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Evaluating demand charge reduction for commercial-scale solar PV coupled with battery storage

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ABSTRACT

Solar PV and battery storage technologies are known to provide savings to customers in the form of reduced electricity charges. Currently, these savings are only determined for the volume component (kWh) and not the demand component (kW or kVA). As interest grows in commercial solar PV and battery storage installations, the need to predict demand charge reductions is great. The aim of this research is to determine, with accuracy and reliability, the ability of solar PV and battery storage technologies in reducing demand charges. Results have shown that when simulated against a commercial-scale electricity consumption profile solar PV was able to reduce the maximum demand across five electricity networks in Australia by 0.05–1.51%. When coupled with a 12 kWh battery storage an additional 1.31–2.02% reduction was experienced. Battery utilisation strategy was shown to be critical in yielding greater demand reduction from the battery storage. Notably, it was shown that in the Ergon Energy electricity network, battery storage was able to supply demand at 34% lower cost ($/kW) than the network was able to. The results detail the first instance of demand reduction evaluation of solar PV coupled with battery storage, focusing on physical and financial outcomes in an Australian context.

1. Introduction

Solar PV and battery storage technologies offer consumers the ability to reduce their electricity bills. The extent to which the savings on these bills is currently being determined within industry is limited to the savings associated with reduced volume consumption of electricity, denoted in kilo watt hours (kWh). Growth in solar PV and battery storage technologies now means that the technology is becoming increasingly attractive to larger electricity consumers. In order to better develop the business case for larger electricity consuming customers, there is a need to be able to readily and accurately determine reductions in peak demand. At present, demand charges currently only apply to the larger non-residential consumers. This need exists because demand charges make up the major portion of commercial electricity bills [1] and, in some cases, are as high as 40% [2].

The aim of this research is to investigate how to calculate demand reduction in the context of two different configurations; solar PV alone and solar PV coupled with battery storage systems. Both financial and physical performance characteristics within the current body of research into demand reduction from solar PV and battery storage will be explored, highlighting the gaps, inconsistencies and inaccurate assumptions which have been developed in previous studies. This research will not assess solar PV tracking systems, rather, fixed solar PV installations as their use is widespread. The findings will be used to guide the development of a model that is able to compute calculations of demand reduction and the subsequent savings on electricity bills.

1.1. Solar PV and battery storage in an Australian context

Solar PV, as part of a national strategy, has become vital in helping Australia reach its carbon reduction goals. An incentive-based system has led the way for high penetration of solar PV in Australia with over 1.4 million registered solar PV system installations [3]. The ability of solar PV to assist in the shaving of critical peak demand within electricity networks is well known [4] and, as a consequence, it has helped to realise reduced network spending on network capacity infrastructure. The addition of storage technologies will assist electricity networks further in reducing stress on its infrastructure during peak loads [5]. Improvements in the affordability of battery storage technologies, particularly lead-

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Nomenclature

ζ	Zenith Angle (degrees)
γ	Temperature Coefficient (%/°C)
η_{inv}	Inverter Efficiency (%)
$\eta_{Round-trip}$	Battery Round-trip Efficiency (%)
B_C	Battery Charge (kW)
$B_{C,R}$	Battery Charge Rating (kW)
B_D	Battery Discharge (kW)
B_D	Battery Discharge Rating (kW)
$C_{Break-even}$	Break-even costs ($/kW)
$C_{D,G}$	Cost per unit of Demand Supplied ($/kW)
C_N	Network Demand Cost ($/kW)
C_T	Technology Cost ($/kW)
D_f	Final Demand (kW)
D_G	Demand Given (kW)
D_L	Demand Load (kW)
$D_{L,S}$	Demand Load after Solar PV (kW)
D_{Max}	Maximum Demand (kW)
D_N	Demand Needed (kW)
D_T	Demand Threshold (kW)
DoD	Depth of Discharge
DNI	Direct Normal Irradiance
E_E	Battery Storage, end of time-step (kWh)
E_{Max}	Battery Storage, maximum capacity (kWh)
E_S	Battery Storage, start of time-step (kWh)
GHI	Global Horizontal Irradiation
N	Number of years of operation
$NOCT$	Normal Operating Cell Temperature (°C)
$N_{PV,P}$	Number of panels in parallel
$N_{PV,S}$	Number of panels in series
P_F	Final Power Output (kW)
P_{PV}	Solar PV Power Output (kW)
$P_{PV,STC}$	Solar PV Power Output, Standard Test Conditions (kW)
S_D	Demand Savings ($)
SOC	State of Charge (%)
T_a	Ambient Air Temperature (°C)
T_C	Cell Temperature (°C)

acid and lithium-ion (Li-ion) batteries, will likely result in many solar PV systems being coupled with energy storage. The coupling of battery storage and solar PV is known to firm investments made in solar PV [6]. Furthermore, the addition of battery storage to a solar PV system will mean that self-consumption of solar PV generated electricity is likely to increase [7]. The introduction of both solar PV and battery storage technologies serve to improve the affordability and reliability of the electricity network in Australia, and for consumers, aim to reduce the costs of electricity - for both demand charges and volume consumption charges.

