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Shared Solar and Battery Storage Configuration Effectiveness for Reducing the Grid Reliance of Apartment Complexes

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Abstract: More than 2 million houses in Australia have installed solar photovoltaic (PV) systems; however, apartment buildings have adopted a low percentage of solar PV and battery storage installations. Given that grid usage reduction through PV and battery storage is a primary objective in most residential buildings, apartments have not yet fully benefited from installations of such systems. This research presents shared microgrid configurations for three apartment buildings with PV and battery storage and evaluates the reduction in grid electricity usage by analyzing self-sufficiency. The results reveal that the three studied sites at White Gum Valley achieved an overall self-sufficiency of more than 60%. Owing to the infancy of the shared solar and battery storage market for apartment complexes and lack of available data, this study fills the research gap by presenting preliminary quantitative findings from implementation in apartment buildings.

Keywords: solar PV; shared energy microgrid; battery storage; self-sufficiency; apartment complexes; empirical analysis; energy autonomy; shared PV storage

1. Introduction

A combination of increasing costs of electricity bills along with the declining price of solar panels, concerns over global climate change, and favorable renewable uptake policies have led to a rapid increase in the solar installation capacity across Australia. Currently, more than 2 million residences in Australia have rooftop solar photovoltaic (PV) systems [1]. Although PV systems have been widely adopted at the residential scale, the lack of a regulatory framework for shared ownership and distribution of cost-benefits have prevented the operationalization of rooftop PV and battery storage systems in medium and high density apartment dwellings. While technical guidelines and installation standards exist [2], shared systems for apartment buildings are seldom addressed in the literature. Only a few multi-residential projects have implemented a shared governance structure [3], and consequently, there is no clear model for ready adoption. A shared governance structure would seem important to increase the uptake of distributed renewable energy systems (DRES) as the price of PV-battery technology is declining and solar irradiance conditions in Australia are favorable [4]. By installing DRES in apartment buildings, the utility network benefits are gained through a single point of supply compared to multiple connections, whereas load distribution can be easily governed by a combination of grid electricity and central battery storage. Needless to say, the main motive behind the uptake of DRES is reduction of grid reliance. Consequently, an increase in self-sufficiency is deemed to be the expected outcome. Self-sufficiency is defined here as the capability of the microgrid to rely on its renewable fraction (load consumption from either PV, battery, or combination of both) without depending on grid electricity [5–10]. The self-sufficiency is often interchanged with self-consumption; however, it is determined as proportion of PV consumption to overall production.

This paper evaluates self-sufficiency obtained from shared microgrid configurations installed at three different apartment buildings in a newly developed precinct at White Gum Valley (WGV) Perth, Australia. The grid connected arrangements combine PV with a battery energy storage system (BESS) and an effective metering infrastructure embedded behind the main meter to monitor the energy demand profiles and also measure the performance of the PV-BESS. It is therefore necessary to also explain the system configuration used for the shared distribution of renewable and grid electricity among apartments. Moreover, the assessment of load profiles is essential because the load consumption is directly influenced by usage patterns and other factors such as generation to consumption ratio and seasonal mismatch, which also impact on self-sufficiency [8,11,12].

The results from this study contribute to existing and forthcoming research on the application of DRES in apartment buildings. It should be noted that the concept of grid reliance reduction in the multi-residential apartments reported in this paper was carried out independently of current or proposed tariff structures for energy, the latter being outside the scope of this research.

The paper is structured as follows:

- Section 2 briefly reviews DRES in residential buildings and identifies the reasons for the low uptake of DRES in apartment buildings.
- Section 3 discusses the role of battery storage in reducing grid reliance and achieving self-sufficiency as supported by the recent research literature.
- Section 4 presents the concept of shared systems.
- The case study is presented in Section 5, which also includes details about microgrid configurations and metering.
- Section 6 describes the methodology and analysis used for the study.
- Section 7 presents analyzed results obtained from the shared configurations on three sites.
- Finally, the paper is concluded in Section 8 by highlighting main outcomes and suggestions for future research.

2. DRES in Residential Dwellings

The positive characteristics of PV and battery storage, which include reduction of grid reliance, peer-to-peer trading, ability to charge batteries, balancing of voltages, and reactive power flow, make solar PV the most promising decentralized solution in recent times. Moreover, the environmental benefits achieved from the uptake of solar PV are significant and include reducing carbon footprints [13]. Given that detached houses already contribute to a reduction of carbon emission [14], multi-residential buildings should also play a major role in decreasing the overall greenhouse gas emissions. Allocation of shared solar in strata developments would also benefit in reaching carbon emission mitigation goals of 441 $MtCO_2e$ by 2030 [3,15] through increased self-consumption and reduction of building emissions [16].

Low Uptake of DRES in Apartments

In recent years, approvals for new apartment construction have surged. During 2017–2018, residences in apartment buildings have made up 30.4% of total dwellings initiated [17]. Across Australia, about 9% of the total population live in apartments (4% in Western Australia) [18]. Concurrently with rising numbers of approvals for apartment buildings [18], construction starts for attached dwellings outpaced those for houses in 2015, indicating a growth trend in apartment dwellers. Employment opportunities and population growth are fundamental drivers of demand for apartment construction [19]. Thus, with the growing portion of apartment buildings in the Australian housing sector, the absence of DRES on such buildings creates issues of energy justice, with a significant portion of the population unable to access the benefits of solar energy. Affordability considerations are relevant in this context, with Australia having some of the highest electricity prices in the world [20].

The uptake in DRES has focused on detached housing, as opposed to a small portion of consumers in apartment buildings, access to PV and battery storage [20–22]. The primary rationale for low uptake in multi-residential dwellings is the absence of a governance model that shares the costs and benefits of DRES among residents, developers, strata managers, and network utility providers [23]. The existing models require the introduction of a shared structure in order to tackle situations such as split incentives [24], through which renters benefit from the electricity bill, whereas the landowner pays for the PV panels causing low capital funding in DRES installations [25]. Technical challenges such as insufficient rooftop area in relation to large number of dwellers together with occupants' interest in approval make the integration of DRES in apartment dwellings a complicated task [26]. The greater proportion of the research literature discusses microgrid design configurations and performance for detached houses and communities [27]. However, PV with BESS configurations in apartment buildings are rarely discussed in published writings. Microgrids are generally commissioned in residential communities, and a number of studies, which focused on PV deployment in apartments, emphasized either technical performance assessment [28] or techno-economic evaluation of microgrid incorporating PV systems [16,22,24,29–31]. Only a few publications thoroughly studied apartment load profiles [23,32]. Apart from these studies, a shared microgrid was discussed in [3], which analyzed the technical performance of shared solar and battery storage for residential apartments. Moreover a techno-economic evaluation was performed in [33] to examine the impact of PV-BESS systems using interval data.

3. Battery Storage in Mitigating Grid Reliance

Battery energy storage plays a key role in supplying load power during peak hours when utility sourced electricity tariffs are higher in costs and there is no available PV to cover the demand [33]. Battery storage allows increased self-consumption by harvesting energy from solar panels during the day time and thus places less stress on the grid during the night time. These characteristics have led to the global battery storage capacity of 29GWh in 2020, which is expected to reach 81GWh by 2024 [34]. Despite the higher manufacturing costs, this increased permeation of battery storage will be instrumental in achieving the renewable energy transition [35]. As an alternative to costly prices, second-life batteries decommissioned from electric vehicles are also a viable option to use with grid applications. When these batteries can no longer provide 80% of rated capacity, they can still be functional to meet demand for energy storage applications (including residential homes) other than electric vehicles [36].

Battery storage can contribute substantially in reducing grid reliance [37–40] and allow users to shift peak demand easily for efficient use of electricity in low tariff periods, thereby utilizing demand side management [41,42]. Among the myriads of battery technologies, lithium-ion (Li-ion) has been demonstrated as the most applicable in the residential sector and preferred in microgrids because of its capability of deep-cycle operation, high specific energy, power density, and high number of charge discharge cycles [33,43]. Lithium-iron phosphate (LFP) is regarded as the safest among the Li-ion battery technologies [36] whilst also offering fast charge, as well as grid stabilization and a longer life cycle. This battery was therefore chosen for commissioning for this study.

Literature Reference

DRES in residential systems have been widely investigated in the literature with the primary intention to mitigate grid usage and increase self-consumption [38,41] and self-sufficiency [37,39,44]. In this regard, the role of battery storage in maximizing self-sufficiency and grid usage reduction has been widely considered as the primary objective [45].

Optimization modeling has been carried out in order to increase the self-sufficiency of households together with the impact of electric vehicle batteries [7]. In that study, combinations of 30 different PV and stationary battery storage sizes were tested. Although self-sufficiency obtained from the electric vehicle battery was found to be similar to that of stationary storage, the duration of electric vehicle plugged-in at home strongly affected the self-sufficiency ratio (SSR). Simulation profiles from different countries have been studied [8] to analyze the techno-economic impact of self-consumption with PV and BESS under various regulation schemes. The analysis found that increasing battery size increases self-sufficiency and that at a certain limit of high battery capacity, the self-sufficiency increment rate becomes marginal compared to normal. Furthermore, the study stressed that full self-sufficiency is impractical, requiring an over-sized system. Three battery technologies with solar PV for a residential building were compared by [9] in Germany. It was shown that the Li-ion battery technology was found to be superior in achieving a high SSR. Seasonal storage was suggested to achieve high SSR in winter. However, this would be a cost-related risk since maintenance costs would be high and maintaining a large battery system is impractical. In [38], the authors used 82 household surveys and monitored electricity consumption and generation data to demonstrate how residential battery storage could reduce grid electricity through an increase in self-consumption of PV. They demonstrated that on-peak grid electricity consumption of 74 houses during on-peak hours were reduced by 8% using smart battery storage. In a comparative study, [46] reported that communal batteries are more beneficial from a system perspective, with reduced electricity import by 56% as compared to a grid reduction of 34% in individual household batteries.

A single integrated approach was used by [12] to investigate variety of buildings and load demand scenarios to study factors that influence the techno-economic feasibility of self-sufficiency. It was ascertained in the study that single detached dwellings easily achieve self-sufficiency because of their geographical advantage. However, with improved PV technologies and battery storage, high self-sufficiencies can be achieved in densely populated multi-residential buildings where rooftop area limitation is the key factor. The paper also discussed a list of research studies on self-sufficiency based on various categories. A different simulation study [44] analyzed 25 residential profiles with PV and Li-ion battery storage optimization over a period of one year and provided results through well-explained metrics such as self-sufficiency. A simulation was performed to compare six scenarios in [47] related to the interaction of renewable energy generation, electricity consumption, and energy storage in individual and collective configurations. The scenarios include systems relying totally on grid to community with individual and communal shared energy storage systems. The grid dependence component was mainly focused on the central parameter of assessing system performance beside carbon emission reduction.

Electricity consumption data from 99 households in Texas was used in [48] to correlate two different battery storage models and understand the energy storage effects on power demand, costs, and carbon emissions. The target zero method sought to reduce grid imported and exported power without demand forecasting, whilst the minimize-power method used optimization to minimize net demand power from the grid. The latter demonstrated a reduction in peak demand power of 32% and reverse power flow of 42%, while the target zero method resulted in demand reduction by 8% and reverse power flow to 5%. Although the minimize-power method provided greater benefits in terms of demand and cost, it deviates from our motivation of grid minimization as the batteries were charged from the grid.

