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# A semi-empirical financial assessment of combining residential photovoltaics, energy efficiency and battery storage systems

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ABSTRACT

Extraordinary declines in the cost of photovoltaic systems (PV), combined with a growing range of energy efficient consumer technologies (EE), has driven significant deployment of these two options in many jurisdictions. This deployment has proven to be a key way to mitigate the risks of catastrophic climate change. However, existing retail electricity arrangements can create mixed incentives for households contemplating investing in both PV and EE. This is caused by net metering arrangements that value self-consumption of PV generation far more than PV exports to the grid. This means that falling household demand due to EE may significantly reduce the financial value of PV. Meanwhile, the continuous cost decline of battery storage systems (BS) has encouraged more PV owners to consider storing PV exports to maximise self-consumption. However, there has been little research on whether the addition of BS could reduce barriers to the combined uptake of PV and EE. In this paper, real PV generation and electricity consumption data is used from numerous households in Sydney (Australia), together with a battery cyclelife model, to assess the financial outcomes of combining PV, EE and BS. The results indicate that EE can reduce PV system revenue, that adding BS to a combination of PV and EE generally increases PV revenue, that BS costs are still high for this residential application, and that the uptake of EE can result in deeper BS cycling which reduces the battery lifetime.

## 1. Introduction

Distributed energy resources have experienced remarkable growth in the last decade in many electricity industries. The significant fall in photovoltaic system (PV) prices, combined with strong government support in many jurisdictions,[1] has driven significant deployment of distributed PV systems [1–3]. This deployment has taken the form of both individual and collective electricity customers. This growth in PV uptake has occurred in parallel to the deployment of a wide range of energy efficiency products (EE) in the building and appliance sectors. Significant advances have been achieved in more efficient heating and cooling systems and other household appliances [4,5]. The growth of these two key clean energy technologies has greatly contributed to mitigating the risks of catastrophic climate change [6] and has also created significant other benefits in many electricity industries [7,8].

Net metering (NM) has been the most widely implemented arrangement for distributed PV deployment. By the end of 2015 more than 50 countries had implemented some form of NM [5]. NM has been a significant contributor to the more than 150 GW of distributed PV capacity in the world, especially in the residential sector [9]. With NM, customers with PV first self-consume their PV generation and any excess generation is exported to the electricity grid. The value of the PV generation which is self-consumed is the avoided retail electricity tariff. The value of generation exported to the grid, or PV exports, is typically set at a flat payment per kWh called a feed-in tariff (FiT). This is the case for both individual and collective customers with PV. There is some variation between jurisdictions in how the FiT is set under NM. In some jurisdictions it means the FiT is set at the retail rate,[2] and the term 'net billing' means the FiT is set at a lower rate [5]. In this paper, the term net metering is used for the last option.

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[1] The term jurisdiction is used to refer to a geographical area with specific energy policies. A jurisdiction can be a whole country, state or another more local form of government.

[2] In practice, in this scenario, when the PV system is exporting generation to the grid a disc accumulator meter reduces household consumption by spinning in the reverse consumption direction.

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In Australia, as in many other jurisdictions, FiTs for new connections are now generally valued to represent only the wholesale component of the tariff, which typically corresponds to less than half of the full retail tariff. This is because when PV electricity is on-sold, the full transmission and distribution charges are applied, and so the only value for the electricity retailer (supplier) is the avoided wholesale value. As a result, the value of PV self-consumption is far greater than the value of PV exports.[3]

For customers wanting to invest in combined PV and EE (PVEE) systems, the reduction in electricity consumption caused by EE can potentially significantly increase household PV exports and so reduce the value – net benefit – of the PV investment. Previous research has highlighted the potential barrier that NM with low FiTs represents to the combined uptake of PV and EE [10]. The still insufficient policy efforts to effectively mitigate climate change [11], and the great potential of these residential technologies to reduce greenhouse gas emissions [12], are key motivations to encourage a further PVEE deployment.

Battery storage systems (BS) have also experienced significant cost declines in recent years [13,14]. BS systems could potentially facilitate further deployment of PVEE systems with NM. This is because BS can be used to maximise the value of PV electricity that would otherwise be exported, which can instead be stored and dispatched later in the day for customer self-consumption. EE could also have a large impact on key operating parameters of a battery: such as depth of discharge (DoD) and charge/discharge rate. This could significantly affect the financial performance of a PV-battery system (PVBS) and there are no granular studies or methodologies reported in this area.

In this paper, the financial value of combining PV, EE and BS is assessed, using empirical hourly household PV generation and electricity consumption data from 300 customers with PV systems from the city of Sydney in New South Wales (NSW), Australia. Australia has the world's highest per capita number of distributed PV systems, with 15% of households now owning a PV system [15]. The average size of Australian household PV systems has been steadily increasing since 2010, with the average size of systems installed in 2017 being more than 4.5 $kW_p$ [16]. Australian households have also strongly engaged in EE investments which has decreased average household consumption [17]. This would increase the amount of PV exports, and so reduce the financial return from their PV systems.[4]

Real life data from numerous households is required to calculate the financial value of these technologies because it can vary markedly depending on factors such as the customer-specific PV output performance, the household consumption patterns and the specific EE energy saving profiles [18,19]. Moreover, previous research has found that using real data is necessary to realistically model the electrochemical degradation of battery systems [20–24]. In this paper, a cyclelife battery model has been developed. It simulates the BS operation as a function of the main operating parameters affected by our highly variable PV, EE and load data. This paper estimates the hourly revenue flows created by household generation and saved from more energy efficient household appliances, then sums hourly results for a whole year and escalates annual results to calculate the net present value (NPV) for individual households.

