School of Design and the Built Environment

Shared Solar Generation and Battery Storage Systems in Residential Microgrids

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Author's Declaration

I certify that, to the best of my knowledge and faith this thesis contains no material which has been accepted for the award of any other degree or diploma in any university neither previously published or written by any other individual except where due reference has been made in the document.

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Supporting documents have been attached in Appendix B.

I admit the support I have received for my research through the provision of Curtin International Postgraduate Research Scholarship.

The research presented in this thesis required no ethics approval.

Moiz Masood Syed

Date: 13/05/2021

Statement of contribution of others

I conceptualised and coordinated as well as undertook the writing, methodology and analysed data for the following publications:

- Syed, M., Hansen, P. & Morrison, G. M. 2020. Performance of a shared solar and battery storage system in an Australian apartment building. Energy and Buildings, 225, p.110321.

- Syed, M. M., Morrison, G. M. & Darbyshire, J. 2020b. Shared solar and battery storage configuration effectiveness for reducing the grid reliance of apartment complexes. Energies, 13, 4820.

- Syed, M. M., Morrison, G. M. & Darbyshire, J. 2020a. Energy allocation strategies for common property load connected to shared solar and battery storage systems in strata apartments. Energies, 13, 6137.

- Syed, M.M. & Morrison, G.M., 2021. A Rapid Review on Community Connected Microgrids. Sustainability, 13(12), p.6753.

Appendix A includes signed and approved statements from all co-authors confirming my contributions.

Moiz Masood Syed

Date: 13/05/2021

Abstract

The utilization of distributed renewable energy resources (DRES) as an alternative generation source can enable pragmatic benefits in terms of environment, cost, reliability and applicability. In recent times, soaring electricity prices, growing environmental concerns alongside abundance of solar potential and declining solar panel prices have led the rapid uptake of solar photovoltaic (PV) in Australia. This uptake is steadily growing since the last decade and more than 2.4 million households in Australia have installed rooftop solar PV systems. To overcome the shortcomings of load demand from DRES in the evening, battery storage systems are emerging as leading technological substitute. Moreover microgrid containing solar PV and battery storage systems in residential setup are becoming increasingly popular. Whilst these systems have been widely installed in stand-alone houses, there is insufficient research on microgrid for distribution of energy in multi-residential buildings and apartments. Due to the existing regulatory barriers and lack of technological governance models, the commissioning of this innovative technology has been slow.

This exegesis presents investigation on performance analysis, technical benefits and challenges on deployment of shared energy microgrid in an Australian apartment precinct at WGV. Performance analysis was conducted to examine load profiles of apartment units and impact of renewable installation was analysed in terms of grid reliance reduction. The shared configurations implemented in three different apartment complexes were studied to assess technical benefits and challenges. The attribution of this real time dataset from these apartment buildings presents a significant contribution to the research. In terms of reduction in grid reliance, the analysis shows that solar PV together with battery storage systems increase self-sufficiency. Moreover it has been observe that shared systems with centralised storage and pulse metering infrastructure provide technical benefits as compared to individual systems thus an encouragement for these systems to be implemented in multi-residential communities. This research presents performance results and identifies implemented configurations from a governance model to assist the uptake of PV and battery storage uptake in apartment buildings. Literature also recognises technical challenges and

regulatory problems occurred in successful implementation of such systems therefore offers a gateway for further research work in this domain.

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PhD is definitely a marathon not a sprint!

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I dedicate this work to every person who believes in believing that dreams can turn into reality.

List of publications included as part of the thesis

I. **Syed, M., Hansen, P. & Morrison, G. M. 2020. Performance of a shared solar and battery storage system in an Australian apartment building. Energy and Buildings, 225, p.110321.**

   Publication I is included in publications section from page 128 to 142. The paper discusses performance analysis of a shared solar PV and battery storage system in Gen Y apartment building. The contents of this publication are included in chapter 2-5.

II. **Syed, M. M., Morrison, G. M. & Darbyshire, J. 2020b. Shared solar and battery storage configuration effectiveness for reducing the grid reliance of apartment complexes. Energies, 13, 4820.**

   Publication II is included in publications section from page 144 to 166. The paper compares self-sufficiency and energy autonomy of three WGV apartment sites that implemented shared solar PV and battery storage configurations to reduce grid electricity reliance. The contents of this publication are included in chapter 3-5.

III. **Syed, M. M., Morrison, G. M. & Darbyshire, J. 2020a. Energy allocation strategies for common property load connected to shared solar and battery storage systems in strata apartments. Energies, 13, 6137.**

   Publication III is included in publications section from page 168 to 195. The publication analyses common areas electricity usage and energy allocation strategies for WGV apartments connected to shared solar and battery storage.

IV. **Syed, M.M. & Morrison, G.M., 2021. A Rapid Review on Community Connected Microgrids. Sustainability, 13(12), p.6753.**

   Publication IV is included in publications section from page 197 to 245. The paper presents a rapid review on configurations and methodologies used in community microgrids. The content of this publication has been included in chapter 2.

Table of Contents

List of Figures

List of Tables

Nomenclature

AC	Alternating Current
ADMD	After Diversity Maximum Demand
BEMS	Building Energy Management System
BESS	Battery Energy Storage Systems
BTM	Behind The Meter
CA	Consumption-Based Allocation
CCM	Community Connected Microgrids
CES	Community Energy System
CO2	Carbon Dioxide
CP	Common Property
Cpcalc	In SA, surplus energy left after supplying CP load
CPx	Individual apartment CP load demand
CSV	Comma Separated Values
CU	Control Unit
DC	Direct Current
DRES	Distributed Renewable Energy Systems
DSO	Distributed System Operator
ECP	CP consumption
ECP,CA	In CA, CP load usage divided between numbers of apartments
EG	Renewable Generation
EGA	Invariable Generation Capacity
ESS	Energy Storage Systems
EV	Electric Vehicles
GW	Gigawatt
HRES	Hybrid Renewable Energy Systems
IC	Instantaneous Consumption
ICES	Integrated Community Energy Systems
IEG	Inverter Embedded Generator
IMMG	Interconnected Multi-Microgrids
IoE	Internet Of Energy
LC	Inductance-Capacitance
LFP	Lithium-Iron Phosphate
Li-ion	Lithium-Ion
Li-ion	Lithium-Ion
MPPT	Maximum Power Point Tracker
NMI	National Measurement Institute
NPV	Net Present Value
PCC	Point Of Common Coupling
PLC	Programmable Logic Controller
PRISMA	Preferred Reporting Items For Systematic Reviews And Meta-Analyses

PV	Photovoltaic
RQ	Research Questions
S2BVS	Solar To Building, Vehicle And Storage
SA	Surplus Allocation
SEM	Shared Energy Microgrid
SES	Smart Energy System
SHAC	Sustainable Housing For Artists And Creatives
SOC	State Of Charge
SQL	Structured Query Language
SSR	Self-Sufficiency Ratio
surplus SA	Surplus
surplusx	Surplus available after usage of allocated energy portion
VS	Voltage Sensor
WGV	White Gum Valley

Chapter 1: Thesis Introduction

This chapter introduces the thesis by stating the problem definition (Section 1.1) and briefly discusses the gap in the existing research (Section 1.2). The research questions and corresponding objectives are presented in Section 1.3. The contribution of the study is summarised in Section 1.4 and the thesis structure is outlined in Section 1.5.

1.1 Problem Definition and Objective

The global energy sector is on the path of energy transition that is, transforming from coal-based power generation to using clean renewable sources of energy. As well as addressing environmental challenges, renewable energy solutions address pressing consumer concerns such as soaring electricity costs arising from use and ownership of energy utilisation. To mitigate carbon emissions and decrease electricity costs, energy policies will play a crucial role in increasing the share of renewable energy in Australia's power generation mix. Australia's renewable energy will be comprised mainly of solar photovoltaic (PV) systems, wind power and battery energy storage systems (BESS). This energy transition will require the integration of renewable sources and digital technology (e.g. information and communications technology).

To ensure a successful transition to renewable energy, the uptake of solar PV and battery storage is of great importance, as evident from global PV capacity reaching 591 GW in 2019 (Wilson, Al-Jassim et al. 2020). Similarly, battery storage capacity is increasing at an exponential rate, and is predicted to grow from 29 GWh in 2020 to 81 GWh in 2024 (Smart Energy Council 2018).

In Australia, the uptake of solar PV has been seen predominantly in the detached residential sector, while installed capacity was 11 GW in 2019 (Clean Energy Council 2019). Apartment buildings have seen significantly lower solar PV uptake and have less access to the techno-economic benefits of using these systems because of the existing technical complexities and regulatory barriers to installing these systems (Roberts, Bruce et al. 2015). However, the increase of apartment construction in cities around the globe means that deploying solar PV with BESS in multi-residential strata apartments could provide benefits such as less consumption from the grid, reduced carbon emissions and the ability to share energy between consumers in neighbourhoods.

Thus, this thesis investigates shared energy system designs with solar PV and battery storage for multi-residential apartment buildings.[1] The study reports extensive energy

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[1] The terms ['apartment units' and 'apartment buildings'] and ['battery storage' and 'BESS'] are used interchangeably used in this thesis.

performance results from the investigation of data from three apartment buildings, identifies system design limitations and provides suggestions for improvement in system efficiency and avenues for future research.

1.2 Research Gap

Unlike PV and BESS deployment in detached dwellings, such deployment in apartment buildings has received less attention in research and practice. The literature related to PV and BESS installation in detached dwellings focuses on techno-economic modelling and the benefits of these systems, as well as on analysis of household consumption (Sommerfeldt and Muyingo 2015, Roberts 2016, Castellazzi, Bertoldi et al. 2017, Sommerfeldt 2017, Komendantova, Manuel Schwarz et al. 2018, Roberts, Bruce et al. 2018). However, little research attention has been paid to the functionality of PV-BESS in apartment buildings.

The fundamental reason for the lack of attention to the use of PV-BESS in apartment buildings lies in the differences between the characteristics of apartment buildings and detached dwellings. This includes differences such as small apartment rooftop area, high common areas electricity usage, diverse load patterns, administrative structures and most importantly, the regulatory issues related to commissioning PV-BESS systems. Although the latest technological innovations such as microgrid with smart metering and embedded networks have been implemented in different business models to assess their techno-economic benefits (Roberts, Bruce et al. 2019), the application of these models are seldom utilised in apartment buildings. This is because of the complexities in regulations, which prevent consumers from adopting PV-BESS in their apartments. These issues represent a new challenge for research community, which has rarely discussed this problem.

This thesis addresses the shortcomings in literature by applying a practical shared energy microgrid (SEM) with a PV and battery storage system in three strata apartment buildings. It also fills the gap of the scarcity of data related to the performance of PV-BESS in Australian multiresidential apartments.

1.3 Thesis Framework

The principle aim of the exegesis has been divided into multiple objectives and further structured into different research questions, as provided below.

Objective 1: Identify existing impediments in uptake of PV and BESS in apartment buildings and present a technical solution through practical implementation.

RQ1. What are the fundamental challenges to PV and BESS deployment in strata apartment buildings?

RQ2. What are the configurations for implementing PV and BESS in apartment buildings and community loads?

Objective 2: Understand the techno-economic benefits for consumers and communities of PV and battery storage deployed under various configurations.

RQ3. What are the technical benefits of shared PV-BESS employed in apartment loads and how do technical configurations allow shared distribution for consumers?

RQ4. What are the outcomes of PV-BESS deployment in relation to meeting common property (CP) load demand?

RQ5. What improvements could be made in future research models to increase the efficiency of shared systems?

1.4 Contribution

This thesis presents the following significant contributions to the research gaps identified in Section 1.2 and addresses the research questions by:

- An extensive literature review of academic and non-academic studies to comprehend the barriers to PV and BESS deployment in apartments.
- Detailed description of shared microgrid design for apartments.
- Empirical analysis of a two-year 15-minute resolution dataset from three apartment complexes, with an emphasis on temporal load profiles, shared PV-BESS performance and its contribution to reducing grid reliance (the apartment data are examined individually and by aggregation)

- Identification of system limitations and provision of recommendations for implementing strategies to enhance shared microgrid effectiveness.

The work included in this thesis can be expanded to broader community projects with similar energy sharing configurations and building characteristics. Most of the research findings related to shared microgrid for apartments included in this study are already published in peer-reviewed journals. The information found in this thesis and its connection to the chapters and objectives are presented in Figure 1.1.

The methodology, results and findings of shared microgrid discussed in this thesis have also been published in public reports, private submissions for consumers, network operators whilst the outcomes have been presented at various workshops and presentations (CRCLCL 2019,ARENA 2018, Byrne 2019, Josh Byrne 2019, CUSP 2021). The comprehensive temporal data from apartment buildings included in this thesis fills the gap of the scant data relating to multiresidential buildings with distributed renewable energy sources (DRES).

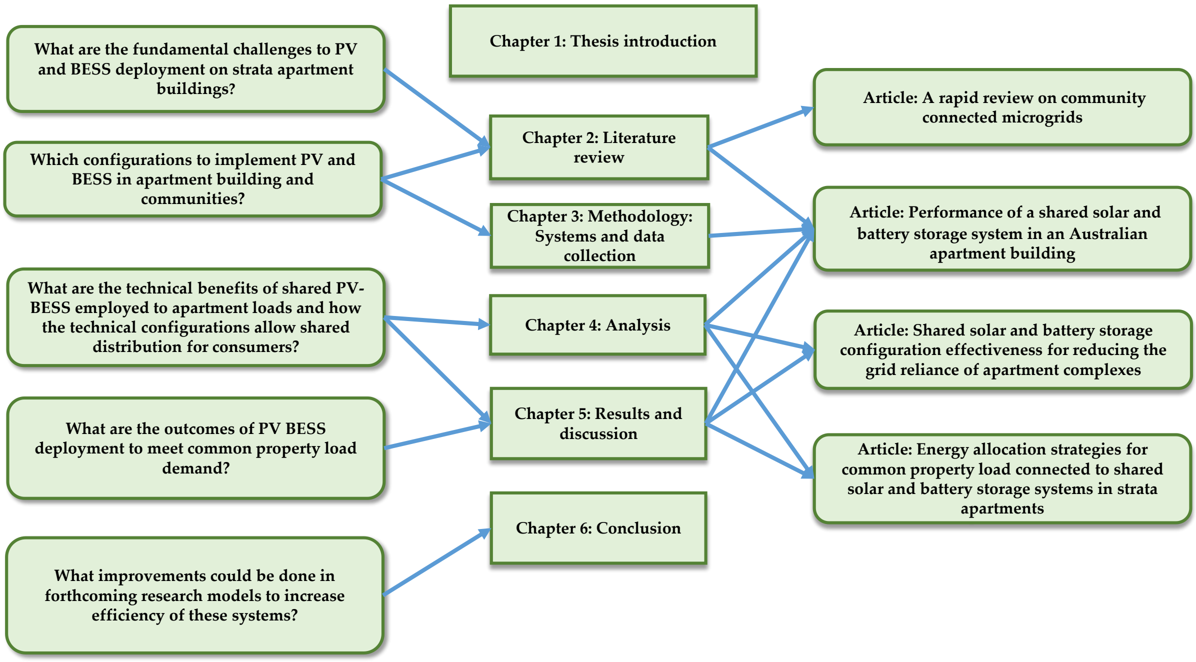

Figure 1.1 Thesis outline: mapping of research questions chapters and articles

1.5 Thesis Structure

The thesis comprises six chapters, which are briefly outlined below.

The present chapter has discussed the research objectives and presented the research questions and methods employed.

Chapter 2 presents the literature review, which reveals the research gap and the barriers to the uptake of solar PV and battery storage in apartments. The chapter also uses rapid review to examine microgrid configurations in communities and multiresidential buildings. The current state of Australian apartment buildings, the regulatory standards and strata law are also briefly discussed. The chapter then clarifies the research gap and objectives of the exegesis in the context of the extant literature.

Chapter 3 discusses the method for creating a shared system design and configuration and describes the data-collection process.

Chapter 4 presents the analysis used in the study to lay the foundation of the results based on the available data.

Chapter 5 examines the energy performance results of three apartment buildings connected to PV-BESS and the grid network. The interaction of these three elements is established through analysis of time-series data to assess the technical benefits, which are mainly grid reliance reduction, load patterns, energy sharing and carbon emissions reduction. Further, the load demand from the CP in three apartments is analysed along with the energy allocation strategies that aim to utilise excess generation and facilitate more utilisation of renewables for common areas. Moreover, the commissioning of PV and battery storage to meet CP load demand is analysed using temporal data from the three sites. The chapter also investigates the technoeconomic benefits for occupants of utilising excess energy through energy allocation strategies.

Chapter 6 concludes the thesis by summarising the barriers of PV-BESS deployment in apartments, review of academic literature and energy performance results. The chapter also makes recommendations for improving the efficiency of shared systems and provides suggestions for future research.

Chapter 2: Research and Literature Review

This chapter reviews the literature related to the research questions on the deployment of DRES in multiresidential buildings and communities. The chapter answers the research questions through narrative review (embodied in published articles of thesis) and rapid review paper (Syed and Morrison, 2021).

2.1 Introduction

This chapter is organised into two main sections based on the following two fundamental research questions.

RQ1. What are the fundamental challenges to PV and BESS deployment in strata apartment buildings?

Although the uptake of PV in detached dwellings is common, the literature provides less evidence about the use of renewable systems, particularly PV with battery storage, in apartments and multi-residential buildings. Moreover, published energy data related to apartments is scarce and there is no information about the characteristics of apartment buildings in relation to the use of shared systems. Therefore, it is imperative to understand the challenges of and barriers to deploying such systems in apartment buildings through reviewing the existing literature.

RQ2. What are the configurations for implementing PV and BESS in apartment buildings and community loads?

PV and storage systems can be deployed in several ways to meet the electricity demands of a building; however, in a multi-residential setup and community microgrids, the system shape and requirements vary because of several factors such as building characteristics, aggregated load demand, energy trading, costs and budget, and environmental goals. The review conducted by this thesis of the available literature on community energy and multiresidential dwellings will assist in identifying the types of technical configurations for microgrids that are implemented to achieve the desired electricity infrastructure for such buildings.

2.2 Role of Solar PV and Battery Storage in Abating Grid Reliance

Solar PV generation is one of the carbon free clean energy sources and more efficient and sustainable energy solutions that can be applied in residential and commercial contexts (Khalilpour and Vassallo 2016). Solar PV technology harnesses free abundant sunlight and does not rely on other natural sources such as water or harmful gases and fuels to operate. PV systems from residential houses to large PV farms can reduce the carbon footprint of energy use and contribute directly to renewable energy transition. Moreover, solar generated energy can help reduce reliance on fossil-fuel-based electricity and potentially reduce electricity prices in the future.

The emergence of technology allowing low-cost PV and battery storage offers the potential for rapid transition in electricity infrastructure. In addition, over the past decade, the global subsidisation of PV, net-metering policies, flexible feed-in tariffs, and the significant reductions in PV panel costs have substantially increased PV capacity for residential electricity use.

The principal advantage of distributed PV over other centralised sources e.g. fossil fuel based generation, is its easy on-site deployment at minimum distance from residence or substation. Despite high levelised cost of energy, the policies favouring renewable energy use and installation convenience have meant that consumers globally prefer rooftop installations in their premises.

Given that PV and wind technology are variable renewable sources and represent the largest portion of the global renewable energy mix (Gielen, Boshell et al. 2019), overcoming their inherent intermittency and replacing them with smooth and secure energy supply becomes a challenge. Thus, it is important to consider the use of multiple generation sources with storage for stabilising energy fluctuations and that the use of PV in hybrid topologies can have a positive effect on electricity grids.

2.2.1 Battery storage

Battery energy storage plays a pivotal role in powering load in peak hours, particularly because of high electricity tariffs and the demand for energy use during periods of low PV generation (Jung, Jeong et al. 2020). High self-consumption can be achieved through batteries, which are charged during the daytime and place less stress on the grid overnight. Installing battery storage alongside PV reduces high grid imports (Agnew and Dargusch 2017; Klingler and Teichtmann 2017; Gjorgievski and Cundeva 2019; Gupta, Bruce-Konuah et al. 2019) and enables consumers to shift their high load demand to low tariff periods through demand-side management techniques (McKenna and Darby 2017; Dato, Durmaz et al. 2020). In 2020, these features resulted in the rapid growth of global battery storage capacity to 29 GWh, and this is expected to increase by 81 GWh in 2024 (Smart Energy Council 2018).

From the community perspective, aggregated load demand produces minimum load spikes compared with single detached houses. The aggregation not only mitigates the battery discharge rate but also reduces the capacity of battery storage (Olgyay, Coan et al. 2020).

Regardless of high manufacturing costs and market prices, it is expected that the increased adoption of batteries on a residential and commercial scale will be central to achieving energy transition (Khalilpour and Vassallo 2016; Chen, Xiong et al. 2019). As a substitute for high priced conventional lithium batteries, second-life electric vehicle (EV) batteries can also be a viable alternative to utilise in microgrids. Even at the time of decommissioning, second-life batteries retain 80% of rated capacity, which is still practical for use in residential applications to meet load demand (Abdel-Monem, Hegazy et al. 2017).

Among the plethora of technologies for batteries, lithium-ion (Li-ion) has proved to be most adaptable and effective in residential microgrid applications owing to high specific energy, deep-cycle operation, large power density and maximum number of charge/discharge cycles (Alimardani, Narimani et al. 2018; Smart Energy Council 2018). Of the Li-ion types, lithium iron phosphate (LFP) is considered the safest (Abdel-Monem, Hegazy et al. 2017) and offers fast charging, grid stability and a longer life cycle.

Among other battery technologies, thermal storage provides 30–60% efficiency, improved energy density (80–250 Wh/kg), less consumption and decreased carbon emissions. Thermochemical storage yields high energy density with reduced loss; however, these systems incur high costs when thermochemical materials are used for buildings. Moreover, they have unsuitable temperature characteristics and provide unstable discharge power (Koirala, Koliou et al. 2016; Hannan, Faisal et al. 2018; Fontenot and Dong 2019).

Hydrogen storage technology is another promising emerging field in long-term energy storage owing to high power ratings and large energy density (33 kWh/kg) (Parra, Swierczynski et al. 2017). This setup converts excess PV electricity through electrolysis into hydrogen and oxygen, which is used to charge fuel cells. However, the great costs of the equipment including the electrolyser are a major drawback of this technology (Neves, Silva et al. 2014; Parra, Swierczynski et al. 2017; Fontenot and Dong 2019).

Despite their substandard efficiency, alternative energy storage sources (e.g. pumped hydro storage and compressed air energy) have high storage capacities and lengthy lifetime

(Planas, Andreu et al. 2015; Koirala, Koliou et al. 2016; Fontenot and Dong 2019). Superconducting magnetic energy storage systems are highly efficient, but are still in the experimentation phase (Planas, Andreu et al. 2015).

2.3 RQ1: What Are the Fundamental Challenges to PV and BESS Deployment in Strata Apartment Buildings?

Over the past ten years, more than two million dwellings in Australia have adopted rooftop solar PV setups, thereby increasing installation capacity to 99%, with a combined capacity exceeding 11 GW (CEC 2019). Nationwide, Western Australia is estimated to undergo the highest consumer solar PV installation rate in the residential sector, which could reach 4.8 GW by 2025 (Graham, Wang et al. 2018). In addition, grid-sourced electricity has also been observed to decrease through rooftop solar PV expansion (Saddler 2013), and has driven towards less energy intensive industries and more energy-efficiency programmes (Saddler 2013). Decentralised PV and battery storage systems are technoeconomically beneficial in many applications, mainly because of grid electricity reduction, peer-to-peer energy trading, demand response and reactive power flow. Additionally, the positive effects of these systems on the environment by reducing carbon footprints are significant (Easthope, Caitlin et al. 2018).

In the past decade, the construction of new apartment buildings has progressively increased whilst in the period 2017–2018, apartment buildings accounted for approximately 30.4% of total housing construction (ABS 2018). In 2015, with the increasing numbers of construction approvals (Easthope, Caitlin et al. 2018), apartments construction surpassed detached dwellings, showing a developing trend in multi-residential housing. The secondary drivers of the increased demand for apartment dwellings are the growing employment opportunities which compelled employees to move into apartments. Another factor was surge in Australia’s population (Shoory 2016).

Although large-scale solar PV installations have reached the freehold residential energy market, shared ownership challenges, lack of a regulatory framework and fewer cost benefits have prevented PV and BESS uptake in strata apartments (Green and Newman 2017; Roberts, Bruce et al. 2018; Syed, Hansen et al. 2020). Despite the established technical guidelines for grid-connected renewable systems (Western-Power 2019), PV and BESS configurations for apartment buildings have not been reported (Green and Newman 2018; Roberts 2016; Müller and Welpe 2018). A lack of renewable system adoption in apartment buildings creates an energy justice issue, depriving a significant portion of the Australian population of the incentives and benefits related to using solar PV energy, which is highly significant in a country with the highest electricity prices in the world (Müller and Welpe 2018).

The primary reason behind the lower uptake of DRES in Australian apartment buildings is the lack of governance models that facilitate the effective distribution of costs, risks and benefits through solar PV installations between developers, household owners and utility networks (Green and Newman 2018). The existing models need transformation to initially address the split incentive issue, which emerges when the renter obtains the benefit of reduced electricity bills, while the owner, who actually invests in the renewable energy system, may not receive any benefits. This leads to an underinvestment in energy-efficiency programmes (Melvin 2018). In addition, incumbents' support of centralised fossil-fuel-based generators is a known barrier to PV deployment (Prehoda, Pearce et al. 2019).

From an authorisation perspective, commissioning of DRES in certain land areas involves approvals from local councils and at times, restrictions may apply as a result of shading from newly built constructions (Roberts, Bruce et al. 2019a). To earn revenue from solar trading and exports, strata management or owners corporations (OC), which facilitate energy trading processes need to be certified as retailers. This certification process implies a chain of operational and cost factors that may hinder the uptake of DRES, particularly in apartment complexes (Roberts, Bruce et al. 2019a).

Actors participating in the energy market have heterogeneous interests. For example, consumers anticipate cheap efficient energy, energy distributors obtain advantage from the management of local generation and energy-efficient operations, energy aggregators desire business models that promise value to be delivered and to magnify flexibility in capacity markets. Similarly, energy regulators, including distributed service operators (DSO), transmission system operators, policymakers and governments, aim to maintain a low-cost balance between supply and consumer demand (Koirala, Koliou et al. 2016).

From a technical perspective, the control of energy between multiple microgrids and DSOs becomes complicated beyond the point of common coupling (PCC) because of the interaction of microgrids, and active/reactive power flows between the grid, DRES and loads (Zou, Mao et al. 2019). Power intermittency arising from weather conditions can be detrimental to the electricity network because of incompetency in system monitoring, diagnosis and maintenance (Hannan, Faisal et al. 2018). Moreover, integration of DRES in the main grid results in resonances and voltage fluctuations (Hannan, Faisal et al. 2018; Rosado and Khadem 2018).

In addition, soaring grid interconnection costs, protection standards, feed-in tariffs and islanding issues impede the uptake of community microgrids (Planas, Andreu et al. 2015; Koirala, Koliou et al. 2016; Roberts, Bruce et al. 2019a). Moreover, inadequate public and private places to install DRES also present challenges for community microgrids. Structural barriers such as roof space limitation in proportion to the number of inhabitants and conflicts of interest from multiple households in relation to solar PV installation mean that the solar PV integration in apartment dwellings is a great challenge.

However, most of the literature in this domain have focused on microgrid configurations and performance assessment for detached dwellings and connected communities (Hirsch, Parag et al. 2018). Few studies have focused on PV installation in apartment buildings. Studies that have focused on PV installation in apartment buildings have conducted a technical performance assessment (Humphries 2013); technoeconomic review of the microgrid (Roberts, Bruce et al. 2018; Roberts 2016; Castellazzi, Bertoldi et al. 2017; Komendantova, Manuel Schwarz et al. 2018; Sommerfeldt and Muyingo 2015; Sommerfeldt 2017); analysis of apartment load profiles (Roberts, Bruce et al. 2017; Roberts, Haghdadi et al. 2019a); and technoeconomic assessment to investigate the effect of PV-BESS in apartments using time-series data (Jung, Jeong et al. 2020).

Around the globe, only few multiresidential apartments exist with shared solar storage, and a thorough search of the relevant literature yielded only few instances of empirical analyses on implemented shared systems (Bruce et al. 2019c). Moreover, while 9% of the Australian population lives in apartments, only few of these buildings have adopted PV systems (Easthope, Caitlin et al. 2018).

Given that detached residential dwellings are mitigating carbon emissions through adoption of PV (Melvin 2018), apartment buildings which have large energy consumption (Syed, Morrison et al. 2020a) could also play a key role in contributing towards overall carbon emission reduction and shared PV system installations in apartments might be helpful in achieving carbon reduction of 441 Mt CO_2e by 2030 (Australian Government 2015; Kabir, Kumar et al. 2018; CEC 2019).

2.4 RQ2. What Are the Configurations for Implementing PV and BESS in Apartments and Community Loads?

To address RQ2 and complete the second part of the literature review, a rapid review was conducted. The knowledge from the rapid review presented in this section was taken from (Syed and Morrison, 2021).

Rapid reviews vary slightly from traditional literature reviews because they are concluded within shorter period (4–5 weeks), whereas systematic literature reviews usually take one to two years to complete (Eon, Breadsell et al. 2020; Ganann, Ciliska et al. 2010). The rapid reviews reduce risk of bias attributable to the fact these articles review the already reviewed articles (Eon, Breadsell et al. 2020). Since it's a review of review articles, a wide range of literature can be examined using rapid review without individual studies being reviewed. Similarly a comprehensive summary with shorter conclusions are provided. Rapid reviews are often conducted in the field of medical science; however, the literature search lack evidence of rapid reviews in renewable energy sector.

Using rapid review and meticulous survey of the literature related to RQ2 (i.e. the configurations for implementing PV and BESS in apartments and community loads) and the microgrids of multiresidential buildings and communities, it was observed that that PV and BESS inside microgrids could be implemented in various ways in multi-residential buildings, communities and apartments. (Syed and Morrison, 2021) generally refers to such a system as 'community connected microgrids' (CCM). Research was gathered on CCM configurations and their characteristics and advantages and disadvantages. The control methodologies and operationalisation barriers relating to CCM were also examined.

The rapid review approach follows these sequential steps:

1. develop research question
2. apply search criteria and filtering method
3. implement screening, eligibility criteria and extraction
4. perform quality assessment of selected studies.

The following focus questions were prepared for the review from (Syed and Morrison, 2021):

- Which type of configuration(s) are installed in community microgrids and multi-residential buildings?
- What are characteristics, benefits and technical challenges in implementing CCM?
- Which control and optimisation methods are used in CCM?
- What are the main barriers to the implementation of CCM?

For the search criteria, the range of year selection was from 2010 to 2020 and four multidisciplinary databases were chosen: Scopus, Web of Science, IEEE and ProQuest. An independent search was also performed in Google Scholar to identify grey literature in the form of reports, whitepapers and other articles that would not be detected using the four databases.

The general search string applied in the four databases consisted of the following search terms: ‘solar’ OR ‘solar PV’ OR ‘PV’ OR ‘solar*’ OR ‘photovoltaic*’ OR ‘microgrid’ OR ‘microgrid*’ OR ‘distributed*’ OR ‘integrated’ AND batter* OR ‘battery’ OR ‘storage’ OR ‘energy storage’ OR ‘battery storage’ AND ‘building*’ OR ‘multi-residential’ OR ‘apartment*’ OR ‘community’ OR ‘communit*’ OR ‘dwelling*’ OR ‘storey’ OR ‘multi-family’ OR ‘condos’ OR ‘suite*’ OR ‘villa*’ OR ‘multi-unit’ AND ‘systematic review’ OR ‘systematic literature review’ OR ‘review’ OR ‘meta-analysis’ OR ‘meta-analysis’

Of 327 recognised searches, 13 articles were considered relevant for rapid review after applying step 2 and 3. Figure 2.1 presents an overview of the article screening processes utilising the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) chart. The publications generally contained detailed information on various microgrid configurations implemented in communities, their strengths and shortcomings, their technical and regulatory challenges, and the optimisation and control methodologies of CCM. Quality evaluation of the selected articles was also conducted in following (Syed and Morrison, 2021). A Measurement Tool to Assess Systematic Reviews version 2 (Shea, Reeves et al. 2017) through 16 targeted questions.

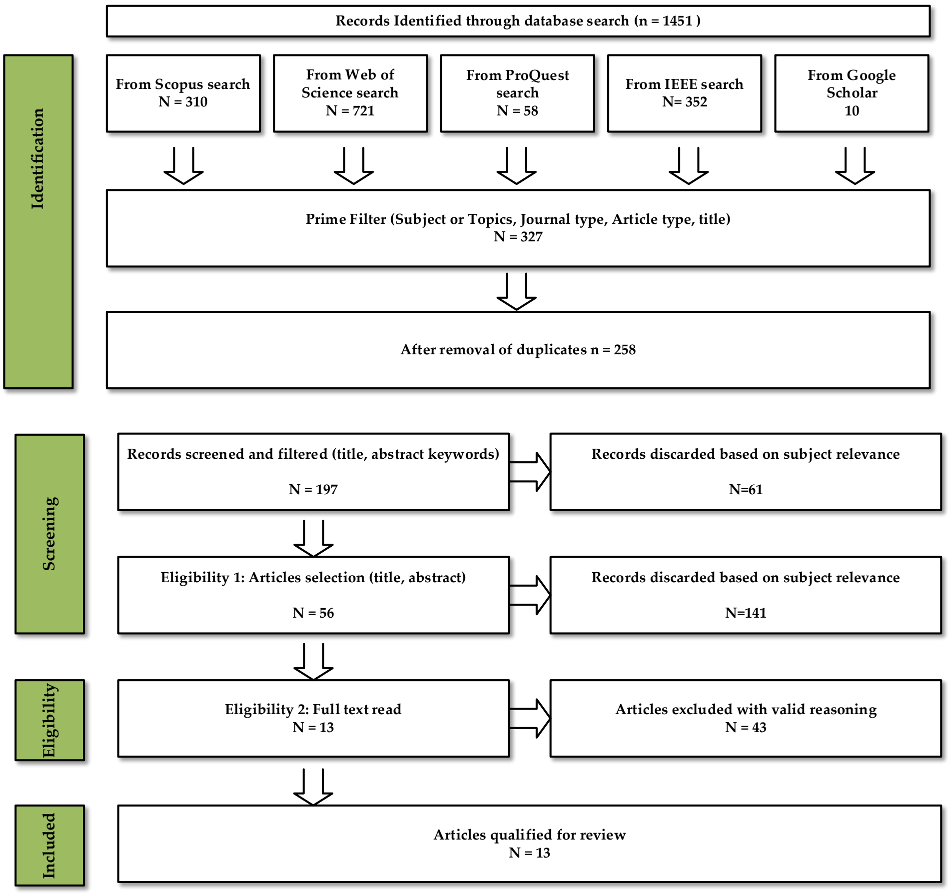

Figure 2.1 Selection of articles using PRISMA chart, adapted from (Syed and Morrison, 2021)

The rapid review consisted of articles that were published between 2015 and 2020. In total, 1700 research articles were reviewed. The articles were from different research contexts around the world: from Australia, as well as from countries in Asia, Africa, Europe and North America. Table 2.1 presents the study characteristics of the articles reviewed.

Several articles examined the microgrid configurations, control topologies, energy management, and modelling challenges (Planas, Andreu et al. 2015; Burmester, Rayudu et al. 2017; Fontenot and Dong 2019; Zou, Mao et al. 2019). The remainder of the articles explored DRES for communities.

Building energy management system (BEMS) technologies based on the internet of energy (IoE) were reviewed by Hannan, Faisal et al. (2018) to discuss DRES, battery storage and network communication for modifying building energy management.

Parra, Swierczynski et al. (2017) reviewed community energy storage (CES), focusing on end-user applications, techno-economic assessment and the socio-environmental aspects of CES. An overview of CES was also presented from the policy, utility network and consumer perspective. Huang, Zhang et al. (2020) discussed solar mobility models in detail and explained different topologies of solar to buildings, vehicles and storage (S2BVS). Koirala, Koliou et al. (2016) introduced a hypothesis of integrated community energy systems (ICES) based on practical models and discussed the challenges of ICES from the socioeconomic, technical, environmental and regulatory perspective. Hybrid renewable energy systems (HRES) were investigated by Neves, Silva et al. (2014), who discussed the design and technological configuration of HRES for micro-communities, and examined load demand and the intricacies of system commissioning. Rosado and Khadem (2018) explained the principle of the community grid, providing knowledge about grid and DRES in the community, as well as discussing DRES participation in energy trading. Rosado and Khadem (2018) also discussed technical problems relating to the community grid and solutions for creating a sustainable network.

Similarly, Ceglia, Esposito et al. (2020) discussed smart energy communities and reviewed prospective applications of smart energy systems (SES) in smart communities. Roberts, Bruce et al. (2019a) examined PV installations on apartments in the Australian context and investigated barriers and opportunities relating to uptake of PV in apartments. Fontenot and Dong (2019) presented an overview of microgrids, their components, control optimisation, and significance to both the grid network and building owners, as well as discussing the technical challenges relating to microgrids. The study of Fontenot and Dong (2019) also provided an overview of several data-forecasting approaches for microgrid controls. Finally, Olgyay, Coan et al. (2020) provided a detailed report on connected communities projects and examined various factors related to such communities. In summary, all studies in the review investigated CCM, noted the gaps in understanding and provided suggestions for social and techno-economic improvement of CCM in future research.

Table 2.1 Summary of key findings from reviewed articles

Author	Title	Study Scope	Key Findings	Recommendations
(Burmester, Rayudu et al. 2017)	A review of nanogrid topologies and technologies	Nanogrids, their control topologies and interconnected networks to facilitate demand-side management	• Nanogrids have smaller capacity than microgrids however multiple nanogrids can be connected via gateways to form a microgrid. • DC nanogrids are more efficient than AC because of fewer power conversion stages and because most electronic components and distributed renewable resources are DC. • Facility of energy sharing between multiple nanogrids and consumers.	• There is a need for demonstration projects for nanogrids to seek benefits for consumers. • Further research on nanogrid networks is required to offer retailers understanding of national demand-side management strategies.
(Ceglia, Esposito et al. 2020)	From smart energy community to smart energy municipalities: Literature review, agendas and pathways	Review of community level smart energy community and their potential applications in smart energy precincts	• Social acceptability is key issue to address the smart energy community modelling strategy. Most often territorial resources for the energy production, often not shared by population. • Lack of legislation for energy may cause customer dissatisfaction.	• Assessment of the legislative context of energy communities and leveraging experimental proposals of energy communities is required.
(Fontenot and Dong 2019)	Modeling and control of building-integrated microgrids for optimal energy management—A review	Overview of microgrids, their components and their significance to utility providers and building owners; examines modelling challenges and reviews several forecasting methods for controlling the microgrid	• Distributed renewable resources generation and occupancy behaviour are unpredictable thus optimal scheduling of resources and operation is complex. • Inclusion of occupancy models, development of agent-based modelling and integration of building-to-grid systems.	• As design models of microgrids become sophisticated, flexible and reliable, optimisation strategies will become necessary and definite.
(Hannan, Faisal et al. 2018)	A review of internet of energy based building energy management systems: Issues and recommendations	Internet of energy-based building energy management system for building energy utilisation enhancement; Internet of energy based building technologies discussed: energy routers, storage systems, distributed technologies and plug-and-play interfaces	• Most challenging issues in building energy management are improving energy efficiency by reducing losses, load consumption and climate change effects. • Internet of energy -based building energy management technologies can leverage substantial energy savings and greenhouse gas emissions reduction.	• Future improvements for building energy utilisation in Internet of energy -based building energy management require scalable, stable and localised systems. • An efficient building data management system entails an advanced platform for security analysis and collecting, managing and processing large amounts of data. • By integrating distributed resources, cost-effective and energy-efficient Internet of energy systems have significant potential for future development.

Author	Title	Study Scope	Key Findings	Recommendations
(Huang, Zhang et al. 2020)	A technical review of modeling techniques for urban solar mobility: Solar to buildings, vehicles, and storage (S2BVS)	Solar mobility concept of solar to buildings, vehicles and storage; discusses modelling of each subsystem in the solar model and related advanced controls	• Solar mobility models can completely utilise the potential of solar PV systems, energy storage, electrical vehicle, and energy-sharing microgrids and design of advanced controls to obtain an optimised performance at the microgrid level i.e. increased self-consumption and energy autonomy.	• The battery charging and discharging properties of an electrical vehicle should be explored in future work to achieve more advanced control techniques and design. • In future, research is needed to design advanced DC systems for large-scale systems and development of building cluster plans.
(Koirala, Koliou et al. 2016)	Energetic communities for community energy: A review of key issues and trends shaping integrated community energy systems	Integrated community energy systems (ICES), which restructure local energy systems to integrate distributed resources and engage local communities; recent ICES energy trends and review of technical, socioeconomic, environmental and organisational issues	• ICES provide energy-related services, network services and operating reserves using the interconnection and can leverage superior community engagement with self-dependence and energy autonomy and security. • The concept of ICES will directly affect different actors as system-wise exchange and interaction occur. Thus, policies need to be formulated according to the interests of all parties for fair distribution of costs and incentives.	• One of the important areas for ICES is to overcome the challenges of the practices and structures related to centralised energy systems. Well-planned business models and institutional design are needed as a regulatory framework before integrating ICES.
(Neves, Silva et al. 2014)	Design and implementation of hybrid renewable energy systems on micro-communities: A review on case studies	Design of hybrid renewable energy systems in remote communities, particularly in isolated islands; explanation of system configuration, load demand and its dynamics, and the complications in installation	• In islands, the standard configuration of hybrid systems is wind/PV/and PV/diesel power generator coupled with batteries in remote villages. • Designing the storage technologies is a great challenge in islands in relation to economics and efficiency.	• Accurate statistics are required for estimation of the demand and security of the supply. • Design methods and tools are needed for optimising the systems, and should be considered in relation to real investment projections, estimation of resources and structure of economic islands. • It will be complex to achieve 50% renewable autonomy unless storage technology is established for hybrid renewable energy systems.
(Olgyay, Coan et al. 2020)	*Connected Communities: A Multi-building Energy Management Approach*	Investigates various factors influencing the development and operation of connected communities and assesses their potential value; detailed description of community projects	• Connected communities can provide a flexible, efficient and reliable grid to achieve the objective of greenhouse gas emissions reduction. • The development of connected communities can provide multiple values streams in energy bill reduction, revenue streams and cost savings while achieving reliability and reducing capacity requirements.	• Central control systems such as energy storage system and PV in relation to building operations are an important component of connected communities. • Projects connecting more diverse building types and offering greater load diversity with a dynamic technologies (distributed energy resources) can leverage multiple value streams.
(Parra, Swierczynski et al. 2017)	An interdisciplinary review of energy storage for communities: Challenges and perspectives	Community energy system (CES) technologies, configurations and applications, as well as role of stakeholders in deployment of CES	• The lessons learned from CES implementation in some countries suggest that citizen engagement based on incentives, local community rights over grid ownership, better energy generation management and a stable policy are imperative.	• The existing CES models that are using battery are costly and other services are required with the CES can be energy efficient. • Future research can explore policies of citizen engagement with access to community rights over a local grid, energy generation management and

Author	Title	Study Scope	Key Findings	Recommendations
			- CES can play a significant role in future energy dynamics if different actors, authorities and governments are involved. Uptake of CES may also be increased through providing economic incentives and relevant regulatory frameworks established by policymakers.	exploring efficient technologies to incorporate with CES to make it cost effective.
(Planas, Andreu et al. 2015)	AC and DC technology in microgrids: A review	AC and DC microgrids, analysis of parameters for AC and DC microgrids; reviews characteristics for designing and configuring microgrids.	- AC microgrids have the advantages of an established technology and provide better protection at the point of common coupling, and are more economical than DC protections. - The cost of the metering systems and controllers are lower for DC microgrids but provide good power quality at long distance transmission.	- The existing microgrids are based on a centralised control that fits well for the small microgrids. Given that the latest microgrids are becoming more complex, the performance of the centralised approach will become unstable. Therefore, research needs to explore a decentralised approach for the microgrid. Moreover, existing protection schemes for microgrids are designed for a customised solution and further research is needed to design universal protection schemes for microgrids.
(Roberts, Bruce et al. 2019a)	Opportunities and barriers for photovoltaics on multi-unit residential buildings: Reviewing the Australian experience	Review of technical, economic and regulatory factors relating to PV deployment in Australian apartments	- PV deployment in apartments needs substantial cooperation between consumers and other actors to share PV-related cost and incentives either in behind the meter systems or in the embedded network. - Despite limitations regarding regulation, governance and finance, viable implementation models exist; however, a shared learning platform can assist consumers in identifying suitable opportunities.	- Although communities have consensus in mutual decisions, energy regulations should also be created with community cooperation. - The scarcity of apartments' energy data is a major barrier to comprehending the value of PV deployment, and availability is imperative for decision making from a regulatory perspective.
(Rosado and Khadem 2018)	Development of community grid: Review of technical issues and challenges	Discussion of technical issues related to the community grid and solutions for making the community grid highly sustainable	- Improved technical systems aid in achieving an energy supply from distributed energy resources for a cost-effective process. - A community grid neutralises disturbance from the distribution network, therefore communication between the community grid controller and distribution network operator is vital.	- Protection systems with a better communication interface will improve the system by introducing new functionalities such as coordination, grid parameter detection and coordination.

