

Assessing the Feasibility of Large-Scale Adoption of Solar Power in the Residential Sector

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Abstract—India is expected to transition towards a future with wide spread deployment of solar power. Hence, it is necessary to understand the technical, economic and policy related issues that are involved in facilitating this transition. This paper outlines preliminary investigations geared towards assessing the impacts of maximizing the use of solar energy at residential consumer level. Detailed simulations are performed for a hypothetical residential building to quantify how much fraction of the demand can be supplied via energy from its rooftop solar panel. Studies indicate that a large fraction of demand (more than a third) can be met by solar only when combined with a suitable storage technology such as a battery. Since panels and batteries require significant investment, the paper also presents comprehensive economic and policy analysis to evaluate the role of subsidies and tariffs in enabling homeowners to adopt solar energy.

I. INTRODUCTION

India is a developing country facing energy adequacy problems due to supply deficits, decrease in fossil fuel reserves and steep increase in fuel prices. The country is also facing challenges related to environmental issues, energy security and energy access. Renewable energy sources such as wind and solar are expected to mitigate these challenges. Since the potential of wind power (≈ 300 GW at 100m height [1]) is lower than the solar power potential (≈ 750 GW [2]), solar energy resources have received a significant attention in India. Indeed, the world's largest solar photovoltaic (PV) project is also in India [3]. The Jawaharlal Nehru national solar mission launched in 2010 with a target of installing 22 GW solar power by 2022 has already lead to a considerable growth in the installed solar capacity with more than 7.5 GW added in last 6 years [4]. A critical question that needs to be immediately answered is whether we can meet a large fraction of our energy needs with solar resources. Also needed is an understanding of the technical, economic and policy considerations involved in facilitating this development. This paper presents preliminary investigations geared towards answering these questions

The deployment of solar energy resources to meet electrical demand has received considerable attention in the past two decades. The literature pertaining to residential can be classified into four main categories. The first category encompasses literature concerned with sizing of solar resources (see for instance, [5] and [6]), wherein the emphasis is on

choosing combinations with lower investment costs or life cycle costs. The second category concerns with research on optimal management of solar PV systems (with batteries and/or other sources such as diesel generators) for meeting demand; examples in this category include [7], [8] and [9], where the focus is minimizing electricity costs. Literature in the third category documents assessment of impacts of wider penetration of solar power in networks, with focus on associated voltage fluctuations (see [10] and [11] for more details). And finally, the fourth category covers policy analysis pertaining to solar adoption; a general consensus is that feed-in tariffs and policy driven renewable targets are the key enablers for large-scale deployment of solar energy [12], [13], [14].

While the know how available today can help India transition towards a future with more solar power integrated into its residential distribution networks, not much is known on how to extract the most out of solar resources. In particular, the technology enablers necessary to meet a large fraction (more than a third) of residential demand using solar power are not precisely known. Also, there is lack of understanding on what role economics and policy will play in promoting large scale use of solar. This paper outlines preliminary investigations focusing on these two important questions.

This paper focuses on the residential consumers and investigates the potential ramifications of using rooftop solar PV for meeting large fractions of residential loads. Specifically, a hypothetical residential building is considered and suitable load and solar PV output profiles are generated for the same. Detailed simulations and sensitivity studies are performed to assess how much fraction of the demand can be supplied via solar PV. Studies are also performed using the industry standard Hybrid Optimization Model for Electric Renewable (HOMER) to understand the economic and technical considerations involved. HOMER-based sensitivity studies allow investigations concerning the role of tariffs and subsidies in facilitating adoption of solar power by residential consumers.

The contributions of this paper are two-fold. It is conclusively illustrated via simulations that solar power can contribute towards large fraction of load only when appropriate storage technology is available. And it is demonstrated that capital subsidies play a vital role in making investment in solar-PV-cum-battery systems worthwhile.

The rest of this paper is organized as follows: the hypothetical residential customer is described in Section II. An assessment of the potential of solar PV with batteries to contribute towards residential demand is described in Section III. A detailed technical, economic and policy analysis concerning large scale use of solar is presented in Section IV and concluding remarks are discussed in Section V.

II. THE RESIDENTIAL CUSTOMER MODEL

The analysis carried out in this paper requires load and solar output profile for the residential consumers. Due to lack of historical data, the studies in this paper use synthetically generated load profiles which reflect the characteristics of loads considered. For generating this data, a location in Mumbai with latitude and longitude of 18.9750^0 N and 72.8258^0 E, respectively is considered. Hourly load and solar data are generated for the representative days considering weekdays and weekends with different seasons to simulate the impact over an entire year. The specific methodology used for obtaining these load and solar output profile is described in this section.