The organisation of the paper is as follows: Section 2 reviews existing research that assesses the financial interactions between PV, EE and BS technologies. The methodology used for this study is presented in Section 3. Section 4 presents the financial outcomes. Finally, Section 5 presents some conclusions of the study.

## 2. Literature review

Estimating the financial value of customers' energy technologies requires the development of granular methodologies that can capture the time and location-varying benefits and costs of distributed energy [25,26]. Many granular studies have assessed the value of distributed PV and BS. They have shown that benefits can be significant but very context-specific. The value of PV alone has been assessed for different types of NM and tariff structures, and for customers in the residential and commercial sectors [27–32].

The addition of BS to a PV system (PVBS) has also been widely studied in [23,24,33–37]. These studies show how the magnitude of the PVBS value is driven by generation matching peak electricity industry costs and tariffs. de Oliveira e Silva and Hendrick [23] and de Oliveira e Silva and Hendrick [24] assess grid parity for households with PV systems and both lead-acid and lithium-ion battery technologies. The studies found that in order to achieve above 40% household self-sufficiency, batteries are needed. This increases the cost of household self-generation, which is ameliorated in the case of collective customers due to the 'economies of scale' of larger generation systems. Olaszi and Ladanyi [36] assessed different BS discharge strategies that maximise self-consumption in order to compare the reduction of different electricity industry costs. Khalilpour and Vassallo [37] found the type of battery and the operation that minimise the electricity bill of different type of customers. Parra and Patel [33] show that rewarding wholesale generation prices to PVBS increases its value only in the short term due to accelerated BS degradation. Ren et al. [34] assess the impact of different tariff structures and conclude that tariffs with demand charges maximise the value of PVBS. Other studies include Lorenzi and Silva [35] which compare the value of batteries versus demand response resources, and Stenzel et al. [22] that indicates that empirical customer data is critical for appropriately assessing the value of BS.

Only limited studies have assessed the financial value of residential EE interacting with PV using granular methodologies. One reason for this is the general lack of data regarding hourly EE energy savings. Oliva H [10] estimated the financial outcomes of combining residential PV and EE, and found that they compete in terms of capturing the household bill savings. In the US context, Satchwell et al. [38] also assessed the combined impact of PV and EE, this time on an electricity utility, and found a significant decline in utility sales and costs.

In summary, little, if any, granular research has modelled the financial outcomes of combining PV, EE and BS technologies, with the use of real life data that captures key semi-empirical correlations between PV intermittency, customer's demand variability, BS electrochemical performance and the EE energy savings. In particular, the addition of EE to an existing PVBS system could significantly change the discharge depth and rate of batteries. Hence, EE could not only reduce the amount of PV self-consumption but also change the battery cyclelife. As such, this paper contributes to the research regarding the circumstances in which batteries can facilitate further clean energy deployment.

## 3. Method

First, this paper assessed the revenue that a PV system, in combination with a number of EE measures, generates for households. This is done by estimating the financial value of one kWh of PV generation, both self-consumed and exported to the grid, and one kWh of saved energy due to EE. These revenue flows are estimated every hour of the year and summed in order to obtain the total annual value.

Second, a BS system is added to the PVEE system in order to assess whether batteries are more valuable in this context. This paper modelled the hourly BS operation for Lithium Ion (Li) battery technologies. The batteries only store excess PV generation (PV exports before adding

[3] In Australia, PV exports are recorded, and the FiT rate value assigned, every half-hour.

[4] Particularly interesting is the situation in the state of New South Wales where over 300,000 households have moved from gross metering arrangements – that paid a subsidised FiT of 60 ¢/kW h for the whole PV generation – to NM where PV exports are paid at around 6 ¢/kWh.

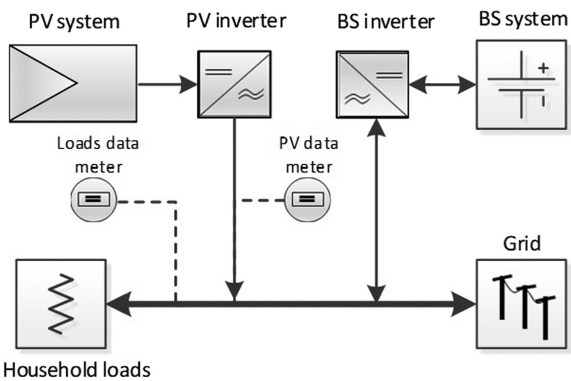


**Fig. 1.** Schematic electrical configuration of the households. The position of the meters indicates the source of the PV and load data used in this study.

BS). They dispatch generation only to meet household demand, not to export electricity to the grid. A diagram of the electrical configuration of the combined PV, EE and BS household system is shown in Fig. 1. Note that the meters in Fig. 1 show the source of the data used in the model, they are not intended to indicate the locations of meters for a real NM system.