Further to this, the role of consumers in the expansion of the battery storage market is important. A study carried out in Queensland [40] revealed consumer motivation and other factors in the uptake of battery storage. Choice modeling was used to demonstrate enablers that are likely to domesticate the battery market. Results from the survey revealed that a majority of consumers preferred purchasing a storage system to meet self-sufficiency, save money on electricity bills, and reduce grid reliance. However, the costs of the storage system was identified as a major barrier.

With respect to multi-residential apartments, there are limited examples of research carried out that focused on increasing self-sufficiency. In [26], a multi-objective optimization model was developed using a programming language to minimize electricity billing costs as well as maximize self-consumption. The results show that the economic viability and self-maximization of shared PV systems depends on variable elements of electricity costs. Load profiles were studied in [49] from five Australian apartments with PV-BESS and it modeled simulated PV generation. The author found that PV-BESS in aggregated dwelling load accomplish higher self-sufficiency than individual loads.

4. Shared Systems

With growing concerns regarding the security, reliability, and affordability of energy, the idea of sharing electricity generated by DRES is gaining popularity with scientists, policymakers, and communities alike [50]. Sharing of battery storage energy as compared to split distribution has proven to be a cost effective and viable solution in community scale systems such as high self-consumption, self-sufficiency, and cost savings to prosumers [51–53]. There are multiple reasons for this: first, large storage systems could easily participate in power markets. Second, the battery storage in individual houses is not utilized when the dweller is not present and hence storage capacity is not fully utilized. Moreover, sharing also follows the path of energy accountability where consumption by an individual user has minimum or no effect on overall usage. On the other hand, a consumer with the highest load consumption in the whole dwelling (following the Pareto distribution principle) could also be expected to shift the peak demand in off-peak hours.

To understand the techno-economic effects of energy sharing, numerous factors pertaining to storage, PV generation, and state of charge must also be considered [54]. Moreover, load management is also a key factor in order to balance the generation to consumption ratio. For instance, in order to maximize the benefits of shared PV systems, it will also be important to logically allocate a portion of DRES to only those users consuming electricity at a particular interval [26].

The occupant consumption behavior, the result of customer daily activities, is usually considered in the energy audit regardless of distribution of load system, i.e., split or shared. In the literature, various approaches have been proposed to investigate the effect of occupant behavior on energy consumption in residential buildings. An algorithm was presented by [55] to simulate any occupancy pattern of any building type based on defined inputs. The model uses data to generate arrival, presence, and departure times that could affect residential energy consumption. A nonintrusive occupant load monitoring approach was applied in [55] to determine the energy-load variation of each occupant at entry and departure events. Furthermore, [56] studied different aspects of occupancy behavior (hot water, energy, heating, windows) using Monte Carlo simulations and found a high variability of approximately 50% in all factors when occupants were changed. In [57] however, it was argued that most of the findings in this field present a good understanding of the effect of occupant behavior on energy consumption, though predictions of exact occupant consumption patterns are still missing. Most if not all of these factors attributed to DRES postulate a standard metering architecture connected behind the main meter to measure temporal readings with precision. While detached buildings integrating DRES have conventionally been metered for revenue identification, there is less information on apartment metering for the shared distribution of energy. This study relies on the pulse metering infrastructure similar to [3], which used distributed arrangement to track the energy generated and used for each apartment. We will discuss this in Section 5.1.

Shared Energy Microgrid

The microgrid in the WGV project consists of solar PV and BESS embedded behind the main grid meter. We refer to [3] to call this the shared energy microgrid (SEM). It does not technically differ from the embedded network given in [23], but the focus has been on mutual proprietorship of the infrastructure and also the element of energy trading that steered the shared microgrid design [3,58]. Figure 1 shows the difference in configurations of both embedded network and SEM. It may be observed that our SEM not only adds additional battery storage but also processes data from metering, which is sent to the software that then handles strata management tasks including billing and the trading framework. The article [58] discusses the implemented governance model in detail. The WGV sites basically employ two types of SEM configuration: 1. AC-coupled and 2. DC-coupled. However, the residential loads at each site are connected in their own shared setup via a single connection point. The detailed description of these two configurations will be covered in Section 5.1. The capacity of PV panels and battery storage was selected considering the goal of grid minimization and number of residential units in each apartment building. Although the three apartment complexes are located adjacent to each other, they do not form a single large microgrid, albeit three separate circuits operate their own DRES independently.

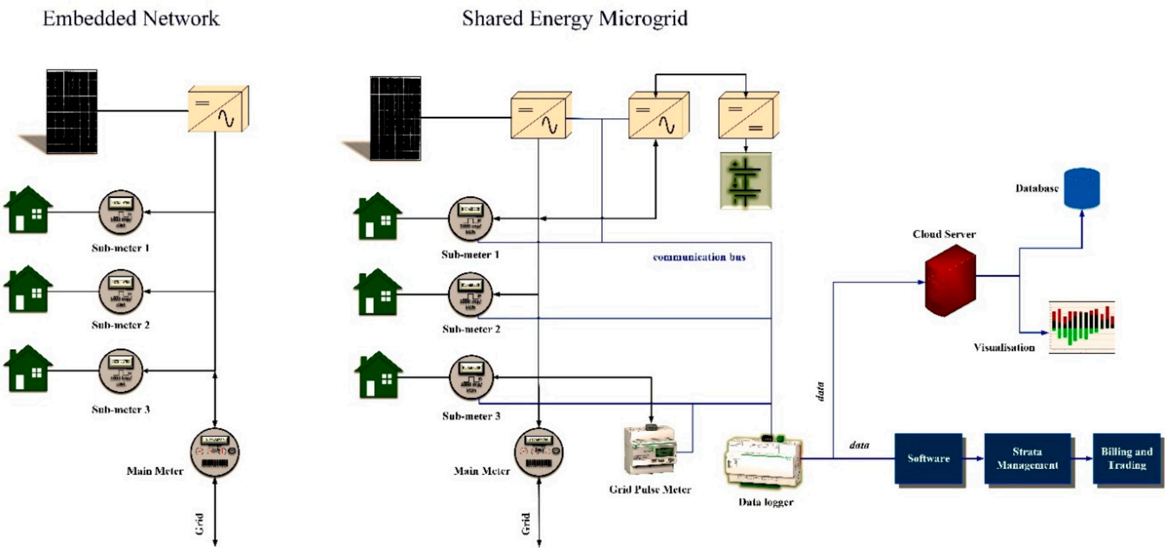

Figure 1. An embedded network (**left**) and shared energy microgrid (**right**).

5. Case Study: WGV

A consortium between the land developer, the city council, and the local community, planned a precinct development at WGV in which environmental considerations and community well-being were essential design criteria [59]. The 2.2 hectare WGV development is situated in the City of Fremantle, Western Australia. The site has been accredited as a One Planet Living community (the One Planet Living scheme is based upon ten simple principles that facilitate in planning, implementation, and communicating sustainable transformation. Anyone from stakeholders, organizations, education departments, and governments can utilize this framework). The WGV site under investigation incorporates three multi-residential apartment buildings known as Evermore [60], Gen Y [59], and SHAC [61]. In this regard, several innovative measures were taken to implement efficient energy, water, and building design use [62,63]. As described above, the complexity of ownership frameworks in strata developments is a main obstacle to increasing the uptake of DRES. Therefore, by trialing DRES and in particular SEM, the WGV research project demonstrated the use of these systems in strata developments. A summary of the housing typologies and system capacity included in the paper is provided in Table 1 below. We define living areas in these apartment complexes as units and do not elaborate individual dwelling characteristics such as floor area, household size, and thermal features. Data collected from each site was individually aggregated and then analyzed as one whole building. These three complexes of the WGV development were set targets to reduce grid electricity usage by 60% [59], with some sites achieving more than the anticipated objectives.

Table 1. White Gum Valley (WGV) apartment buildings and system information.

Building	Units	System Size	Configuration
Gen Y	3 one-bedroom	9 kWp–10 kWh-Li-ion	AC-coupled
Evermore	24 units	54.6 kWp–150 kWh-Li-ion	AC-coupled
SHAC	12, 2 shared studios	19.6 kWp–40 kWh-Li-ion	DC-coupled

5.1. SEM Configurations

Typical house connections import electricity via a single connection point. However, in SEM here, a central PV and BESS distributes electricity individually to each unit in the apartment. Fundamentally, PV and BESS are conjugated through two possible combinations of AC-coupled and DC-coupled systems [64–66]. In AC-coupled systems, PV as the main source with battery storage is coupled on the AC bus. The battery is mainly charged through another inverter connected to the AC bus. AC-coupled systems have the compatibility of connecting to other AC sources without any complexity, and large sized residential systems can be installed if permitted by network regulation of particular jurisdiction. In DC-coupled systems, PV modules are linked on a DC bus whilst the inverter connected to the DC bus supplies the load. DC coupling generally demands one conversion and hence requires less power converting equipment. Both of these configurations have advantages and disadvantages in terms of flexibility, operation, and efficiencies. In terms of efficiencies, conversion losses should also be compared in both configurations before commissioning [65]. AC-coupled systems have higher efficiency than DC-coupled systems [67,68] and with the combination of battery storage, they can deliver more supply to the loads [69]. On community locations, AC-coupled systems are relevant configurations for installation because there is no direct PV production [70]. In terms of cost, a higher number of conversions can be a disadvantage in AC-coupled systems. Similarly, in terms of technical performance, DC-coupled systems have shown much improved performance and longevity [69]; however, when DC-coupled systems are integrated with battery storage, multiple dc–dc and dc–ac conversions would be required, which also raises system costs and energy losses.

As shown in Figure 2, the buildings at Evermore and Gen Y implemented AC-coupled systems, whereas a DC-coupled system was installed at SHAC. The primary operation of these configurations is based on the following three priorities; (1) storage of PV-produced energy in batteries during the availability of sunlight, (2) meet the energy demand of residential loads prioritizing PV-BESS as source (in AC-coupled system) and then from the grid, and (3) export surplus energy to the utility. The PV-BESS modeling for three configurations was carried out using an end-use approach; anticipating typical appliance-based consumption patterns and assuming some residents would stay home during the daytime. Thus, the PV-BESS was designed to cover midday load demand. In addition, on-peak demand was also considered in battery storage capacity. Notwithstanding, a change of lifestyle and varying activities may impact the load consumption patterns decreasing PV-BESS effectiveness in abating grid reliance. Any unused electricity generation due to lower than expected demand will be exported to the grid ensuring the battery storage is full. It is necessary here to use the PV to charge the battery, otherwise the expected increase in self-sufficiency from grid charging and BESS discharging will be lost [51]. For the purpose of monitoring the data from SEM, submetering based on pulse meters were added to configurations as shown in Figure 2.

The perceptible benefits of submetering are improved energy efficiency, reduction in energy usage, detection of system faults, and tariff structure adjustments [71]. In terms of energy and cost savings, the intention behind the installation of submetering was not only analysis of the energy statistics but also to make consumers aware of their energy consumption [72]. Considering resource minimization and cost-effective solutions, employing a hybrid metering architecture provides better data reliability, provided they offer multiple basic communication protocols such as Modbus and TCP/IP.

