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Impact of shared battery energy storage systems on photovoltaic self-consumption and electricity bills in apartment buildings

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Abstract

Distributed photovoltaics (PV) is playing a growing role in electricity industries around the world, while Battery Energy Storage Systems (BESS) are falling in cost and starting to be deployed by energy consumers with PV. Apartment buildings offer an opportunity to apply central BESS and shared PV generation to aggregated apartment and common loads through an embedded network (EN) or microgrid. We present a study of energy and financial flows in five Australian apartment buildings with PV and BESS using real apartment interval-metered load profiles and simulated PV generation profiles, modelled using an open source tool developed for the purpose. Central BESS of 2-3kWh per apartment can increase PV self-consumption by up to 19% and building self-sufficiency by up to 12%, and shave overall building peak demand by up to 30%. Although the economic case for BESS applied to apartment building embedded networks is not compelling at current BESS capital prices, with cost thresholds of AU$400 – AU$750/kWh compared to AU$750 – AU$1000/kWh for individual household systems, there are clear financial benefits to combined PV-BESS-EN systems for many sites.

Keywords

Photovoltaics, apartments, battery energy storage system, community energy storage, residential electricity, embedded network.

1. Introduction

1.1. Self-consumption in apartment buildings

Global capacity of solar photovoltaics (PV) now exceeds 400GW [1] and it continues to play a major role in the transition to a cleaner electricity sector, comprising over half of new renewable generating capacity in 2017, a greater level of new capacity than net additions of fossil-fuel and nuclear capacity combined. Unlike other electricity generation options, PV is also inherently scalable from kW household systems to now GW scale utility projects. Indeed,

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Abbreviations: AEMC, Australian Energy Market Commission; BAU, Business as Usual; BESS, Battery Energy Storage System; BOM, Bureau of Meteorology; BTM, Behind the Meter; CP, Common Property; DOD, Depth of Discharge; EN, Embedded Network; ENO, Embedded Network Operator; CREN, Community Renewable Energy Network; CES, Community Energy Storage; DSM, Demand-Side Management; FiT, Feed-in Tariff; GST, Goods and Services Tax; HVAC, Heating, ventilation and Air Conditioning; NEM, National Energy Market; NPV, Net Present Value; NSW, New South Wales; PD, Peak Demand; PV, Photovoltaic; SC, Self-Consumption; SOC, State of Charge; SS, Self-Sufficiency; SGSC, Smart Grid Smart City; TOU, Time of Use; VB, Virtual Building

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distributed PV represents a significant proportion of the PV market in many jurisdictions. While early rooftop PV deployment was generally driven by government-subsidised feed-in tariffs (FiTs), these have now been discontinued in a growing number of jurisdictions, with a shift to net metering arrangements where self-consumed PV generation saves consumers the equivalent of their retail tariffs, while any excess 'exported' PV generation is paid a market-based FiT. Falling costs for PV systems and rising retail tariffs have made rooftop PV deployment an increasingly financially attractive for energy users.

In this context, increased self-consumption of rooftop PV has the potential to benefit energy users (due to the typical disparity between the volumetric retail tariffs they pay for electricity from the grid and the far lower FiTs they receive for exports) as well as help manage some of the network challenges of high PV penetration including voltage rise due to reverse power flows. Both Battery Energy Storage Systems (BESS) and Demand Side Management (DSM), when deployed in conjunction with distributed PV, have the potential to significantly increase self-consumption and there is growing interest in understanding the economic impacts of these options.

Australia ranks fifth globally for total PV capacity per person [1], with the majority connected to the low-voltage distribution network, including on 22% of all houses [2]. Moreover, falling PV costs and high energy prices continue to drive record levels of installations. At present, BESS deployment is far lower. However, market growth, facilitated by technological advances and increased manufacturing scale and hence falling costs, is predicted both for BESS installed in conjunction with new small scale PV and for BESS retrofitted to existing PV systems, globally and in Australia [3]. The Australian residential market is seen as a key opportunity for both PV and BESS due to the relatively straightforward regulatory environment and typically the highest electricity prices paid by energy consumers. Although the anticipated dramatic reductions in installed costs for BESS are yet to materialize [4], over 20,000 new Australian household PV systems in 2017 (around 15% of new installations) included BESS [5] and in some jurisdictions the price of solar plus storage is reported to be less than retail electricity prices [6].

However, not all Australian households are currently participating in this revolutionary opportunity to save on electricity bills whilst also reducing environmental impacts. In particular, the growing opportunity for PV deployment on apartment buildings remains largely unexploited, despite 60% of the country's 1.4 million apartments (around 14% of total housing stock) being in two or three story buildings [7] which are likely to have a high ratio of potential rooftop solar generation to load [8]. Although this residential sector presents significant barriers to PV deployment [9, 10], it also presents an opportunity to aggregate apartment household loads and thereby flatten load profiles, increase self-consumption of on-site PV and leverage favourable commercial tariffs for imported electricity [11, 12]. The addition of BESS may further enhance these benefits by increasing overall self-consumption (SC, the proportion of PV generation used to meet on-site consumption) of PV generation, and self-sufficiency (SS, the proportion of total consumption supplied by onsite generation), reducing peak demand (PD) and thereby increasing the value of PV deployment for apartment households.

1.2. Battery energy storage systems (BESS)

There is a wealth of literature examining the potential for behind-the-meter (BTM) BESS to increase PV SC, maximise SS and create financial benefits for residential customers in stand-

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alone housing. A review of this literature (predominantly from Europe) from 2015 [13] suggests that BESS has the potential to increase SC of PV in a residential property by 13-24% (which is more than the increase achievable through DSM), with the increase tending to grow with the battery capacity normalised to rated PV power. The review also revealed large variations in the SC increase between different climate zones, load profiles and initial SC, but also suggested that SC calculated on hourly (or longer) interval meter data is likely to result in an overestimate. The authors suggest the ratio of SC to SS is an important metric when comparing different systems.

There is high variability in the absolute level of SC achievable with PV and storage, because of its dependence on load profile and climate as well as on PV and BESS energy and power sizing, but there is widespread agreement that 100% SC (other than for low capacity PV systems) is not achievable without disproportionately high investment in BESS [14, 15], and that for any system there is a maximum BESS capacity above which increases in SC are negligible [16].

Some researchers have identified an optimal size of BESS capacity for maximising financial benefits of a residential PV system [17] or the cost optimal storage capacity normalised by peak PV power [16]. Studies [18, 19] have shown that unsubsidised PV-BESS systems are rarely cost-effective with existing tariffs and capital costs while others [14, 19-23] have gone on to determine a threshold price for BESS that would make such systems viable, with results highly variable across different contexts (from EUR150/kWh to EUR900/kWh).

Optimal BESS control strategy is application-specific with options including shifting PV generation (to maximise SC) [18, 19, 24, 25], demand/load shifting, or PD shaving [26, 27]. Other applications, such as retail arbitrage or control of grid voltage and/or frequency [28, 29] may also be available to customers. The value of appropriate combination and prioritisation of these functions is dependent on ownership and financial settings [30, 31].

1.3. Shared / community PV and BESS

Aggregation of household loads can flatten profiles and increase self-consumption of PV, while BESS, added behind the meter either in individual households or at the community level, may further increase SC and hence energy consumer value [32-34]. A study of 21 detached houses with PV [35] found that BESS of capacity 2kWh/kWp increased SC by 9% installed individually or 14% if shared, while a US study [36] found that community energy storage (CES) only required 65% as much capacity as individual BESS for the same benefits.

Parra et al [37] found that the benefits of CES, including increased round-trip efficiency due to the lower charge and discharge rates needed to respond to flatter aggregated load profiles, are sufficient to halve the optimum storage capacity compared to individual BESS, with breakeven costs of US$360/kWh to US$430/kWh for different tariff settings. A Dutch study [38] found both CES and individual BESS to be economically unfeasible for capex costs of EUR1000/kWh. In the UK, Parra et al. [39-41] found that application of CES to shift both PV generation and demand could reduce the levelized cost by 56% [40] or 37% [41] compared to a single house BESS.

In Australia, Tomc et al. [15, 42] modelled different arrangements for storage on a residential microgrid with PV and found a combination of individual PV and storage *and* communal storage could reduce grid import by over 90% and reduce aggregated customer bills by 95.5% (without consideration of capital or operating costs).

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1.4. PV-BESS in apartment buildings

The studies discussed in Section 1.3 concern the application of shared and/or individual BESS to a community of detached dwellings with individual PV systems. However, to our knowledge, there has been little detailed techno-economic analysis of PV-BESS systems that consider the particular technical and financial characteristics of multi-occupancy residential buildings. Notwithstanding the considerable variability of apartment load profiles, some studies suggest that apartments have specific characteristics that differ from those of stand-alone dwellings, including lower total load, lower load per occupant and higher daily variability [43-51]. There is also the presence of common property (CP) load for shared areas of apartment buildings. Moreover, common ownership of roof space and economies of scale may favour deployment of a single, large PV system applied to aggregated load instead of multiple small PV systems supplying individual apartments, while installation of a shared BESS on common property may be safer and more practical than installing individual BESS for each apartment. These factors, combined with close proximity, shared building structure and organisational arrangements allowing common ownership, may favour apartment buildings as local energy communities with potential to exploit the broader socio-economic benefits of CES, including reduced dependence on fossil fuels, reduced energy bills and *"higher social cohesion and local economy*" [52].

In this paper, we present the results of a techno-economic study of PV-BESS deployment in five Australian low to medium rise apartment buildings of different sizes and characteristics. The study combines real apartment load profiles drawn from a study of over 2000 such households, with those of CP from the five buildings, along with PV generation profiles based on real-year satellite weather data. We explore a range of PV and BESS system capacities as well as different possible battery dispatch strategies, comparing the technical and financial impacts of BESS when applied to individual or aggregated apartment household loads with onsite PV generation.

We have previously modelled the costs and benefits of applying shared PV to loads aggregated across apartment buildings under a range of technical arrangements and financial settings [11]. Here, we explore to what extent and under what conditions the addition of BESS to apartment PV systems can increase self-consumption and self-sufficiency, shave PD and add value for customers. A particular contribution of the work lies in the use of a large dataset of 12-month half-hourly apartment load profiles and the analysis of PV-BESS applied with multiple control strategies to embedded network (EN)[2] arrangements that are common in multi-occupancy buildings.

The remainder of the paper is set out as follows: Section 2 gives a brief outline of some technical options available for connecting PV-BESS systems in apartment buildings. Section 3 introduces the model, the data and the method used for the study, while Section 4 explains the energy and financial metrics output by the model. In Section 5 we present an analysis of the impact of PV on self-consumption, self-sufficiency and peak demand, and in Section 6 we compare the financial costs and benefits of different scenarios. Finally, in Section 7, we

[2] An embedded network (EN) is defined by the Australian Energy Market Commission (AEMC) as "a private electricity network that serves multiple premises and is located within, or connected to, a distribution or transmission system through a parent connection in the National Electricity Market (NEM)" [53]. ENs are also called micro-grids but typically do not have the facility to disconnect from the distribution network.