Author	Title	Study Scope	Key Findings	Recommendations
(Zou, Mao et al. 2019)	A survey of energy management in interconnected multimicrogrids	Energy management systems in multimicrogrids and review of control and optimisation algorithms	• Multimicrogirds are operatable in islanded or grid-connected mode. They provide better system efficiency by operating in distributed architecture as well as facilitating energy trading within neighbouring microgrids neglecting transmission losses, consequently decreasing the stress on grid.	• The intermittent and volatile characteristics of DRES with dynamic loads in microgrids pose new challenges in designing optimal scheduling techniques in power systems. • The load demands are diverse for consumers and utilities, which should also be managed by multimicrogirds to satisfy bilateral requirements. • The optimisation scheduling techniques should focus on active and reactive power sharing and trading in multimicrogirds to improve the reliability and robustness of the power system.

2.5 Configurations of Microgrids

A microgrid is generally comprised of DRES, controlling components and house loads. The DRES incorporate distributed generators, power conversion equipment and energy storage. Other elements of the microgrid contain the PCC, distribution and control, monitoring and protections. The configuration of the different components of a microgrid depends on different kinds of power sources, for example, alternating current (AC) and direct current (DC) supply, and on the requirements of the particular building or site. The combination of these components in DRES allow the appropriate utilisation of resources (e.g. solar, wind) and enhances the power quality, stability, and overall functionality of the microgrid (Planas, Andreu et al. 2015). This section discusses various configurations specific to CCM as discussed in the reviewed studies.

2.5.1 Behind the meter configuration

Behind the meter (BTM) installations contain microgrids with the PV source connected behind the grid and are usually owned by the building proprietor to reduce grid load demand. BTM is commonly found in apartments where PV panels occupy the shared roof space and CP demand is met (Roberts, Bruce et al. 2019b). The subconfigurations of BTM include separate PV connections connected to individual apartments, shared PV distributing to all units, an embedded network or a virtual net metering. Although the configurations in BTM, similar to PV installations are easier to implement, there are technical, governance, financial and regulatory challenges associated with BTM (Roberts, Bruce et al. 2019b). For example, significant governance problems are roof space limitations of apartments and split incentives (i.e. distributing the earned energy benefits among the owner and tenant). A financial challenge is collecting levies and funds for strata management and determining the strata solar tariff. From the technical perspective, the lack of data gained from research and projects limits knowledge about the success of shared system configurations. From a regulatory perspective, few regulations exist in relation to the retail and technical aspects that could facilitate BTM usage.

2.5.2 Nanogrids

Nanogrids are grid-connected distribution systems for a single dwelling that have the property of operating independently or with other power sources using a gateway controller that manages bidirectional power flow (Khalilpour and Vassallo 2016; Burmester, Rayudu et al. 2017). Nanogrid has the advantage of being integrated to other nanogrids in multi-housing environments to form a big microgrid. The bidirectional power flow and communication between the nanogrid, extended microgrid and utility grid is handled by the gateway controller. Nanogrids can be connected in AC-coupled or DC-coupled mode with both topologies facilitating power converters adaptable to AC or DC conditions. Nanogrids are reported to experience protection issues. This includes ground and line faults that occurs at the output terminals, loads and switching devices. These damaging faults can be managed by inserting arcing-type circuit breaker protection (Burmester, Rayudu et al. 2017).

2.5.3 Community grids

Community microgrid architecture consists of a central community grid controller that manages and operates in a virtual microgrid mode. The main objective of the deployment of the community grid prioritises electricity to be consumed from DRES rather than from the utility grid without compromising the stability of the grid (Rosado and Khadem 2018; Olgyay, Coan et al. 2020). Community grids offer the benefits of balanced energy operation and energy trading for consumers. Community grids also face technical issues, including intermittency, fluctuation in voltage, resonance, switching harmonics and islanding operation. The voltage fluctuations and intermittency affect the active and reactive power flow in the distribution feeders, these can be adjusted using power conversion equipment, static synchronous compensators and tap changers (Rosado and Khadem 2018). The mitigation of switching harmonics can be performed by using active and passive filters or optimising the switching of power electronic equipment. Resonances are generated by the shunt capacitors connected in the grid. Capacitor size could be increased along with designing filters to reduce the resonances (Rosado and Khadem 2018). For removing anti-islanding problems, certain protection schemes are needed, which Rosado and Khadem (2018) note could be passive, active or hybrid and algorithm based.

2.5.4 Integrated community energy systems

ICES are hypothetically termed configurations for the combination of different DRES topologies. ICES provide energy-related services to large-scale networks and generating reserves and offer energy independence and security for communities (Koirala, Koliou et al. 2016). ICES satisfy the energy requirements of communities by maintaining good coordination between communities and energy utility. The technical challenges related to the ICES include intermittency, energy efficiency, and demand and supply mismatch.

2.5.5 Smart energy systems

SES improve the reliability, power supply attributes, electricity cost reduction and enables participation of the local community in energy market (Ceglia, Esposito et al. 2020). SES also support DRES uptake by mitigating electricity peak demands and greenhouse gas emissions. Moreover, SES address several sociotechnical issues in rural areas, specifically energy poverty and energy autonomy. SES also address technical issues such as data-driven problems relating to demand prediction and resolve these problems by placing precise measurement sensors and loggers for analysing energy flow. SES can use different approaches (e.g. a multi-energy approach) towards utilising several other DRES (e.g. hydrogen, biogas for electricity cooling/heating loads). SES enable energy sharing by which consumers locally share energy from a central microgrid sourced by DRES. Moreover, excess energy from DRES can be stored in EVs to further supply end users via vehicles to building technology. SES envisages nearly zero-energy buildings to fulfil most of the household load demand through dynamic renewable energy solutions.

2.5.6 Interconnected multi-microgrids

Several individual microgrids are integrated in interconnected multi-microgrids (IMMGs), which are proximal to each other and connected to a common distribution bus. IMMG can work both in the grid-connected or the islanded mode and yield better economic results in terms of energy saving. IMMGs improve the reliability of the distribution network and facilitate energy trading among the nearest microgrids (Zou, Mao et al. 2019). There are three fundamental configurations used in IMMGs: radial, mesh and daisy chain. Multi-microgrids establish a star layout in the radial topology where each microgrid is connected to the grid directly through a distribution bus. In the daisy-chain configuration, two-way energy flow occurs between the grid and the microgrid as well as the neighbouring microgrids. In the radial and mesh configuration, microgrids are interconnected in a complex way, and therefore require a sophisticated communication network with intelligent control.

2.5.7 Hybrid renewable energy systems

In addition to these two configurations, HRES are typically designed for remote communities and islands. HRES incorporate multiple sources such as a diesel generator utility grid and other form of DRES such as battery storage and wind (Neves, Silva et al. 2014).

2.6 Energy Sharing

Energy sharing improves the self-consumption of communities or groups of buildings, consequently decreasing grid demand. To exploit the benefits of energy sharing, different techniques can be applied to exchange power between prosumers or systems. Currently, energy sharing is established on AC transmission; however, there is a strong recommendation from researchers to shift technology to DC microgrids because of the vast DC powered applications (Huang, Zhang et al. 2020).

Conventionally, a central battery storage or any source from DRES shares surplus energy between buildings or connected communities in the simplest circuit while unused power is exported to the main grid (Zou, Mao et al. 2019; Koirala, Koliou et al. 2016; Ceglia, Esposito et al. 2020; Burmester, Rayudu et al. 2017). This operation is facilitated by rigid metering and communication equipment to leverage energy transactions and billings (Roberts, Bruce et al. 2019b). There are various energy trading methods implemented in energy sharing, depending on the type of shared configuration, the two most common of which are tariff-based trading and blockchain powered energy transactions. Further, energy sharing can be implemented using local energy trading, a type of peer-to-peer trading process applied by finding the difference between PV exported energy and imported grid energy (Roberts, Bruce et al. 2019a). The process can be digitised by interfacing it with graphical gadgets for the convenience of prosumers (Rosado and Khadem 2018).

The concept of shared energy from renewable sources has emerged among the scientific community, policy developers and energy sectors at a time when concerns about energy security, reliability of supply and affordability are also being raised (Wu, Kalathil et al. 2016).

On the community scale, shared batteries deployed in microgrids are considered a more cost-effective solution than individual connection systems, and they provide high self-consumption, high self-sufficiency and lower electricity costs for consumers (Rodrigues, Ye et al. 2020; AlSkaif, Luna et al. 2017; Taşcıkaraoğlu 2018).

There are various underlying reasons for the effectiveness of shared PV and battery storage. First, large storage systems can easily participate in capacity markets. Second, a central PV and battery storage system can be shared among multiple consumers living in the apartment cluster, which is not the case with individual houses because battery storage in these buildings is not fully utilised when the dweller is not present in the house.

In relation to load consumption, an individual consumer in an energy-sharing microgrid has very little effect on overall electricity usage. In addition, a user with maximum load consumption (according to the principle of Pareto distribution) could shift the high load to off-peak hours. Implementation and testing of shared systems is necessary to understand their techno-economic effects, which often encompass generation, load and state of charge (SOC) (Tomc and Vassallo 2018). Further, load management balances the renewable generation to load consumption ratio. To maximise the cost benefits for consumers, it is important to allocate equally the portion of DRES to users in a shared microgrid. This approach implies that if any user exceeds allocation, then exceeded usage is charged according to the set tariff (Fina, Fleischhacker et al. 2018). Moreover, consumer load behaviour (i.e. daily consumption patterns) is given high importance in energy audits irrespective of the microgrid topology (Khalilpour and Vassallo 2016; Giusti and Almoosawi 2017).

Different methods of investigating the effect of occupant behaviour on energy consumption are proposed in the literature. A study by Huang, Zhang et al. (2020) extended the solar to building model to vehicles and storage. Similar to other configurations, the solar to building mobility model shares surplus PV among buildings from a central microgrid to reduce grid electricity reliance. The solar to vehicle model connects the PV with grid-connected EVs. Energy flow between solar, grid and EV is managed by local energy management controllers.

Rafsanjani and Ahn (2016) presented an algorithm that simulated occupancy patterns in different building types. The model used a non-intrusive load monitoring approach to create arrival, departure and occupancy times, revealing the effects of these time factors on residential energy consumption. Rouleau, Gosselin et al. (2019) simulated scenarios using Monte Carlo methods to study the different aspects of occupancy behaviour (e.g. heating/cooling and energy) and discovered high variation of almost 50% when different occupants were followed. Delzendeh, Wu et al. (2017) argued that the literature has sufficient findings for current occupancy behaviour but that future predictions that are accurate in relation to occupant load patterns remain in question.

All the measurable factors discussed above demonstrate a need for metering architecture that is connected to the loads to ensure the measuring of precise readings. While detached dwellings that integrate DRES are traditionally monitored for revenue identification purposes, there is a lack of data related to multiresidential buildings metered for shared energy distribution which challenges massive rollout of these systems.

2.7 Shared Microgrid

Although the shared microgrid has been theoretically proposed in the literature, limited examples of real-time operational sites have been published which will be briefly discussed in this section.

Long, Wu et al. (2018b) demonstrated that excess renewable energy shared between users in the neighbourhood via aggregated small-scale batteries reduced 30% of energy-related costs compared with the excess PV exports to the grid.

Awad and Gül (2018) used a Monte Carlo method to simulate the energy demand of multiple households in a community to optimise a shared solar PV system. Vindel, Berges et al. (2019) simulated a time model to analyse grid reduction in a net-zero communal microgrid. Various publications have also investigated virtual energy-sharing algorithms in microgrids with PV and battery storage (Brooks, Manur et al. 2016; Lee, Shenoy et al. 2018).

Tomc and Vassallo (2016) simulated an energy model consisting of PV and battery storage systems connected to a grid from a detached dwelling and shared communal setup. Extending this research, Tomc and Vassallo (2018) investigated the effects of energy autonomy and the environment on shared PV generation, battery storage and community load consumption. They found out that weather effects significantly on achieving energy autonomy (grid independence) due to the highest consumption occurring at the lowest PV generation periods. Barbour, Parra et al. (2018) simulated a framework demonstrating battery storage selection for a community formation using 15-minute interval data. These researchers observed that community battery storage offers high self-sufficiency in exchange for large surplus solar exports, which are otherwise fed to the utility.

Hafiz, de Queiroz et al. (2019) proposed a novel framework for energy management that examined five community residential units with PV and storage. The multi-stage stochastic programme managed energy in individual and shared configurations. The sharing strategy decreased the total electricity costs purchased from the grid and required less battery storage capacity compared with individual houses. Besides technical research, shared systems have also been studied from a socio-technical perspective (Hansen, Morrison et al. 2020). It was argued that when shared system framework was applied on renewable project, relationship between actors (stakeholders) and implemented governance model (shared system) remain unchanged. Socio-economic factors were considered to influence the shared system.

It can be inferred from the literature review that although DRES uptake in multi-residential apartment buildings is lower due to different infrastructural, governance and technical challenges, the opportunities and benefits after implementing the shared systems are enormous. However the uptake would not merely be accomplished just by installation of systems but also require consortium from involved actors (developers, stakeholders, research and industry) on socio-technical and regulatory perspective. Table 2.2 lists some examples from around the world of installed microgrids in communities and multiresidential buildings.

Table 2.2 Examples of community microgrids around the globe with DRES

Site	Location	Building Type	System	Description
Seasons at Ontario	United States	Multifamily, 80-unit buildings; five buildings; shared benefits between building owner and tenants	140 kW solar PV rooftop, which is allocated to the common areas	Demonstrated near-zero-energy building that integrates distributed energy resources including solar PV; objectives to increase energy efficiency and apply demand response strategies to decrease energy costs and operational expenses
Lancaster Virtual Power Plant	United States	Mix of schools, homes and city facilities	10 MW PV and 5 MW energy storage; the large development includes 125 kW/500 kWh flywheel installation serving as virtual power plant	Virtual power plant aggregates distributed energy resources within the service territory of Lancaster Choice Energy; optimises distributed energy resources for maximising distributed energy resources value, cost savings, increased revenue generation and grid stability
Peña Station NEXT	United States	Planned 382-acre 100-building mixed-use community located in Denver; designed to have a 'portfolio microgrid' that would enable multiple stakeholders to share the assets and the benefits and services of the solar plus battery energy storage.	Microgrid with 1 MW PV, 2 MWh battery storage; 259 kW rooftop PV array coupled with battery storage supplies Panasonic facility; separate 1.6 MW DC grid-connected solar carport system	Microgrid improves operational resilience with voltage and frequency regulation capabilities, while the battery and demand response reduce infrastructural costs of an already-constrained grid
Reynolds Landing	United States	Sixty-two single-family homes	Microgrid with 800 kW on-site generation and 600 kWh battery storage	Microgrid controller is integrated with the home energy management system and managed by the utility company; distributed energy resources provide grid service benefits to the utility and efficient energy performance for consumers
FortZED project	United States	Mixed-use community within two square miles; several project partners	4 MW of generation from PV, combined-heat-and-power, and conventional generators; also 760 kW demand-side management and load shed resources	Dwellings and distributed energy resources are virtually connected with a central controller that establishes communication between the distributed generators and building automation connected with load shedding and flexible load capacity
Isle au Haut	United States	Island	Microgrid with 250 kW solar array; a 1000 kWh battery storage; a diesel generator and six air-to-water heat pumps with thermal storage capability	Project will incorporate a metering system and blockchain-based energy valuation network

Site	Location	Building Type	System	Description
Alkimos Beach	Australia	More than 100 residential homes equipped with PV	PV and Li-ion battery (250 kW/1.1 MWh)	The retail model will showcase that integration of technologies supported by innovative products and services provide benefits from solar PV to consumers, land developers, retailers and network operators
gridSMART project	United States	Area includes 150 square miles, including parts in different counties	Li-ion batteries (25 kW/25 kWh; up to 80 units) plus sodium sulphur battery (1 MW/6 MWh)	Alongside distributed energy resources, distribution management system includes different components such as community battery storage, volt-VAR control and metering; these technologies will be combined with information sharing platform, demand response and dynamic pricing, as well as plug-in hybrid vehicles
Kelsterbach	Germany	Individual houses	Li-ion battery (50 kW/135 kWh)	Installation maximises self-consumption and optimises combined heat power
CES for Grid Support	United States	Individual houses	Li-ion batteries (25 kW 50 kWh; up to 20 units)	Demonstrates peak shaving capability, voltage support, distributed energy resources shifting, remote and automatic monitoring when integrated to the utility grid
Feldheim	Germany	Thirty-seven households	81.1 MW wind farm, 2.25 MWp solar farm and a 500 kWe/500 kWt biomass plant for district heating and storage; through 10 MWh battery, provision of frequency control services to a transmission system operator.	Meets all its local load demand and sells 99% of the solar PV generation to the utility grid
NEXT21	Japan	Eighteen-unit housing project	100 kW combined heat power based on fuel cells	Project based on the concept of energy sharing among consumers that can exchange energy with each other
Smart Energy City	Japan	Four thousand smart houses	Integrates home energy management system with PV of 27000 kW and 2000 EVs	Solar energy community with distributed energy resources supply residential energy needs meeting 80% of the total energy demand
Wiltshire Wildlife Community Energy	Switzerland	Approximately 500 Homes	Ground mounted PV farms of 1 MW and 9.1 MW	Promotes sustainability by introducing renewables supply
Sifnos Island Cooperative	Greece		6.9 MW wind farm and 2 MW PV	Project seeks 100% energy-autonomous system and sustainable future for the local community by utilising distributed energy resources.

Site	Location	Building Type	System	Description
The Leaf Community Project	Ancona, Italy	Mixed use	Five PV systems, two mini-hydroelectric plants, ground source heat pump, condensing boiler, fuel cell, storage) electric vehicle.	Industrial research project for achieving sustainability and social responsibility conducted by both engineers/technical practitioners, scholars and public managers

Chapter 3: Methodology, Systems and Data Collection

Drawing on the literature review, identified gaps in knowledge and the proposed research questions, this chapter investigates and discusses shared system configurations and the metering data collection methodology. The data germinates from the shared system functionality to provide numeric data of apartments and shared microgrid in a readable form. The chapter includes information already published in Syed, Hansen et al. (2020); Syed, Morrison et al. (2020a); and Syed, Morrison et al. (2020b). I was a key person in implementing the shared solar storage and data systems (in the SHAC and Evermore developments) and in itself is an important contribution to the findings presented in this exegesis and the attached published research articles.

3.1 Introduction

Chapter 2 investigated the barriers to the uptake of PV and battery storage in apartments and the systems that are hosted in multi-residential buildings and community settings. This chapter presents the metering data collection procedure employed to analyse shared microgrid configurations deployed in multi-residential apartments, as well as the operational philosophy of microgrids. The three elements employed in the data collection (Figure 3.1) provide energy data that shows the outcomes of shared system utilisation in apartments. Given that apartments have a wide range of possibilities for PV and battery storage adoption (Syed, Hansen et al. 2020; Roberts, Bruce et al. 2019c; Roberts, Bruce et al. 2017), the following sections discuss different types of shared microgrid configurations for apartments.

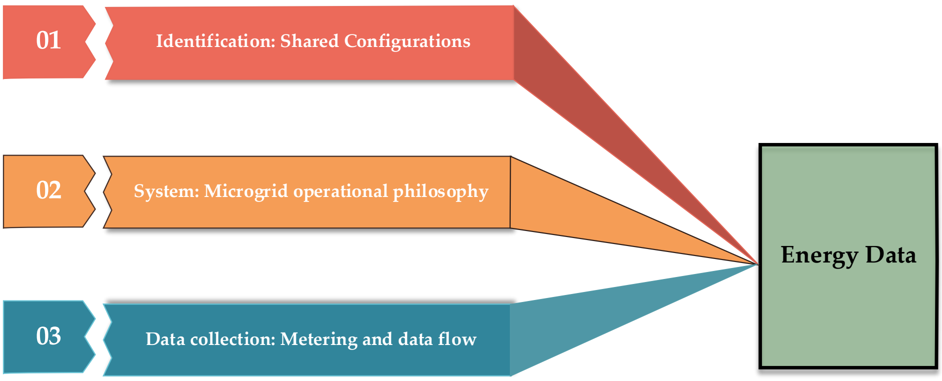

Figure 3.1 Structural overview of SEM data collection method

3.2 System Configurations for Apartments

As stated in Chapter 2, Roberts, Bruce et al. (2019b) identified suitable PV configurations for apartments (e.g. individual PV, BTM and embedded networks, see Table 3.1). The present thesis takes the practical approach of presenting the implemented architecture for shared microgrids in three apartment complexes. The design concept of the shared microgrid is somewhat similar to the embedded network; however, the difference between embedded network and SEM includes automation, battery storage, metering infrastructure, and communication network of SEM. The design of SEM was also driven by the possible implementation of energy trading in which the trading software would be handled by strata management for billing purposes and energy trading transactions.

Table 3.1 Comparison of configurations

Individual	BTM	Embedded Network	SEM
This is the simplest arrangement for a single apartment to connect individual PV for offsetting the load. The configuration does not require any governance structure to operate. There is less adoption because of the inequitable distribution of a shared resource to individual apartments.	This provides shared PV generation to supply the CP load BTM. CP either directly connects to PV or connected to a network of parallel connected residential units. BTM is beneficial for reducing common areas load demand, thus, the billing process is easier for the strata body. Individual apartments cannot profit from this arrangement.	This is a grid-connected shared PV system supplying an entire apartment building (residential and CP). Energy from the grid is distributed through a single grid connection. The disadvantages are the cost and time of operation limits (i.e. PV can be used as a renewable source only during daytime hours).	This is a shared PV and battery storage system that transfers energy to the entire apartment building. The metering infrastructure enables digital energy accounting for billing and energy trading purposes. A high self-consumption is projected depending on the availability of battery storage.

Figure 3.2 graphically presents the difference between an embedded network configuration and an SEM. A detailed description of SEM operation and metering infrastructure will be discussed in Sections 3.4 and 3.5. It should be noted that SEM incorporates storage as well as metering and data communication infrastructure which sends the data using software coding to the strata management for billing and energy trading. The governance model for PV implementation in apartments was discussed in detail in Hansen, Morrison et al. (2020).

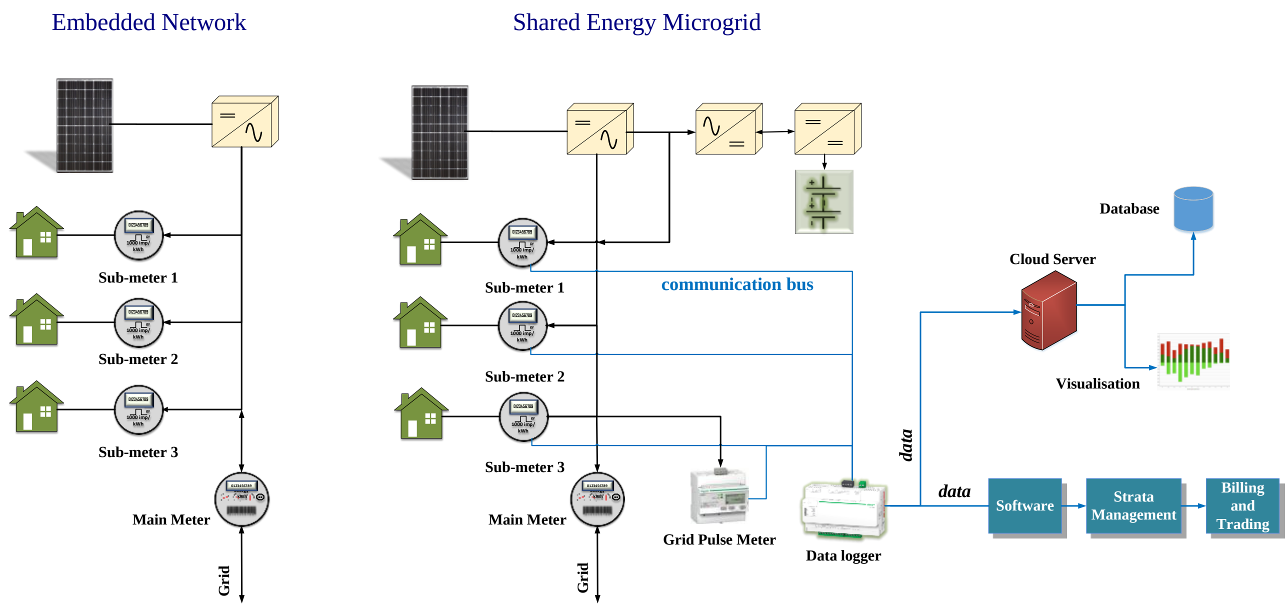

Figure 3.2 Difference between an embedded network and an SEM

3.3 Case Study: White Gum Valley

White Gum Valley (WGV) is located in the city of Fremantle, Perth, Australia. The development is on a 2.2-hectare plot of land that holds three multi-residential apartment complexes: Evermore (Evermore WGV 2018); Generation Y (Gen Y) (Landcorp 2017); and Sustainable Housing for Artists and Creatives (SHAC) (Access-Housing 2016) (see Figure 3.3). The governance model with the application of solar PV and BESS in these strata apartments enables effective sharing of the energy and financial benefits among households, strata, owners, developers and utilities. The apartments vary in construction and size. Evermore has 24 units (one-, two- and three-bedroom apartments). Gen Y has two storey three unit apartments. SHAC provides affordable housing built for artists and creatives, with 12 affordable apartment units and two communal artist studios.

Although these buildings are dissimilar in construction, the study presented in this thesis does not rely on dwelling features such as floor size, number of households and thermal characteristics. Rather, the focus is on analysing the energy behaviour of each building to provide understanding of the effects of PV and battery storage. Table 3.2 presents the dwelling characteristics and system sizes of the three WGV apartments.

Table 3.2 WGV dwelling characteristics and system size

Development	Developer	Total Dwellings	Solar PV (kW)	Battery Storage (kWh)
Evermore	Yolk	24	54	150
SHAC	Access	13	19.6	40
Gen Y	Landcorp/Development WA	3	9	10

3.3.1 Shared Microgrid

The SEM in WGV blends a number of power, communication and metering components to develop into an automated to shared system that delivers regulated power from PV modules to the apartment loads with the purpose of grid minimisation. The SEM at the WGV apartments is constructed using the following two basic systems:

- **Energy Converter:** consists of power conversion components and storage from PV generation to the grid
- **Metering:** Monitoring of energy flow through pulse meters in combination with the energy server and communication devices.

The capacity of PV panels and battery storage in SEM was selected in consideration of the goal of grid minimisation and the number of residential units in each apartment building (Syed, Morrison et al. 2020b). Although various battery classes have been investigated with respect to efficiency and cost comparison (Zhang, Wei et al. 2018), for residential applications, Li-ion technologies are the most feasible option (Darcovich, Henquin et al. 2013). Li-ion batteries have high energy density, high efficiency, large life cycle and high power capability (Janek and Zeier 2016). Nevertheless, their cost factor remains a major barrier to their mass deployment (Leadbetter and Swan 2012). With the growth of the EV market, the price of Li-ion technology is predicted to decrease over the coming years to $100 US /kWh (Katz, van Haaren et al. 2015; Mo and Jeon 2018). Among Li-ion technology, LFP is considered the most durable (Janek and Zeier 2016).

Although the three apartment complexes are situated adjacently to each other, they do not form a single large microgrid; the three separate circuits operate their own DRES independently. Moreover, the categorisation of system design is heterogeneous at each site, designed according to the requirements of each building as well as to the available resources (differentiated by PV and battery size). Every component in SEM complies with the Australia standards that regulate the quality and standard of each type of equipment (Syed, Hansen et al. 2020). The following subsections discuss the system topologies used at each site.

3.4 Configurations

Detached residential dwellings are generally powered by a single electrical connection. In SEM, electricity is shared by the central PV-BESS and is distributed to multiple apartment units. The design of SEM consists of various components, with each operating through different control methods. Utility network guidelines have characterised grid-connected PV-BESS systems as inverter embedded generators (IEGs) (Western-Power 2019). Several configurations can be installed using IEG topology based on different applications, but the standard arrangement usually consists of two components: PV with or without battery storage and PV with converters. The converters are usually bidirectional DC-DC and then link to a DC-AC inverter (Sandelic, Sangwongwanich et al. 2019; Weniger, Tjaden et al. 2014; Reinders, Verlinden et al. 2017; Boeckl and Kienberger 2019). The following are the two most commonly installed configurations for IEG: (1) AC coupled, in which the AC bus connects to the PV and BESS via bidirectional converters; and (2) DC coupled, in which the PV connects with BESS on the DC bus and the AC bus is connected to the BESS inverter.

(a)

(b)

(c)

Figure 3.3 Apartment sites investigated in this thesis: (a) Evermore; (b) Gen Y; (c) SHAC

In SEM, electricity is shared by the central PV-BESS, which is distributed to multiple apartment units. Similar to IEG, the SEM incorporates AC-coupled and DC-coupled configurations (see Figure 3.4). PV and BESS are connected to the AC bus in AC-coupled systems. The battery is charged by another bidirectional inverter tied on the AC bus. A major advantage of this configuration is its integration with other AC-converter systems and its ability to be expanded with increasing energy demand.

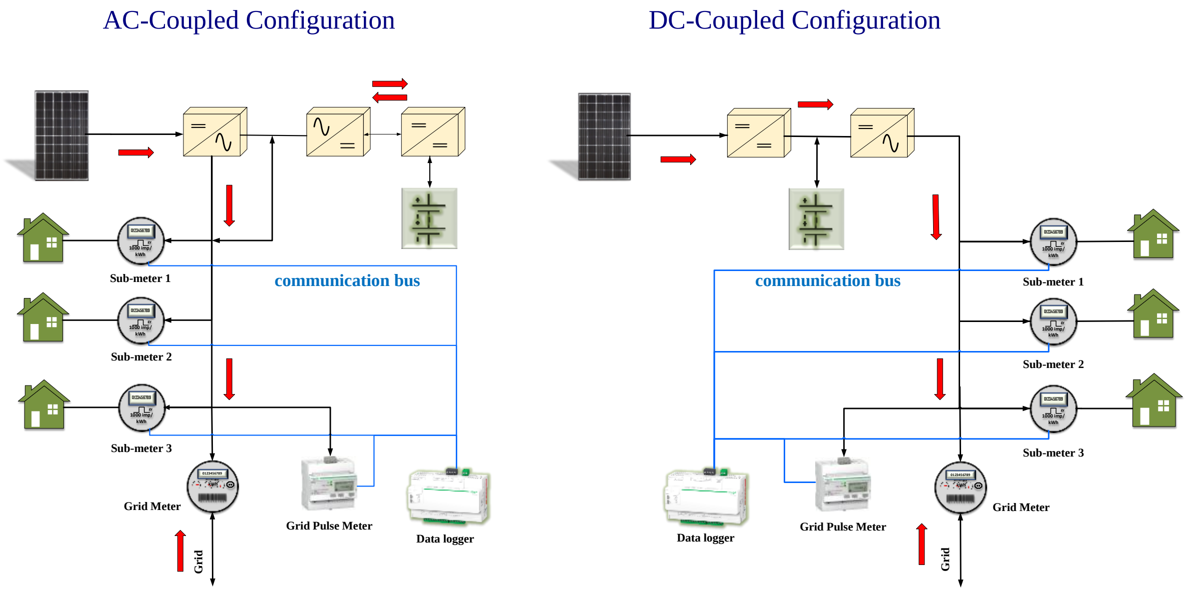

Figure 3.4 Configurations in SEM

In addition, the battery storage unit can operate independently of the PV input (Ranaweera and Midtgård 2016). In DC-coupled systems, PV output and BESS input are connected to the DC bus while the BESS inverter is connected to the AC side with loads. The configuration requires one conversion from DC to AC, which means that conversion losses are expected to be lower.

The two configurations have distinct advantages and disadvantages in relation to functionality and efficiency. For measuring efficiencies, conversion losses must be considered before installation. In the few studies found, AC-coupled systems are shown to have higher efficiency (Atia, Shakya et al. 2016; Ranaweera and Midtgård 2016; Sandelic, Sangwongwanich et al. 2019; He, Yang et al. 2020) and ability to deliver more supply to the loads (Afxentis, Florides et al. 2017). In a remote community setup, AC-coupled systems are highly appropriate configurations because electricity can be produced by a hybrid combination of multiple generators (Afxentis, Florides et al. 2017). From a cost perspective, performing multiple conversions (i.e. AC-DC then DC-AC) is a disadvantage. From a technical perspective, DC-coupled systems have high performance and a long life cycle (Chauhan and Saini 2014; Sandelic, Sangwongwanich et al. 2019), however, as battery storage is added to the system, multiple conversions are needed, which increases system costs and power losses.

In the WGV apartments, Evermore and Gen Y implemented AC-coupled systems while SHAC installed a DC-coupled system (Syed, Morrison et al. 2020b). However, the main objective of all these configurations is based on the following operations:

1. storing PV-generated energy in the battery during daytime
2. meeting the load demand of apartments from PV and battery storage (in the AC-coupled system) and then from the grid in case generation and storage are unavailable
3. feeding excess power back to the utility.

The SEM modelling for the three sites was performed employing an end-use approach, that is, by predicting typical appliance usage patterns and daytime occupancy behaviour. Therefore, the design of PV and battery storage was arranged to meet midday load demand and on-peak demand (Syed, Morrison et al. 2020b). Nevertheless, residents' changing lifestyles, practices and activities may alter the typical assumed load consumption patterns (Khalilpour and Vassallo 2016; Haas, Auer et al. 1998), which in turn would require optimisation of PV-BESS to operate at different hours (Linssen, Stenzel et al. 2017). In the case of PV, load consumption behaviour outside daytime hours may reduce the effectiveness of SEM in abating grid usage. The surplus PV generation will be exported to the grid ensuring storage is at full capacity. The priority in designing the SEM was given to charging the battery to maximum through PV, otherwise the anticipated self-sufficiency from grid charging and battery discharging would be lost (Rodrigues, Ye et al. 2020).

3.4.1 Gen Y

The Gen Y SEM contains battery storage, bidirectional DC-DC and DC-AC inverter, protection devices and several sensors that communicate and send signals back to the control system (Syed, Hansen et al. 2020). Table 3.3 lists the components of the Gen Y SEM. The number of PV modules were maximised in consideration of system sizing to yield maximum PV energy during the daytime. The modules are arranged to connect with two maximum power point trackers (MPPTs) in 12 separate strings: six strings of three modules for each MPPT.

Table 3.3 Gen Y SEM components

Component	Manufacturer
PV modules	Q.PRO-G3/250 36x250 W polycrystalline material
PV inverter	SMA Sunny Tripower inverter 8 kW (8000TL-20)
BESS	BYD, 10 kWh battery, bidirectional DC-DC+DC-AC inverter

The battery technology used is LFP with a depth of discharge of 80%, thus, the actual capacity of the battery is approximately 8 kWh of storage. A block diagram of the system is presented in Figure 3.5.

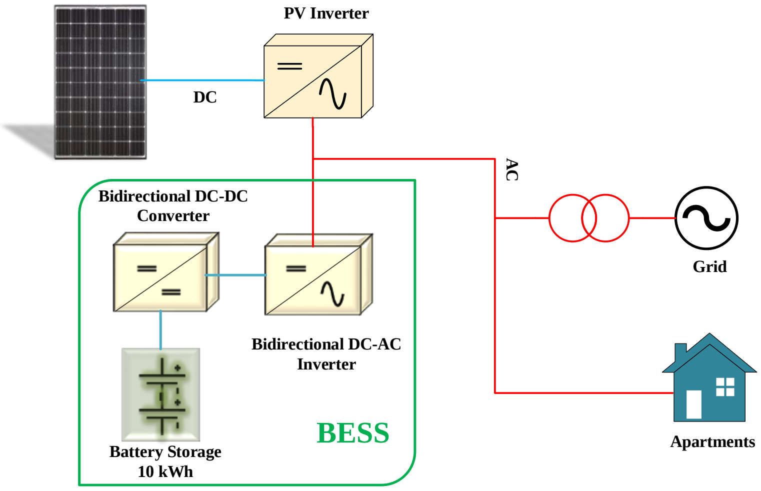

Figure 3.5 AC-coupled SEM configuration at Gen Y

The system operates based on the following principles:

- PV output to charge the battery and then the inverter is utilised for apartment loads. In case of cloud cover during PV generation, the batteries will discharge and feed the apartment loads.
- If the load demand exceeds PV generation and available battery storage, the system switches to grid supply. Similarly, if the storage reaches a minimum 4% of SOC while no PV is available, then grid supply will be used to maintain the battery charge.

- BESS will discharge as soon as the SOC goes beyond 5%.
- If the system ceases to operate because of any technical fault, then the grid will resume supplying the apartments load.

3.4.2 SHAC and Evermore

The design concept of the SHAC and Evermore apartments was selected considering the large number of apartment units, estimated load consumption and most importantly, the optimal system operation with respect to changing system and load behaviour. Therefore, regardless of the input (weather effects on PV intermittency) or load behaviour, the control of battery storage and inverter operation ensure the management of the renewable system, which increases the effectiveness of the system. In consideration of the requirements, the Siemens SINAMICS drive system was chosen for these two apartment sites (Siemens 2014). The SINAMICS inverter and converter provide the efficiency and high productivity that has proven to be suitable for industrial processes (Siemens 2010) and in WGV, for residential applications.

The integrated setup was selected because of the convenience in configuring and replacing the components. The configuration used for Evermore is AC coupled and that of SHAC is DC coupled (Figure 3.6 and Figure 3.7, respectively). Table 3.4 lists the main component description used in the SEM at Evermore and SHAC.

Table 3.4 Components used in SEM at Evermore and SHAC

Component	Manufacturer
PV modules (Evermore)	GCL System Integration Technology
PV modules (SHAC)	Q Cells
PV inverter	SMA
PLC	Siemens S7-1200
Main inverter	Active line module: Siemens SINAMICS S120
Filter	Active interface module
VS	Voltage sensing module: Siemens VSM10
CU	CU320
Battery management system	BYD
DC-DC converter	Siemens DC Power Converter

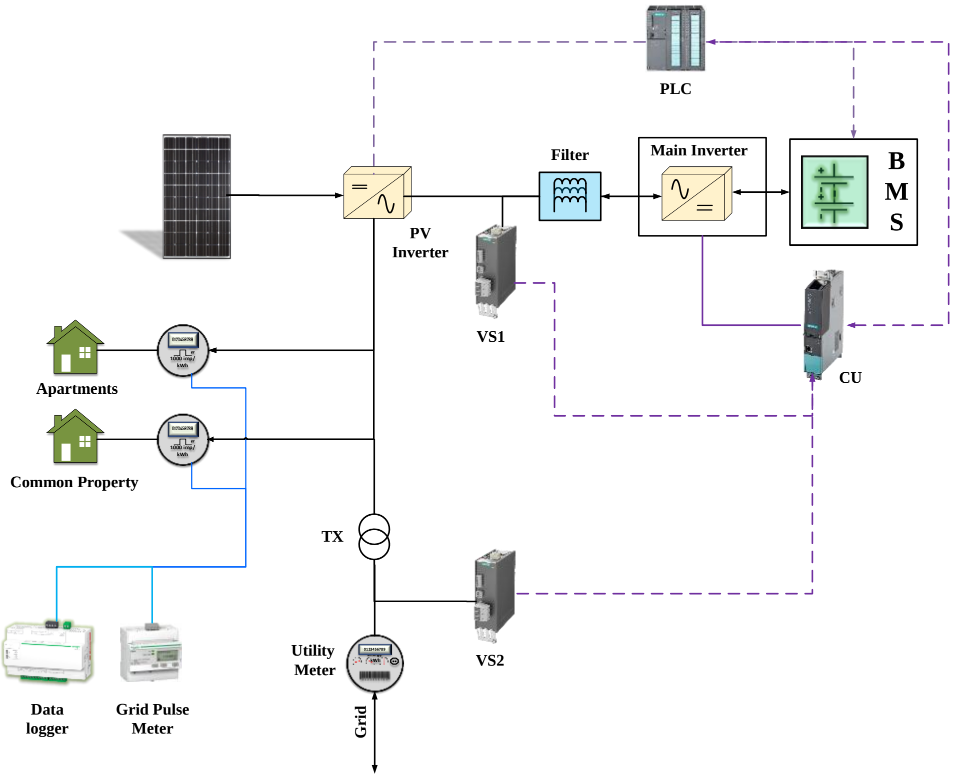

Figure 3.6 System configuration of SEM at Evermore

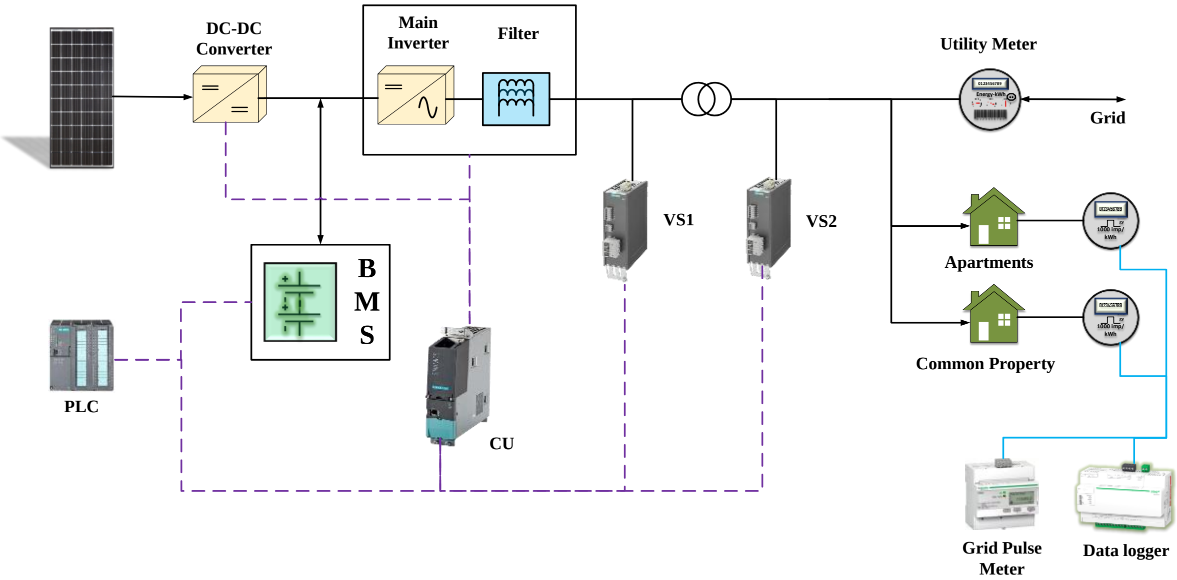

Figure 3.7 System configuration of SEM at SHAC

3.5 System Operation

The foundation of the SEM configuration used in this thesis depends on the conversion, sensing and feedback control components (Zhengtang, Xiangdong et al. 2020). A programmable logic controller (PLC) in this scheme performs the controlling function with the control unit (CU). A PLC is a rugged device used mainly in industry to monitor and control various industrial processes (Wang and Liu 2004; Birbir and Nogay 2008). It monitors through input modules connected to several sensors while controlling the interface operation by triggering the output modules, which may be connected to relays, contactors or drives. The processing of data is a key feature of PLC, and occurs by scanning inputs, storing data and sequentially executing the program instructions (Reis and Webb John 1998). The major advantage of bringing PLC into a system is the manner in which it isolates input and output devices; it is successful in organised surroundings such as building management, while being equally effective in harsh extreme industrial environments to operate large motors and turbines (Alphonsus and Abdullah 2016). The CU centrally controls the closed-loop and open-loop functions for inverters and motor modules (Zhengtang, Xiangdong et al. 2020). The CU can establish communication links between multiple drives in a system if required. It is simple to configure and stores data from all connected sensors and devices. A firmware contains different configurable drive control modes, which can be adjusted to optimise drive performance. The voltage sensor (VS) measures voltage from a single or three-phase supply line, which is fed back to the CU for closed-loop control. The main inverter provides bidirectional energy in the system. The inverter regulates constant DC voltage despite fluctuations in the line voltage (Schroeder, Shen et al. 2013). The main inverter is supplemented by the interface module, which usually contains an LC and LCL filter and pre-charging for the main inverter, a VS and other sensor equipment. PLC senses different input and output parameters from the PV inverter output, VS at grid connection point, as well as the main inverter output, CU and battery management system. This provides PLC holistic control of every section of the microgrid behind the load.