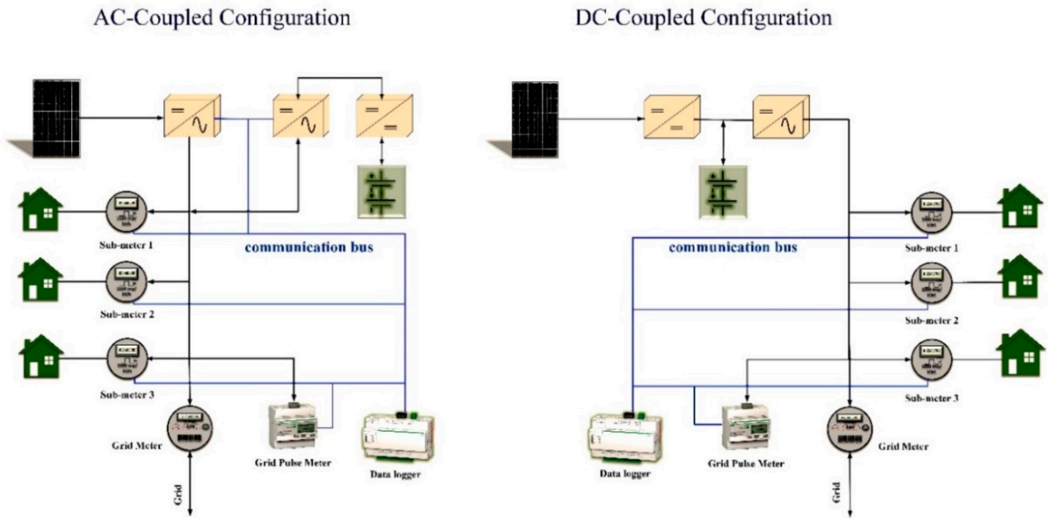

Figure 2. AC-coupled (**left**) and DC-coupled (**right**) configurations used in the study.

As given in Table 2, the pulse submeters KMP1-50 (from K-Mac Powerheads) and PMC-220 (from CET) connected to residential units measure unidirectional power, whilst bidirectional power is measured by IEM3255 (from Schneider). The readings from these pulse energy meters are then sent to a database where monthly or per day data is managed. For the purpose of revenue gradation, pulse submeters must follow NMI (NMI is a regulatory authority in Australia that maintains measurement system standards.) standards; therefore, all pulse meters commissioned at WGV were NMI compliant.

Table 2. Meters utilized in shared energy microgrid (SEM).

Building	Pulse Submeter	Energy Meter
Evermore	PMC-220	IEM3255
Gen Y	KMP1-50	IEM3255
SHAC	KMP1-50	IEM3255

6. Methodology and Analysis

6.1. Data Collection

The fundamental methodology as shown in Figure 3 relies on the collection of numeric real-time data from metering and communication equipment installed at the WGV project site [3]. All three sites have similar, although independent, communication infrastructure setups. The Com'X 510 (from Schneider Electric) data logger collects data from the systems and submeters. The connection between the data-logger and submeters was established via Modbus serial communication protocol. The dataset resolution set in the logger is 15 min. The data reaches the logger either from each meter directly or through an interface module SIM10M (from Schneider Electric), which maximizes the number of meters to be interfaced over Modbus protocol. In addition, the data-logger also maintains internal backup storage of the connected meter data locally. An interminable broadband internet connects the data-logger to a cloud server where data is stored in an SQL database. This raw data, after adjustments of headers and proper attributes, are then pushed to a Google studio database where the data are managed, outliers are removed, and data become presentable in spreadsheet. This hybrid arrangement was selected based on the motive of resource minimization, which eradicates the requirement for a sophisticated data management platform and results in significant cost savings.

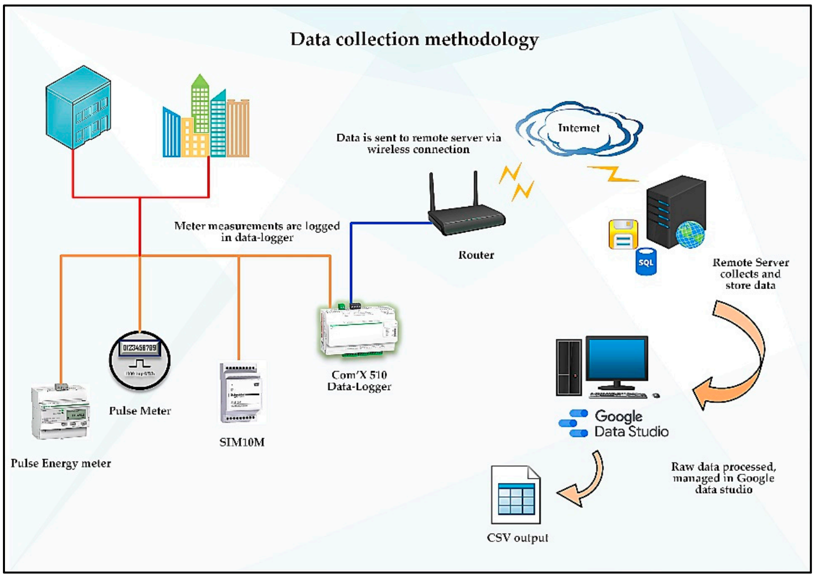

Figure 3. Methodology for data collection (redrawn from [3]).

The gathered dataset contains one year of measurements for Gen Y (January 2019 to December 2019), 9 months for Evermore (November 2018–July 2019), and 8 months for SHAC (November 2018–June 2019).

6.2. Analysis

The main objective of analyzing the data from SEM at three sites is to exhibit grid reliance reduction; therefore, findings should be interpreted accordingly. Electricity measurements from the metering data were evaluated on different scales and parameters, mainly real-power in kW and energy in kWh. Because pulse submetering was used in three apartments, the energy values measured exist in a cumulative form whilst parameters such as power were instantaneously recorded. We used Equation (1) to extract specific interval values from the cumulative data.

$$\Delta X_t = Y_t - Y_{t-1} \quad (1)$$

where t represents the interval, X the yearned output, and Y is the cumulative parameter, respectively. If we consider 15 min of interval, data per-day would generate 96 interval points. Hence, the expression to compute daily energy values from (1) could be given through Equation (2).

$$Energy_{\,kWh\ per\ day} = \sum_{n=0}^{95} (\Delta X_n) \quad (2)$$

The plots containing mean values were arranged by averaging similar timestamps over the full period with normalized values, while data points with zero or spurious values were omitted. This was done to keep data in its original form.

To analyze grid reduction, performance was assessed in terms of SSR and energy autonomy. SSR is sometimes also referred to as energy autonomy [73]. However, we will use energy autonomy in Section 7.3 to define the operated time period of the PV-BESS. Daily SSR can be calculated by dividing the renewable portion of consumption by the total load [8,9,11] or alternatively using Equation (3).

$$\text{SSR}\ (\%) = \left(1 - \frac{\sum_{t=0}^{95}(E_{grid})}{\sum_{t=0}^{95}(E_{load})}\right) \times 100 \quad (3)$$

where t is interval, E_{grid} is grid energy usage, and E_{load} is total consumption, respectively

7. Results and Discussions

This section presents the results obtained from the data recorded by the pulse meters. We organize our findings by first analyzing the load profiles in detail, then assessing the energy distribution from the main sources under investigation, and finally providing self-sufficiency outcomes. Diversity in system topology, PV-BESS capacity, and load size at each site should be considered before looking at the results. Dwelling characteristics, system losses, and efficiencies have not been included in this analysis.

7.1. Seasonal Load Profiles

Averaging monthly electricity data from different seasonal months into diurnal profiles provide perspectives about load consumption patterns for the different buildings. The seasonal load patterns are a good starting point to analyze the generation to consumption ratio of apartment loads connected in shared configuration, which could envision future research directions toward optimization of renewable systems. The data for seasonal load profiles are from the months of December and June, the usual southern hemisphere summer and winter months, respectively. As can be seen from Figure 4, PV generation at the Evermore site recorded the highest power (42 kW) during the favorable sunny conditions of summer. Similarly, PV at Gen Y as illustrated in Figure 5 generated 6 kW.

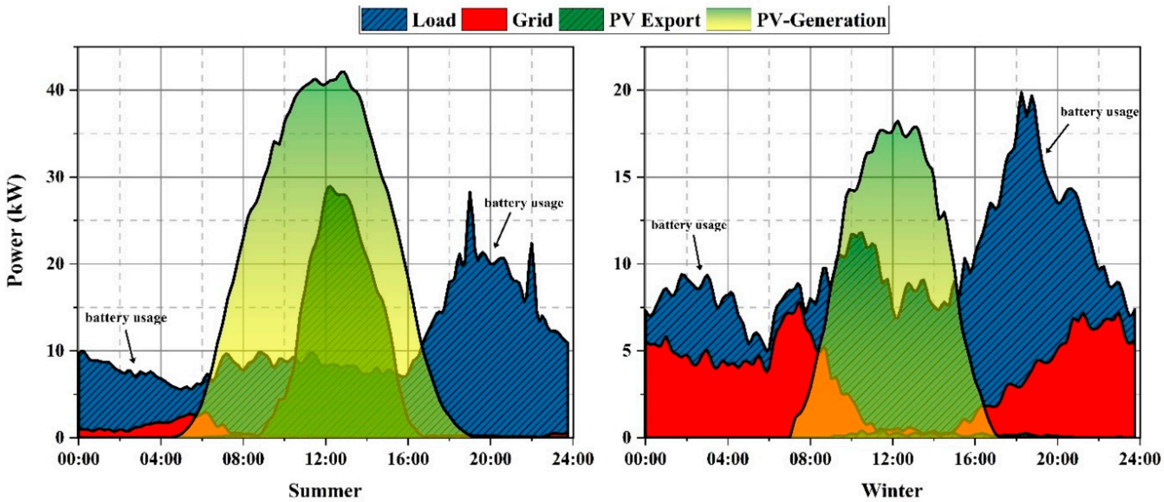

Figure 4. Seasonal load profile for Evermore.

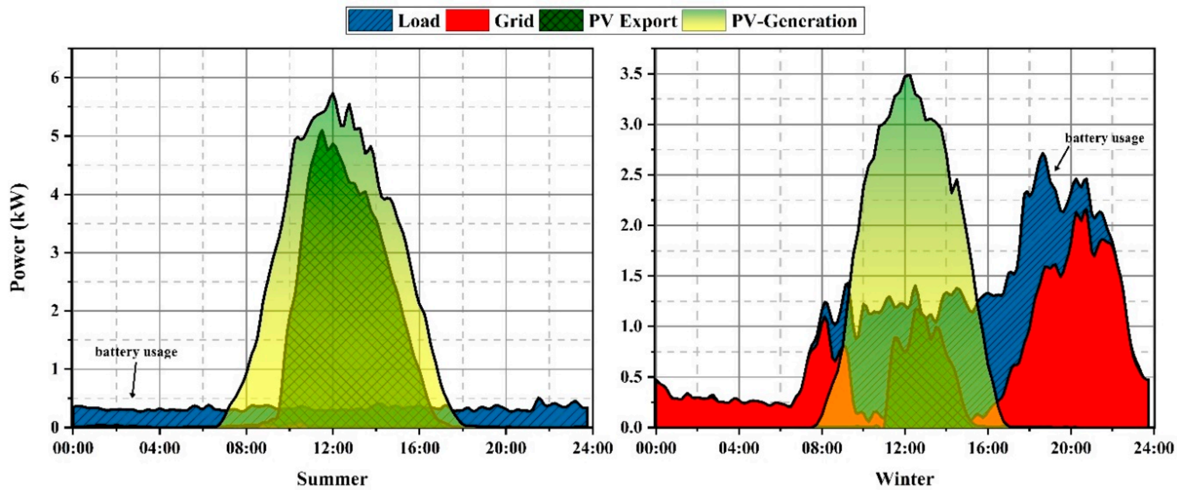

Figure 5. Seasonal load profile for Gen Y.