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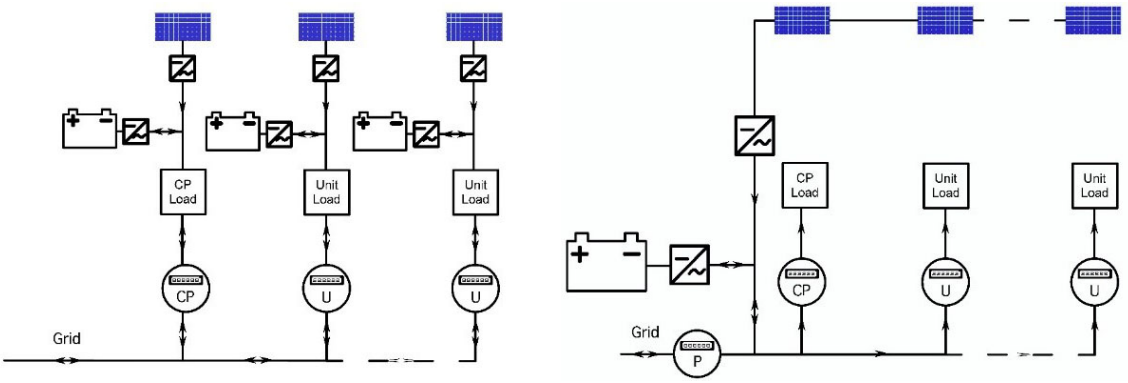
present some tentative conclusions and provide some suggestions for future investigations.

2. PV-BESS technical arrangements

In Australia, most apartments are organised under Strata Title, whereby a purchaser buys the interior space of an apartment and a share of the building structure (including the roof) and common property (CP) which are managed by a strata body (the Owners' Corporation or Body Corporate) on behalf of all owners [54, 55]. The strata body is also responsible for electricity supply to cover CP loads, which may include lifts, carpark ventilation and lighting, water heating and pumping for pools and centralised HVAC, water heating for apartments and lighting for stairwells, corridors and other common areas. Beyond this, apartment residents (whether owner-occupiers or tenants) are responsible for their own electricity supply including choice of retailer and paying the bills.

The simplest and most common arrangement for deployment of PV is for the strata body to install a PV system to meet CP load. For many (particularly high-rise) sites with high CP loads and relatively low roof area, this arrangement achieves 100% SC for the building. However, for buildings with low CP load, particularly the 60% of Australian apartments in buildings of three storeys or leqss [7] with relatively high potential PV capacity, there may be additional value in application of PV to apartment loads as well as CP. Individually owned PV systems can be connected behind the meter (BTM) to meet individual unit and/or CP loads as shown in Figure 1(a). Although this arrangement (*btm_i*) is technically straightforward, as for stand-alone dwellings, SC levels are highly dependent on household characteristics, including appliance ownership and occupancy patterns. SC may of course be increased by addition of a BESS.



(a) Individual BTM, btm_i, *(b) Embedded Network, en*

Figure 1: Possible technical arrangements for PV and BESS[3]

An alternative arrangement (Figure 1(b)) is to apply shared PV generation to aggregated building load through an embedded network (EN). In this arrangement, an 'Embedded Network Operator' (ENO) purchases electricity from the grid via a 'parent' or 'gateway' meter and on-sells it (along with onsite PV generation) through a 'child' meter for each apartment. This arrangement allows access to economies of scale in PV installation costs and to lower commercial (rather than residential) tariffs for the grid-purchased electricity, providing a margin for the ENO which may be shared with the strata body to help offset capital costs.

[3] The BESS costs used in the modelling assumed AC coupled BESS, as shown, to allow for addition of BESS to an existing PV system, although DC-coupled BESS using a hybrid inverter may be more common and could result in a slight cost reduction.

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Application of PV to aggregated building load increases SC (and thereby reduces costs for residents), while further benefits may be achievable by the addition of a central BESS to the EN. Although, in Australia as elsewhere, retrofitting an EN to existing residential buildings can face regulatory and technical barriers [9, 56, 57], the arrangement is widespread for new developments and may provide a viable mechanism for sharing PV-BESS assets.

3. Dataset and modelling methodology

This study utilises the *Multi-Occupancy Residential Electricity with PV and Storage* (morePVs) tool to model electricity flows and financial transactions in apartment buildings with PV and BESS deployed under a range of technical and financial settings. The Python code has been made available open source [58] for transparency and a graphical user interface is being developed to increase accessibility for all interested stakeholders and for application to other datasets. The model is described in more detail in its on-line documentation [58]. The model inputs used for this study, including load and generation profiles, network arrangements, BESS technical and operational parameters, capital and operational costs and tariff settings, are described below.

3.1. Virtual buildings: load and generation profiles

In common with our previous work [11], this study utilises 12 months of interval load data for CP and apartments combined from two sources. The CP data, collected for apartment building energy audits, is for five low- and medium-rise buildings at sites across Sydney with sufficient roof area to meet a significant proportion of building load from rooftop PV deployment and, since the period of data collection for the CP load did not match that for the apartment loads, selected to exclude evident temperature-dependent common load (such as HVAC or swimming pools).

The apartment load profiles were selected from a publicly available dataset of 2000 NSW apartments, collected for the AusGrid Smart Grid Smart City (SGSC) trial undertaken over 2012–15. Details of the trial and the dataset may be found in the various SGSC reports [59-62], while characteristics of the apartment load profiles, as well as the methodology used to prepare complete 30 minute load profiles for 2013 from the dataset are described in forthcoming articles [11, 51].

Because, for most of the apartments included in the SGSC dataset, only limited information is available about building and household characteristics, we have adopted a stochastic approach to the modelling. For each of the five sites, fifty 'Virtual Buildings' (VBs) were created, each one combining the actual CP profile for the site with a randomly selected sample of SGSC apartment load profiles, one for each apartment in the actual building. Table 1 shows characteristics of the five sites and the total annual load and 'CP Ratio' (the ratio of CP load to total load) averaged across the 50 VBs at each site.

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Table 1 Virtual Building Site Characteristics: note that site tags summarise, in order, the number of apartments, number of floors and percentage of load that is CP.

Site Tag	Apartments	Floors	Total Load (MWh/year)	Mean CP Ratio	*max_pv* (kWp)	*max_PV* (kWp/ unit)	PV Ratio (%)	PV Systems Modelled (kWp/unit)
a48_f4_cp09	48	4	190	9%	52.5	1.09	36.5	0.5, 1.0, 1.09
a44_f4_cp17	44	4	180	17%	76.8	1.74	54.7	0.5, 1.0, 1.5, 1.74
a52_f3_cp27	52	3	250	27%	141.5	2.72	78.1	0.5, 1.0, 1.5, 2.0, 2.5, 2.72
a20_f5_cp37	20	5	110	37%	31.5	1.58	41.5	0.5, 1.0, 1.58
a26_f4_cp44	26	4	160	44%	78.5	3.02	67.5	0.5, 1.0, 1.5, 2.0, 2.5, 3.02

For each of the five sites, the maximum size (*max_pv)* for a potential rooftop PV system was determined through a visual analysis of the roof area, using multi-viewpoint aerial imagery [63] to take account of roof orientation, inclination, obstructions and shading. As shown in Table 1, smaller systems (in steps of 500W / apartment) were designed by successively excluding roof areas with the lowest insolation.

For each system, the energy generation was simulated for every half hour of the year 2013, using NREL's System Advisor Model (SAM) [64, 65] PV Watts module and Australian Bureau of Meteorology (BOM) satellite-derived irradiance data [66] for each site, along with temperature and wind speed from the nearest automatic weather station.

The average daily winter and summer PV generation profiles for each modelled system size, and daily load profiles including CP for each VB (and the overall average for each site across all 50 VBs) are shown in Figure 2.

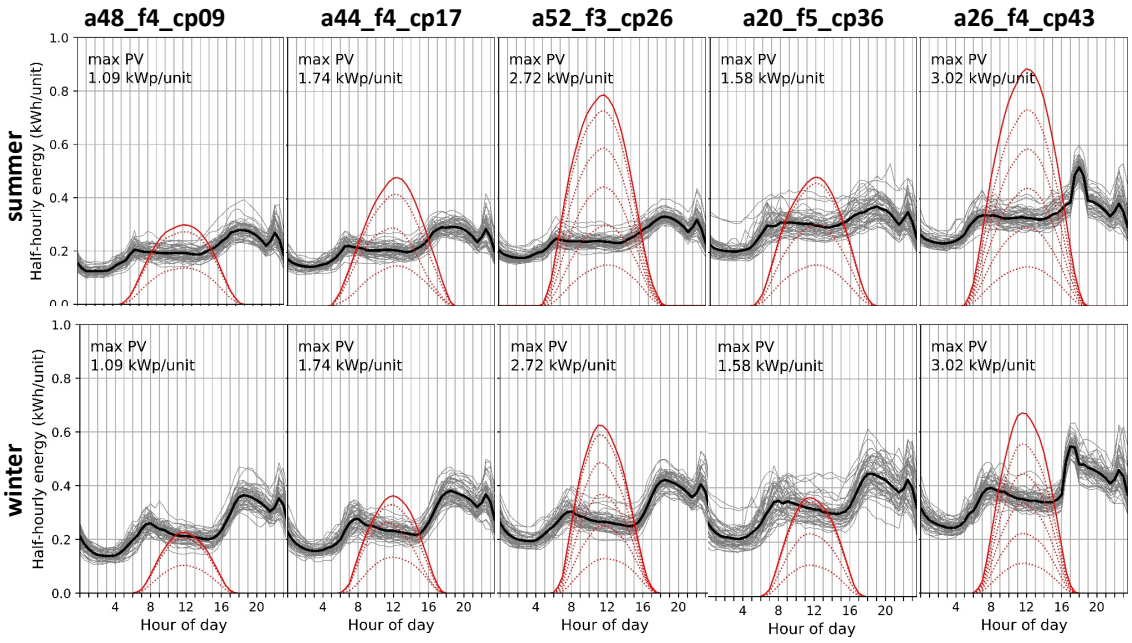

Figure 2 Average load and generation profiles for 50 VBs at each site over summer and winter – the dark line is the average load profile across all VBs, while generation profiles are for all modelled PV sizes.

