Site Specific Battery Simulation Model

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Abstract

Battery costs have already decreased significantly over the past few years; a point highlighted by the high-profile launch of the Tesla Powerwall. However, installing a battery system is still expensive when considering the combined inverter, installation and balance of system (BOS) costs (Parkinson, 2014). Hence it is important to assess the economic feasibility of a potential battery system for each individual PV consumer.

A simulation model is proposed in this paper which takes advantage of the high resolution energy data collected from hundreds of existing Solar Analytics customers to determine the economic feasibility of installing a battery system for these residential PV consumers. In contrast to previous studies, we use actual PV generation and consumption data over a 12-month period to obtain a consumption/generation pattern. Then by considering different charging scenarios and battery parameters, a charge/discharge pattern is determined for over a year. Furthermore, optimal battery sizes and configurations can be determined by taking account of various economic input parameters such as technology cost and electricity price, thereby enabling the potential profitability of battery storage to be calculated for each customer with a high degree of certainty.

Results from simulations indicate that based on the current battery costs, the estimated payback period of installing a battery system is still over 15 years without any policy incentives. However the payback period is expected to be improved as battery costs are decreasing rapidly. Additionally, we conclude that smart battery control and monitoring can significantly improve the profitability of energy storage systems.

1. Introduction

The energy storage market in Australia is expected to see a rapid growth in the coming years, mainly driven by falling prices, as was the case in the PV market. Already major electricity retailers such as AGL and Energy Australia have announced battery storage rollouts. Battery storage offers the potential to solve the problem of intermittency in solar generation and provide increased energy autonomy for home and business owners. With the upcoming expiration of generous solar feed-in tariffs in several Australian states, batteries could enable many users to maintain their low energy bills by maximising their self-consumption of solar energy.

Previous studies regarding the economic viability of battery systems as a function of PV, storage capacities and costs have generally relied on estimates of generation and consumption. Many studies such as Arun et al. (2009) and Jallouli et al. (2012) used solar insolation data to estimate a normally distributed hourly solar curve for each month. Using past consumption data was explored by Colmenar-Santos et al. (2012) and Kaldellis (2008) to create a monthly consumption pattern. These estimations are based on a large group of PV households and the accuracy is sufficient to support an overall economic analysis. However, since an individual household could have significantly different generation and consumption patterns, it is not feasible to apply the results of a broad analysis to every PV consumer included in the scope of a study. Hence it remains unclear how to quantitatively determine whether battery storage is economical and what battery size and configuration is appropriate for an individual PV consumer based on their specific circumstances. Moreover, the authors could not find evidence of current research into evaluating the impacts of different charging scenarios on the economic profitability of battery storage systems.

2. Methodology

In this study energy data derived from existing Solar Analytics customers is analysed using a simulation model to produce a consumption/generation pattern for each specific site (Solar Analytics, no date). By applying the relevant economic factors and charging scenarios it is then possible to evaluate the profitability of installing a battery storage system on a case by case basis.

2.1 Data Collection

PV generation and consumption data is collected via smart monitoring devices installed on existing PV sites. The device is able to collect PV/consumption data at 5 second resolution granularity, however, the amount of historically available 5 second data is insufficient to support a sophisticated analysis. Hence in this study data with 5-minute resolution has been collected from hundreds of Australian Solar Analytics customers with a subset of that dataset used as the input data of our battery simulation model.

An initial filtering process was performed to select suitable sites for this simulation model which included more than one year of usage data. This subset of data is assumed to provide a closer estimate of a consumer’s generation/consumption pattern. A performance assessment can then be applied to find sites that have a consistent and ideal performance throughout their monitored periods. During the performance evaluation, a PV prediction algorithm is used to generate hourly expected PV generation by utilising relevant weather data and the system configuration of a specific PV system (Copper, 2014). The expected generation can then be compared with the measured data to assess the system performance, a site with measured generation close or slightly higher compared to its expected generation is considered to have a good performance. Only systems with good overall performance have been included for the simulation model, as sites with underperformance issues can cause high uncertainties to the analysis. As a result, 13 representative residential sites have met all the criteria and are included in the final dataset.

