Thermoeconomic Analysis of Residential Rooftop Photovoltaic Systems with Integrated Energy Storage and Resulting Impacts on Electrical Distribution Networks

Thomas T.D. Tran, Amanda D. Smith*

Department of Mechanical Engineering, University of Utah, Salt Lake City, UT 84112

Abstract

This paper investigates residential rooftop photovoltaic (PV) systems for long-term thermoeconomic benefits from PV homeowners' perspectives and for impacts on the electrical distribution network from grid operators' perspectives. The costs of generating electricity from grid-connected PV systems are studied with and without energy storage at the PV homeowners' sites. Three selling scenarios for excess PV energy conversion are considered: net metering, wholesale pricing, and no payback. PV systems in Utah are utilized as case studies in this analysis. The presence of PV systems gives homeowners economic benefits such as reduced annual electricity bills. However, the levelized costs of electricity are considerably higher than the weighted electricity price in Utah. Currently, the addition of energy storage only benefits customers in Utah under the no payback policy. The impacts of PV systems toward electrical distribution networks are then studied on a distribution test system. Excess PV generation from residential PV systems causes voltage rise in the electrical distribution network. The results from this paper can educate consumers about the lifetime benefit of integrating solar energy into their homes. For grid operators, residential PV systems with energy storage can reduce the negative impacts on the grid compared with high PV penetration alone.

Keywords: LCOE, rooftop PV, net metering, distribution network, energy storage

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1. Introduction

Distributed generation has become a popular choice for power generation in recent decades [1]. Distributed energy systems, especially those incorporating renewable energy generation, are emerging as more widespread choices for power generation, while presenting unique challenges for integration into the existing electric utility system [2]. Among different renewable energy technologies, solar PV is one of the most popular options. These

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*Site-Specific Energy Systems Laboratory

Email address: amanda.d.smith@utah.edu (Amanda D. Smith)

systems enter the market in a range of different sizes: utility-scale (1–10 MW), medium-scale (10–1,000 kW), and small-scale (<10 kW) [3, 4]. In the United States, the number of small-scale residential PV systems have increased significantly (1 million homes in 2016) and have become an important part of distributed generation resources [5]. Depending on the application and the facility served by the electrical generation, PV power systems can be sized to meet the electricity demand. However, the timing of PV generation and a building's electrical needs rarely coincide.

There are two popular options to configure residential PV systems: grid-connected and off-grid systems [6, 7]. Even though the option for grid defection using residential solar PV systems can be achieved, generation costs are highly expensive at present [8]. As a result, the majority of residential PV systems in the U.S. are grid-connected. Furthermore, these systems are often configured either with or without energy storage. For the grid-connected residential PV option without energy storage, there are two essential elements to interacting with the electric utility: sending electricity to the grid and receiving electricity from the grid. During the day when energy demand is less than the energy conversion from rooftop solar PV, PV homeowners can sell the excess electricity to the grid. Contrarily, homeowners with PV systems draw energy from the grid at night since there is no energy conversion from the rooftop solar PV. The method for selling excess electricity depends on local policies. Some of the programs that have been used are net metering, wholesale pricing, or no payback [9, 10, 11, 12, 13]. Under the net metering policy, PV homeowners receive utility credits for sending excess PV generation to the grid, whereas PV homeowners under the wholesale pricing policy sell the excess PV generation to the grid at wholesale prices. Furthermore, the no payback policy means that PV homeowners will not receive credits for excess PV generation. The second option for homeowners with PV is to purchase energy storage to store the unconsumed energy [14]. However, the addition of energy storage introduces extra costs to the PV system as a whole. In this configuration, electricity can still be drawn from the grid if the energy demand is more than the PV generation or the stored energy available.

The addition of PV systems can create potential problems to the existing distribution networks. A large amount of PV penetration (i.e. excess PV generation being sent the grid) can cause voltage rise and reverse power flow, which reduces the stability of the networks [15, 16, 17]. Energy storage in PV systems has been cited as a solution to reduce the impacts of those issues [18, 19, 20]. As a result, grid operators can benefit from the presence of energy storage in PV systems. However, the option for installing energy storage in residential PV systems is usually determined by the homeowners. From the consumer's viewpoints, this option will largely be influenced by the cost benefits. Therefore, the decision made by PV homeowners can potentially affect the electrical network stability. The inclusion of energy storage in PV systems can increase the total cost of the systems while reducing the likelihood of network instability. On the other hand, the electrical network will be more likely to experience network instability in the event of high PV penetration from PV systems without energy storage. Ultimately, the actual benefit of energy storage involves interrelated parties and needs to be studied based on specific locations with local electricity price and energy policy.

The effects of PV generation will be examined from both the consumers' and the grid operators' perspectives in this paper. A case study with 12 different locations in Utah will be considered. This study incorporates the effective levelized cost of electricity (LCOE) as a metric to quantify the long-term benefit for PV homeowners with and without energy storage. Knowledge of costs and financial benefits to install rooftop PV systems and energy storage can assist the consumers with the decision making. Three different selling scenarios (net metering, wholesale pricing, and no payback) for the excess PV energy produced are used. Comparing different policy options is useful for analyzing the pros and cons of each policy, as demonstrated in Table 1.

The results from PV and energy storage investments introduce different effective prices for electricity, which will be compared to the price of electricity from the local utility. Additionally, grid operators can identify potential problems with the electrical networks due to the high penetration of PV generation. Analysis on the effects of PV systems toward the distribution networks will be performed to ensure the stability of the electrical networks. Moreover, the integration of customer-side energy storage into the PV systems will be explored to evaluate its effectiveness of minimizing voltage rises to the grid.

2. Methodology

2.1. Costs of Electricity Generation from PV Systems

A thermoeconomic analysis needs to be established to evaluate the economic benefits of electricity generation from PV systems. Generating electricity with rooftop solar PV systems requires several components. Solar PV panels and inverter (DC to AC) are the two main components, whereas energy storage is an optional add-on to the system. The capital costs of installing a solar PV system consist of the cost of solar PV panels, inverter, energy storage (optional), and miscellaneous costs. The miscellaneous costs include site permitting, labor cost, site preparation, wiring, and start up cost.

The residential PV systems can be scaled to meet the location-based electricity demand of residential units. The methodology for sizing the PV systems in this study is based on guidelines for sizing residential rooftop PV systems [21, 22]. The calculation for sizing PV systems takes into consideration system latitude, average daily sunlight hours, module type, and array type. The residential daily average electricity usage in kWh is obtained from the residential hourly load database, which is maintained by the U.S. Department of Energy [23]. The database contains hourly load profiles for reference residential building models at the 12 study locations in Utah (Figure 1). Based on the sunlight hours at specific study locations, the wattage of the solar PV systems in kW can be determined from dividing the average daily kWh by the average daily sunlight hours. Using the designed wattage value from the previous step and the specifications of commercially available solar panels in terms of kW/m^2, the area of the panels in m^2 can be computed. In summary, the system design parameters used are listed in Table 2 [24, 25].

The amount of residential rooftop PV generation can be calculated based on the size and the location of the PV systems. The solar PV energy conversion is calculated, as seen in the following equation:

$$E_{PV} = A * I * \eta * PR \tag{1}$$

Table 1: Selling scenarios considered for excess PV electricity production.

Selling Scenario	Homeowner Impacts	Grid Operator Impacts
Net metering	Credit received for electricity produced that can be used for electricity purchased at another time at the retail rate.	Grid system acts as storage on behalf of the homeowner.
Wholesale pricing	Compensation received for electricity produced at the current wholesale rate.	Grid purchases additional non-dispatchable generation at times of excess PV production.
No payback	Homeowner receives no credit, compensation, or penalty for exporting electricity to the grid.	Grid receives additional non-dispatchable generation at times of excess PV production.

where E_{PV} is the electricity production from the PV panels, A is the solar panel area, I is the solar irradiation on the tilted panels, η is the efficiency of the panels, and PR is the performance ratio. The PR includes the losses in inverter, cable, temperature, shading, dust, snow, etc. The panels are tilted based on latitude angles in the 12 study locations (ranging from 37.08 deg to 41.20 deg). Solar irradiation data are obtained from the Typical Meteorological Year 3 (TMY3) weather database [26]. The TMY3 provides hourly solar irradiation data obtained from weather stations at locations such as airports at the 12 study locations in Utah (Figure 1). These locations are located in 3 different climate zones, as described by the U.S. Department of Energy and the International Energy Conservation Code [27, 28]. Utah generally has a dry climate; within the state, Zone 3 is warm, Zone 5 is cool, and Zone 6 is cold.

Table 2: System design parameters [24, 25].