1.2. Modelling generation and storage technologies

In order to determine the value of installing solar PV and battery storage technologies, several performance and evaluation models have been developed for residential [5] [8] [9] [10] and commercial applications [11] [12] [13] [14] [1]. The importance of developing a model has been noted for several reasons. Firstly, almost no two buildings or electrical load requirements are alike [1]. Second, any financial evaluation is individually determined based upon electricity usage, network tariffs, solar PV/battery storage capacity, and technology application [14]. Third, for adequate certainty to exist for both sellers and buyers of such technologies the variables need to be well understood and it is clear that, in support of the comments made by Nottrott, Kleissl and Washom [1], there is a requirement for the development of evaluation techniques and tools for improved estimation of the economic value of solar PV and battery storage. The basic requirement of a model is to simulate the performance of both technologies in differing locations, loads and financial circumstances. To date, no such model has been established for the evaluation of these technologies in an Australian context and, furthermore, it will be shown that existing research either does not include or misrepresents certain characteristics that may be applicable to commercial-scale electricity consumers.

1.2.1. Solar data

Various scales of data measurement have been used in storing weather data information. Previous models have used 30-min Global Horizontal Irradiation (GHI) data [12], 15-min GHI [1], one-minute GHI data [6], and data supplied by PVoutput.org [4] or PVsyst [5], which are online solar PV software tools that utilise one-hour data. In Australia various time-steps are available, with the smallest being one-minute GHI data provided by the Bureau of Meteorology (BOM) for select locations.

For the study of demand charge reduction it is most appropriate to use the smallest time interval available as demand is measured by the network as the highest kW or kVA value during any 15 or 30 min period. For this very reason some apprehension may be applied to the studies by Ru, Kleissl and Martinez [12], and Nottrott, Kleissl and Washom [1] into demand reduction. Moreover, Glassmire, Komor and Lilienthal's [2] research utilised one-minute interval data, but proceeded to average the data into 15 min intervals to simplify the computation, compromising the accuracy of their research into demand reduction of a commercial site.

1.2.2. Solar generated electricity

The means by which solar data is then interpreted to determine solar PV generation also differs in practice. The method for determining solar generated electricity during any time-step has been well established. It has been shown that with adequate air temperature and solar radiation data the cell temperature can be determined [15]. As the relationship between PV cell output and cell temperature is known to be important [15], the accuracy of demand reduction calculated by Ref. [2] can be questioned as it conducts simulations using HOMER (http://www.homerenergy.com) which determines cell temperature based on radiation data alone and does not consider ambient air temperature. For this very reason Bortolini, Gamberi and Graziani [16] sought to develop a temperature dependent model for solar PV generation which can be applied to simulation models.

1.2.3. Battery storage and performance

Battery storage technology for solar PV has been investigated in applications of reducing the amount of grid purchased electricity [11] [6], as well as in off-grid applications [12]. As the former of these two is more common and more applicable to commercial-scale consumers, it will be focused on in this review into reducing demand. For example, in California it has been shown that solar PV reduced demand by 19.6% in July and 11.4% in November. Additionally, when coupled with battery storage the demand reduced by a further 6.0% in July and 9.3% in November [6]. Despite these results being able to quantify the reduced demand as a result of solar PV and battery storage, Hanna et al. [6] found that the system did not satisfy return on investment requirements (i.e. positive NPV). This outcome is echoed in similar research outcomes [1] [11], and [17].

The cost of battery storage can be denominated either by $/kWh, which denotes the storage capacity, or by $/kW, which denotes the discharge capacity. Nottrott, Kleissl and Washom [1] investigated the value at which battery storage technology would be viable and stated that in the range of 200–400 USD/kWh battery storage technology had a positive Net Present Value (NPV). Nevertheless, the authors comment that each application is subject to the site-specific variables; location, network tariffs, electricity costs, electricity consumption characteristic. Additionally, the validity of the results found by Nottrott, Kleissl and Washom [1] could be questioned as they assumed that there were no costs associated with importing and exporting electricity from the grid, which in real world applications would be inadequate for accurate financial assessment, as these are part of the costs that these technologies seek to defer.

1.2.4. Battery utilisation strategy (BUS)

The flexibility which battery storage provides assists consumers that either; consume energy in excess of solar PV generation, consume energy in non-generating times, or both. For commercial consumers it is likely that they consume in excess of solar PV generation and consume in hours where solar generation is not available. This is due mainly to the fact that commercial loads have higher demand than that which is typically output by a solar PV system, which is limited to a rating less than 100 kW under Australia's Small-scale Technology Certificate (STC) mechanism [18]. It should be noted that solar PV generation is typically better suited to commercial applications as the synchronisation between generation and consumption is far greater than that of residential applications [19]. As such, determining the way in which battery storage is utilised becomes more complex and dependent on the usage scenario.

The main options for battery utilisation strategy (BUS) which have been examined to date are; on/off, real-time, and optimisation schedules [1]. The first of these, on/off represents a simple dispatch schedule where battery storage is discharged during the period of peak usage for example: 10am-4pm. Due to its ease of application, the on/off BUS strategy can be assessed as it is most reliable and likely to be adapted in commercial application [6]. As there are many battery utilisation strategies, the desired outcome needs to be considered. Nottrott, Kleissl and Washom [1] targeted peak usage and demand charges with the aforementioned strategies. Similarly, Richardson and Harvey [20] and Ranaweera and Midtgard [21] analysed the application of solar PV and battery storage in providing the lowest cost of energy. As this research proposes to establish a reliable method for predicting demand charge reduction it will be the sole objective in applying battery storage technology. As such, a demand threshold BUS will be assessed to determine its applicability and economic prospects as a useful demand charge reducing mechanism.