The BS cyclelife model is then used to estimate the BS capacity degradation over time and its impact on PV self-consumption and export revenue. In order to escalate FiTs and revenue from self-consumption, future wholesale electricity prices and retail tariffs are used in NSW from [39]. This study assumes that EE measures are present for the 25 years of analysis. However, note that in practice this assumption may involve equipment replacement and/or improvements which have not been included here. The NPV analysis is performed only for the PVBS investment. Details of the household energy technologies are presented below.

### 3.1. The addition of photovoltaics

This study uses publicly available hourly PV generation and electricity consumption data from 300 Australian households located on Ausgrid's distribution network in Sydney (for the year 2011) from [40]. The annual PV generation and annual consumption of these households averages 1250 kW h/kW/year and 6980 kW h/house/year respectively. The average size of the PV systems is 1.7 $kW_p$, which has been escalated up to 3 $kW_p$ to align more with the current average household PV system in NSW. After escalation, the average PV generation per household is 3800 kW h/year. The average ratio between household PV generation and load is 120%. Fig. 2 compares the PV generation with electricity consumption for the 300 households used in this study.

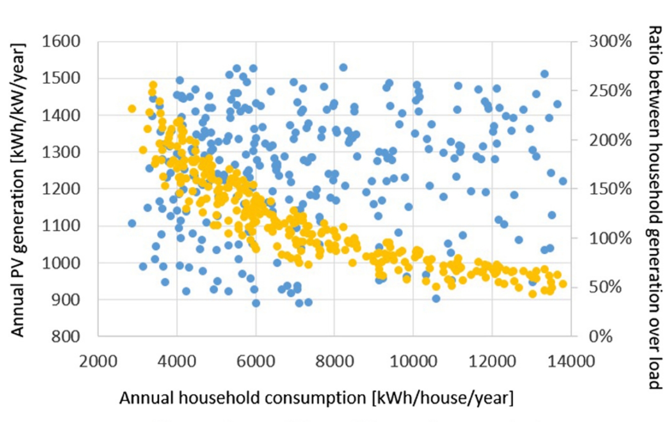


**Fig. 2.** Annual household PV generation and electricity consumption.

### 3.2. The addition of energy efficiency

Three household EE measures are chosen for this study. They occur through upgrades of appliances that together represent around 65% of the total electricity consumption of a typical Australian household [41]. A description of these EE measures is shown in Table 1.

The load profiles for these appliances were constructed for the 300 households as follows. Using a seasonal hourly appliance usage dataset for the NSW residential sector [42], for every hour of the year ($t$), the appliance load as a percentage of the total household electricity load was estimated (giving $AL\%_t$). This percentage profile was then applied to the hourly load data of the 300 households ($L_t$) in order to build the desired appliance load profile.

Finally, to create an hourly annual profile of EE energy savings in kW h ($ES_t$), EE energy savings data in Australia was applied, as fixed percentages ($ES\%$), to the constructed appliance load profile, every hour of the year. $ES\%$ data was obtained from [41] for Light-EE and from [43] for Refri-EE. The AC-EE energy savings have been estimated from the Energy rating [43] calculator. This approach is summarised in Eq. (1), Table 1 and Fig. 3. Eq. (1) has been applied to each appliance type separately.

$$ES_t = ES\% \times AL\%_t \times L_t \quad (1)$$

Here, the combination of the three EE measures of Table 1 (that is the sum of $ES_t$ of each appliance type) has been referred as the 'with EE' scenario (denoted 'wEE'). The 'without EE' scenario is denoted 'woEE'.

Fig. 3 illustrates the PV, EE and load energy profiles for an average day in summer and winter. EE lines represent the amount of load reduction available from each option, 'wEE' is the sum of the three EE lines, 'Load - wEE' is the household load after implementing 'wEE', and 'Load after PV' is the household load without EE but after the PV generation. The increase in PV export after the EE measures is clearly evident.

### 3.3. The addition of battery storage

In this paper the BS cyclelife model is configured so that batteries store excess generation from the PV system and supply it during times of low or zero solar resource availability. This configuration increases PV self-consumption. The PV generation is used to meet the household demand first, then used to charge the BS before exporting to the grid. Similarly, household demand is met from the BS before electricity is imported from the grid, and the BS is not allowed to discharge to the grid at any time.

At a given hour $t$, the battery is charged with all the PV generation that exceeds the load, assuming that enough storage is available. Otherwise the battery is charged as in Eq. (2). The battery discharges to meet all the load that exceeds PV generation if enough electricity is available in the battery. Otherwise the battery is just fully discharged as in Eq. (3). The battery state of charge after discharge is then updated as in Eq. (4).

$$BS_t = (BScap_d - SoC_t)/BS_{eff} \quad (2)$$

$$BS_t = -(SoC_t - BScap_d \times SoC_{min}) \times BS_{eff} \quad (3)$$

$$SoC_{t+1} = SoC_t + BS_t/BS_{eff} \quad (4)$$

where at hour $t$, the parameters are:

$BS_t$: Generation charged or discharged from the BS system under limitations in kW h.
$BScap_d$: BS capacity in the day $d$ of operation in kW h.
$SoC_t$: State of charge of the BS system in kW h.
$BS_{eff}$: Charge/discharge efficiency of the BS system, set at 95%.
$SoC_{min}$: Minimum allowed state of charge as a proportion of $BScap_d$, set at 30%.

