Residential Solar Energy: A Mathematical Cost Analysis

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ABSTRACT: This research studied the way by which residential solar energy production can offset the power drawn from the utility and its overall financial impact on the customer through mathematical cost analysis. A sample annual electricity bill was used as the baseline for the analysis. The publicly available energy generation and pricing structure of Tesla® Solar Solution were used for the calculation. Several rate plans from Salt River Project (SRP) were analyzed for their impact on the electricity bill for the same usage pattern with and without solar generation. Inferences were drawn about the benefit of solar generation with recommendations for maximizing the return on investment.

KEYWORDS: Solar energy generation; utility rate; storage batteries; net energy metering; demand charge.

Introduction

Energy generation in the US is dominated by non-replenishable fossil fuels. Renewable energy has been an active topic of discussion lately due to the real threats of climate change. Renewable energy sources provide an alternative to non-replenishable and polluting fossil fuels by being produced from sources that will not become depleted. The most commonly available renewable energy sources are solar and wind energy. Solar energy is poised to take a lead role in clean and renewable production of energy.[1] It is based on the concept of photovoltaic effect. Solar photovoltaic (PV) energy generates renewable electricity by converting energy from the sun.[2] The energy of the sun is captured by the solar panel, which excites the electrons. The current that flows due to the excited electrons is converted using electronic components into a form that can be utilized by a household to offset the energy drawn from the electric utility. If the solar energy production is greater than the household's needs, the excess energy can be returned to the electrical utility or even be stored in a local rechargeable battery to be used at a later time. The trend is moving toward incorporating solar into more buildings and beyond panels being placed on roofs. Some possible applications include: solar tiles, solar film, solar roadways, and solar windows.[3]

Many states, such as Arizona and California, offer incentives for switching to renewable energy. As part of their commitment to reduce carbon emissions, electric utility companies in the Phoenix Metropolitan area (Salt River Project [SRP] and Arizona Public Service [APS]) are making investments in solar and wind energy farms. Additionally, energy providers have been making changes to their utility plans to encourage homeowners to convert to more renewable energy sources. SRP provides several electricity rate plans to give customers an opportunity to balance their budgets to their electricity consumption. Several commercial residential solar energy solutions are available from vendors like SunRun® and Tesla®. However, consumers remain skeptical about the practicality and benefits of solar energy, as witnessed by the slow adoption of this technology. This begs the question of whether people are oblivious to the financial and other benefits, or uncomfortable with new technology. Although most people understand solar energy production in general, cost-benefit analyses are not freely available to prospective customers particularly with the battery storage option. This research attempts to address the gap using a residential case as an example and deriving a model to explain and de-mystify the factors involved in residential solar energy. The next section explains utility rate plans and presents a simple mathematical model for estimating solar energy generation and electricity consumption for a residential setting. The formulas are then used to understand energy balance patterns and cost projections for various solar energy solution configurations. Finally, inferences are made about the Return-of-Investment (RoI) potential for residential solar energy.

Model for Solar Energy Estimation:
Solar Energy Generation

The energy produced by solar panels is very strongly a function of the time of day and season. This is largely dependent on the extent of exposure to the sun. Each solar panel has a limit on the maximum power that can be generated. Depending on the house size and model, there are different sizes of solar panels and different numbers of storage batteries. For instance, Tesla® offers Small, Medium and Large configurations[4] that produce a maximum output of 3.8kWh, 7.6kWh or 11.4kWh, respectively. Similarly, there is an upper limit on the energy storage and the maximum power that can be supported by each power storage battery. Each Tesla® battery (called PowerWall2TM) can store up to 13.5kWh of energy, which can be discharged at a 5kW maximum rate. The battery storage solution can be stacked to meet the needs of the household. They store energy by converting electrical energy into chemical through a chemical reaction. Energy can be stored for a period of time and can be released when required by means of a conversion of chemical energy to a voltage potential across the positive and the negative electrodes that lie in the battery electrolyte.[5]

In order to facilitate a model for energy generation, a simple experiment was conducted to first understand the productive hours of the day and study the pattern of available solar