1.2.5. Inverter efficiencies and parameters

Inverters are required not only for discharging battery electricity, but also solar PV generated power, as it too is DC. Many of the models developed for determining reduced demand make differing assumptions regarding inverter efficiencies. These include; assuming 97% efficiency [14], 95% efficiency [5], inverters are lossless [1] [6], or have constant performance [12]. To assume that inverters and converters are lossless is not reflective of reality as the introduction of errors magnifies dependent on the number of inverters and/or converters. The assumption of constant efficiency may be considered as an acceptable introduction of error as inverters and converters have relatively unchanged efficiency above 20% rated input [9]. Inverter efficiencies have an impact on both the solar PV supplied energy and the battery storage supplied energy, so maximising the value of these systems is important in reducing grid purchased electricity costs.

1.3. Demand-side and utility-side interaction

In the context of technology deployment, such as solar PV and battery storage, there is competing interests as to what kinds of rules and regulations should be imposed on both the demand-side and utility-side of the electricity network. For example, the interests of the utility are to protect their distribution and transmissions infrastructure, while consumers seek to minimise costs associated with their consumption. Although the intention of this paper is to focus on the consumer level benefits, the benefits to the utility include reducing the grid load at peak times and, thus, lower the need for network expansions [5]. This benefit has been particularly apparent on feeders with a high proportion of commercial loads [19].

1.3.1. Grid-purchased electricity

Reducing grid–purchased electricity has, to date, been recognised as the major financial savings characteristic for solar PV. The way in which modelling simulates and addresses grid purchased electricity differs greatly. This is due to differing costs of energy in different locations. Some simulations have assumed there is no cost associated with purchasing electricity from the grid [1] [6]. This, in combination with understanding exporting solar generated electricity, can impact on the accuracy of financial evaluation of solar PV and/or battery storage systems.

1.3.2. Exporting solar generated electricity

In determining the financial benefits of solar PV generated electricity the influence of feed-in tariffs (FIT) is known to improve the value of solar installations [22], particularly if generation exceeds consumption. This may be the case for commercial applications during the weekends or holidays. The value of exported electricity is comparatively low for most states in the National Electricity Market (NEM) and, as such, has not had a large impact as compared to what has been seen overseas. For example, Li and Danzer [5] considered a FIT of 30 euro-cents, whereas in Australia FIT are in the range of 4–9 cents or optional even in some states [23]. Critical to understanding how this may influence simulation of commercial-scale consumers in Australia is the current rules regarding exporting of solar generated electricity into the grid. At present, some electricity networks are able to deny solar installations over a certain kW rated capacity, meaning that solar installations are required to have zero-export devices, denying customers of the benefits of FIT. This is a key consideration in the analysis of solar PV in an Australian context, as many other countries regulate that renewable generated electricity be sold into the grid at a premium. For example, solar installations of 30–100 kW in size in the Ergon Energy electricity network require systems to have a non-export device [24].

1.4. Economic evaluation

In the absence of the sole desire to reduce carbon emissions, providing a lucrative economic outcome for any technology investment is the main driver for adoption of solar PV and battery storage technologies. Traditionally, solar PV projects have only provided economic incentive for the volume reduction (kWh), but as has been recommended, demand reduction (kW or kVA) remains relatively unknown, both in a physical and fiscal sense. Fig. 1 gives a systematic overview of the system inputs to both savings measures. Attributing each of these variables in a financial performance evaluation requires up-to-date market costs, as well as location relevant energy and network costs.

1.4.1. Understanding network charges

To better comprehend the available savings associated with reduced demand a summary table of all 12 network providers in the NEM, with their demand charges, is given in Table 1. The variance in demand charges is considerable, from 5.4376 $/kVA/month for United Energy (in Victoria) to 28.780 $/kW/month for Ergon Energy (in Queensland). Additionally, some electricity networks charge demand in real power (kW) and in apparent power (kVA). Consideration needs to be given in assessing the demand charges associated with each network. First, the magnitude of the demand charges will play a significant role in determining the overall impact that demand reduction has on the financial viability of a given project, as has been noted previously by Su, Huang and Lin [14]. Second, the time-base upon which the demand charge is determined. For example, in the Powercor network the maximum demand is determined by the highest kW value in a 12-month period. Alternatively, in the Energex network it is determined by the highest kVA value in a one-month period. This correlates with how consistently solar PV and battery storage need to reduce demand over the demand charge set period.