Parameter	Value
Solar PV panel capital cost	\$3.0/W
Solar PV panel lifetime	20 years
Solar PV panel efficiency	15%
Performance ratio	75%
Energy storage capital cost	\$350/kWh
Charging/Discharging Efficiency	90%
Inverter capital cost	\$35/kW
Discount rate	5%

The energy conversion from rooftop solar PV panels can be greater or less than the energy demand of the home at a given time during the day. The net energy (Equation 2) is defined as the difference between energy load from the home and the energy conversion from the rooftop PV panels. The net energy is useful to determine the amount of energy that will be exported to the grid, stored in an energy storage system, or purchased from the

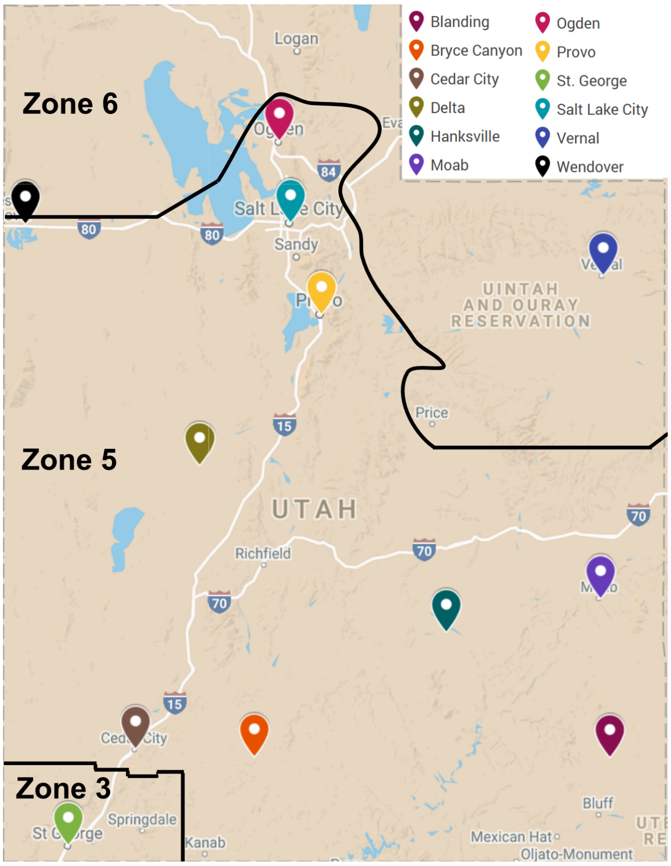


Figure 1: Locations of study areas and their associated ASHRAE climate zones [29, 30, 28].

grid.

$$E_{net} = E_{load} - E_{PV} \tag{2}$$

2.1.1. PV Systems without Energy Storage

The capital cost of a PV system without energy storage is shown as follows:

$$C_{capital,PVonly} = C_{capital,PVpanel} + C_{capital,invt} + C_{capital,misc} \tag{3}$$

where $C_{capital,PVonly}$ is the capital cost of the PV system without energy storage, $C_{capital,PVpanel}$ is the capital cost of the solar PV panels, $C_{capital,invt}$ is the capital cost of the inverter, and $C_{capital,misc}$ is miscellaneous costs, including permitting, balance-of-system, and labor costs.

Without energy storage, residential PV systems rely on the local utility any time that PV power generation is less than the home electricity demand. Since residential PV systems require low maintenance, the annual operation and maintenance (O&M) cost is neglected. Furthermore, the study also neglects the costs to replace solar panels within their lifetime. Even though the solar panels are designed for a lifetime of 20 years, individual replacements can occur because of unexpected conditions such as severe weather and defective panels. However, the data to quantify the frequency of solar panel replacements is rather lacking

[31]. Therefore, the annual cost for a grid-connected PV system without energy storage is equal to the annual utility electricity bill.

The annual utility electricity bill calculation depends on different billing scenarios. Equation 4, 5, and 6 describe the annual electricity bill from utility under net metering, wholesale pricing, or no payback scenarios, respectively.

$$\text{Net Metering: } C_{bill,annual} = \sum_{E_{net}>0} R_{utility} * E_{net} - \sum_{E_{net}<0} R_{utility} * |E_{net}| \tag{4}$$

$$\text{Wholesale pricing: } C_{bill,annual} = \sum_{E_{net}>0} R_{utility} * E_{net} - \sum_{E_{net}<0} R_{wholesale} * |E_{net}| \tag{5}$$

$$\text{No Payback: } C_{bill,annual} = \sum_{E_{net}>0} R_{utility} * E_{net} \tag{6}$$

The effective levelized cost of generating electricity from PV system is computed by the following equation:

$$LCOE_{PV} = \frac{Total\ Lifetime\ Cost}{Total\ Lifetime\ Electricity\ Consumed} = \frac{C_{capital} + \sum_{n=1}^{Lifetime} C_{bill,annual}}{\sum E_{net}} \tag{7}$$

2.1.2. PV Systems with Energy Storage

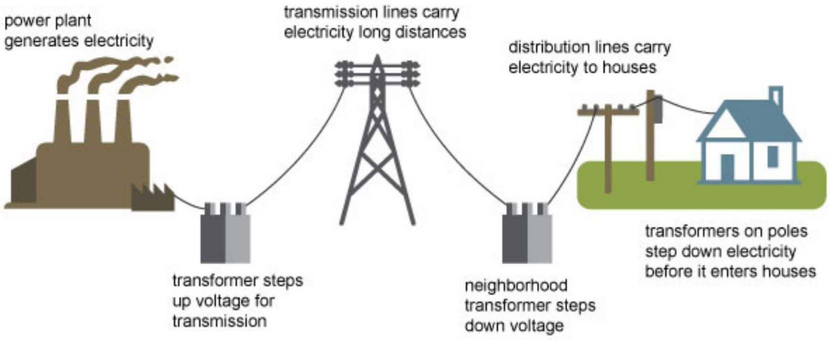
The addition of energy storage allows PV systems to store unused energy while introducing additional costs to the system, particularly the capital cost. There are many battery technologies for residential energy storage, such as Lead-acid, Nickel-cadmium, and Lithium-ion [32]. Among different technologies, Lithium-ion technology is the most common type of storage [24]. In this study, Lithium-ion batteries are utilized as energy storage systems for the residential solar PV systems. The energy storage capacity used in this study is 5 kWh, which is a common size of battery for residential PV applications [24]. The control algorithm of the battery system is illustrated in Figure 6. The capital cost of this system (Equation 8) includes the capital costs of PV panels, inverter, energy storage, and miscellaneous costs.

$$C_{capital,PV+ES} = C_{capital,PVpanel} + C_{capital,invt} + C_{capital,ES} + C_{capital,mics} \tag{8}$$

The procedures to calculate the annual utility electricity bill for rooftop PV systems with energy storage are identical to those without energy storage. Equation 4, 5, and 6 can be used to calculate the annual utility electricity bill under net metering, wholesale pricing, or no payback scenarios. As a result of incorporating an energy storage system, the net energy values at each time step in Equation 2 will be different with the presence of the energy storage. Equation 7 is then used to calculate the levelized cost of generating electricity from a PV system with energy storage.

2.2. The Role of Energy Storage in Residential Solar PV Systems from Grid Operators' Perspectives

From the grid operators' perspectives, excess PV generation from residential solar PV systems can lead to potential problems in terms of the stability of the grid. The power flow in a traditional network is often uni-directional, that is from utilities to consumers. In the grid-connected mode of residential solar PV systems, the power flow can be bi-directional. In other words, power can flow from consumers to utilities when the residential load demand is less than the power generation from PV systems. As a result, this phenomenon can cause instability in the electrical networks, which can negatively impact the performance and lifetime of electrical components such as transformers [17, 20]. The impacts of excess PV generation on distribution networks is examined on a test system. In this study, the test system is the IEEE 123 Node Test Feeder, which is representative for medium size distribution networks in terms of infrastructure and specifications [33]. Among different test systems, this test system provides researchers with opportunities to study voltage drops/rises problems while having minimal convergence problems [34]. The nominal voltage of this 3-phase test system is 4.16 kV. The total active power in the system is 3.6 MW, while the total reactive power is 1.3 MW.



Source: Adapted from National Energy Education Development Project (public domain)

Figure 2: Simple illustration of the electricity network [35, 36].

The presence of energy storage at PV homeowners' sites will be included to examine whether it is beneficial for the networks in terms of voltage stability. In the field of electrical engineering, the per-unit system is typically used to express voltages as fractions of the defined base voltages. A voltage is considered to be in normal operating conditions when its p.u range falls between 0.95 and 1.05. Three scenarios with different amounts of PV penetration percentage are simulated (10%, 30%, and 50%). The amounts of PV penetration are percentages of the active power of the test system at a given point in time. Multiple residential rooftop PV systems are combined to be a single power injection at the nearest bus location in the test system. The PV generation occurs equally at 10 different nodes that are uniformly distributed in the test system. This selection of nodes showcases one example of how solar PV generation can be injected to the distribution network. Other selections of nodes might produce different results due to the infrastructure of the test system. Additionally, the PV injection occurs primarily between 10 am and 4 pm to match with the daylight hour. In this study, the voltage at the end of the feeder is examined under different operating conditions. A feeder is a voltage power line that transfers power from a distribution substation to the distribution transformer [33]. Figure 2 illustrates the distribution network with respect to the entire electricity grid [35, 36]. Power flow studies are investigated by using power flow software called Open Distribution System Simulator (OpenDSS). The software was developed by Electric Power Research Institute (EPRI) to study electric utility power distribution systems [37]. This steady state stability analysis in terms of phase voltages is performed to study the impact of PV penetration and energy storage on an example electrical distribution network.

3. Results & Discussion

3.1. Electricity Load and PV Energy Conversion

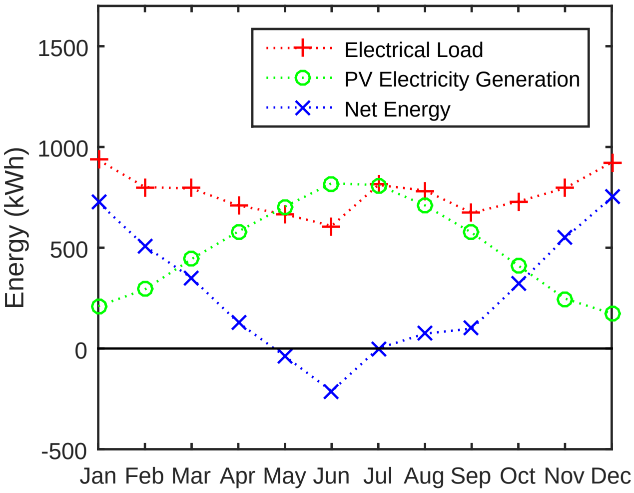


Figure 3: Average monthly electrical load, PV energy conversion, and net energy use for Salt Lake City.