A. Load Profile

A bottom-up approach is adopted for generating daily, seasonal and annual load profiles. This requires information regarding the type of house, occupancy patterns (number of persons, working hours), type of appliances and their rating, seasonal information and usage pattern (different for weekdays and weekends). For the simulations reported here, a three bedroom independent house occupied by three adults and a child considered. A day is divided into time slots that demarcate the occupancy and usage patterns, as listed in Table I. A certain number of common electrical appliances, listed in Table II, are assumed to be present in the house. The bottom-up approach involves multiplying the power rating of the appliances by the number of hours of operation [15]. Using this approach and assuming standard consumer activities, electrical load curves for the residential consumer is generated.

The usage of electrical appliances varies on weekdays and weekends. Moreover, seasonal variations are also possible. All these are considered while generating representative load profiles for analysis. In this paper, six patterns are considered corresponding to whether the day is a weekend or weekday and the three – summer, winter and rainy – seasons. The usage of electrical appliances in the time slots specified in table I depends also on different types of occupancy scenarios. Due to the lack of data for appliance usage, certain assumptions have been made for occupancy in the house [16]. The house is assumed to be occupied all the time, but occupancy patterns change with time slots and limited number of appliances are used at any given time. The load profiles generated in this

TABLE I: Time slots for a day

Time slot	From	To
Before wakeup	10 PM	5 AM
After wakeup and before office	5 AM	9 AM
Office hours	9 AM	6 PM
After office and before sleep	6 PM	10 PM

TABLE II: Appliance details for the house under consideration

Appliance	No.of Appliance	Rating (W)
Light	15	30
Fan	9	50
Fridge	1	150
Television	1	100
Washing Machine	1	1200
Air Conditioner	2	1900
Rice cooker	1	1000
Security lamp	2	18
Water heater	1	1000
Iron	1	1100
Personal Computer	1	120

manner for the weekdays and weekends for three different seasons are shown in the Fig. 1.

Notice that the load profiles exhibit typical load behavior. For instance, the load during the “office hours” is higher on weekends than weekdays, in all seasons. Furthermore, the load in the winter season for weekdays and weekends is almost identical with the peak occurring in the morning and in the evening. This is not the case during summer, where weekday and weekend patterns differ significantly and peak load occurs once each in the morning, evening and at night. In the rainy season, the load pattern is quite similar to load pattern in the winter with slight change in the peak in the evenings.

B. Solar Photovoltaic Output

The power generation from the solar PV can be calculated from the solar radiation incident on the panel. The incident

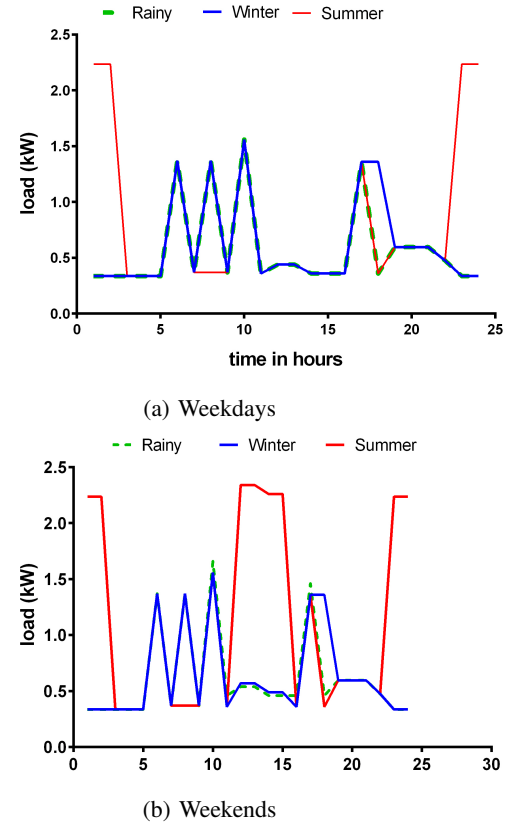


Fig. 1: Load curves for different seasons

solar radiation can be found from the extraterrestrial solar radiation, its declination angle, solar hour angle, and clearness index. The steps used to calculate solar radiation falling on a PV panel are outlined in [17] while the global hourly horizontal solar radiation at the surface are available at [18].