2.2 Simulation Model

2.2.1 Generation/consumption pattern

The developed simulation model requires one year of generation/consumption data to produce a usable generation/consumption pattern for an individual site. It is assumed generation/consumption of a site throughout a year will remain fairly constant in the future.

The selected sites can be categorised into Type I and Type II sites based on their load distributions: Type I sites have most of their consumption during night time (6pm to 6 am), whereas the majority of consumption with Type II sites happens in daytime (6 am to 6pm). Out of the 13 representative sites, nine of them are Type I sites and four of them are Type II sites.

Figure 1 compares the hourly load distribution of a Type I site and a Type II site throughout a whole year. The hourly percentage is determined by dividing all the consumption made in an hour interval by the total consumption throughout a year. Since PV generation only occurs in daytime, surplus PV generation will be apparent for Type I sites. Therefore, these two site categories will generate various battery simulation results and it is necessary to analyse them separately.

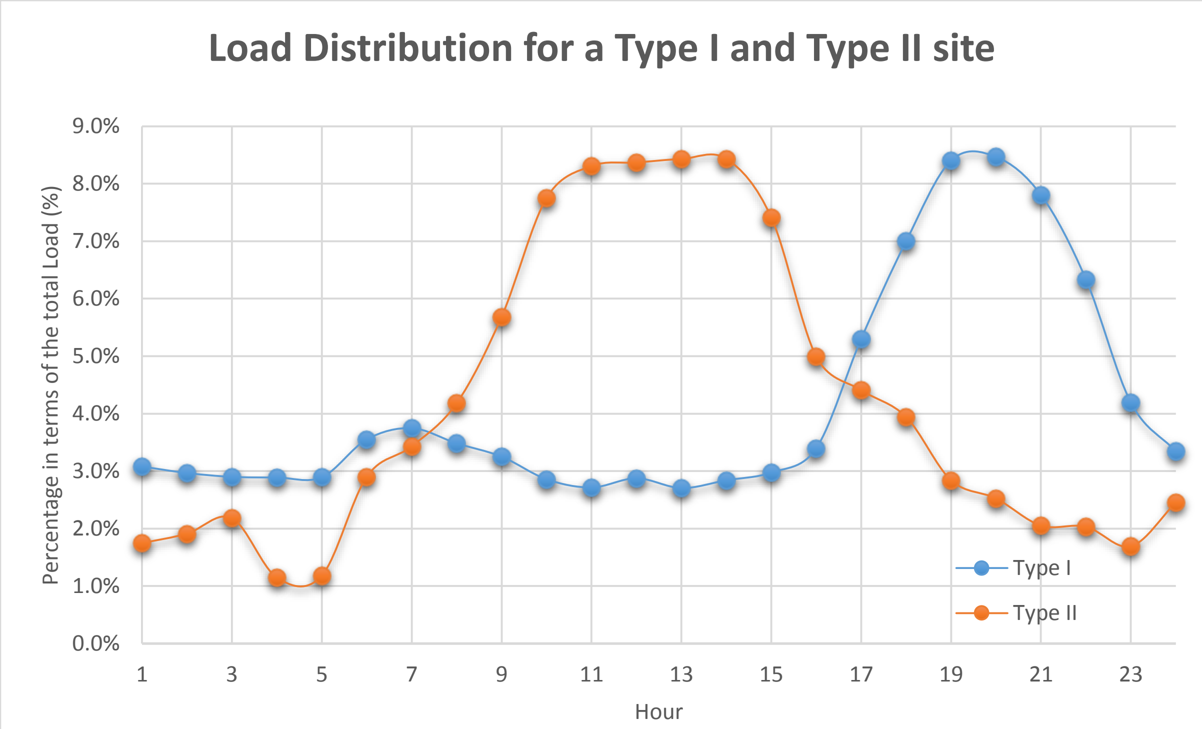

Figure 1: Hourly Load Distribution over a day for a Type I and Type II site

2.2.2 Battery parameters

The following battery parameters are considered in this simulation model:

- Battery Nominal Capacity (generally referred as battery size)
- Maximum Depth of Discharge (DOD)/Usable State of Charge (SOC)
- Coulombic Efficiency
- Battery Life Time
- Battery Self-Discharge Rate
- Maximum Charge/Discharge Power

The battery type is set to be lithium-ion since this technology is projected to have the major market share in the near future (Bernstein, 2014). As mentioned above, one purpose of this simulation model is to find an optimal battery size for a specific site. Hence battery nominal capacity is the only independent variable in regards to battery specifications. Maximum DOD, coulombic efficiency, battery self-discharge rate and life time are set to be constant, with maximum charging/discharging power dependent on the battery size.

2.2.3 Economic factors

The economic parameters included in this study can be classified into two categories: battery related costs and tariffs. The input factors included in the battery related costs are listed in Table 1. It should be noted that the values of these input factors are derived by some rough estimations of the current Australian storage market and they may vary considerably for individual customers.

Table 1: Initial Input Values of Battery Related Costs

Battery Related Costs	Initial Value
Cost of battery	1000 AUD/kWh
Cost of inverter and Balance of System (BOS)	600 AUD/kWh
Cost of installation	500 AUD/site
O&M Costs	30 AUD/kWh/year
Nominal Discount Rate	3%

The simulation model utilises two sets of tariffs as shown below in Table 2:

Table 2: Initial Input Values of Tariffs

Tariff Type	Import Rate (cent/kWh)	Export Rate (cent/kWh)
Fixed Tariff	30	6
Time of use Tariff	Peak (3pm to 9 pm): 45 Off-peak (10pm to 7am): 10 Shoulder (the rest of a day): 20	6
Tariff inflation rate: 2%		

2.2.4 Charging scenarios

Various charging scenarios can be applied to alter the economic outcomes of a PV system with battery storage. Three charging scenarios are compared in this study:

- Unregulated Charging: When there is surplus PV generation, energy is used to charge batteries until a full charge is achieved. When consumption is higher than generated energy, batteries discharge to supply the surplus consumption until depleted.
- Static Off-peak Charging: Off peak electricity is used to charge batteries until a constant level of SOC. This off-peak SOC is set to be constant throughout the lifetime of the battery system. During the remaining off-peak hours, the SOC of the batteries is maintained and consumption is supplied only by the grid. In other words, during off-peak hours, batteries are functioning under an Uninterruptible Power Supply (UPS) mode as no energy is drawn from the batteries. For peak and shoulder hours, batteries still undertake an unregulated charging scheme.
- Dynamic Off-peak Charging: Off peak electricity is used to charge batteries until a certain level of SOC. However, instead of using a constant off-peak SOC, a dynamic off-peak SOC is applied. By using the generation/consumption pattern, energy consumed and generated on the next day can be forecasted and the value of off-peak SOC can be determined by finding the gap between consumption and generation of the next day. For peak and shoulder hours, batteries still have unregulated charging.

2.2.5 Simulation Structure

Figure 2 illustrates the main procedures of the simulation model. By applying relevant battery parameters and charging scenarios, a charging pattern throughout a year can be determined. Economic factors are then applied to the algorithm in order to calculate the economic profitability of a battery system for an existing PV site. Finally, by varying the size of the battery the algorithm is able to generate an estimated system capacity to provide optimal economic profitability for the PV consumer.