As described in Section 2, the location-based electrical loads for 12 study locations in Utah are obtained from the residential hourly load database [23], while the PV energy conversion are calculated based on Equation 1. Figure 3 shows the electricity load, PV energy conversion, and the net energy produced for an example homeowner with PV in Salt Lake City for illustrative purposes. Electricity load is high in winter and summer while the PV energy conversion reaches maximum in the summer. The net energy is the difference between the electricity load and PV energy conversion, as described in Equation 2. The trends are similar for other areas in Utah. Figure 4 illustrates the PV energy conversion for a PV system using the design parameters in Table 2 for 12 locations in Utah. Cities in the southern part of the state (e.g. Moab, Cedar, and St. George) tend to have higher PV energy conversion due to the higher availability of solar irradiation, despite their higher electrical loads due to increased cooling needs.

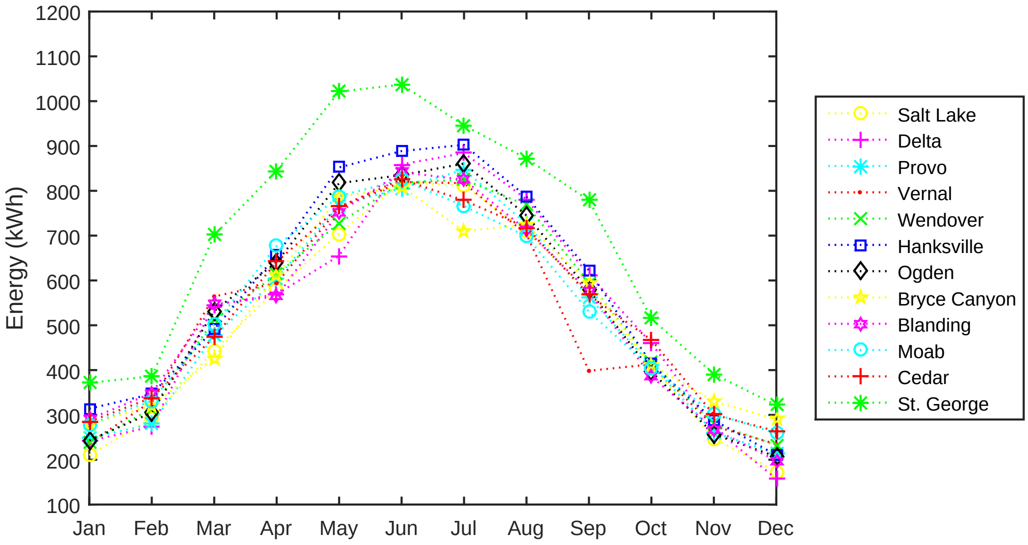


Figure 4: PV energy conversion for 12 locations in Utah.

3.2. *Levelized Cost of Electricity*

To calculate the levelized cost of electricity of PV systems with and without energy storage, it is important to assess the local electricity rates, as they represent the homeowner's option for purchasing electrical power rather than producing it. In Utah, Rocky Mountain Power serves a majority of the state and offers various rates for multiple tiers at different time of the year. Although Provo, Blanding, and St. George have separate municipal utilities, each city in this analysis is evaluated using the same rate schedule so that the comparison is only between cities with different levels of solar availability and electrical demand.

Residential units follow Schedule 1 and the corresponding electricity rates are shown in Table 3. The electricity rates are used to calculate the annual electricity bills, which are part of the levelized cost of electricity equation.

Table 3: Residential electricity price in Utah [38].

	Range	Rate ($/kWh)
May through September	1st 400 kWh	0.0885
	Next 600 kWh	0.1154
	All additional kWh	0.1445
October through April	1st 400 kWh	0.0885
	All additional kWh	0.1071

3.2.1. *PV Systems without Energy Storage*

The method to calculate the LCOE of PV Systems without energy storage is described in Section 2.1.1. Table 4 and Figure 5 display the results for calculated LCOE values under different selling scenarios for different cities in Utah. Under the net metering scenario, the incentive rates for excess PV energy conversion are equivalent to the electricity rate in Table 3, according to Schedule 135 [39]. Conversely, wholesale electricity rates vary dynamically and thus are real time data. Since Rocky Mountain Power does not provide real time wholesale electricity prices in Utah, California ISO (CAISO) data are utilized for estimating the wholesale electricity prices [40]. It is important to note that California has more renewables on the grid than Utah because California has adopted renewable portfolio standards (RPS) to increase power generation from renewable energy. On the contrary, Utah does not have a binding RPS. In this study, the real time wholesale electricity prices are adjusted based on the weighted residential electricity prices in Utah and California [41]. Even though the estimated wholesale electricity prices in Utah are not representative of the actual prices, they are used as approximations of how much electricity costs might vary in real time in Utah, particularly if Utah did integrate more electricity generation from renewables. Furthermore, it is important to note that the electricity wholesale market in Utah is only for generators with a minimum power capacity of 200 kW. As a result, the residential rooftop solar PV systems will not qualify for participation in the wholesale market. However, this portion of the study assumes that PV homeowners can participate in the wholesale market. This is to establish a mathematical framework for calculating LCOE under the wholesale pricing policy. Thus, the framework can be applied to different locations in the case that wholesale market participation was possible for generators with a power capacity below 200 kW.

In each city in Utah, as expected, the LCOE under a no payback scenario is the highest since there is no credit or compensation for excess PV electricity that is produced and exported by PV customers. The LCOE under a wholesale pricing scenario is lower than with the no payback scenario, meaning that each kWh produced costs less to the homeowner, because this scenario allows the homeowner to receive compensation. However, the LCOE for wholesale pricing is higher than the LCOE for net metering. This is due to the fact that the electricity wholesale prices are often less than the electricity utility price. As a result, consumers effectively receive less when excess electricity is sold at wholesale because they purchase electricity at retail, a higher price than wholesale. The differences between the LCOEs under wholesale pricing scenario and the LCOEs under net metering scenario are different across 12 locations, although the difference is usually less than \$0.01/kWh, as shown in Figure 5.

3.2.2. PV Systems with Energy Storage

An electrical battery is used to store and release electrical energy according to the simple control scheme shown in Figure 6. The charging and discharging scenarios are determined based on the net energy (E_{net}). The battery is charged when the PV energy conversion is greater than the electrical load and the battery is not fully charged. Once the battery is fully charged, the excess PV energy conversion is sent to the grid. Battery discharging occurs when there is electrical demand and the battery level is above the minimum discharge level. To ensure the long-term reliability of the battery, the minimum allowable discharge level is set to be 20% in this study.

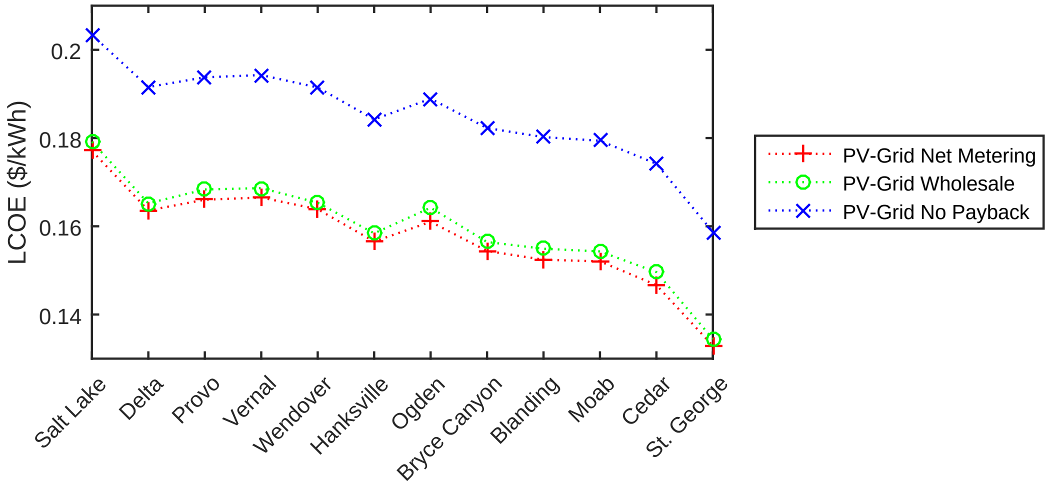


Figure 5: LCOEs of PV systems without energy storage under different scenarios.

Table 4: LCOE of PV generation without energy storage at major locations in Utah [41].

	PV-Grid Net Metering ($/kWh)	PV-Grid Wholesale Pricing ($/kWh)	PV-Grid No Payback ($/kWh)
Salt Lake	0.1771	0.1792	0.2034
Delta	0.1636	0.1652	0.1916
Provo	0.1660	0.1683	0.1938
Vernal	0.1665	0.1687	0.1943
Wendover	0.1639	0.1653	0.1915
Hanksville	0.1565	0.1584	0.1842
Odgen	0.1610	0.1642	0.1889
Bryce Canyon	0.1544	0.1564	0.1823
Blanding	0.1524	0.1549	0.1802
Moab	0.1520	0.1543	0.1794
Cedar	0.1467	0.1496	0.1742
St. George	0.1329	0.1344	0.1587
Weighted electricity price in Utah	$0.1129/kWh		

From consumers' viewpoints, the initial outlay in terms of capital costs is an important concern for decision making about PV installations. Annual electricity bills give the impression of monetary savings from installing PV systems, indicating a return on their investment. Figure 7 illustrates the annual electricity bills (calculated using the rates in Table 3) for the 12 locations in Utah under each of the three selling scenarios both without (PV-Grid) and with (PV-ES-Grid) electrical energy storage.