**Table 1**
The EE measures explored.

| EE measure short name | Description of the EE measures | Electricity consumption of a typical Australian household | Energy savings as % of total appliance load (*ES%*) |
|---|---|---|---|
| AC-EE | Upgrading a typical reverse cycle air conditioner system with a 3 star rating for heating and cooling to a new one with a 10 star rating. | 40% | 68% |
| Refri-EE | Upgrading a typical Australian household refrigerator with a 3 star rating to a new one with an 8 star rating. | 18% | 73% |
| Light-EE | Upgrading halogen lighting to LED lighting. All lights in a typical Australian household are changed. | 6% | 88% |

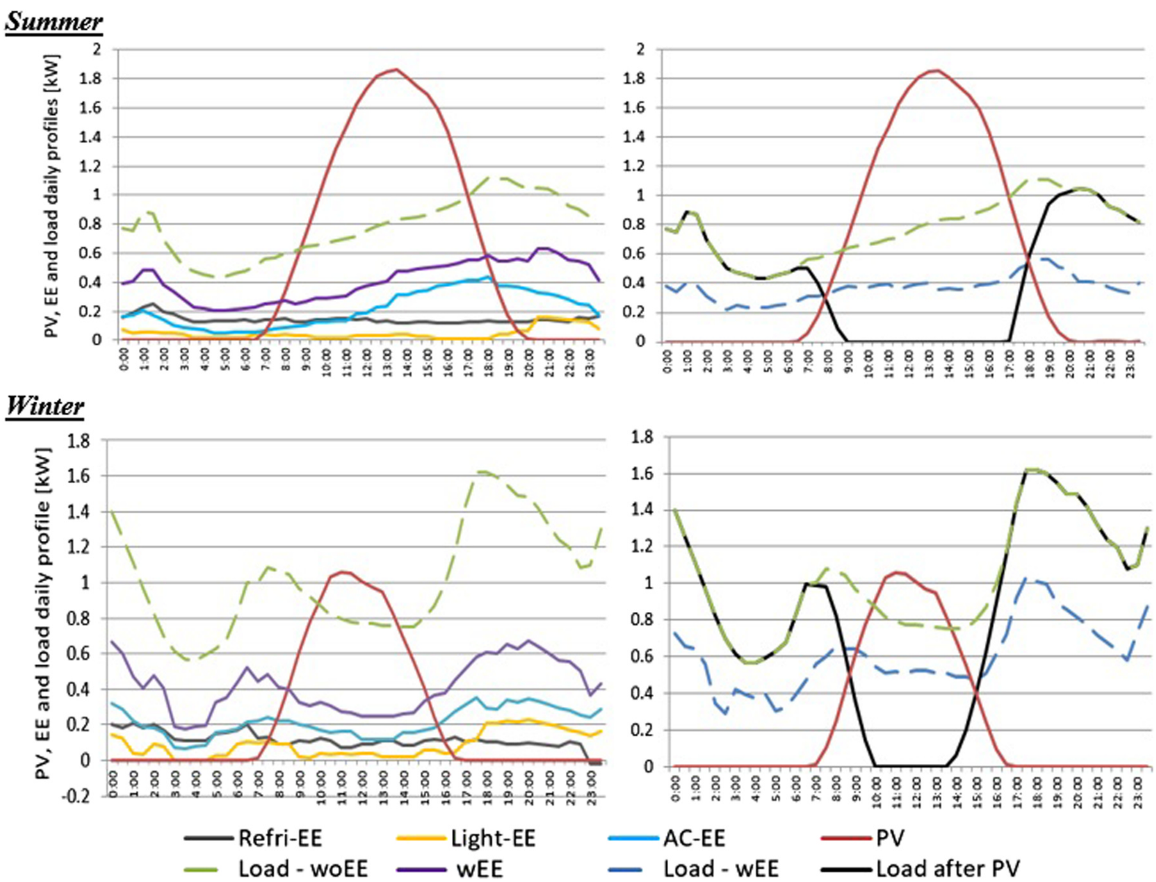


**Fig. 3.** Daily average profile of the PV generation, load and the EE energy savings of the 300 households for the month of January (summer) and July (winter).

Note that this model does not impose a maximum C-rate. However, our results verify that for this application the resulting maximum charge/discharge BS power does not surpass 2 $kW_p$ which is in line with typical residential battery and inverter sizes.

The BS degradation rate strongly depends on the depth and rate of charges/discharges which are driven by our empirical household PV, load and EE data. The BS degradation model in function of key operating parameters is described below.

### 3.3.1. *A BS cyclelife model in function of operating parameters*

The degradation of battery systems refers to the loss of capacity due to the change in the chemical composition of electrolytes and the formation of a solid-electrolyte interphase on the electrodes. The main cause of degradation in residential applications is the charging and discharging cycling of the battery.[5] The number of complete cycles a battery can perform before reaching an 'end of life' (EOL) condition is called the BS cyclelife. EOL is declared when the capacity and ratings of the battery reach a certain limit. Cycling degradation depends on factors such as depth of discharge, charging/discharging rate, temperature, construction and materials used for electrodes and electrolyte [44].