For embedded network (*en*) arrangements, the PV was treated as a single system connected between the parent and child meters, with the PV energy netted off the aggregate building load, while for individual behind the meter arrangements (*btm_i*), a percentage of the total PV capacity equal to the CP Ratio was applied to the CP load, with the remaining capacity

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allocated equally to separate systems applied to each individual apartment load.

3.2. Battery energy storage system

The BESS model assumed a Li-ion battery with similar technical characteristics to the Tesla Powerwall2 [30], i.e. round trip efficiency of 89.0%, maximum state of charge (SOC) of 90% and maximum depth of discharge (DOD) of 100%. A range of storage capacities were modelled, corresponding to 1.0, 2.0, 3.0 and 4.0 kWh of storage for each unit in the building, with maximum charge and discharge rate of 0.38C, equivalent to the 5kW / 13.2kWh Powerwall.

For embedded network arrangements (*en*), a single BESS (with capacity $C_{central}$ given by the number of units (n_{units}) multiplied by nominal storage per unit) was connected centrally (between the parent and child meters) and applied to the aggregated building load under a range of control strategies. For individual arrangements (*btm_i*), smaller BESSs were applied to common property (C_{cp}) and to each apartment (C_{unit}) with capacities given by Equations (1) and (2).

$$C_{CP} \in \{i * n_{units} * CP\ ratio \mid i \in (1,2,3,4)\} \qquad \textit{Equation (1)}$$

$$C_{unit} \in \{i * (1 - CP\ ratio) \mid i \in (1,2,3,4)\} \qquad \textit{Equation (2)}$$

3.3. BESS control strategies

Potential customer benefits from BESS include increased SC of onsite PV generation, increased SS, reduced PD, provision of emergency power during grid outages, and demand shifting to off-peak periods. The control and discharge strategy for the BESS is chosen according to the required apartment household benefits, which may depend on tariffs and other financial settings as well as on the load and generation characteristics of the overall system. For this study, a range of BESS control strategies, time periods and charge and discharge rates were modelled, as shown in Table 2 and described below, in order to assess their technical and financial benefits.

As discussed earlier, the clearest value proposition for BESS is to maximise SC of PV generation hence 'earning' the retail tariff rather than the lower FiT on exported generation. However, with some tariff arrangements there can be additional value in targeting particular time periods or peak demand. The simplest approach to increasing self-consumption is to use a simple *evening discharge* (***ed***) strategy, whereby the BESS is charged from excess PV generation (after meeting coincident on-site demand) and discharged at the maximum discharge rate to meet on-site demand during the evening peak period (here modelled as starting at 16:30, 17:00 or 17:30 and ending at 20:00).

However, because on days of low insolation this approach is likely to result in inadequate battery SOC to meet some evening peak loads and may result in under-utilization of the BESS, a range of augmented evening discharge strategies have also been modelled. Adding *charge-priority* to an evening discharge strategy (***ch_ed***) applies PV generation to BESS charging first, with any excess used to meet on-site loads. A further step to maintain SOC is to use a *single cycle* (***sc***) strategy whereby grid import is increased to charge the BESS during the night-time off-peak period. A *double cycle* (***dc***) strategy maximises BESS utilisation by charging overnight, discharging to meet morning load peak, charging from PV generation and/or network import during the day and discharging in the evening peak period.

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Table 2 BESS Control Strategies

Tag	Description	Charging			Discharge	
		Source	Grid Charge Period[3]	Rate	Period[4]	Rate
ed1700_cmax_dmax	Evening Discharge	Excess PV only	None	0.38C	1700-2000	0.38C
ed1730_cmax_dmax	Evening Discharge	Excess PV only	None	0.38C	1730-2000	0.38C
ed1700_c20_d20	Evening Discharge	Excess PV only	None	0.20C	1700-2000	0.20C
ed1630_c20_d20	Evening Discharge	Excess PV only	None	0.20C	1630-2000	0.20C
ch_ed1700_cmax_dmax	Charge Priority Evening Discharge	Gross PV	None	0.38C	1700-2000	0.38C
ch_ed1630_cmax_d20	Charge Priority Evening Discharge	Gross PV	None	0.38C	1630-2000	0.20C
sc1700_ cmax_dmax	Single Cycle	PV / Grid	0100-0600	0.38C	1700-2000	0.38C
dc1700_cmax_dmax	Double Cycle	PV / Grid	0100-0600 1130-1400	0.38C	0700-0900 1700-2000	0.38C
pdt_sc_xx (for xx = 35, 40….80%)	Peak Demand Threshold	PV / Grid	0100-0600	0.38C	1400-2000	0.38C
				load >= xx% of annual peak		

Where customers are subject to a tariff which includes capacity charges, a single half-hour period of high demand can have a disproportionate effect on energy bills. A peak demand threshold strategy prioritises reduction of demand peaks, and only discharges the BESS when grid imports would otherwise be above a threshold level, here set at a percentage of the highest PD throughout the year.

Modelled charge and discharge rates are either at the technical maximum of the BESS (0.38C) for strategies tagged ***cmax*** and ***dmax*** or at the lower rate of 0.2C (tagged ***c20*** and ***d20***) to avoid premature draining of the battery.

3.4. Capital and operating costs

Average installed costs (after Federal government subsidies and Federal goods and services tax (GST) of 10%) for residential and commercial PV installations in NSW of AU$1.01 to AU$1.84 per Watt were used to calculate the capital costs of the PV systems. Inverter replacement (assumed necessary every ten years) was included at between AU$0.31/Watt and AU$1.10/Watt, depending on the size. Other operating costs, including replacement of electrical balance-of-system components and occasional cleaning, are likely to be low in comparison to decreases in inverter costs, and have therefore been omitted from this study. Full details are given in Appendix A.

The costs of retrofitting an EN to an apartment building are highly variable and depend on building characteristics, particularly the age of the existing electrical installation, as well as on jurisdictional regulatory requirements. We have explored sensitivity of EN benefits to these costs elsewhere [11] but for this study we have used a medium cost setting of AU$20,000 per site (to cover gateway meter installation and switchboard upgrades) plus AU$400 per unit for the child meter installations. EN opex has been estimated at AU$250 per customer, slightly

[4] All charge and discharge periods are shifted by an hour in summer to align with daylight saving time.

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above the estimated operational costs (AU$230 [68]) of a NSW electricity retailer.
Globally, installed cost estimates for Lithium-ion BESS vary between US$200/kWh and US$1260/kWh [3] (AU$265 – AU$1670/kWh[5]), with average costs predicted by some to drop to US$160 (AU$212) /kWh by 2025 [68]. In Australia, in part because of supply issues [69] and controversy around installation standards [70], prices have remained buoyant [4], with average installed battery costs of AU$930/kWh and average installed battery-plus-inverter system costs of AU$1290/kWh [71]. Given these disparities, we have modelled a range of values between AU$200/kWh and AUD$1000/kWh to explore sensitivity to future price reductions. The BESS has been assumed to have a lifetime of 7300 cycles (as quoted for the Tesla Powerwall2 [30]) so would not require replacement within the 20-year modelling period given daily cycling.
The capital costs of installed infrastructure – PV, BESS and EN – have been amortized over a 20-year period with a discount rate of 6%.

3.5. Tariff structure and rates

Residential tariff arrangements in Australia's National Electricity Market (NEM) are far from simple, with hundreds of tariffs offered by some 70 retailers. For this study, we have modelled 'typical' arrangements, but note that financial outcomes for actual customers will depend on their specific retail arrangements. For Business-as-Usual (BAU) and *btm_i* scenarios, all customers have been assumed to be paying their retailer a typical market Time of Use (TOU) tariff equivalent to a 15% discount[6] applied to all fixed and volumetric components of a 2017 "standing offer" TOU tariff in the relevant network area [73]. For customers with individual PV systems (*btm_i*), we have modelled a flat-rate solar feed-in tariff (FiT) of 8c/kWh, in line with the state regulator's 'all time benchmark' rate of 8-9c/kWh for 2018-19 [74]. Given recent downward trends in FiT rates, we have also modelled a zero-rate FiT to explore how this affects the value of BESS.

A key driver for ENs is that the size of an aggregated building load is likely to trigger access to a commercial 'large energy consumer' tariff (comprising a regulated network component and a market retail energy component) at the parent meter. These typically have volumetric rates lower than residential tariffs which act to reduce the value of self-consumed PV, and less disparity between peak and off-peak rates, which can reduce the value of BESS. However, they often include a significant capacity charge component which can add value both to BESS and to PV. For this study, we have used scenarios with high ('TOU12') and low ('TOU9') market prices from early 2018, combined with a FiT of 8c/kWh at the parent meter and with no FiT. More details of these parent tariffs are given in Appendix B.

4. Energy and Financial Metrics

4.1. Self-consumption and self-sufficiency

Luthander et al. [13] define SC and SS as the overlapping part of the generation and load profiles calculated as a proportion of the total generation and total load, respectively, as shown in equations (3) and (4), where *L(t)* and *G(t)* are the instantaneous load and generation

[5] All costs in this paper are AU$ where AU$1.00 = US$ 0.7544 [67]
[6] The total bill of a 'representative customer' on a 'representative market offer' in NSW in 2016 was equivalent to a 15% discount off the standing offer tariff [72].

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and S(t) is the power charging to (*S(t)* < 0) or discharging from (*S(t)* > 0) the BESS. This formulation ensures the correct treatment of efficiency losses in the BESS charge-discharge cycle.

$$\mathrm{SC} = \frac{\int min\{L(t), G(t) + S(t)\}dt}{\int G(t)\,dt} \qquad \textit{Equation (3)}$$

$$\mathrm{SS} = \frac{\int min\{L(t), G(t) + S(t)\}dt}{\int L(t)\,dt} \qquad \textit{Equation (4)}$$

If $L(t_i)$, $G(t_i)$ and $S(t_i)$ are, respectively, the energy used, generated and discharged from the battery in discrete time periods t_i, (determined by the temporal resolution of the relevant meters), the *measurable* SC (i.e. the proportion of total annual on-site PV generation that is *usefully* consumed within the building), and the measurable SS (the proportion of the total annual building load that is met by on-site generation) are given by Equations (5) and (6).

$$\mathrm{SC} = \frac{\sum_{i=1}^{17520} min\{L(t_i),\ G(t_i) +\ S(t_i)\ \}}{\sum_{i=1}^{17520} G(t_i)} \times 100\% \qquad \textit{Equation (5)}$$

$$\mathrm{SS} = \frac{\sum_{i=1}^{17520} min\{L(t_i),\ G(t_i) +\ S(t_i)\ \}}{\sum_{i=1}^{17520} L(t_i)} \times 100\% \qquad \textit{Equation (6)}$$

Note that these *measurable* metrics are likely to be higher than the *true* SC and SS as t_i increases, because any non-simultaneous imports and exports within the time interval of measurement (30 minutes) are treated as simultaneous [75].