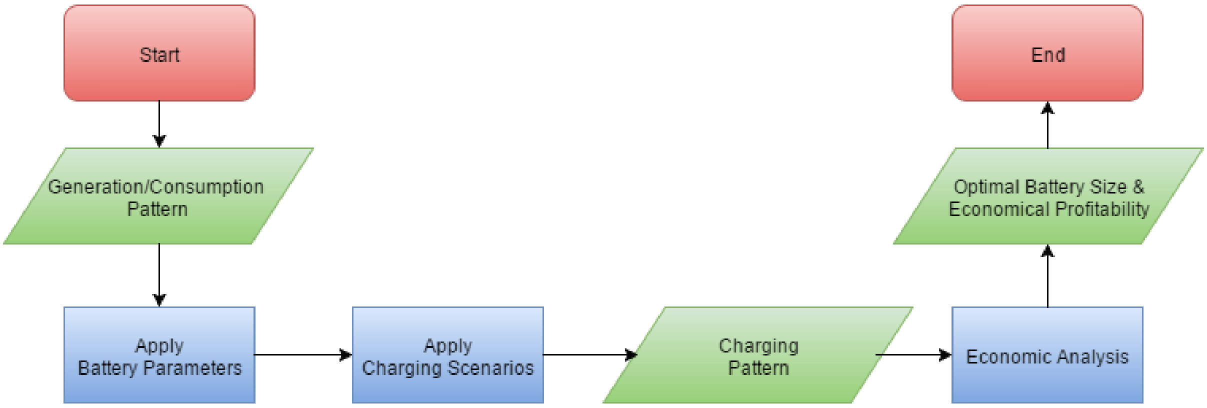

Figure 2: Flowchart of the simulation model

3. Results and Discussion

The analysis of the presented simulation model is achieved by importing generation and consumption data of each valid test site. Simulation results below illustrate charging patterns and economic profitability utilising the charging scenarios described in Section 2.2.4.

3.1 Charging Patterns

3.1.1 Unregulated Charging

Figure 3 and Figure 4 show 48-hour charging patterns for Type I and Type II sites named Site A and Site B respectively.

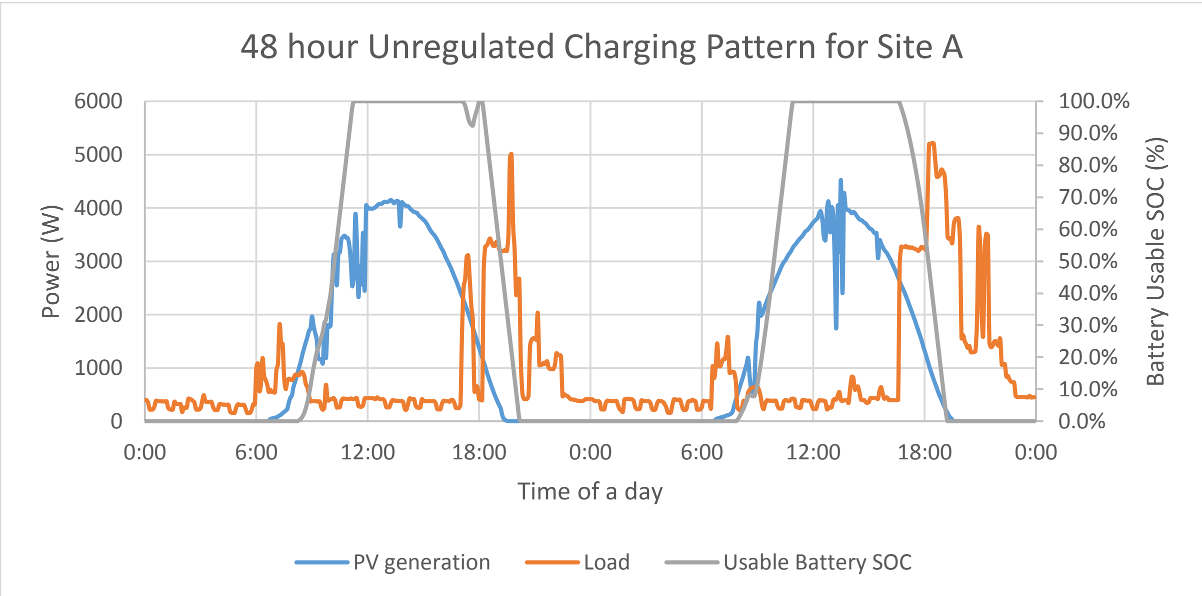

Figure 3: 48 hour Unregulated Charging Pattern for Site A, utilising a 6 kWh battery system