Using the residential electrical loads and the local electricity price, homeowners in Utah without PV systems would expect to pay approximately between $800 and $1,000 every year for electricity bills. The electricity bills in St. George are substantially higher because the city is located in a hot climate where there is more electricity demand in summer for

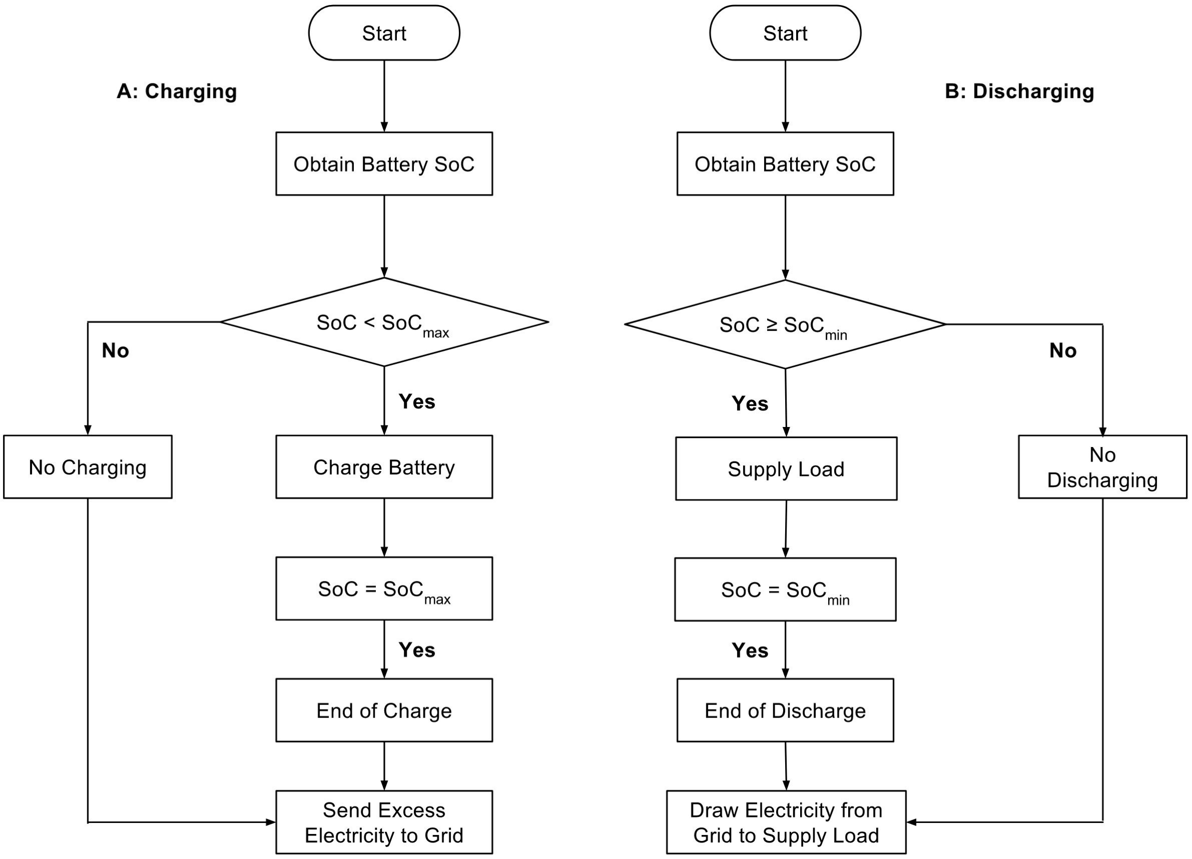


Figure 6: Battery control scheme: Charging (A) and Discharging (B).

cooling than in the other cities considered. With the addition of solar PV panels, the annual electricity bills drop significantly (ranging between 30% and 75% reduction) among all scenarios, as seen in Figure 7. Comparing all three selling policies, the net metering policy (PV-Grid and PV-ES-Grid Net Metering) offers the most reduction in terms of annual electricity bills because PV homeowners receive the most credit from excess PV generation. It is important to note that this might not be the case if the PV system were larger (more electricity conversion) or if the homeowner did not use all of the utility credits received (less electricity consumption).

When comparing the potential benefits of energy storage on the annual electricity bills, the no payback policy shows the most notable difference between the annual electricity bill with and with energy storage. In the case of PV systems with no payback option, having energy storage (PV-ES-Grid No Payback) reduces the annual electricity bills even more (up to 10% additional reduction), compared to those without energy storage (PV-Grid No Payback). However, the situation is opposite under net metering scenario. Under the net metering policy, the annual electricity bills with energy storage (PV-ES-Grid Net Metering) are higher than the annual electricity bills without energy storage (PV-Grid Net Metering). Since consumers receive utility credit for excess PV generation, the grid is acting as long-

Table 5: Capital costs and annual electricity bills.

Location	Capital Cost of PV System		Annual Bill						
				Net Metering		Wholesale		No Payback	
	PV	PV-ES	Only Grid	PV-Grid	PV-ES-Grid	PV-Grid	PV-ES-Grid	PV-Grid	PV-ES-Grid
Salt Lake	17,588.51	18,838.51	817.73	288.42	309.71	308.30	328.78	540.83	445.80
Delta	17,484.72	18,734.72	812.91	254.25	275.21	270.61	291.67	537.63	439.93
Provo	17,376.61	18,626.61	807.88	258.78	279.92	281.88	299.14	535.02	435.75
Vernal	17,262.78	18,512.78	802.59	258.31	280.51	279.36	296.46	532.28	432.71
Wendover	17,599.26	18,849.26	818.23	256.63	279.04	271.57	293.68	537.64	434.85
Hanksville	18,161.20	19,411.20	844.36	244.77	267.18	265.04	284.87	545.68	440.19
Ogden	17,569.57	18,819.57	816.85	248.78	269.73	281.79	297.97	536.23	435.22
Bryce Canyon	16,215.59	17,465.59	816.73	259.38	282.89	279.89	306.13	540.96	437.06
Blanding	16,093.84	17,343.84	810.59	252.14	274.06	277.36	294.48	533.57	432.67
Moab	16,203.96	17,453.96	816.14	252.84	275.89	275.90	295.53	532.14	424.72
Cedar	15,934.34	17,184.34	802.56	233.90	257.20	264.16	282.98	517.48	410.18
St. George	18,918.85	20,168.85	952.88	228.27	252.04	248.57	269.97	567.34	444.06

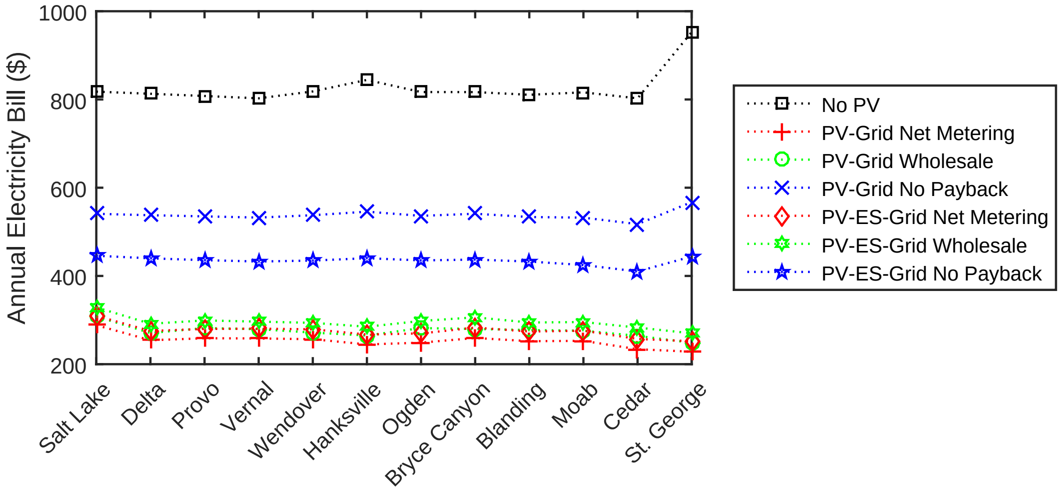


Figure 7: Consumers' annual electricity bills without PV and with PV under 3 different scenarios, both without and with energy storage.

term "energy storage" for consumers. On the other hand, on-site customer-purchased energy storage has the same purpose, along with the added difficulties of increased capital costs and maintenance, and losses due to inefficiencies during charging and discharging. Finally, under the wholesale pricing policy, the annual electricity bills with and without energy storage are almost identical. This is again due to the inefficiencies of energy storage and lower wholesale payment (compared to receiving utility credit under the net metering policy). In short, when the annual electricity bills are considered, having energy storage with the PV system yields no economic benefits if the net metering policy or wholesale pricing policy is in place.