4.2. Net present value of savings

To understand the effect of BESS on the value of PV, the Net Present Value (NPV) of annual savings for the whole building, compared to business as usual (BAU) was calculated and divided by the number of units in the building. Note that for this study, the modelling was used to assess overall outcomes for the building, without consideration of the distribution of financial benefits between residents, owners and the strata body. For transparency, and to avoid dependence on arbitrary projections of future energy costs, only a single year of operation was modelled with capital expenditure (for EN, PV, and BESS in *en* arrangements, or for PV and BESS in *btm_i* arrangements) amortised at a discount rate of 6% over 20 years to calculate monthly repayments.

As commonly used in the literature [76], the Net Present Value (NPV), of an initial investment C_O after time T is defined as the sum of cashflows F_t for each time period t and is given by Equation (7) for a discount rate d.

$$NPV = \sum_{t=1}^{T} \frac{F_t}{(1+d)^t} - C_0 \qquad \textit{Equation (7)}$$

If $E_{t,s}$ and $O_{t,s}$ are the electricity cost and operating cost in period t for scenario s and $C_{0,s}$ is the capital cost for that scenario, the NPV relative to the Business as Usual (BAU) scenario is given by Equation (8).

$$NPV_s = \sum_{t=1}^{T} \frac{E_{t,BAU} - E_{t,s} - O_{t,s}}{(1+d)^t} - C_{0,s} \qquad \textit{Equation (8)}$$

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5. Results: Energy Flows, SC and SS and PD Impacts of PV and BESS

5.1. Self-consumption and self-sufficiency

Figure 3 shows the SC of on-site generation and the building SS for shared PV generation and a central battery applied to an EN (*en*) and for individual PV systems and batteries applied BTM to each apartment load and CP load (*btm_i*), using a simple evening discharge control strategy. The addition of BESS increases SC by 15% - 19% for *en* and 16% - 22% for *btm_i*, depending on the site, but the marginal benefits are reduced for BESS sized at above 1kWh/unit and negligible above 2 - 3kWh/unit. Similarly, SS is increased by up to 12% for *en* and 10% for *btm_i*.

Although application of the PV system to aggregated load rather than individual loads increases SC and SS, the additional SC achievable from adding a central BESS to an EN with PV is generally less than for adding individual BESS to BTM PV systems. However, for some sites (notably *a52_f3_cp26, a44_f4_cp17* and *a20_f5_cp36*) the central BESS increases SS by up to 3% more than the individual BESS.

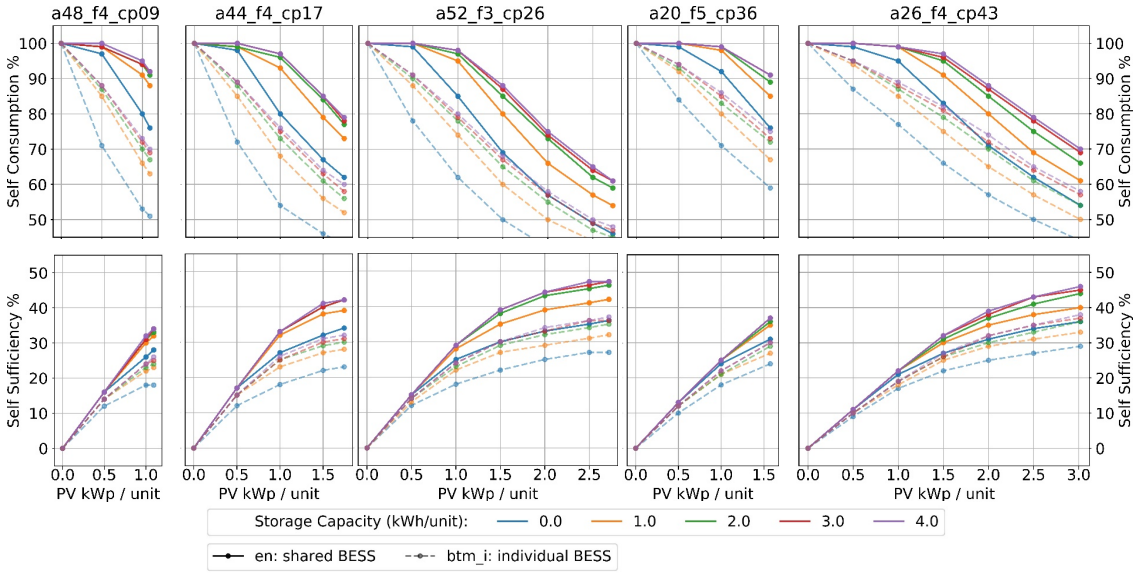

Figure 3 Self-consumption and self-sufficiency averaged across 50VBs at each site for simple evening discharge strategy ed1700_cmax_dmax

Figure 4 shows the variation of SC with rated capacity of shared PV systems applied to aggregated building loads through an EN for a range of shared BESS capacities and control strategies. The top two rows show simple evening discharge (***ed***) strategies with different discharge periods and charge / discharge rates. In all cases starting the discharge period 30 minutes earlier results in an increase in SC, while reducing the charge and discharge rate from 0.38C to 0.2C decreases SC, although both effects are small. The optimum power and time parameters for this strategy, and the achievable increases in SC and SS are dependent on the characteristics of the load profile at each site.

When PV generation is applied to BESS charging in preference to on-site load (***ch_ed***), more electricity is imported from the grid, particularly on days of low solar insolation, and so self-consumption is considerably lower than for a simple evening discharge strategy. For PV systems sized at 1kWp/unit or less, BESS operation with this strategy reduces self-consumption below the level with no BESS, although increases in SC of up to 5% (compared to no BESS) are achievable where excess generation from a 4kWp/unit PV system is available to

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charge the BESS.

When a BESS is charged from the grid, energy losses in the charge-discharge cycle result in grid imports greater than exports from BESS discharge and therefore reduced self-consumption compared to no BESS. This is evident for the single cycle strategy (***sc***) as well as for the double cycle (***dc***) strategy for smaller PV systems. However, with a ***dc*** strategy applied where there is a larger PV system (above 1.0 - 1.5 kWp/unit, depending on the site), the BESS is more often charged from onsite generation, grid import is reduced, and modest increases in SC of up to 4% can be achieved.

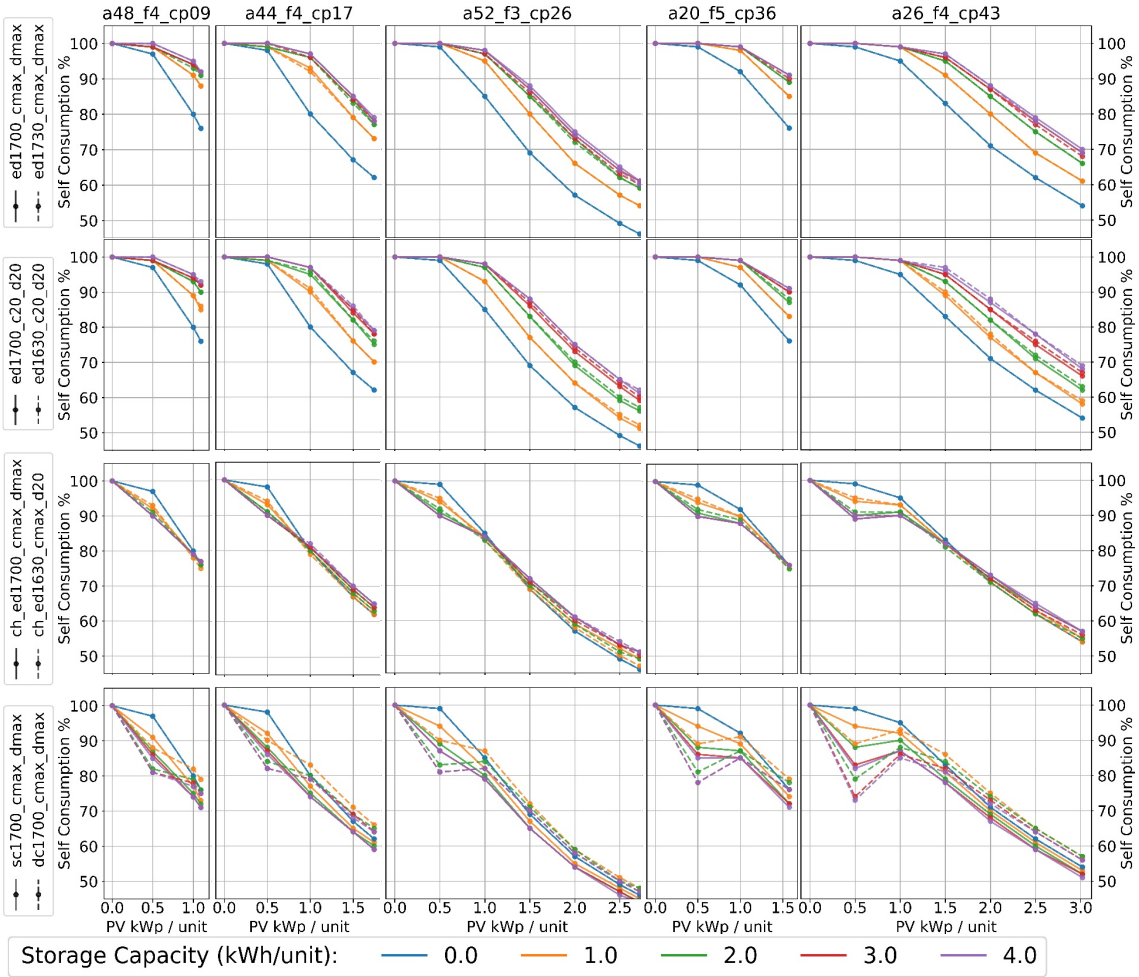

Figure 4 Self-consumption of PV generation for shared BESS applied to EN with shared PV using augmented evening discharge strategies

5.2. Battery state of charge

Analysis of the hourly and seasonal variations in BESS SOC can assist in optimising BESS capacity and control strategy.

Figure 5(top) shows the SOC throughout the year and the average SOC for each hour of the day for a BESS applied, using a simple evening discharge strategy, to an EN at each site with the maximum charge and discharge rate of 0.38C. PV systems sized below 1.0 kWp/unit are not shown as generation is largely absorbed by on-site load and the BESS is rarely charged. The difference between the maximum and minimum of the average daily SOC gives an indication of the suitability of the BESS capacity, while the density of the annual plot shows

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the extent of BESS utilisation.

For those sites where a PV sized at 2.0 kWp/unit or above can be installed, a BESS of 1.0 kWh/unit is well utilised throughout the year, while a higher capacity BESS is rarely fully discharged during the summer months and rarely fully charged during the winter. For smaller PV systems, the BESS is often insufficiently charged in winter and under-utilised even in the summer. Note however, that for some battery technologies, low utilisation levels can prolong battery life and may therefore be advantageous.