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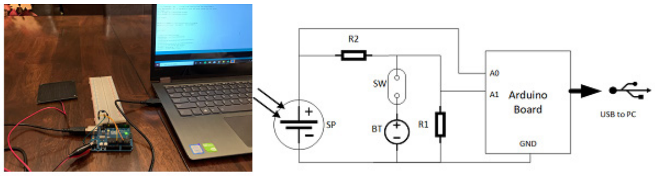

Figure 1: Experimental setup for studying solar energy generation showing a. picture of the setup, and b. electrical circuit connection.

energy. Using a commercially available Solar Panel rated at 5V/100mA, one experiment was to track the current produced by the Solar panel during the day by monitoring voltage across a resistor load. A second experiment was conducted to study how an electric load is shared between solar energy and the utility. A rechargeable battery was used to represent the utility. The measurement was conducted throughout the day over a 12-hour period (6:30am to 6:30pm), which required an automated voltage measurement system for accuracy and repeatability. An Arduino kit6 was employed to measure and record the voltage across the resistor at periodic intervals. Figure 1 shows a picture of the experimental setup for studying solar energy generation along with the electrical circuit diagram. In the first experiment, the switch (SW) was left open. The solar voltage across the panel (SP) was measured at input pin A0 of the Arduino kit and current flow was deduced based on the total resistance (R1+R2). In the second experiment, the switch (SW) was closed to connect the battery (BT). The current through the solar panel (SP) and battery (BT) was calculated by observing the voltage at points A0 and A1. The battery was nominally at 1.5V and discharged into resistor R1 as long as the solar voltage was lower than 1.5V. The panel prevented backflow of current into itself. The measured results of the experiment are described later in this section.

Understanding Electric Utility Rates and Solar Energy Solution:

A sample SRP residential electricity bill over the year 2019 from January to December was used as the control parameter for this study and a reference for further analysis. The various price plans described in SRP's website (www.srpnet.com/menu/electricres/priceplans.aspx) were analyzed and the sample electricity bill was taken to mathematically project the annual bill without and with a Solar Energy Solution by creating equations for each specific price plan. For the analysis, Tesla® (Solar City) was chosen as the solar energy solution provider because of the public information available from their website (www.tesla.com/energy/design) as well as the Google Project Sunroof (www.google.com/get/sunroof) website on the configurations.

Several conventional price plans are offered by SRP, such as Basic, EZ-3 and Time-Of-Use. Most people use the Basic and Time-of-Use plans. The basic rate charges electricity usage at a flat rate throughout the day, whereas the Time-of-Use plan charges at a lower rate during the "Off-Peak" hours and higher rate during the "On-Peak" hours. The off-peak and on-peak hours depend on the season, as shown in the chart in Figure 2. In Arizona, winter months are November-April, summer months are May-June and September-October, and peak summer months are July-August.

Figure 2: Off-peak and On-peak Hours over the year for SRP Rate Plans.

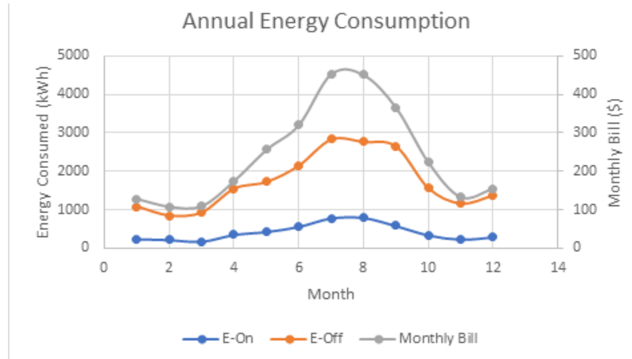

Figure 3: Annual Energy Consumption of a sample household.

The SRP monthly electricity bill and website[7] provide a wealth of information about energy consumption by a subscribing household. The annual energy consumption by the sample AZ household on the Time-of-Use plan being studied in this project was compiled from the monthly SRP electricity bill over a period of 12 months. The data is shown in Figure 3. The energy consumption during on-peak and off-peak hours per month is on the left axis, while the monthly electricity bill on the Time-of-Use plan is shown to the right. The energy consumption is highest during the hot summer months when the AC is running, and lowest through the winter months. This annual energy consumption was used as the baseline reference for studying the various rate plans and solar energy solutions.