Therefore, by using the radiation incident on the PV panel, power output of a PV panel can be calculated as below,

$$P_{PV}(t) = Y_{PV} f_{PV} \left(\frac{G_T(t)}{G_{T,STC}} \right). \quad (1)$$

Here Y_{PV} is the rated capacity of the PV array power output under standard test conditions (kW), f_{PV} is the PV derating factor, $G_T(t)$ is the solar radiation incident on the PV array at time t (kW/m²) and $G_{T,STC}$ is the incident radiation at the standard test conditions (1000 W/m²). The PV power generated from a panel with rated capacity of 5 kW calculated for the three seasons is shown in the Fig. 2.

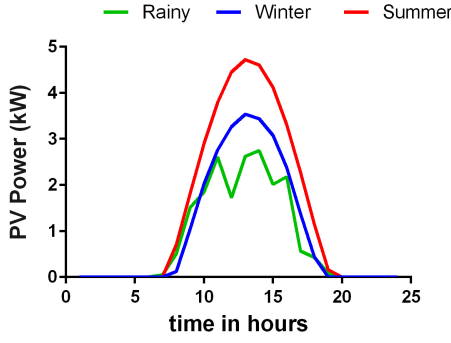


Fig. 2: PV output from the 5 kW panel for different seasons

Again, the solar output profiles exhibit the typical behavior. The peak power output from the 5 kW PV panel in summer, which is 4.7 kW, is higher than in winter and rainy season. Moreover in the rainy season, the panel output fluctuates due to cloud cover. Finally, the operational time for the solar PV system is more in summer and rainy season than in winter season.

III. MAXIMIZING USE OF SOLAR WITH BATTERIES

This section presents a quantitative analysis on how much fraction of the load can be met by solar energy by effective use of solar PV and battery storage resources. The residential consumer of the preceeding section is assumed to own a PV panel and a battery which is only charged using PV output and discharged to meet the residential load. Simulations for different combinations of solar PV panel sizes and batteries are performed to evaluate their contribution towards meeting the residential demand. This section describes the battery management strategy used and nature of simulations along with an interpretation of the results.

The power output from the solar PV is used to feed the load, charge the battery as well as sell power to the grid. Thus, at any instant of time t ,

$$P_{pv}(t) = P_{pv2L}(t) + P_{ch}(t) + P_{sell}(t), \quad (2)$$

where, $P_{pv}(t)$ is the solar PV output, $P_{pv2L}(t)$ is the power delivered from PV to the load, $P_{ch}(t)$ is the power used to charge the battery and $P_{sell}(t)$ is the power that is sold to the grid. Similarly, the load $P_{load}(t)$ at any instant of time t can be met directly from PV panel, the discharging battery and the grid depending on the amount of the power PV generates and the power availability in the battery. That is, at time t ,

$$P_{load}(t) = P_{pv2L}(t) + P_{dis}(t) + P_{buy}(t), \quad (3)$$

where, $P_{dis}(t)$ is the power discharged from the battery and P_{buy} is the power purchased from the grid.

The energy stored in the battery ($E_{sto}(t)$) follows the dynamics stated below,

$$E_{sto}(t) = E_{sto}(t-1) + P_{ch}(t)\Delta t \times \eta_{ch} - P_{dis}(t)\Delta t \times \eta_{dis}^{-1}. \quad (4)$$

Here, Δt is the time interval, η_{ch} is the charging efficiency of the battery and η_{dis} is the discharging efficiency. At all times, this stored energy must satisfy

$$E_{sto}^{\min} \leq E_{sto}(t) \leq E_{sto}^{\max}, \text{ for all } t \quad (5)$$

where E_{sto}^{\min} and E_{sto}^{\max} are the capacity limits for energy storage. Furthermore, the battery charging and discharging may be limited due to the converter interface

$$P_{ch}(t) \leq P_{ch}^{\max} \quad \text{and} \quad P_{dis}(t) \leq P_{dis}^{\max} \quad (6)$$

The following strategy is adopted for the combined operation of solar PV and battery:

- When the power generating from the PV is greater than the demand, load is completely satisfied by solar power. Specifically, battery is not discharged and no power is purchased from the grid. Excess power is first used for charging the battery if capacity is available and then sold to grid.
- When power generating from the PV is less than the demand, all the solar power is fed to the load with no power available for charging the battery or selling to the grid. The remaining load is satisfied by discharging the battery when available and buying from the grid as a last resort.