The lower chart in Figure 5 shows the aggregate SOC for multiple individual BESS (with the same total storage capacity) applied seperately to unit and CP loads with individual BTM PV systems. Note the lower DOD in this arrangement as the energy stored at any time may be on a different part of the network to the coincident load, and so grid import may be required to meet demand during the evening discharge period even when SOC is non-zero.

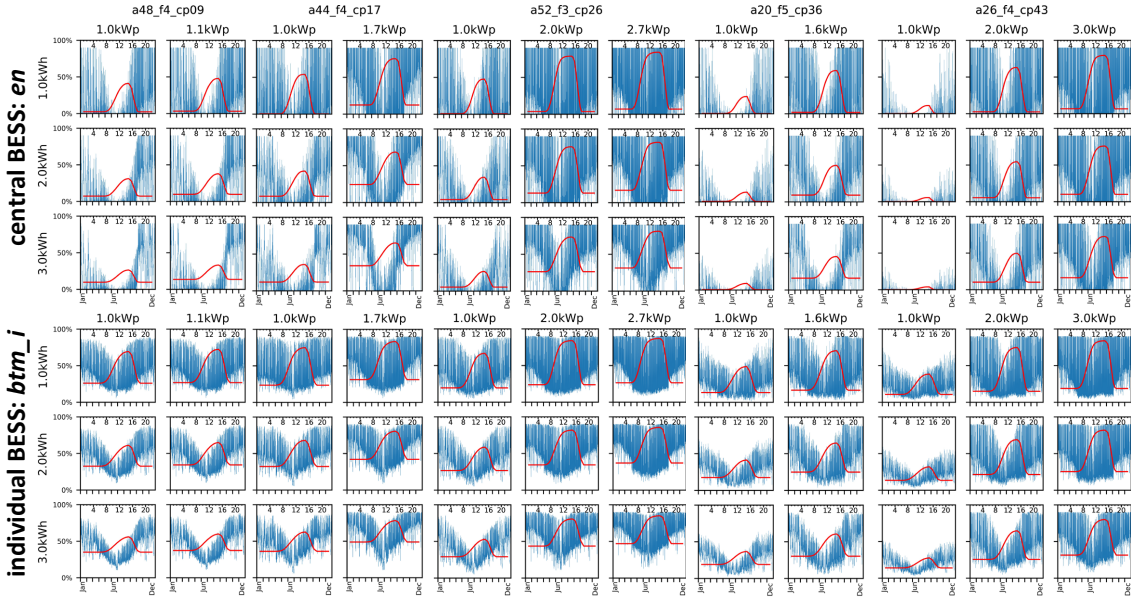

Figure 5 Average daily SOC (red, top axis) and annual SOC (blue, bottom axis) for one VB at each site with simple evening discharge strategy and charge / discharge rate of 0.38C

Figure 6(top) shows SOC for a central BESS applied to an EN at a single site, operated under different control strategies. Note the higher levels of BESS utilisation and average SOC when charging off-peak from the grid (***sc*** or ***dc***) or from PV (***ch_ed***) in preference to meeting onsite load.

A BESS of 4kWh operated under a ***sc*** or ***dc*** strategy rarely reaches its maximum DOD, even in winter, and therefore retains capacity to meet winter heating loads.

For individual systems, aggregate SOC, as shown in the lower part of Figure 6, is maintained at a higher level, even though an individual BESS may reach maximum DOD.

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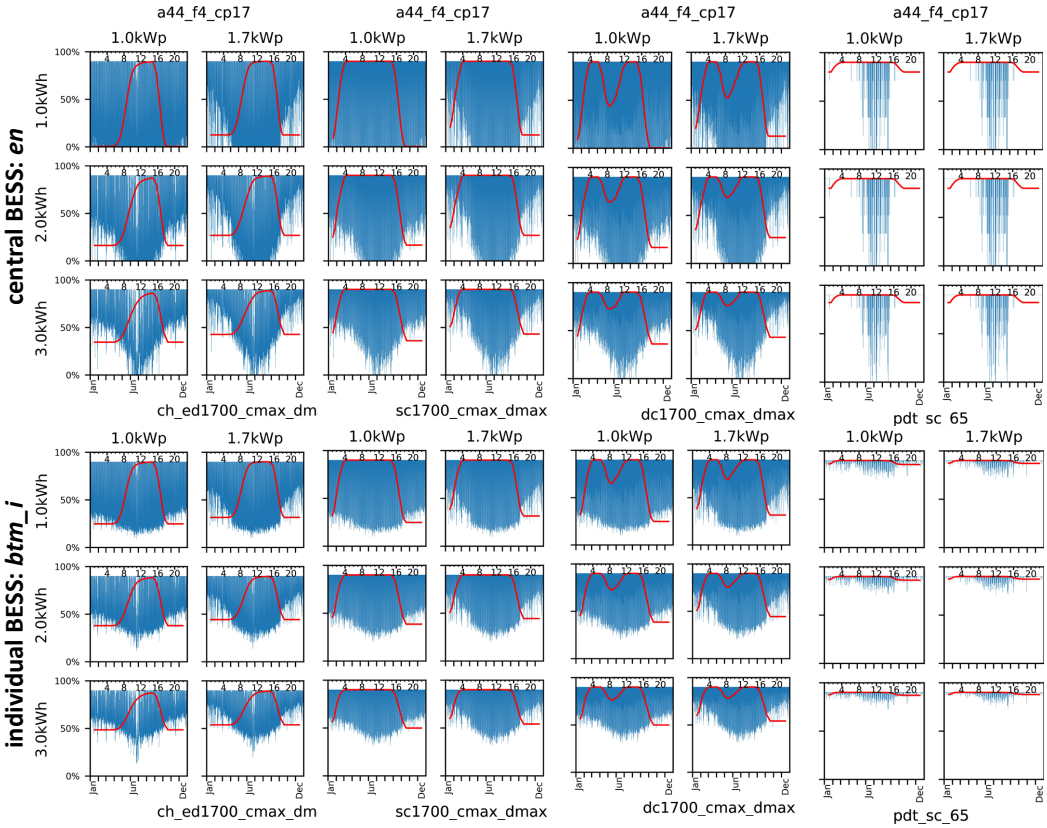

Figure 6 Average daily SOC (red, top axis) and annual SOC (blue, bottom axis) for one VB at one site under charge priority, single cycle, double cycle and peak demand threshold BESS control strategies

5.3. Peak demand reduction

Table 3 shows the percentage reduction in PD achievable at each site under different BESS control strategies, for a central BESS applied in *en* and *btm_i* arrangements. This is the maximum reduction achieved in the average of the top ten demand peak peaks averaged across 50 VBs, for all technical arrangements for each strategy at each site, and in most cases corresponds to the maximum PV size and BESS capacity of 4.0 kWh/unit.

The variation of PD reductions with BESS capacity for different PV systems is shown in Figure 7. Many of the peaks in the load profiles are due to winter heating loads (Figure 2), while battery SOC is low in winter (Figure 5) due to a combination of high load and low PV generation. Therefore, a BESS operated with an *evening discharge* (***ed***) strategy has a low impact on PD if applied to aggregated building load, because the BESS is not able to restore its SOC between successive winter peaks. Individual BESS applied to individual customer loads, however, have a greater impact on aggregated PD, as stored energy is applied directly to individual peaks.

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Table 3 Maximum achievable average peak demand reduction across 50 VBs for each site under all modelled PV and BESS sizes and operational strategies.

	a48_f4_cp09		**a44_f4_cp17**		**a52_f3_cp27**		**a20_f5_cp37**		**a26_f4_cp44**	
	en	**btm_i**	**en**	**btm_i**	**en**	**btm_i**	**en**	**btm_i**	**en**	**btm_i**
ed1700_cmax_dmax	1.0	10.6	2.7	16.8	3.5	22.0	1.7	10.8	6.3	16.2
ed1700_c20_d20	1.3	11.5	4.6	18.3	8.4	23.2	2.7	11.5	9.1	16.6
ed1730_cmax_dmax	1.3	11.8	4.0	15.7	6.3	18.1	2.4	10.7	4.9	7.7
ed1630_c20_d20	1.1	10.1	3.7	16.5	6.3	22.2	2.0	10.6	7.7	18.4
ch_ed1630_cmax_d20	22.8	26.5	31.9	34.1	40.8	39.6	24.7	26.9	39.4	37.7
ch_ed1700_cmax_dmax	9.1	24.9	18.0	29.0	25.2	30.8	13.7	23.8	17.1	20.7
sc1700_cmax_dmax	33.5	33.2	32.7	32.3	31.2	31.3	26.3	27.1	19.1	20.9
dc1700_cmax_dmax	33.5	33.2	32.7	32.3	31.2	31.3	26.3	27.1	19.1	20.9
pdt_sc_60	33.0	15.2	32.4	11.3	33.0	20.3	29.4	10.4	23.7	12.7
pdt_sc_65	28.3	13.1	28.2	9.0	29.2	18.7	26.8	7.9	23.5	11.2
pdt_sc_70	23.3	11.3	23.5	7.3	24.7	17.2	22.8	5.9	21.7	8.6
pdt_sc_75	18.3	9.7	18.6	5.4	20.1	16.1	18.1	4.6	18.2	6.4
pdt_sc_80	13.7	8.2	13.8	4.0	15.4	14.9	13.7	3.3	13.9	4.9

Both for individual and centralised BESS, much greater reductions are achieved using a charge priority (***ch***) strategy, particularly for larger BESS capacity, provided the PV system capacity is sufficient to maintain the BESS SOC. For a centralised BESS, best results are obtained using a lower discharge power, while oversizing the BESS compared to the PV system results in low SOC and reduced capacity to manage peak loads.

For *single cycle* (***sc***) and *double cycle* (***dc***) strategies, peak reduction increases with BESS capacity but is not greatly affected by PV capacity (as BESS is charged primarily from the grid). For capacities of 3kWh/unit or less, greater peak reductions are achieved by applying BESS to individual loads, while a BESS of 4kWh/unit approaches the maximum possible peak reduction for this strategy, as the BESS never fully discharges and so has capacity to mitigate all peak loads.

A *peak demand threshold* (***pdt***) strategy has a bigger impact on aggregated PD for a centralised BESS than if applied to *btm_i* for most sites. For PV of 1kWp/unit, a threshold of 65% achieves greatest PD reduction, while one of 80% achieves its maximum effect for a BESS of 1kWh/unit. Figure 8 shows how the effectiveness of this strategy varies with the chosen threshold, here described as a percentage. For a shared BESS sized at 1.0 - 2.0 kWh/unit and a shared PV system of 1.0kWp/unit, a threshold of 65% - 75% can reduce PD by 15% - 22% but note that the exact threshold is dependent on the characteristics of the building load profile, and choice of threshold requires fore knowledge of the timing and extent of the annual peak load. For threshold levels below the optimum, BESS SOC falls below the level necessary for successful operation of this strategy, so effectiveness is reduced.