Similar to other renewable systems, the energy flows in SEM from PV to the loads and grid. The optimum DC voltage at the input of the main inverter from PV generation is highly dependent on the intensity of solar radiation (Lee and Lee 2013). In an AC-coupled system, the main inverter maintains the DC link voltage and charges the batteries, while in a DC-coupled system the DC-DC converter utilises MPPT to generate optimum voltage that directly communicates with the main inverter. The main inverter operates in closed-loop control, the DC-DC converter charges the DC link of the main inverter. Grid synchronisation occurs when PV-generated energy is utilised to magnetise the transformer and then the circuit breaker at the transformer's secondary winding is closed for grid connection of the microgrid (Ping, Ting et al. 2014). The SEM at Evermore and SHAC provides further support functions e.g. grid support, magnetisation and grid synchronisation.

The grid support mode clears system faults and offers override through service without power failure. The grid support function controls the network in the case of voltage fluctuation for a particular time. After activation of this mode, the faulted network is controlled by injecting reactive current from the distributed generation, which depends on the line voltage fault. Thus, the reactive current controller increases the output voltage if the line voltage is low and vice versa if the line voltage becomes higher.

The primary function of magnetisation in microgrid is to magnetise the transformer before transferring the microgrid to the main grid. The process is mandatory because without magnetisation, a large flow of inrush currents would cause high grid harmonics (Ye, Bai et al. 2016). The magnetisation helps the transformer develop the magnetic flux in the core. After pre-charging of the DC link, the main inverter generates an output voltage for pre-magnetisation of transformer primary windings.

In grid synchronisation, the voltage sensors (VS1 and VS2) measure the output voltages at two sides of the microgrid, the output of the main inverter and the secondary side of the transformer. The CU computes the frequency, amplitude and phase angle of the voltages and sends it to the main inverter control, which adjusts the generated voltage synchronising with the main grid. Afterwards the infeed is connected to the grid through the circuit breaker.

3.6 Data-collection Method

The method employed for data collection in this research fundamentally relies on gathering the meter data from the three apartments. WGV apartments have comparable but separate metering communication infrastructures, which mainly consist of pulse submeters, pulse energy meters, ComX’510 data logger and a network router or communication device (Syed, Hansen et al. 2020). The metering architecture is similar for the three sites, differentiated only by the number of apartments and hence the number of measuring devices (Syed, Morrison et al. 2020b). Table 3.5 lists the metering equipment used in the data collection.

Table 3.5 Equipment used in monitoring and data collection

Unit	Electricity Meter
Gen Y	KMP1-50 (Apartments), IEM3255 (grid/overall load)
SHAC	KMP1-50 (Apartments), IEM3255 (grid/common area), IEM3350 (EV charger)
Evermore	PMC-220 (Apartments), IEM3255 (grid/overall load)
Interface	SIM10M
Data logger	ComX’510

The pulse energy metering used at WGV consists of KMP1-50 and PMC-220 submeters for measuring apartment loads with pulse weight of 1000 imp/kWh and class B precision of 1%, while IEM3255 measures bidirectional energy flow from the grid and PV-BESS. IEM3255 meters are built for monitoring three-phase electrical systems and have a pulse weight of 5000 imp/kWh, precision of class C (0.5%) (Bekauri 2016). This functions bidirectionally when measuring energy flow (i.e. grid import and export). IEM3255 is used in billing management and electricity measuring applications. All meters and appliances are national measurement institute (NMI)[2] compliant. Separate additional meters for measuring EV charging at SHAC and Evermore were also installed. Figure 3.8 displays measuring meters and logger used in this study.

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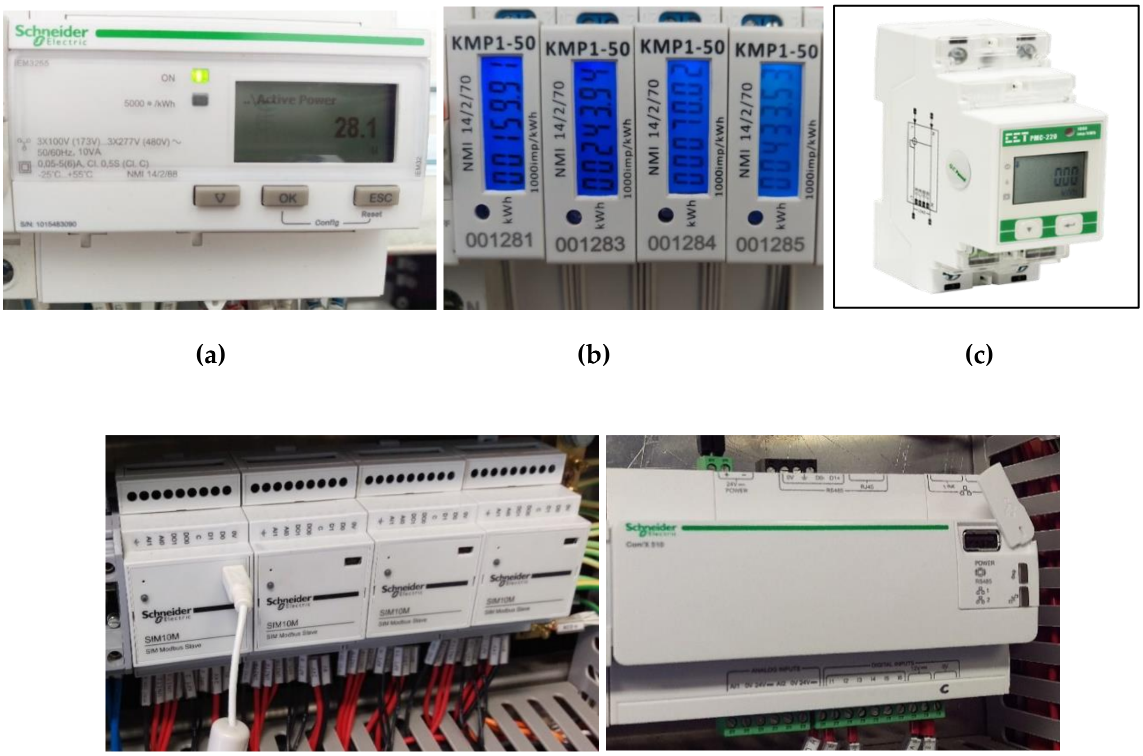
[2] National measurement institute (NMI) is a governing body responsible for maintaining measurement system and standards in Australia.



(a) (b) (c)

(d) (e)

Figure 3.8 Equipment used in monitoring (a) IEM3255 meter; (b) KMP1-50 pulse meter; (c) PMC-220 pulse meter; (d) SIM10M interface module; (e) data logger ComX'510

All measuring appliances are configured internally and then in the data logger ComX'510 (Kermani, Carnì et al. 2020; Matroja 2018; García, Moreno et al. 2019) to first test the handshaking and finally to fix the settings. Therefore, before metering equipment selection, it is important that all measuring devices and the logger are compatible with each other. As shown in the Figure 3.9, which outlines the method of data collection, the data are collected by the logger via submeters connected through Modbus protocol, which is the standard protocol used for data communication internally at WGV. Modbus RS485 is a serial communication protocol with the ability to interface multiple devices (up to 256) connected to the same bus (Thomas 2008).

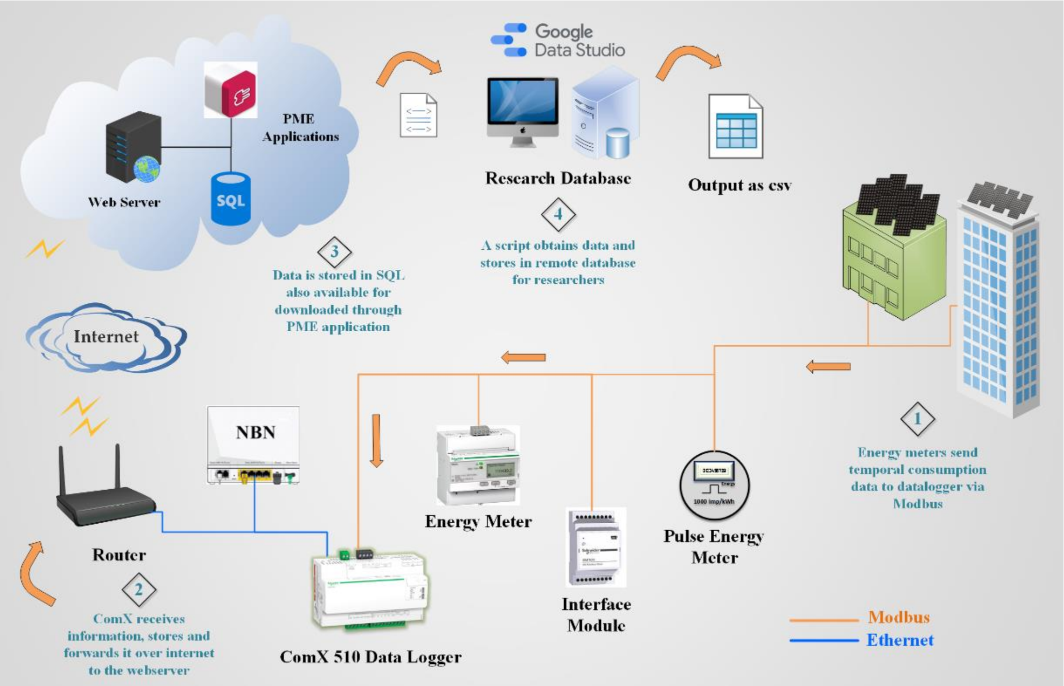


Figure 3.9 Method of data collection (redrawn from Syed, Hansen et al. 2020)

This arrangement removes the requirement for various interfaces to scan multiple devices. The Modbus functions on a master/slave framework (Tamboli, Rawale et al. 2015). The master (in this case the data logger) transmits the signal to detect the slave (pulse meters and other devices), which act like a receiver. The slave is usually assigned a unique Modbus identification. The pulse meters generate cumulative data, which reach the data logger either directly or through an interface module (SIM10M). The reason for placing SIM10M is connected to the low number of logger inputs. Given that the logger contains only six digital inputs, a site with more than six meters would require an interfacing device to facilitate a greater number of meters and other measuring appliances.

The pulse submeters were installed in a parent–child configuration (Bedwell, Leygue et al. 2014). The grid power is measured by the main utility meter of the premises as well as the check meter, which is the grid pulse meter (IEM3255) connected behind the main utility meter. Individual apartments, including CP loads, are wired by means of KMP1-50 pulse meters. This configuration has the advantage of eliminating multiple grid connections, which offers substantial cost savings.

3.7 Data Management

The data are then stored in the internal registers of the logger, which also maintain a backup storage. Logger also provides access to reports such as on-board devices and circuit summary pages, as well as on-board data logging. A two-stage process delivers the data from the three sites to the end users. Using an external broadband internet service, the logger at each site connects individually to a cloud server (Bekauri 2016) where incoming data are stored using a structured query language (SQL) database (Byrne, Law et al. 2019). The unrefined data from SQL is then adjusted into tables with proper attributes (Byrne, Law et al. 2019). A unique identifier is allocated to each measuring device, which recognises the equipment and its parameters. Data from here are pushed to another remote server using coding scripts. The scripts extract information from the SQL database and push it to the BigQuery database, which utilises Google Data Studio (Tigani and Naidu 2014).

The main query accomplishes initial refining by assembling metadata into managed columns while erasing non-essential headers and fields (Byrne, Law et al. 2019). The query then gathers all parameters from each site, manages them in temporal 15-minute measurements and forwards information in comma separated values (CSV) format to the server. The query also substitutes missing data with specific data jargon to indicate cells with missing values. To curtail the number of streams, the data resolution is set to 30 minutes with two 15-minute intervals contained in a CSV file. Although the data transfer process is intricate, resource minimisation was considered by project stakeholders a top priority to save costs associated with the implementation of expensive data management platforms. As with smart meters, the temporal measurements from this hybrid setup may help in forecasting load profiles, thus facilitating optimisation to reduce electricity costs and provide autonomy to prosumers to predict the best period for selling excess PV energy to the grid.

3.8 Data Flow and Integration

Granularity in the case of data flow has the utmost importance, confirming the accuracy and uninterrupted temporal transmission of data (Byrne, Hosking et al. 2019). More granularity helps in identifying diurnal household daily profiles as well as system performance data, which are fed on a 15-minute resolution that builds per-day and per-month data, respectively. Figure 3.10 provides an overview of the research data stream. Each stage of the data stream (ingestion, validation and indexing, data access) meets a range of filter and conditions to shape the data accurately.

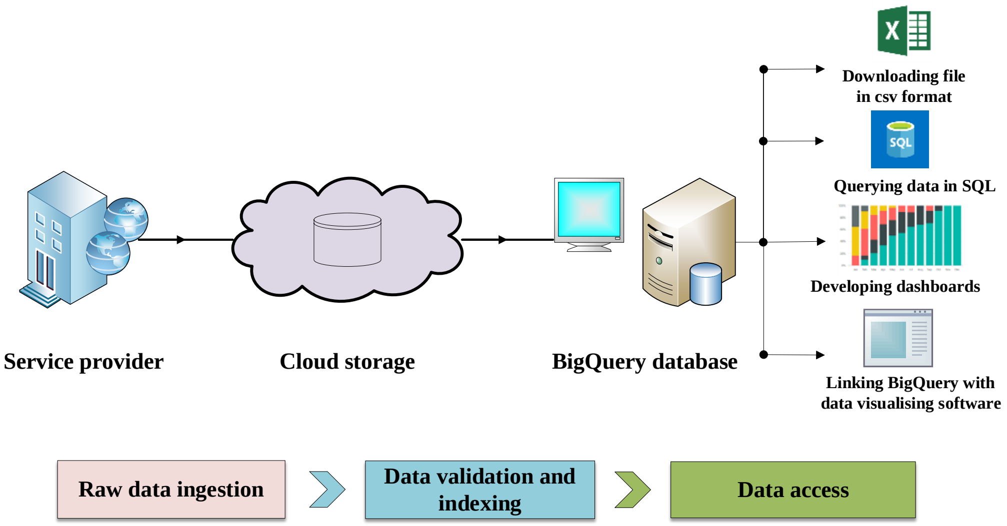


Figure 3.10 Research data stream

3.8.1 Data ingestion

The primary objective of this stage is to ensure an easily accessible and secure method for obtaining data from the remote server. The key attributes of this design stage are as follows:

- A Google Cloud Storage bucket is created. This offers an easily accessible platform, secure encryption, frequent backups and flexible disk space for saving incoming data.
- A command line utility at the cloud server transfers the data from the SQL database to the Google Cloud Storage bucket. This utility encrypts data during transmission and upon failure, can attempt to run the script multiple times until execution.
- For secure transmission, the cloud server uses a unique cryptographic key for uploading data, which also permits write access and prevents anyone from modifying or downloading data. This establishes additional insurance in case of key loss/hack.
- Finally, data are stored in separate folders distributed per building (Gen Y, SHAC and Evermore) further categorised by date. Data transfer occurs every 30 minutes

with a CSV file that contains two 15-minute intervals. One advantage of this stream is the historical data transfer option, which can send a feed containing data of a longer period if intermittency affects the data feed during the normal process.

3.8.2 Validation and indexing

The validation and indexing process enhances the quality of data and manages the data in a more practical way. Validation and indexing is accomplished using a two-step approach.

4. validation of data schema—verification if input data are valid, have in-range values and expected number of records (i.e. for 15-minute resolution interval, 96 data rows per day)
5. saving the records in a manageable structured database—containing data types and correct units for parameters.

The important characteristics of the validation and indexing process are as follows:

- Data are analysed on a per-day basis. The schema of the data file are cross-checked with standard format, which consists of an exact number of columns and header fields per site. Moreover, the total number of rows and columns are verified. Considering 15-minute resolution, the total number of records per day would be 96 (i.e. every 15 minutes for 24 hours: 4 x 24 = 96).

- Different types of alarms can be sent in the event data file mismatch with the standard format (i.e. difference in number of columns and rows).

- The managed data are then merged into the main SQL database, which is called BigQuery. Data here are stored in temporal rows and columns, with correct parameter headers and units. The benefit of forming this portal is that the validation of defined value ranges (minimum–maximum), any value out of this range would be considered false, will be flagged and quarantined.

- Data fields can automatically be indexed for rapidly obtaining desired sets of information. Requested information could be records of a specific parameter between certain time and date, further filtered to a particular range of values. The freedom in downloading data is greater rather than obtaining an entire subset of data, which can be a problem for a truncated dataset.

3.8.3 Data access

The data stream can be collected and visualised using the following methods:

- Users are allowed to download a data file in CSV format. This allows researchers independence in applying the data using any method or tool they desire. Protection and security of the data is given first priority in this process.
- Google Data Studio with BigQuery can create dashboards, charts and reports with the feature of sharing work with other users (and other users can edit and modify the content).
- BigQuery can easily be connected externally with interactive data visualisation software such as Tableau and Qlikview (Troyansky, Gibson et al. 2015).

Moreover, data can be queried using SQL. The advantage of using SQL is its ability to write simple queries and to facilitate sorting or filtering data. To apply a protection level, permission can be granted to view data with less granularity, that is, a particular user (not a researcher) can access data for daily or monthly viewing, but minimum resolution (in minutes) is restricted to protect sensitive research data or fields.

Chapter 4: Analysis

This chapter provides an overview of the analysis performed on numeric data, which was obtained from the data-collection methods described in Chapter 3. The formulae and parameters discussed here were published in Syed, Hansen et al. (2020); Syed, Morrison et al. (2020a); Syed, Morrison et al. (2020b). This chapter will present an overview analysis, and Chapter 5 will present the results of this overview in the form of charts and tables.

4.1 Analysis

The objective of the analysis conducted in this research is to examine the load profiles of individual apartments and CP and assess grid reliance reduction by shared configurations in apartments. The analysis represents the first step to answering RQ3: What are the technical benefits of shared PV-BESS employed in apartment loads and how do technical configurations allow shared distribution for consumers?

The analysis presented here centres around data collection and computation of energy consumption and generation at 15-minute resolution (Syed, Hansen et al. 2020). Further, the data and variable characterisation are based on resolution, location and equipment type. The following sections explain these computations and parameters.

After the removal of outliers and missing values, the filtered data were collected for analysis using the method described in section 3.6 and 3.7. Time-series analysis is usually conducted for two purposes: to understand generated data series and to forecast the next set of values based on the historical data (Cryer and Chan 2008). This type of analysis is used in diverse scientific applications—in fields from economics to engineering—that involve the analysis of hourly, daily and monthly figures (Shumway and Stoffer 2017). Each application provides different data representations, which can be continuous or discrete. The analysis in this chapter mainly consists of discrete series, where observations are measured at a fixed interval (i.e. 15 minutes) regardless of the values at the particular point in time.

4.2 Cumulative Measurements

Given that most of the measuring equipment in the WGV project uses pulse metering, the measurements are saved as cumulative values incremented proportionally to every kWh of consumption or energy generation (Makonin, Ellert et al. 2016; Bickford, Farnsworth et al. 1991). To obtain the real consumption value, each numeric value is subtracted from the previous interval measurement. Instantaneous values such as power (Watts) are recorded by logger in original values.

To obtain the desired output, Equation 1 can be applied on cumulative data (Syed, Hansen et al. 2020):

$$\Delta X_n = Y_n - Y_{n-1} \quad \textbf{(1)}$$

Where n represents a particular interval, and X and Y are the desired output and cumulative data measurements, respectively. Given that the data resolution is 15 minutes, one day of 24 hours generates 96 intervals. Equation 2 was used to calculate daily energy output values:

$$Energy_{\ kWh/day} = \sum_{n=0}^{96} (\Delta X_n) \quad \textbf{(2)}$$

4.3 Energy Allocation Strategies

Energy allocation strategies allocate and distribute surplus energy from the PV to reduce grid consumption for CP. The method varies between different conventional peer-to-peer trading strategies such as blockchain algorithms (Han, Sun et al. 2020); auction-based approaches (Fleischhacker, Auer et al. 2018; Chen, Xu et al. 2019; Hayes, Thakur et al. 2020); or game theory (Liu, Yu et al. 2017; Zhang, Wu et al. 2018). The strategies discussed here removes any sophisticated forecasting methods applied for energy trading.

Energy allocation can be implemented by virtually managing the computation of energy flows alongside the functional system. An aggregator or middle body (OC in strata) can then manage the virtual energy trading, which is then used to set the market arrangement. The methods are directly associated with data from physical meters (Zafar, Mahmood et al. 2018; Zhang, Wu et al. 2018).

The conventional energy trading models use a portion of renewable energy to allocate the particular number of units at each time interval. If consumption is less than generation, energy is stored in the battery or exported to the grid. A similar standard energy trading mechanism can be seen in Figure 4.1. After an apartment is allocated a certain portion of renewable energy, the process checks whether the energy usage is lower than the allocation, which enables the trading process to occur. However, when the consumption is under the allocated limit, there is a waste of locally generated energy into the grid. The surplus exported to grid is compounded by the low feed-in tariffs in locations such as Western Australia (Syed, Morrison et al. 2020b).

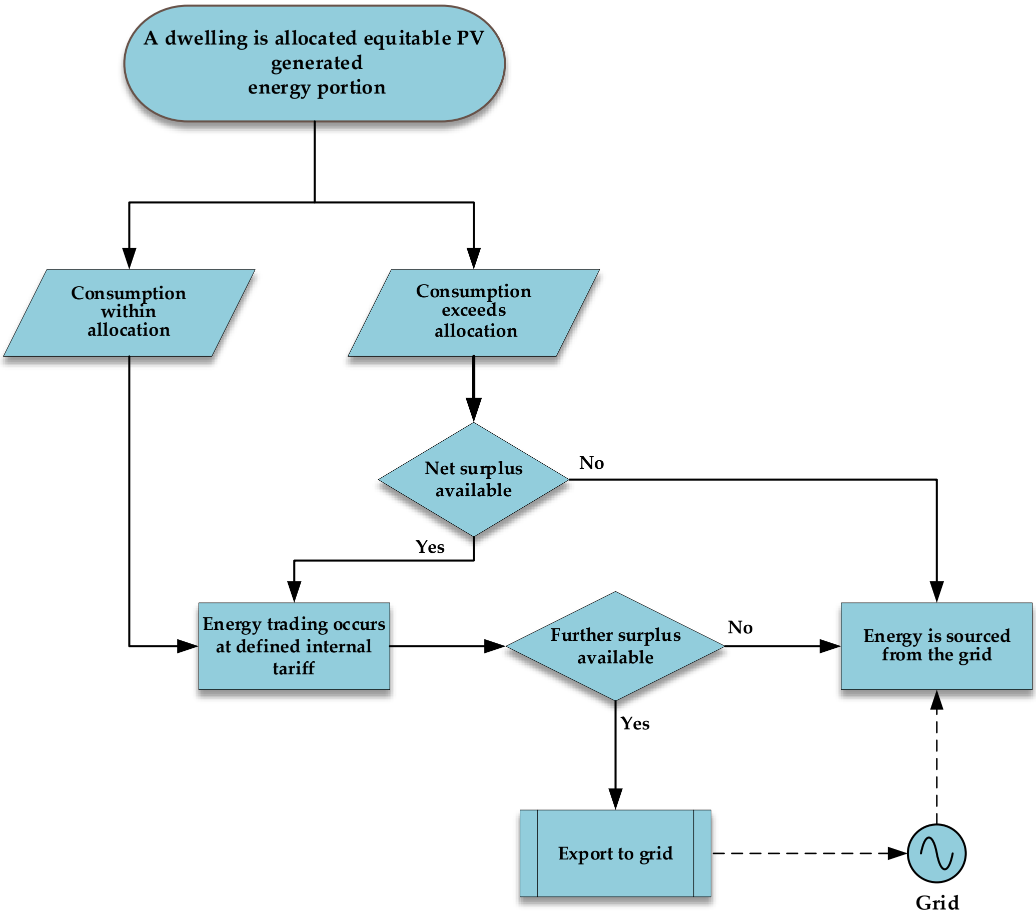


Figure 4.1 Conventional energy trading mechanism in a typical grid-connected renewable system

Utilising real-time apartment building data, this research employs the energy allocation approach for CP loads to compare three allocation strategies and present the grid energy reduction and financial benefits for residents. The allocation strategies can be intertwined with other conventional methods of sharing surplus energy among several customers using the same microgrid at the retail rate regulated by the local aggregator. This excess energy shared between consumers and CP load is an efficient method to compare the existing energy allocation models that feed power back to the grid at a cheaper tariff. Figure 4.2 presents the workflow of these allocation strategies. The strategies are referred to as 'instantaneous consumption' (IC); 'surplus allocation' (SA), and 'consumption-based allocation' (CA).

4.3.1 Instantaneous consumption

Although there is no single best solution for energy accounting, energy consumption in a shared system reveals the implementation of a particular computation method. IC works on the principle of energy apportioning, which determines the share of energy sources (grid and PV-BESS) responsible for the load consumption of individual apartments. The energy apportioning assists in generating energy bills and the distribution of energy demand contingent on system output. Moreover energy apportioning can be applied to fragment energy from multiple sources (e.g. PV, storage and grid). Many approaches have been taken to identify apportioned usage, for example, non-intrusive load monitoring (Hay and Rice 2009; Kelly 2016; Devlin and Hayes 2019); static apportionment (Hay and Rice 2009; Vergara, Nadjm-Tehrani et al. 2016); clustering (Funde, Dhabu et al. 2019); and controlled sharing of energy (Huang, Zhu et al. 2014).

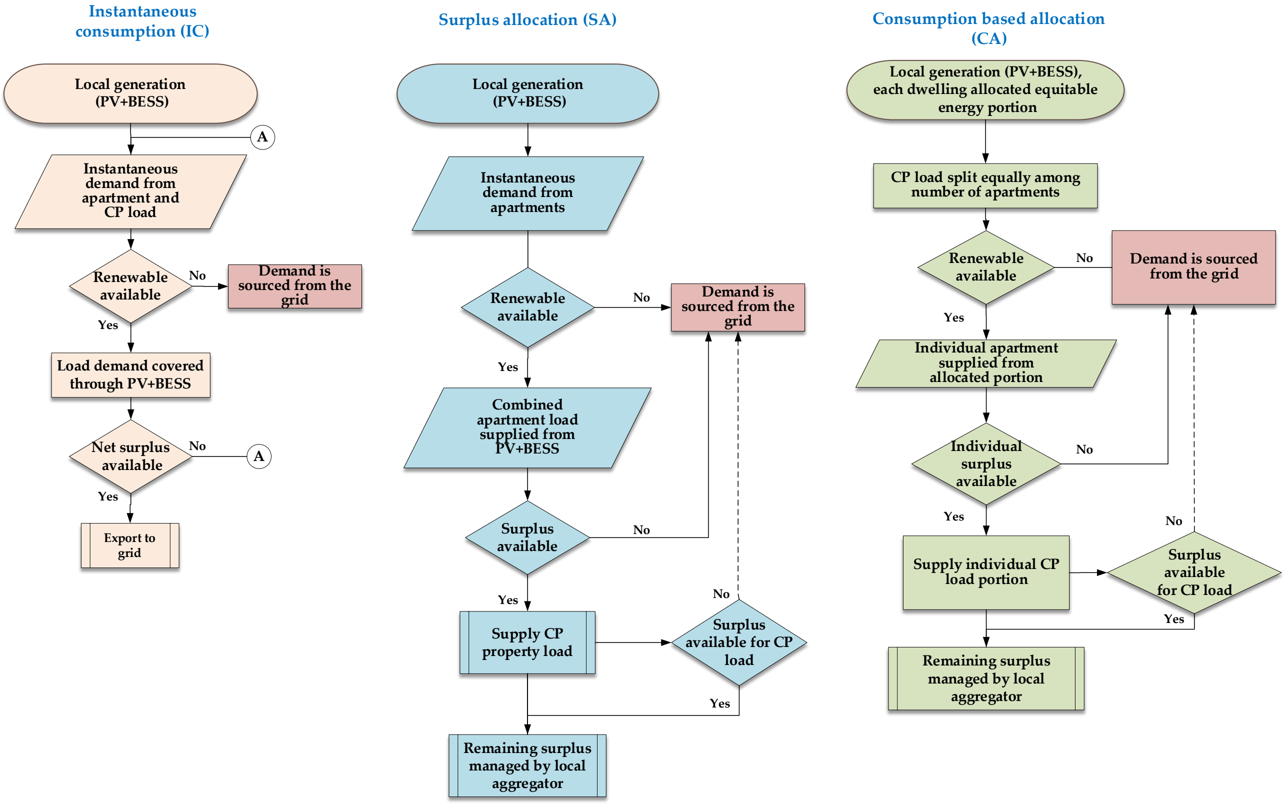


Figure 4.2 Energy allocation strategies workflow for offsetting CP load demand

One easy solution to the problem of energy allocation is to apply static apportionment (Hay and Rice 2009; Vergara, Nadjm-Tehrani et al. 2016) by which energy is equally divided among all apartments. This seems straightforward to calculate but is inadequate in relation to the actual consumption allocation. Another solution of this conflict is to time the operation of sources alternatively (Huang, Zhu et al. 2014). However, given that the WGV is grid connected with uncontrollable loads, a switching operation could become difficult, particularly during battery discharge when the system operates continuously on grid and PV-BESS. Hay and Rice (2009) explored alternative apportionment policies, for example, a personal load policy, which allocates a certain amount of power to each dweller and divides the remaining power equally.

In AC-coupled systems, the demand is met from the PV and BESS instantaneously, while DC-coupled systems meet load demand through a battery inverter after PV charging. In the event of lower PV capacity, the system imports power from the grid, and the surplus generation is fed to the grid.

The apportionment is presented in Figure 4.3 and is computed for the load consumption by initially taking out the percentage of energy contribution from each source. After this step, the percentages further broken down into individual unit consumption through two values: consumption from renewables and consumption from grid.

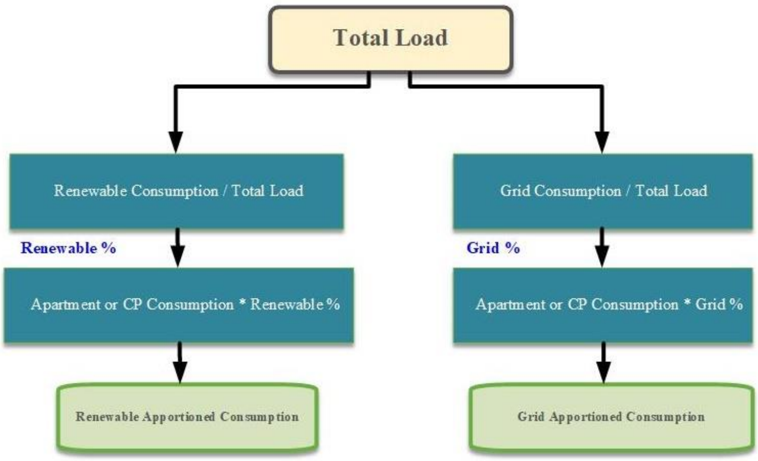


Figure 4.3 IC through apportionment method to distribute load consumption by grid and renewable energy sources

The equation provides a basic solution to distributing energy in a shared system; any apartment is billed or incentivised based on its load consumption. The distribution can be verified through a simple expression, that is, the sum of individual load consumption should be equal to total the energy supplied by the grid and PV-BESS. A simple method for clarifying this phenomenon is presented through Equations 3 and 4 (Syed, Hansen et al. 2020).

The renewable fraction is energy supply from the source (either grid or PV-BESS) to cover load demand, where t denotes 96 iterations per day with data resolution of 15 minutes.

$$\text{Source (\%)} = \sum_{t=0}^{95}[\text{Renewable fraction}]_t(\text{kWh})/\text{Total Load}_t(\text{kWh}) * 100 \quad (3)$$

$$\text{IC (kWh)} = \text{Source (\%)} * \text{Unit Consumption (kWh)} \quad (4)$$

The unit mentioned here can be the apartment or CP loads. The calculations can be implemented in a shared scheme where residents and strata management agree to gain equal benefits from the shared system based on consumers' electricity consumption. It is noted that the apportioned load consumption is congruent with the monthly fraction of PV-BESS and grid. However, when energy trading mechanisms are applied, the method needs improvement in energy resource allocation to gain further benefits.

4.3.2 Surplus allocation

As expressed in Equation 5, in the SA strategy, apartment instantaneous load demand is initially prioritised by supplying renewable generation (E_G) while the surplus ($Surplus_{SA}$) remainder will cover CP load before being exported to the local aggregator or strata manager. The strategy includes temporal calculations from metering data, represented in Equation 4 (Liu, Yu et al. 2017; Long, Wu et al. 2018b; Zhang, Wu et al. 2018).

$$Surplus_{SA}(kWh) = \sum_{t=0}^{95}\left[E_{G,t} - \left(\sum_{0}^{n} E_{apt,t}(n)\right)\right] \quad \mathbf{(5)}$$

Where n represents the total number of residential units.

If Equation 5 returns a positive value (i.e. surplus) then this energy supplies the CP load (E_{cp}) as given in Equation 6 (Lee 2014). The excess energy remaining after supplying the CP load would be managed by the local aggregator shown as excess.

$$\text{If } Surplus_{SA} > 0 \left(\sum_{t=0}^{95} \left(CP_{calc,t} = Surplus_{SA,t} - E_{cp,t}\right)\right) \quad \mathbf{(6)}$$

$$\text{If } \boldsymbol{CP_{calc}} < 0\text{; supplies from grid } \boldsymbol{CP_{calc}} > 0\text{; Excess}$$

4.3.3 Consumption based allocation

In the CA strategy, an invariable generation capacity (E_{GA}) is allocated to each apartment unit for each time interval (15 minutes). Further, the consumption from CP ($E_{cp,CA}$) is also proportionally divided among apartments to keep consistency in net energy exchange. Afterwards, individual apartment's consumption is net from its allocated energy portion. Any available surplus ($Surplus_x$) after energy utilisation is then available to meet the assigned portion of CP demand (CP_x) (Liu, Yu et al. 2017; Long, Wu et al. 2018b; Zhang, Wu et al. 2018). In CP_x subscript x denotes a particular apartment unit. If an individual consumer uses more than their allocated portion, the grid-imported electricity is used to fulfil the remaining demand. Although each apartment unit has a fixed allocated energy portion, the actual distribution of energy could digress from the allocated portion.

The unit that consumes more energy can benefit from importing renewable energy at a much cheaper rate from the neighbouring consumer if energy trading mechanisms are implemented with CA. The individual energy surplus after meeting CP load demand ($CP_x > 0$) can then be facilitated by the aggregator to leverage subsequent financial benefits. Choudhry, Dimobi et al. (2019) employed a similar concept, where an apartment with a positive net difference was referred to as a 'prosumer' whereas an apartment with a negative value was referred to as a 'consumer'. Equations 7 and 8 determine the values for the implemented CA strategy.

$$E_{CP,ca}\ (kWh) = \sum_{t=0}^{95}\left(\frac{E_{cp,CA,t}}{number\ of\ apartments}\right) \quad \textbf{(7)}$$

$$Surplus_x(kWh) = \sum_{t=0}^{95}\left(E_{GA,t} - E_{apt,t}(x)\right) \quad \textbf{(8)}$$

If $Surplus_x > 0$, $[CP_{x,t} = \sum_{t=0}^{95}(Surplus_{x,t} - E_{cp,ca,t})]$

If $CP_x < 0$; supplies from grid and if $CP_x > 0$, Excess

Table 4.1 lists advantages and disadvantages of energy allocation strategies

Table 4.1 Advantages and disadvantages of the allocation strategies

Title	Advantages	Disadvantages
IC	Beneficial in shared systems where residents and strata management agree to gain benefits from PV-BESS based on individual apartments' electricity consumption	Energy portion is unallocated, thus residents are not aware of their energy consumption
	Individual apartment or CP may use maximum PV-generated energy in case other units are not consuming	Distribution of energy fraction depends completely on individual unit's consumption
		Surplus PV is sent back to the grid
		Because exported energy is unallocated, cost benefits for individual consumers are not explicitly determined
SA	Surplus renewable energy can supply CP load after apartments' consumption	Depends on load consumption of apartments; if PV production is equal or less than total apartment load, grid will supply CP load
	Maximum renewable energy may be utilised by CP if apartments are not consuming	Because exported energy is unallocated, cost benefits of individual residents are not explicitly determined
	High grid usage reduction can be achieved in buildings that have high surplus generation availability	
CA	Renewable generation in equal portions is allocated to each apartment unit alongside proportionate CP load consumption allocated to all apartment units	Limitation of fixed allocated PV energy portion; in case allocated energy portion expires, CP load is supplied through grid electricity
	Residents remain conscious of their energy consumption because of the allocated share of PV energy	
	Potential to implement peer-to-peer trading between consumers, with financial benefits offered if a particular apartment consumes less than the allocated portion	
	Aggregation of excess energy and more cost benefits than IC and SA strategies.	

4.4 Self-sufficiency

The motivation behind the uptake of DRES is to mitigate grid electricity usage. Thus, high self-sufficiency is expected as the general outcome of using DRES. Self-sufficiency is defined as the capacity of the microgrid to operate its internal renewable sources such as PV and battery storage without depending on grid-imported electricity. This is also referred to as 'energy autonomy' (Rae and Bradley 2012).

The metric is often confused with self-consumption, which defines the ratio of PV usage consumed by loads to PV generation (Luthander, Widén et al. 2015). In Mavromatidis, Orehounig et al. (2017) energy autonomy is calculated as in equation 9:

$$\text{Self-Sufficiency (\%)} = (1 - \frac{\sum_{n=0}^{n'}(E_{grid})}{\sum_{n=0}^{n'}(E_{load})}) \text{ x } 100 \quad \textbf{(9)}$$

Where E_{grid} represents temporal grid-imported energy and E_{load} is total load consumption. Energy autonomy assists in comprehending the share of grid electricity and PV-generated electricity in meeting the load demand. This allows the financial benefits to be determined to increase the renewable portion.

Residential systems with DRES have been examined with the primary aim of reducing grid electricity and increasing self-sufficiency (De Oliviera e Silva and Hendrick 2017; Klingler and Teichtmann 2017; Gjorgievski and Cundeva 2019) and self-consumption (McKenna and Darby 2017; Gupta, Bruce-Konuah et al. 2019). Battery storage has been widely considered the principal factor to increase self-sufficiency and self-consumption (Barzegkar-Ntovom, Chatzigeorgiou et al. 2020).

An alternative metric of determining self-sufficiency is to evaluate energy autonomy, which can be defined as the duration that the renewable system is able to remain self-sufficient in supplying loads (Kaldellis and Zafirakis 2007). Depending on the time series, energy autonomy can be measured in minutes, hours or days. A significant amount of research has discussed the role of DRES in achieving self-sufficiency, the primary metric for analysing grid usage reduction.

To enhance the self-sufficiency of households in combination with EV batteries, modelling optimisation was conducted in Gudmunds, Nyholm et al. (2020) The study tested 30 different combinations of PV and battery storage. The EV plugged-in duration affected the self-sufficiency ratio (SSR), while the overall SSR compared between EV batteries and stationary batteries was similar. Quoilin and Zucker (2016) examined technoeconomic impact of PV-BESS under different schemes by simulating the energy profiles of different countries when assessing self-consumption. The results revealed that self-sufficiency increases with increasing battery size until a certain limit of battery capacity and then the effect becomes marginal. The authors stressed that achieving 100% SSR is impractical because it requires an oversized system. Zhang, Lundblad et al. (2016) examined a residential building in Sweden to compare three storage technologies with PV in relation to SSR. Li-ion achieved higher SSR than the other battery technologies. The authors suggested that to achieve high SSR, it is best to use seasonal storage with a conventional lead acid or Li-ion battery; however, they noted there are anticipated cost-related risks and maintenance.

A survey and electricity data of 82 households in Gupta, Bruce-Konuah et al. (2019) demonstrated the reduction of grid electricity usage through increased self-consumption with implemented PV and battery storage. The impact of installing smart battery storage reduced grid electricity by 8%. Gstöhl and Pfenninger (2020) employed an integrated approach to analyse the factors influencing the technoeconomic feasibility of self-sufficiency. Their study found that detached dwellings achieved high self-sufficiency because of their construction. Nonetheless, the authors predicted that multiresidential buildings with rooftop as a limiting factor could also attain high self-sufficiency through improved PV and storage technologies.

Chapter 5: Results

Following from the analysis in Chapter 4, this chapter takes RQ3 further to present the energy performance results from apartments connected to SEM. The energy consumption profiles of apartments are considered to include seasonal effects on load patterns and PV generation. The apartments' load constitutes from individual apartments as well as CP. For the assessment of grid minimisation, parameters such as self-sufficiency are analysed for the three sites and the energy allocation strategies are examined.

5.1 Apartments Load Profiles

The load profile for Gen Y is characterised by distinct peaks in the morning and evening, with the highest demand occurring in the winter period (June 2018–August 2018) as a result of consumption through heating appliances (Tomc and Vassallo 2016). The decreased load power during the summer period (December 2017–February 2018), as opposed to the other three seasons, was a result of occupancy behaviour; that is, the resident of Unit A travelled during that period. The diurnal load profile in Figure 5.1 presents the Gen Y apartment patterns during the four quarters of the year (the summer months in Perth are December to February). The dwelling baseload was 300 W throughout the available period. This was calculated by considering seasonal power values and minimum plot values (Kauffman and Morgan 2016).