While the annual electricity bills provide the annual monetary savings from having PV systems (with or without energy storage), the LCOEs are more informative in terms of the long-term benefits because LCOEs include the total lifetime cost and the total lifetime energy consumed. The time value of money is also included in the form of the discount rate. Figure 8 compares the LCOEs of PV systems with and without energy storage under 3 scenarios. Under no payback scenario, the LCOEs of PV systems with energy storage are lower than the LCOEs of PV systems without energy storage. In this scenario, energy storage is beneficial since excess PV energy conversion can be stored and used later. Contrarily, adding energy

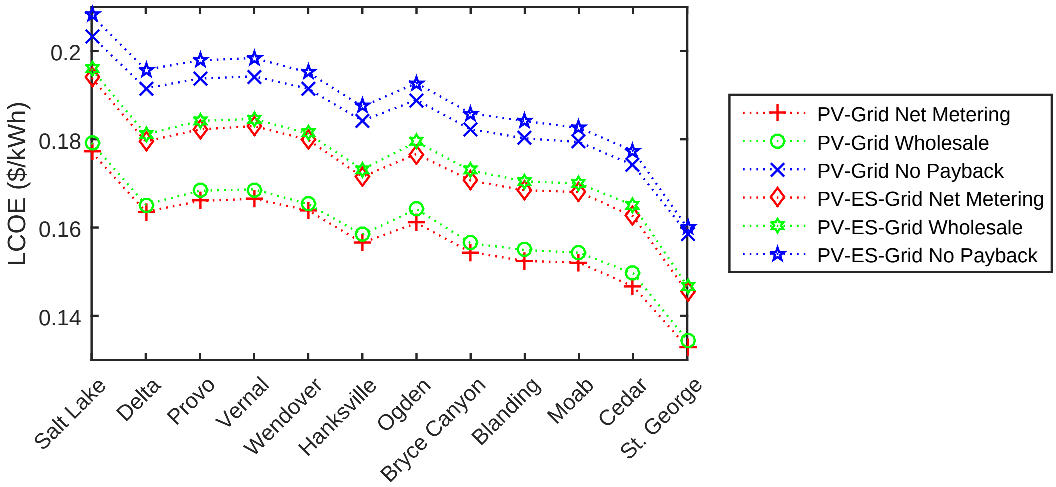


Figure 8: LCOEs of PV systems under 3 different scenarios, both without and with energy storage.

storage to PV systems under a net metering scenario or wholesale pricing scenario increases the LCOEs. The reasons for the high LCOEs are due to the high price of energy storage and low price of electricity in Utah. Furthermore, under the no payback policy customers do not benefit from the credits received for excess PV electricity generation. As a result, under net metering policy or wholesale pricing policy, there is little economic incentive for energy storage, given the current affordable electricity rate in Utah.

3.2.3. Maximum Allowable Capital Cost Investment for Financial Benefits

As mentioned in Section 3.2.1 and 3.2.2, the LCOEs of PV systems in the 12 study locations are higher than the weighted electricity price in Utah. The high capital costs of the PV systems are the main contributor the the high LCOEs. This section illustrates the capital cost investment as a function of electricity rate in Salt Lake City and St. George under the net metering and no payback policies. Plots for other locations can be constructed in a similar manner.

Using the simple payback period, the maximum allowable capital cost investments at different electricity rates are calculated based on electricity bill savings and acceptable payback periods (PBP). Figure 9 and 10 show the maximum allowable capital cost investment for PV systems without energy storage in Salt Lake City and St. George, respectively. On the other hand, the allowable capital cost investment for PV systems with energy storage in Salt Lake City and St. George is shown in Figure 11 and 12, respectively. Using the electricity rate ($0.0885/kWh), the maximum allowable capital cost investments of PV systems without energy storage in Salt Lake City under the net metering policy (Figure 9 left) are $10,500 for a PBP of 20 years, $13,200 for a PBP of 25 years, and $15,800 for a PBP of 30 years. To put this into perspective, the capital cost of a PV system without energy storage in Salt Lake City is $17,588.51, as seen in Table 5. Comparing to the net metering policy in Salt Lake City, the maximum allowable capital cost investment under the no payback policy is even lower. This is due to the smaller electricity bill savings under the no payback policy. On the other hand, the maximum allowable capital cost investments of PV systems without energy storage in St. George under the net metering policy (Figure 10 left) are \$14,500 for a PBP of 20 years, \$17,900 for a PBP of 25 years, and \$21,800 for a PBP of 30 years. The capital cost of a PV system without energy storage in St. George is \$18,918.85. The maximum allowable capital cost investment in St. George is higher than that of Salt Lake City, which means that there is more potential for accumulated electricity bill savings in St. George than Salt Lake City.

Adding the energy storage into the PV systems, the maximum allowable capital cost investment under the net metering policy is lower compared to that of PV systems without the energy storage. This is because the energy storage does not provide electricity bill savings (Table 5), which reduces the maximum allowable capital cost investment. However, the situation is opposite under the no payback policy. Even though there is still an additional capital cost of the energy storage, it can be used to stored the excess PV generation, which ultimately increases the electricity bill savings. In short, the maximum allowable capital cost investment shows the threshold of installing the PV system. It depends on acceptable payback periods and electricity bill savings. A higher maximum allowable capital cost investment allows for more opportunities for electricity bill savings.

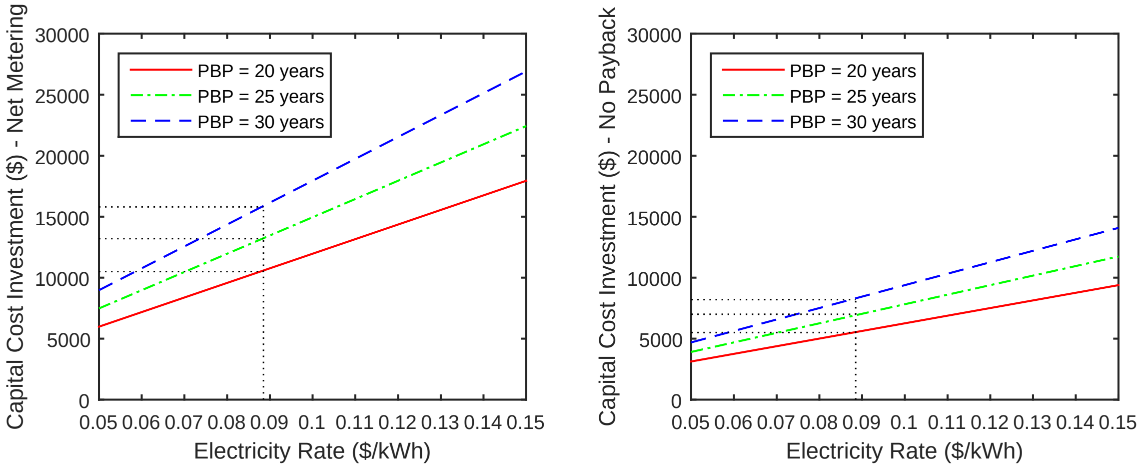


Figure 9: Capital cost investment as a function of electricity rate with varying payback period (PBP) for PV systems without energy storage in Salt Lake City: Net metering (left) and No payback (right).

3.3. The Role of Energy Storage in Residential Solar PV Systems from Grid Operators' Perspectives

This section highlights results from integrating energy storage with residential solar PV systems from the grid operators' viewpoints. There are three main aspects of the test system (IEEE 123 Node Test Feeder) used in this section: the test system under normal operating conditions, the test system under three PV penetration scenarios, and the test system with energy storage present in residential solar PV systems. Under normal conditions (no PV penetration from residential solar PV systems), phase voltages at the feeder over the course of a day are presented in Figure 13 and Figure 14. The first plot shows the phase voltages

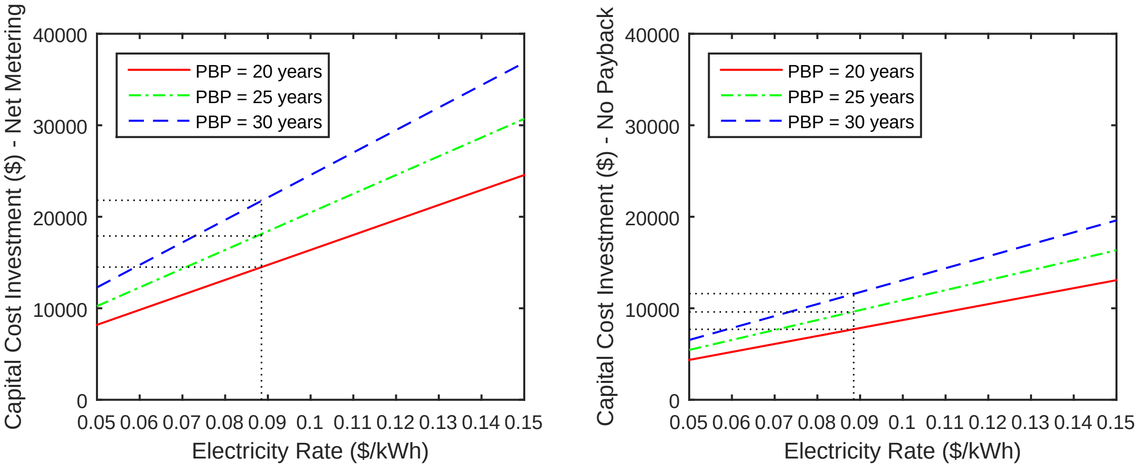


Figure 10: Capital cost investment as a function of electricity rate with varying payback period (PBP) for PV systems without energy storage in St. George: Net metering (left) and No payback (right).

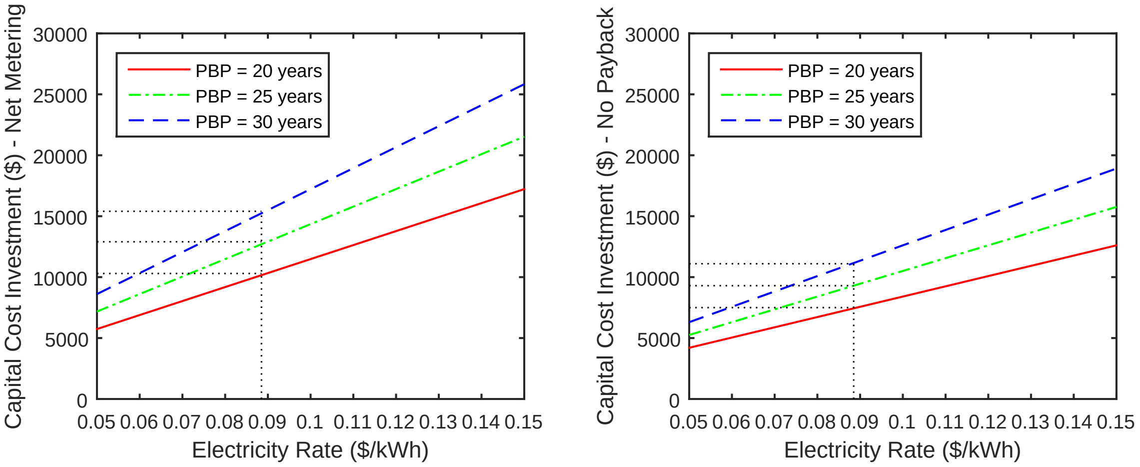


Figure 11: Capital cost investment as a function of electricity rate with varying payback period (PBP) for PV systems with energy storage in Salt Lake City: Net metering (left) and No payback (right).

in conventional system terms (Volt), whereas the second plot illustrates the phase voltages in a per-unit system (p.u.).