SRP also offers various electricity rate plans for consumers that install residential solar energy systems, such as Solar Time-of-Use, Average Demand and Customer Generation Plans. The Solar Time-of-Use and Customer Generation Plans were chosen for study in this project. Key information about various solar and non-solar energy rate plans compiled from SRP's website is summarized in Table 1 below. The table shows the rates in each season as well as the basic service charge for each price plan. Every rate plan has seasonal variations in the on/off-peak rates because the electricity bill for each plan can be different for the same usage pattern. The electricity rate is higher during the summer months than winter months. Coupled with the observation that higher energy is consumed during summer months, the electricity bill during summer months can be four-times that of the winter months (Figure 3). The Time-of-Use plan allows consumers to reduce their bill by moving high energy consuming activity (e.g., laundry, pool pump) to off-peak hours. The Solar Time-of-Use plan has the same rates as the non-solar plan, but the utility provides a flat-rate credit for energy returned to the grid. The Solar Customer Generation plan has the lowest electricity rate, and the credit for energy returned to the utility is the same rate as the charge for energy consumed.

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This is referred to as 'Net-Metering'. However, this plan has a penalty called 'Demand Charge' which is an extra amount that must be paid each month proportional to the maximum power drawn from the grid during on-peak hours. Table 2 shows the Demand Charge rates as a function of peak power and the season. As shown, the demand charge penalty is significantly higher for higher peak demand. Thus, households with Solar Customer Generation plan must be aware of this penalty if they have equipment that draws high instantaneous (or peak) power. The next section describes the equations that were formulated to model these price plans.

Table 1: Key Information of various Energy Plans under study.

Plan Name	Non-Solar Flat	Non-Solar Time-of-Use	Solar Time-of-Use	Solar Customer Generation
Plan Name	E23	E26	E13	E27
Service Charge ($)	20	20	32.44	32.44
Summer On Peak Rate ($/kWh)	.1134 (>2K)	0.2094	0.2094	0.0462
Summer Off Peak Rate ($/kWh)	0.1091 (<2K)	0.0727	0.0727	0.036
Peak Summer On Peak ($/kWh)	0.127 (>2K)	0.2409	0.2409	0.0622
Peak Summer Off Peak ($/kWh)	0.1157 (<2K)	0.073	0.073	0.0412
Winter On Peak Rate ($/kWh)	0.0782	0.0951	0.0951	0.041
Winter Off Peak ($/kWh)	0.0782	0.0691	0.0691	0.037
Demand Charge ($/kW)	0	0	0	See Table 2
Credit ($/kWh)	0	0	$0.0281	Same as charge

Table 2: Demand Charge Rate for Solar Customer Generation Plan/E27.

Peak Demand	0-3 kW	3-10 kW	> 10 kW
Summer ($/kW)	7.89	14.37	27.28
Peak Summer ($/kW)	9.43	17.51	33.59
Winter ($/kW)	3.49	5.58	9.57

Model for Monthly Bill Estimation for Various Plans :

The objective of this project was to estimate the electricity bill for the plans described in Table 1 for the annual usage pattern shown in Figure 3. The SRP website does not offer equations for any plan, so the first task was to formulate equations that accurately represent each plan. The equations cover the base charge for energy consumption, credit for solar energy generation/storage and applicable power penalty/taxes. The variables describing the monthly base charge for energy consumption are:

● Service_Charge: The base charge for any given plan

● Energyk: Total energy consumed for the month at the rate 'k', where k represents on-peak or off-peak (except Flat Rate plan, where k represents rate <2KWh or >2KWh)

● Ratek: Billing rate for the month at the rate 'k', where k represents on-peak or off-peak (except Flat Rate plan, where k represents rate <2KWh or >2KWh)

The base energy consumption charge for each plan is

$$Energy\ Consumption\ Charge = \left[Service\_Charge + \sum_{k=on-peak,off-peak} (Energy_k * Rate_k)\right]$$