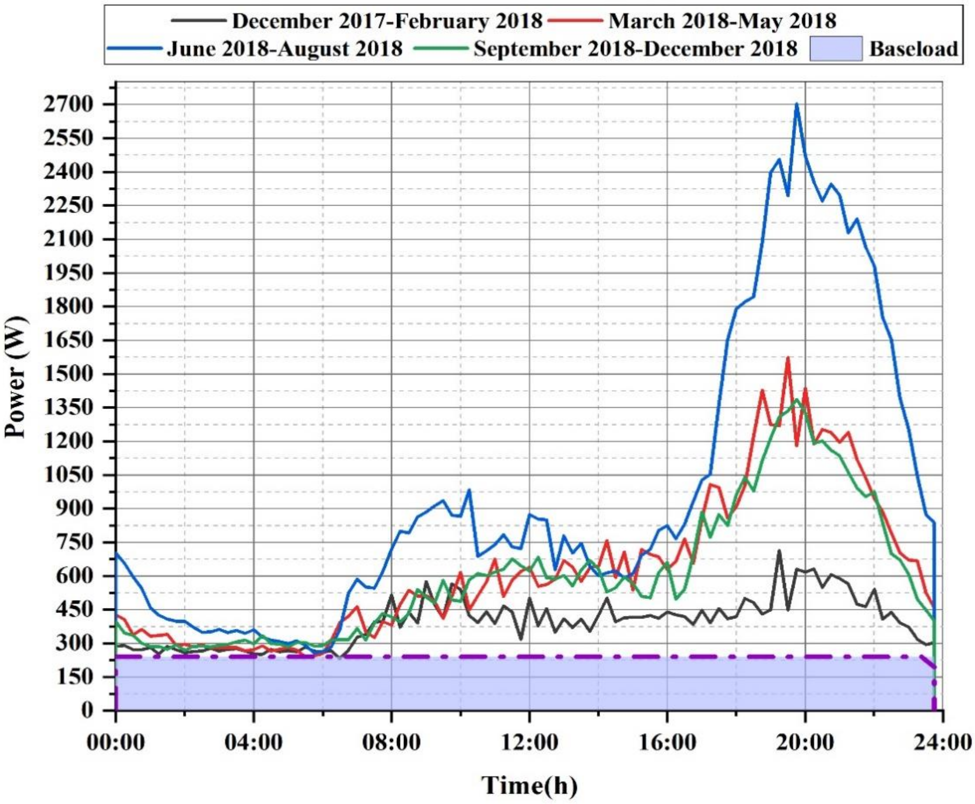


Figure 5.1 Gen Y load profile for four different seasons of the dataset period

The conventional morning and evening peaks can be seen in the plot representing the household consumption behaviour (Tomc and Vassallo 2016). Comparing seasonal consumption, winter period usage (June 2018–August 2018) had the highest demand (2700 W), which is usually due to the use of home heating appliances (Tomc and Vassallo

2016). In addition to the seasonal effect, occupancy may also affect the consumption, as seen in the summer period (December 2017–February 2018) compared with the other three seasons. This occurred because one resident (Unit A) travelled during that period, thus affecting the overall aggregated usage. The shoulder months (other than summer and winter) show idiosyncrasies in the load patterns. Figure 5.2 illustrates monthly energy usage for the Gen Y building compared with three-person detached household energy consumption. For clarity, the household size was kept equal in numbers (three) for both the actual data and the reference data. Other characteristics (e.g. dwelling construction and its relation to energy) were not considered. The benchmark data taken from (Allen 2015) calculated daily energy consumption throughout all quarters of the year.

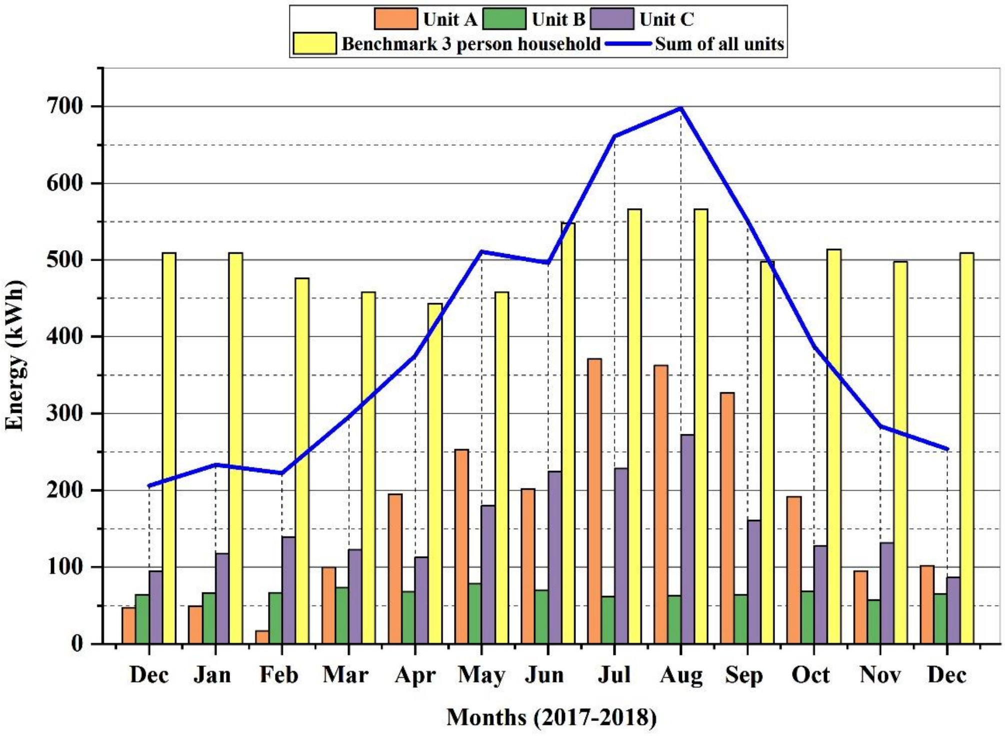


Figure 5.2 Monthly load consumption from Gen Y

The comparison resulted in 22% lower energy consumption of the Gen Y building than of the benchmark energy consumption data, not including the months of May 2018 and June 2018–September 2018, where apartments used heating appliances in the winter season. Grid imported electricity remained minimal because of the greater availability of PV and battery storage. The consumption other than the grid occurred from PV and battery storage computed by the net of the grid power from the total load.

The Evermore diurnal profile (Figure 5.3) for the entire apartment shows that the usual morning and evening peaks are higher than in Gen Y because the apartments in Evermore are larger. The dataset for this chart was collated from November 2018 to November 2019. The load profile of SHAC (Figure 5.4) illustrate much higher consumption, with a difference of peak load prolonged over a much larger period than seen in Evermore. The peak load in Evermore decreases after 8:00 pm whereas in SHAC, this occurs after 10:00 pm.

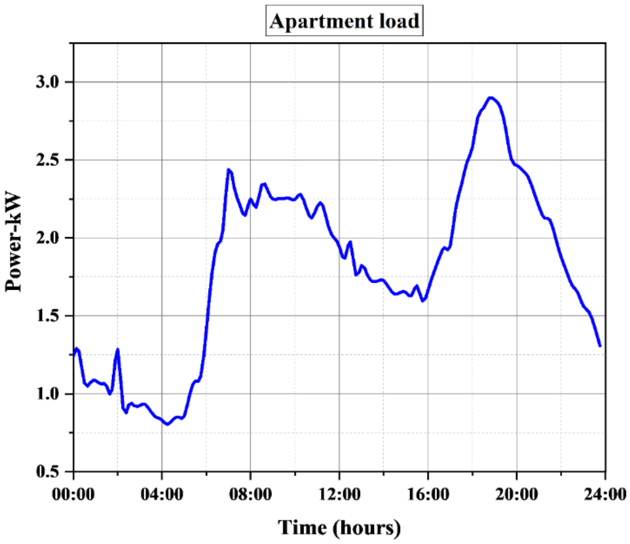


Figure 5.3 Evermore apartment diurnal load profile for period (November 2018–November 2019)

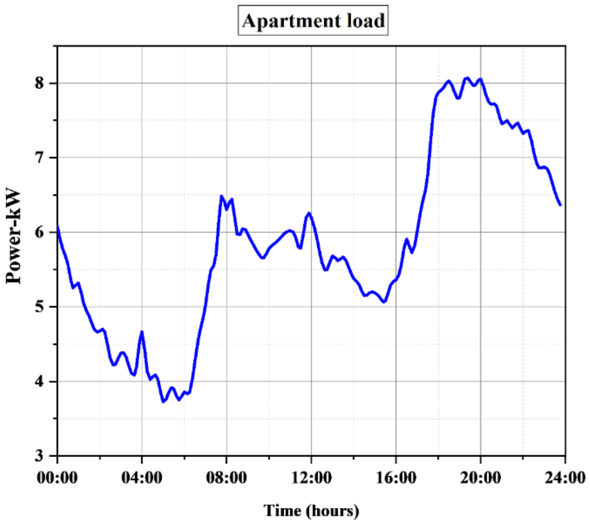


Figure 5.4 SHAC apartment diurnal load profile for period (November 2018–November 2019)

5.2 Seasonal Load Profiles

Estimating monthly load profile data from all seasons through diurnal analysis provides useful information about energy consumption patterns. This information could enable the optimisation of the microgrid based on the load data. The gathered data are from the southern hemisphere months of December (summer) and June (winter).

Figure 5.5 presents the seasonal profile for Gen Y. Given that Western Australia has 300 days of sunshine (average 8 hours/day) and irradiance of 5 kWh/m2/day, the summer period in the months of December to February experience full PV generation. A summer day shows a large section of PV generation feeding back to the grid (10:00 am–06:00 pm), with PV generation peaking at close to 5.8 kW.

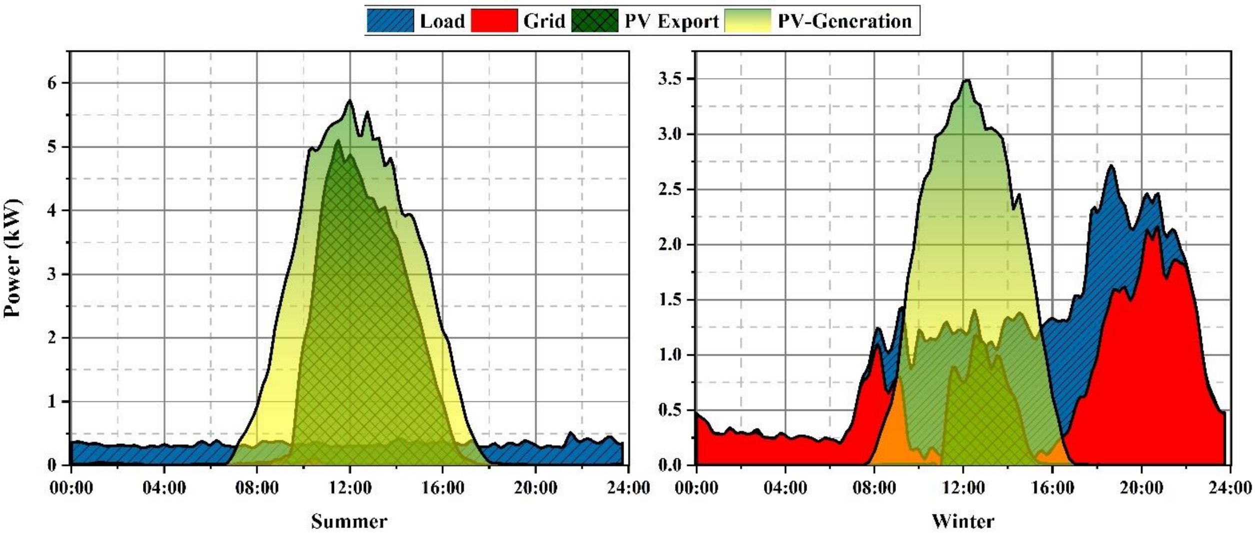


Figure 5.5 Seasonal load profile: Gen Y House

PV production at Evermore (Figure 5.6) measured 42 kW during the favourable diurnal summer profile. As a result, the grid import remained at a minimum, which occurred for two reasons. First, the connection of the AC-coupled system supplied the load power directly from the PV inverter. Second, the surplus generation adequately charged the batteries to supply apartment load demand. At Evermore, the exported PV energy to the grid was approximately 35% of the daily yield, and was approximately 63% at Gen Y.

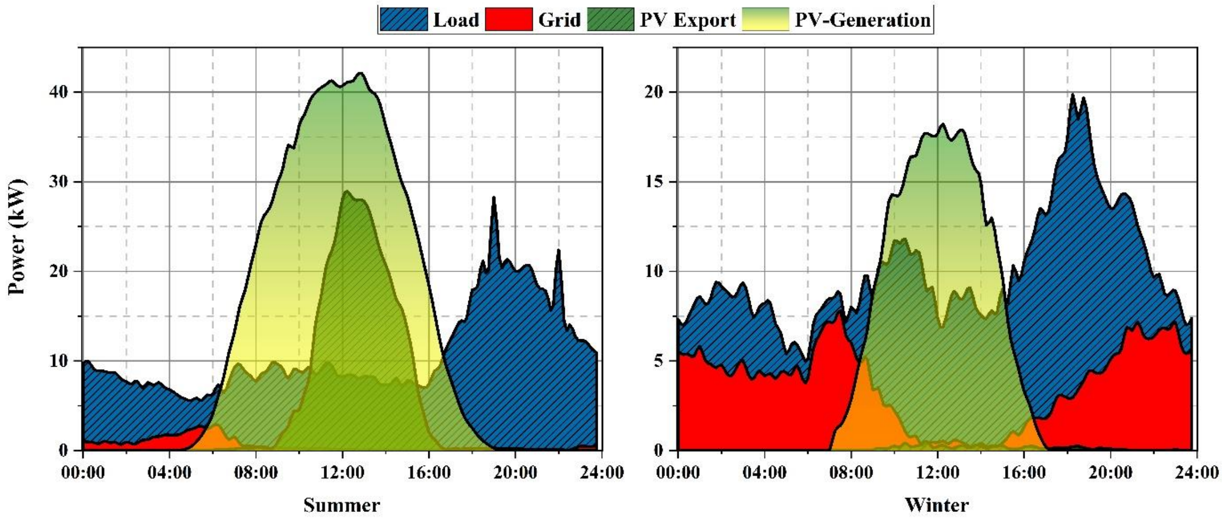


Figure 5.6 Seasonal load profile: Evermore

The seasonal profile in winter exhibits different trends because the grid is mostly used because of the lower availability of sunlight and the rain. This results in a lower generation to consumption ratio (Tomc and Vassallo 2016) and less storage (Chekired, Smara et al. 2017; Hachem-Vermette, Cubi et al. 2016; Bojić, Nikolić et al. 2011). Another reason for the different trends is that there is high electricity consumption because of the use of heating appliances in cold conditions.

Gen Y residents consumed 70% higher load power than in summer, PV generation remained lower, and an insignificant amount of PV was sent back to the grid. The winter charts presented in Figure 5.5 and Figure 5.6 consist of averaged measurements over one month of data in winter, where it is expected to have more days without PV generation, resulting in lower self-sufficiency. However, the presence of the battery in Gen Y SEM significantly improves the demand coverage in peak hours, which used 24% of the electricity from BESS on the worst performing day.

In contrast, winter load consumption at Evermore was 10% lower than in summer. As indicated by Breadsell, Byrne et al. (2019), one of the main reasons for this lower consumption is the usage of reverse cycle air-conditioning by some apartment dwellers rather than traditional gas or oil heaters, which consume more electricity than reverse cycle air-conditioning systems. Additionally, most of the dwellers were thermally comfortable in their apartments during winter and did not need extra heating appliances Breadsell, Byrne et al. (2019).

The interpretation of the SHAC temporal load patterns is slightly different from it is for Gen Y and Evermore. The energy plots show the combined output resulting from PV and BESS. As seen in Figure 5.7, data from a typical summer day reveals the renewable generation profile extended to a much longer period than was seen in the plots from Gen Y and Evermore, mainly because of the presence of storage capacity alongside PV generation. That is, the generation to consumption ratio on a summer is greatly reduced in SHAC compared with Gen Y and Evermore because of SHAC's undersized PV and battery storage. At SHAC, a small decrease in grid usage was observed during the daytime between 09:00 am and 07:30 pm, reaching load value again after 09:00 pm. In addition, a small amount of PV generation was exported during the daytime. The renewable generation from PV in winter remained lower than the load consumption. PV exports were almost negligible, while grid-imported energy was highest outside PV generation hours.

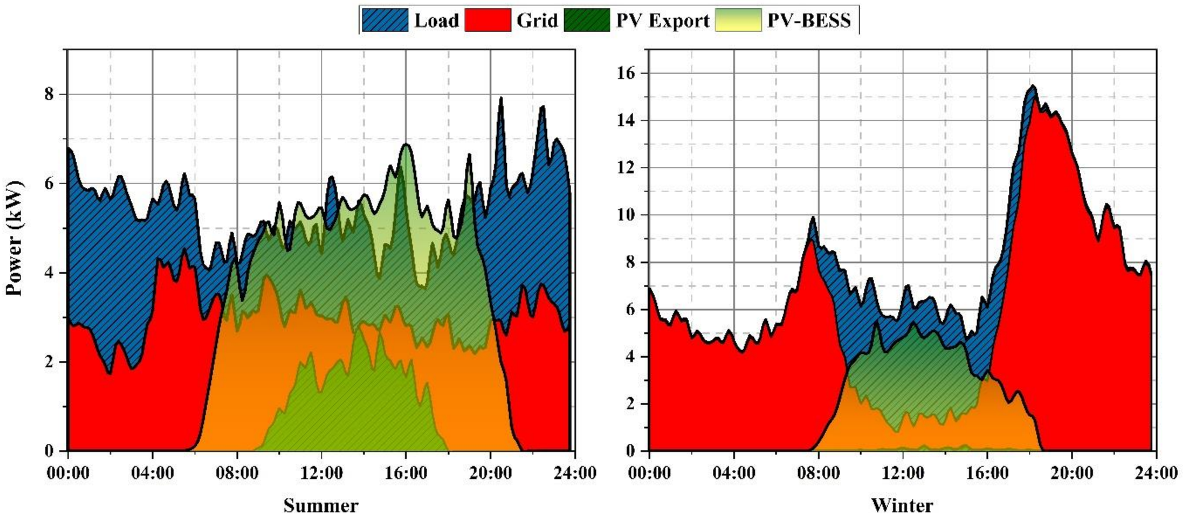


Figure 5.7 Seasonal load profile: SHAC

When comparing the PV generation to consumption plots of all apartments load profiles, the renewable systems at SHAC require optimisation strategies to shift the load or reduce peak-hour grid-imported electricity. Lower PV-storage capacity during winter can be expected from the systems at all three apartments. Load demand strategies and seasonal storage options are crucial for the winter months to achieve high self-sufficiency.

The large exports seem profitable in the form of feed-in tariffs, even considering the previous tariff rate of Western Australia (7 cents/kWh) (Li, Edwards et al. 2020) and that the time-of-use tariff introduced in November 2020, provides a lower benefit of 10 cents/kWh (3:00 pm–9:00 pm) and 3 cents/kWh at other times (Australian Government Department of Industry, Science, Energy and Resources 2020). Given that the internal strata electricity tariffs are still significantly less than the retail tariffs, strata developers may utilise these large PV exports as a potential way to access the wholesale market and implement community microgrid peer-to-peer trading mechanisms (Long, Wu et al. 2018a). 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 neighbour next door (Long, Wu et al. 2018b). From a systems perspective, the idle battery state with 100% SOC forced the export to the grid. Nevertheless, the active feed-in power is also effective for utility grid in relation to lower transmission losses and reduced investments in new generation units (Nwaigwe, Mutabilwa et al. 2019). In addition, the occupancy factor should not be overlooked because of dependence on load consumption. For example, occupants living at Gen Y had changing work schedules, which caused minimum and maximum consumption in particular months.

5.3 Diurnal Load Profiles

For building a more detailed load pattern, WGV data were accumulated for multiple months and analysed (Figure 5.8) as the average daily pattern of load consumption sourced from grid electricity and PV-BESS. Figure 5.8 represents total load consumption from each apartment as ‘load’, grid usage as ‘grid consumption’, and load consumed from PV and battery storage as ‘PV-BESS consumption’. The charts are differentially scaled according to the load consumption values.

The load patterns show idiosyncrasies for on-peak consumption in the morning period (06:00 am–10:00 am) and the evening period (06:00 am–09:00 pm), which form a ‘duck curve’ silhouette (Hou, Zhang et al. 2019; Kosowatz 2018). However, the charts presented in this study differ from the conventional duck curve which usually forms a dip in the mid-afternoon via solar integration, and then increasing to shape an arch later. In this study, the net load curve is flattened because of the SEM configurations containing battery storage.

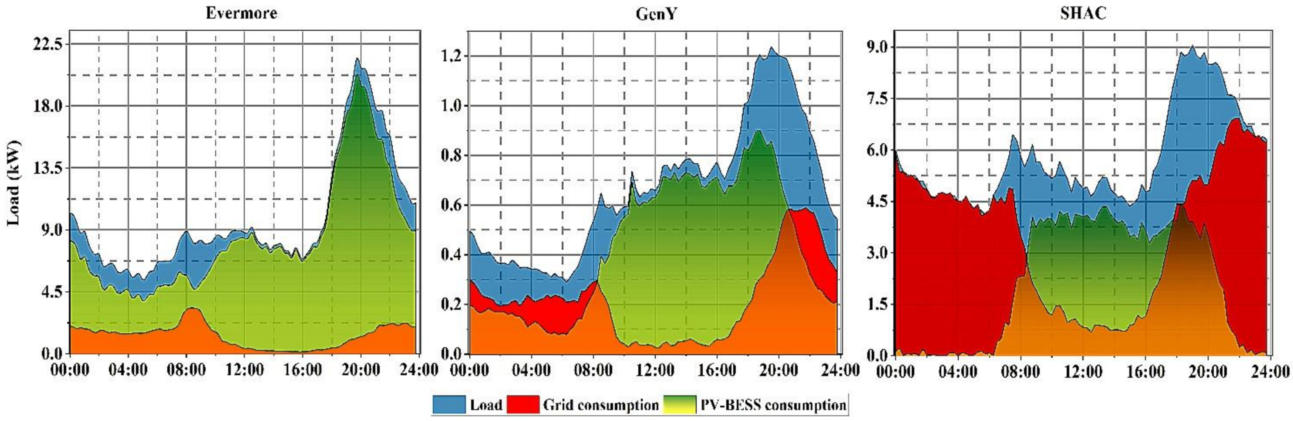


Figure 5.8 Diurnal load profiles from Evermore, Gen Y and SHAC

The load trends vary for each site in a different manner in the early hours of the day. Overall, the Evermore loads relied 30% on grid usage and 70% on PV-BESS. The large availability of battery storage in the evening as well as the AC-coupled PV system is the reason for the lower grid import. Similarly, Gen Y used more electricity from PV-BESS (59%) than from the grid (41%), while SHAC relied 60% on grid-sourced electricity and 40% on PV and battery storage. Evening peak hours are mostly emphasised in the literature because this period accounts for the maximum energy consumption in the residential sector(Andersen, Baldini et al. 2017).

Shared energy systems with BESS are found to reduce grid reliance during peak hours (Taşcikaraoğlu 2018). In peak hours, a major load portion was supplied by battery storage at Evermore (94%), while grid imports were at a minimum (6%). Similarly, the PV-BESS at Gen Y covered the greater portion of on-peak demand (66%) and the grid contributed (34%) during on-peak hours.

However, SHAC had a higher contribution of load consumption from the grid (60%) than from battery usage (40%). Unlike Evermore and Gen Y, the battery storage at SHAC decreased to a minimum before midnight and therefore, to establish the minimum SOC and system ancillary components, grid electricity was used. A graph illustrating the averaged diurnal share of PV-BESS and the grid is presented in Figure 5.9. The apartment load profiles shown here might vary from detached residential houses because of various factors such as building size, construction characteristics and household size (Roberts, Haghdadi et al. 2019b).

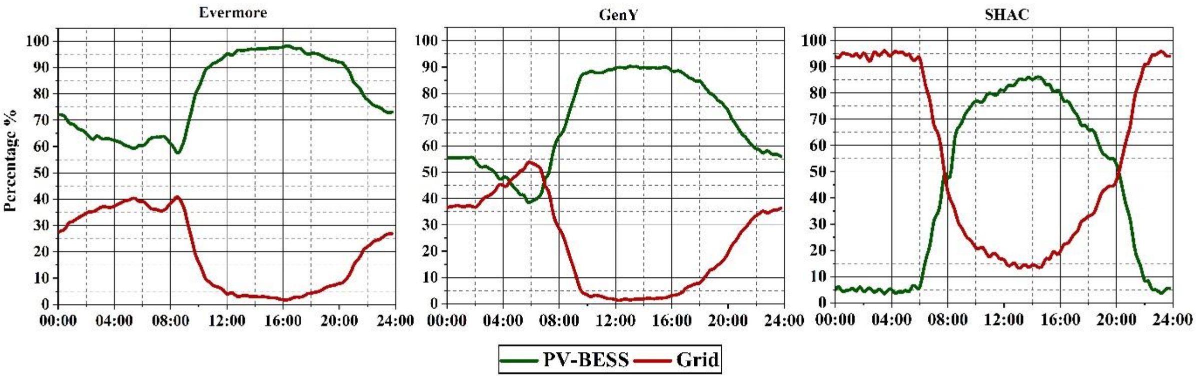


Figure 5.9 Averaged diurnal share from PV-BESS and grid at the three sites averaged over different periods: Evermore (November 2018–July 2019); Gen Y (January 2019–December 2019); SHAC (November 2018–June 2019).

In detached residential dwellings, energy usage patterns may fluctuate, and the load consumption might increase owing to the higher number of residents and larger living areas than are generally seen in apartments. Seasonal variation is another element that affects generation and consumption patterns. Nevertheless, the load distribution data from the PV-BESS and the grid illustrated in Figure 5.9 can enable demand optimisation of apartment loads in the future. In particular, the after diversity maximum demand, undertaken by the Western Power (Power 2017) can be implemented in suburbs with apartments that have installed SEM configurations.

5.4 Battery Storage

In Figure 5.10, the data from Gen Y BESS shows the daily average SOC over the four quarters in the calendar year (December 2017–December 2018). As stated, the depth of discharge of the BESS was set to 80% (i.e. 8 kWh of usable capacity to preserve the battery lifetime). Therefore, the graphs explicitly show 8 kWh of battery capacity at full SOC.

It is apparent from the plot that the self-consumption ratios change with the different seasons. The summer (December 2017–February 2018) and spring (September 2018–December 2018) profiles reveal a large capacity of storage over an extended period, which supports a shaving of the peak load while mitigating use of grid-imported electricity. Most commonly, First PV and then BESS supply residential loads during the daytime; however, during on-peak hours, the demand is usually higher in parallel with no generation and adequate storage-level availability, which increases cost of electricity bills.

SOC remained at 80% on average during the peak load period (6:00 pm–9:00 pm) in the summer season. As a result, the battery capacity of approximately 6.4 kWh was able to cover total load demand and achieved self-sufficiency of more than 80%. In contrast, the SOC in the winter season profile (June 2018–August 2018) reveals a small percentage of available storage because of the lower solar irradiance and rainy weather, which affect the battery charging process through the PV.

These outcomes can be compared with Vieira, Moura et al. (2017), who found that seasonal variations affect battery capacity. Despite these limitations, the storage capacity remained between 1.6 kWh and 3.2 kWh in the peak period.

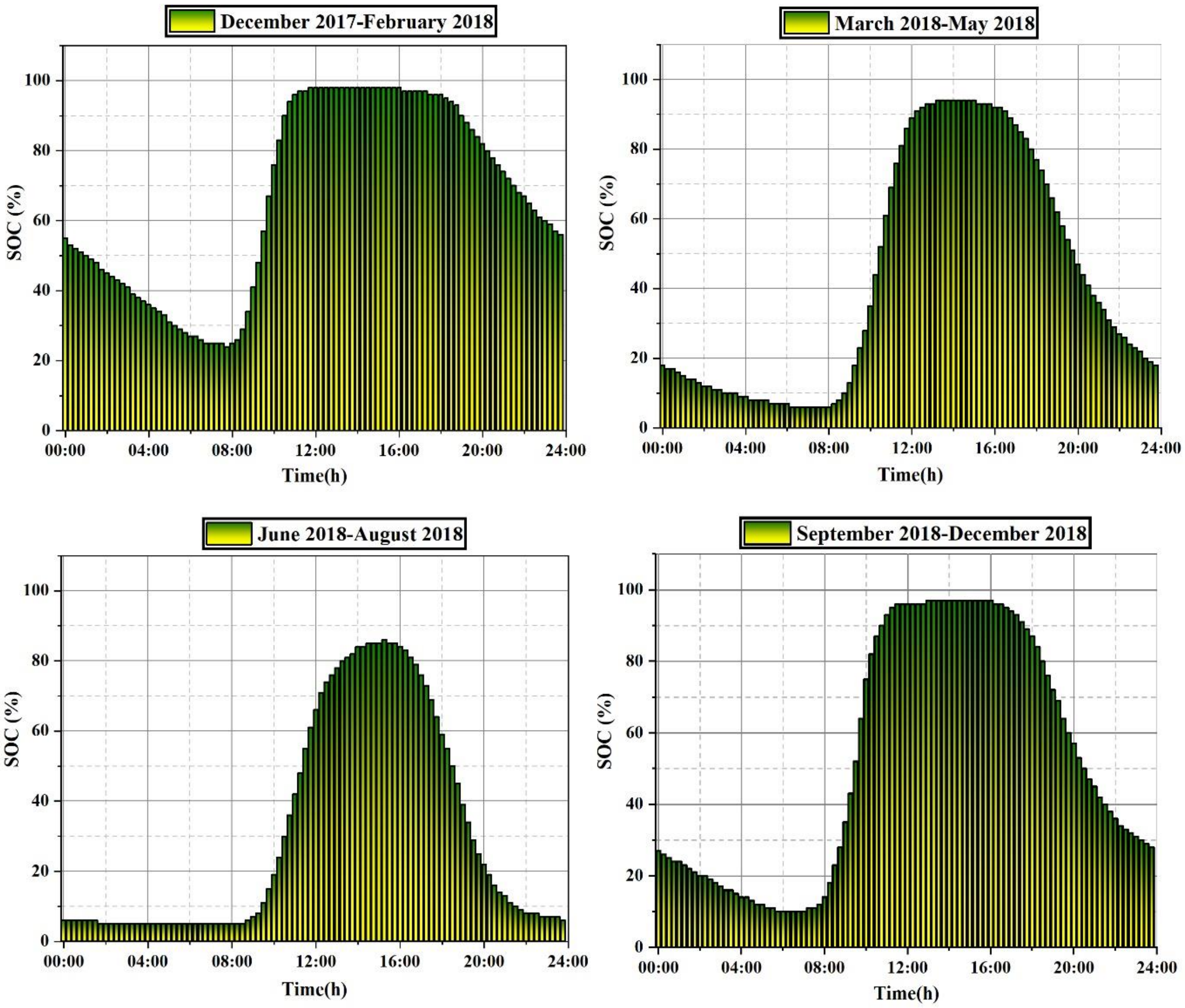


Figure 5.10 Gen Y BESS SOC profile during different periods of the dataset

Alongside SOC, it is also important to consider temporal battery storage use during seasonal changes (winter and summer). Figure 5.11 presents an example of evening storage, where the range of the time plot begins from early evening and goes until early morning (6:00 pm–6:00 am). The energy consumption during the summer peak period retained 2 kWh capacity, while usage increased to 40% in the winter season.

Because of the limitations of the standard tariffs used at WGV, time-of-use pricing is not applicable, that may benefit in optimising the battery storage capacity. Despite time-of-use pricing unavailability, various scheduling strategies (Roberts, Bruce et al. 2019c) for obtaining high self-sufficiency may be considered by designers. Referring to Figure 5.11, it is also suggested that shifting battery storage capacity to be utilised during the last portion of the evening (06:00 pm to 10:00 pm) could prove effective in winter. This stems from the fact that AC-coupled PV configuration supplies load during the daytime while if shifted to operate during the last portion of the evening, battery storage could reduce grid imports.

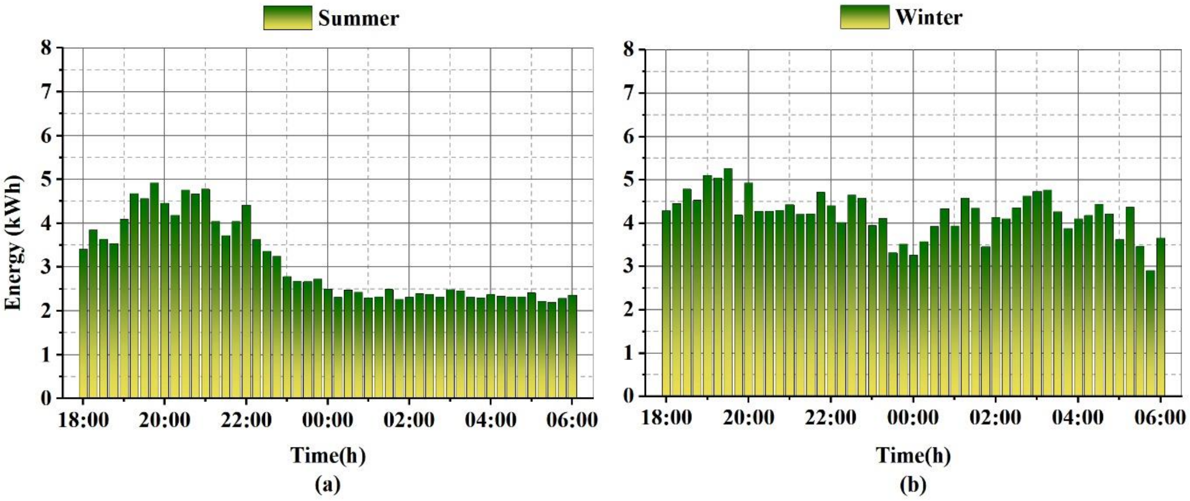


Figure 5.11 Battery consumption (averaged) during evening hours of (a) summer (b) winter

5.5 Self-Sufficiency

The load profiles provide a solid foundation for evaluating the monthly self-sufficiency of the apartment buildings. Monthly energy distribution for each site should is plotted, followed by the self-sufficiency results. Figure 5.12 is presented to demonstrate the load fractions from the grid and renewable sources for Gen Y residential units, forming the basis for self-sufficiency.

The load fraction shows that in Gen Y, Unit A and Unit C used more PV-generated energy (1286 kWh and 1252 kWh, respectively) than did Unit B, which consumed only 611 kWh.

Similarly, when the CP energy fraction is determined, grid consumption is seen to increase during the winter months from 40 kWh in May 2018 to 53 kWh in August 2018. Given that the CP load appliances mainly run during night hours, an increased grid import can be noted during winter demonstrating low availability of battery storage.

Figure 5.13 shows the monthly distribution of energy demand from each source (PV-BESS and grid) and the exported PV energy. The SSR’s are shown on the right side of the plot. A mismatch between PV production and the load consumption at Evermore caused high PV exports and low grid electricity imports (approximately 10%) during the first six months of the dataset. However, the last three months of the dataset illustrate an increase in grid electricity by 46%, likely because of the effects of the winter season reducing PV generation. The share of the PV-BESS at Evermore resulted in and average 78% SSR over the dataset period. Similarly, the system at Gen Y meets 95% of the summer load demand and 50% of the winter load demand.

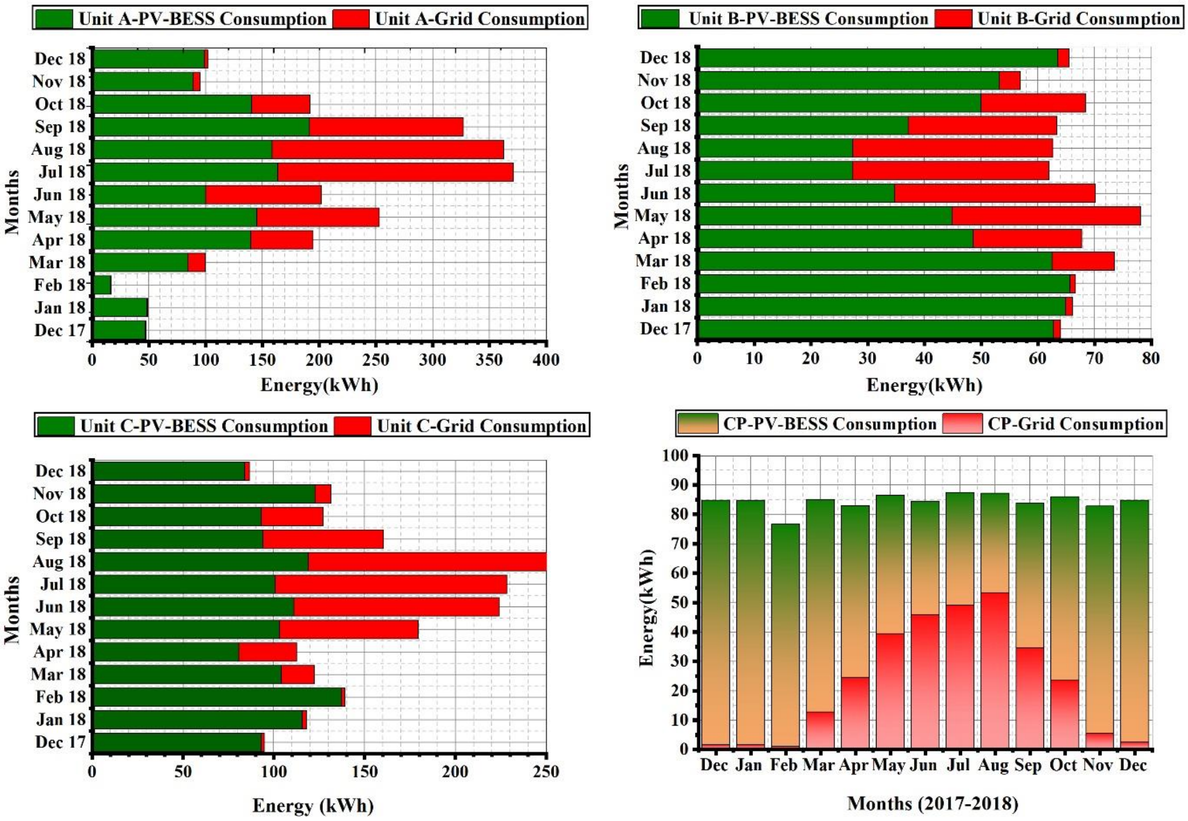


Figure 5.12 Energy fraction of Gen Y apartment units and CP consumption

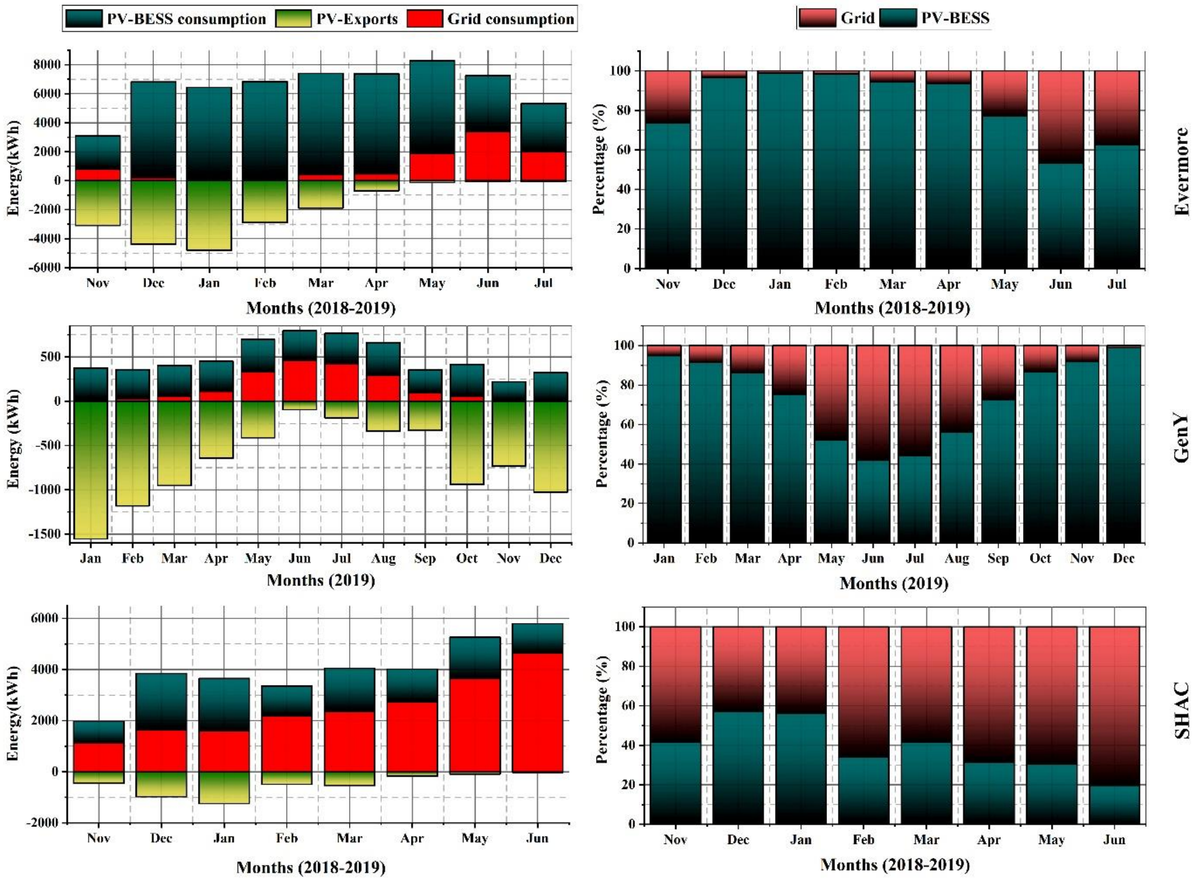


Figure 5.13 Monthly energy distribution (left) and resultant self-sufficiency (right)

For Gen Y, a large portion of PV energy was exported for almost six months of the dataset period because of high PV generation alongside reduced load consumption. Meanwhile, in the winter months (May to August), grid electricity import increased to approximately 50% of load value. Overall, Gen Y achieved 66% SSR for the dataset period. However, the SEM at SHAC depended mainly on electricity sourced from the grid (60%), resulting in an SSR of only 40%. The data presented in Figure 5.11 demonstrate that overall, the three apartments of WGV achieved 60% SSR. Seemingly, all charts illustrate high consumption from the grid in the winter months. Hybrid solutions for seasonal storage, such as hydrogen fuel-cell-based storage with PV-BESS, could be used to address this issue to significantly reduce grid usage. However, power converter efficiency should also be considered because electrochemical conversion losses have also been reported (Lokar and Virtič 2020).

Figure 5.14, Figure 5.15 and Figure 5.16 present charts from the updated data in the year 2020 based on parameters similar to those in Figure 5.13. The full-year data reveal that

Evermore achieved an average of 60% SSR, while Gen Y retained its average SSR from 2019 (78%). The decline in Evermore's SSR in Figure 5.14 is likely due to inclusion of full data for the period of August 2020–November 2020, which shows more consumption and use of grid energy. Nevertheless, the full data are satisfactory for Evermore and Gen Y because both apartments achieve the net-zero energy performance criterion (Berardi, Bisegna et al. 2018; Shin, Baltazar et al. 2019; Doiron, O'Brien et al. 2011). In contrast, the SSR of SHAC changed significantly. Renewable usage dropped twice as low as presented in Figure 5.13. Consequently, grid usage was increased, which reduced overall SSR (22.6%). Nevertheless, if PV exports are considered with PV-BESS usage, SHAC contributes to the PV generation, consumption and export of 50% from DRES (i.e. net zero).

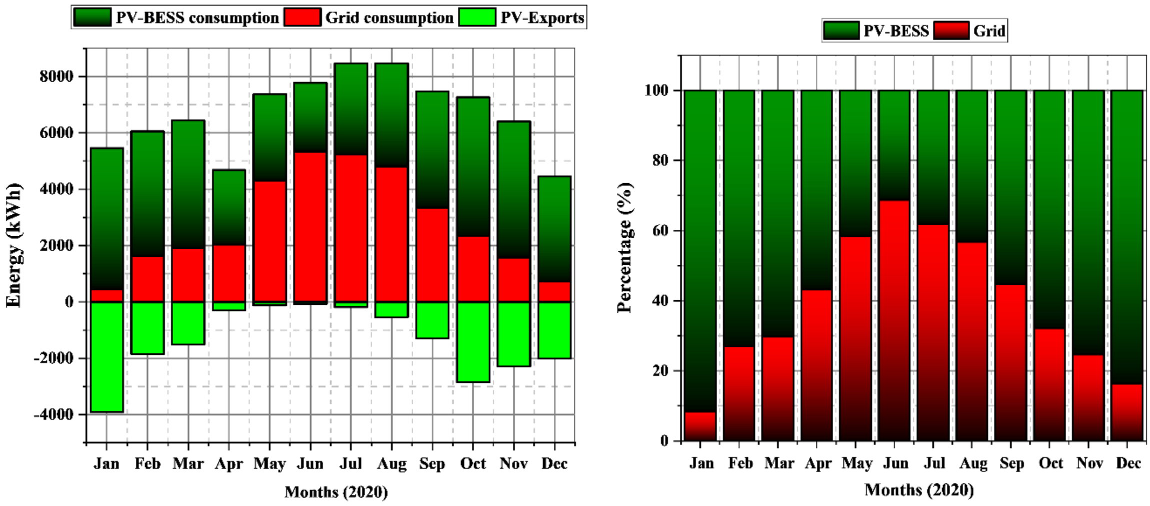


Figure 5.14 Evermore monthly energy distribution (left) and resultant self-sufficiency (right)

The high self-sufficiency at Evermore and Gen Y confirm that adequate storage capacity with PV generation is required (Barzegkar-Ntovom, Chatzigeorgiou et al. 2020). Li-ion battery technology provides high self-sufficiency results (De Oliviera e Silva and Hendrick 2017), leading to reduced grid usage (Fares and Webber 2017; Gupta, Bruce-Konuah et al. 2019). In shared microgrid conditions, the results support that central battery storage with PV enables high self-sufficiency (Marczinkowski and Østergaard 2018), while it also eliminates the complexity of multiple grid connections.