In the second aspect of the test system, PV generation from residential rooftop systems is injected at different percentages, and an instantaneous analysis is performed for each hour of the day. PV generation at levels of 10%, 30%, and 50% of the active power in the test system were studied in this paper. The percentages are calculated based on the total active power in the test system. These percentages represent the additional electricity generation that comes from the rooftop residential PV systems, that would not have been generated by those homeowners if there was no PV in place. Figure 15 shows the effects of PV generation on the feeder phase voltages. As the percentage of PV generation increases, the phase voltages also increase. Even though the phase voltages are still within the safe operating range (0.95 p.u. to 1.05 p.u.), the rise in phase voltages causes the nominal voltage (Figure 16) to slowly

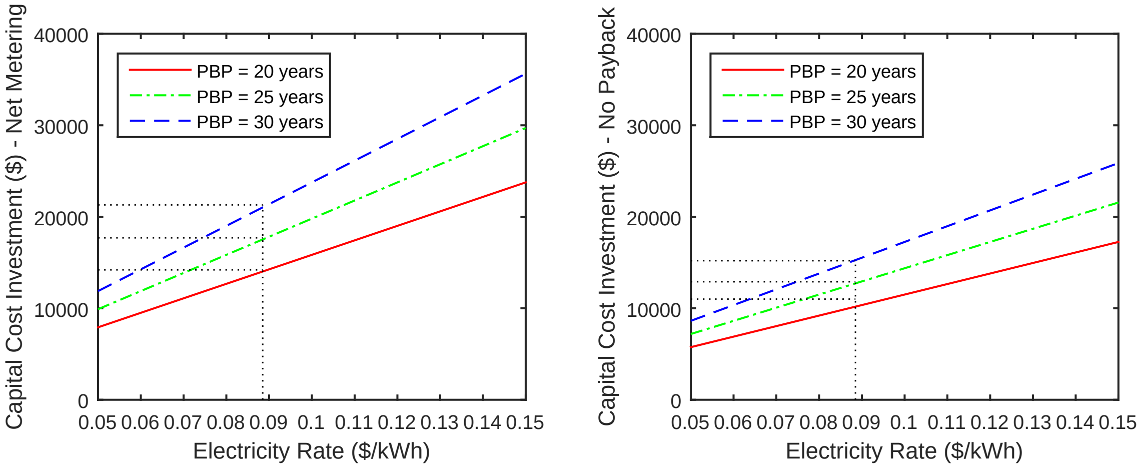


Figure 12: Capital cost investment as a function of electricity rate with varying payback period (PBP) for PV systems with energy storage in St. George: Net metering (left) and No payback (right).

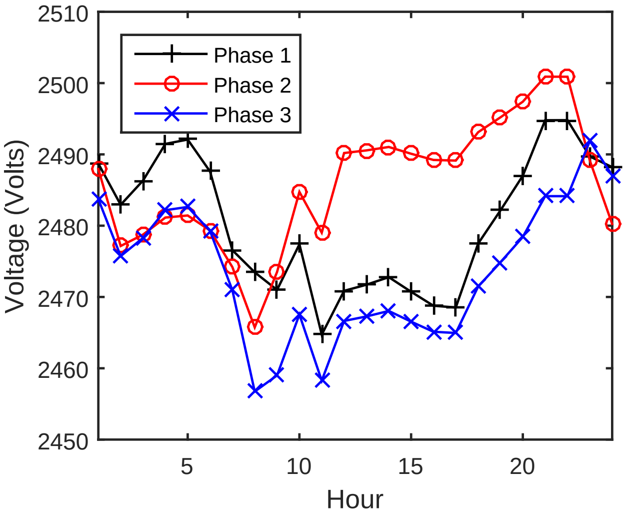


Figure 13: Phase voltage magnitudes at the feeder end.

approach the upper limit (1.05 p.u.), which can be a concern for grid operators.

Electrical energy storage can be used to mitigate voltage rise caused by excess PV generation, as seen in Figure 17 and Figure 18. In these figures, PV injection at 50% is studied both without and with energy storage. Energy storage allows excess PV energy conversion to be stored locally, rather than sent back to the grid, which can cause voltage increases that may be problematic for grid operators. The addition of energy storage in residential solar PV systems decreases the phase voltages significantly, reducing them down to the level of the base case when there is no PV generation. The nominal voltage is also reduced as a result of decreasing phase voltages. In short, the results from this analysis suggest that residential rooftop PV systems with energy storage are favorable for the electrical grid when

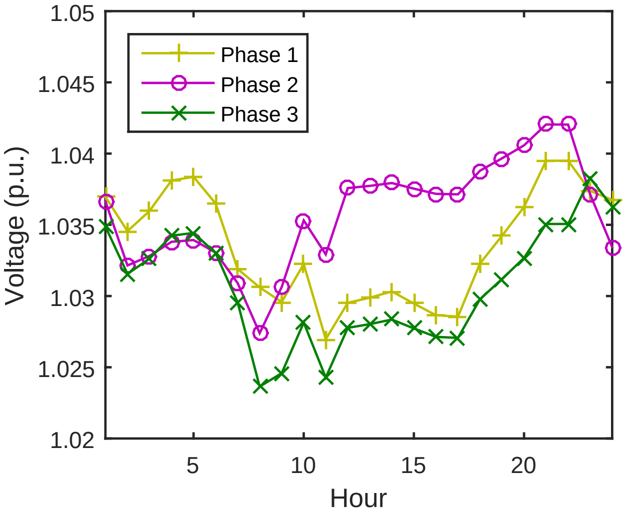


Figure 14: Phase voltages per unit at the feeder end.

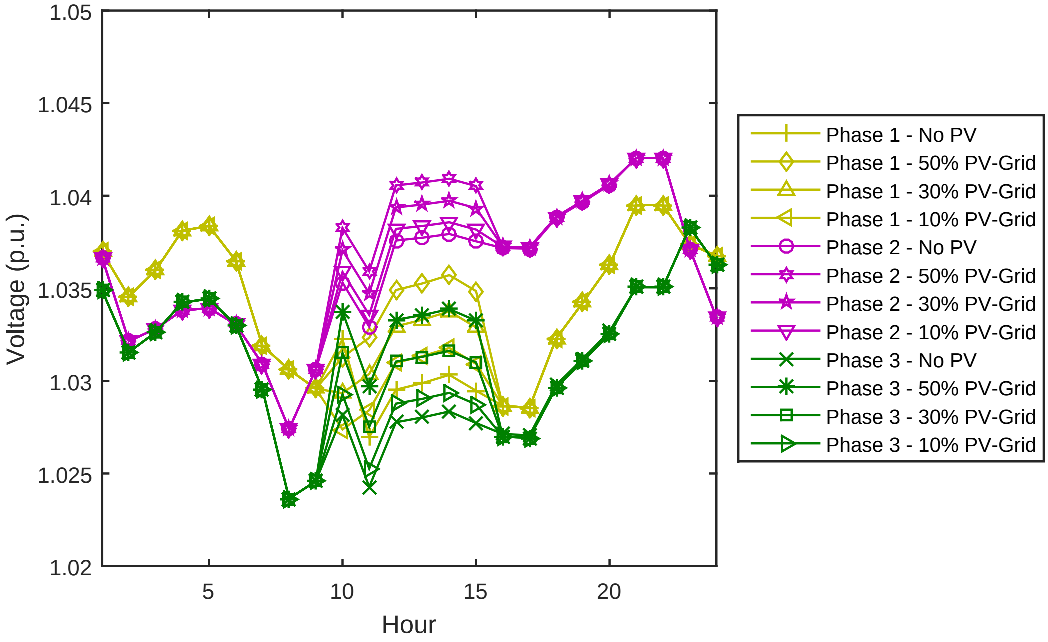


Figure 15: Comparing phase voltages (p.u.) at the feeder end with and without PV generation.

energy storage can alleviate the voltage rise issues. It is important to note that energy storage currently would not offer PV homeowners in Utah with substantial financial benefits in terms of LCOE under the net metering and wholesale pricing policies. However, under the aforementioned conditions the presence of energy storage in a residential solar PV system can provide the grid operators with benefits, potentially preventing the phase and nominal voltages from rising out of the safe operating range.