The Flat Rate and Time of Use plans simply account for the service charge and energy consumed at each rate. The Solar energy plans provide a credit to the consumer for the amount of solar energy generated. The energy generated by the solar panels can be used to power the home, offsetting the energy drawn from the utility. With the Solar Time of Use Plan, the excess solar energy may be returned to the grid for a flat-rate credit (2.81c/kWh) which is typically much lower than the rate at which the customer is charged for the energy drawn from the grid. While the Solar Customer Generated plan is similar to the Solar Time of Use concept, a key difference is in the credit for the excess solar energy returned to the grid. Per the Net-Metering concept, the consumer is charged for the net energy drawn from or returned to the grid at on-peak or off-peak rates. Effectively, the customer gets the full credit for all generated solar energy. It is important to estimate the energy generated during on-peak and off-peak hours for both Solar Plans. The method for estimating on-peak and off-peak solar energy generation is described later in this section. The variables describing the solar energy generation credit are defined as:

● Generationk: Total Energy generated for the month at the rate 'k', where k represents on-peak or off-peak for the Customer Generated Plan

● Creditk: Credit rate for the month at the rate 'k', where k represents on-peak or off-peak for the Customer Generated Plan

● Excess Generation: Total energy returned to the grid for the month for the Solar Time of Use Plan

● Flat_Credit: Flat rate credit (2.81c/kWh) for energy returned to the grid in Solar Time of Use Plan

Then, the utility credit for each plan is

$$Customer\ Generation\ Credit = \left[\sum_{k=on-peak,off-peak} (Generation_k * Credit_k)\right]$$

$$Solar\ Time\ of\ Use\ Credit = Excess\ Generation * Flat\ Credit$$

In order to estimate the solar energy generated during on-peak and off-peak hours, the solar cycle over the year must be understood first. The experimental setup described in Figure 1 was used for this purpose, with the results shown in Figure 4. The left graph in Figure 4 shows the Current and Voltage generated by the Solar Panel, showing a bell curve through the day from 6:30am to 6:30pm. This shows that the current and voltage are directly proportional to the amount of sunlight with maximum production at mid-day. The right graph of Figure 4 shows the result of the second experiment, plotting the current drawn from the battery connected in parallel with the solar panel. When the solar production is low, the charge stored in the battery feeds the resistor load. When the curve drops below zero, the battery current is negative, so the solar energy is feeding the load as well as returning charge to the battery. This shows the basic idea of using Solar Panels to offset the energy drawn from the electric utility. The battery is discharging from time 6:30am-10am and 3:30pm-6:30pm. It is charging from 10am-3.30pm.

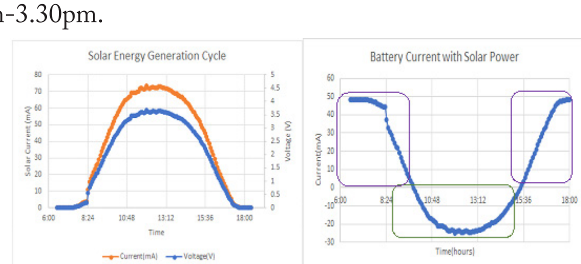

Figure 4: Solar Generation Cycle and Battery Current with Solar Power showing a: Solar panel voltage and current, and b: charge/discharge cycle of the storage battery.

Figure 4 shows that the solar energy generation cycle through the day is highly non-linear. In order to estimate the solar energy generated during on-peak and off-peak hours, the solar cycle must be approximated into a simpler form for a study of the scale. Likewise, domestic energy consumption patterns are also non-linear. For this study, some simplifying assumptions were made regarding the average energy generation and consumption patterns through the seasons in order to analyze the annual bill for various plans. Figure 5 shows a piecewise linear approximation of daily energy generation and consumption patterns for the summer and winter months. The orange lines are a simplification of the bell-curve shaped solar energy generation pattern. The blue lines show a simplified representation of energy usage patterns based on a study of the SRP bill over a twelve-month period. This represents the usage pattern for a typical family that is out of the house during office/school hours. Energy consumption is lower during the middle of the day but higher through the evening and night when the family is home.

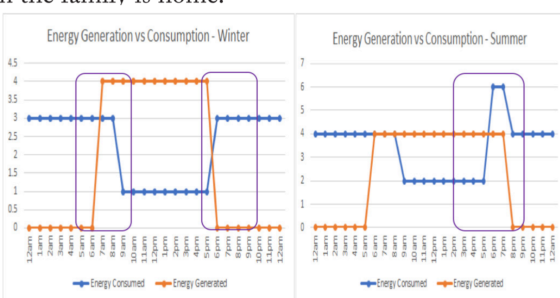

Figure 5: Energy Generation vs. Consumption Patterns-Winter and Summer.