1.4.2. Technology economics

Of the authors who have previously modelled demand reduction and its associated financial benefits, varying costing have been given for the price of solar PV ($/kW), battery storage ($/kWh or $/kW) and inverter/converters ($/kW). As with most technological learning curves, pricing for technology changes rapidly. Stadler [11], and Hoff, Perez and Margolis [13] modelled their work on a solar PV price of over 6000 USD/kW. The most recent pricing for Solar PV shows that a 100 kW system in Australia is $1212/kW, inclusive of inverter and government subsidy [37]. It is clear to see how quickly the price of solar PV has dropped and, as such, requires remodelling inclusive of these updated economics. Similar results can be seen for battery storage technology. Stadler [11], Ru, Kleissl and Martinez [12], and Hoff, Perez and Margolis [13] modelled battery storage in the price range of 150–200 USD/kWh. Most recently Dufo-Lopez and Bernal-Augustin [38] concluded that both Li-ion and lead-acid battery technologies did not yield positive NPV when applied to the Spanish electricity market at a price of 90 €/kWh. Though some studies did simulate future forecasted prices, application of current market estimates should be used to ensure accuracy of financial evaluation. Recently, prices for Li-ion batteries were reported to be in the price range of 140–620 USD/kWh, with the average being 300USD/kWh [39]. To date, prices in this range are not being experienced in Australia. A recent survey of battery storage products yielded battery storage costs inclusive of installation and inverter to range from 1171.88 to 2667 $/kWh or, alternatively, 1440–7692.30 $/kW rated continuous output capacity [40]. Application of the most competitive results will be utilised in this research. Assuming a discharge (kW) to storage capacity (kWh) ration of 1: 1.2. Depth-of-discharge specification of 80% [16] and round-trip efficiency of 90% [11]. The application of current market pricing should be central in the financial evaluation of technologies, particularly if the results modelled are to be applicable to the current Australian market.

2. Method

2.1. Electricity consumption profile

Modelling of the solar PV and battery storage systems is to be applied to the following electricity load profile, see Fig. 2. This profile was selected as it followed the shape of consumption data available from network sub-station feeders located in industrial areas of the Ergon Network [41] and provides a good example for usage characteristics for commercial-scale consumers.

This consumption profile's key characteristics can be summarised as; maximum demand, D_{max}, of 250 kW and an annual volume consumption of 1596 MWh. These values will provide the benchmark from which any demand reduction savings are determined. This load profile will be constant in the application of solar PV and battery storage technologies across 5 locations.

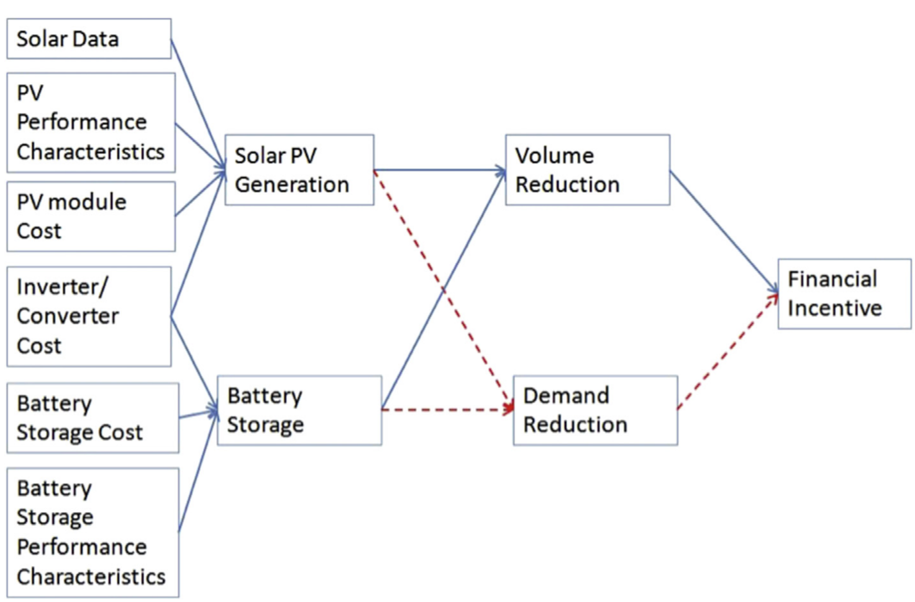

Fig. 1. System Inputs and Savings Mechanisms. Red lines represent the demand savings which are not being determined by others. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Network demand charge summary.

Network	Demand Charge per Month	Charge Set Period	Location	Ref.
SA Power Networks	8.701 $/kVA	Monthly	South Australia	[25]
CitiPower	8.9008 $/kW	Annually	Victoria	[26]
Powercor	12.845 $/kW	Annually	Victoria	[27]
United Energy	5.4376 $/kVA	Monthly	Victoria	[28]
SP Ausnet	7.6300 $/kVA	Annually	Victoria	[29]
Jemena	8.86625 $/kW	Annually	Victoria	[30]
Essential Energy	8.1296 $/kVA	Monthly	New South Wales	[31]
Endeavour Energy	9.5791 $/kVA	Monthly	New South Wales	[32]
AusGrid	10.5549 $/kVA	Annually	New South Wales	[33]
Energex	18.754 $/kVA	Monthly	Queensland	[34]
Ergon	28.780 $/kVA	Monthly	Queensland	[35]
Aurora	15.7455 $/kVA	Annually	Tasmania	[36]

2.2. Solar and temperature data

Solar data is provided from the Australian Bureau of Meteorology's One-minute Solar Data resource [42], to cover the locations of Wagga Wagga (NSW), Cape Grim (Tas), Rockhampton (QLD), Melbourne (Vic), and Adelaide (SA). Diffuse Horizontal Irradiance (DHI), Direct Normal Irradiance (DNI), and zenith angle (ζ) are to be used to obtain the Global Horizontal Irradiance (GHI) using the following,

$$GHI = DHI + DNI \cdot cos(\zeta) \tag{1}$$

Weather data is also to be provided by the Bureau of Meteorology, though the resolution of data available is not as high as the one-minute solar data. Maximum and minimum daily temperatures are provided for the same period for which the one-minute solar irradiance data is given. As solar PV output decreases with increases in cell temperature the maximum temperature for a given day should be used in calculating the solar PV output, as this represents the *worst case scenario* from which the demand reduction is determined.