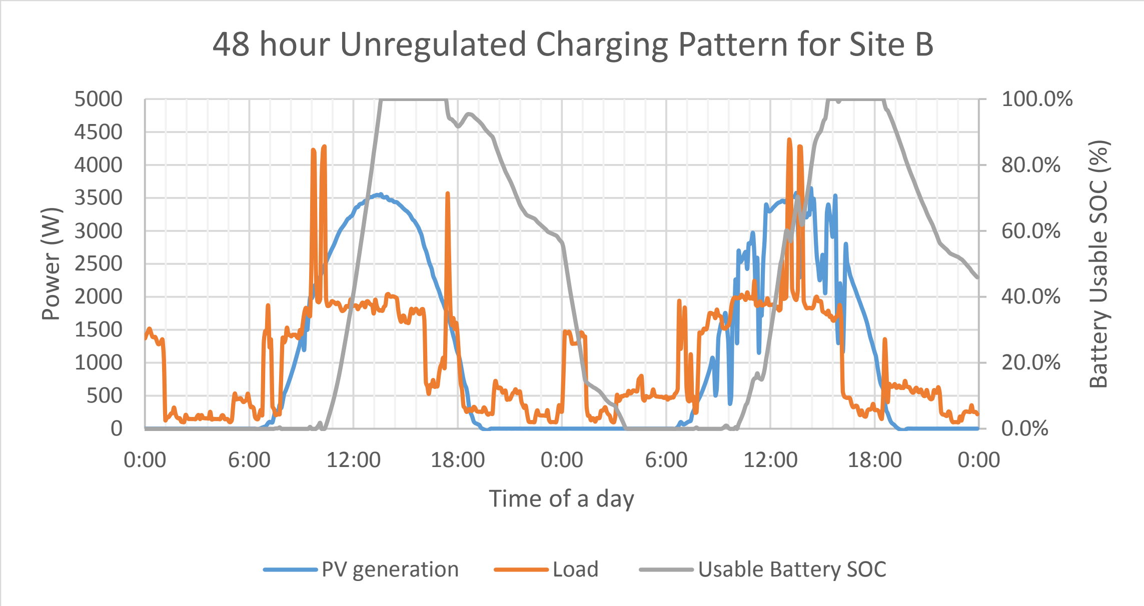

Figure 4: 48 hour Unregulated charging pattern for Site B, utilising a 6 kWh battery system

The unregulated charging scenario results in batteries generally charged during solar hours and depleted during the night. For Site A, most of its consumption is within the period without PV generation, hence the SOC of the batteries dramatically reaches and stays to a high level during the solar period. The batteries can then be seen quickly depleting during the evening peak. Alternatively, for Site B the SOC is increased to a high level around noon then slowly discharges to a zero SOC in the early morning of the next day.

3.1.2 Static Off-peak Charging

Figure 5 indicates a 48-hour charging pattern for Site A under 50% static off-peak charging scheme.