A mathematical spreadsheet model was built for estimating solar energy generation using the simplifying assumptions outlined in Figure 5. The Google SunRoof[8] project site provided an estimate of the total energy generation over the entire year for any solar panel configuration. In order to derive the energy generation for any month, the average daylight time for each month was listed, and the total estimated energy generation was distributed over the months in direct proportion of the daylight time. This simplification does ignore the effect of temperature on efficiency of energy generation, but this should be acceptable for this project. For each month, the energy generated was split into on-peak and off-peak production ($Generation_{on\text{-}peak}$ and $Generation_{off\text{-}peak}$) by mapping the productive hours with the on-peak and off-peak hours chart shown in Figure 2. Weekends and holidays are treated at off-peak rates over the entire day. The Excess Generation for the Solar ToU plan was then computed as:

If $Generation_{on\text{-}peak} > Energy_{on\text{-}peak}$, then $Excess_{on\text{-}peak} = Generation_{on\text{-}peak} - Energy_{on\text{-}peak}$, else = 0

If $Generation_{off\text{-}peak} > Energy_{off\text{-}peak}$, then $Excess_{off\text{-}peak} = Generation_{off\text{-}peak} - Energy_{off\text{-}peak}$, else = 0

$$Excess\ Generation = \sum_{k=on-peak,off-peak} (Excess_k)$$

A downside of the Customer Generation plan is that the utility charges a penalty for the maximum power drawn from the grid over any hour during the on-peak periods of the month, referred to as Demand Charge, listed in Table 2. The penalty is higher if the household has equipment (such as old AC models) that draw higher peak current. Then depending on the peak power, the Demand Charge is:

$$Demand\ Charge = \sum_{k=1,2,3} (Power_k * Charge_k), \text{ where}$$

k=1 represents power between 0-3kW, k=2 is power between 3kW-10kW, k=3 is power >10kW.

All the equations described in this section were used to put together monthly bill estimates for various plans. Figure 6 shows the flow diagram for applying charges and credits towards the monthly bill.

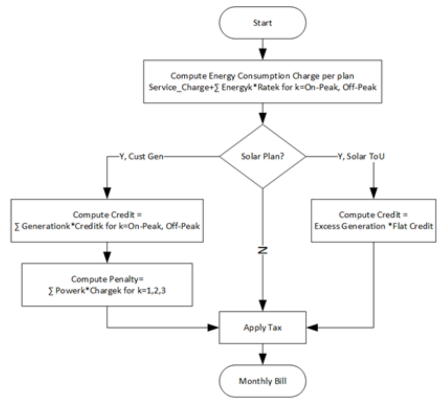

Figure 6: Flowchart for computing the monthly electricity bill for each plan.

Battery Storage:

The piecewise uniform energy model of Figure 5 reveals that periods for peak daily energy consumption and generation are mismatched. It also suggests that less energy is generated during the on-peak hours (marked in purple box) than off-peak hours. A hypothesis is that savings in solar electricity bill may be limited due to this mismatch if the solar energy is instantaneously consumed or returned to the grid. If it is possible to harness the excess energy generated during the cheaper off-peak hours and use it to power the house during the expensive on-peak hours, it would arguably have a greater effect on reducing the electricity bill. Storage batteries may be used to implement this possibility.

Battery storage was considered for the Solar Time-of-Use and Customer Generated plans. This model assumes that during the daylight hours, the solar energy is first used to meet the residential energy consumption. The excess energy is first allocated for battery storage, and once the battery capacity is reached, the residual excess energy is returned to the utility for energy credits. Once the sun is down, the energy stored in the battery is first used to meet the energy consumption during on-peak hours. The residual energy is consumed during off-peak hours. An alternative model could be one where all the solar energy generated during off-peak hours is used to charge the battery, and the battery primarily provides the power during the on-peak hours.

In case of the Customer Generation Plan, the peak power drawn is first serviced by the battery, and the utility only covers the amount of peak power that exceeds the battery's discharge rate. This greatly reduces the demand charge for this plan. For

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the Solar ToU plan, the utility of the battery is mostly to alleviate the power drawn from the utility during on-peak hours.