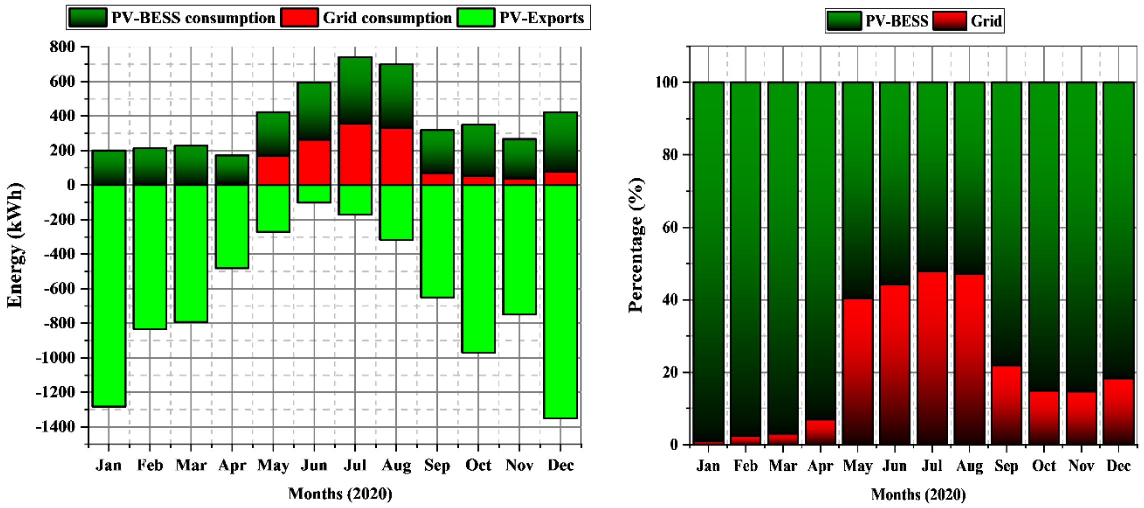


Figure 5.15 Gen Y monthly energy distribution (left) and resultant self-sufficiency (right)

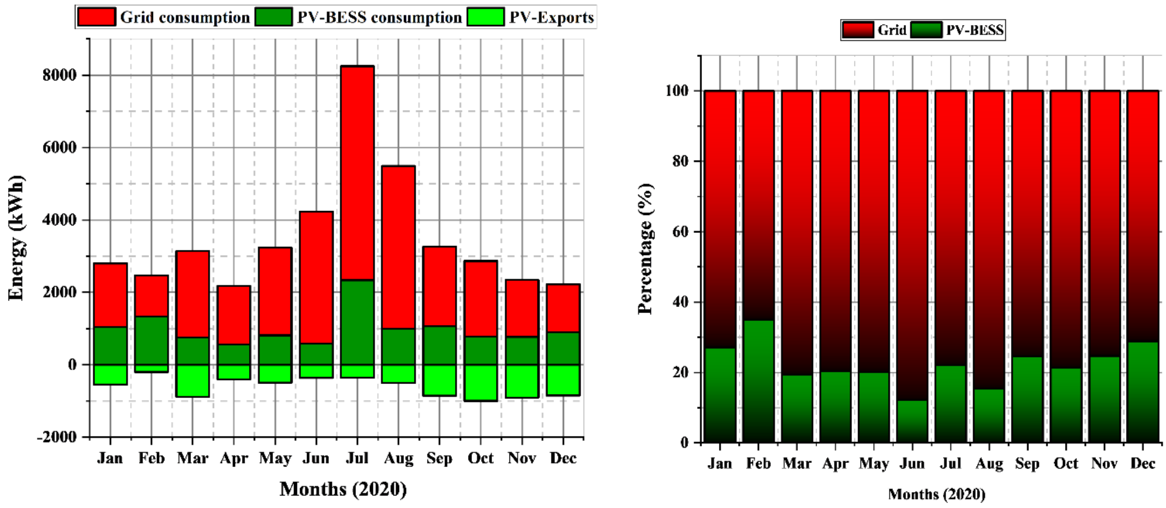


Figure 5.16 SHAC monthly energy distribution (left) and resultant self-sufficiency (right)

Further, the AC-coupled microgrid at Evermore and Gen Y obtained greater SSR than the DC-coupled system at SHAC. Nonetheless, both AC-coupled shared configurations bring technical merits and demerits. The number of (AC/DC) conversion losses and cost could be of critical importance when choosing any one configuration, while installation is considered a secondary factor. The perfect system selection can be identified only if a matched sized AC/DC-coupled PV-storage configuration is commissioned to supply a fixed load and then system efficiency is compared.

The decreased SSR in SHAC is the result of an undersized PV storage in relation to the number of households. This is evident from the PV allocation to consumer ratio by comparing three apartments where the value for SHAC (1.4) is less than that of Evermore (2.275) and Gen Y (2.25). Further research should explore energy optimisation in relation to sharing and distribution in the microgrid. Other factors which can decrease SSR include consumer behaviour and consumer mobility. Certain measures could be taken to enhance the energy performance of the shared systems. PV-BESS dispatching optimisation with load forecast estimation methods can be implemented but this relies on historical energy data, weather information and tariff structure. In contrast, long-term forecasting with the stochastic nature of DRES cannot be promised to be accurate because while weather and historical usage data can be used as inputs, they are not adequate to predict the exact load pattern.

Although the reduced SSR in winters can be ameliorated through implementing many optimisation strategies, the export limitation method can be applied as a basic solution. If the battery holds the capacity in the final hours of the day and SEM is set to zero export in surplus generation periods, the outcomes will indicate increased self-sufficiency. Figure 5.17 presents the average export pattern during the winter season (May–August 2018), and the total export energy per month is presented in Figure 5.17(b). Exported energy seen in Figure 5.17(b) is then utilised to meet residential load demand, which reflects the SSR in the months of May–August. 2018 to 88%, 74%, 66%, and 82%, respectively, as presented in Figure 5.17(c).

Other than optimisation, the occupancy of dwellers at certain hours is not assured, which may additionally enhance or reduce the energy performance metrics (i.e. the possibility of higher or lower grid usage depending on the changes in consumers' occupancy during winter).

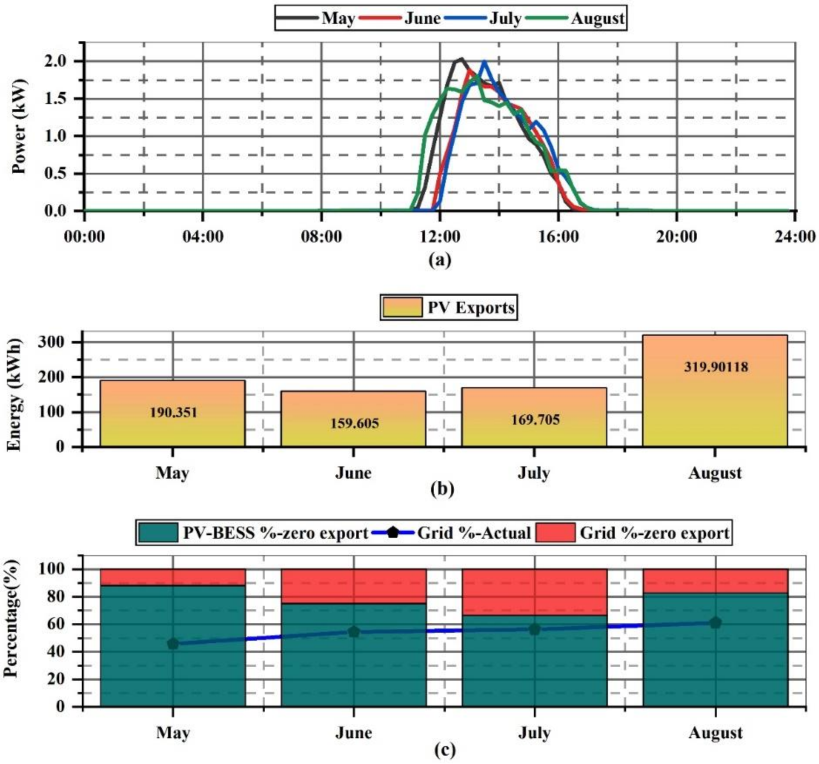


Figure 5.17 PV export limitation (May to August 2018): (a) Export energy pattern during winter; (b) Monthly PV exports; (c) SSR after zero export

A time-of-use tariff can provide a good opportunity for consumers to schedule electricity usage during an economically beneficial tariff interval. It also unlocks the possibility of a price-based forecasting input. Indeed, the application of multiple forecasting methods, which could also include the factor of consumer occupancy changes, might be effective in setting PV-BESS to achieve high self-sufficiency.

It is now certain that large battery size increases self-sufficiency (Syed, Morrison et al. 2020b). However, on each added battery capacity, the ratio of battery size increment and self-sufficiency becomes lower (Khalilpour and Vassallo 2016). This varying effect of battery size on SSR is shown in Figure 5.18. The estimation of battery size versus SSR was computed based on parameters from the periodic data, including apartment load consumption, system PV generation, and the renewable energy fraction (Figure 5.19). This assessment can be seen from system operational data rather than conventional modelling, which considers parameters such as voltage, current, ampere hour and depth of discharge.

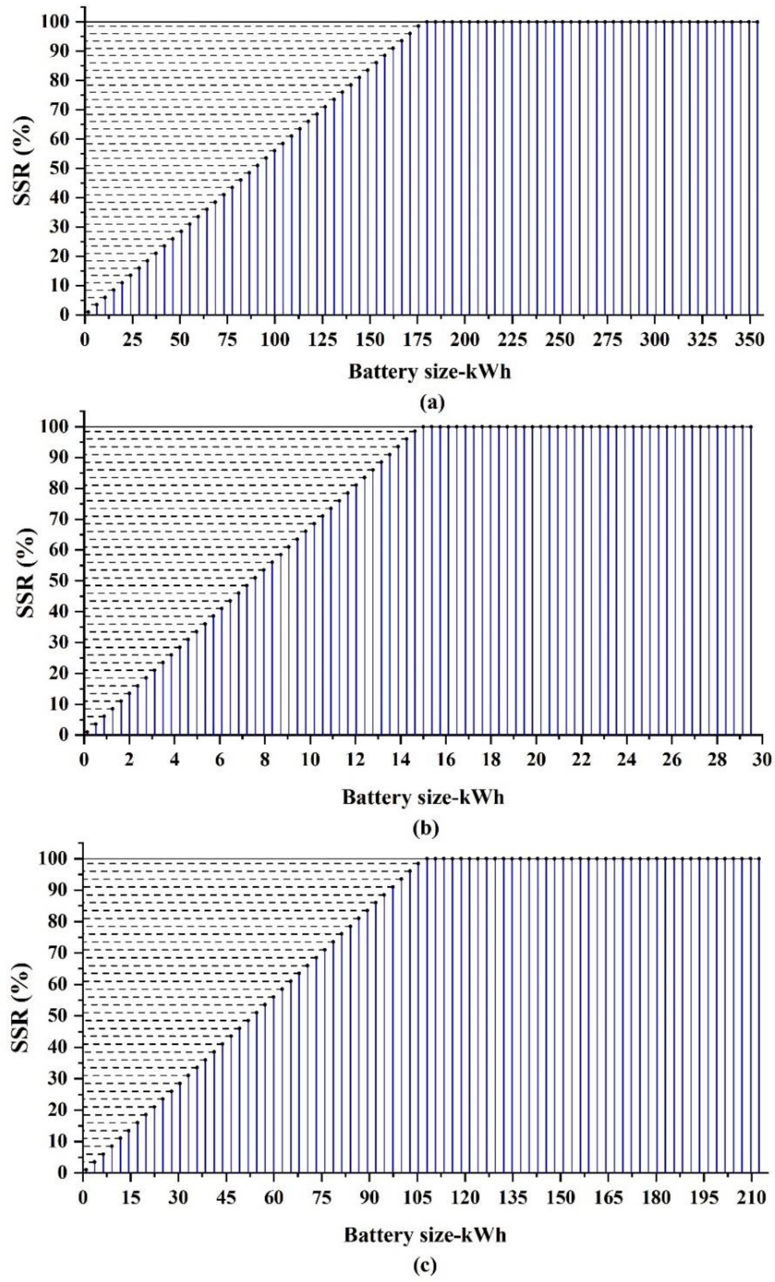


Figure 5.18 Battery size effect on the SSR: (a) Evermore (installed battery xx kWh); (b) Gen Y (installed battery yy kWh); (c) SHAC (installed battery zz kWh)

In addition, the shared microgrid at Evermore and Gen Y is AC coupled, therefore PV generation meets load demand in parallel to charging, which means that the primary criterion of load consumption was selected. Based on per-day average load consumption and SSR, the desired PV generation was ascertained by the PV utilisation factor, which determines the ratio between PV generation, the renewable fraction and losses (Weniger, Tjaden et al. 2014). After daily PV generation was calculated, PV and battery storage were proportionally sized. The design method of the PV and battery storage system can be found in the literature (Weniger, Tjaden et al. 2014) on optimal sizing for PV and battery storage.

It is apparent that beyond a certain increase in battery capacity, the SSR marginally increases until the horizontal curve becomes flat (Quoilin and Zucker 2016; Ollas, Persson et al. 2018). Likewise, the economic disadvantages of an increased but costly system sizing and operational performance cannot be avoided.

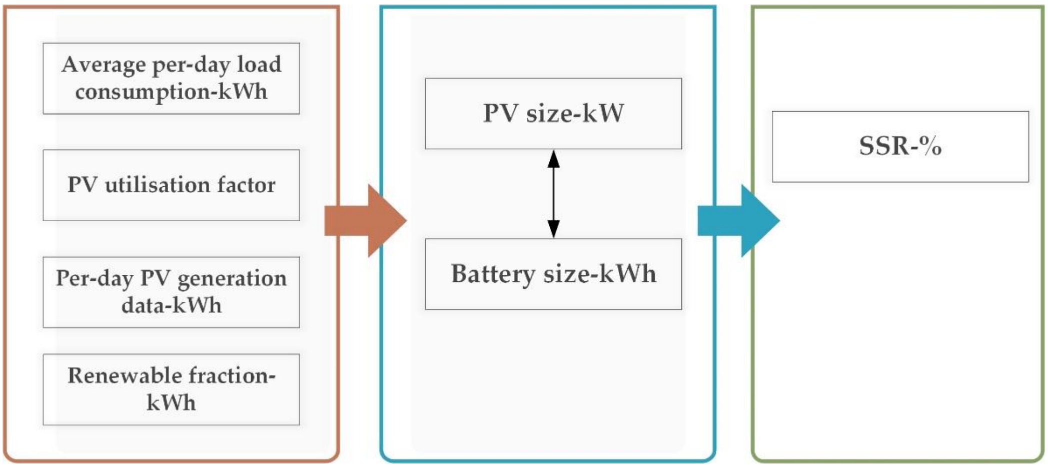
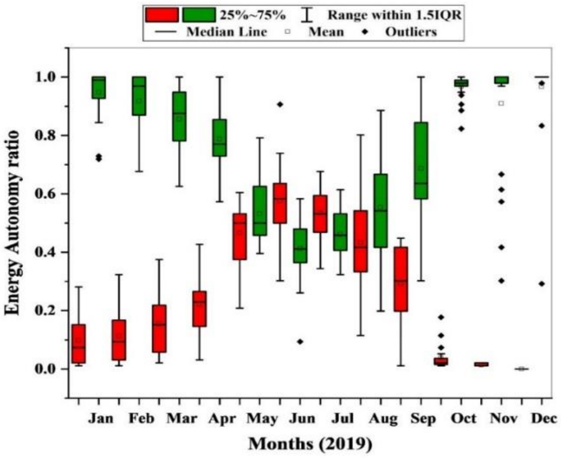


Figure 5.19 Estimation method of battery size effect on SSR

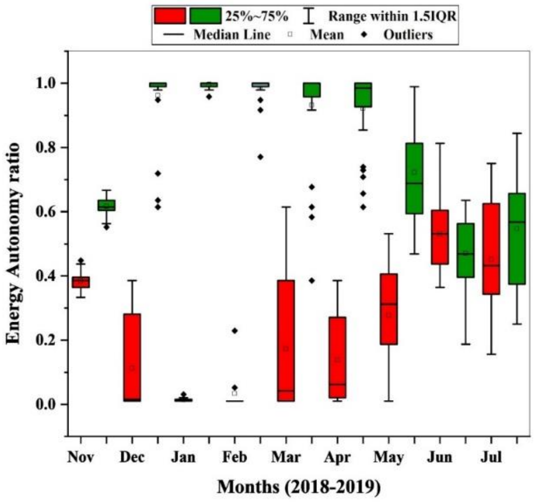
Although the cost factor ($/kWh) of changing battery sizes with SSR would need further analysis, and might affect the installation of PV battery storage, it is also important to regulate additional battery cost less than demand charges. Certain measures can be taken to enhance net present value (NPV) and payback periods, for example, decreasing PV size while maintaining definite battery storage (DiOrio, Dobos et al. 2015). This is largely due to load consumption occurring in the morning and evening periods, when the PV generation is usually lower. Therefore, system optimisation is important for finding the optimal PV-BESS configuration in relation to costs (Khalilpour and Vassallo 2016; Boeckl and Kienberger 2019). It is suggested that forthcoming studies conduct an economic analysis of changing battery sizes with SSR evaluation for multiresidential buildings.

5.6 Energy Autonomy

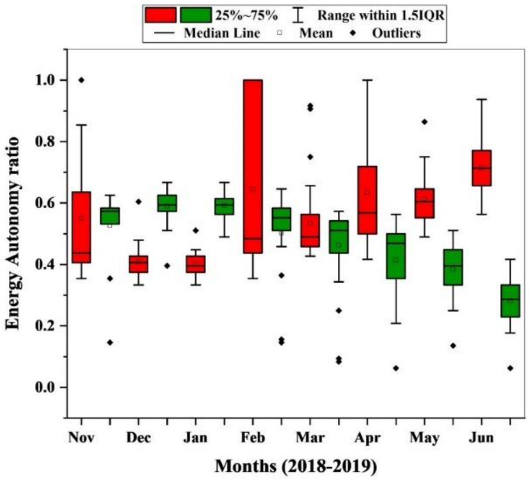
SEM configurations at WGV are mostly grid connected, so achieving 100% energy autonomy over an extended period is unattainable. The boxplot in Figure 5.20 illustrates energy autonomy, which is the ratio of the period when PV battery storage was operational, and is larger than equal to 50% of the total load.



(a)



(b)



(c)

Figure 5.20 Energy-autonomy ratio for configurations at the three sites: (a) Evermore; (b) Gen Y; (c) SHAC

Through the distribution of daily autonomy, the chart determines the symmetry and skewness of the period when grid or PV-BESS were sourced. The consumption period from PV-BESS is represented by the green boxes, while the grid consumption period is represented by red boxes. The time-series data for these charts was managed by calculating the proportion of grid and PV-BESS usage from the total load by applying the same criteria as detailed in Section 4.4.

5.7 Common Areas Electricity

This section discusses the outcomes obtained by analysing data from CP metering, thus answering RQ4: What are the outcomes of PV-BESS deployment in relation to meeting CP load demand?

In the literature, CP load demand is usually sourced through the grid and PV (Sun, Kiaee et al. 2018; Sajjad, Manganelli et al. 2015). At the WGV apartments, the CP load connected to SEM is supplied by the grid, PV and BESS. The average daily demand from the common areas of the three apartments is presented in Figure 5.21. The averaged time-series data consisted of 15-minute measurements over one year (January 2019–December 2019). Because of the differences in CP geographical area, appliances and operational sequence, the data representation varies at the three sites. The Gen Y chart shows a much flatter response, whereas Evermore consumption peaks at midday and in the evening period (9:00 pm). CP load at the Gen Y site is relatively smaller than is seen in high-rise apartments (Myors, O'Leary et al. 2005) and than is seen in Evermore and SHAC. The load patterns illustrate an identical trend with little variation in the power pattern because of unchanging operation (Syed, Hansen et al. 2020).

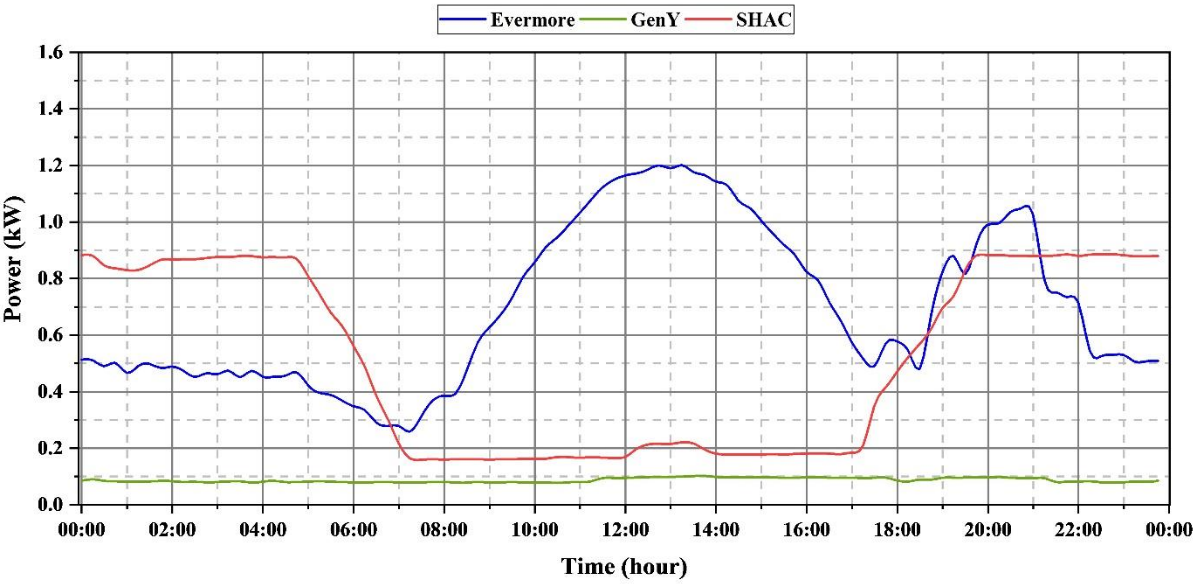


Figure 5.21 Weekday CP load profile averaged over the dataset period

The CP load circuit operates the walkway lights in the evening hours until morning, but the sensors receive uninterruptible power from supplies. The SHAC CP load patterns provide a conventional load sequence (for common areas), which increases in the evening hours until the morning period (Komendantova, Manuel Schwarz et al. 2018). This increase occurs because of the requirement for operating light during that particular period. As discussed, the CP load pattern can alter depending on the requirements and structure of the dwelling. In some instances, CP load is higher during the daytime, which is evident for Evermore. This is mainly because of the heating and ventilation requirements of the battery room. The large battery room with different switchboards for the electrical circuit and appliances created heat generated by switching of power electronic components, therefore the temperature was controlled by the ventilator fans and air-conditioner in the room.

In addition, the switchboard room at Evermore was constructed in an open space away from the individual apartment units; thus, it received direct sunlight on its roof and walls around midday, contributing to increased heat inside the battery room. In contrast, at Gen Y and

SHAC, battery rooms were located on the shaded ground floor, facilitating sufficient wind passage. This means that ventilator fans were sufficient for maintaining the temperature. The daylight period energy usage of SHAC's CP was smaller than in the evening.

Nevertheless, the load patterns presented in Figure 5.21 identify an intriguing case of meeting CP demand by renewables at separate times of a day. For example, most of the load demand at Evermore can be met through solar PV. However, if considering the similar case of SHAC, the apartments relying only on a PV source would need support from battery storage to reduce the evening grid electricity usage. Figure 5.22 presents the weekend CP load consumption trends based on the same data period; however, the CP load profiles show no special difference between the weekday and weekend trends (Choi, Cho et al. 2012; Ur Rehman, Bhatti et al. 2020), thus exhibiting a fixed load switching sequence of common areas.

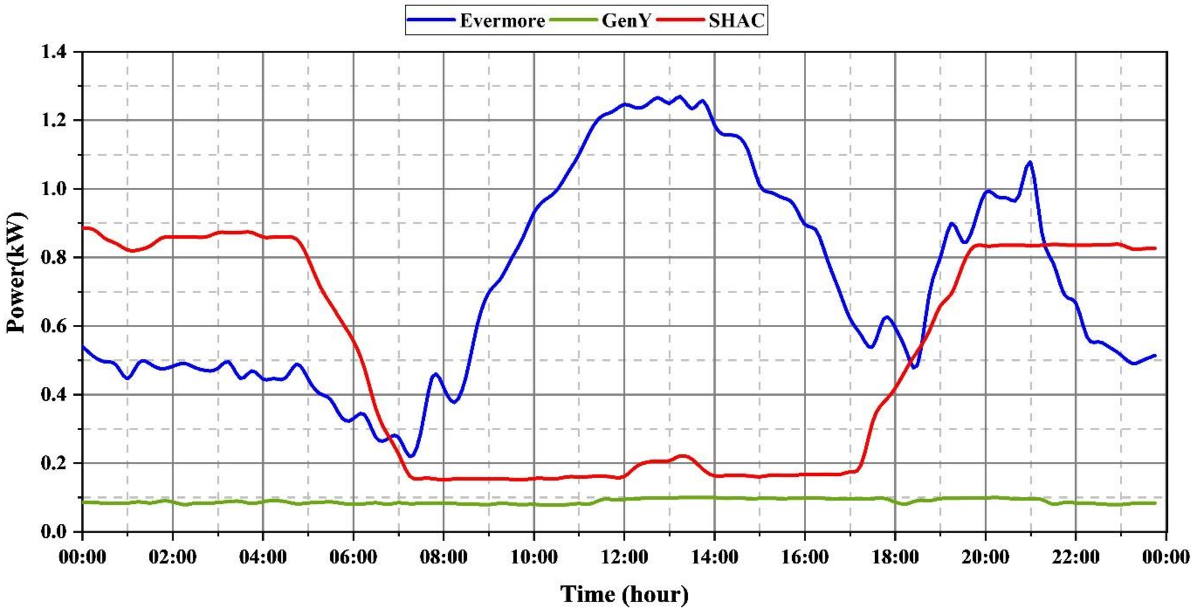


Figure 5.22 Weekend CP load profile averaged over the dataset period

Figure 5.23 presents the monthly CP load consumption over the same data period as shown in Figure 5.22. The charts indicate homogeneous consumption of CP load in SHAC and Gen Y with no seasonal effect observed. The Evermore apartments had high electricity consumption in the summer because of the aforementioned space-cooling requirements inside the battery room.

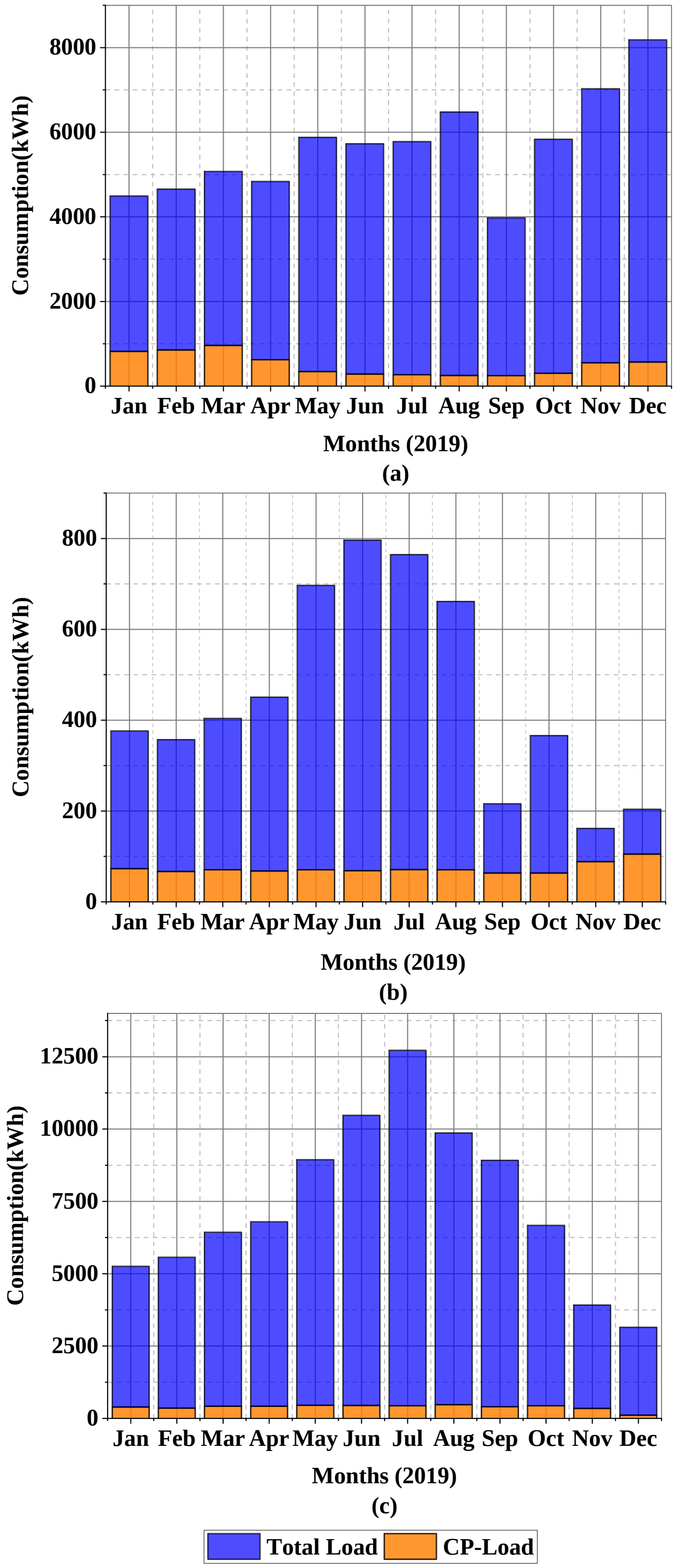


Figure 5.23 Monthly consumption proportion of total apartment load and CP for each site: (a) Evermore; (b) Gen Y; (c) SHAC

As discussed, the load of the common areas can vary according to the apartment building requirements such as coverage area and time-of-use. The high heating and cooling requirements in high-rise apartments may also have a significant influence on the monthly energy consumption of common areas. In addition, high-rise apartments usually have elevators for vertical transport. Apartments may also require a large carpark underground, thus requiring non-stop ventilation and lighting.

The total apartment load to CP load ratio suggests a relatively smaller CP load in the three sites (Table 5.1), which has been documented as being a great deal higher in other research, and could be larger than the sum of individual apartment consumption (Roberts 2016).

Table 5.1 CP load to total load ratio of WGV apartments

Apartment	Total Load (kWh)	CP Load (kWh)	Proportion (%)
Evermore	67936.188	6071.057145	8.93
Gen Y	5452.007	878.793	16.11
SHAC	108154.9	5977.335	5.52

Irrespective of CP load size, the main objective here is to analyse how PV and battery storage in SEM mitigate grid reliance while meeting CP demand. This presents an important topic for most apartments without PV and battery storage systems, which thus rely heavily on wholesale market electricity.

5.8 Energy Allocation Strategies

Based on the CP load proportion (Table 5.1), the shared configurations of SEM and the load patterns (Figure 5.21 and Figure 5.22), the energy allocation strategies will be explored with the motive of providing knowledge on energy sharing and grid electricity reduction.

5.8.1 Instantaneous consumption

The IC strategy distributes a portion of renewable and grid energy based on instantaneous load demand. Figure 5.24 illustrates renewable fraction and grid consumption of CP loads in the three sites. The pie charts on the left show energy fraction percentages from PV-BESS and the grid over the dataset period (January 2019–December 2019). The CP load distribution on a monthly basis is shown on the right side, apportioned according to PV-BESS and grid usage. The metric can also be specified as self-sufficiency (Syed, Morrison et al. 2020b). Evermore and Gen Y show identical trends (i.e. renewable usage of 66% and grid electricity imports of 33%) while SHAC relied 47% on renewables and 53% on the grid.

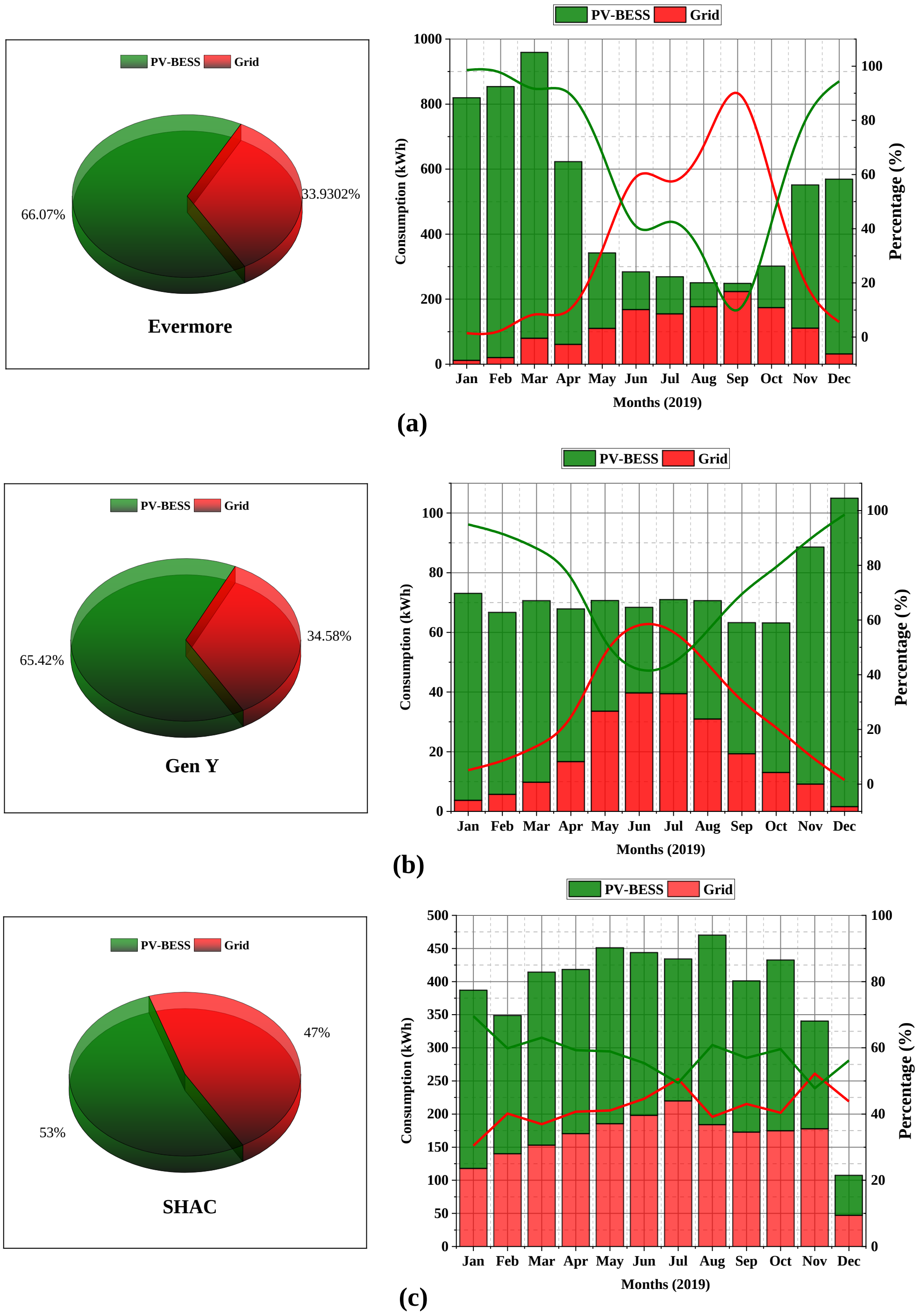


Figure 5.24 Total renewable and grid fractions for CP load represented by pie chart with monthly bar graphs of using IC: (a) Evermore; (b) Gen Y; (c) SHAC

The CP consumption trends illustrate monthly consumption against a line chart of energy fraction percentages from the grid and PV-BESS. The CP bar charts present IC. Apparently, the three sites demonstrate a seasonal variation load effect during the winter months (May–August), which is likely due to consecutive usage of heating and the unavailability of adequate PV generation reducing renewables usage in the evening (Syed, Hansen et al. 2020; Syed, Morrison et al. 2020b). Given that a centralised microgrid shares energy to all connected loads, the low PV generation availability demands high energy from the grid. However, the summer months (December–March) see large energy production and supply from PV-BESS.

Given that CP usage at SHAC increases in the evening period, more battery storage would be required in SHAC than by Evermore and Gen Y to meet CP demand.

Without considering the load patterns, adequate PV and battery storage capacity is essential. In most apartments, where consumption of common areas is larger than in the individual apartments, the IC strategy would certainly need system optimisation to allocate more renewable energy from the shared microgrid to common areas. Further, seasonal effects on load demand might be addressed by integrating hydrogen-based solutions for common areas (Leonard and Michaelides 2018).

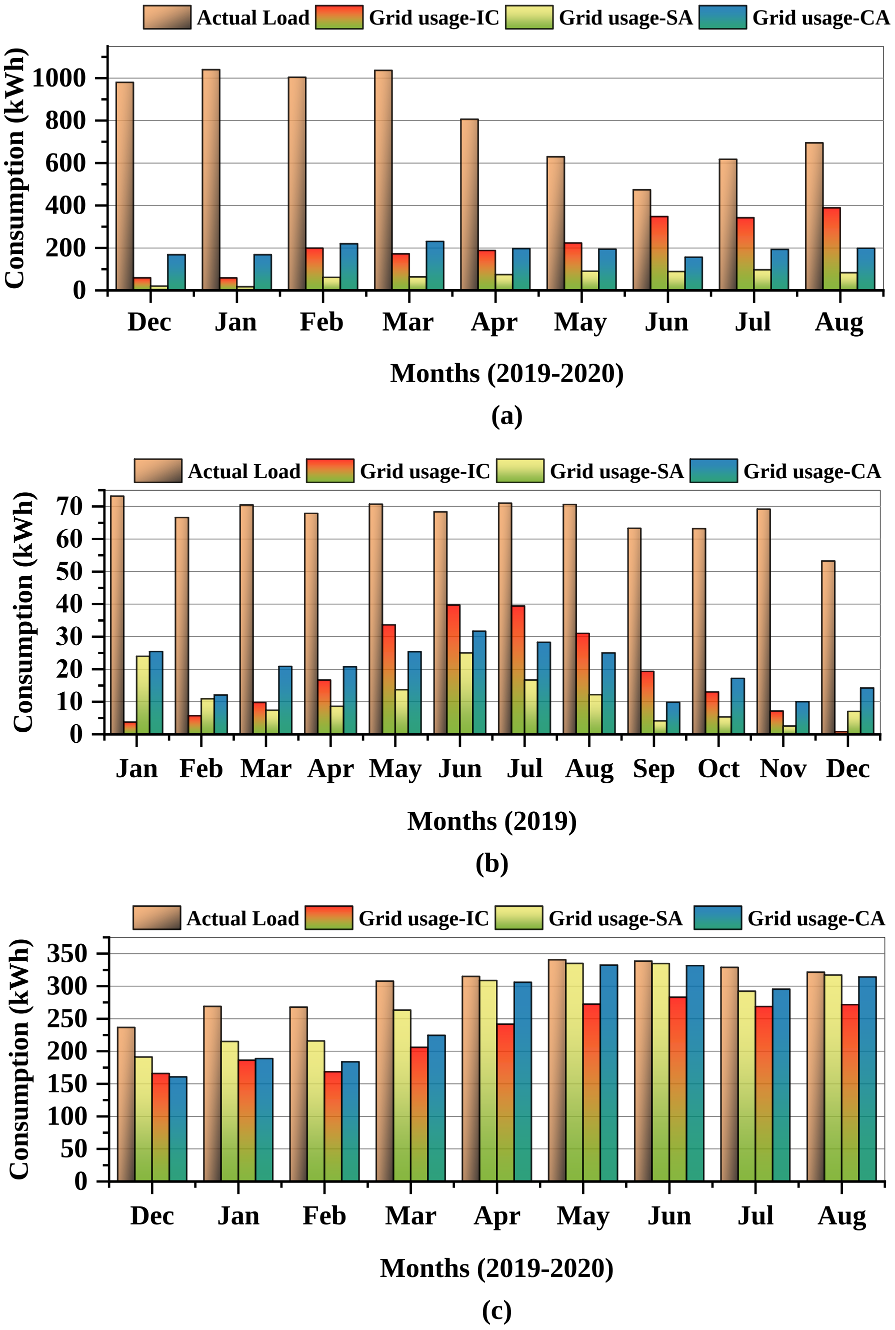
5.8.2 Comparison of strategies

This section compares the three strategies (IC, SA, and CA) and analyses monthly grid reduction for different datasets. The Gen Y dataset was similar to the CP load profile presented in Figure 5.21, while the datasets for Evermore and SHAC were chosen for the period December 2019–August 2020. As illustrated in Figure 5.25, SA at Evermore reduced 91% of grid consumption, CA reduced 76% and IC reduced 72%. Similarly, at Gen Y, SA reduced 82% of grid consumption, IC reduced 72%, and CA reduced 70%.

SHAC experienced high grid usage because of its undersized microgrid in parallel with large load consumption (Syed, Morrison et al. 2020b). The highest grid abatement was achieved by IC (24%), followed by CA (14%), and SA (9%). Notably, the three strategies attained grid usage reduction in a different manner across all apartments, except SA, which contributed the largest reduction in Evermore and Gen Y.

The analysed data did not identify any seasonal variation trends at Evermore; however, Gen Y and SHAC experienced their highest consumption in winter (May–August). Presumably, the large excess energy availability at Evermore and Gen Y reduced large grid imports through the SA strategy. Similarly, low PV production and large load consumption in SHAC contributed to lower grid mitigation from SA. Table 5.2, Table 5.4 and Table 5.6 provide the details of monthly energy distribution.

If seasonal variation is considered, surplus PV generation is foreseen in summer months (December–March). The remaining generation capacity after implementation of any strategy will also depend on individual apartment consumption influencing the CP load demand. The excess PV energy is presented in Figure 5.26, obtained after energy exchanges were carried out by the three strategies. This implies that the apartment and CP loads utilised renewable energy at each time interval and the remaining surplus energy was then aggregated. The cost credits arising from the monthly excess energy are shown on the right axis.



(a)

(b)

(c)

Figure 5.25 Comparison of three strategies to analyse grid usage reduction: (a) Evermore; (b) Gen Y; (c) SHAC

The excess energy internal tariff rate was selected at 15 cents/kWh. Excess energy is plainly defined in following equations as ‘Excess’, followed by each strategy’s acronym.

The related costs from the three strategies are computed as stated in Equations 10–12 below

For IC: If surplus exported to the grid = Excess-IC (kWh), then,

$$\text{Cost IC (\$)} = \text{Excess-IC (kWh)} \times 0.15 \qquad \textbf{(10)}$$

For SA: If CPcalc > 0; CPcalc = Excess-SA (kWh), then,

$$\text{Cost SA (\$)} = \text{Excess-SA (kWh)} \times 0.15 \qquad \textbf{(11)}$$

For CA: If CPx > 0; Sum of all CPx = Excess-CA (kWh), then,

$$\text{Cost CA (\$)} = \text{Excess-CA (kWh)} \times 0.15 \qquad \textbf{(12)}$$

The summer period generates more surplus energy. This is shown in the chart, where it is seen that the December–February months provide the highest excess energy.