The strategy is illustrated in Fig. 3.

In what follows, this operating strategy is applied to different combinations of solar PV panel and battery combinations, and simulations are performed to evaluate the contributions of these combinations towards meeting the residential demand described in the preceding section. Specifically, different PV panels are considered with capacities ranging from 0 to 5 kW, while battery storage capacities range from 0 kWh to 2.4 kWh. The 6 representative load profiles described earlier are used to simulate the PV and battery operations for the entire year. The percentage contribution of the solar energy derived from the PV and battery combination towards meeting the annual load demand is illustrated in Fig. 4.

Figure 4 clearly illustrates that solar PV generates excess power over load at any given point of time only beyond 1 kW. Hence, batteries or grid connections are not required for panels

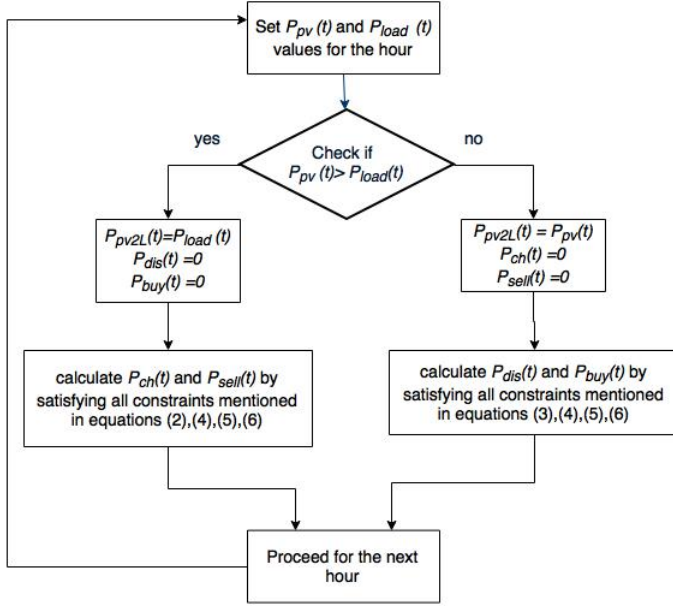


Fig. 3: Solar and battery operating strategy

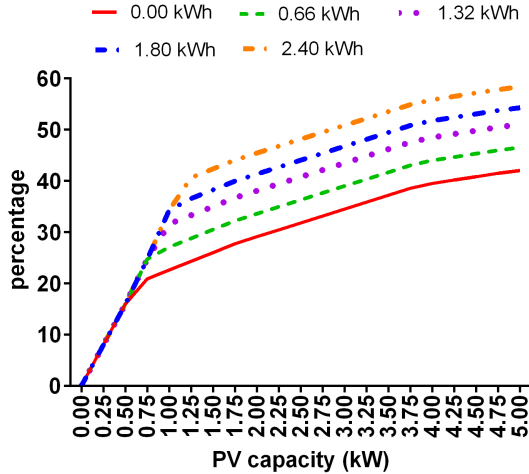


Fig. 4: Percentage contribution of solar energy to annual load demand for different PV capacities and battery sizes

smaller than 1 kW. While excess PV output can be stored in the battery, the plot illustrates how small panels need not require large batteries. For instance, for 1 kW panel battery storage beyond 1.80 kWh is not useful since there is no excess energy for 1 kW panel for higher size of batteries.

Figure 4 clearly shows that for contributing towards a large fraction of the demand, investing in batteries is a must. While the increasing capacity of the solar PV panels improves the contribution towards load demand, a saturation limit is reached as seen for the plot without battery (0 kWh). Furthermore, larger panel sizes may be deemed unrealistic due to area constraints and budget limitations.

Note that the simulations reported here are performed for representative days on a year, with each day divided on an hourly basis, and then the results are appropriately averaged to evaluate impacts over the whole year. Hence, the results are

an approximation. A more detailed analysis for all hours of the year is conducted using HOMER, as outlined the following section.

IV. TECHNICAL, ECONOMIC AND POLICY ANALYSIS

This sections summarizes the results obtained via simulations in HOMER [19]. The objectives of the studies are two-fold. First, to perform detailed simulations for a more accurate estimate of how much solar PV-battery combinations contribute towards load demand. And second, to investigate the impacts of different energy policies on economics of the residential consumer. Simulations are set up in HOMER to this effect specifying various parameters.