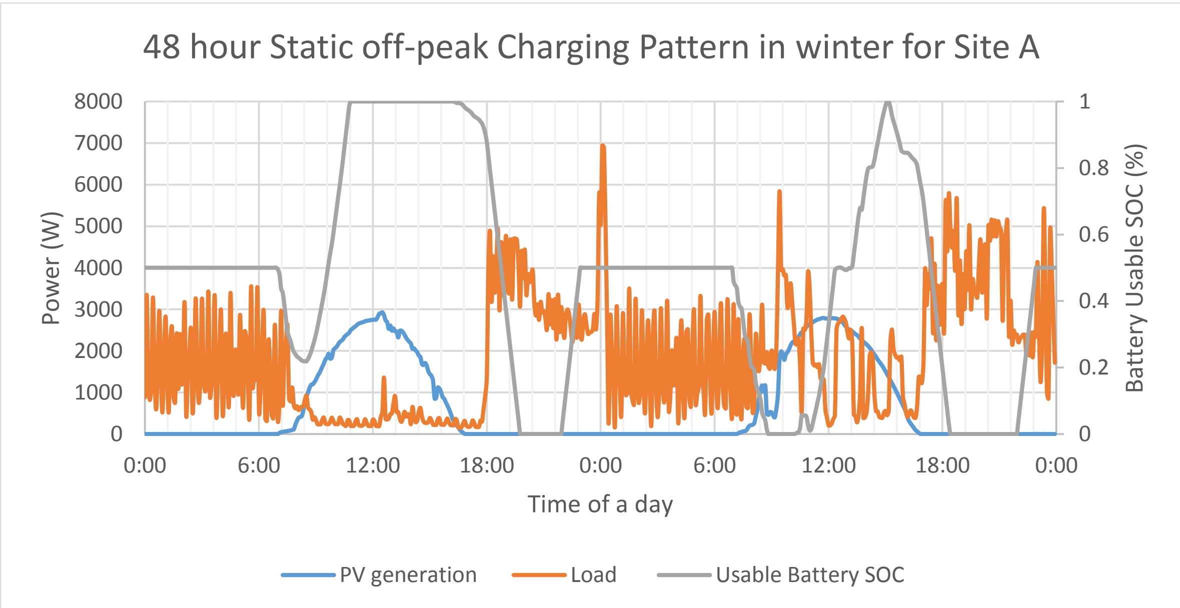

Figure 5: 48 hour 50% Static off-peak charging pattern for Site A, utilising a 6 kWh battery system

During off-peak hours, batteries are charged to 50% usable SOC then the UPS mode is enabled. For other periods the batteries function under an unregulated charging scheme. The advantage of using off-peak electricity to charge the batteries is that it can reduce electricity consumed during peak and shoulder hours thus creating economic benefits for end-consumers.

3.1.3 Dynamic off-peak charging

A 48-hour dynamic off-peak charging pattern is shown in Figure 6. By predicting the PV generation and consumption of the next day, a daily off-peak SOC is determined which can potentially fill in the gap between the consumption and generation hence reduce the electricity consumed during the peak and shoulder hours of the following day.