2.3. Solar PV generation

Solar PV Generation is a function of multiple data inputs, these are; the GHI, temperature data, solar PV module characteristics, as well as solar PV system design. The system being simulated is a 99.64 kWp system. Solar PV output is given by the following,

$$P_{PV} = \frac{P_{PV,STC} \cdot GHI \cdot [1 - \gamma \cdot (T_C - 25)]}{1000} \cdot N_{PV,S} \cdot N_{PV,P} \tag{2}$$

$P_{PV,STC}$ and γ are the solar PV output under standard test conditions and the temperature coefficient respectively. These factors are supplied by the solar module manufacturer. $N_{PV,S}$ and $N_{PV,P}$ are determined by the system design. See Riffonneau et al. [9] for the complete method. The cell temperature, T_C, is typically not recorded, though an estimate can be used based on ambient temperature and GHI,

$$T_C = T_a + \frac{GHI \cdot (NOCT - 20)}{800} \tag{3}$$

Where T_a is the ambient temperature and NOCT is the Normal Operating Cell Temperature, which is provided by the manufacturer and is typically 20–40° higher than the ambient temperature during daylight hours [15]. This calculation is to be carried out for the above-mentioned locations using a full year's temperature and solar data to detail the demand reduction of a typical commercial-scale electricity load profile.

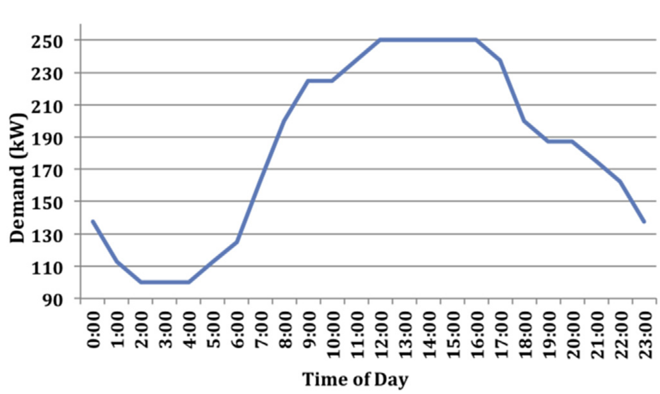

Fig. 2. Electricity consumption profile.

2.4. Solar PV inverter

Solar PV inverters facilitate the conversion of solar PV DC power to AC at the required voltage (typically 240 V for Australia). The efficiency with which the conversion takes place is dependent upon the efficiency curve for the particular inverter. The inverter being modelled in this study is an ABB Trio-27.6-TL-OUTD [43]. The ABB Trio-27.6-TL-OUTD inverter has a European weighted efficiency of 97.92%, reflecting an average operating inverter efficiency across a year. The product of inverter efficiency (η_{inv}) and the solar PV generated (P_{PV}) electricity will give P_F, the final power output for the combined solar PV system and inversion from DC to AC.

2.5. Battery storage

Battery Storage is to be utilised with the *Simple* strategy, as well as with a *Threshold* strategy, in order to investigate its ability to reduce demand and investigate the importance of having a battery utilisation strategy. The two battery utilisation strategies will be described in section 2.6. The battery system will adhere to the following constraints:

1. $20\% < State\ of\ Charge < 100\%$, in order to preserve battery lifetime [16],
2. Battery Discharge (kW), B_D, is limited to $0 < B_D < B_{D,R}$, where $B_{D,R}$ is the rated output for the battery,
3. Battery Charge (kW), B_C, is limited to $0 < B_C < B_{C,R}$, where $B_{C,R}$ is the rated charging power,
4. Round-trip Efficiency, $\eta_{Round-trip}$, is 90% as a result of energy losses incurred through charging, discharging and time losses in the battery storage [11],

5. Energy Discharge to Energy Storage ratio of 1:1.2, this will allow the simulation of various battery storage system sizes.

2.6. Battery utilisation strategy (BUS)

Battery storage systems will be simulated across various sizes (0–30 kW rated systems) utilising both *Simple* and *Threshold* BUS's in order to determine the optimally sized system under various scenarios and highlight the best economic outcomes from this technology application. The *Threshold* BUS is novel as the amount of battery energy being discharged is dependent upon the demand threshold value configured. The ability of the BUS to reach the demand reduction threshold is contingent on the solar PV output and the capacity of the battery storage system. As such, multiple sized battery storage systems and threshold values require evaluation.

2.6.1. Simple battery utilisation strategy

Battery Discharge:

$$10am < time < 6pm,\ then$$
$$B_D = \frac{E_{Max} \cdot DoD}{8}$$
$$6pm < time < 10am, then$$
$$B_D = 0,$$

where E_{Max} is the maximum storage capacity of the battery storage system and DoD is the depth of discharge.

Battery Charge:

$$11pm < time < 7am, then$$
$$B_C = B_{C,R}$$
$$7am < time < 11pm, B_C = 0,$$

where the 11pm to 7am time constraint allows the battery to charge from grid-purchased electricity during off-peak lower pricing periods.