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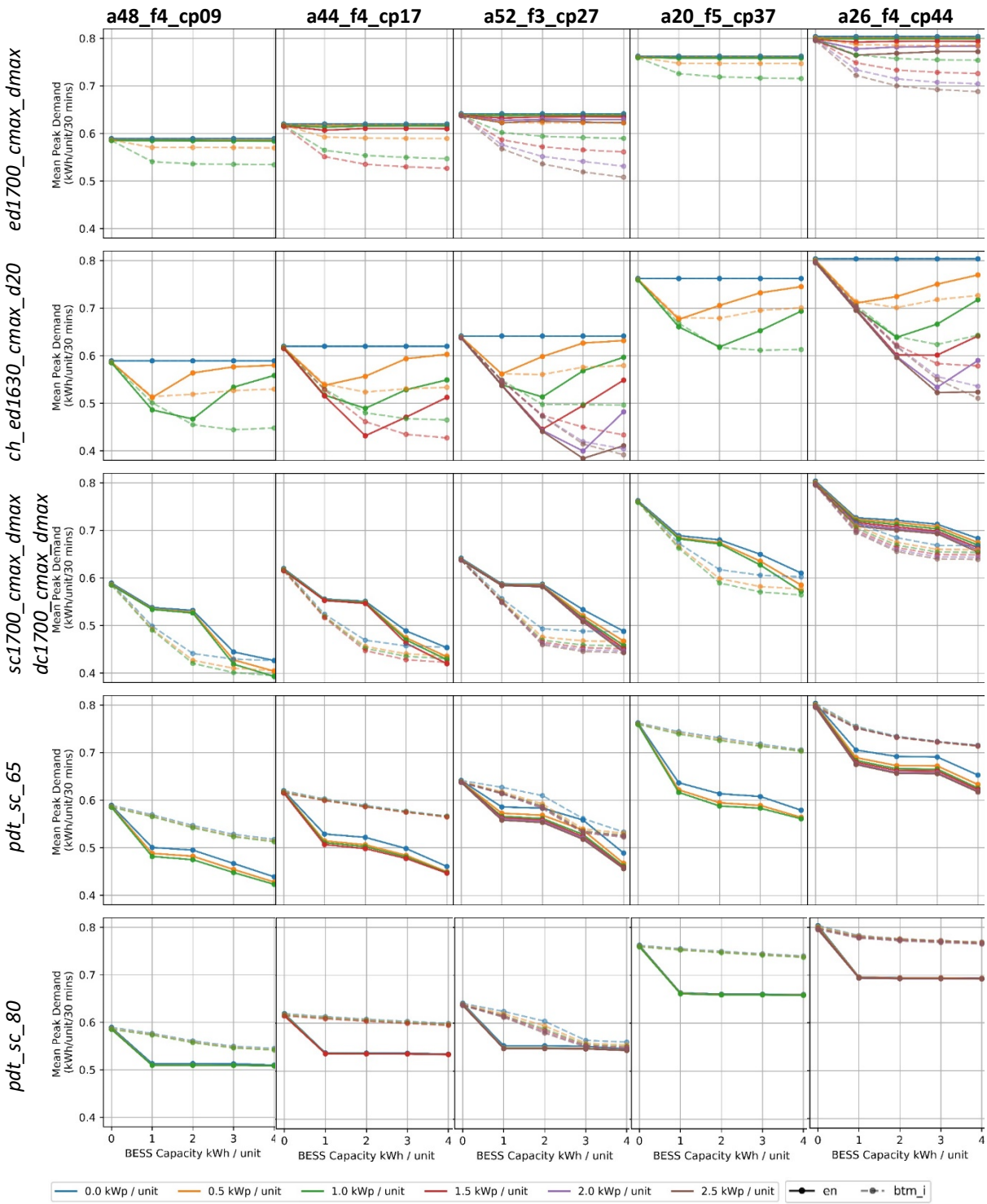

Figure 7 Variation of average of top 10 demand peaks with PV system size for 50 VBs at each site for different BESS capacities and dispatch strategies

With a larger BESS capacity and a threshold level reduced to 40%-50%, PD reductions of 30% - 40% can be achieved on some sites. The reason for the sharp increase in achievable PD reduction for a BESS of 4kWh is that SOC never falls to zero, even in winter, so there is always energy stored to address winter heating peak loads, unlike, for example, the complete discharge shown for BESS of 3kWh or less at site *a44_f4_cp17* (shown in Figure 6). Note that

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for *en* with BESS of 3-4kWh/unit, the achievable percentage PD reduction is lower for sites with higher load (and higher CP ratio).

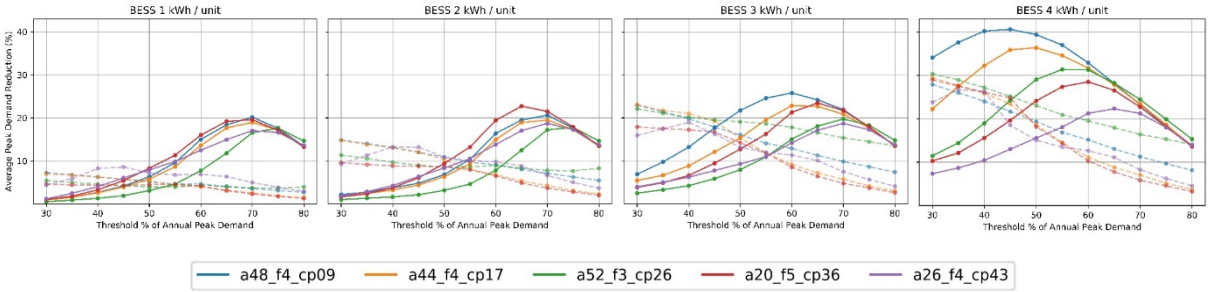

Figure 8 Average PD reduction for BESS peak demand threshold strategies with PV system of 1.0kWp /unit applied to an EN or to individual loads

In contrast, when the same strategy is applied to the equivalent capacity BESS and PV as individual systems for apartments and common property, aggregate SOC doesn't reach zero even for BESS capacity of only 1kWh, yet there may not be energy available to meet PD. With this arrangement, dispatching energy at lower demand levels is more likely to address peak loads and optimum thresholds are below 40% in most cases. However, it is important to note that reducing PD is unlikely to translate into reduced electricity charges for individual on-market customers as retail tariffs commonly consist only of fixed and volumetric (flat or TOU) components.

6. Results & Discussion: Financial Outcomes with PV and BESS

Table 4 shows the maximum NPV of annual savings per customer achievable from adding a central BESS, operated under any of the strategies described above, to an EN with PV. With no FiT at the parent meter, the greatest savings are achieved on some sites from applying an *evening discharge* strategy to maximise SC for high capacity PV systems, with optimum BESS capacity of 1-2kWh. With an 8c/kWh FiT at the parent meter, however, the benefits of increased SC are reduced, and greatest value is obtained from applying BESS of capacity 1kWh/unit to shaving PD using a *peak demand threshold* of 75%-80% of annual peak load for an EN with PV of 0.5–1.7kWp/unit.

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Table 4 Maximum average annual NPV of additional savings from adding BESS to en with PV, showing optimum PV and BESS capacities, for BESS CAPEX of AU$200/kWh and parent tariff of TOU12. The maximum achievable NPV for each site is highlighted. [$/unit/year (kWp,kWh)]

		a48_f4_cp09	a44_f4_cp17	a52_f3_cp27	a20_f5_cp37	a26_f4_cp44
ed1700_cmax_dmax	No FiT	8.2 (1.1, 1.0)	16.3 (1.5, 1.0)	30.2 (2.5, 2.0)	13.6 (1.6, 1.0)	34.4 (3.0, 4.0)
	8c FiT	0.0 (1.1, 0.0)	4.6 (1.7, 1.0)	6.1 (2.7, 1.0)	2.7 (1.6, 1.0)	12.4 (3.0, 2.0)
ed1730_cmax_dmax	No FiT	8.6 (1.1, 1.0)	17.5 (1.7, 1.0)	30.0 (2.7, 2.0)	13.8 (1.6, 1.0)	35.8 (3.0, 2.0)
	8c FiT	0.0 (1.1, 1.0)	5.3 (1.7, 1.0)	7.7 (2.7, 1.0)	3.0 (1.6, 1.0)	10.7 (3.0, 2.0)
ed1700_c20_d20	No FiT	5.2 (1.1, 1.0)	13.0 (1.7, 2.0)	24.4 (2.7, 3.0)	9.0 (1.6, 2.0)	29.8 (3.0, 4.0)
	8c FiT	0.0 (1.1, 0.0)	2.0 (1.7, 1.0)	5.6 (2.7, 1.0)	0.6 (1.6, 1.0)	8.1 (3.0, 1.0)
ed1630_c20_d20	No FiT	5.1 (1.1, 1.0)	13.9 (1.7, 2.0)	25.4 (2.7, 3.0)	9.6 (1.6, 2.0)	31.2 (3.0, 4.0)
	8c FiT	0.0 (1.1, 0.0)	2.0 (1.7, 1.0)	4.4 (2.7, 1.0)	0.2 (1.6, 1.0)	7.6 (3.0, 1.0)
ch_ed1700_cmax_dmax	No FiT	0.6 (1.1, 1.0)	3.7 (1.5, 1.0)	9.1 (2.7, 1.0)	3.8 (1.6, 1.0)	11.5 (3.0, 1.0)
	8c FiT	0.0 (1.1, 0.0)	1.3 (1.5, 1.0)	2.5 (2.7, 1.0)	2.0 (1.6, 1.0)	7.1 (3.0, 1.0)
sc1700_cmax_dmax	No FiT	5.5 (0.5, 3.0)	5.4 (0.5, 1.0)	3.4 (2.7, 4.0)	7.1 (0.5, 1.0)	8.6 (3.0, 1.0)
	8c FiT	5.5 (0.5, 3.0)	5.4 (0.5, 1.0)	3.4 (2.7, 4.0)	7.1 (0.5, 1.0)	8.6 (3.0, 1.0)
dc1700_cmax_dmax	No FiT	9.3 (1.1, 3.0)	13.1 (1.7, 4.0)	14.1 (2.5, 4.0)	9.5 (1.6, 4.0)	13.1 (3.0, 4.0)
	8c FiT	5.9 (1.1, 3.0)	7.8 (1.7, 4.0)	8.0 (2.5, 4.0)	4.2 (1.6, 4.0)	4.7 (3.0, 1.0)
pdt_sc_70	No FiT	9.8 (1.1, 1.0)	9.5 (1.5, 1.0)	0.6 (2.5, 1.0)	13.9 (1.6, 1.0)	10.1 (3.0, 1.0)
	8c FiT	9.8 (1.1, 1.0)	9.5 (1.5, 1.0)	0.6 (2.5, 1.0)	13.9 (1.6, 1.0)	10.1 (3.0, 1.0)
pdt_sc_75	No FiT	12.1 (1.1, 1.0)	10.8 (1.7, 1.0)	6.7 (2.5, 1.0)	17.7 (1.0, 1.0)	13.0 (2.5, 1.0)
	8c FiT	12.1 (1.1, 1.0)	10.8 (1.7, 1.0)	6.7 (2.5, 1.0)	17.7 (1.0, 1.0)	13.0 (2.5, 1.0)
pdt_sc_80	No FiT	10.5 (0.5, 1.0)	10.4 (0.5, 1.0)	8.4 (1.5, 1.0)	16.6 (0.5, 1.0)	15.2 (0.5, 1.0)
	8c FiT	10.5 (0.5, 1.0)	10.4 (0.5, 1.0)	8.4 (1.5, 1.0)	16.6 (0.5, 1.0)	15.2 (0.5, 1.0)