The load profiles modeled in Section II are used to generate hourly load data for an entire year to serve as input to HOMER. Likewise, PV output profiles Are generated for all hours of the year using data available at [18] and used as input to HOMER. The software then performs an hour-by-hour simulation for a representative year and evaluates various metrics. Of interest to studies here are the following:

- cost of energy (COE) representing the levelized cost of supply,
- net present cost(NPC) representing the current value of all the costs minus benefits incurred over the project lifetime,
- payback period denoting the break even point for the customer,
- energy purchased from the grid to met the residual demand, and,
- the excess solar energy sold to the grid.

For the simulations discussed in this section, the solar PV system with battery connected to the grid is simulated for different PV capacities ranging from 1 kW to 2 kW, while the battery capacity is chosen as 2.40 kWh (based on results of the previous section). The 1 kW lower limit for the PV capacity is chosen to based on the current MNRE policy for minimum PV capacity for grid connected PV systems. The upper 2 kW limit is chosen considering realistic limitations on available roof top area. The system components and the corresponding costs are shown in the Table III.

TABLE III: Costs of system components

Assumptions	Value
Discount rate (%)	8
Annual capacity shortage (%)	100
Project life time (Yrs)	25
PV Panel	
PV panel cost	Rs. 52/Watt
Derating factor (%)	80
life time (Yrs)	25
O & M costs	Rs. 1200/year
Battery	
Battery cost	Rs. 15814/kWh
O & M costs	Rs.500/year
Life throughout the output	800 kWh
Converter	
Converter cost	Rs. 10000
Life time (Yrs)	10
Efficiency (%)	96

The grid power price input to the model is Rs. 7 Rs/kWh and the grid selling price is taken to represent the different

feed-in tariff rates in different Indian states – 7.95 Rs/kWh, 12 Rs/kWh and 15.18 Rs/kWh – which are referred to as T1, T2 and T3 respectively. Additionally, two subsidy scenarios are considered: 30% (S1) and 50% (S2). The HOMER software simulates the system for these various cases and provides the metrics outlined earlier.

Figure 5 shows the fraction of total demand which is purchased from the grid as well as the fraction of total solar energy produced which is sold to the grid. Clearly, increasing PV capacity reduces the reliance on the grid, but it also leads to a correspondingly large fraction of the energy to be sold back to grid. For instance, for a 2 kW panel, nearly half the solar energy produced is sold back to grid, while the remaining half only contributes towards meeting 30 % of the load. While selling to the grid may be economically attractive, the plot clearly illustrates that larger PV panels are not leading to larger fraction of individual demand being met by solar energy. Furthermore, selling large amounts of solar energy back to the grid can have ramifications up stream and need special attention.

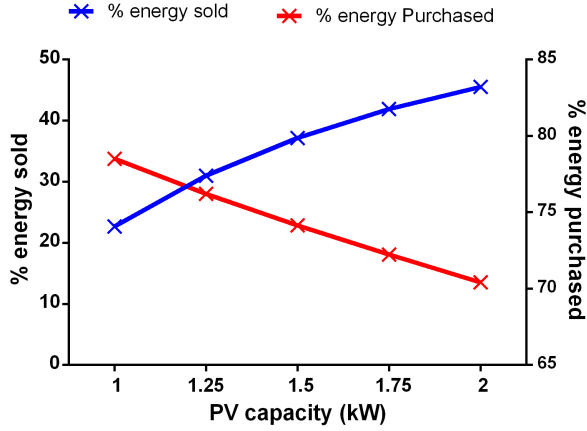


Fig. 5: Fraction of produced solar energy sold to grid and fraction of annual load demand procured from grid

The COE and the NPC for different tariff rates and subsidies for the different PV sizes are shown in the Fig. 6 and 7. The COE and NPC decrease with increasing PV capacity. It can also be observed that there is only a slight decrease in the COE and NPC for higher subsidy as compared to decrease associated with higher tariffs. Thus, tariffs play a prominent role as compared to subsidies for the evaluation of COE and NPC. A high feed-in tariff (>12 Rs/kWh) can lower COE to less than 3 Rs/kWh, making solar energy as competitively priced as fossil fuel-based electricity.

The payback period for different tariffs and subsidies are shown in the Fig. 8. Note that the payback period decreases as the feed in tariff rates increase resulting in more profit by selling the energy to the grid. However, the plot clearly shows that a higher subsidy can shave off close to half or full year and the payback period is more impacted by subsidy than tariffs.