A BS cyclelife model is developed in order to estimate the loss of capacity of Li batteries using our household empirical data. This is necessary as the battery manufacturer's stated lifetime is only relevant under a constant BS operation, which is not the case in the scenarios modelled here. It was developed based on a semi-empirical model originally proposed in [45] and then refined by [46] as in Eq. (5). This model provides, from experimental data, relationships between capacity degradation, charging rate, temperature and cumulative battery charge.

$$Q_{loss} = e^{\frac{D + bRT + GI_{rate} + aRTe^{-\lambda I_{rate}}}{RT}} (Q_{total})^{z} \tag{5}$$

where the parameters are:

[5] Note that batteries also experience the so-called 'calendar degradation'. This occurs when BS is neither charging nor discharging and hence self-discharging is responsible. For residential applications, the contribution of cycling degradation is far greater than the calendar degradation.

$Q_{loss}$: Cumulated capacity loss as a percentage of the initial capacity in %.
$Q_{total}$: Cumulated charge in Ampere-hour (Ah).
$I_{rate}$: Maximum charging rate normalised by the BS degraded capacity in hours$^{-1}$.
*RT:* Product between the universal gas constant and the ambient temperature (set at 25 °C).
*a*, *b*, *z*, *D*, *G* and λ are the model parameters derived from the experimental data.

The model in [45] considers only a constant $I_{rate}$ value. However, in this residential application $I_{rate}$ is very variable. The degraded BS capacity is updated every day *d* of operation. Hence, the marginal capacity degradation is calculated every day from Eq. (6) to then compute a daily $Q_{loss}$ as in Eq. (7).

$$\frac{dQ_{loss}}{dQ_{total}} = z \bullet e^{\frac{D+bRT+GI_{rate}+aRTe^{-\lambda I_{rate}}}{RT}}(Q_{total})^{z-1} \tag{6}$$

$$Q_{loss}(d) = Q_{loss}(d-1) + \frac{dQ_{loss}}{dQ_{total}}\left(d\right) \times (Q_{total}(d) - Q_{total}(d-1)) \tag{7}$$

$Q_{total}$ and $I_{rate}$ in function of the BS charging generation $BS_t$ (in kW h) are shown in Eq. (8) and (9). $V_{BS}$ is the operating voltage of the battery and *t* represents the hours of the day *d* where the battery has been charged. Here, Eq. (8) captures the impact of the daily depth of charge/discharge on the battery degradation.[6]

$$Q_{total}(d) = Q_{total}(d-1) + \frac{1}{V_{BS}}\sum_t BS_t \tag{8}$$

$$I_{rate}\left(d\right) = \frac{\underset{t}{\mathrm{Max}}\{BS_t\}}{BScap_d} \tag{9}$$

The model considers an EOL condition when $Q_{loss}$ reaches 20% as in [46].

The parameters *a*, *b*, *z*, *D*, *G* and λ are estimated from experimental data associated to the Li battery technology in [47]. This study estimates and validates these parameters following the methods used in [46]. Parameters are shown in Table 2.

### 3.4. Combined PV-EE-BS financial value

As such, with the final inclusion of the battery technology, the hourly household revenue from the combined PV, EE and BS system ($\Delta Hrev_t$) is shown in Eq. (10),

$$\Delta Hrev_t = R_t \times (SC_t + ES_t + BS_t) + FiT \times Exp_t \tag{10}$$

where at hour *t*, the parameters are:

$R_t$: Electricity retail tariff rate in $/kW h.
$SC_t$: PV generation self-consumed by the household in kW h.
$ES_t$: Energy savings from the three EE measures in kW h.
$BS_t$: Generation discharged from the BS system in kW h.
*FiT*: Current low feed-in tariff for PV generation exported to the grid in $/kW h.
$Exp_t$: PV generation which is exported to the grid in kW h.

Revenue calculations have been undertaken using 2016 Flat and Time of Use (TOU) retail electricity rates for customers within the Ausgrid distribution network, in Sydney, from [48]. The net metering low FiT rate for PV exports is 6 ¢/kW h in line with Origin's offer [48][7].

[6] Note that in our model we work with $I_{rate}$ in per unit.
[7] Origin Energy is the Australia's largest retailer with a very significant presence in NSW.

**Table 2**
Parameters estimated for Li batteries.

| Parameter | Values |
|---|---|
| a | 1.2197 |
| b | 9.2566 |
| z | 0.4331 |
| D | − 31500 |
| G | 370.3 |
| λ | 0.2801 |

This is less than a quarter of the average household retail rate. All the tariffs used in this study are shown in Table 3.

## 4. Results

### 4.1. First year household energy revenue

Hourly revenue streams are calculated with Eq. (10), for one year, in order to estimate the first year total revenue from the various combinations of PV, EE and BS systems. All scenarios include PV. Fig. 4 shows the annual results for Li batteries of 7 kW h and 14 kW h of capacity, which are two standard sizes available for the residential market. Fig. 4 averages the results of the 300 households and separates the total revenue into revenue from self-consumption, from PV exports and from the EE energy savings. PV electricity captured by the battery, that would otherwise be exported, is counted as self-consumed electricity (after allowing for battery losses).

Fig. 4 demonstrates that total revenue and the proportion of revenue from PV exports vary considerably between the different scenarios. While the addition of EE clearly reduces the PV revenue, the addition of BS increases it, although the total PVBS value is still reduced when EE is used. This is a result of both the changing proportions of self-consumption and PV exports and the different tariff rates used here for PV self-consumption.

As already indicated in [10] for another Sydney network area, EE measures can significantly reduce revenue from the PV system under current NM arrangements. On average, the addition of EE increases PV export levels by 45%. Thus, PV is a much less attractive investment for households with energy efficient equipment.