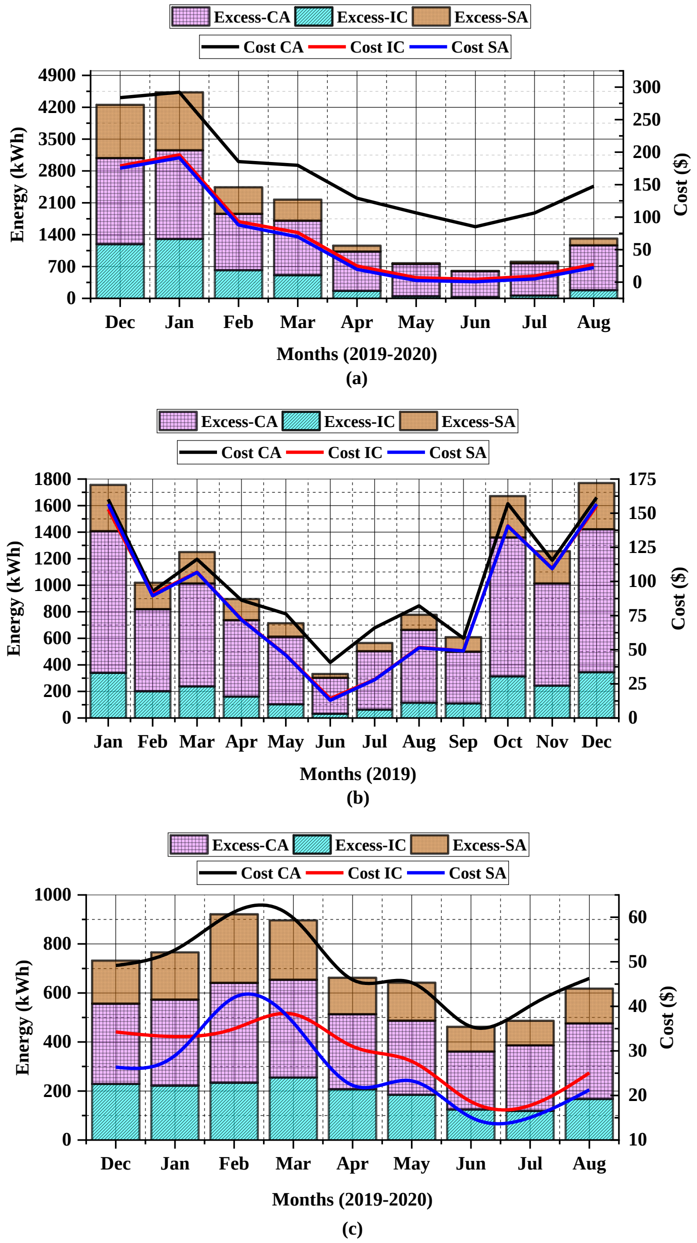


Figure 5.26 Excess energy acquired from three strategies and associated cost benefits: (a) Evermore; (b) Gen Y; (c) SHAC

It seems that the CA strategy presented in Figure 5.26 achieved more surplus energy and costs benefits for all three sites. That is, Gen Y had 8086.20 kWh ($1212.93), Evermore had 10,106.26 kWh ($1519.9) and SHAC had 2906.12 kWh ($435.9). The surplus energy and cost benefits from the other two strategies (IC and SA) were less than those of CA (Syed, Morrison et al. 2020a). SA gathered 3827.3 kWh ($574) at Evermore; 2264.16 kWh ($1018.8) at Gen Y; and 1537.12 kWh ($230.5) at SHAC. IC gathered 4111.9 kWh ($616.78) at Evermore;

2262 kWh ($1017.9) at Gen Y; and 1738.8 kWh ($260.8) at SHAC (Syed, Morrison et al. 2020a). Monthly metrics of surplus energy and related costs for the three sites are presented in Table 5.3, Table 5.5, and Table 5.7. The difference in results can be interpreted for IC and SA by the net of available energy from the total load (in SA CP load is excluded from the total load). The CA strategy contrastingly allocates portion of renewable energy and CP load usage to each apartment.

In Figure 5.27, the excess energy obtained from CA is analysed and shown as the yearly energy contribution from the individual apartments. This explains the surplus energy produced by each apartment after meeting the individual demand and then its allocated CP usage. Any individual apartment, which uses minimal electricity is accredited with high excess energy and receives more cost benefits. A similar practice is performed in Choudhry, Dimobi et al. (2019), where the residents are referred to either as a 'prosumer' or 'consumer' based on the level of energy consumption. A user with energy-efficient outcomes receives greater cost benefits. The individual apartment units presented in Figure 5.27 are labelled alphabetically PX (X represents the apartment). The graph displays only the minimum and maximum energy bars (by colour bars) obtained by individual apartments. Consumer PO accumulated the highest surplus energy (550 kWh) at Evermore, PY (3043 kWh) at Gen Y, and PB (334 kWh) at SHAC. Conversely, apartment unit PQ (234 kWh) gained less energy at Evermore because of higher load consumption, PX (2314 kWh) at Gen Y, and PD (136 kWh) at SHAC. Figure 5.28 presents the cost benefits obtained for individual apartments after implementing the CA strategy.

Higher excess energy is generated by the Evermore and Gen Y residents, while SHAC generated the lowest. These results suggest that renewable systems should be adequately sized for incentivising consumers if surplus energy is properly controlled. Similarly, the excess energy and probable financial benefits revealed in the results offer an opportunity to apply a trading mechanism in apartment buildings.

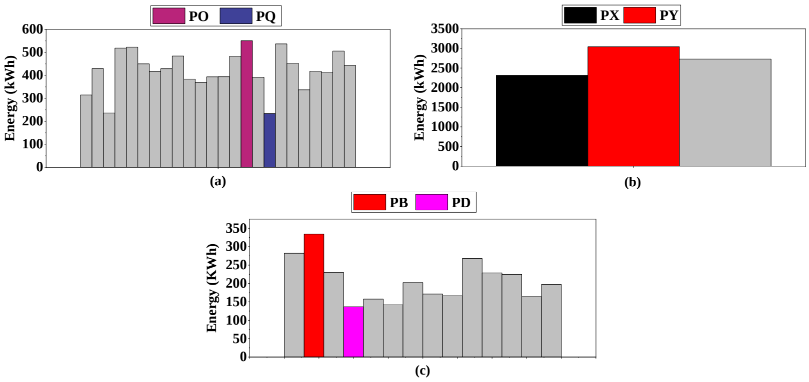
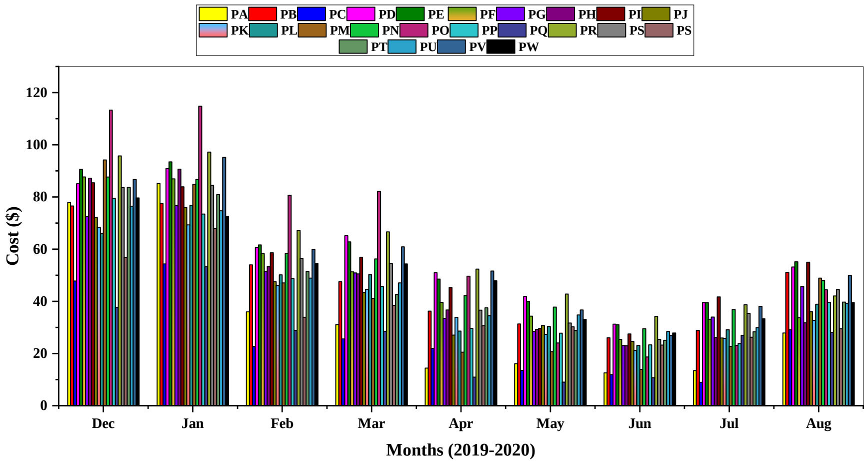


Figure 5.27 Excess energy gained from CA strategy: (a) Evermore; (b) Gen Y; (c) SHAC



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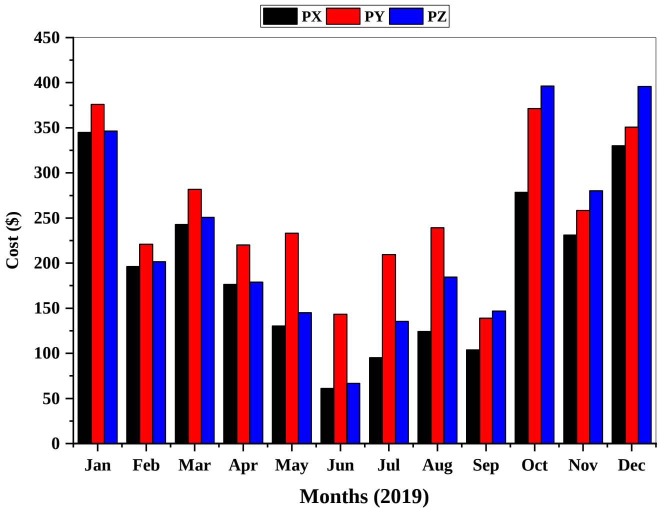

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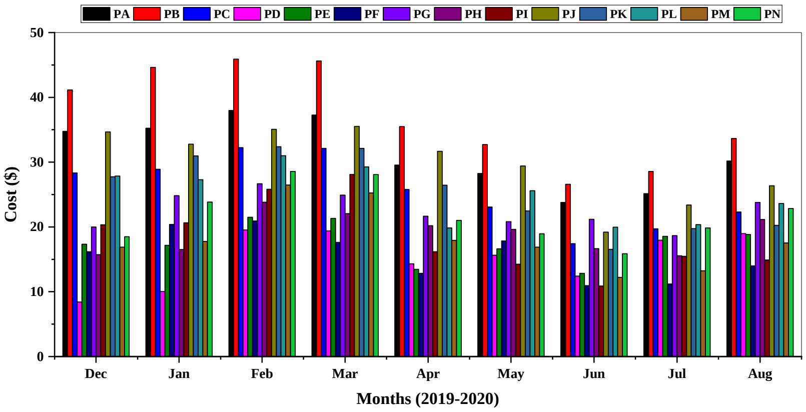


(c)

Figure 5.28 Associated monthly costs achieved from excess energy retrieved by apartment units at: (a) Evermore; (b) Gen Y; (c) SHAC

5.9 Results Summary

The apartment load profiles indicate discernible patterns in morning and evening peak demands. The lowest average baseload threshold was consistent across the three sites on a 24-hour scale (i.e. measurements recorded the lowest between 04:00 am to 06:00 am and the highest occurred between 04:00 pm and 11:00 pm). Nevertheless, the baseload values from the metering data at the three sites indicate key information about the low and high consumption periods. Moreover, based on the data, the minimum demand required to operate appliances for the three sites is calculated as approximately 7.2 kWh/day at Gen Y, 18 kWh/day at Evermore, and 91.2k Wh/day at SHAC.

To understand the load profile in detail and to observe peaks, measuring instantaneous demand with high data resolution of less than 1 minute is generally recommended because this demand could be missed using 15-minute interval data (Lusis, Khalilpour et al. 2017). The 15-second household resolution data (Stegner, Glaß et al. 2019) matched precisely with traditional 15-minute pulse meters. Given that load profile data from Australian apartment buildings are scarce, it would be an interesting subject for research in future studies.

Because of the abundance of PV generation, load profile data from the three sites illustrate positive energy performance for the building during the summer period. Conversely, high consumption in winter implies that space cooling and heating contribute to a large portion of electricity consumption in Australia (Energy-Consult 2015). One method to reduce electricity costs during winter is applying demand response strategies to programme battery storage capacity utilisation in peak periods.

To leverage the utilisation of SEM to meet load demand, self-sufficiency was measured using grid and PV-BESS. The SSR throughout the dataset period was higher for Gen Y and Evermore, and satisfactory at SHAC. Although an increased PV size improves the SSR, various studies have ascertained that the addition of a battery storage considerably mitigates grid dependency (Weniger, Tjaden et al. 2014; Luthander, Widén et al. 2015; Khalilpour and Vassallo 2016; Siraganyan, Mauree et al. 2017). However, as Figure 5.18 suggests, after achieving a particular level of storage capacity, the increasing battery size on SSR becomes marginal. The achieved self-sufficiency targets in Evermore, Gen Y and SHAC can be improved significantly by system operation optimisation, notably via control of PV exported energy, and through utilisation of the battery during large consumption periods. Centralised storage effectively increases self-consumption (Luthander, Widén et al. 2016). On a large scale, the presence of battery storage could benefit the network utility in managing evening peak load demand. Moreover, embedded networks such as SEM can reduce peak demand (Roberts, Bruce et al. 2019c). Until now, the focus in relation to battery storage has been given to detached housing, therefore understanding shared energy systems with battery storage in apartments requires more research. Certain operational strategies (Schneider, Boras et al. 2014) can also prove plausible for improving self-supply, mitigating load peaks and reducing investment costs. The results from the autonomy ratio also confirm that high self-sufficiency can be achieved if emphasis is given to improving system performance during winter.

The load profiles of the common areas from the three sites confirmed that load patterns can be largely building specific; nevertheless, CP loads usually have a fixed operating sequence. The yearly CP load ratio from three WGV sites demonstrated lower electricity usage than conventional apartments.

Moreover, three allocation strategies were implemented to evaluate grid electricity reduction for CP load and its resultant cost effectiveness. The IC strategy used grid-sourced electricity and PV-BESS to meet the combined instantaneous load demand from CP and the individual apartments. The other two strategies (SA and CA) utilised surplus PV energy to power CP load instead of exporting energy back to the grid. The IC strategy achieved an overall grid mitigation of 72% at Evermore, 72% at Gen Y, and 24% at SHAC. Similarly, the SA strategy reduced grid usage of CP load by 91% at Evermore, 82% at Gen Y, and 9% at SHAC. The lack of energy allocation criteria in IC and SA means that the cost benefits obtained from excess energy are aggregated but cannot be specified to any individual consumer. The CA strategy attained grid electricity abatement of 76% at Evermore, 70% at Gen Y, and 14% at SHAC. Despite complete abatement of grid electricity for CP being impractical, the investigated strategies obtained cost benefits by decreased grid usage (through SA), while acquiring surplus energy and cost benefits (through CA).

The analysis of the shared microgrid in this thesis lack detailed economic analysis, which can be conducted to observe electricity and system costs to help in the effectiveness of such systems in the long term. Understanding levelized cost of energy is more complete when capital costs and energy output are analysed in a balanced way. That is, it is important to know what are the total costs divided by the energy produced over the lifetime of PV (Fuentealba, Ferrada et al. 2015). The outcomes are then compared with existing electricity prices based on the market with the objective of achieving grid parity (Delfanti, Olivieri et al. 2013).

However, associated electricity costs are difficult to predict because unforeseen amendments to energy policy and regulation may occur without notice. Internally, project costs also have differences (VGB PowerTech 2015). Given that shared microgrid configurations are relatively new, there were various unanticipated issues that increased the final costs. For example, increased installation costs arising from miscommunication between scaffolders and contractors and technical issues such as BESS and inverter reconfigurations, which may require additional engineering expertise.

Moreover, cost parameters such as NPV can be used to calculate the return on investment of shared systems (Roberts, Bruce et al. 2019c). By analysing the profits made from the investments and translating those returns into monetary flows, the worthiness of the project can be assessed.

Table 5.2 Monthly grid usage reduction for CP load using IC, SA and CA at Evermore

Months	**Actual Load (kWh)**	**Grid Usage: IC (kWh)**	**Reduction (%)**	**Grid Usage: SA (kWh)**	**Reduction (%)**	**Grid Usage: CA (kWh)**	**Reduction (%)**
Dec	979.58	59.15	93.97	19.98	97.97	167.89	97.97
Jan	1040.02	58.29	94.4	17	98.37	167.91	98.37
Feb	1003.95	198.87	80.2	61.43	93.89	219.87	93.89
Mar	1036.58	172.5	83.36	63.38	93.89	230.67	93.89
Apr	806.2	188.08	76.68	74.4	90.78	197.25	90.78
May	629.16	223.18	64.53	90.26	85.66	194.28	85.66
Jun	473.43	347.61	26.58	88.72	81.27	156.4	81.27
Jul	617.97	341.93	44.67	96.98	84.31	193.06	84.31
Aug	694.69	389.07	44	83.23	88.03	198.35	88.03

Table 5.3 Total monthly excess energy and costs obtained from IC, SA and CA at Evermore

Months	**Excess: IC (kWh)**	**Excess: CA (kWh)**	**Excess: SA (kWh)**	**Cost: IC ($)**	**Cost: SA ($)**	**Cost: CA ($)**
Dec	1192.09	1892.14	1168.32	178.82	175.25	283.83
Jan	1305.68	1947.34	1274.92	195.86	191.24	292.11
Feb	620.81	1236.24	585.6	93.13	87.84	185.44
Mar	509.02	1198.1	463.98	76.36	69.6	179.72
Apr	166.07	860.65	131.19	24.91	19.68	129.1
May	45.53	710.36	16.34	6.83	2.46	106.56
Jun	29.36	567.85	4	4.41	0.6	85.18
Jul	62.32	709.68	33.26	9.35	4.99	106.46
Aug	181.08	983.95	149.74	27.17	22.47	147.6

Table 5.4 Monthly grid usage reduction for CP load using IC, SA and CA at Gen Y

Months	Actual Load (kWh)	Grid Usage: IC (kWh)	Reduction (%)	Grid Usage: CA (kWh)	Reduction (%)	Grid Usage: SA (kWh)	Reduction (%)
Jan	73.15	3.72	94.93	25.42	65.25	23.96	67.25
Feb	66.61	5.7	91.46	12.09	81.86	10.91	83.64
Mar	70.46	9.75	86.17	20.83	70.45	7.37	89.55
Apr	67.86	16.67	75.44	20.75	69.43	8.57	87.39
May	70.7	33.62	52.45	25.39	64.1	13.7	80.63
Jun	68.37	39.71	41.93	31.68	53.67	25.01	63.43
Jul	71.02	39.45	44.46	28.25	60.23	16.67	76.53
Aug	70.62	30.97	56.15	25.02	64.58	12.2	82.74
Sep	63.27	19.33	69.46	9.79	84.54	4.12	93.51
Oct	63.21	13.04	79.38	17.14	72.89	5.36	91.53
Nov	69.18	7.14	89.69	10.01	85.55	2.51	96.38
Dec	53.24	0.8	98.5	14.22	73.3	7	86.86

Table 5.5 Total monthly excess energy and costs obtained from IC, SA and CA at Gen Y

Months	Excess: IC (kWh)	Excess: CA (kWh)	Excess: SA (kWh)	Cost: IC ($)	Cost: SA ($)	Cost: CA ($)
Jan	339.7	1067.31	348.24	152.87	156.71	160.1
Feb	201.28	618.58	198.81	90.58	89.47	92.79
Mar	237.53	775.19	236.93	106.89	106.62	116.28
Apr	160.7	575.45	159.99	72.32	72	86.32
May	102.76	508.55	102.27	46.25	46.02	76.29
Jun	31.56	270.94	28.77	14.2	12.95	40.64
Jul	62.77	440.06	62.23	28.25	28	66.01
Aug	114.96	548.04	114.19	51.73	51.39	82.21
Sep	109.46	389.69	109.24	49.26	49.16	58.46
Oct	312.8	1046.13	312.37	140.76	140.57	156.92
Nov	243.54	769.73	242.96	109.6	109.33	115.46
Dec	345.02	1076.6	348.24	155.26	156.71	161.49

Table 5.6 Monthly grid usage reduction for CP load using IC, SA and CA at SHAC

Months	Actual Load (kWh)	Grid Usage: CA (kWh)	Reduction (%)	Grid Usage: IC (kWh)	Reduction (%)	Grid Usage: SA (kWh)	Reduction (%)
Dec	236.43	160.53	32.11	165.83	29.87	190.99	19.23
Jan	268.89	188.55	29.88	186.18	30.77	214.8	20.12
Feb	267.72	183.6	31.42	168.48	37.07	215.69	19.44
Mar	307.72	224.33	27.1	205.96	33.07	263.11	14.5
Apr	314.92	305.78	2.91	241.54	23.31	308.47	2.05
May	340.41	332.36	2.37	272.35	20	334.71	1.68
Jun	338.46	331.53	2.05	282.89	16.42	334.63	1.14
Jul	328.73	295.28	10.18	268.56	18.31	292.17	11.13
Aug	321.38	314.25	2.22	271.59	15.5	317.08	1.34

Table 5.7 Total monthly excess energy and costs obtained from IC, SA and CA at SHAC

Months	Excess: IC (kWh)	Excess: CA (kWh)	Excess: SA (kWh)	Cost: IC ($)	Cost: SA ($)	Cost: CA ($)
Dec	228.37	327.81	175.62	34.26	26.35	49.18
Jan	221.41	350.99	193.06	33.22	28.96	52.65
Feb	233.24	407.83	279.92	34.99	41.99	61.18
Mar	254.91	398.69	242.37	38.24	36.36	59.81
Apr	206.72	306.41	148.47	31.01	22.27	45.97
May	184.42	302.15	155.05	27.67	23.26	45.33
Jun	124.23	236.51	100.6	18.64	15.09	35.48
Jul	118.48	267.42	100.27	17.78	15.04	40.12
Aug	167.11	308.43	141.81	25.07	21.28	46.27

5.9.1 Pareto principle and its effects on energy distribution

Pareto principle provides a rough estimation of quantity distribution. It is an observation which ascertains that 80% of outcomes (vital few) will generate from just 20% of the actions (Dunford, Su et al. 2014). However the figures do not have to be exactly 80/20, it could be either 90/10 or even 90/20. The concept is widely used in economics as well as in all fields containing distributions such as software engineering (Kiremire 2011). Likewise, pareto principle can be applied to energy distribution (Wasilewski and Baczynski 2017). Implementing it on the three energy sharing strategies would yield different results that could assist in optimising the system operation.

Plots of Figure 5.29 illustrate monthly grid consumption that may actually reflect energy bought from the utility. For instance, pareto chart of Figure 5.29 (a) establishes that the first six months cause 81.75% of the total energy demand from grid using IC strategy. However, the initial three months (May, June, and July) actually need improvement in order to control the energy costs. SA strategy on the other hand consumes less grid energy in total when the first five months represent 70% of the total grid demand. Similarly using CA strategy, the initial 08 months consumed 80.84% of the total energy demand from the grid. Overall, this gives an impression that winter energy usage is main reason of higher energy costs.

In the same manner, pareto optimal situation occurs when it is impossible to improve one method without making the other criterion worse off. When Fi(a) is ith objective function, a^* is a Pareto optimal solution when there is no "a" that satisfies the following expression

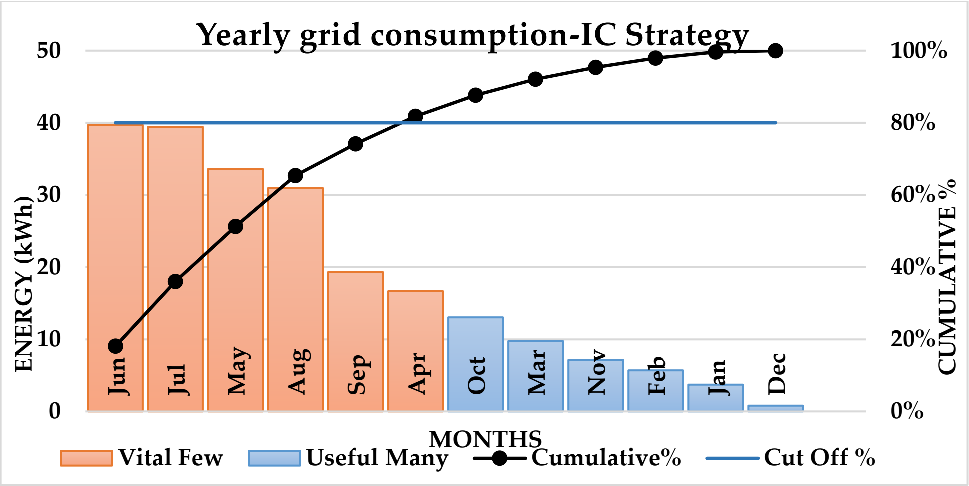
$$F_i(a_1) \leq F_i(a_2)\ \forall\ i \in \{1,\ldots\ldots z\} \text{ and } \exists\ j \in \{1,\ldots\ldots z\} \mid F_j(a_1) < F_j(a_2)$$

In other words quantity a is pareto efficient if no other policy dominates it. In terms of energy output and based on results from energy strategies used we can elucidate it by following expression if one energy source is preferred over the other

$$E_i(r) > E_i(g)$$

Where E_i is energy consumed, r represents renewable and g represents grid components.

In Figure 5.30, three strategies are plotted to find pareto optimal points for energy cost reduction and maximum renewable utilisation.



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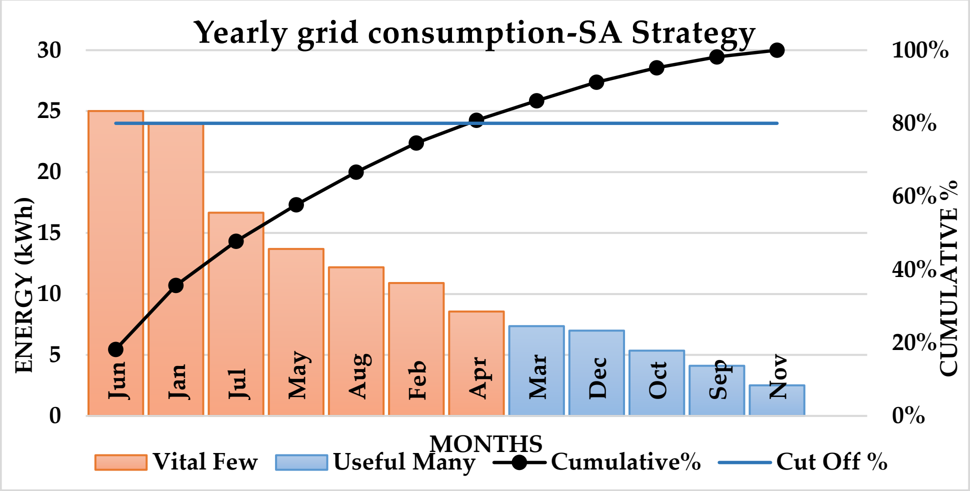

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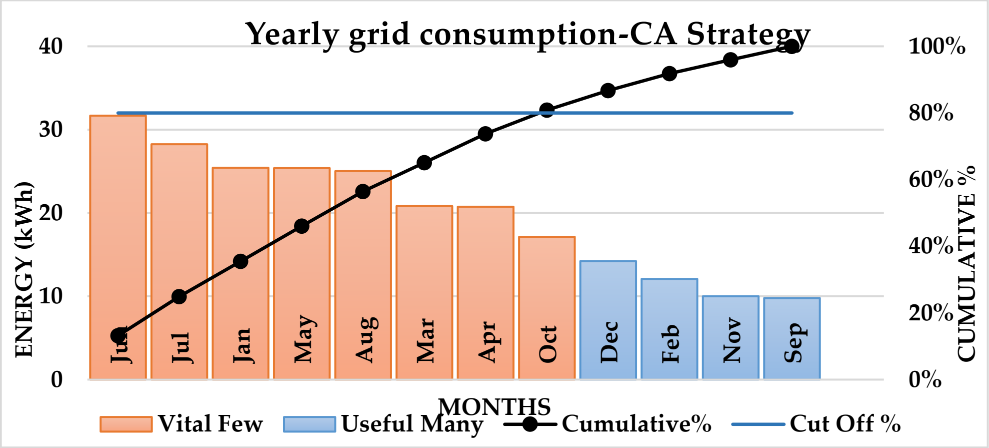
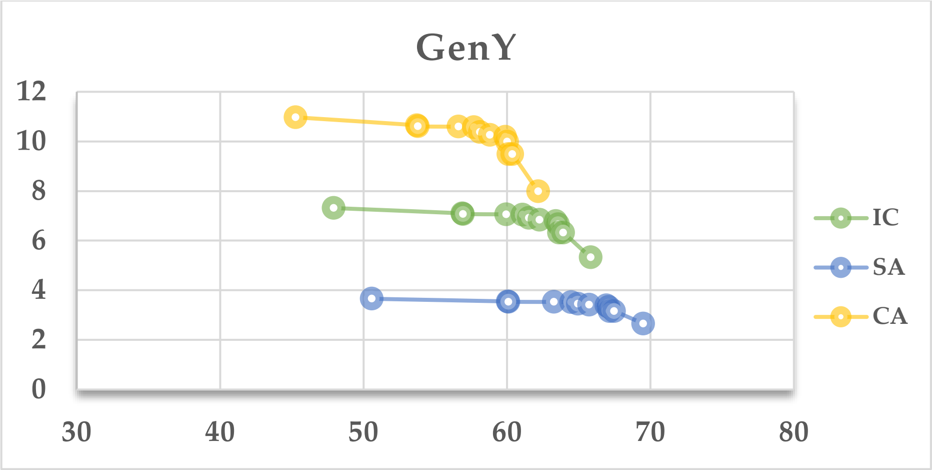


(c)

Figure 5.29 Pareto charts to identify higher grid usage months (a) IC (b) SA (c) CA



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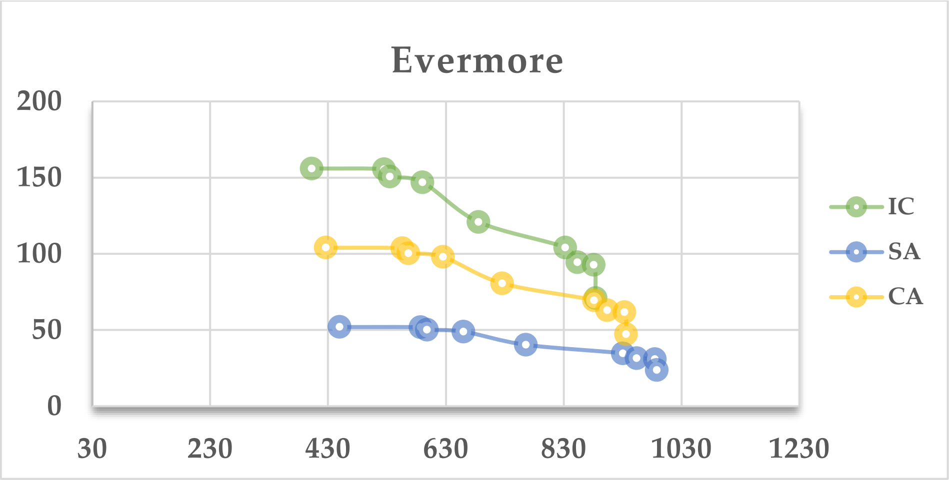

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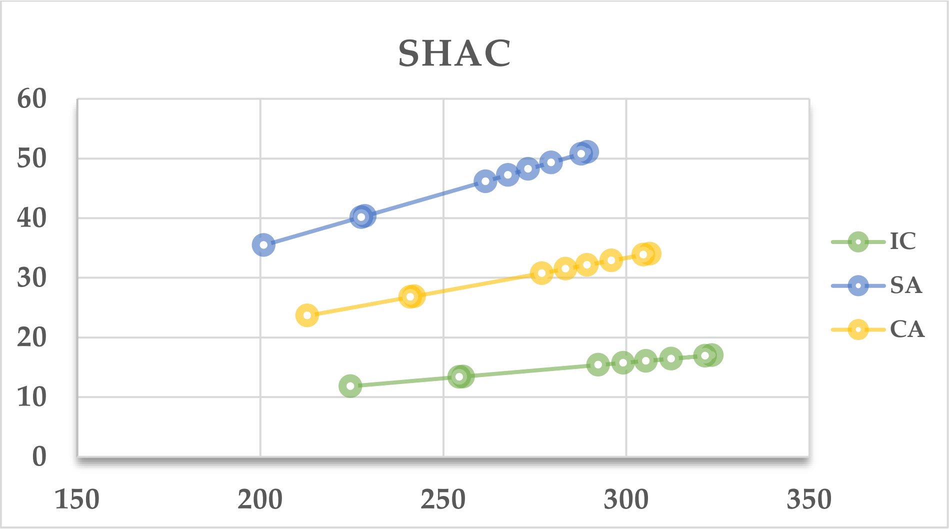

(c)

Figure 5.30 Pareto optimal points for load usage from energy sources (a) Gen Y (b) Evermore (c) SHAC

Based on pareto optimality criterion, certain portion of energy is allocated to both power sources. This allocation is supposed and calculated from previously learned performance outputs by three strategies in section 5.8.

If E_L is the total load consumption then for Gen Y apartment it is supposed that:

$$E_i(r) = r * E_L \ \& \ E_i(g) = g * E_L \qquad \textbf{(13)}$$

Where r and g are energy allocation factors for renewable and grid usage respectively. Allocation factors for three apartments have been listed in Table 5.8.

Table 5.8 Allocation factors for WGV apartments for sharing algorithms.

Strategies	**Gen Y**		**Evermore**		**SHAC**	
	r	g	r	g	r	g
IC	0.85	0.15	0.85	0.15	0.95	0.05
SA	0.95	0.05	0.95	0.05	0.85	0.15
CA	0.9	0.1	0.9	0.1	0.9	0.1

Considering renewable consumption on x-axis and grid consumption on y-axis, the plot in Figure 5.30 (a) demonstrates that SA strategy in Gen Y and Evermore apartments gives most optimal solution in terms of energy cost reduction and maximum solar utilisation. This can be observed from orientation of each curve towards a particular axis, e.g. SA dominates on x-axis. On the contrary, IC strategy at SHAC apartments provides more energy optimal solution. In terms of energy autonomy, evermore building offer better flexibility than the other two apartment dwellings. This is due to large backup storage availability.

Established on the analysis, it is apparent that strategy SA could play major role in reducing energy costs as well maximum solar utilisation however in case of lower PV production, IC strategy could also be useful to mitigate energy costs down and keeping battery supply at maximum.

Chapter 6: Conclusion

This conclusion chapter answers RQ5: What improvements could be made in future research models to increase the efficiency of shared systems?

This thesis has offered new insights into shared systems for apartments through discussing the design, structure and outcomes and empirical results to further technical understanding of DRES applications in apartments. Although the empirical findings from the three apartments of WGV may not reflect outcomes from all other existing shared configurations, the thesis emphasised a particular SEM for Australian strata apartments, providing valuable details to further understanding in this area.

The empirical analysis examined load patterns of apartments, while the effect of DRES installation was assessed in relation to grid reliance reduction. The WGV dataset from the metering infrastructure and the outcomes from the analysis of the collected data contribute substantially to this area of energy research for apartments.

The load profiles from the three apartments imitated the conventional diurnal load curve from detached dwellings (i.e. morning and evening peaks). However, the distinguishing factor in WGV is the aggregated distribution of energy in the apartment buildings. Creating aggregated loads supplied by a shared microgrid is significantly more effective than single house individual systems. The aggregated supply ensures that PV or battery storage are fully utilised depending on the occupancy of consumers. In addition, cost saving occurs by supplying energy from one grid connection to individual apartment units rather than several individual connections.

SEM provided overall self-sufficiency of 60% from the three WGV apartments. Winter caused a deficit in renewable energy generation, resulting in grid imports. There could be an improvement in SSR of 78% in Evermore, 65% in Gen Y, and 40% at SHAC through system optimisation, which includes PV exports control and battery storage utilisation during peak hours. On a large scale, this optimisation could reduce the stress on the utility grid in managing evening peak demand.

An increased battery size plays a central role in achieving high SSR; however, the effects on increasing battery size turn marginal after reaching a certain limit. Nevertheless, the high battery costs could be an obstacle in relation to project management. Moreover, the autonomy ratio from the data indicates that system improvement is needed in the winter period.

The results also demonstrated that load patterns of common areas are highly building specific; nevertheless, CP diurnal energy usage is invariant because of identical appliance operation. The monthly usage and yearly CP to apartment load ratio in the WGV apartments was lower than it is in traditional apartments, where common areas consume a large amount of electricity. Energy allocation strategies from the real-time data were also applied for grid mitigation of CP load. The IC strategy utilised PV-BESS supply to fulfil instantaneous demand from CP and individual apartments. The other two strategies (SA and CA) employed surplus PV power to supply CP load as opposed to grid export.

In apartments where common areas consume a large amount of electricity, SEM along with allocation strategies could prove effective. Large exports from the Evermore and Gen Y apartments could provide a good model to operationalise energy trading to incentivise consumers. Individually, prosumers may take advantage of implementing these strategies by remaining mindful of their energy usage. A practical solution is by linking and gamifying energy transactions with visualisation platforms having dynamic tariffs, providing temporal, weekly or monthly energy trading insights to consumers. The process can be virtually regulated by strata retail management or a local energy aggregator. On a large scale, aggregation could be performed with other sites in a virtual power plant. Although energy allocation and usage aligned with the appropriate schedule are more useful for obtaining better efficiency, consumer behaviour should not be disregarded. Seasonal variations in winter also affected allocation strategies, particularly the IC strategy. These volatilities might be overcome by commissioning hybrid seasonal storage technologies and other forms of DRES with SEM (Leonard and Michaelides 2018).

There are bilateral benefits using these energy sharing algorithms, consumer gets rewarded by reshaping their consumption, whereas the community benefits from reduced energy costs. In the view of these algorithms, strata organisation and engineering solution providers should devise policies supportive for consumers. This could be based on residents' usage behaviour, daily routine, choice of tariff selection, and energy source option.

This research explored data from three WGV apartments; however, occupancy patterns, effect of building size and building thermal characteristics were not analysed, which are an important subject for further research. From the sociotechnical perspective, community engagement is also indispensable for assessing the requirements for customising system operation, and should therefore be included in a holistic system approach. Future research should explore the effects of these parameters and facilitate optimisation of a shared microgrid for achieving better technoeconomic benefits.

Regulatory frameworks are necessary for the effective commissioning of SEM (Planas, Andreu et al. 2015; Koirala, Koliou et al. 2016; Ceglia, Esposito et al. 2020; Roberts, Bruce et al. 2019a). From a policy perspective, benefits such as attractive feed-in tariffs and subsidies can increase the rollout of DRES to encourage their participation in ancillary services (Parra, Swierczynski et al. 2017; Ceglia, Esposito et al. 2020; Roberts, Bruce et al. 2019a), while taxes imposed may have an opposite effect on CCM installations (Parra, Swierczynski et al. 2017; Huang, Zhang et al. 2020; Roberts, Bruce et al. 2019a).

A benchmark comparison with other apartments consisting of proximate technical configurations would be significant for determining the load patterns and application of demand-side management. Nevertheless, the scarcity of apartment building data is another major limitation to progressing such research. Moreover, the availability of advanced data insights from SEM is critical in influencing regulators and policymakers to facilitate and implement strategies for the uptake of DRES in apartment buildings.

SEM may bring techno-economic benefits if implemented in apartments and communities; however, the reduced roof size of apartments and skyscrapers, network regulations and complex DRES legislation for multi-residential buildings may hinder adoption on a large scale. Moreover, additional battery storage would be needed to satisfy the low PV generation when there is the issue of limited roof space. It is expected that experimentation of semi-transparent solar windows on apartments could remove the limitation of limited roof space; however, the efficiency of these panels remains unclear. Universal standards, for example, in technical rules such as IEEE 1547 (DER interconnection with grid) should be consolidated for SEM. Likewise, DC microgrids need developed regulations.

To enable the maximum potential of SEM, a common ground should be established to bring together energy communities, policy makers and regulators to create policies to overcome the SEM implementation barriers (Parra, Swierczynski et al. 2017; Koirala, Koliou et al. 2016; Ceglia, Esposito et al. 2020).

In view of a global upsurge in apartment building construction and high electricity usage, the adoption of DRES is incredibly important to curtail high electricity costs and carbon emissions. Energy transition to DRES can phase out fossil-fuel-reliant incumbents in Australian regional networks such as the South West Interconnected System and similar jurisdictions across the globe. Based on the suggestions provided by this thesis, WGV may set the precedent for other multiresidential dwellings with similar characteristics and utility network guidelines, and thus can contribute to progressing energy transition.

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Performance of a shared solar and battery storage system in an Australian apartment building

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ABSTRACT

This study presents the energy performance of a three unit apartment building in Perth, Western Australia equipped with a shared energy microgrid. Although there has been a dramatic growth of residential rooftop solar PV across Australia, apartment buildings and their occupants are rarely able to access the benefits associated with onsite renewable energy generation and consumption. To address this, an apartment building in Perth was fitted with a PV and battery energy storage system, with metering architecture. The microgrid configuration enabled the sharing of energy between the apartment units. A one year dataset (December 2017-December 2018) obtained from onsite pulse meters was analysed. Load profiles were assessed and grid minimisation was evaluated through self-sufficiency metric. The three unit apartment showed a 22% reduction in average yearly energy consumption against the benchmark. The findings demonstrated an overall 75% dependency of the microgrid on renewables; and suggest that a shared energy microgrid may be more effective than separate supply connections.

1. Introduction

Increasing costs of network supplied electricity coupled with decreasing costs of solar panels [1] and policies supporting the uptake of renewables, have resulted in investments at scale in rooftop solar Photovoltaics (PV) [2]. An increase in installation capacity of 99% across Australia over the past ten years has led to more than 2 million dwellings with rooftop solar PV setups and a combined capacity exceeding 11 GW [3]. Western Australia is projected to experience the highest customer growth and the highest rate of growth in residential rooftop solar PV capacity in Australia, to reach 4.8 GW by 2025 [4]. Concurrently, a decline in grid sourced energy has been observed [5] as a result of a combination of a move towards less energy intensive industries, the effects of energy efficiency programs, and rising electricity prices. In addition, reduction in grid demand has also occurred with the expansion of rooftop solar PV and distributed generators [5]. The energy transition towards an embedded decentralised renewable energy system is further enabled by finance for renewable energy innovation such as efficient PV panels, battery storage technologies and smart metering [6].

While rooftop PV has widely diffused into the detached residential housing market, challenges with shared ownership, absence of a regulatory framework and cost incentives have impeded the uptake of PV and Battery Energy Storage Systems (BESS)[1] in multi-residential apartment and strata[2] developments [8]. Although utility networks have established technical guidelines to assess regulations and standards for grid connected renewable systems [9], PV and BESS configurations suitable for shared distribution in apartment buildings have not been reported. Only a few cases of multi-residential solar-storage developments with shared governance exist in practice; to the authors' knowledge no empirical analyses based on an implemented system exist in the literature. The aim of this paper is to present the energy performance of an apartment building designed for grid usage minimisation. The building is located in Fremantle, Western Australia and connected to a shared microgrid utilising solar PV and BESS combined with a metering architecture.

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[1] *Abbreviations: BESS – Battery Energy Storage System; CP – Common Property; IEG – Inverter Embedded Generator; Li-ion – Lithium-ion; LFP – Lithium iron phosphate; MPPT – Maximum Power Point Tracker; PV – Photovoltaic; SEM – Shared Energy Microgrid; SOC – State of charge*

[2] *Strata titled properties combine individual ownership of lots with shared ownership of common property through a legal entity referred to as strata company or owners corporation* [7].

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1.1. Issues concerning the uptake of renewables in apartment buildings

The growth in rooftop PV and BESS has occurred predominantly in freehold dwellings, with a limited number of residents of apartment buildings having access to solar energy [10-12]. A key reason for the exclusion of apartment buildings in these trends is the lack of governance structures that enable effective sharing of the costs, risks, and benefits of solar installations between households, developers, owners and utilities [10]. With nearly 9% of the Australian population living in apartments [13], sharing models need to address the split incentive issue. This arises when the benefit of reduced electricity bills is not accessed by the owner investing in the renewable source, but the tenant occupying their property, which leads to underinvestment in energy saving measures [14]. Physical limitations such as restricted roof space in proportion to numbers of residents combine with the complexity of conflicting interests of multiple households and thereby mean that the integration of solar PV in apartment buildings is a challenge. Despite all these problems, installation of solar PV can provide benefits in terms of reduced electricity bills [27] and significant reduction of carbon emissions [15]. Unlocking residential multi-dwelling developments to the benefits of solar energy could assist Australia in achieving carbon reduction targets of 441 $MtCO_2e$ by 2030 [16] and in an increase in self-consumption of the buildings [8].

1.2. Residential microgrid

Microgrids in general adopt PV as the main energy generation source along with other renewable technologies depending on feasibility [17] and also due to their enhanced design topologies, performance, efficiency and safety, all of which is improving with continued advancement in technology [18].