The simulations serve to illustrate two important points:

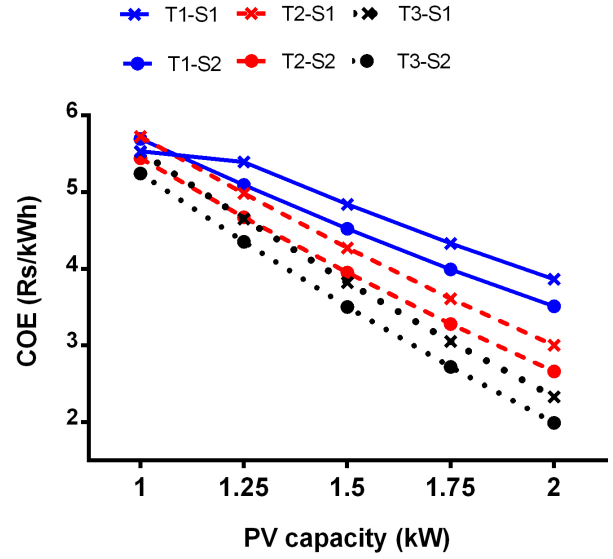


Fig. 6: COE for different tariff rates and subsidies

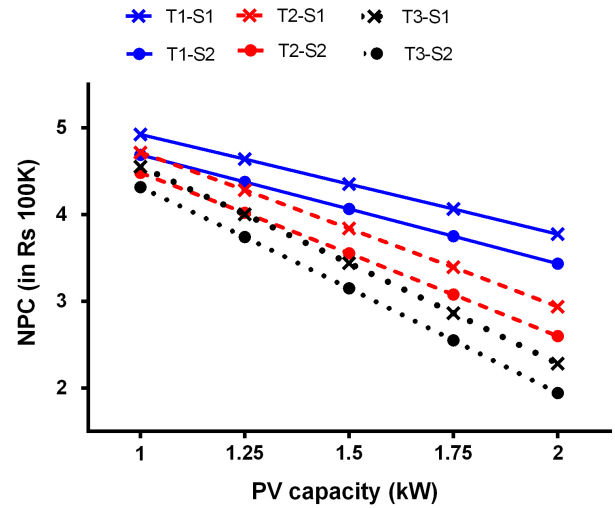


Fig. 7: NPC for different tariff rates and subsidies

- While larger panels can contribute more towards the consumer's individual demand, it leads to a large amounts of solar injections in the grid which need to be taken into account by the utilities in their operations and planning studies.
- Both feed-in tariffs and subsidies have an important role to play in making investment in solar PV and batteries economically attractive, since they impact the COE, NPC and payback period.

V. CONCLUSION

This paper presents technical and economic analysis of rooftop mounted solar PV systems in residential sector. The residential load and solar PV outputs are modeled for representative days considering different seasons. Results indicate that

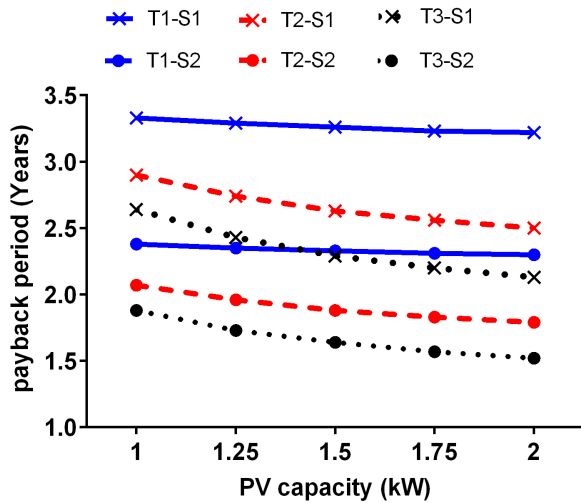


Fig. 8: Payback period for different tariff rates and subsidies

a large fraction of demand (more than a third) can be met by solar only when combined with a suitable storage technology such as a battery. Also, to attract consumers towards solar installations, suitable tariffs and subsidies are needed. Finally, large-scale adoption of solar will imply larger fractions of solar energy being injected into the grid and require suitable changes to grid operations.

Future work will entail design of an optimization framework to optimize the scheduling of the solar PV and battery combination. The ramifications of large solar energy injections on system operations will also be investigated.

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