Results and Discussion

The flow described in the previous section was used to calculate the net monthly electricity bill. This section presents the results of the comparative analysis across various plans. The annual energy consumption pattern shown in Figure 3 was used in all cases.

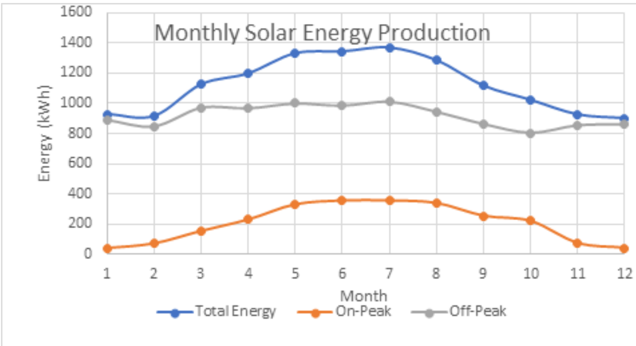

Figure 7: Monthly Solar Energy Production.

The graph in Figure 7 shows the results of the model for energy produced by the Solar Panels over one year, broken out in on-peak and off-peak production. The model is based on a Google Sunroof estimated annual production of 13,500 kWh for a mid-sized 7.6kW Solar System in Arizona. As expected, the highest energy is produced during the summer months. It is interesting to note that most of the energy is produced during off-peak hours, which is consistent with Figure 5. This limits the amount of credit to the customer during on-peak hours. Figure 3 shows that average energy consumption is also lower during the on-peak hours than off-peak hours. However, the offset between energy consumption and generation patterns still results in a penalty for the consumer. This model accounts for varying daylight hours over the seasons. The energy generated during the on-peak hours was considerably (5x-10x) less than the energy generated in the off-peak hours. This shows that it is difficult to offset the price of energy consumed during on-peak hours. Since most of the energy is harvested during off-peak hours, batteries can be a beneficial addition to the solar panels.

Figure 8 compares the annual electricity bill for the two non-solar and two solar plans under study. Additional benefit from battery storage was also studied for the Solar plans. Based on research, SRP does not permit the use of storage batteries without a Solar Energy Generation solution. Among the non-solar solutions, the Time-of-Use plan offers incremental annual savings (~$250) over the flat rate plan. The potential savings incentivize customers to move higher electricity usage to the Off-Peak hours.

As seen from Figure 8, both the Solar Time-of-Use and Customer Generated Plans result in a lower electricity bill than the two non-solar plans by about $500-$750 even without the use of batteries. Use of power storage batteries results in a further reduction of the annual bill. Interestingly, storage batteries yield a greater value with the Customer generation plan than the Solar Time-of-Use plan. With the Solar Time-of-Use plan, batteries provide a fixed amount of offset to the energy consumed by the household, and the credit for energy returned to the utility is very small. On the other hand, Net-Metering in the Customer Generated plan provides credits that are better balanced with the energy consumption. Further, the batteries reduce the peak energy demand from the grid during On-Peak time, directly mitigating the Demand Charge penalty. The Customer Generated Price Plan shows the greatest price drop with the second battery by nearly eliminating demand charge.

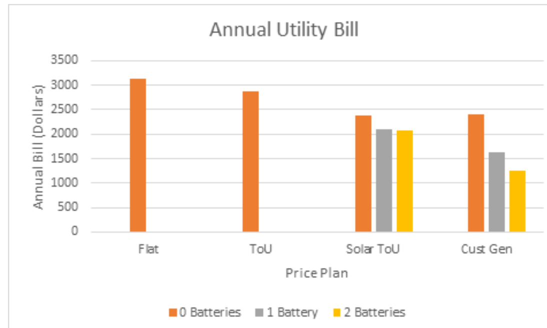

Figure 8: Annual Utility Bill for scenarios under study.

It is clear from Figure 8 that residential solar energy systems yield significant reductions in annual electricity bill (~25%) compared to the non-solar baseline plan. Use of storage batteries can result in even greater savings (~60%). This reduction of electricity bill by 60% seems very attractive. However, the initial cost of solar energy solution installation can be a big deterrent for most families. The Federal government offers tax credits (~26% in 2020) for solar energy installations, with additional rebates from individual states and utility companies. Still, the total installation cost can run into several thousand dollars. For instance, after rebates and incentives, the Tesla® Solar Energy solution can be about $12,000 without batteries, and up to $22,000 with batteries. The expectation, then, is that it would take several years for a customer to recuperate the installation cost even with a substantial reduction in the annual electricity bill. Further, solar energy equipment is typically projected to have a productive lifespan of 12-15 years.