Adding BESS to individual BTM PV systems (Table 5) can achieve greater savings, with optimum BESS size of 3-4kWh/unit using either an *evening discharge* strategy to shift PV generation or *single-* or *double-cycle* strategies to reduce consumption during peak periods to take advantage of the greater difference between peak rates and FiT / off-peak rates[7].

Table 5 Maximum average aggregated annual NPV of additional savings from adding individual BESS to PV btm_i at each site, showing optimum PV and BESS capacities, for BESS CAPEX of AU$200/kWh. The maximum achievable NPV for each site is highlighted. [$/unit/year (kWp, kWh)]

		a48_f4_cp09	a44_f4_cp17	a52_f3_cp27	a20_f5_cp37	a26_f4_cp44
ed1700_cmax _dmax	No FiT	38.3 (1.1, 2.0)	55.0 (1.7, 3.0)	75.0 (2.7, 3.0)	52.1 (1.6, 3.0)	102.4 (3.0, 4.0)
	8c FiT	26.3 (1.1, 2.0)	38.4 (1.7, 2.0)	53.2 (2.7, 3.0)	36.8 (1.6, 2.0)	73.2 (3.0, 3.0)
ed1730_cmax _dmax	No FiT	35.2 (1.1, 2.0)	49.1 (1.7, 3.0)	66.3 (2.5, 3.0)	48.2 (1.6, 2.0)	90.5 (3.0, 4.0)
	8c FiT	23.8 (1.1, 2.0)	34.5 (1.7, 2.0)	46.4 (2.5, 3.0)	34.1 (1.6, 2.0)	65.2 (3.0, 3.0)
ed1700_c20_d20	No FiT	29.2 (1.1, 2.0)	42.5 (1.7, 3.0)	58.9 (2.5, 4.0)	41.8 (1.6, 3.0)	78.3 (3.0, 4.0)
	8c FiT	19.0 (1.1, 2.0)	27.5 (1.7, 3.0)	39.8 (2.5, 3.0)	26.9 (1.6, 3.0)	53.7 (3.0, 4.0)
ed1630_c20_d20	No FiT	31.5 (1.1, 2.0)	46.5 (1.7, 3.0)	65.7 (2.5, 4.0)	44.9 (1.6, 3.0)	86.0 (3.0, 4.0)
	8c FiT	20.9 (1.1, 2.0)	30.6 (1.7, 3.0)	44.5 (2.5, 3.0)	29.3 (1.6, 3.0)	59.8 (3.0, 4.0)
ch_ed1700_cmax _dmax	No FiT	29.7 (1.1, 2.0)	35.7 (1.0, 2.0)	47.0 (2.7, 2.0)	39.5 (1.6, 3.0)	62.7 (3.0, 3.0)
	8c FiT	23.9 (1.1, 2.0)	29.4 (1.0, 2.0)	37.4 (2.7, 2.0)	33.7 (1.6, 2.0)	51.6 (3.0, 3.0)
sc1700_cmax _dmax	No FiT	39.7 (0.5, 3.0)	44.5 (0.5, 3.0)	50.8 (0.5, 3.0)	60.5 (0.5, 3.0)	82.1 (0.5, 3.0)
	8c FiT	39.6 (0.5, 3.0)	44.5 (0.5, 3.0)	50.8 (0.5, 3.0)	60.5 (0.5, 3.0)	82.1 (0.5, 3.0)
dc1700_cmax _dmax	No FiT	42.9 (1.1, 3.0)	50.6 (1.0, 3.0)	56.4 (1.5, 3.0)	61.6 (1.6, 3.0)	84.6 (2.5, 4.0)
	8c FiT	38.5 (1.1, 3.0)	46.0 (1.0, 3.0)	50.6 (1.5, 3.0)	56.1 (1.6, 3.0)	76.2 (2.5, 4.0)

[7] The retail peak rate modelled is 51.3c compared to off-peak 14.2c and FiT of 8c per kWh, while the commercial peak rate is 20.5c compared to 13.2c and FiT of 8c (see Section 3.5 and Appendix B)

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Despite the relatively slight benefits of adding a centralised BESS, the combined savings from installing PV-BESS-EN compared to the base case with no EN are significant, as shown in Table 6 for different parent tariffs. Note that a BESS size of 1kWh/unit is optimum in most cases and that PD shaving is the optimal strategy for all sites if a FiT is available at the parent meter, while in the absence of a FiT, the relative benefits of shaving PD and maximising self-consumption are site-dependent.

Table 6 Maximum average annual NPV of savings from combined EN-PV-BESS, showing optimum PV and BESS capacities and dispatch strategy, for BESS CAPEX of AU$200/kWh. [$/unit/year (kWp, kWh)]

		a48_f4_cp09	**a44_f4_cp17**	**a52_f3_cp27**	**a20_f5_cp37**	**a26_f4_cp44**
TOU9	No FiT	103 (0.5, 1.0) pdt_sc_75	117 (0.5, 1.0) pdt_sc_75	183 (1.0, 1.0) pdt_sc_80	23 (1.0, 1.0) pdt_sc_75	146 (1.0, 1.0) pdt_sc_80
	8c FiT	116 (1.1, 1.0) pdt_sc_75	129 (1.5, 1.0) pdt_sc_75	198 (2.0, 1.0) pdt_sc_80	34 (1.6, 1.0) pdt_sc_75	174 (3.0, 1.0) pdt_sc_80
TOU12	No FiT	53 (1.1, 1.0) pdt_sc_75	60 (1.0, 1.0) ed1730_cmax_dmax	123 (1.0, 1.0) pdt_sc_80	-48 (1.0, 1.0) pdt_sc_75	72 (2.0, 2.0) ed1700_cmax_dmax
	8c FiT	69 (1.1, 1.0) pdt_sc_75	82 (1.7, 1.0) pdt_sc_75	145 (2.0, 1.0) pdt_sc_80	-30 (1.6, 1.0) pdt_sc_75	107 (3.0, 1.0) pdt_sc_80

Table 7 shows the maximum NPV and optimum system capacities and strategies for individual PV-BESS connected *btm_i*. Note that (except for site *a20_f5_cp37*) the combined savings are significantly less than can be achieved from EN-PV-BESS systems with a low (TOU9) parent tariff. However, for a higher parent tariff (TOU12), the advantage of EN is less clear and, for some sites, individual BTM PV-BESS systems are preferable.

Table 7 Maximum average aggregated annual NPV of savings from combined PV-BESS connected btm_i, showing optimum PV and BESS capacities and dispatch strategy, for BESS CAPEX of AU$200/kWh. [$/unit/year (kWp, kWh)]

Site	**No FiT**		**8c FiT**	
a48_f4_cp09	47 (0.5, 3.0)	sc1700_cmax_dmax	56 (0.5, 3.0)	sc1700_cmax_dmax
a44_f4_cp17	66 (0.5, 3.0)	sc1700_cmax_dmax	75 (0.5, 3.0)	sc1700_cmax_dmax
a52_f3_cp27	78 (0.5, 3.0)	sc1700_cmax_dmax	86 (0.5, 3.0)	sc1700_cmax_dmax
a20_f5_cp37	89 (0.5, 3.0)	sc1700_cmax_dmax	105 (1.6, 3.0)	dc1700_cmax_dmax
a26_f4_cp44	114 (1.0, 3.0)	sc1700_cmax_dmax	151 (2.0, 4.0)	dc1700_cmax_dmax

Figure 9 shows the variation with system size of NPV of annual savings from a combined PV-BESS-EN installation with a parent tariff of TOU12 in the absence of a FiT. For all these scenarios, except for site *a26_f4_cp44,* NPV is maximised for PV sized at between 1kWp and 1.5kWp/unit and BESS at 1.0kWh/unit. Note the significant variability across 50 VBs at each site, highlighting the dependence of BESS and PV value on the shape of aggregated load profiles.

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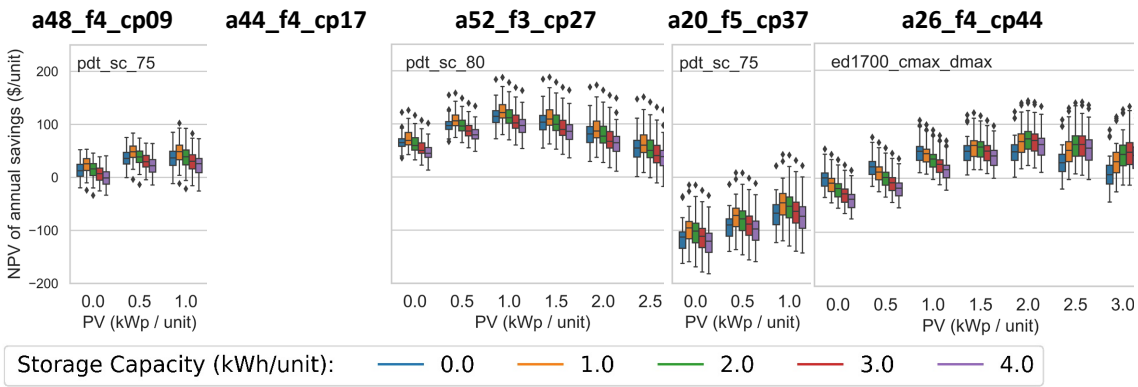

Figure 9 NPV of annual savings from combined EN-PV-BESS with optimum control strategy at each site for BESS CAPEX of AU$200/kWh, parent tariff TOU12 and no FiT

If the ENO can access a lower TOU9 tariff at the parent meter, the maximum average NPV is increased by AU$45 - AU$83/unit/year, for optimal PV capacity of 0.5–1.0kWp, while a FiT of 8c/kWh at the parent meter increases the optimal PV system size to 2.0kWp for site *a52_f3_cp27* and to *max_pv* for the remaining sites, increasing the average NPV by AU$18 - AU$45 for BESS of 1kWh/unit.