The PV revenue without EE and without BS is slightly greater with Flat tariffs than with TOU tariffs. Conversely, with the addition of BS, the more cost-reflective the customers' tariff (for example, TOU more than Flat), the higher the PVBS revenue. This is because the generally large proportion of household load occurring at the tariff peak time can be offset by the BS generation. More cost-reflective tariffs with thinner peak periods and higher peak rates than shown here (such as 'critical peak prices' or demand charges in kW) could further increase the value of the BS generation. However, EE could change these dynamics because it changes the household peak load profile.

The addition of BS always increases PV revenue. For this household sample, on average (considering both 7 kW h and 14 kW h BS), BS increases PV revenue by about 45% and 70% without EE and with EE respectively. This shows that EE increases the value added by the BS system alone (BS value) in the short term. This is especially the case for the Flat tariff. This suggests that BS systems could be more financially attractive to households already with PVEE systems (than only with PV).

EE largely increases the BS value with the Flat tariffs (for example, from 24% to 65% for the 7 kW h BS in Fig. 4). However, there is not a similar increase for the TOU tariffs. This is because EE reduces the amount of electricity that can be offset by the batteries in the evening summer peak time. Note that this effect is ameliorated in winter as there is still load for BS self-consumption at peak times as shown in Fig. 3. Under the TOU tariff, the value of the electricity offset by batteries is greater, and so EE results in a greater loss of value. This shows a

**Table 3**
Retail tariffs for 2016[a].

| Type of Tariff | Tariff Component | Rate [¢/kW h] |
|---|---|---|
| ***Flat tariff*** | | |
| | All electricity consumption | 27 |
| ***TOU tariffs*** | | |
| | Peak consumption (2–8 p.m. on business days): | 53 |
| | Shoulder consumption (7 a.m. – 2 p.m. and 8 p.m. – 10 p.m. business days and 7 a.m. – 10 p.m. on weekends): | 22 |
| | Off peak consumption (10 p.m. – 7 a.m. everyday): | 13 |
| ***Feed-in tariff*** | All exported electricity | 6 |

[a] All prices are shown in Australian dollars. These prices include the so-called 'goods and services tax' (GST) which is a broad-based tax of 10% on most goods, services and other items sold or consumed in Australia.

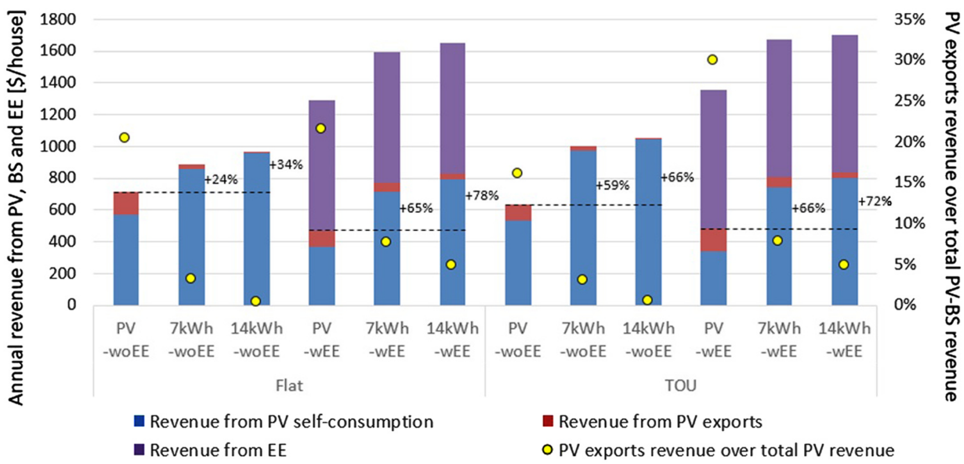


**Fig. 4.** Household annual energy revenue for different combinations of PV, EE, BS and tariffs (all columns include PV). Horizontal dotted lines and percentages at the right side of a column indicate the added BS value.

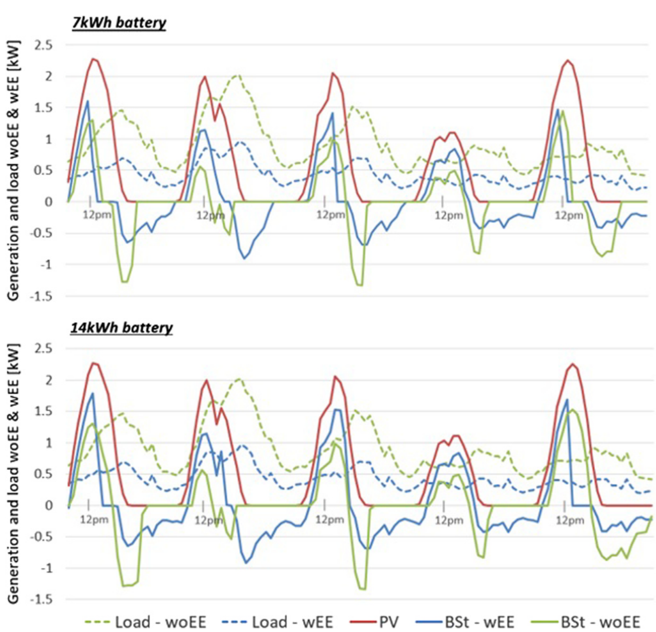


**Fig. 5.** Summer operation of the Li batteries in the first year of operation without EE and with EE.

competition between EE and BS technologies to capture peak time electricity savings. While for the 7 kW h BS the addition of EE increases the off-peak overnight self-consumption from 0% up to 25%, for the 14 kW h the addition of EE results in an increase from 20% to 42%. Fig. 5 clearly illustrates this situation showing the operation of the batteries for some average summer days.

