without FIT	US$1,726.4/year with FIT	US$906.72/year without FIT
Cost	US$12,717	US$12,717	US$25,200 (Average price in Gainesville)	US$25,200 (Average price in Gainesville)
30% federal credits	US$3,815	US$3,815	US$7,560	US$7,560
US$1/W for solar rebate program	None	US$6,417.6	None	US$6,417.6
Total rebate R	US$3,815	US$10,232	US$7,560	US$14,261
ROI	0.19	0.36	0.098	0.082
Period for ROI (i.e., 1/ROI)	5.26 years	2.77 years	10.2 years	12 years

$$\begin{aligned}\text{ROI} &= \frac{\text{Net profit}}{\text{Cost} - \text{Tax credit}}\\ &= \frac{906.72}{12717 - 10232}\\ &= 0.36.\end{aligned}$$

The payback periods can be written as

$$\begin{aligned}\text{Payback Period} &= \frac{\text{Total Investment}}{\text{Net profit}}\\ &= \frac{1}{\text{ROI}}.\end{aligned}$$

The ROIs of PV systems on different scenarios are illustrated in Table 3.

Interpretation of the ROI results

The ROI estimation presented in Table 3 can be summarized as follows: For projects with a licensed contractor, the payback periods for the two contractor-installed projects in Table 3 are 10.2 years and 12 years, respectively.

The payback period for a system installed with the solar electric rebate and federal credits is the shortest—2.77 years. Compared with the contractor-installed projects, the payback periods are much shorter, which highly enhances the economic performance of the investments. Therefore, if possible, it would be desirable for customers to design and install the PV system by themselves.

Conclusion

From the presented design process, we can see that without the cooperation of licensed contractors, homeowners can prepare documentation requirements for a residential solar PV system. Sophisticated computer software such as Sketchup, SMA Sunny Design, and PVWatt, among others, provides customers with solutions for PV system sizing, site analysis, PV system performance optimization, and roof space evaluation. If customers are able to design their own systems, contractors can simply analyze customer-prepared designs and charge a lower rate. Reducing the cost of hiring a contractor would make solar panels more attractive for wide-scale deployment in residential areas.

The ROI report illustrates the advantages of planning and documenting a residential PV system. With the incentive programs, the payback period of a grid-tied PV system would be only two to six years. In addition, the PV systems with FIT programs provide approximately US$1,800 in revenue per year. Thus, DIY installation of a solar system provides an attractive means for reducing energy costs and air pollution.

Read more about it

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