Final Demand after application:

$$D_F = D_L - D_G * \eta_{Round-trip} \tag{4}$$

where D_F is the final demand for the time-step (kW), D_L is demand load required by the consumer (kW), and D_G is the demand given by the battery storage system (kW).

2.6.2. Threshold battery utilisation strategy

Demand Threshold, D_T, is set dependent on the desired demand level to be achieved. This is to be tested in 5 kW intervals over the range of 220–250 kW to assess the ability of the BUS to reach its target, as well as its performance compared to the *Simple* strategy for similarly sized systems.

Demand Needed (kW):

The demand required by the battery storage, D_N, is given by,

$$D_N = D_{L,S} - D_T \tag{5}$$

where $D_{L,S}$ is the demand load required after solar PV generation has been taken into account for the interval (kW), and given that $D_L > D_T$.

Battery Discharge: When $10am < time < 6pm$, then:

- *if* $D_N < B_{D,R}$, then $B_D = B_{D,R}$, given that $E_S < B_D/60$, or
- *if* $D_N < B_{D,R}$, then $B_D = D_N$, given that $E_S > B_D/60$

$$When\ 6pm < time < 10am, then$$
$$B_D = 0,$$

where E_S is the battery storage at the beginning of a time-step (kWh).

Battery Charge

$$7am < time < 11pm, then \quad B_C = 0 \qquad 11pm < time < 7am, then \quad B_C = B_{C,R},$$

given that $E_S < E_{max}$.

Energy Stored:

Energy Stored at the start of any given interval, *n*, is given by,

$$E_{S,n} = E_{E,n-1} + \frac{B_{D,n-1} + B_{C,n-1}}{60} \tag{6}$$

where E_E is the battery storage at the end of a time-step (kWh). Energy Stored at the end of any given interval, *n*, is given by,

$$E_{E,n} = E_{S,n} + B_{D,n} + \frac{B_{C,n}}{60} \tag{7}$$

Final Demand after application:

$$D_F = D_L - D_G \cdot \eta_{Round-trip} \tag{8}$$

2.6.3. Financial evaluation of simulated systems

Technology Cost, CT ($), given by,

$$C_T = System\ Cost + Battery\ Charging\ Costs, \tag{9}$$

where, System Cost is the combined cost of the technologies being simulated and grid-purchased electricity is assumed to cost 6 cents per kWh. Demand Savings per annum, SD ($), given by,

$$S_D = C_N \cdot (D_{max} - D_F), \tag{10}$$

where C_N is the network demand cost per annum, as detailed in Table 1. Cost per unit of Demand Given, $C_{D,G}$ ($/kW), given by,

$$C_{D,G} = \frac{C_T \cdot (D_{max} - D_F)}{N}, \tag{11}$$

where N is the number of years of operation of the technology. Break-even Cost, $C_{Break-even}$ ($/kW),

$$C_{Break-even} = C_N * (D_{max} - D_F) * N \tag{12}$$

This is the cost at which battery storage should be in order to be cost competitive with Network supplied demand.

3. Results and discussion

This section shows the demand reduction for a range of technical parameters that are summarised in Table 2.

3.1. Solar PV alone

The first test scenario to be assessed is that of solar PV's ability to reliably reduce demand for a typical commercial electricity load throughout the year. A summary of the simulation results can be seen in Table 3.

It is clear to see that the impact that solar PV alone has on reducing maximum demand is limited, ranging between 0.05 and 1.51%. This outcome is significantly different to that established in

Table 2
System parameter input summary.

System Component	Input Parameter	Value
Solar PV [44]	$P_{PV,STC}$, Maximum Power	265 W
	η, Module Efficiency STC	16.19%
	γ, Temperature Coefficient	−0.41%
	NOCT Normal Operating Cell Temperature	45±2°C
	$N_{PV,S}$, Number of Modules in Series	94
	$N_{PV,P}$, Number of Modules in Parallel	4
	N_{PV}, Number of years of operation	25 years
Solar PV Inverter [43]	European weighted average Efficiency	97.92%
Solar Radiation and Air Temperature [42]	*DHI*, *DNI* and ζ	One-minute time resolution
	Ta, Maximum Air Temperature	Daily time resolution
Battery Storage [40]	N_B, Number of years of operation	10 Years
	kWh:kW ratio	1.2:1
	DoD, Depth of Discharge	80%
	Battery Storage System Cost	$1172/kW
	$\eta_{Battery}$, Storage Round-trip Efficiency	90%

Table 3
Solar PV alone results summary.

Location	Demand Reduction, New Monthly Average (kW)	Demand Reduction, By percentage (%)	Network	Demand Reduction Savings per annum
Adelaide	246.80	1.28%	SA Power Networks	$333.97
Cape Grim	249.87	0.05%	Aurora	$23.86
Melbourne	249.32	0.27%	CitiPower	$72.12
Rockhampton	246.23	1.51%	Ergon	$1301.15
Wagga Wagga	247.35	1.06%y	Essential Energy	$258.69

previous work by Hanna et al. [6] who found that when only solar PV was employed that demand reductions for the months of July and November were 19.6% and 11.4% respectively on average. This discrepancy may be due to showing the reduction in average demand rather than showing the reduction of the maximum demand. The variability of the demand reduction can been seen in Fig. 3 where a typical 7 day period shows solar PV's ability to reduce demand.