Recent developments in microgrids have focused on residential communities as ideal applications [19]. Whilst studies related to PV deployment in apartments have focused on technical performance evaluation [20] and techno-economic analysis of simplified microgrids with PV systems [8,21-25], few publications have studied apartment electricity loads in detail [26,27]. Shared microgrids containing PV and battery storage in multi-residential apartments have been relatively poorly investigated. A techno-economic study was performed by [28] to analyse the impact of PV-BESS systems using apartment interval data, although the deployment of actual PV-BESS on a particular apartment building has not been investigated.

In this context, we present a Shared Energy Microgrid (SEM) utilising a combined solar PV and BESS with metering architecture connected to apartment units. Energy performance is evaluated in its first year of operation; this is a significant contribution to the literature because apartment buildings are rarely discussed explicitly; performance data on these developments is scarce and such configurations provide a new and efficient way to enable the sharing of solar energy for residents. The paper begins with a descriptive approach to understand the problem; information about the systems is then presented, followed by methodology, analysis and finally discussion of results.

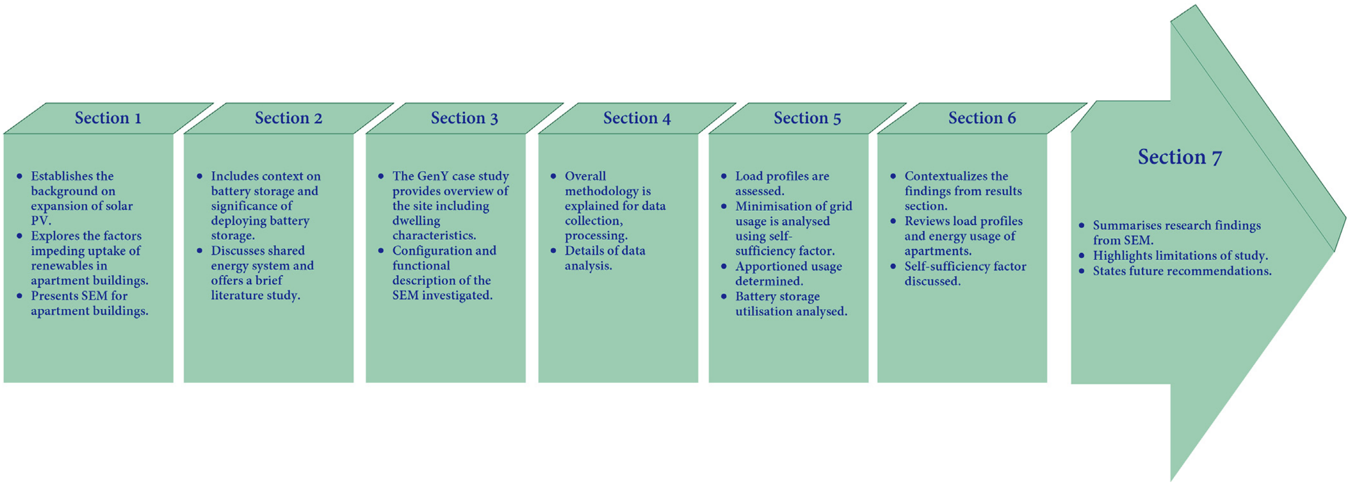
The paper is structured as illustrated by the arrow diagram of Fig. 1. The article begins from Section 1 by describing high level issues related to the uptake of renewables in apartment buildings which guides us to the background discussion of energy storage and shared energy systems covered in section 2. The significance of shared energy is also discussed with examples in different studies. On the basis of this context, we introduce the SEM in Section 3, with configuration details and technical description of the whole system. Section 4 discusses the methodology and analysis. The findings from the data analysis are presented in Section 5 with two main objectives. First, load consumption profiles from real time data were assessed for the apartment building with respect to average diurnal and monthly usage which has not been previously discussed in the literature. Secondly, the minimisation of grid energy usage is determined through the evaluation of self-sufficiency. The results also include the share of both sources in the load consumption, and battery utilisation in peak periods. Section 6 is a discussion of the analysed results. Finally, we conclude the paper by pointing out key findings and suggestions for future research in Section 7.

2. Battery storage and shared systems

2.1. Battery storage

The demand for battery storage is growing rapidly due to its potential to provide the backup for intermittent renewable sources. It is predicted that global installed battery storage capacity will increase from 29GWh in 2020 to 81GWh in 2024 [29]. Meanwhile in Australia household battery storage capacity reached 1GWh in 2019 [30]. Moreover, with the falling costs of batteries, hybrid systems are becoming increasingly attractive for Australian households [31].

Energy storage systems can increase the reliability and quality of power supply and self-consumption for end consumers [32] and can help defer grid extensions through reduction in peak



Section 1
- Establishes the background on expansion of solar PV.
- Explores the factors impeding uptake of renewables in apartment buildings.
- Presents SEM for apartment buildings.

Section 2
- Includes context on battery storage and significance of deploying battery storage.
- Discusses shared energy system and offers a brief literature study.

Section 3
- The GenY case study provides overview of the site including dwelling characteristics.
- Configuration and functional description of the SEM investigated.

Section 4
- Overall methodology is explained for data collection, processing.
- Details of data analysis.

Section 5
- Load profiles are assessed.
- Minimisation of grid usage is analysed using self-sufficiency factor.
- Apportioned usage determined.
- Battery storage utilisation analysed.

Section 6
- Contextualizes the findings from results section.
- Reviews load profiles and energy usage of apartments.
- Self-sufficiency factor discussed.

Section 7
- Summarises research findings from SEM.
- Highlights limitations of study.
- States future recommendations.

Fig. 1. Overview of article structure.

demand [12]. They reduce grid imported electricity by peak shaving [12,33-36] and through optimisation of the renewable source and battery operation [34,37-40].

Several battery technologies have been researched and compared in terms of their efficiency, costs, lifecycles and other parameters [41] however, for residential microgrids and small scale applications, Lithium-ion (Li-ion) battery technology has proven to be the most viable option [42]. Li-ion batteries have high energy density, improved life cycle, high efficiency and possess high power capability [43]. However, the cost factor is a major barrier in large scale deployment [35]. Due to expansion of the global electric vehicle market, Li-ion battery prices are expected to decrease over the next three years to $100/kWh [44,45].

A growing body of literature has evaluated BESS models for the purpose of curtailing grid reliance. An energy storage system design has been simulated to reduce electricity bills for a residential Zero-Energy Building in Portugal [32] which achieved a reduction of grid export and import energy by 76% and 78% respectively. Different battery storage models were compared by [46] through the use of measured electricity data from 99 Texas households. The peak demand power using a target zero method was reduced to 32% while a minimising power method reduced the peak demand to 8%.

2.2. Shared energy system

Given that 86% of the Australian population live in urban areas [47], the implementation of renewable energy sharing is a challenge in metropolitan environments where apartment buildings are in a space constrained area with ubiquitous availability of grid sourced electricity. Approaches to the integration of PV systems in apartment developments thus far have focussed either on connecting units to independent PV systems; on sharing the energy generated by a PV system through an embedded network; or on supplying energy to the common property (CP) only [11]. However, the business models that enable the sharing of energy via solar PV BESS [12] are not well developed. Energy sharing is usually discussed for multi-residential buildings in a community or more than one detached dwelling. In that regard, we establish our definition of SEM as an embedded network behind the main grid in which the renewable system is owned jointly by apartment owners for electrical supply while high level benefits such as cost reduction and lower environmental footprint are envisaged. We use the term SEM to differentiate between a conventional embedded network [27] and the case study, where an explicit focus on collective ownership of the infrastructure and the possibility of peer-to-peer trading guided the design of the system. The implemented governance structure is discussed in [60].Moreover, there is a minor difference between SEM and community microgrids: while both configurations rely on a centralised renewable source, a community microgrid is monitored in an aggregate manner whereas in SEM residential loads are monitored via sub-meters [48]. In the case of shared systems the energy consumption disseminates in a set of residential units, averaging out load variances to offer a cost effective storage solution resulting from the fact that someone in the community at any particular instant would be utilising energy from the battery [12]. If an occupant vacates, the allocated share could be sold to a new entity [49]. Therefore high self-consumption ratios and high self-sufficiencies are also achievable from a microgrid using a centralized resource approach with shared load configuration [50].

A SEM generates energy based on rated capacity, which is then de-multiplexed among different users through electrical distribution. Traditionally these loads decrease consumer accession costs by eliminating the requirement of several site assessments as compared to a single community site. In other words, entire residential units draw the utility and PV-BESS sourced power via a single connection point.

2.3. SEM in the literature

SEM has been the subject of many pilot studies around the globe however, there are very few instances of real-time operational sites. One study [51] allowed surplus renewable energy to be shared between prosumers in a neighbourhood through aggregated small scale batteries, thereby reducing 30% of energy cost compared to surplus PV exports. An investigation simulated the energy demand of a few households in a community using the Monte Carlo method to optimise the size and layout of a community shared solar PV system [52]. A discrete-time simulation model assessed the reduction in grid interaction from energy sharing in a net zero communal microgrid [53].

A number of studies have developed virtual energy sharing algorithms utilising PV and battery storage [54,55]. A simulation of an energy system model was performed by [56] from a simple household grid connection through to interconnected shared communal and individual PV with battery storage. In extension to this, [57] studied autonomy and environmental impacts due to shared generation, storage and communal consumption. Community formation was simulated using 15 minute interval consumption data in [58] and a framework was used to demonstrate storage selection. The authors discovered that community battery storage provides increased self-sufficiency and significantly reduces the surplus solar exports which are fed to the utility. A novel new energy management framework for a five unit communal PV and battery storage was presented in [59]. A multistage stochastic program was used to manage energy considering individual and shared control strategies. The proposed shared storage strategy reduced the overall electricity purchase costs and storage capacity compared with individual energy management of households. In addition to technical studies, socio-technical analyses of shared renewable energy systems have also emerged (e.g. [60]).

3. Case study - Gen Y demonstration housing

The Gen Y demonstration house project envisioned a design which encapsulated the sense of community, sustainability and affordability to suit 21st century living i.e. meeting the lifestyle demands of Generation Y. Built on an area of 250 m^2, it is a free-standing two storey, three apartment multi-residential dwelling nestled within the 2.2 ha White Gum Valley precinct located in the City of Fremantle, near Perth, the state capital of Western Australia. The size of Gen Y is significantly smaller than the average floor area of an Australian dwelling (240m^2) [61,62].

3.1. Dwelling characteristics

The Gen Y demonstration design incorporates a SEM fitted with a 9kWp solar PV and BESS with 10 kWh Lithium iron phosphate (LFP) in a microgrid topology [10]. LFP is considered as the most durable of Li-ion battery technologies [43]. The owners' corporation owns the solar PV and BESS and generated and stored electricity. The shared areas and facilities within the building are communally owned and managed by an agency nominated by the owner-occupiers. In the governance model, a fixed proportion of the PV generated electricity is allocated to each apartment in the building as well as to the CP [60]. Electricity bills are paid to strata management which use a blockchain billing system to allocate a fair distribution of energy generated on-site, and the margin earned can be used to offset strata levies. The SEM installed at Gen Y was projected to cover 60% of the energy demand through PV and

BESS, while the remaining 40% capacity would be provided through the electrical grid.

3.2. Energy system configuration

The SEM of Gen Y is comprised of a number of components in its design. Each component has its own operating principles and control methods. The system containing PV and battery storage (in line with distribution network guidelines [9]) is also defined as an Inverter Embedded Generator (IEG). There are several configurations to install IEG systems on the basis of applications but typically the arrangement contains two main elements i.e. PV source with or without storage medium and bidirectional DC-DC converter and then DC-AC inverter [9]. Generally two configurations for residential IEG systems are used (1) AC coupled where the PV and BESS comprised of bidirectional converters are connected on the AC bus and (2) DC coupled where the PV is connected on the DC bus with BESS and AC side is connected to BESS inverter. Fig. 2 illustrates the AC coupled configuration deployed at Gen Y.

One advantage of this connection is integration of different AC compatible converter systems to the loads and grid and a second advantage is that this configuration can be easily expanded to meet increasing energy demand. Moreover, the battery storage component can function independently of PV source [18]. All IEG systems connected to the utility network as a rule comply with the Australian standard AS/NZS 4777 [9]. Component ratings and pulse metering information for this microgrid are provided in Table 1. Roof mounted PV panels of 9 kWp PV were connected in a combination of 36 × 250 W (poly-crystalline) PV modules. The system consisted of two Maximum Power Point Tracker (MPPT) circuits coupled with 12 separate strings of three PV modules each, six strings for the 1st MPPT with six strings for the 2nd MPPT. A Sunny Tripower inverter,labelled as PV Inverter in Figure 2 is an integral part of this AC coupled system which converts PV generated DC into AC output which is then fed into the BESS.

3.3. SEM operation

Each apartment connects to the microgrid in an embedded configuration with a centralized BESS as shown in Fig. 3. The main objectives of commissioning the microgrid were (1) Store PV generated energy during daylight hours in LFP batteries (2) Supply on site loads and (3) Feed excess energy back to the grid while releasing the stored energy to supply loads during the night time or when there is no availability of PV. If the load demand exceeds available solar PV generation and battery storage capacity, then the loads are also fed from the grid. A bidirectional inverter inside the BESS charges the battery. It also provides the path for PV generated AC power to supply the load, and transfers excess power to the grid. Generally the battery is not charged from the grid when it is configured for self-consumption with excess export [9] however, the BESS in SEM is charged through the grid to maintain a minimum operational State of Charge (SOC). The bidirectional inverter provides dynamic functions such as protection, synchronization and anti-islanding. Metering plays a central role in the measurement of bidirectional energy flow, generation as well as electricity consumption of households. The pulse metering used at Gen Y consists of KMP1-50 sub-meters connected to monitor residential loads with pulse weight of 1000 imp/kWh and class B precision of 1%, whereas IEM3255 pulse energy meters are used to measure bidirectional energy flow from grid and PV-BESS. IEM3255 meters hold pulse weight of 5000 imp/kWh and class C precision of 0.5%. All meters are connected to a ComX'510 data-logger which has data resolution of 15 minutes. This combination of pulse meter and data-logger records temporal measurements of load consumed and energy generated. Therefore much like smart meters, they may help in predicting the optimised load profiles based on obtained data thus reducing electricity costs and also incentivising prosumers to forecast the best period for selling excess PV energy to the grid [63].

Table 1
Gen Y SEM component specifications.

Sub-meter	KMP1-50
Pulse energy meter	IEM3255
Interface Modules	SIM10M
Data logger	Com'X 510
BESS	BYD 10kWh
Solar PV Modules	9kWp Hanwa Q cells Poly Crystalline
PV-Inverter	SMA Sunny Tri power

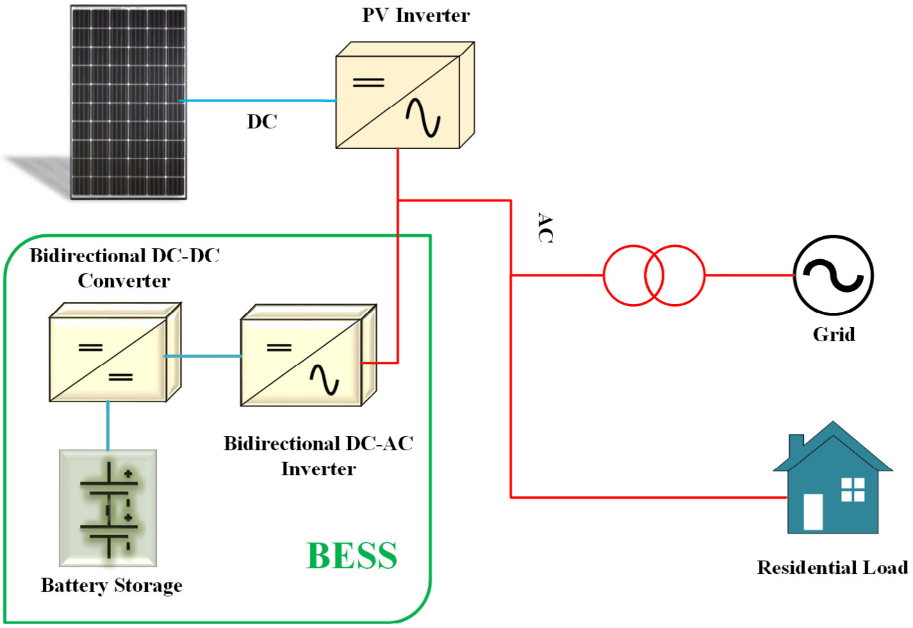


Fig. 2. AC-coupled system used in Gen Y configured as IEG topology.

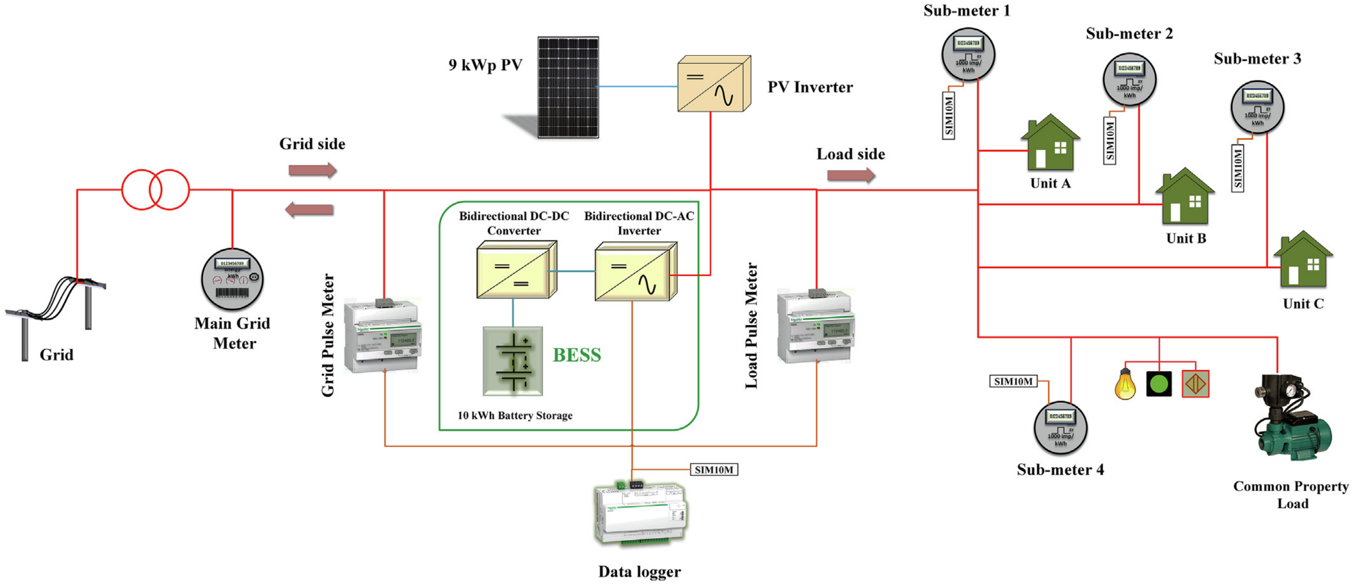


Fig. 3. The block diagram of Gen Y SEM.

The installation of SEM pulse meters was arranged in parent and child configuration [64]. Electricity passes through the loads from the grid *via* main grid meter and grid pulse meter IEM3255 and individual apartments are wired by means of KMP1-50 pulse sub-meters. For reconciliation, another load pulse energy meter was also installed to measure the total load measurements.This metering configuration balances load distribution as well as eliminates multiple grid connections which provides significant cost savings. The hybrid metering network protocol used in Gen Y is Modbus-RS485. All meters used for electricity billing are approved and meet NMI Regulations[3]. Moreover, a cloud based energy monitoring system including a ComX'510 data-logger system was configured to collect and measure electricity consumption from onsite meters [65] and the resolution set for obtaining data from the data-logger is 15 minutes.

4. Methodology

4.1. Data collection

This section describes the overall methodology used for data collection, processing and analysis. The methodological scheme is shown in Fig. 4. The consumption data from the three units were taken from on-site pulse meters through an interface module (SIM10M) and data-logger. The metering network communicates *via* Modbus-RS485 which terminates at the data-logger. Pulse meters employ internal Modbus registers to measure different parameters which are then stored in ComX'510. The network is also connected to an interminable onsite broadband internet as a means to transfer and store the data to the web server. The web server is hosted by a project participant organisation which runs Schneider PME application which is the bridging platform for managing data using a SQL database. The SQL database manages data in the form of tables and each metering device added has a unique ID identifier for inputs. An external script extracts information from the SQL database and pushes it to the big-query database which utilises Google studio with proper validation and indexing to remove any discrepancies before providing the data to researchers in CSV form.

4.2. Analysis

As illustrated in Fig. 3 the case study depends on pulse-metered electricity data for three apartments in the Gen Y building. The apartments are named Unit A, Unit B and Unit C. The dataset was collected over the period of one full year from December 2017-December 2018 and the data was analysed in time series. Initially, the characterisation of data and variables was based on resolution, location and type of equipment whilst missing values and outliers were identified and removed. Owing to the pioneer status of this demonstration, benchmark data for such developments is scarce. Therefore, the monthly energy usage plot in section 5.1 is compared with the average consumption of a three person household across Australian detached houses, except Western Australia[4]. Consumption data was taken from [66] with consideration that those houses also utilised gas for cooking and electricity to run the rest of the appliances in a similar manner to Gen Y. As the metering architecture is comprised of pulse meters, the dataset containing energy values are mostly cumulative whilst parameters such as Power (Watts) and SOC are instantaneously recorded. In order to get the desired interval output from the cumulative data, equation (1) was applied.

$$\Delta X_n = Y_n - Y_{n-1} \tag{1}$$

Where n is the number of a particular interval whilst X and Y are defined as output and cumulative data values, respectively.

Given the data resolution is 15 minute, 24-hour data in a day generates 96 intervals. To calculate daily values the output from equation (1) was added to provide equation (2).

$$Energy_{kWhperday} = \sum_{n=0}^{95} (\Delta X_n) \tag{2}$$

4.3. Self-sufficiency

Self-sufficiency can be defined as the ability of the microgrid to operate on its own sources (PV and battery) without relying on grid electricity [21], and is also often referred to as energy autonomy [67]. This metric is sometimes confused with self-consumption,

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[3] NMI regulates and maintains measurement system standards in Australia

[4] Western Australia is not connected to the National Energy Market (NEM) and has its own separate regulatory arrangements and electrical infrastructure. Residential electricity consumption datasets from Western Australia are not currently available.

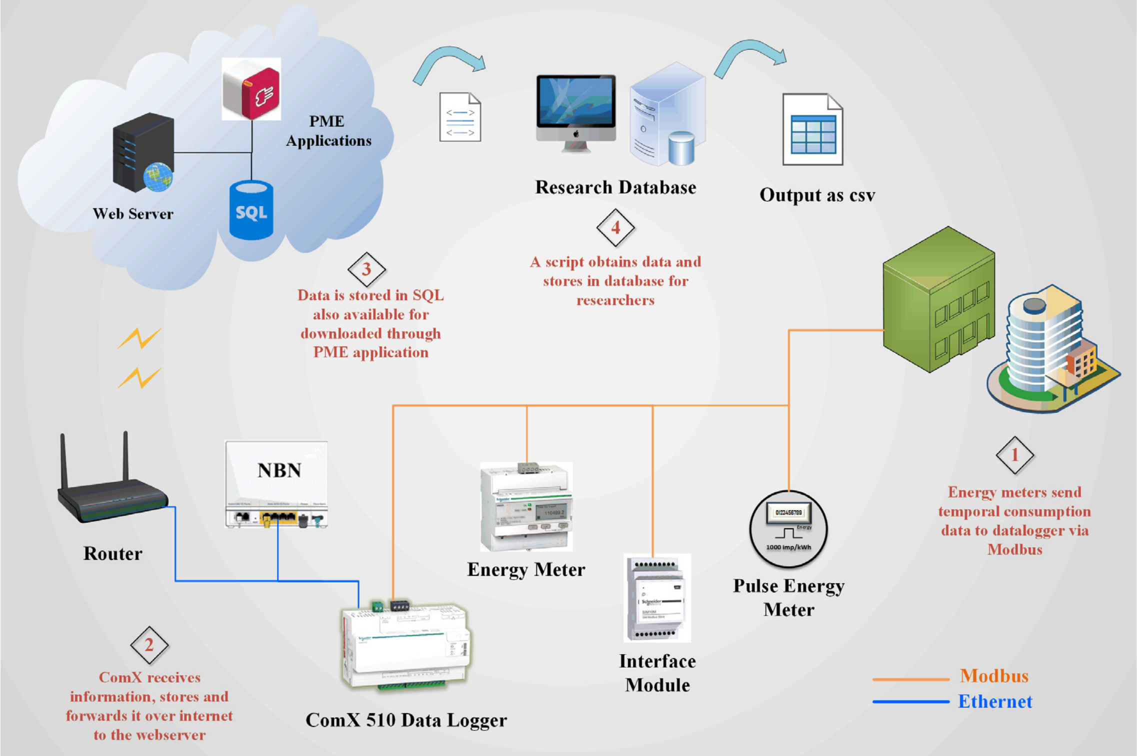

Fig. 4. Representation of the system methodology used in this case study.

which is the ratio of PV use by loads to total PV generation [68]. The self-sufficiency ratio can be calculated from the autonomy requirement equation given in [69] as:

$$\mathrm{Self-Sufficiency}(\%) = \left(1 - \frac{\sum_{n=0}^{95} E_{grid}}{\sum_{n=0}^{95} E_{load}}\right) \times 100 \tag{3}$$

Where n denotes the number of intervals in a day whilst E_{grid} and E_{load} represent temporal grid imported energy and total load consumption respectively. For calculating monthly self-sufficiency, the number of intervals would depend on the total number of days in each month, e.g. in January the maximum value of n would be 2976. Self-Sufficiency also facilitates an understanding of the overall share of both sources in the total load consumption and subsequent cost benefits could be identified in order to increase or decrease the renewable system size.

Similarly apportioning of energy usage would be insightful to examine the share of both sources i.e. grid and PV-BESS, in individual load consumption of apartments. Although the main benefits of apportionment are allocation of energy bills and management of energy demand contingent on desired system output, we can also apply this method in the present scenario where energy has to be fragmented from multiple sources i.e. grid and renewables terminating on a single AC coupled bus. Various approaches have been employed to determine apportioned usage such as clustering [70], non-intrusive load monitoring [71–73] as well as static apportionment [73,74] and controlled switch energy sharing in [75]. However we apportion grid and PV-BESS usage for each of the three residential units by first itemising total load consumption into self-sufficiency percentages of sources (grid or PV-BESS) as given in Eq. (4),

$$\mathrm{Source\%} = \frac{\mathrm{Source\ (PV + BESS\ or\ Grid)consumption\ (kWh)}}{\mathrm{Total\ Load\ (kWh)}} \times 100 \tag{4}$$

Subsequently applied percentages will disaggregate individual units' consumption into two additional measurements, i.e. consumption from PV-BESS and grid supply represented as apportioned consumption in Eq. (5).

$$\mathrm{Apportioned\ consumption,\ (kWh)} = \mathrm{Source\%} \times \mathrm{Unit\ Consumption(kWh)} \tag{5}$$

This rationale provides a realistic figure relative to the usage of a particular unit, i.e. an apartment which consumes a certain amount of energy is billed or incentivised based on the ratio of both energy sources. The method satisfies the numerical composition of total energy, i.e. the sum of all individual loads was equal to total load supplied by the grid and PV-BESS.

5. Results

In this section, we present the energy performance results obtained from operating the SEM in Gen Y apartments. Performance is analysed by initially looking into energy consumption of apartments. Seasonal load profiles illustrate diurnal consumption patterns while the monthly energy usage plot is compared with the benchmark. Power profiles of summer and winter days indicate PV generation and load consumption from grid and PV-BESS. Results from the CP load are also shown because it constitutes an important part of most multi-unit developments. Subsequently grid minimisation is assessed by evaluating the monthly self-sufficiency ratio, and based on outcomes; the share of each source in consumption is shown. Finally we will look into battery storage performance in different periods which plays an important role in meeting the load demand.

5.1. Apartment load profile

The seasonal diurnal load profile of the Gen Y building as shown in Fig. 5 was segregated into four different periods of the year to observe power consumption against hour cycle. The baseload remained under 300W throughout the average 24-hour period cal-

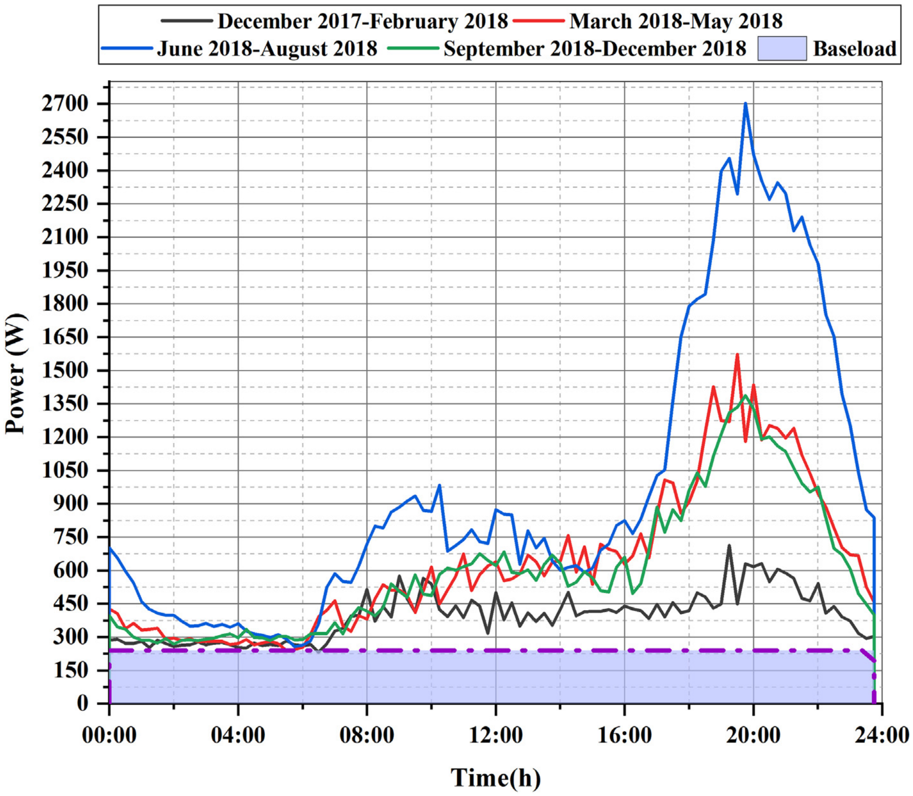

Fig. 5. The seasonal load profiles during four periods of the year (December 2017-December 2018).

culated through lowest values and considering seasonal variation as identified by [76]. The load profile shows commonly recognised peaks in the morning and evening, with the highest demand occurring in the winter period (June 2018-August 2018) as a result of consumption from heating appliances [56].

The decreased load power during the summer period (December 2017–February 2018) as opposed to the other three seasons is a result of occupancy behaviour; the resident of Unit A travelled during that period. Consumption between midnight to early morning hours (6:00 am) in all periods remained under 500 W, with exception of load power in period June-August decreasing from 700W at midnight to 264 W at 6:00 am. The average usage during this period (315W) confirms that the bulk of activity occurs during the day time. The highest consumption during morning peak hours in the dataset was observed between 8:00 am-11:00 am, particularly during the winter period (982W). Similarly, evening peak hours (7:00-9:00 pm) show increased usage, with winter consumption among the highest (2700W), whilst shouldering months (March 2018-May 2018 and September 2018-December 2018) in comparison, exhibited idiosyncrasies.

Fig. 6 represents monthly consumption of all three units in comparison with the average consumption of a three person household in Australia. This benchmark data from [66] was quantified taking per day consumption values across four quarters of a year. The consumption of the three Gen Y units is compared to the benchmark values of one house given the equal number of occupants, i.e. three. The benchmark values are not tailored to characteristics of the dwellings such as floor space.

However the energy consumption at Gen Y is still found to be lower considering the size of units, total of 3 units (Gen Y) to one house (benchmark). The overall average consumption of three units at Gen Y was 22% lower than the benchmark consumption, except for the month of May 2018 and the period of July 2018-September 2018 when the total consumption of all apartments remained 14% higher than benchmark values. The overall lower consumption average may be attributed to energy efficiency features of the building (cross ventilation, access to natural light, light wells, louvres and energy efficient bulbs), and smaller than average living spaces. Occupancy factor should not be overlooked while analysing load profiles. For example, in contrast to the other two units, Unit B does not show any variation in consumption trends over 12 months. This is largely due to the fact that the resident of Unit B worked full time during the day and remained conscious of electricity consumption throughout the year. In comparison, the other two residents worked from home most of the times and would therefore have used heating appliances during the day in winter.

Western Australia boasts an abundance of sunshine, with an irradiance ratio of 5.22kWh/m^2/day [77] and approximately 8 hours per day of sunlight availability. Fig. 7 (a) shows the power profile of a sunny summer day. Clearly a large portion of PV generation (87%) was fed back to the grid between 10:00 am-6:00 pm whilst the remainder was utilised by the loads and for charging the battery. Due to excess PV generation and large availability of battery storage, grid imported power remained minimal throughout the day as shown in Fig. 7(a). The PV+BESS consumption parameter was calculated by subtracting the grid imported power from total consumed power. Similarly, energy consumed from battery storage in the evening shown as BESS Consumption was computed using the same method however, it excluded PV day generation (i.e. calculated between sunset and sunrise). Further details of this battery storage utilisation is given in section 5.4.

The winter day profile is quite dissimilar to the summer period as shown in Fig. 7 (b) and reveals a major portion of grid imported electricity while the battery comes into play later in the day. The major influencing factors on low PV power production are the rainy season, lower availability of solar radiation, changed winter sun path causing shorter sun hours. Consequently, the lower avail-

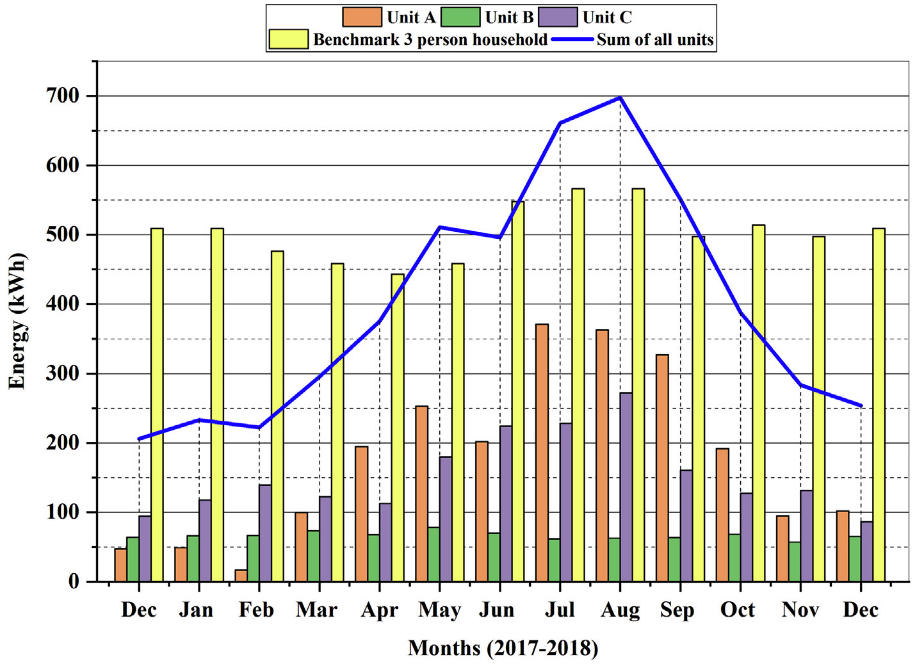

Fig. 6. Monthly energy usage of individual units in Gen Y apartment.

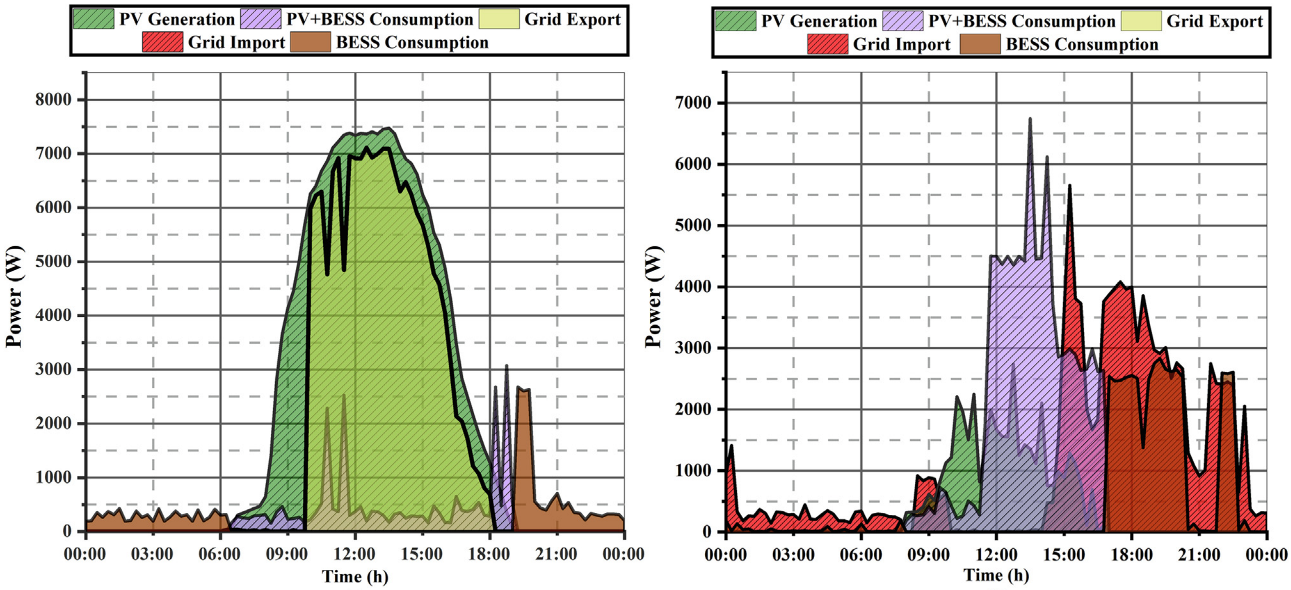

Fig. 7. Power profile of Gen Y on (a) Summer day (Dec-10 2018). (b) Winter day (July 15, 2018).

ability of PV output in winter affects PV generation to consumption ratio [56]. On the other hand, the battery stores less energy and hence loads rely on utility power [78-80]. Nevertheless, the Gen Y SEM maintained the battery and supplied 24% of electricity to the load during peak hours for the worst performing day as shown in Fig. 7 (b). Such a response highlights the significance of the BESS installation in parallel to PV, which provides a backup under extreme seasonal conditions.

5.2. CP load profile

The CP load at Gen Y consists of walkway lights, parking sensors, and entry lights. Contrary to large developments where the CP requirements constitute a significant portion of energy consumption [81] the CP load at Gen Y is relatively small. CP demand in previous studies [21,82] was only covered by grid and PV. In comparison, the available proportion of grid and PV-BESSin SEM meet CP demand at Gen Y. As illustrated in Fig. 8 (a), the CP load demonstrates an average yearly profile operating mostly throughout the night while baseload remains around 80W to keep the control supplies energised for sensors during the day time. The profile does not distinguish weekdays and weekends as given in [11] however, it does exhibit an identical pattern differing only in amplitudes (110–120W). The power value increment after 6:00 pm and the drop after 5:00 am in the morning reflects the load control sequence implemented through a programing relay which oper-

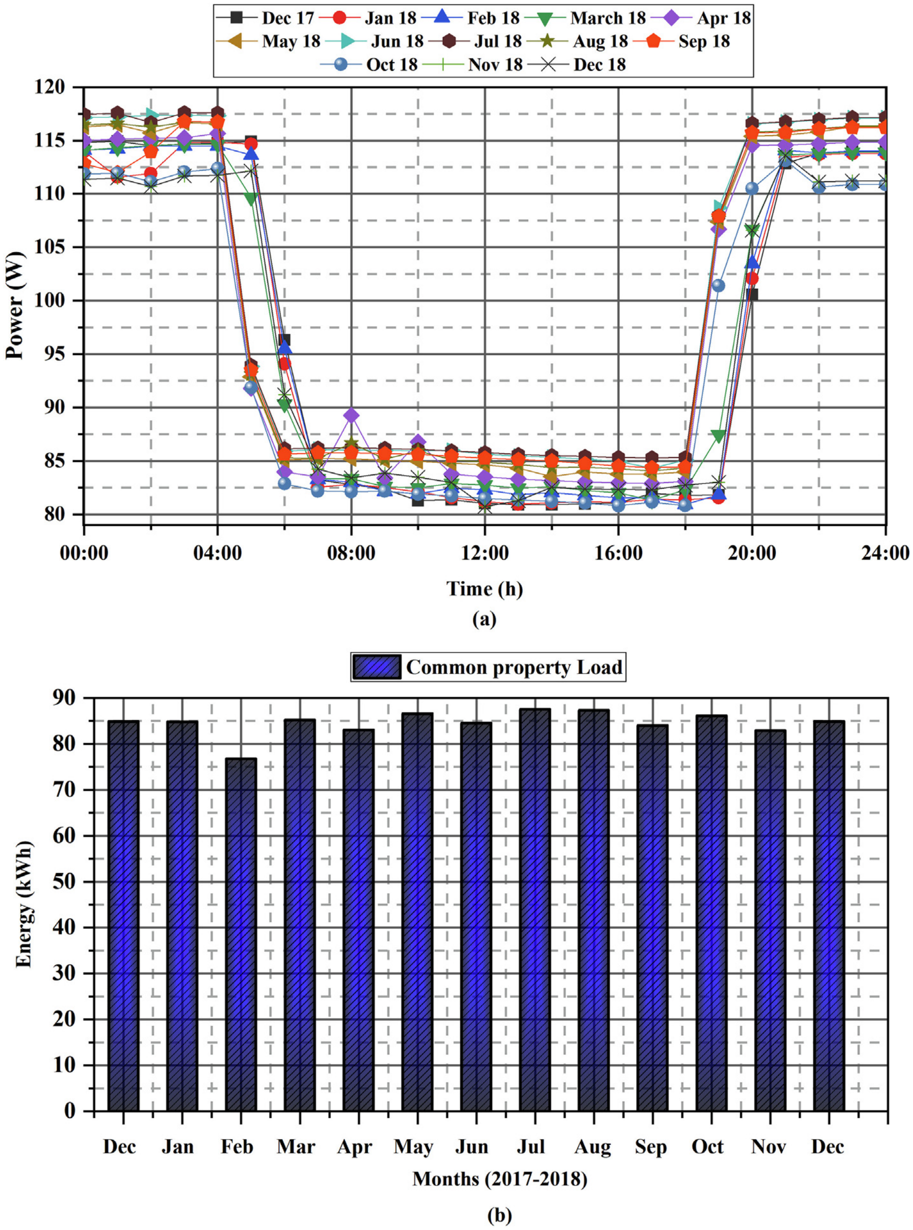

Fig. 8. (a) CP yearly average load consumption profile. (b) Monthly energy consumption of CP load.

ates according to seasonal daylight hours. It can be deduced that the CP load, despite its profile specificity, contributes to the total baseload level (in Fig. 5) with standby mode for other residential loads. Fig. 8 (b) shows the monthly chart clearly indicating an average CP consumption of 85kWh (2.8kWh/day) which constituted 37% of the total load during the first three months of data, with a decrease to 22% for the remaining period. The reason for the increased percentage during the first quarter was an overall lower consumption from individual apartments (forming the total load together with CP) which increased the CP consumption ratio of the total load. Likewise, the remaining quarters observed a steady share (22%) due to increased energy usage of other primary apartment loads which lowered the CP portion.

Therefore CP load, despite following the identical yearly load pattern as shown in Fig. 8(a), contributes to overall consumption upon aggregation with apartments' load which vary during different periods as shown in Fig. 5. This demonstrates the importance of SEM's embedded metering, which contains all loads including CP, connected in a shared arrangement rather than separate electrical connection [64]. As long as renewable capacity to consumption ratio is higher or equal, the CP load as part of the overall load will be supplied by PV and BESS, thus reducing grid reliance and also avoiding additional cost of separate connection.