Over the longer term, the degradation of the BS system will reduce these first year revenues. Moreover, as is shown in the next section, EE can also have an impact on the lifespan of the BS system.

### 4.2. The long term economics

This section calculates the net present value (NPV) and discounted payback period of the average PVBS investment of our household sample by comparing the total PVBS revenue with the cost of PV and BS in Australia. The EE measures are assumed to be in place but their direct costs and benefits are excluded from the NPV analysis. Discounted cumulative revenues – in real terms – are shown in Fig. 6, where a discount rate of 3.7% has been used as in [34].

According to Solar Choice [49], the average price of a PV system in Sydney, including government capital subsidies, in October 2017, fluctuates around AUD\$1100/kW$_p$ for systems of 3 kW$_p$. Adding a cost of AUD\$250/kW$_p$ for the replacement of the PV inverter in year 15 of operation [50], discounted at 3.7%, results in a total average 3 kW$_p$ PV price of around AUD\$3800.

For the BS system, a cost of USD\$350/kW h is used for Li batteries from [13] and a middle range installation cost of USD\$1400 is added from [51]. This is about AUD\$5000 and AUD\$8200 for the 7 kW h and the 14 kW h batteries respectively.

Fig. 6 shows that for this residential dataset, adding EE to a household with an average PV system significantly reduces its NPV and increases its payback period. Adding a BS to a PVEE system helps to recover the PV revenue loss caused by EE. However, now the payback period of the combined PVBS investment increases due to the high cost of the BS system. Without EE, the addition of a BS also increases the revenue of the PV investment, but again does not provide sufficient value to reduce the payback period.

Interestingly, it could be argued that in some circumstances BS

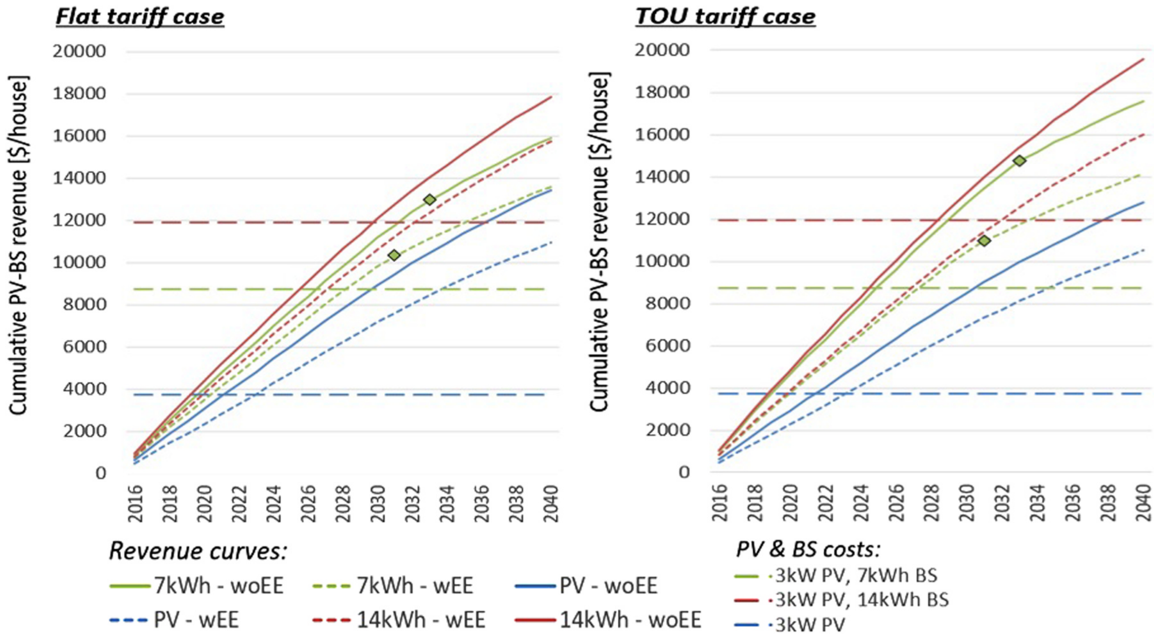


**Fig. 6.** Cumulative discounted PV revenue, without EE and with EE, for different BS systems. Diamonds indicate battery's end of life (All curves include PV).

systems in electric vehicles may not represent an additional expense to households. These batteries could be used to maximise self-consumption, especially where the vehicle is charged and in the house during the peak time period as the batteries could be used to meet household self-consumption. This highlights the benefits of not charging electric vehicles during the evening peak, but where possible, earlier in the day and then much later in the night. Note that more research is required in this area, as electric vehicle batteries have very different characteristics to household batteries, and the increased cycling driven by home use would decrease their lifetime.