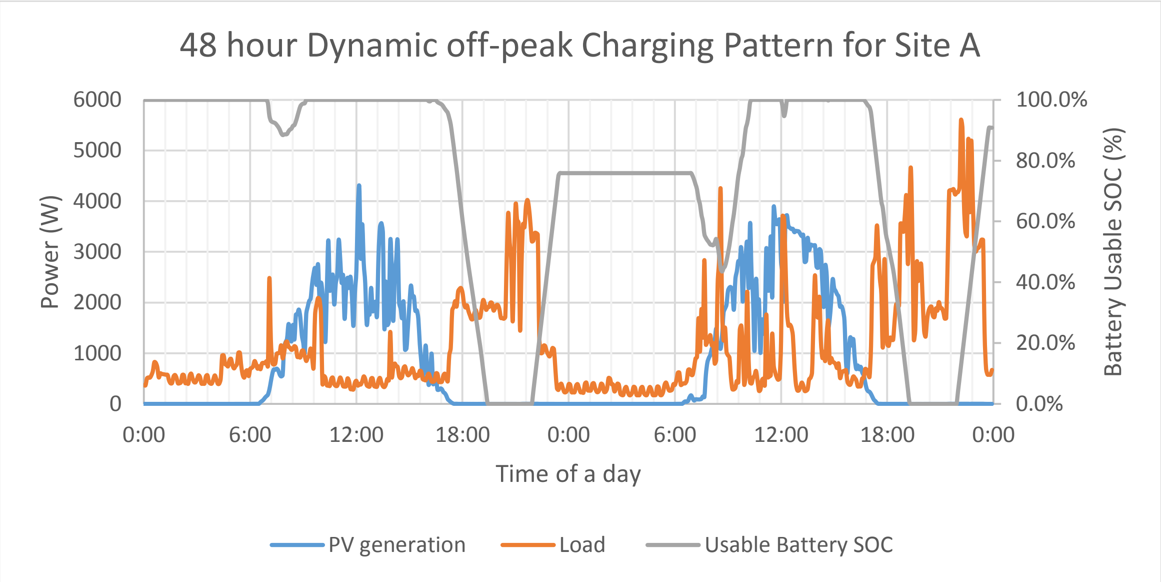

Figure 6: 48 hour Dynamic off-peak charging pattern for Site A, utilising a 6 kWh battery system

3.2 Economic profitability

3.2.1 Impact of Tariff

Figure 7 shows the average payback periods of different battery sizes utilising the unregulated charging scenario for Type I and Type II sites with fixed and time of use tariffs.

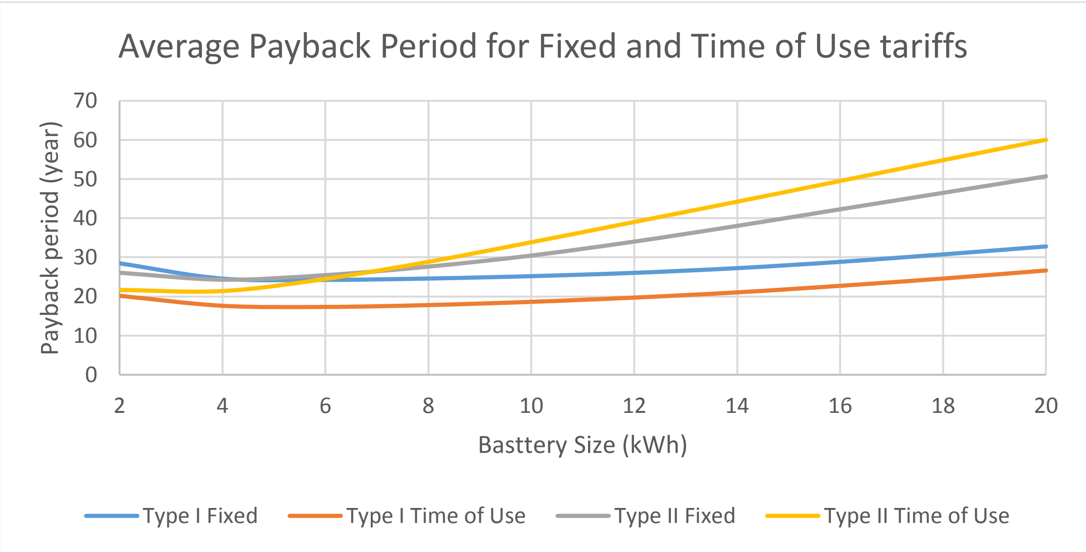

Figure 7: Average payback period of different battery sizes for Type I and Type II sites with both Fixed and Time of Use tariffs

The simulation results indicate that without economic incentives and charging strategies the payback of installing a battery system for an existing PV consumer is above 15 years regardless of the tariff the consumer is on. For Type I sites, time of use tariff is always more beneficial for end-consumers. Although time of use tariff is also more economical for Type II sites with small size batteries, fixed tariff leads to shorter payback periods for battery sizes larger than 8 kWh.