The associated financial benefits have also been determined, ranging from 23.86 to 1301.15 $ per annum. This significant range is due to two main reasons; firstly the network providers which billed on monthly rather than annual maximum demand showed higher levels of savings, and second, the correlation between more expensive networks and greater savings is very much apparent. On face value these savings appear somewhat insignificant, but when projected over the lifetime of a typical solar PV system (20–25 years) the accrued savings may indeed have a tangible impact on whether or not a project may proceed. For example, the Rockhampton system would be able to realise an additional $62,100 worth of savings assuming a modest increase in network demand costs of 5% per year over 25 years.

Some uncertainty exists with the results obtained. Firstly, solar data sets were not complete for the entirety of the years simulated. To overcome this linear interpolation was done between data points when the data were missing for a period less than 3 h. For missing data sets greater than 3 h it was assumed that the previous full day's data be used instead. These two steps were required to ensure that the model could complete the simulation of the full year's worth of data at the expense of some introduced errors. Second, the simulation of these results is reliant upon the fact that all equipment being simulated is to perform as stipulated in the specifications; for example, if an inverter were to malfunction

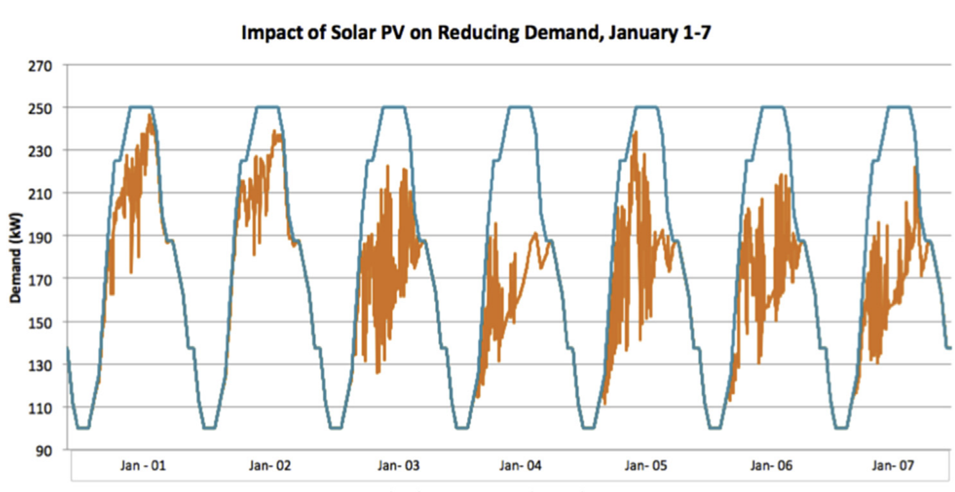

Fig. 3. Impact of Solar PV on Reducing Demand for the week of January 1–7 2013.

Table 4
Additional Demand Reduction for 10 kW/12 kWh Battery Storage system coupled with Solar PV.

Location	Solar PV, Demand Reduction (kW)	*Threshold* BUS, Demand Reduction (kW)	*Threshold* BUS, Savings p.a. ($)	*Simple* BUS, Demand Reduction (kW)	*Simple* BUS, Savings p.a. ($)
Adelaide	3.20	5.047	$527	1.125	$117
Cape Grim	0.13	4.386	$829	1.125	$213
Melbourne	0.68	3.890	$415	1.125	$120
Rockhampton	3.77	3.715	$1283	1.125	$389
Wagga Wagga	2.65	3.263	$318	1.125	$110

Table 5
Comparison of Battery Utilisation Strategies at optimum storage size.

Location	Optimum Storage Size (kW)	Demand Reduction		Cost per Unit of Demand Supplied		
		Simple BUS (kW)	*Threshold* BUS (kW)	*Simple* BUS ($/kW)	*Threshold* BUS ($/kW)	Difference (%)
Adelaide	2.5	0.281	1.501	1041.78	195.23	534%
Cape Grim	10	1.125	4.386	1041.78	267.17	390%
Melbourne	5	0.563	2.845	1041.78	205.95	506%
Rockhampton	2.5	0.281	1.296	1041.78	226.11	461%
Wagga Wagga	2.5	0.281	1.245	1041.78	235.29	443%

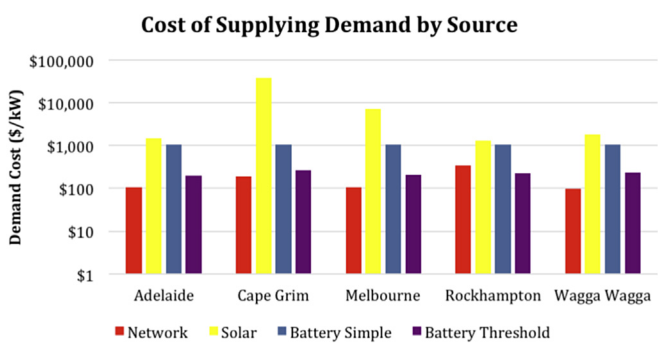

Fig. 4. Demand cost by source.

momentarily then any reductions in demand for the measurement period may be compromised and the associated financial benefits lost.