The size of the BS system has only a modest impact on revenue as the amount of electricity provided by the battery is very similar in both cases. This is because without EE the 7 kW h BS is almost enough to capture all the PV export (the 14 kW h BS does not store much more energy), while with EE there is not enough household load to fully discharge the 14 kW h BS (Fig. 7). In addition, a proportion of the extra electricity from the larger BS system (14 kW h) ends up offsetting electricity use at only 13 ¢/kW h under the TOU tariff overnight, compared to 27 ¢/kW h under the Flat tariff. Thus, although the shallow charge of the 14 kW h battery extends its life considerably, the extra revenue is insufficient to justify the additional expense.

When EE is added to an existing PVBS system the life of the battery is generally reduced. This is because with EE deeper charges/discharges occur as Fig. 7 shows. This increases $Q_{total}$ in Eq. (5). For this semi-empirical study, EE reduces the life of the 7 kW h battery by 2 years (Fig. 6). This reduces the value of the 7 kW h BS in the long term. However, EE only slightly degrades the 14 kW h battery. Here, $Q_{loss}$ without EE and with EE reaches 18.5% and 19% in year 25 respectively. It has been verified that indeed EE results in the 7 kW h battery undergoing deeper discharges than the 14 kW h battery (see for example fifth day of the 14 kW h in Fig. 7).

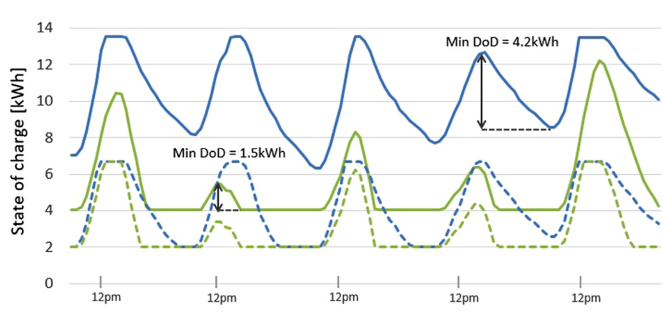


**Fig. 7.** State of charge of the batteries in the first year of operation without EE and with EE (same summer days as Fig. 5). 'Min DoD' refers to 'minimum depth of discharge'.

However, Fig. 4 showed that EE increases the BS value (alone), especially for the Flat tariff. Hence, the overall impact of EE on the BS value has been assessed. Overall, EE does not reduce the 7 kW h BS value with Flat tariffs but does reduce it by about 30% with TOU tariffs. Testing a higher discount rate (up to 8%) just ameliorates this negative impact of EE. On the other hand, overall, EE does not reduce the 14 kWh BS value as EE does not degrade this battery significantly.

## 5. Conclusions and policy implications

The still insufficient policy efforts to mitigate climate change impacts has been a key motivation to find ways to accelerate the deployment of more clean energy technologies such as photovoltaics (PV) and energy efficiency (EE). This article highlights how today's net metering arrangements can create barriers to households wishing to invest in both PV and EE, and the degree to which battery storage technologies (BS) could provide a solution has been assessed.

A novel semi-empirical approach has been applied, that uses hourly real data from 300 households with PV systems in order to capture realistic financial outcomes, under some reasonable modelling assumptions. The use of this methodology is crucial to capture the real time-varying value of these technologies as it correlates the PV output performance, household consumption patterns, residential appliance usage and the electrochemical performance of the batteries. Moreover, the battery cyclelife model is particularly important for assessing the impact of highly variable data on the degradation of battery capacity. Further research could include the use of more granular data, with shorter than hourly time intervals, which would improve the quality of the results,

Our findings demonstrate that currently BS do not compensate for the reduced value obtained from the PV system when EE is also taken up. With EE, a significant proportion of the self-consumption of the BS electricity moves to the off-peak TOU time during the summer season.

Under Flat tariffs, although batteries certainly improve the PV revenue, this additional revenue is not quite enough to compensate for its cost. Additional BS revenue could be created where the BS reduces the grid peak demand and hence grid costs, and is remunerated for this. This suggests that BS could become more financially viable in a few years with the expected decline in battery costs. In general, the smaller the size of the battery, the greater its net value. However, much larger collective BS systems could present economies of scale and some collective financing advantages, and more research is needed in this area. Moreover, batteries in electric vehicles could also be used to maximise PV self-consumption at possibly no extra cost. Assessing the optimal BS operation in electric vehicles is a key area of future work.

This study also found that there seems to be competition between EE and BS technologies to capture bill savings at peak times with net metering. The more cost-reflective the tariff the stronger this competition. In fact, EE not only affects revenue flows but also could accelerate the degradation of the batteries. This is especially the case for batteries sized for deep charge/discharge operation. The early battery end-of-life further reduces the NPV of the BS investment.

Finally, it is important to note that this study uses feed-in tariffs (FiTs) that represent only the wholesale value of generation. In Australia, PV export sales are charged the full transmission and distribution costs. However, in most cases customer exports use only a small segment (or level) of the distribution grid. FiTs will likely evolve with increased uptake of the new smart metering infrastructure and this could change our financial outcomes. Moreover, the tariffs used are far from fully reflecting the time and location-varying costs of electricity supply. Thus, this study does not represent the true value that customers' PV, EE and BS systems could offer to the electricity industry. More cost-reflective tariffs would likely result in batteries providing better value because of their ability to shave electricity industry peak costs. The need for retail market reforms will become more evident with the deployment of more smart meters and the expected cost decline of batteries. More research in this area would greatly assist electricity customers and distribution companies in the search for a cleaner and more cost-effective electricity industry.

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