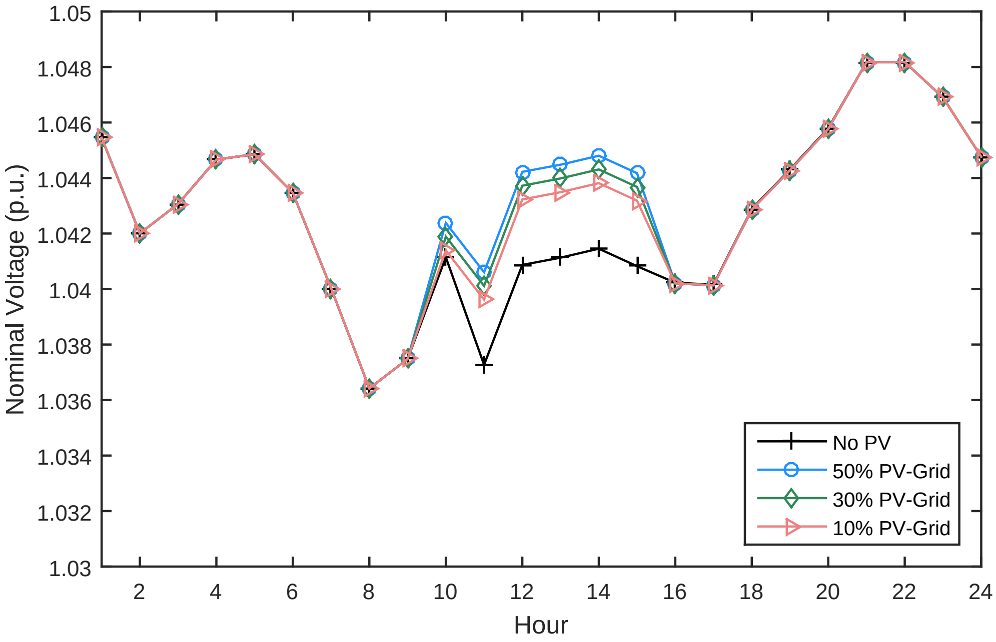


Figure 16: Comparing nominal voltage (p.u.) at the feeder end with and without PV generation.

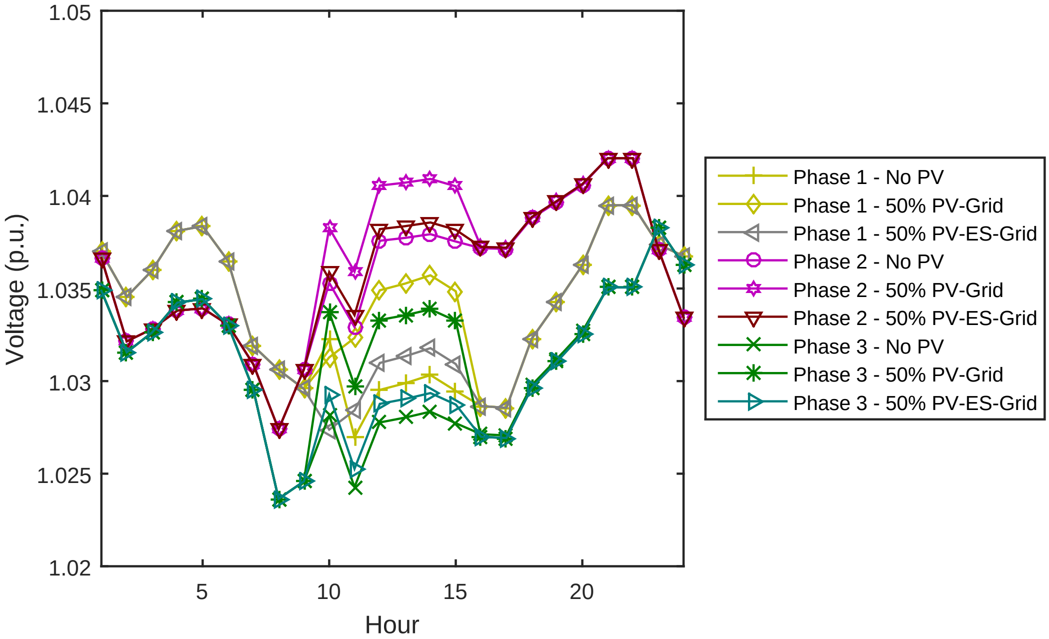


Figure 17: Impacts of energy storage on phase voltages (p.u.) at the feeder end.

3.4. Sensitivity Analysis

A sensitivity analysis is performed on the PV model to identify the impacts of varying input values for system parameters on the LCOEs of the PV systems. PV panel unit price,

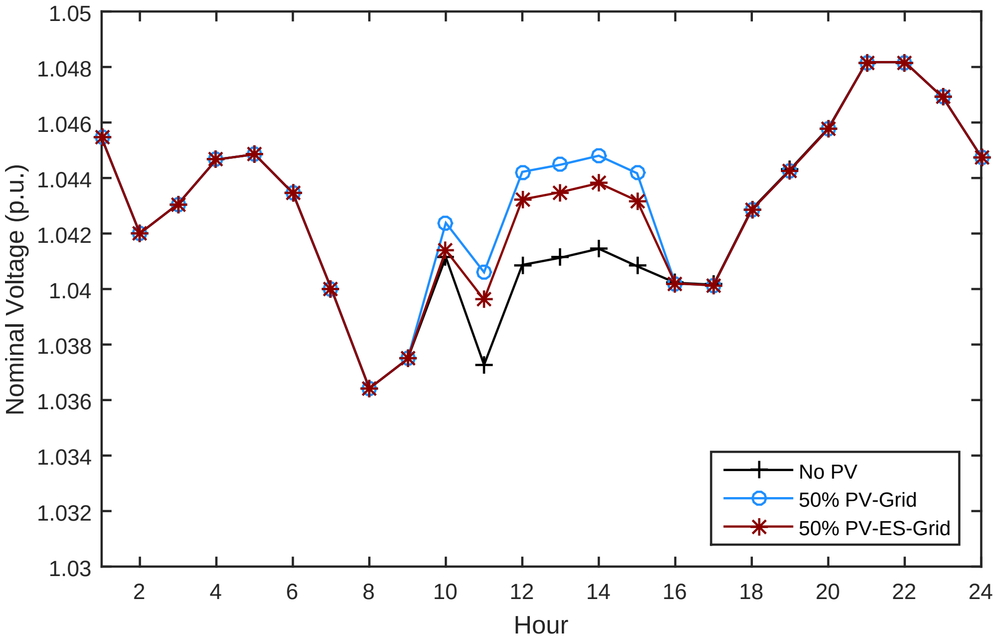


Figure 18: Impacts of energy storage on nominal voltage (p.u.) at the feeder end.

panel efficiency, battery unit price, and electricity rate are studied in this section. For simplicity, the LCOEs of PV systems with energy storage under 3 different selling scenarios are illustrated here for Salt Lake City and St. George only, while varying these system parameters. The LCOEs at other locations can be analyzed in the same manner. Table 6 details the range used for varying the system parameters.

Table 6: System parameters varied as part of the sensitivity analysis.

Parameters	Range	Design Value
PV panel unit price (\$/W)	1.0 - 5.0	3.0
PV panel efficiency (%)	13 - 20	15
Battery unit price (\$/kWh)	300 - 370	350
Electricity rate (\$/kWh)	0.0885 - 0.1585	0.0885

The effect of varying the PV panel unit price on the LCOEs is shown in Figure 19. The unit price of PV panels directly influences the capital cost of the system. A higher PV panel unit price results in higher capital cost, which increases the LCOEs. Reducing the PV panel unit price from \$5.0/W to \$1.0/W can lower the LCOEs between \$0.15/kWh and \$0.19/kWh, as seen in Figure 19. Furthermore, Figure 20 shows how the LCOEs change while varying the PV panel efficiency. More efficient panels reduce the capital cost of the system (for a given power output). According to the simple sensitivity analysis, increasing the solar panel efficiency from 13% to 20% reduces the LCOEs by as much as \$0.10/kWh. In terms of energy storage unit price, the reduction in LCOE is modest (Figure 21). Even

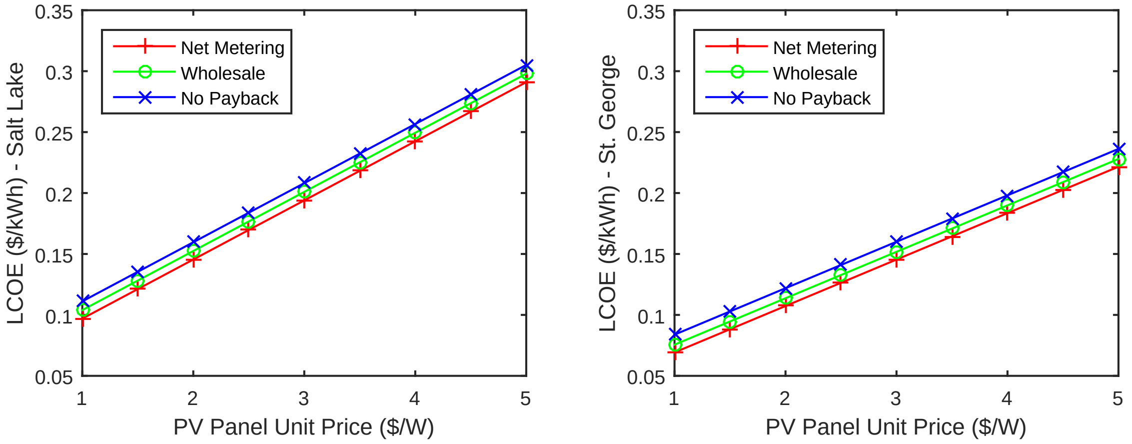


Figure 19: LCOEs of residential solar PV systems with energy storage under varying PV panel unit price: Salt Lake City (left) and St. George (right).