Consequently, the grid usage remained significantly lower than generation, which was caused by two factors. Firstly, the AC-coupled configuration at Evermore and Gen Y supplied load directly through PV panels. Secondly, the excess generation charged the batteries sufficiently to deliver the rest of the daily load demand. The remaining PV excess exported back to the grid was almost 35% of total daily yield at Evermore and 63% at Gen Y. The present feed-in-tariff in the Western Australian region is available at $7 cents/kWh (fixed) [74], whilst a recent distributed time varying tariff announced will provide a small incentive of 10 cents/kWh (3 pm to 9 pm) and 3 cents/kWh at other times [75]. As these tariffs are still significantly less than the buying tariffs, strata developers may utilize these large PV exports as a potential to access wholesale market and implement community microgrid peer-to-peer trading mechanisms [76]. Likewise, with the help of recent peer-to-peer trading mechanisms, consumers in a shared community microgrid can share surplus PV exports generated by a neighbor next door [76]. From a technical point of view, the idle state of the battery (fully charged) made this export inevitable. Nonetheless, the active feed-in power is also beneficial for the grid in terms of reduced transmission losses and lower investments in new utility generation units [77].

On the contrary, the winter profile exhibits dissimilarity in terms of load consumption, PV generation capacity, and grid usage. This disparity occurred due to less favorable solar conditions in June when PV panels are unable to yield enough production in the southern hemisphere. Another factor is the use of high electricity consumption appliances such as heaters due to cold weather. Moreover, the PV generation becomes insufficient to fully charge the battery making grid imports during the evening higher than usual. It is interesting to note that the overall load consumption observed at Evermore during the winter period was 10% lower than the summer season. One of the main causes we infer from [62] is the use of reverse cycle air-conditioning by some residents rather than conventional oil or gas heaters, which consume high electricity. Moreover, most of the residents felt thermally comfortable without heating appliance in the homes during winters. Regardless of load consumption, the lower PV generation in the winter period from the AC-coupled configuration also ensured partial battery charging and load supply.

The Gen Y winter profile demonstrated 70% higher load consumption than summer, whilst PV generation remained lower and also a small portion of PV surplus was exported to the grid. Occupants living at Gen Y had varied worked routines, which may also cause minimum consumption in particular months. However, we would not divert our focus on occupancy behavior on load consumption in this study. It is apparent that due to limited generation and thus small storage availability, the grid usage dominated throughout the day except during the PV generation period. We should necessarily take into consideration that the plot here contains average values of one month data in winter, and therefore, there would be more days without PV generation, causing lower self-sufficiency.

The seasonal plot from SHAC on the other hand is the result from PV-BESS of DC-coupled system providing combined output, and therefore, the interpretation of temporal patterns is slightly distinct from the previous two buildings. As shown in Figure 6, a typical summer day sees the renewable generation profile stretched out to a much longer duration than previous sites, mainly due to the decline of battery storage alongside PV generation. Due to an undersized PV-BESS, the generation to consumption ratio during a summer day at SHAC appears to be much lower as compared to apartments at the Gen Y and Evermore sites. A minor drop in grid usage was seen during the daytime between 09:00 a.m.–07:30 p.m., and then it started reaching back to load value again after 09:00 p.m. Furthermore, some PV export was also noticed during the daytime. As expected, the generation from PV-BESS in winter remained less than the load consumption with nearly zero exports and equivalent grid consumption to the load outside PV generation hours. When comparing PV-BESS generation to consumption plots of all load profiles, it is evident that the system at SHAC would require further optimization strategies in terms of load shifting and peak shaving in order to reduce grid sourced electricity. Presumably lower PV-BESS contribution can be expected in all systems at the three sites during the cold season. Demand management strategies as well as alternative seasonal storage options are imperative for the winter months in order to achieve high self-sufficiency.

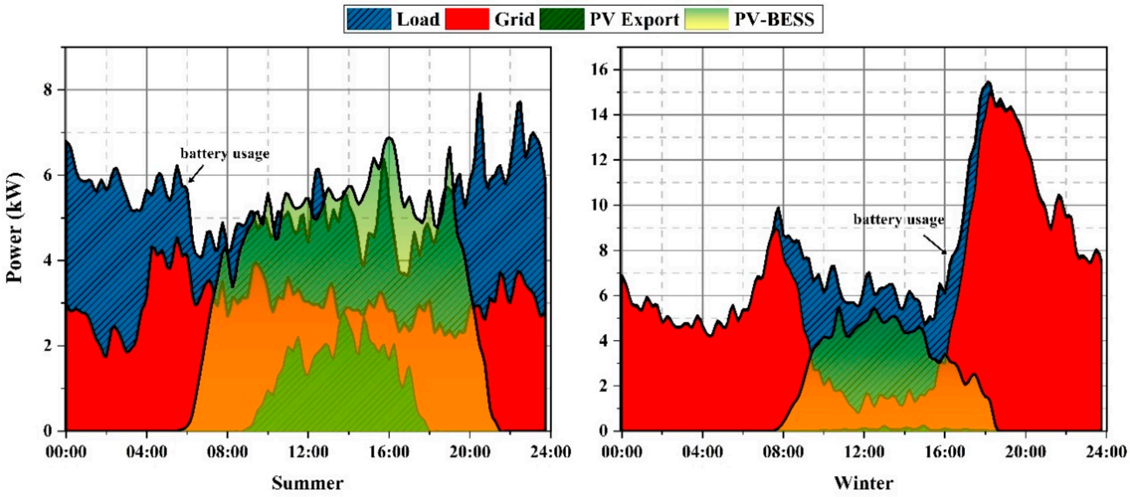

Figure 6. Seasonal load profile for SHAC.

7.2. Diurnal Load Profiles

Building upon seasonal load profiles, we accumulated WGV site data for multiple months and analyzed the average daily pattern of load consumption sourced from grid electricity and PV-BESS. Figure 7 represents total load consumption at each site as load, grid consumption as grid import, and PV-BESS consumption. The scaling of each plot has been fixed according to the amount of load consumed. The consumption from PV-BESS or renewable fraction [78] is expected to increase as opposed to grid usage [79] and carbon emissions [80]; however, it is subjected to large capital. The load patterns indicate an idiosyncrasy in terms of on-peak consumption in the morning (06:00–10:00 a.m.) and evening (06:00–09:00 p.m.) that form a silhouette of the duck curve [81,82]; however, the plots in this study differ from the traditional duck curve, which is usually belly shaped by PV integration in the mid-afternoon, ramping up to develop an arch in later hours. The SEM configurations discussed in this study also contain battery storage; therefore, the net load curve is more flattened.

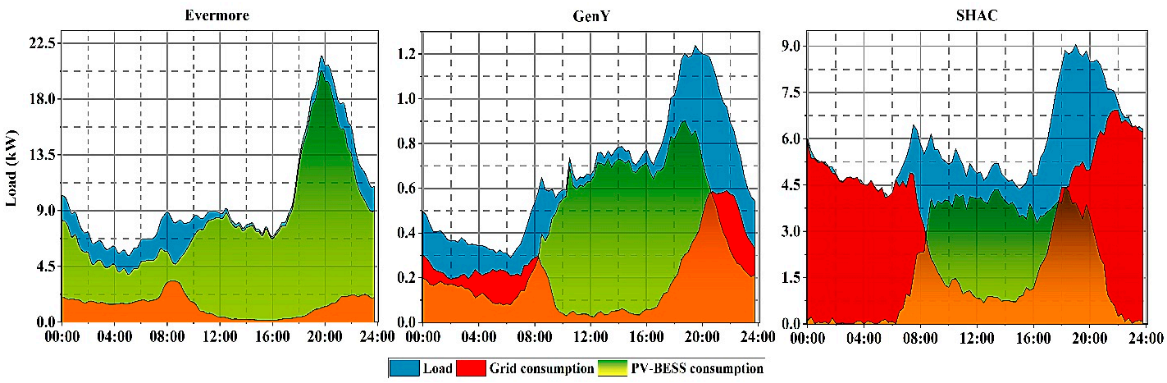

Figure 7. Averaged diurnal load profiles (from left to right; Evermore, Gen Y, and SHAC).

For the sake of clarity, we distribute the peak hours in morning and evening peaks to compare the effects of both sources. In the early hours of the day, we notice that the trends vary for each site in a different manner. Overall, Evermore relied 70% on the supply from PV-BESS and the remaining 30% on the grid usage. The obvious reason for a lower grid portion is the availability of large storage supplying the load in the evening until the PV resumes generation in morning. Similarly, Gen Y drew more electricity on average from the PV-BESS (59%) than the grid (41%), whilst SHAC depended more on grid sourced electricity, 60% against 40% of PV-BESS. Evening peak hours are mostly highlighted in the studies because this period accounts for the highest electricity consumption in residential buildings.

Shared systems with battery storage have been observed to minimize grid usage in peak hours [53]. A major portion of the battery at Evermore (94%) supplied load demand throughout on-peak hours with a slight share of grid (6%). The system at Gen Y covered the greater portion of on-peak hours with a combination of grid (34%) and battery (66%). On the contrary, the load consumption from the grid at SHAC remained at 60% as compared to the battery portion of 40%. It is noteworthy that in SHAC, unlike the two other sites, the battery storage dropped to a minimum before midnight and hence, to maintain the minimum state of charge and ancillary loads, grid electricity was imported. A supplementary graph showing diurnal share of PV-BESS and grid is included in Appendix A.

The apartment load profile characteristics given here might differ from detached houses based on several factors, such as dwelling sizes, construction, and size of household [32]. In detached houses, the pattern of energy use could fluctuate, and the load value may increase due to the high number of occupants and the large area as compared to apartments. Seasonal variation is another factor that changes the generation and consumption patterns. Nonetheless, the load distribution data of apartments from the PV-BESS and the grid illustrated in Figure A1 are important for enabling demand optimization of apartment loads in the future. For instance, the average maximum demand per dwelling, also known as after diversity maximum demand (ADMD), set by the local Western Australian utility network [83] can be adjusted accordingly for suburbs with apartment buildings enabled by SEM configurations.

7.3. Self-Sufficiency

After analyzing the load profiles of all apartments, we have seen in detail the contribution of the PV-BESS and grid usage in average diurnal patterns and also its seasonal effects, which provide a good foundation to evaluate monthly self-sufficiency from these systems. We will stepwise look at the monthly energy distribution of each site and then present the self-sufficiency results.