A Total Cost-of-Ownership calculation was performed for all four plans under study to determine the financial merits of a solar energy solution. A cumulative annual bill for 15 years was compiled and added to the initial price of installation of the solar energy solution to project the final cost to the consumer. Cumulative payments were compared to determine if and when the solar price plan is cheaper than just drawing energy from the electrical grid. Figure 9 shows an overlay graph of the cumulative cost of ownership of various energy solutions. It is assumed that the electricity rates charged by the utility have an annual inflation rate of 3%. This is the average rate of inflation over the past 20 years.

All the graphs are slightly non-linear with varying slopes. The Flat rate (Flat) plan and the Time of Use (ToU) plan both started out as the least expensive since there is no upfront capital cost, but the Flat Rate ended up being the second most expensive price plan. The Customer Generated Plan (CustGen) with no batteries and the Time of Use (ToU) plan ended up with similar cost after 15 years. The Solar Time-of-Use plan with 2 batteries (Batt ToU2) remained the most expensive throughout the 15 years. The Customer Generated plan with 2 Batteries (Batt Cust2) was the most cost effective in the long run as it ended up with the least cumulative price despite having the highest upfront cost. This plan has an 11-year breakeven point with a 40% return of investment in 15 years.

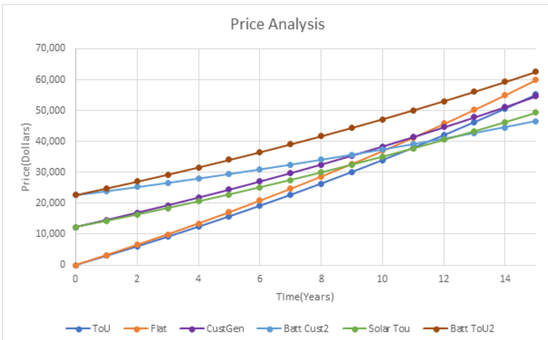

Figure 9: Annual Utility Bill for scenarios under study.

It is clear that Solar energy solutions require a high upfront investment in terms of installation costs. Even with a lower electricity bill, it takes several years to recuperate the cost. Most importantly, the rate of energy reduction is a strong function of the configuration of the solar energy solution and the utility rate plan. If not matched properly, it is possible for some consumers to never achieve a breakeven point. On the other hand, with a wise selection of the energy solution and utility plan, it is possible to break even within 10 years or less. The optimal solution may vary depending on the consumer lifestyle (stay at home all day vs mostly being outside during the daytime hours).

Solar panels should be taken care of regularly and placed strategically to maximize the energy generation. Optimal placement in residential settings is often on rooftops along the side that gets maximum exposure to the sun, preferably towards the south in the US with little surrounding tree cover. The panels should also be washed and wiped at periodic intervals to remove the dust and debris that collects on them over time. With regular care, the solar panels can generate energy for a long time, with little degradation over the years. The energy storage batteries usually do not require maintenance or servicing; however, experts need to be brought in if problems arise.

Conclusion

In conclusion, a thorough mathematical analysis of the electrical utility bill was presented for various configurations of Tesla® solar energy solution and SRP bill pay schemes. It is shown that solar energy generation can significantly reduce the electricity bill and pay for itself over a period of time, but the benefits can be limited by the mismatch between when the energy is generated and when it is consumed. Storing the excess energy in batteries for later consumption was seen to have a greater effect in reducing the electricity bill. The analysis shows that a solar energy solution that utilizes two Powerwall2TM batteries and is on SRP's Customer Generation Price Plan (E27) presents the best opportunity to offset the upfront installation costs in the least amount of time. The spreadsheet tool created in this project was proved out on a specific sample electricity bill but can be used to provide an assessment for a variety of consumption scenarios and solar energy configurations. As shown through the study, policies that dictate rates would heavily influence solar deployment in residential sectors in addition to advances in solar energy technology. Continuous improvements in battery technology and pricing schemes will give a boost to solar energy for increased utility scale deployment.

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