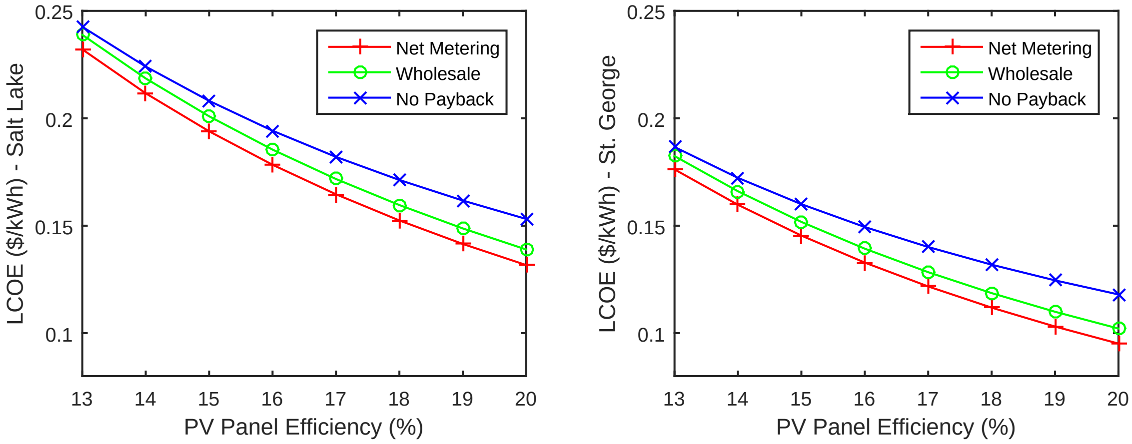


Figure 20: LCOEs of residential solar PV systems with energy storage under varying PV panel efficiency: Salt Lake City (left) and St. George (right).

though the addition of energy storage introduces extra capital cost, this increase is relatively small compared to the total lifetime cost of the whole PV system.

The effect of varying the electricity rate on the LCOEs is shown in Figure 22. As the electricity rate increases from $0.0885/kWh to $0.1585/kWh, the LCOEs under different selling scenarios in Salt Lake increase between $0.0255/kWh and $0.0367/kWh. Similarly, the LCOEs in St. George also rise between $0.0152/kWh and $0.0267/kWh under the same range of electricity rates. It is important to realize that the rate of LCOE increase is smaller than the rate of the electricity rate increase. This indicates that the LCOE and the electricity rate will eventually become equal. Furthermore, the wide range of electricity prices in the sensitivity analysis can be used to illustrate LCOEs of PV systems with similar design parameters (Table 2) at different electricity rates. Thus, the results from this study can be used for a broader analysis in locations outside of the 12 case study locations in Utah.

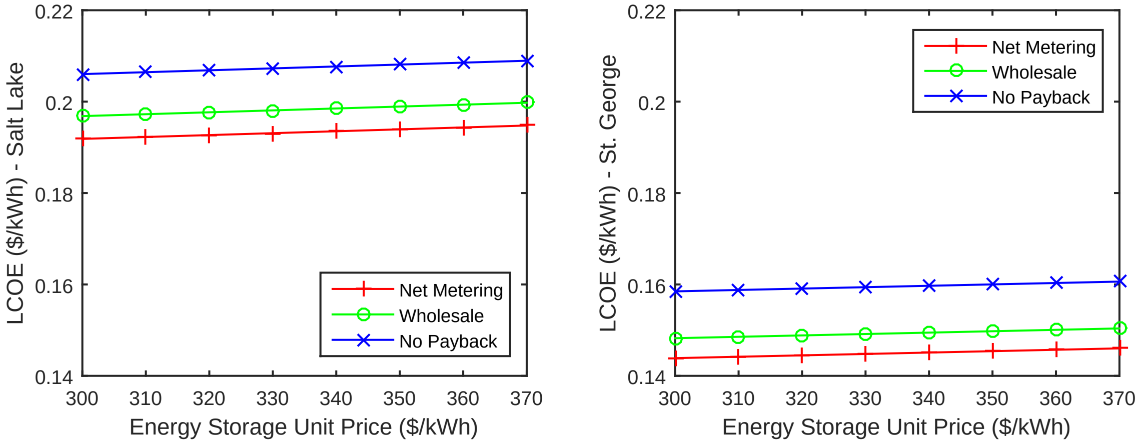


Figure 21: LCOEs of residential solar PV systems with energy storage under varying battery unit price: Salt Lake City (left) and St. George (right).

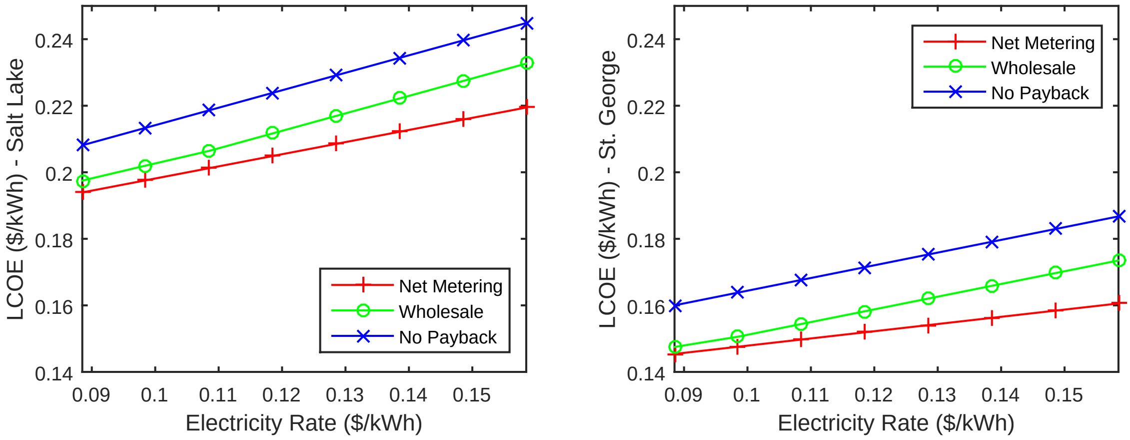


Figure 22: LCOEs of residential solar PV systems with energy storage under varying electricity rate: Salt Lake City (left) and St. George (right).

Comparing the LCOEs of residential PV systems in Salt Lake City and St. George, the changes in PV panel unit price, PV panel efficiency, and battery unit price are more impactful for Salt Lake City (with lower annual irradiation) than St. George (with higher annual irradiation). This is because the LCOEs at St. George are already lower than those at Salt Lake City at the design values. Therefore, the rate of LCOE reduction is more substantial for Salt Lake City than St. George. However, the LCOEs from the sensitivity analyses for St. George would reach grid parity once the panel unit price approaches $2.0/W, while the LCOEs for Salt Lake City remain higher than weighted average electricity price in Utah ($0.1129/kWh) unless the panel unit price is below $1.5/W. Nonetheless, the system LCOEs can significantly benefit from cheaper and more efficient components.

4. Conclusions

Residential rooftop PV systems and options for selling excess PV conversion have been investigated in this paper. Three selling scenarios are studied: net metering, wholesale pricing, and no payback for excess PV energy conversion. The integration of energy storage is also thermo-economically considered for systems in Utah as case studies. The analysis in this paper lays the groundwork for incorporating LCOE calculation for residential PV systems at locations of interest with corresponding data for solar potential and local price of electricity.

The addition of PV systems reduces the annual electricity bill (up to 75% reduction). A net metering policy offers PV homeowners with the most benefit in terms of annual electricity bills. However, the addition of energy storage under the net metering and wholesale pricing policies increases the annual electricity bills compared to similar systems without energy storage. This is due to losses associated with charging and discharging the battery.

Additionally, the effective LCOEs over the lifetime of the panels are still higher than the weighted electricity price ($0.1129/kWh) [41]. The LCOEs for 12 locations in Utah range from $0.1329/kWh – $0.1771/kWh under the net metering policy, from $0.1344/kWh – $0.1792/kWh under the wholesale pricing policy, and from $0.1587/kWh – $0.2034/kWh under the no payback policy. This underscores the importance to the homeowner of understanding the policies for selling back electricity, because the same home with the same electrical demand and PV system will have very different levelized costs under the different scenarios considered.

Locations with high annual solar irradiation (e.g. St. George, Cedar City, and Moab) have lower LCOEs compared to other locations with low annual solar irradiation (e.g. Salt Lake and Provo). Only PV homeowners under the no payback policy receive economic benefits as a result of installing energy storage. Energy storage offers no benefit to the PV homeowners under the net metering and wholesale pricing policies. If there is net metering or wholesale pricing, PV homeowners are better off without energy storage. This is because the price of energy storage is high, while the price of purchased electricity is relatively low. Lowering the capital cost of the system (i.e. cheaper PV panels per unit of capacity) and investing in improved technology (i.e. more efficient PV panels) can significantly reduce the LCOEs.

Moreover, the impacts of excess PV generation on a test electrical distribution system have also considered. The distribution network with the PV systems can lead to phase voltages and the nominal voltage rising during events of high PV penetration. The result of voltage rise can cause instability in the distribution network. The addition of energy storage attenuates the voltage rise, which enhances the reliability of the electrical distribution network. As discussed previously, energy storage is beneficial for PV homeowners under the no payback policy while it increases the costs for PV homeowners under the net metering and wholesale pricing policies. From both consumers' and operators' points of view, energy storage can offer benefits, increasing the stability of the grid while also increasing the cost of ownership for PV systems.

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Abbreviations

ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CAISO	California Independent System Operator
EIA	Energy Information Administration
EPRI	Electric Power Research Institute
ES	Energy Storage
IECC	International Energy Conservation Code
NREL	National Renewable Energy Laboratory
PBP	Payback period
OpenDSS	Open Distribution System Simulator
O&M	Operations and maintenance

Nomenclature

η	Solar PV efficiency (%)
A	Solar PV panel area (m^2)
C	Cost ($)
E	Energy (kWh)
I	Solar irradiation ($\mathrm{kWh/m}^2$)
$LCOE$	Levelized cost of electricity ($/kWh)
n	Annual electricity bill payment (Year)
PR	Performance ratio (%)
$R_{utility}$	Utility electricity price ($/kWh)
$R_{wholesale}$	Wholesale electricity price ($/kWh)

Subscripts

$_{bill,annual}$	Annual electricity bill
$_{capital}$	Capital cost
$_{ES}$	Energy storage (battery) system
$_{invt}$	Inverter
$_{misc}$	Miscellaneous
$_{PVonly}$	PV system without energy storage
$_{PV+ES}$	PV system with energy storage
$_{net}$	Net energy
$_{load}$	Electrical load

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