Figure 8 illustrates the monthly energy demand consumption in terms of sources utilized and also exported PV energy to the grid. Against these plots, the resulting SSR's are presented on the right side. At Evermore, the reason for the high level of PV exports and insignificant grid electricity usage of approximately 10% during the first six months is possibly because of a mismatch between PV generation and the load consumption pattern. However, the last three months of the dataset show an increase in grid electricity by 46%, which is likely due to the lower availability of sunlight hours and cloud cover in winter, which in turn reduces PV productivity. The contribution of the PV-BESS at Evermore on average provided 78% SSR over the given period. Similarly, the PV-BESS in SEM of Gen Y covered 95% of load demand in the summer months whilst it remained 50% in winter. A significant portion of grid export was also noticed for almost six months of the dataset period owing to high PV-BESS production in parallel to the reduced load consumption. Meanwhile, grid imports surging to approximately 50% of load value were observed only in the winter months (May to August). This is due to the aforementioned factors of lower sun intensity, higher winter consumption, and generation to consumption mismatch. Overall, the SSR obtained at Gen Y was 66% for the dataset period. The system at SHAC on the other hand depended largely on grid sourced electricity (60%), yielding an SSR of just 40%. Overall, the three developments at WGV achieved 60% SSR through PV-BESS generated electricity.

Apparently, all plots show high grid consumption during the winter season. To address this problem, hybrid solutions for seasonal storage, such as hydrogen fuel-cell-based storage with PV-BESS, might significantly contribute to reducing grid usage; however, chemical to electrical conversion losses have also been reported [84].

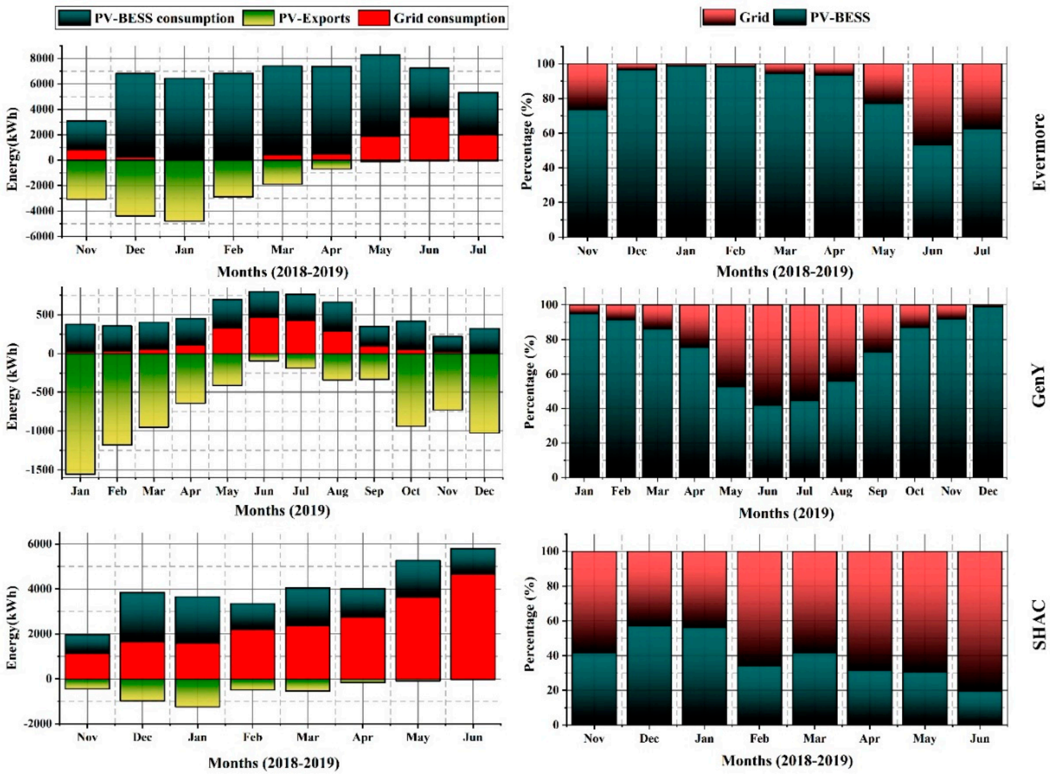

Figure 8. (**left**) Monthly energy distribution and PV exports (**right**) resultant self-sufficiency.

These results corroborate that adequate battery capacity with PV yields high self-sufficiency [45]. Li-ion technology facilitated in providing higher self-sufficiency targets [44], which resulted in reduced grid usage [38,48]. In the shared context, the findings support the idea of central storage with PV in order to achieve high self-sufficiency [46], whereas it also eradicates the technical complexity of installing multiple grid connections. Additionally, we have noticed that the AC-coupled systems at Evermore and Gen Y achieved higher SSR than the DC-coupled system at SHAC. Nevertheless, both configurations have their functional merits and demerits, although the best arrangement depends entirely on the application. As mentioned in Section 5.1, the number of conversions (DC/AC) and cost factor might be of significant importance when choosing one variety of configuration, whereas ease of installation is viewed as a secondary factor. The ideal selection can only be determined if a uniform sized AC or DC coupled PV-BESS configuration is implemented supplying a similar load and then compared in terms of efficiency. The low SSR in SHAC points towards an undersized PV system of SHAC in relation to the number of households. Comparing three apartments from a shared context, the PV allocation to consumer ratio in SHAC (1.4) is less than Evermore (2.275) and Gen Y (2.25). However, further research should explore optimal energy allocation, sharing or trading, and distribution in the microgrid. Other factors that should also be considered are the consumption behavior and mobility of consumers.

In conjunction with this, certain measures could improve the energy performance of the investigated systems in this study. PV-BESS dispatching can be optimized with the help of load forecast estimation, which may consider inputs such as historical consumption, weather information, and tariff structures (discussed in Section 7.1). Long-term forecasting, due to its stochastic nature, cannot be guaranteed because weather and historical usage alone would not be sufficient to predict the exact pattern. In a time-of-use tariff market, this could become a good case since consumers usually prefer to schedule electricity usage during an economically advantageous tariff time interval. This opens the possibility of a price-based forecasting input. Nevertheless, an interlocking of multiple forecasting methods, which could also include consumer mobility factor, might be effective in setting PV-BESS operation for achieving high self-sufficiency.

It is obvious from the results that large battery size increases the SSR. However, each added capacity leads to lower consumption. Figure 9 shows this battery size varying effect for each site. The battery size for the respective SSR was estimated based on parameters taken from the periodic data for the three sites, including apartment load consumption, PV generation, and renewable energy fraction as shown in Figure A2. This estimation can be viewed from actual functional system data rather than a conventional modeling, which takes into account amp-hour, voltage, current, depth of discharge, and other metrics. Moreover, systems at Evermore and Gen Y are AC-coupled, and it is apparent that a portion of PV generation meet load demand other than charging, hence the inclusion of load consumption was considered a primary criterion. Depending on average per-day load consumption and SSR percentage, the required generation was determined by the PV utilization factor, which ascertains the ratio between total PV generation and the renewable fraction and includes actual losses [66]. After the required per-day PV generation was obtained, PV and battery were proportionally sized based on actual average per day generation data. Once again, all the assumptions, conversion factors, and losses are attributed to actual data. The detail design methodology of the PV and battery storage system was not within the scope of this paper, hence readers are suggested to refer to literature on optimal sizing for PV and battery storage. It can be seen that beyond certain kWh of battery storage, the SSR value marginally increases and the horizontal curve becomes flatter [8,85].

In the same manner, the economic implications of system sizing and performance cannot be neglected. The cost component ($/kWh) of varying battery sizes with SSR would need further analysis, which may impact commissioning of PV-BESS. It is essential to keep the cost of additional battery size less than demand charge costs. Certain measures, such as reducing PV size while maintaining fixed battery storage, can be taken in order to improve net present value and payback periods [86]. This is due to the fact that majority of the load occurs in the morning and evening when PV generation is small. Hence, system optimization would be necessary to find the cost-optimal PV-BESS configuration [66]. It is recommended that future studies address the economic case of varying battery sizing alongside SSR evaluation for multi-residential buildings.

Another way of ascertaining self-sufficiency can be done by evaluating the metric of energy autonomy, which is defined as the duration for which the DRES independently supplies residential loads [87]. Energy autonomy can be quantified in terms of minutes, hours, and days depending on the analytical representation. Our configurations are grid connected and achieving full autonomy over a longer period is impractical, and consequently, we assume energy autonomy in this analysis as the ratio of PV-BESS operation period, which accounted for greater than and equal to 50% of the total load. This is shown in the boxplot of Figure 10, which illustrates the distribution of daily autonomy and identifies the symmetry and skewness of the duration when grid or PV-BESS were utilized. The green box represents the consumption period from PV-BESS, while red represents the grid consumption period. The temporal data for these plots was arranged by calculating the ratio of grid and PV-BESS consumption from the total load.

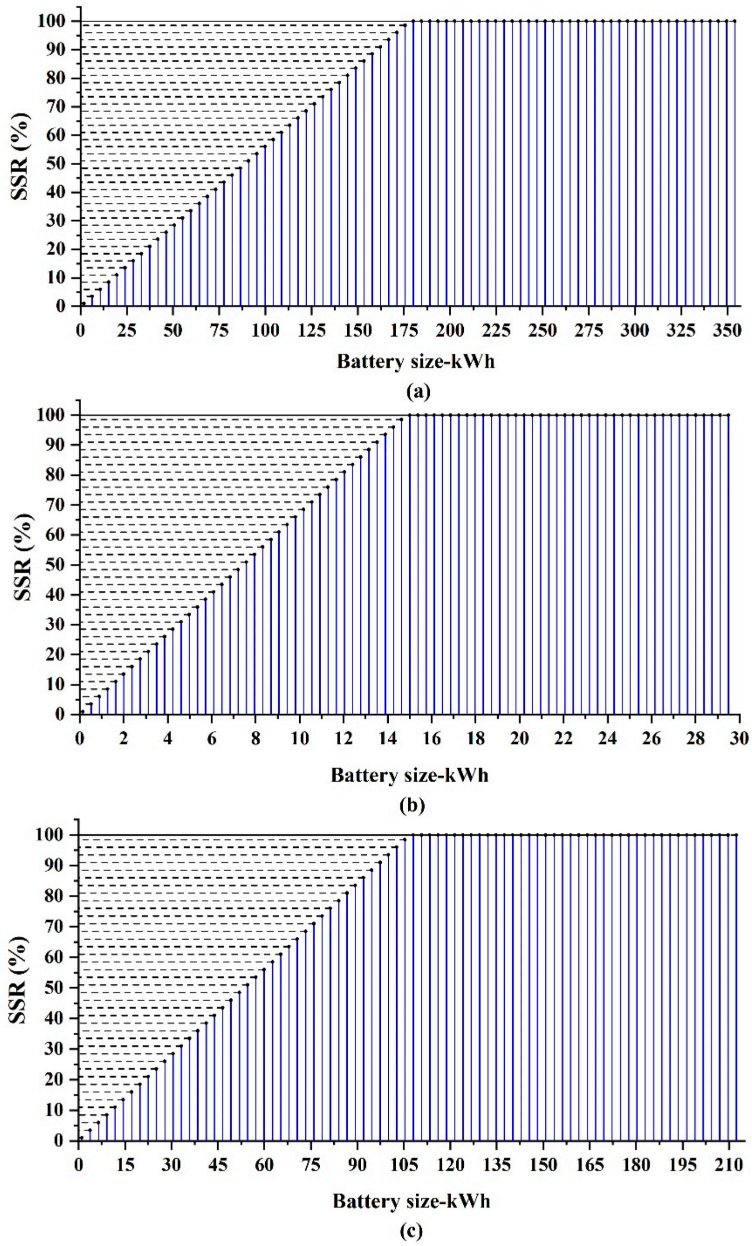

Figure 9. Impact of battery size on the SSR for (**a**) Evermore, (**b**) Gen Y, and (**c**) SHAC.