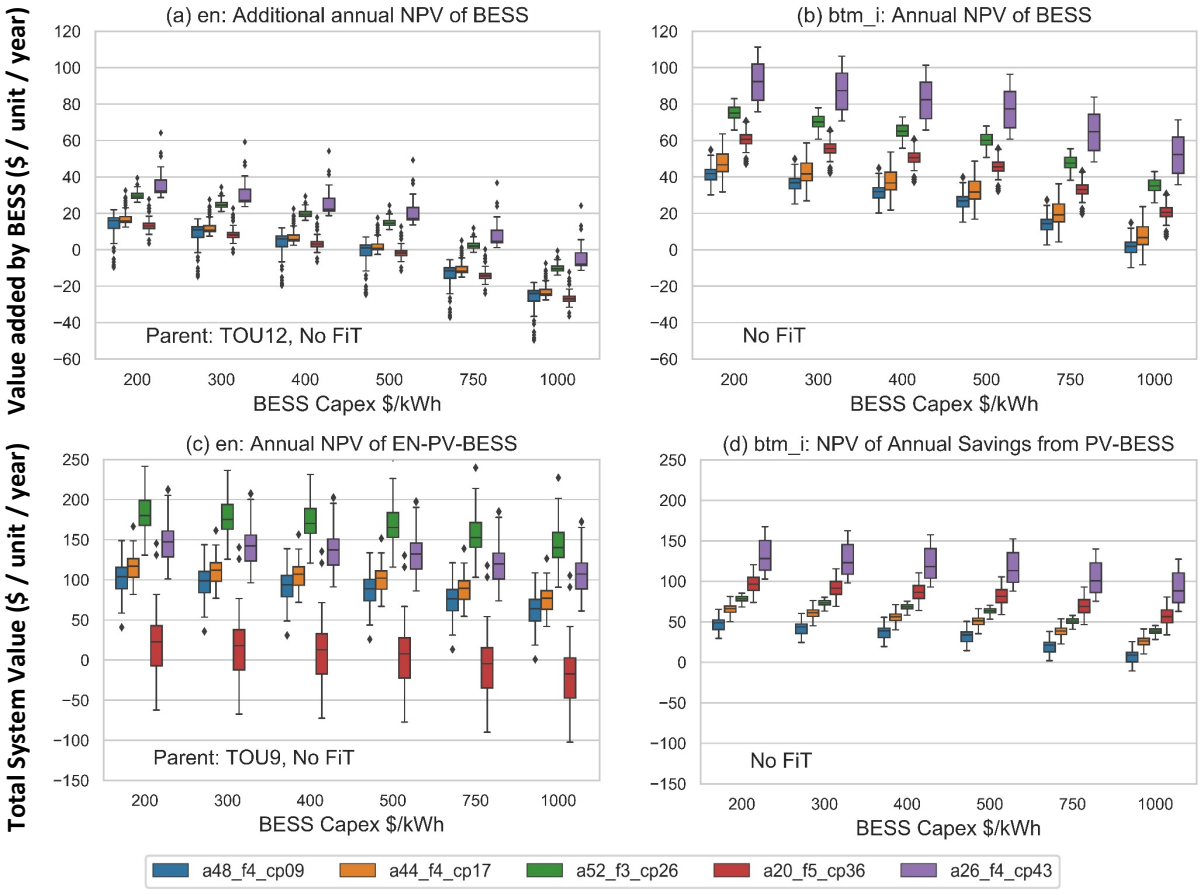

Figure 10 NPV of (top) annual BESS savings and (bottom) annual total system savings for (left) en and (right) btm_i with kWp, kWh and discharge strategy at each site optimised to maximise NPV, as shown in Tables 4 - 7

While the foregoing results are based on a projected future BESS capex of $200/kWh, for four of the sites, the median NPV of additional savings from BESS applied to *en* remains positive for BESS CAPEX costs up to AU$400/kWh (Figure 10(a)) but is negative for costs more aligned

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with current Australian market rates (Section 3.4). By contrast, for *btm_i* arrangements, NPV is positive for all sites with BESS capex up to $750/kWh or AU$1000/kWh (Figure 10(b)). Nevertheless, except for the smallest site (*a20_f5*_cp36) where the assumed costs of EN installation exceed any likely benefits, the combined savings from EN-PV-BESS have a positive NPV even for installed BESS capex of AU$1000/kWh (Figure 10(c)) and, on average, exceed those from PV-BESS connected BTM in the absence of a FiT (Figure 10(d)).

7. Conclusions

Notwithstanding the complexity of interaction between load profile, PV variability, battery energy capacity, charge / discharge power and control strategy, our findings demonstrate that addition of a central BESS to an EN with PV can increase SC and SS and reduce PD. In the scenarios modelled, application of PV-BESS to aggregated building load achieves higher SC and SS than application to individual loads, but the impact of adding BESS to an existing PV system is similar in both cases.

The economic benefits of retrofitting EN-PV-BESS to a brownfield site are evident for all but the smallest site, while benefits for a greenfield site (with substantially lower marginal capex costs) will be greater still. Nevertheless, the economic case for BESS in either EN scenario is not compelling and would require a much lower threshold capex cost than for BESS applied to individual dwellings, due to the lower volumetric rate and lower TOU disparity of commercial retail tariffs. ASs electricity prices continue to rise, it would be useful to extend the study to include a range of higher rates that may be more aligned with future commercial tariffs, and which may result in a higher threshold BESS capex cost. However, with current (and short-term future) tariffs and BESS costs, thermal energy storage using hot water systems [77] or space heating [78] may be a more financially attractive method of storing PV generation in multi-occupancy residential buildings, and comprehensive techno-economic modelling of this option would also be a valuable topic for future study.

Although our results suggest that BESS dispatch strategies targeting PD reduction may be the most appropriate for central BESS in an EN, optimal dispatch strategy design is highly site-specific and greater benefits may be achievable by combining different strategies with forecasting of load and generation. Also note that the scale of central BESS compared with individual household systems may make it better placed to access markets for ancillary power system services which could improve the economic case. However, as with community energy generation, it is also important not to overlook the potential broader, non-economic benefits of CES at household, community and societal levels [52].

Because of the complexity of factors affecting financial outcomes from PV-BESS deployment, including sensitivity to the size and temporal distribution of building electricity load, building-specific modelling is necessary to accurately assess the opportunities for a particular site. In this context, open source tools, such as the one used for this study, may be a helpful resource to assist stakeholders in decision making, as well as allowing other researchers to compare outcomes with alternative jurisdictional tariff arrangements.

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Appendix A: Capital Cost Data for PV and BESS

Table 8 shows installed costs for residential and commercial PV systems in New South Wales [79] averaged over 6 months to May 2018 to smooth sudden price fluctuations. These costs include Federal government subsidies and federal goods and services tax (GST) of 10%

Although PV panels have expected lifetimes exceeding 25 years [80] and 25-year warrantees are now common, inverter replacement is likely during the lifetime of the system and constitutes the largest ongoing cost for a PV system [80]. In line with other studies [80, 81], and given the availability of ten-year warrantees from some manufacturers [82, 83], a lifetime of ten years for inverters has been assumed, with replacement inverter costs based on median wholesale prices [84] in each range plus estimated installation costs, and a typical retail margin of 24% plus GST. It should be noted that although inverter lifetimes significantly greater than ten years are unlikely to be cost effective in the near future, inverter costs are likely to continue to fall as manufacturing volumes increase [85].

Table 8 Installed CAPEX costs for PV systems and replacement inverters

PV System Size (kWp)		Installed System Cost ($ / Watt)		Inverter Replacement
Min	**Max**	**Before Subsidy**	**With Subsidy**	**($ / Watt)**
0	1.5	2.49	1.84	1.1
1.5	2	2.35	1.7	1.1
2	3	2.21	1.56	0.95
3	4	1.9	1.25	0.8
4	5	1.75	1.1	0.83
5	7	1.66	1.01	0.65
7	10	1.73	1.08	0.65
10	20	1.85	1.2	0.65
20	30	1.83	1.18	0.42
30	50	1.81	1.16	0.42
50	70	1.77	1.12	0.31
70	100	1.75	1.1	0.31
100		1.73	1.08	0.31

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Appendix B: Commercial Tariffs at the Parent Meter

The tariff paid by the ENO at the parent meter would comprise a regulated network component and a market retail energy component. In the relevant network area of the study, the network component for a low voltage connection would be EA305 or EA310, depending on annual load. These network tariffs have a relatively high ratio of fixed and capacity to volumetric charges, as shown in Table 9, with the daily capacity charge based on the customer's peak load in the preceding 12-month period.

The energy and retail component, determined by negotiation with the retailer and therefore subject to a high degree of variability and to a lack of transparency, is likely to be significantly lower than the estimated 14.63 c/kWh paid by a representative NSW retail customer [86] in 2017/18, and to include a TOU component. We have used a range of high ('TOU12') and low ('TOU9') market prices from early 2018 plus environmental charges of 1.71 c/kWh and GST.

Table 9 Commercial tariffs payable at the parent meter

Component	Name	Annual Energy Use (MWh)	Fixed Charge (c / day)	Peak Rate (c / kWh)	Shoulder Rate (c / kWh)	Off-peak Rate (c / kWh)	Capacity Charge (c/kVA/day)
Network (ex GST) [87]	EA305	160-750 MWh	1905.85	4.95	2.27	1.26	35.74
	EA310	> 750 MWh	2403.13	4.40	2.11	1.39	35.74
Retail / Energy (ex GST)	TOU9			9.00	9.00	6.50	
	TOU12			12.00	12.00	9.00	
Environmental Charges				1.71	1.71	1.71	
Combined tariff (inc GST)	EA305_TOU9		2096.435	17.226	14.278	10.417	39.314
	EA305_TOU12		2096.435	20.526	17.578	13.167	39.314
	EA310_wTOU9		2643.443	16.621	14.102	10.56	39.314
	EA310_TOU12		2643.443	19.921	17.402	13.31	39.314

Although avoided transmission use of service costs may be paid for embedded generation where network benefit is demonstrated [88], it is unusual, though possible, for commercial customers to receive a FiT applied to PV export. However, for this study, two scenarios were tested: a FiT of 8c/kWh at the parent meter (in line with the state regulator's 2018-19 'all time benchmark' rate for retail FiTs [74]) and no payment for exported generation.