3.2. Solar PV coupled with battery storage

The inclusion of battery storage to the embedded generation of the solar PV system yielded improved demand reduction. This is due to the nature of electricity supplies Solar PV is intermittent and controllable, whereas the battery storage system is controlled. The demand reduction provided by the system differed greatly depending on the BUS. Both the *Simple* and *Threshold* strategies yielded improved demand reduction when contrasted to the system that had solar PV only. For example, Table 4 shows the additional demand reduction when a 10 kW battery storage system (with both BUS's) is coupled to the solar PV system.

The size of the battery storage system selected for each location differed due to; the consumption profile, solar generation, and BUS selected. Optimum sizing for Adelaide, Rockhampton and Wagga Wagga was 2.5 kW rated storage, while for Cape Grim it was 10 kW, and for Melbourne 5 kW, operating with the *Threshold* BUS. As the *Simple* strategy provided a flat reduction of demand across the time period 10am-6pm the optimum battery size was varied as the demand reduction experienced was linear from zero through to the minimum demand experience required by the system during the time period. As such, comparison of the *Threshold* and *Simple* BUS's was made between system sizes as determined as optimum for the *Threshold* BUS.

Table 5 indicates that the performance of the Battery storage system is significantly improved when the *Threshold* BUS is implemented when contrasted to the *Simple* BUS. Indeed the variance in performance between the two BUS's range by a factor of

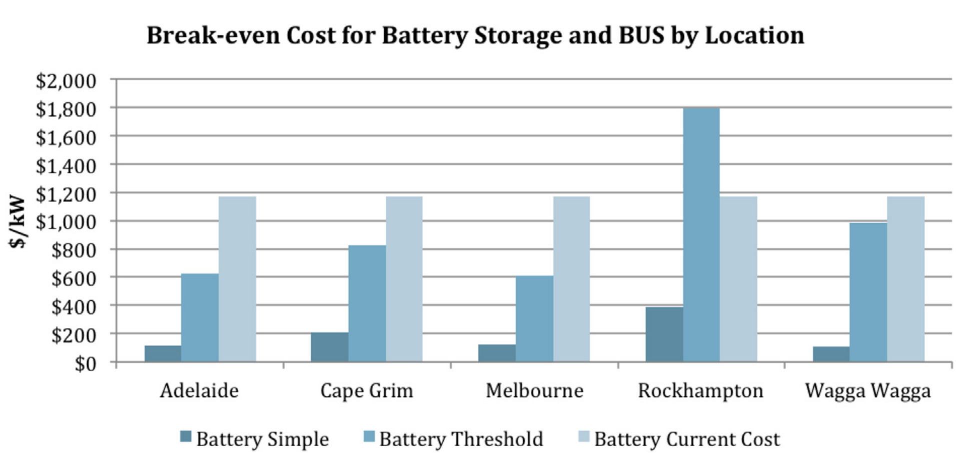

Fig. 5. Break-even cost for battery storage and BUS by location.

3.9–5.3 across the five locations. This would suggest that the way in which battery storage is used is highly important in deriving both greater demand reduction as well as greater financial return on investment.

When the cost of demand supplied by source is compared across the Network, Solar PV, and Battery Storage (*Threshold* and *Simple* BUS's) the Network's cost for supplying one unit of demand (kW) is the cheapest in all scenarios bar one. This result can be seen in Fig. 4, where it is evident that for the Network located in Rockhampton, the battery storage with *Threshold* BUS is able to supply demand at cheaper cost per unit than the electricity network. This is a significant result in that it suggests that a cheaper alternative to the electricity network exists at current market prices.

Solar PV is the most expensive source of demand across all locations due to the intermittent nature of the technology as a generator. Though this negative result needs to be viewed in light of the fact that solar PV is typically installed with the objective of reducing the volume, not the demand and, as such, is able to derive greater financial performance in reducing the volume of electricity purchased from the grid for any given consumption site.

Fig. 5 shows the cost at which battery storage needs to achieve in order to become cost competitive with the Network to supply demand to an electricity consumer. These costs are benchmarked against the current market cost of battery storage of $1172/kW. As mentioned early, it can be observed that for Rockhampton the cost of battery storage technology is already sufficient to produce an economic incentive for demand reduction with battery storage using the *Threshold* BUS. For battery storage, utilising the *Simple* BUS the cost for battery storage will need to decrease to the range of $109.75/kW for Wagga Wagga up to $388.53/kW in Rockhampton to become cost competitive with demand supplied by the Network. For the *Threshold* BUS, costs range from $607.72/kW for Melbourne to $1790.12/kW for Rockhampton in order to be cost competitive with Network supplied demand.

4. Conclusion

This report has detailed the necessity of research into the ability of both solar PV and battery storage technologies to reduce electricity demand and its associated charges. Gaps in the method with which demand reductions are determined have been highlighted and an alternative methodology suggested. Results have shown that solar PV alone has a limited impact on reducing demand (0.05–1.51%) and its associated savings (23.86–1301.15 $ per annum). The addition of a 12 kWh battery storage yielded an additional reduction in demand (1.31–2.02%) and had associated financial saving of 318-1283$ per annum. Comparison of two BUS showed that significant difference in maximum billable demand was experienced between the *Simple* and *Threshold* BUS. The costs at which battery storage technologies must reach in order to be cost-equivalent with network supplied demand have been shown to range from as high as 1790.12$/kW in Rockhampton to as low as 607.22 $/kW in Melbourne.

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