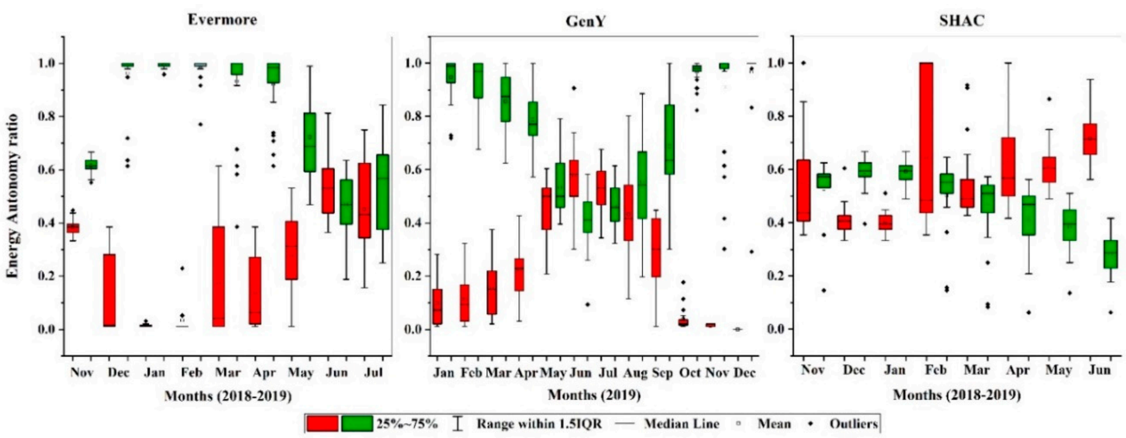

Figure 10. Energy autonomy ratio for configurations at three sites.

A filter was then purposely applied to select values equal or greater than 50%. Outliers and zero-values were eliminated from the data. Given the duration of measured interval is 15 min, the number of intervals per day (96) generated a total of 1440 min. The daily values for both the grid and the PV-BESS were then divided by 1440 to get the energy autonomy ratio. The values excluded from the range (less than 50%) would mean load consumption contributed in a hybrid way either by grid or PV-BESS. In Evermore, the majority of the data can be observed as skewed. Starting from November, it is apparent that the interquartile range (IQR) remained near unity until April, and then with the start of winter in May, the autonomy distribution balanced out and moved towards symmetry. The longer IQR variation for grid period is seen in December, March, April, and May. There were no high and low outliers identified in the data. Similarly, in Gen Y, autonomy IQR remained close to maximum from January to April, gradually decreasing and showed symmetry in the winter months, and then increasing again from the period of September to December. On the contrary, we can see less variation in IQR between PV-BESS and grid in SHAC apartments. Moreover, a box plot of SHAC shows less energy autonomy in which PV-BESS IQR exceeded the grid IQR only in December and January while it continued to plummet in the other months of the dataset. If we include the full data range (0–100% of autonomy values), less outliers will appear in the plots.

8. Conclusions and Future Recommendations

This study evaluated the self-sufficiency for shared microgrid configurations implemented on three different apartment complexes. Our findings indicate that the SEM comprised of PV with BESS resulted in increased self-sufficiency by reducing the grid electricity imports. Although a complete annual data set could not be collected from SHAC and Evermore, the load profiles from each site represented similar characteristics in diurnal consumption patterns, whilst the portion of renewable consumption varied according to the availability of the PV-BESS. It has been observed that winters create a renewable energy deficit, which is covered mostly by grid imported electricity. For attaining high self-sufficiency in winters, hybrid solutions such as PV-BESS with hydrogen fuel-cells [84] would hold substantial preference. Moreover, the achieved self-sufficiency targets of 78% in Evermore, 65% in Gen Y, and 40% at SHAC could be improved significantly by optimizing the system operation, especially through PV exports control, and also via utilization of battery storage during higher consumption periods. Battery size plays an important role in achieving high SSR; however, as Figure 9 suggests, after a certain level of battery storage, the effects become marginal. Moreover, the autonomy ratio from the data also asserts that in order to achieve high self-sufficiency, emphasis must be given to improve system performance during the winter period. On a large scale, this could also benefit the utility network in handling evening peak demand.

A benchmark comparison to other developments with a similar technical setup would be important for ascertaining the usage patterns; however, the lack of consumption data from apartment buildings is still a limitation to expansion of this research domain. This study focused on aggregated electricity data from three apartment complexes, while effects of occupancy, dwelling size, floor area, and thermal characteristics were not explored. Therefore, future studies can further investigate the effects on load profiles by collecting more inputs pertaining to dwelling characteristics and conducting analyses of how the operation of configurations can be optimized and improve the self-sufficiency. The findings from WGV may favor other multi-residential dwellings with similar characteristics, albeit the suggestions provided in this study must be anticipated before design.

Author Contributions: Conceptualization, M.M.S. and J.D.; methodology, M.M.S.; software, M.M.S.; validation, M.M.S., G.M.M. and J.D.; formal analysis, M.M.S.; investigation, M.M.S.; resources, M.M.S.; data curation, M.M.S.; writing—original draft preparation, M.M.S.; writing—review and editing, G.M.M.; visualization, M.M.S.; supervision, G.M.M.; project administration, M.M.S. and G.M.M.; funding acquisition, G.M.M. All authors have read and agreed to the published version of the manuscript.

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Appendix A

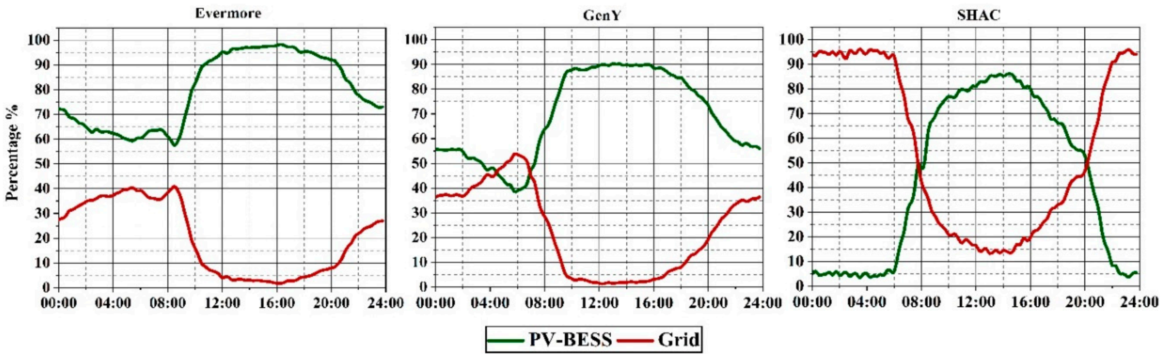

Figure A1. Averaged diurnal share of sources.

Figure A1 determines the diurnal share of both PV-BESS and grid based on data presented in Figure 7. Seemingly, the ratio of PV-BESS as compared to grid usage remained higher at Evermore and Gen Y from noon until 12:00 a.m. in the morning. At SHAC, the share of PV-BESS matches with the PV generation pattern, until significant grid proportion overcomes it from 08:00 p.m. till 06:00 a.m. in the morning before declining to a minimum of 15% at midday. In fact, all the plots in Figure A1 show the effects of PV-BESS from midday until 08:00 p.m. Hence, the redundant storage available to smooth the evening peak is of critical importance. In scenarios similar to SHAC, shifting storage to the later part of the day by utilizing the demand side management becomes imperative. Rather than keeping the battery functioning during peak generation time, the shifting of the storage in the evening will decrease grid demand during peak hours, thus avoiding high priced peak-hour electricity tariffs.

Appendix B

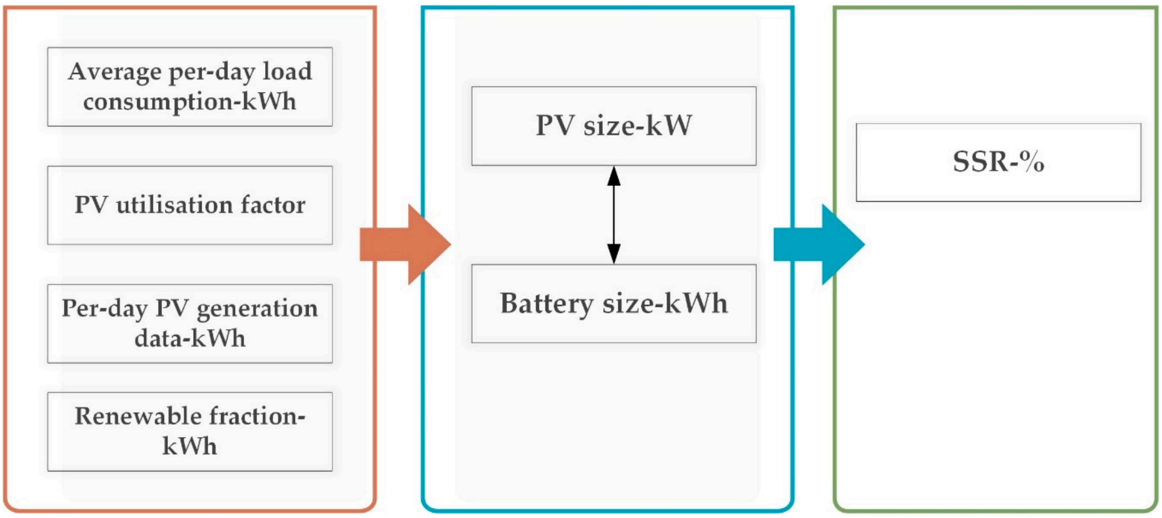

Figure A2. Estimation process of varying battery sizes on SSR.