3.2.2 Impact of Charging Scenarios

For each site, each battery size is used to obtain a payback period under each charging scheme. An optimal payback period is defined as the smallest payback period under one charging scenario. Table 3 and Table 4 show the average optimal payback periods for Type I and Type II sites with time of use tariff and fixed tariff respectively under various charging schemes.

Table 3: Optimal payback periods for Type I and Type II sites with time of use tariff under different charging scenarios

Type	Unregulated Optimal Payback (year)	25% Static Optimal Payback (year)	50% Static Optimal Payback (year)	75% Static Optimal Payback (year)	100% Static Optimal Payback (year)	Dynamic Optimal Payback (year)
Type I	17.34	16.61	16.43	16.38	16.41	16.02
Type II	21.4	20.05	19.45	19.11	19.13	18.74

Table 4: Optimal payback periods for Type I and Type II sites with fixed tariff under different charging scenarios

Type	Unregulated Optimal Payback (year)	25% Static Optimal Payback (year)	50% Static Optimal Payback (year)	75% Static Optimal Payback (year)	100% Static Optimal Payback (year)	Dynamic Optimal Payback (year)
Type I	24.27	29.13	36.89	52.75	93.77	39.35
Type II	24.29	28.62	35.63	48.50	80.87	38.16

Evidently off-peak charging is not beneficial for consumers with fixed tariffs as they cannot take advantage of the low electricity rate during off-peak hours.

For sites with time of use tariffs, dynamic off-peak charging is more economical compared to unregulated charging and static off-peak charging as it generates the lowest payback periods. Also, 75% static off-peak charging SOC seems to be more desirable than other levels of static off-peak charging. However, it should be noted these improvements are not very significant.

3.2.3 Optimal Battery Size

An optimal battery capacity is determined for each site under various circumstances. For a Type I site, the optimal battery size is generally between 5 to 7 kWh regardless of what tariff or charging scenario is in use. On the other hand, the optimal battery size for Type II sites is normally around 3-4 kWh. Hence we can conclude that it is not economical for a residential PV consumer to install a battery system that is larger than 7 kWh.

4. Conclusion

In this study, 5 minute generation and consumption data collected from existing PV systems is used to create a generation/consumption pattern for each site. This data is then utilised with the presented simulation model to obtain charging patterns, economic outcomes and optimal battery sizes for each individual PV consumer.

An analysis of the simulation results has demonstrated the current optimal battery size for residential sites is generally lower than 8 kWh and the payback period is still over 15 years. Furthermore, the results revealed installing a battery system is more economical for sites with high evening loads (Type I sites) compared to sites with high daytime consumption (Type II sites). This is due to the amount of load shift achievable with Type II sites being relatively less than the amount for Type I sites, as most of its consumption can be met directly by PV generation.

Tariff settings can also significantly affect the economic viability of installing batteries. For sites with fixed tariffs, off-peak charging was found not beneficial for them. However, static and dynamic off-peak charging scenarios are likely to increase the economic profitability for sites with time of use tariffs.

It is important for PV consumers who are considering installing a battery system to understand the generation/consumption patterns of their systems, as they will have noticeable impacts on the economic viability of installing a battery system. Results have demonstrated that a well-designed battery charging scheme can improve the economic profitability of a storage system. Therefore, a sophisticated battery monitoring and control system is necessary in order for PV consumers to maximise the value gained from their battery/PV systems.

5. Recommendations and Future Work

In order to further improve the economic profitability of an energy storage system more sophisticated charging schemes should be developed for residential and commercial sites by incorporating both PV generation and electricity consumption forecasts. This requires more advanced prediction algorithms to achieve a high level of accuracy.

Furthermore, the prediction of the battery SOC is also essential for simulating the charge patterns of batteries. In this study, battery SOC is assumed to be changed linearly. However, since batteries are generally considered as dynamic systems and their charging behaviours are affected by many internal and external factors, the actual SOC will experience non-linear changes. Hence, sufficient battery data and parameters are required to develop more advanced prediction models that can accurately estimate the charging patterns of batteries.

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