References

1. Swanston, M. *Two Million Plus Solar Roofs: What's in It for the Consumers? Behind and Beyond the Meter*; Elsevier: Amsterdam, The Netherlands, 2020; pp. 381–406. [CrossRef]
2. Western-Power. Network Integration Guideline: Inverter Embedded Generation. 2019. Available online: https://westernpower.com.au/media/3403/network-integration-guideline-inverter-embedded-generation-20190802.pdf (accessed on 20 May 2020).
3. Syed, M.M.; Hansen, P.; Morrison, G.M. Performance of a shared solar and battery storage system in an Australian apartment building. *Energy Build.* **2020**, *225*, 110321. [CrossRef]
4. Imteaz, M.A.; Ahsan, A. Solar panels: Real efficiencies, potential productions and payback periods for major Australian cities. *Sustain. Energy Technol. Assess.* **2018**, *25*, 119–125. [CrossRef]
5. Rae, C.; Bradley, F. Energy autonomy in sustainable communities—A review of key issues. *Renew. Sustain. Energy Rev.* **2012**, *16*, 6497–6506. [CrossRef]
6. Luthander, R.; Widén, J.; Nilsson, D.; Palm, J. Photovoltaic self-consumption in buildings: A review. *Appl. Energy* **2015**, *142*, 80–94. [CrossRef]
7. Gudmunds, D.; Nyholm, E.; Taljegard, M.; Odenberger, M. Self-Consumption and Self-Sufficiency for Household Solar Producers When Introducing an Electric Vehicle. *SSRN Electron. J.* **2018**, *148*, 1200–1215. [CrossRef]
8. Quoilin, S.; Zucker, A. Techno-Economic Evaluation of Self-Consumption with Pv/Battery Systems under Different Regulation Schemes. In Proceedings of the 29th international conference on Efficiency, Cost, Optimisation, Simulation and Environmental Impact of Energy Systems, Portoroz, Slovenia, 19–23 June 2016. Available online: http://hdl.handle.net/2268/205134 (accessed on 5 June 2020).
9. Zhang, Y.; Lundblad, A.; Campana, P.E.; Yan, J. Employing Battery Storage to Increase Photovoltaic Self-sufficiency in a Residential Building of Sweden. *Energy Procedia* **2016**, *88*, 455–461. [CrossRef]
10. Sugiartha, N.; Sugina, I.M.; Widiantara, I.B.G.; Tri Putra, I.D.G.A.; Indra, I.B.P. Solar photovoltaic system with self-consumption in villa. *J. Phys. Conf. Ser.* **2020**, *1450*, 012105. [CrossRef]
11. Masson, G.; Briano, J.I.; Baez, M.J. Review and analysis of PV self-consumption policies. *IEA Photovolt. Power Syst. Program. (PVPS)* **2016**, *1*, 1–82. Available online: https://www.sunwindenergy.com/sites/default/files/iea-pvps_-_self-consumption_policies_-_2016_-_2_0.pdf (accessed on 5 June 2020).
12. Gstöhl, U.; Pfenninger, S. Energy self-sufficient households with photovoltaics and electric vehicles are feasible in temperate climate. *PLoS ONE* **2020**, *15*, e0227368. [CrossRef]
13. Kabir, E.; Kumar, P.; Kumar, S.; Adelodun, A.A.; Kim, K.-H. Solar energy: Potential and future prospects. Renewable and Sustainable. *Energy Rev.* **2018**, *82*, 894–900. [CrossRef]
14. Üçtuğ, F.G.; Azapagic, A. Environmental impacts of small-scale hybrid energy systems: Coupling solar photovoltaics and lithium-ion batteries. *Sci. Total Environ.* **2018**, *643*, 1579–1589. [CrossRef] [PubMed]
15. Australian-Government. Australia's 2030 Climate Change Target. 2015. Available online: https://publications.industry.gov.au/publications/climate-change/system/files/resources/c42/factsheet-australias-2030-climate-change-target.pdf (accessed on 1 July 2020).
16. Roberts, M.B.; Bruce, A.; MacGill, I. Collective Prosumerism: Accessing the Potential of Embedded Networks to Increase the Deployment of Distributed Generation on Australian Apartment Buildings. In Proceedings of the 2018 IEEE International Energy Conference (ENERGYCON), Limassol, Cyprus, 3–7 June 2018. [CrossRef]
17. ABS Telling storeys—Characteristics of apartment building heights. 8752.0—Building Activity Australia. 2018. Available online: https://www.abs.gov.au/ausstats/abs@.nsf/Lookup/8752.0Feature+Article1Dec%202018 (accessed on 25 June 2020).
18. Easthope, H.; Caitlin, B.; Vandana, M.; Australian National Strata Data 2018. UNSW. Available online: https://cityfutures.be.unsw.edu.au/research/projects/national-strata-data-analysis/ (accessed on 25 June 2020).
19. Shoory, M.; The Growth of Apartment Construction in Australia. RBA Bulletin, 19–26 June 2016. Available online: https://www.rba.gov.au/publications/bulletin/2016/jun/pdf/bu-0616-3.pdf (accessed on 25 June 2020).
20. Müller, S.C.; Welpe, I.M. Sharing electricity storage at the community level: An empirical analysis of potential business models and barriers. *Energy Policy* **2018**, *118*, 492–503. [CrossRef]
21. Green, J.; Newman, P. Citizen utilities: The emerging power paradigm. *Energy Policy* **2017**, *105*, 283–293. [CrossRef]

22. Roberts, M.B.; Huxham, G.; Bruce, A.; MacGill, I.; Strata, A.E. Using PV to help meet Common Property Energy Demand in Residential Apartment Buildings. In Proceedings of the Australian Summer Study on Energy Productivity, University of Technology, Sydney, Australia, 24–26 February 2016. [CrossRef]
23. Roberts, M.; Bruce, A.; MacGill, I. PV for Apartment Buildings: Which Side of the Meter? In Proceedings of the Asia Pacific Solar Research Conference. Melbourne, Australia, 5–7 December 2017. Available online: https://apo.org.au/node/234221 (accessed on 2 June 2020).
24. Castellazzi, L.; Bertoldi, P.; Economidou, M. *Overcoming the Split Incentive Barrier in the Building Sector*; Publications Office of the European Union: Luxembourg, 2017. Available online: https://ec.europa.eu/jrc/en/publication/eur-scientific-and-technical-research-reports/overcoming-split-incentive-barrier-building-sector (accessed on 27 June 2020).
25. Melvin, J. The split incentives energy efficiency problem: Evidence of underinvestment by landlords. *Energy Policy* **2018**, *115*, 342–352. Available online: http://dx.doi.org/10.1016/j.enpol.2017.11.069 (accessed on 1 July 2020). [CrossRef]
26. Fina, B.; Fleischhacker, A.; Auer, H.; Lettner, G. Economic Assessment and Business Models of Rooftop Photovoltaic Systems in Multiapartment Buildings: Case Studies for Austria and Germany. *J. Renew. Energy* **2018**, *2018*, 1–16. [CrossRef]
27. Hirsch, A.; Parag, Y.; Guerrero, J.M. Microgrids: A review of technologies, key drivers, and outstanding issues. *Renew. Sustain. Energy Rev.* **2018**, *90*, 402–411. [CrossRef]
28. Humphries, H.E.H. Evaluation of PV Systems in Gårdsten. In *Citeseer*; Doctoral Dissertation, University of Chalmers: Göteborg, Sweden, 2013; pp. 1–62. Available online: http://publications.lib.chalmers.se/records/fulltext/185610/185610.pdf (accessed on 29 June 2020).
29. Komendantova, N.; Manuel Schwarz, M.; Amann, W. Economic and regulatory feasibility of solar PV in the Austrian multi-apartment housing sector. *AIMS Energy* **2018**, *6*, 810–831. [CrossRef]
30. Sommerfeldt, N.; Muyingo, H. Lessons in Community Owned PV from Swedish Multi-Family Housing Cooperatives. In Proceedings of the 31st European Photovoltaic Solar Energy Conference and Exhibition, Hamburg, Germany, 14–18 September 2015; pp. 2745–2750. Available online: http://kth.diva-portal.org/smash/record.jsf?pid=diva2%3A1048957&dswid=8818 (accessed on 29 June 2020).
31. Sommerfeldt, N.; Madani, H. Solar PV for Swedish Prosumers—A Comprehensive Techno-Economic Analysis. In Proceedings of the EuroSun2016, International Solar Energy Society, Palma, Spain, 11–14 October 2016. Available online: http://dx.doi.org/10.18086/eurosun.2016.08.01 (accessed on 30 June 2020).
32. Roberts, M.B.; Haghdadi, N.; Bruce, A.; MacGill, I. Cluster-based characterisation of Australian apartment electricity demand and its implications for low-carbon cities. *Energy* **2019**, *180*, 242–257. [CrossRef]
33. Jung, W.; Jeong, J.; Kim, J.; Chang, D. Optimization of hybrid off-grid system consisting of renewables and Li-ion batteries. *J. Power Sources* **2020**, *451*, 227754. [CrossRef]
34. Council, S.E. *Australian Energy Storage Market Analysis*; Smart Energy Council: Canberra, Australia, 2018; pp. 1–40. Available online: https://www.smartenergy.org.au/sites/default/files/uploaded-content/field_f_content_file/australian_energy_storage_market_analysis_report_sep18_final.pdf (accessed on 30 June 2020).
35. Chen, B.; Xiong, R.; Li, H.; Sun, Q.; Yang, J. Pathways for sustainable energy transition. *J. Clean. Prod.* **2019**, *228*, 1564–1571. [CrossRef]
36. Abdel-Monem, M.; Hegazy, O.; Omar, N.; Trad, K.; Van den Bossche, P.; Van Mierlo, J. Lithium-ion batteries: Comprehensive technical analysis of second-life batteries for smart grid applications. In Proceedings of the 2017 19th European Conference on Power Electronics and Applications (EPE'17 ECCE Europe), Warsaw, Poland, 11–14 September 2017. Available online: http://dx.doi.org/10.23919/epe17ecceeurope.2017.8099385 (accessed on 2 July 2020).
37. Gjorgievski, V.; Cundeva, S. The Effects of Residential Battery Storage on Grid Impact Indicators. In Proceedings of the 2019 IEEE Milan PowerTech, Milan, Italy, 27 June 2019. [CrossRef]
38. Gupta, R.; Bruce-Konuah, A.; Howard, A. Achieving energy resilience through smart storage of solar electricity at dwelling and community level. *Energy Build.* **2019**, *195*, 1–15. [CrossRef]
39. Klingler, A.-L.; Teichtmann, L. Impacts of a forecast-based operation strategy for grid-connected PV storage systems on profitability and the energy system. *Sol. Energy* **2017**, *158*, 861–868. [CrossRef]
40. Agnew, S.; Dargusch, P. Consumer preferences for household-level battery energy storage. *Renew. Sustain. Energy Rev.* **2017**, *75*, 609–617. [CrossRef]

41. McKenna, E.; Darby, S.J. How Much Could Domestic Demand Response Technologies Reduce CO2 Emissions? European Council for an Energy-Efficiency Economy. ECEEE 2017 Summer Study—Consumption, Efficiency & Limits. 2017. Available online: https://www.eceee.org/library/conference_proceedings/eceee_Summer_Studies/2017/2-policy-governance-design-implementation-and-evaluation-challenges/how-much-could-domestic-demand-response-technologies-reduce-co2-emissions/ (accessed on 4 July 2020).
42. Dato, P.; Durmaz, T.; Pommeret, A. Smart grids and renewable electricity generation by households. *Energy Econ.* **2020**, *86*. [CrossRef]
43. Alimardani, M.; Narimani, M.; Al-Mutawaly, N. A New Approach to Improve Li-Ion Battery Lifetime in Home Energy Storage System with Photovoltaic Modules. In Proceedings of the 2018 IEEE Canadian Conference on Electrical & Computer Engineering (CCECE), Quebec City, QC, Cananda, 13–16 May 2018. [CrossRef]
44. De Oliveira e Silva, G.; Hendrick, P. Photovoltaic self-sufficiency of Belgian households using lithium-ion batteries, and its impact on the grid. *Appl. Energy* **2017**, *195*, 786–799. [CrossRef]
45. Barzegkar-Ntovom, G.A.; Chatzigeorgiou, N.G.; Nousdilis, A.I.; Vomva, S.A.; Kryonidis, G.C.; Kontis, E.O.; Georghiou, G.E.; Christoforidis, G.C.; Papagiannis, G. Assessing the viability of battery energy storage systems coupled with photovoltaics under a pure self-consumption scheme. *Renew. Energy* **2020**, *152*, 1302–1309. [CrossRef]
46. Marczinkowski, H.M.; Østergaard, P.A. Residential versus communal combination of photovoltaic and battery in smart energy systems. *Energy* **2018**, *152*, 466–475. [CrossRef]
47. Tomc, E.; Vassallo, A.M. The effect of individual and communal electricity generation, consumption and storage on urban Community Renewable Energy Networks (CREN): An Australian case study. *Int. J. Sustain. Energy Plan. Manag.* **2016**, *11*, 15–32. [CrossRef]
48. Fares, R.L.; Webber, M.E. The impacts of storing solar energy in the home to reduce reliance on the utility. *Nat. Energy* **2017**, *2*, 17001. [CrossRef]
49. Roberts, M.B.; Bruce, A.; MacGill, I. Impact of shared battery energy storage systems on photovoltaic self-consumption and electricity bills in apartment buildings. *Appl. Energy* **2019**, *245*, 78–95. [CrossRef]
50. Wu, C.; Kalathil, D.; Poolla, K.; Varaiya, P. Sharing electricity storage. In Proceedings of the 2016 IEEE 55th Conference on Decision and Control (CDC), Las Vegas, NV, USA, 12–16 December 2016. [CrossRef]
51. Rodrigues, D.L.; Ye, X.; Xia, X.; Zhu, B. Battery energy storage sizing optimisation for different ownership structures in a peer-to-peer energy sharing community. *Appl. Energy* **2020**, *262*, 114498. [CrossRef]
52. AlSkaif, T.; Luna, A.C.; Zapata, M.G.; Guerrero, J.M.; Bellalta, B. Reputation-based joint scheduling of households appliances and storage in a microgrid with a shared battery. *Energy Build.* **2017**, *138*, 228–239. [CrossRef]
53. Taşcıkaraoğlu, A. Economic and operational benefits of energy storage sharing for a neighborhood of prosumers in a dynamic pricing environment. *Sustain. Cities Soc.* **2018**, *38*, 219–229. [CrossRef]
54. Tomc, E.; Vassallo, A.M. Community electricity and storage central management for multi-dwelling developments: An analysis of operating options. *Int. J. Sustain. Energy Plan. Manag.* **2018**, *17*, 15–30. [CrossRef]
55. Rafsanjani, H.N.; Ahn, C. Linking Building Energy-Load Variations with Occupants' Energy-Use Behaviors in Commercial Buildings: Non-Intrusive Occupant Load Monitoring (NIOLM). *Procedia Eng.* **2016**, *145*, 532–539. [CrossRef]
56. Rouleau, J.; Gosselin, L.; Blanchet, P. Robustness of energy consumption and comfort in high-performance residential building with respect to occupant behavior. *Energy* **2019**, *188*, 115978. [CrossRef]
57. Delzendeh, E.; Wu, S.; Lee, A.; Zhou, Y. The impact of occupants' behaviours on building energy analysis: A research review. *Renew. Sustain. Energy Rev.* **2017**, *80*, 1061–1071. [CrossRef]
58. Hansen, P.; Morrison, G.M.; Zaman, A.; Liu, X. Smart technology needs smarter management: Disentangling the dynamics of digitalism in the governance of shared solar energy in Australia. *Energy Res. Soc. Sci.* **2020**, *60*, 101322. [CrossRef]
59. Landcorp. Initiative Gen Y Project. Innovation through Demonstration. 2017. Available online: https://www.landcorp.com.au/innovation/wgv/initiatives/Gen-Y-House/ (accessed on 7 July 2020).
60. Evermore-wgv. Solar Battery Innovation. News. 2018. Available online: http://www.evermorewgv.com.au/solar-powered-apartments-fremantle-wgv.html (accessed on 7 July 2020).

61. Access-housing. Solar to power Access Housing's White Gum Valley development. News. 2016. Available online: https://www.accesshousing.org.au/solar-to-power-access-housings-white-gum-valley-development/ (accessed on 7 July 2020).
62. Breadsell, J.K.; Byrne, J.J.; Morrison, G.M. Household Energy and Water Practices Change Post-Occupancy in an Australian Low-Carbon Development. *Sustainability* **2019**, *11*, 5559. [CrossRef]
63. Wiktorowicz, J.; Babaeff, T.; Breadsell, J.; Byrne, J.; Eggleston, J.; Newman, P. WGV: An Australian Urban Precinct Case Study to Demonstrate the 1.5 °C Agenda Including Multiple SDGs. *Urban Plan.* **2018**, *3*, 64–81. [CrossRef]
64. Reinders, A.; Verlinden, P.; van Sark, W.; Freundlich, A. (Eds.) *Photovoltaic Solar Energy*; John Wiley & Sons Ltd.: Hoboken, NJ, USA, 2016. [CrossRef]
65. Boeckl, B.; Kienberger, T. Sizing of PV storage systems for different household types. *Energy Storage* **2019**, *24*, 100763. [CrossRef]
66. Weniger, J.; Tjaden, T.; Quaschning, V. Sizing of Residential PV Battery Systems. *Energy Procedia* **2014**, *46*, 78–87. [CrossRef]
67. Atia, H.R.; Shakya, A.; Tandukar, P.; Tamrakar, U.; Hansen, T.M.; Tonkoski, R. Efficiency analysis of AC coupled and DC coupled microgrids considering load profile variations. In Proceedings of the 2016 IEEE International Conference on Electro Information Technology, Grand Forks, ND, USA, 19–21 May 2016. [CrossRef]
68. He, J.; Yang, Y.; Vinnikov, D. Energy Storage for 1500 V Photovoltaic Systems: A Comparative Reliability Analysis of DC- and AC-Coupling. *Energies* **2020**, *13*, 3355. [CrossRef]
69. Sandelic, M.; Sangwongwanich, A.; Blaabjerg, F. Reliability Evaluation of PV Systems with Integrated Battery Energy Storage Systems: DC-Coupled and AC-Coupled Configurations. *Electronics* **2019**, *8*, 1059. [CrossRef]
70. Afxentis, S.; Florides, M.; Anastasiou, C.; Efthymiou, V.; Georghiou, G.E.; Norgaard, P. Guidelines for the Design of Residential and Community Level Storage Systems Combined with Photovoltaics (PV). 2017. Available online: https://zenodo.org/record/2580980/files/7th%20solar%20integration%20workshop.pdf (accessed on 10 July 2020).
71. Rao, P.; Muller, M.R.; Gunn, G. Conducting a metering assessment to identify submetering needs at a manufacturing facility. *CIRP J. Manuf. Sci. Technol.* **2017**, *18*, 107–114. [CrossRef]
72. Clements, D. The Impact of Sub-Metering Requirements on Building Electrical Systems Design. Master's Thesis, Kansas State University, Manhattan, NY, USA, 2020. Available online: https://krex.k-state.edu/dspace/handle/2097/40365 (accessed on 20 July 2020).
73. Mavromatidis, G.; Orehounig, K.; Carmeliet, J. Designing electrically self-sufficient distributed energy systems under energy demand and solar radiation uncertainty. *Energy Procedia* **2017**, *122*, 1027–1032. [CrossRef]
74. Li, H.X.; Edwards, D.J.; Hosseini, M.R.; Costin, G.P. A review on renewable energy transition in Australia: An updated depiction. *J. Clean. Prod.* **2020**, *242*, 118475. [CrossRef]
75. Electricity feed-in tariff. 2020. Available online: https://www.energy.gov.au/rebates/electricity-feed-tariff-0 (accessed on 20 July 2020).
76. Long, C.; Wu, J.; Zhou, Y.; Jenkins, N. Peer-to-peer energy sharing through a two-stage aggregated battery control in a community Microgrid. *Appl. Energy* **2018**, *226*, 261–276. [CrossRef]
77. Nwaigwe, K.N.; Mutabilwa, P.; Dintwa, E. An overview of solar power (PV systems) integration into electricity grids. *Mater. Sci. Energy Technol.* **2019**, *2*, 629–633. [CrossRef]
78. Hiendro, A.; Yusuf, I.; Pontia Wigyarianto, F.T.; Hie Khwee, K.; Junaidi, J. Optimum Renewable Fraction for Grid-connected Photovoltaic in Office Building Energy Systems in Indonesia. *Int. J. Power Electron. Drive Syst. (IJPEDS)* **2018**, *9*, 1866–1874. [CrossRef]
79. Fulzele, J.B.; Daigawane, M.B.; Daigawane, P.M. Design of hybrid PV-wind stand-alone renewable energy system: Case study. *J. Inf. Optim. Sci.* **2017**, *39*, 345–355. [CrossRef]
80. Rahman, M.M.; Khan, M.M.-U.-H.; Ullah, M.A.; Zhang, X.; Kumar, A. A hybrid renewable energy system for a North American off-grid community. *Energy* **2016**, *97*, 151–160. [CrossRef]
81. Hou, Q.; Zhang, N.; Du, E.; Miao, M.; Peng, F.; Kang, C. Probabilistic duck curve in high PV penetration power system: Concept, modeling, and empirical analysis in China. *Appl. Energy* **2019**, *242*, 205–215. [CrossRef]
82. Kosowatz, J. Energy Storage Smooths the Duck Curve. *Mech. Eng.* **2018**, *140*, 30–35. [CrossRef]

83. Power, W. Maximum Demand Calculator. 2017. Available online: https://westernpower.com.au/industry/calculators-tools/maximum-demand-calculator/ (accessed on 1 August 2020).
84. Lokar, J.; Virtič, P. The potential for integration of hydrogen for complete energy self-sufficiency in residential buildings with photovoltaic and battery storage systems. *Int. J. Hydrogen Energy* **2020**. [CrossRef]
85. Ollas, P.; Persson, J.; Markusson, C.; Alfadel, U. Impact of Battery Sizing on Self-Consumption, Self-Sufficiency and Peak Power Demand for a Low Energy Single-Family House with PV Production in Sweden. In Proceedings of the 2018 IEEE 7th World Conference on Photovoltaic Energy Conversion (WCPEC) (A Joint Conference of 45th IEEE PVSC, 28th PVSEC & 34th EU PVSEC), Waikoloa Village, HI, USA, 10–15 June 2018. [CrossRef]
86. DiOrio, N.; Dobos, A.; Janzou, S. *Economic Analysis Case Studies of Battery Energy Storage with SAM*; National Renewable Energy Lab. (NREL): Golden, CO, USA, 2015. Available online: https://www.nrel.gov/docs/fy16osti/64987pdf (accessed on 9 September 2020).
87. Kaldellis, J.K.; Zafirakis, D. Optimum energy storage techniques for the improvement of renewable energy sources-based electricity generation economic efficiency. *Energy* **2007**, *32*, 2295–2305. [CrossRef]