5.3. Self-Sufficiency

The yearly self-sufficiency ratio obtained from equation (3) in Fig. 9 reflects on average 75% dependency of the microgrid on PV-BESS and 25% on the grid. The system maintained a self-sufficiency of 80% for half of the year while the poorest period for the achievement of satisfactory percentages were the winter months (June, July, and August).

The lower self-sufficiency ratio in winters can be improved using various optimisation strategies however we can also apply export limitation method as a facile solution. Considering the availability of battery storage in later hours of the day, if we regu-

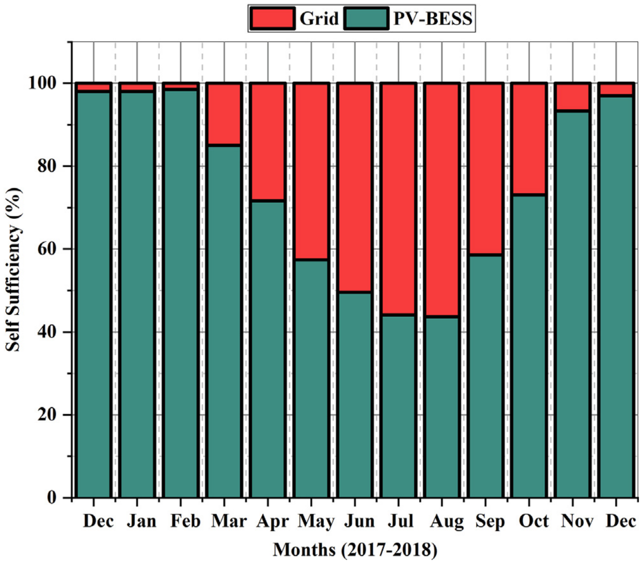

Fig. 9. Monthly self-sufficiency ratio of SEM.

late the SEM on export limitation(zero export) during excess generation hours, the results will suggest overall increased self-sufficiency with more PV-BESS consumption and less grid percentage. Fig. 10 (a) shows average export pattern during four winter months (May-August), while the total export energy per month is plotted in Fig. 10(b). Subsequently if this exported energy is utilised to supply residential loads, the self-sufficiency ratio reflected in Fig. 10(c)increases for the months of May-August to 88%, 74%, 66% and 82% respectively.

On the other hand, the presence of an individual dweller at any particular instant is not guaranteed which could further improve the energy performance metrics i.e. the possibility of even less grid consumption if an occupant moved out frequently during winters and created a surplus storage capacity for other units. The method is helpful in underlining the effectiveness of a shared system and it further offers improvements for system optimisation.

The energy fraction of each load resulting from from the apportionment method is shown in Fig. 11 which reveals that Unit A and Unit C consumed more renewable energy in total (1286kWh and 1252kWh respectively) than Unit B which consumed only 611kWh.

In the same manner when the apportionment method was applied to determine CP energy fraction, an increasing grid consumption response was noticed during winter increasing from 40kWh in May to 53kWh in August. Since the majority of CP load operates during night hours, an increased grid usage can be observed in winters with less availability of battery storage.

5.4. Battery storage in SEM

Fig. 12 illustrates the average daily SOC over three different periods in the calendar year (December 2017-December 2018). To preserve usable battery lifetime, the depth of discharge of the BESS is set to 80%, i.e., 8kWh of usable capacity, which means the illustrated graphs represent 8kWh of maximum battery capac-

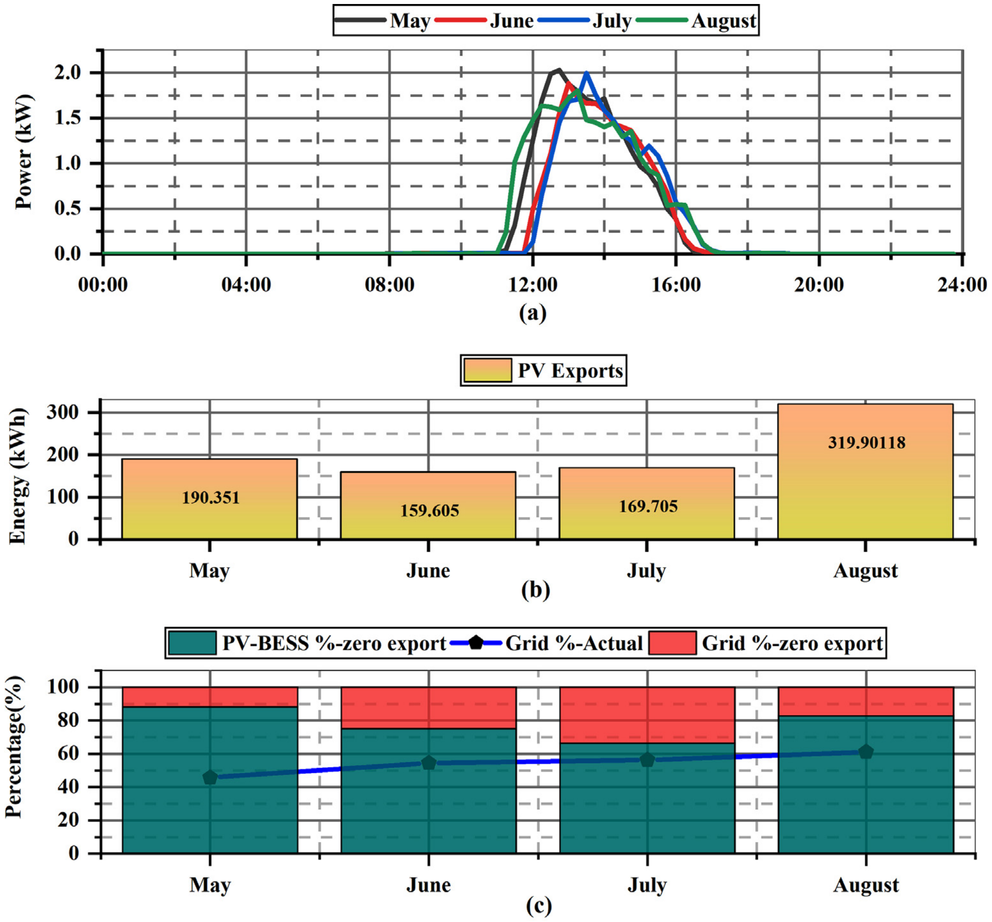

Fig. 10. Resultant self-sufficiency ratio after zero export limitation (May to August): (a) Average PV export pattern in winters (b) Monthly PV exported energy (c) Self-sufficiency ratio after zero export.

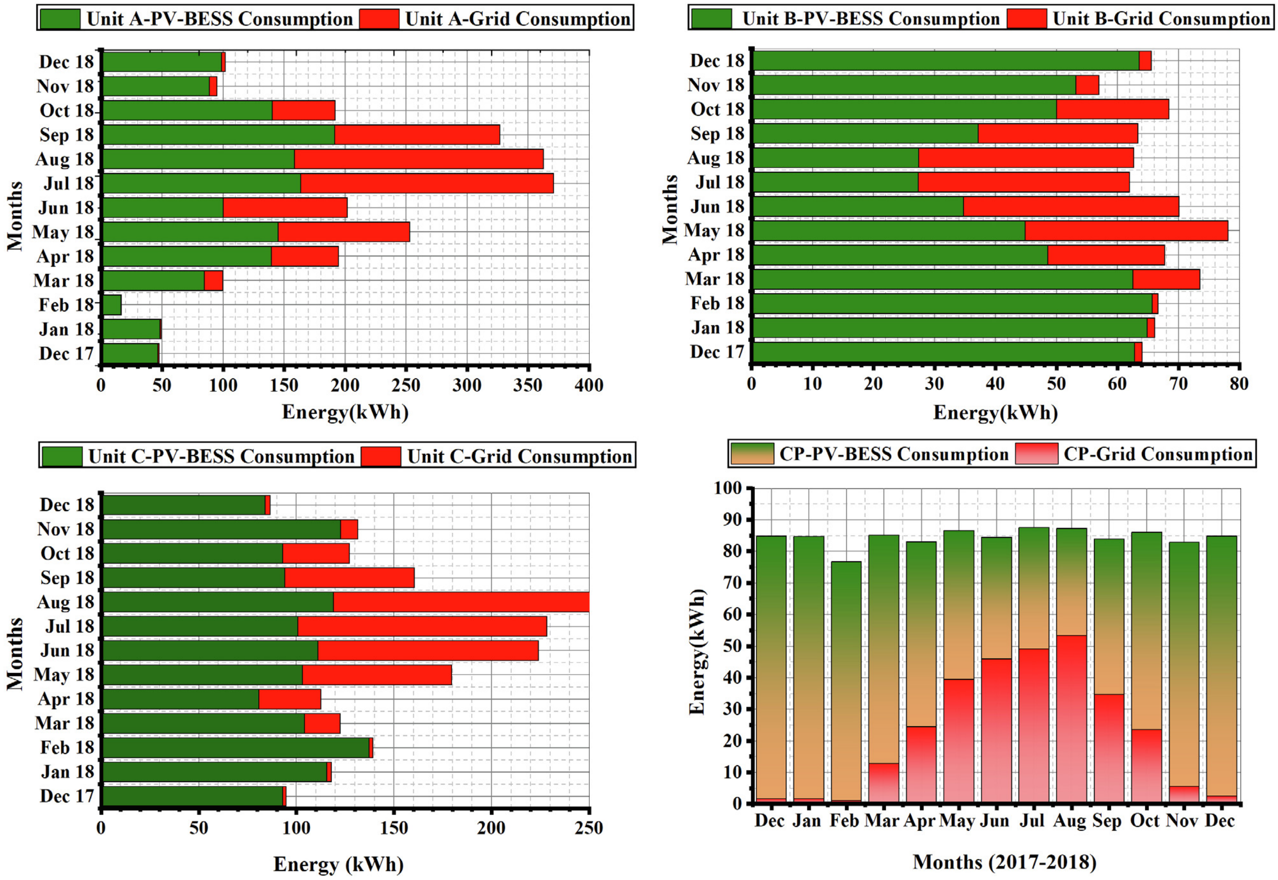

Fig. 11. Energy fraction of residential units and CP load according to apportionment method.

ity at 100% SOC. Self-consumption ratios of PV-BESS vary greatly with changing seasons which is apparent from the plot. The summer (December 2017- February 2018) and spring (September 2018-December 2018) profiles exhibit a high level of storage capacity over a longer period, which aids in shaving the peak load and reduces grid imports.

Usually, on-site loads are supplied by PV and BESS during the daytime in summer; however, it is generally the peak demand period which affects the electricity bills. During summer the SOC remained at 80% on average during the peak load period (6:00 pm-9:00 pm). Hence, 6.4kWh of battery capacity was available to cover load demand for the total load and self-sufficiency of more than 80% during this period was achieved. The SOC profile for winter (June 2018-August 2018) shows a low percentage of storage due to the lower availability of PV unable to fully charge the battery.

These findings are comparable to the simulations of [32] on a similar scale where seasonal variation affected the SOC profiles. Despite these limitations the battery still maintained a stored capacity between 1.6kWh and 3.2kWh over the peak period to supply loads which were complimented by grid imported energy when required. Besides SOC information, it is also important to understand temporal battery energy usage in the peak seasons i.e summer and winter. In Fig. 13, the time considered for the plot ranges from evening to early morning (6:00 am-6:00 pm). The summer consumption during peak period maintained a threshold of 2kWh from midnight to the rest of the period whilst in winter the trend shows 40% higher usage.

Since the configuration at Gen Y employs a standard flat rate tariff, the possibility to apply any time-of-use pricing for charging the battery through the grid is not applicable here. However, it is feasible to consider different BESS scheduling strategies for the peak periods in order to achieve high self -sufficiency and reduce costs. Moreover, the battery utilisation depends strictly on load demand and high consumption. Fig. 13 suggests that deferring battery utilisation to a later part of the evening would be beneficial to achieve high self-sufficiency in winter. As battery utilisation during the daytime in SEM is supported by solar PV, discharging the BESS in the evening peak period would reduce large grid imports. Our current operational method closely resembles the evening discharge strategy modelled by [28], although the latter discharges the battery in the evening.

6. Discussion

The shared diurnal load profile of the apartment building indicates discernible characteristics independent of the sources' impact on consumption. The minimum baseload threshold remained consistent on a 24-hour scale, i.e. values were lowest around 6:00 am in the morning throughout the year whilst the highest occurred between 4:00 pm-11:00 pm. These findings differ from those of [83], who reported that 50% of lowest consumption intervals occurred during midnight to 8:00 am and also showed that baseload variation was significant among different dwellings. Nonetheless, the observation from the Gen Y metering data gives key information about the consumption intervals and minimum energy value (approximately 7.2kWh/day) required to operate appliances. In a shared context, benefits to manage a shared connection are greater than separate loads. This is due to the fact that individually connected loads are subject to several factors such as occupancy and user behaviour [84-87].

If distribution of power is considered, average load power of all profiles would occur at less than 800W which bears a close resem-

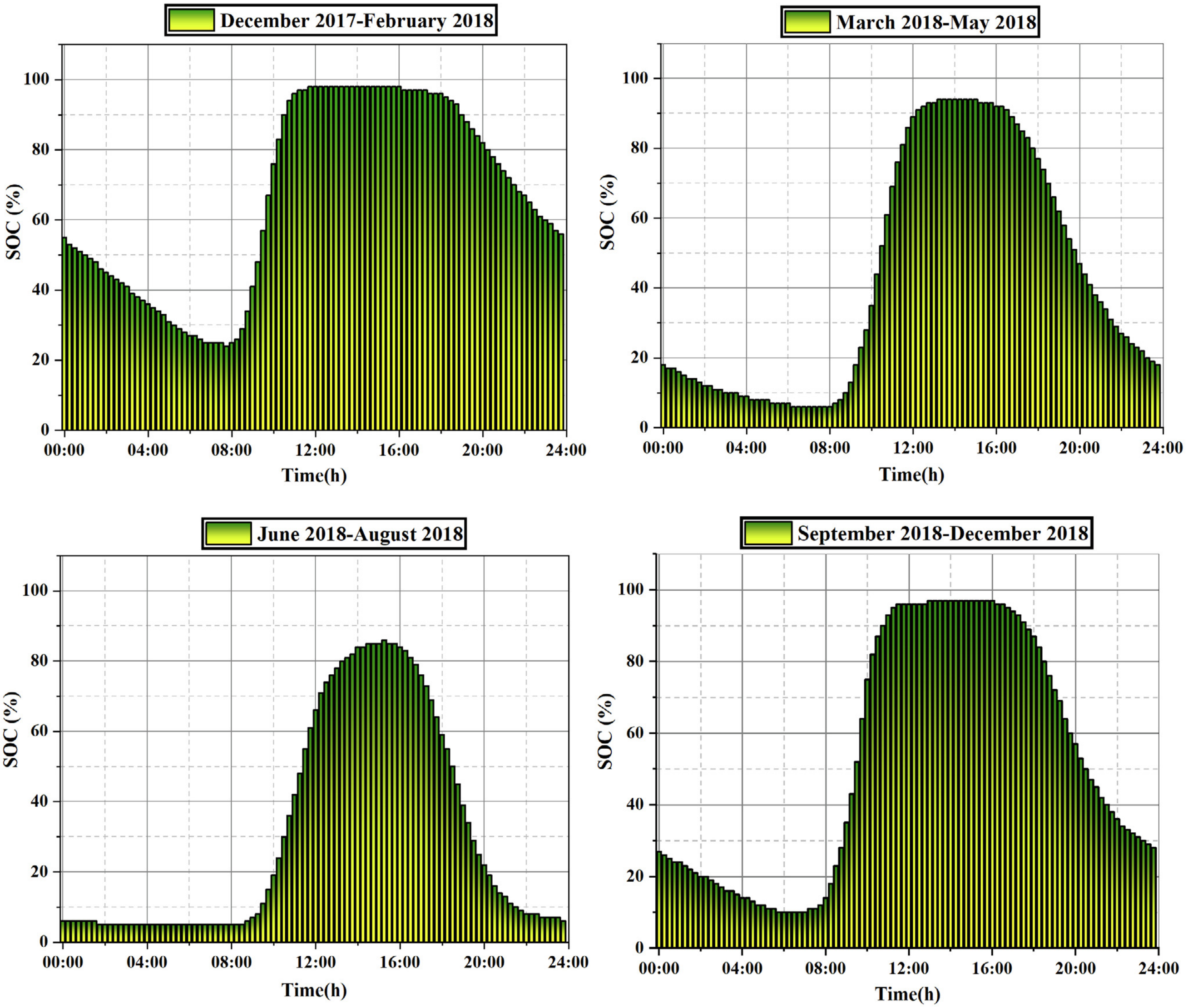

Fig. 12. Average diurnal SOC profile for four different periods.

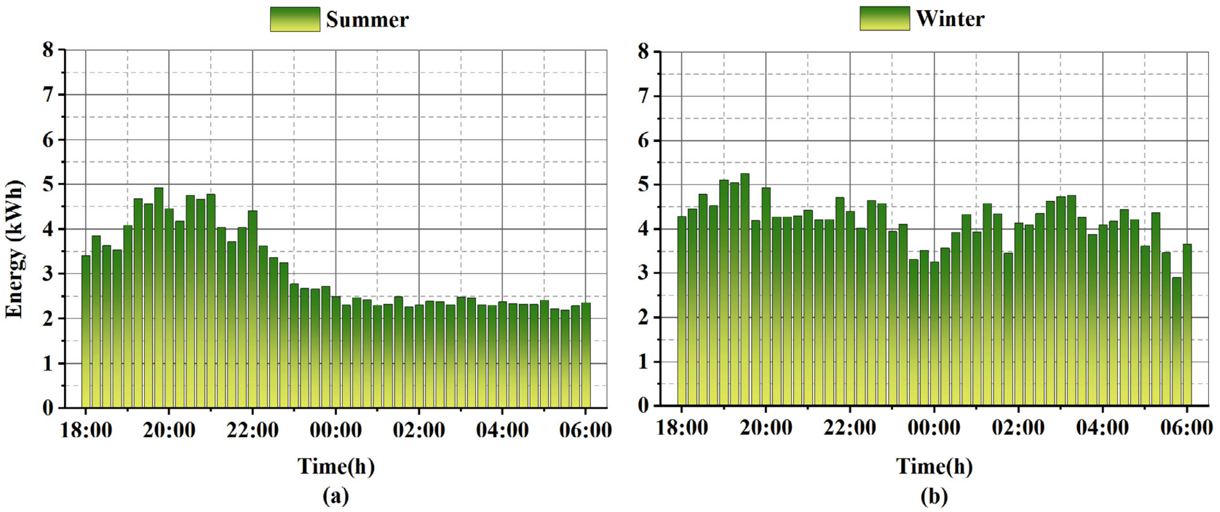

Fig. 13. Average battery consumption in evening hours for (a) Summer (b) Winter.

blance to the one reported by [88]. However, these authors strongly emphasized the use of high temporal resolution (less than 1 minute) data for instantaneous power because even 15 minute intervals could lose the valuable peaks which occurred during high consumption periods. Nevertheless, the pooling of households from 15 second resolution data matched precisely with conventional 15 minute pulse meters. Due to the lack of load profile data from Australian apartments, this remains subject to further studies.

Overall, the sum of the three units' energy consumption over the period of one year was 22% lower than benchmark values for a 3 person detached dwelling, as given in Fig. 6. While household sizes, occupancy behaviour and dwelling characteristics affect electricity consumption, load profile data illustrates positive energy performance for the building in summer due to the abundance of PV generation. In contrast, high electricity usage in winter implies that space conditioning constitutes a large portion of energy consumption in Australia, as identified by [89]. To achieve cost savings during winter, consumption patterns from this dataset could be analysed and extrapolated to apply demand response strategies by utilising battery storage during peak periods alone.

To capitalise on the commissioning of SEM for meeting load demand, PV-BESS utilisation was measured against the grid reliance. The self-sufficiency ratio throughout the year remained higher as a result of available battery storage in the evening peak hours. Even though an increased PV size as a renewable source could have improved the self-sufficiency ratio, numerous studies have discovered that the inclusion of a battery storage significantly reduces the grid dependency [68,90,91]. In this context, the research findings have focused more on detached housing, and hence shared energy systems in apartment buildings need to be studied further. It is highlighted by [92] that centralised battery storage in a shared residential setup could effectively increase self-consumption and reduce grid reliance. Moreover [28] having simulated different models and strategies, stressed the usefulness of embedded networks with PV-BESS in reducing peak demand and increasing self sufficiency. On the other hand, four operational strategies suggested in [93] are also plausible in proposing a method to improve self-supply, reducing peaks and also proposing a control strategy to lower investment costs.

7. Conclusion

The study provides energy performance results for an apartment building connected to SEM. Pulse metering played a vital role in providing real-time performance of the shared system since each electricity distribution and consumption node was monitored that helped in energy analysis. It also provided an accurate representation of a customer's electricity usage pattern over different periods. The lower consumption of Gen Y apartments than benchmark value could involve multiple factors such as number of households, occupancy behaviour, dwelling infrastructure and improved thermal performance features. Further research into the effects of occupancy behaviour on energy consumption, and empirical assessments of the effect of construction design in the context of apartment buildings is needed.

Our findings also indicate that utilisation of SEM has increased self-consumption and achieved an overall self-sufficiency of 75%. Certain imperfections such as excess availability of renewable energy during summer and lack of battery storage in winter require further exploration. Comprehensive optimisation modelling would be an interesting research topic for studies in this subject area. A hybrid energy system with an energy sharing mechanism [94] could be modelled to resolve the seasonal consumption issue however, such a system would not prove to be cost effective. Improved results may be achieved on different apartment sites by zero export or export limitation during particular periods or deploying optimal BESS control and scheduling strategies backed by load forecast.

We also analysed the results from the BESS which in parallel to PV, played a key role in meeting the majority of load demand. As apartment construction designs vary significantly, identification of the single best battery type for a particular apartment is premature. Moreover, BESS optimisation strategies must be deployed before searching for other options because if BESS usage is not configured properly, even optimal capacity may not result in increasing self-sufficiency and cost savings.

The SEM configuration in Gen Y, if replicated in other apartment buildings, might be helpful in curtailing lgrid imported electricity and bringing financial benefits however, the reduced surface area of the roof might become a limitation to generating enough PV energy and therefore adequate battery storage sizing is integral to support limited PV generation. The insights provided by the Gen Y data may be relevant to other jurisdictions with similar system capacity and network design guidelines, however individual load performance, different climate conditions and dwelling characteristics should be considered during system design.

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CRediT authorship contribution statement

Moiz Masood Syed: Conceptualization, Investigation, Methodology, Formal analysis, Data curation, Visualization, Writing - review & editing. **Paula Hansen:** Conceptualization, Writing - review & editing. **Gregory M. Morrison:** Writing - review & editing, Supervision, Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enbuild.2020.110321.

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Article

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

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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.

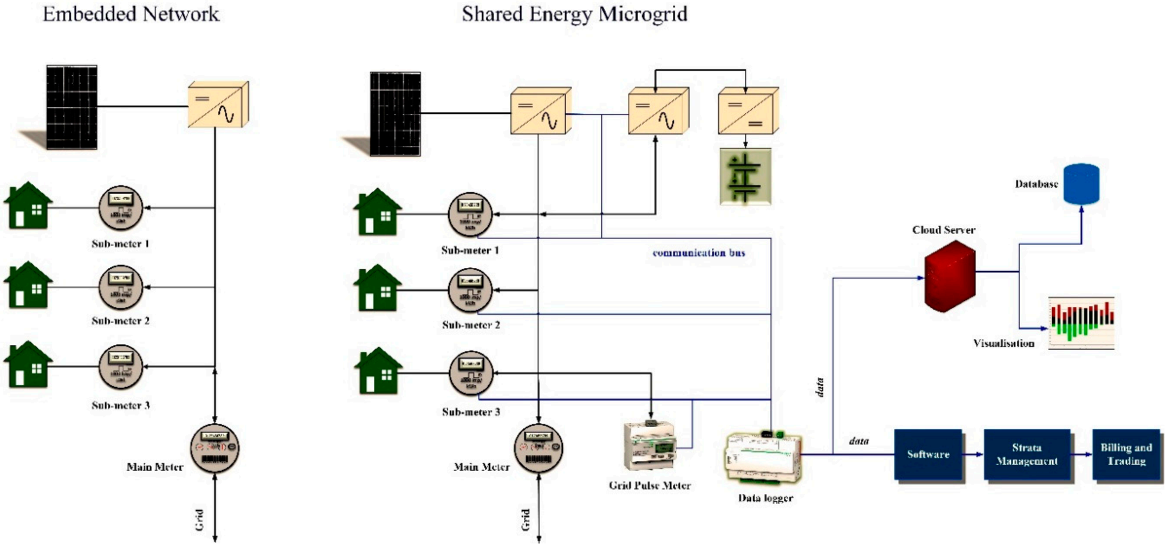

Figure 1. An embedded network (**left**) and shared energy microgrid (**right**).

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.

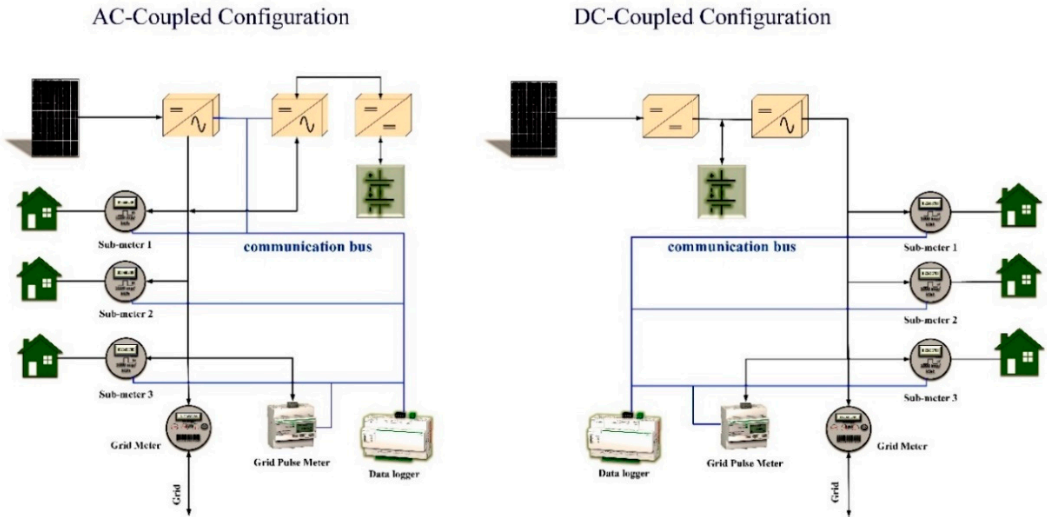

Figure 2. AC-coupled (**left**) and DC-coupled (**right**) configurations used in the study.

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.

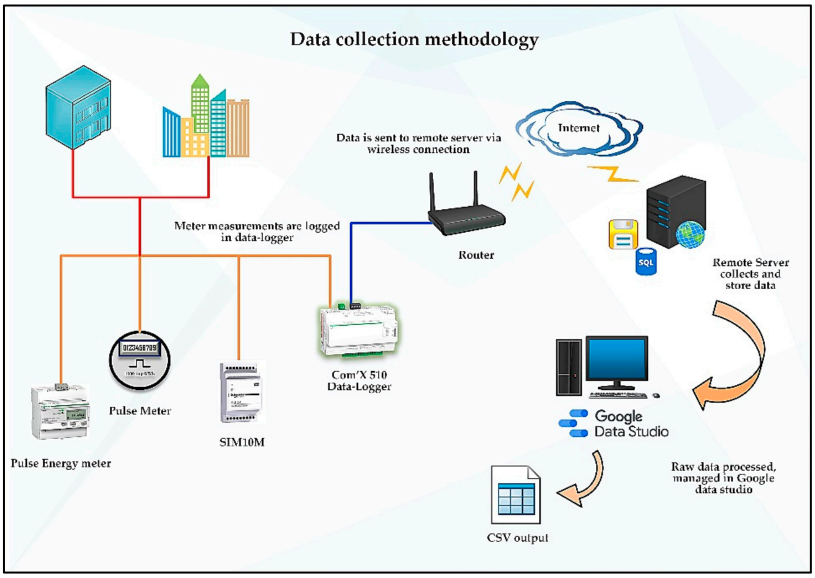

Figure 3. Methodology for data collection (redrawn from [3]).

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.

$$\Delta X_t = Y_t - Y_{t-1} \tag{1}$$

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).

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

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).

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

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.

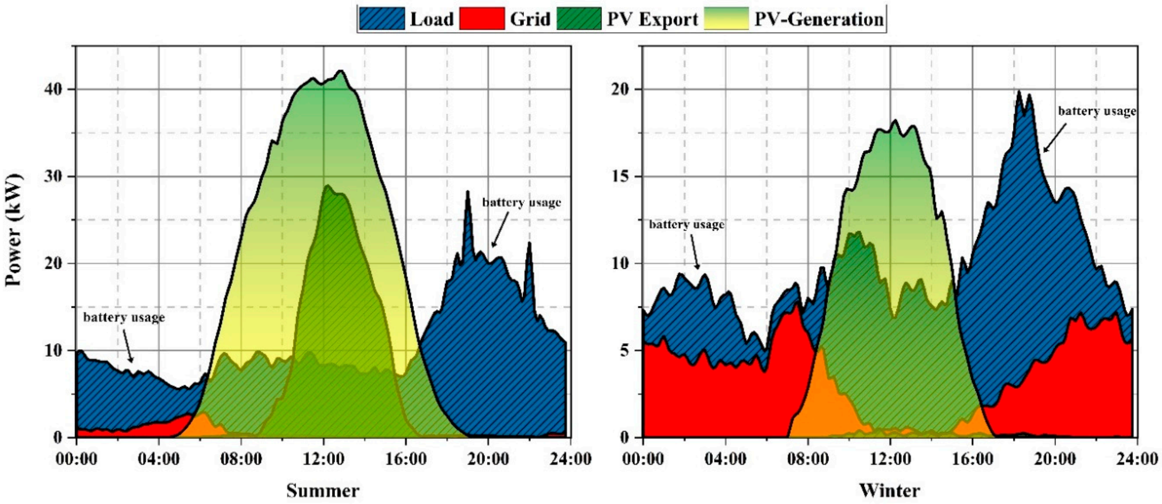

Figure 4. Seasonal load profile for Evermore.

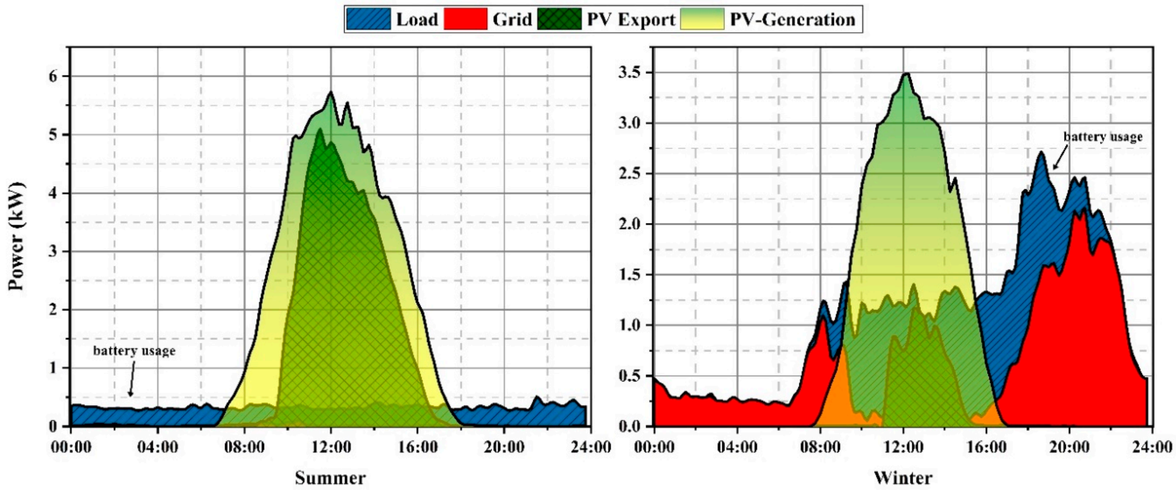

Figure 5. Seasonal load profile for Gen Y.

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.

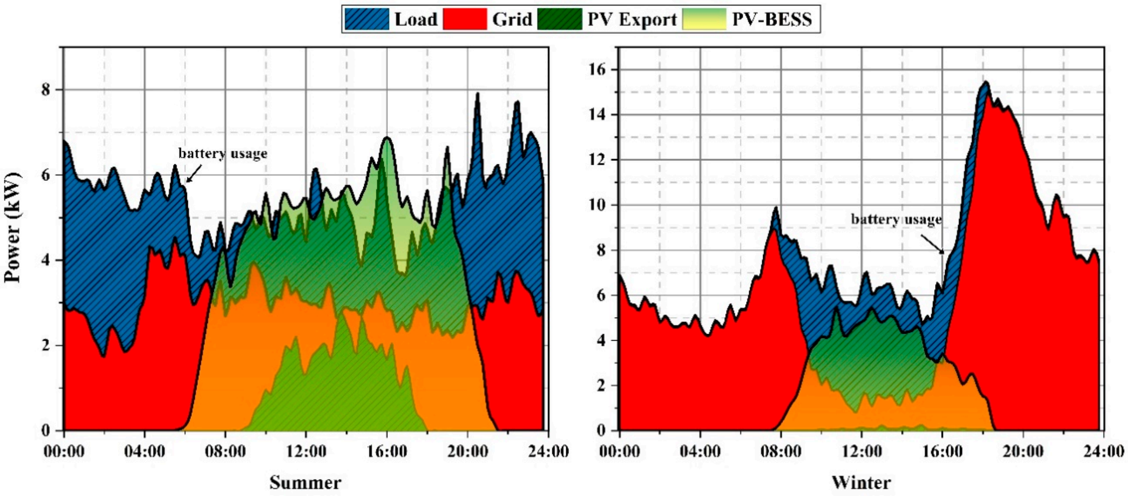

Figure 6. Seasonal load profile for SHAC.

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.

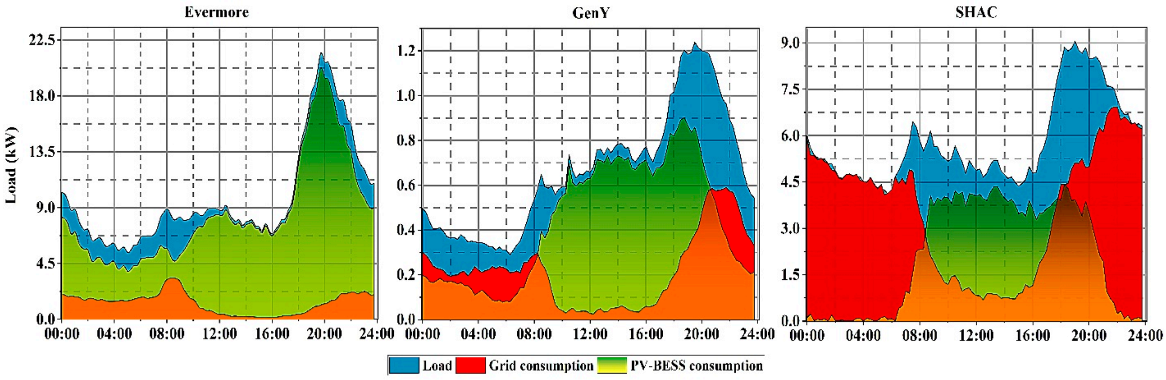

Figure 7. Averaged diurnal load profiles (from left to right; Evermore, Gen Y, and SHAC).

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].

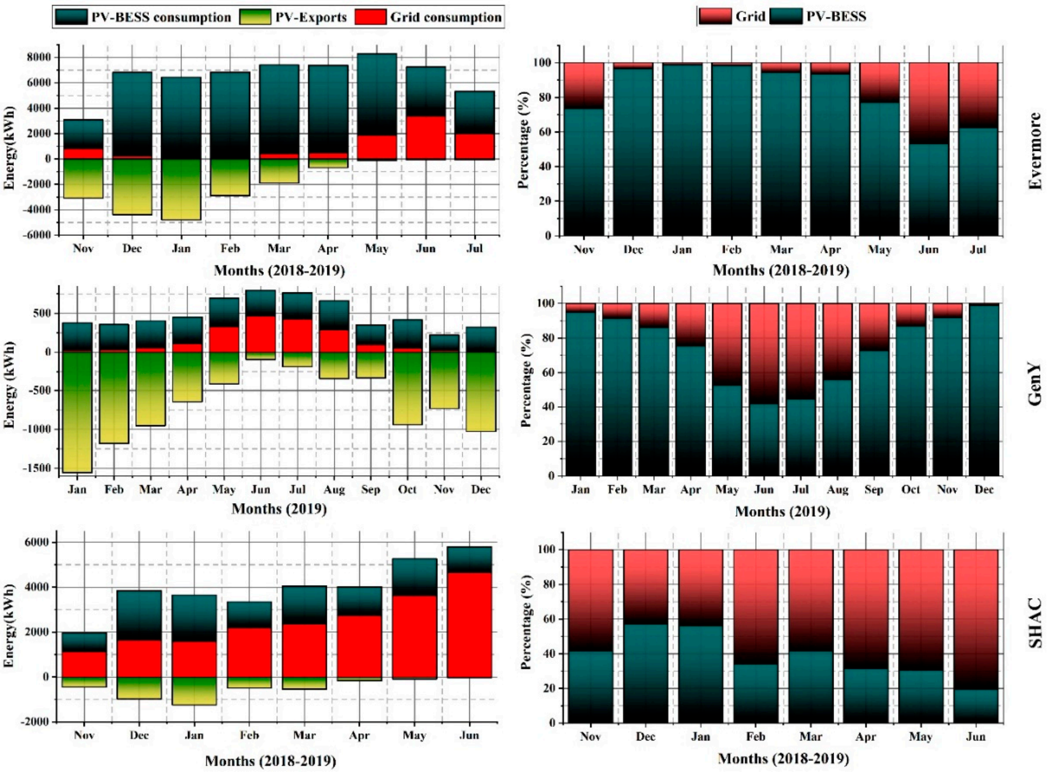

Figure 8. (**left**) Monthly energy distribution and PV exports (**right**) resultant self-sufficiency.

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.

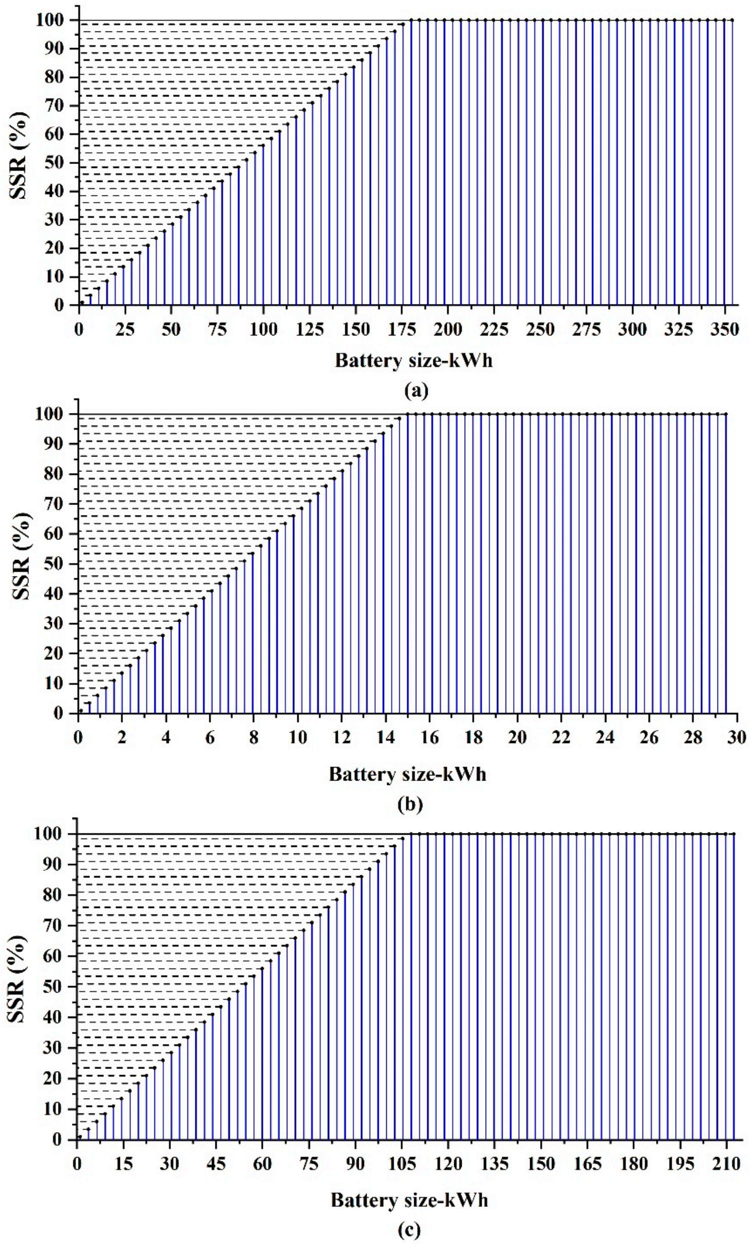

Figure 9. Impact of battery size on the SSR for (**a**) Evermore, (**b**) Gen Y, and (**c**) SHAC.

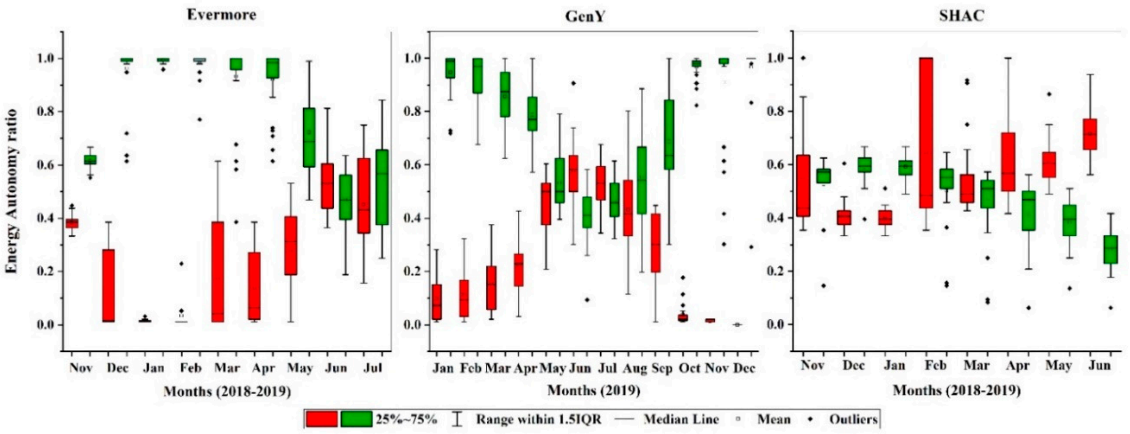

Figure 10. Energy autonomy ratio for configurations at three sites.

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.

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Appendix A

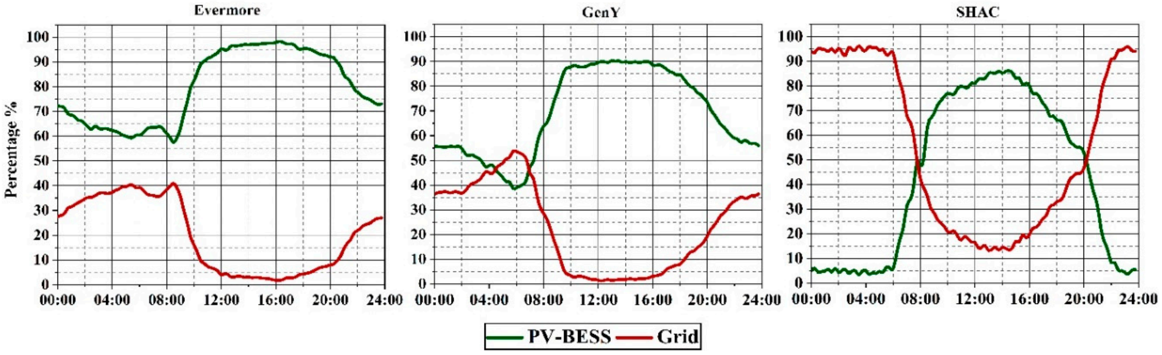

Figure A1. Averaged diurnal share of sources.

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

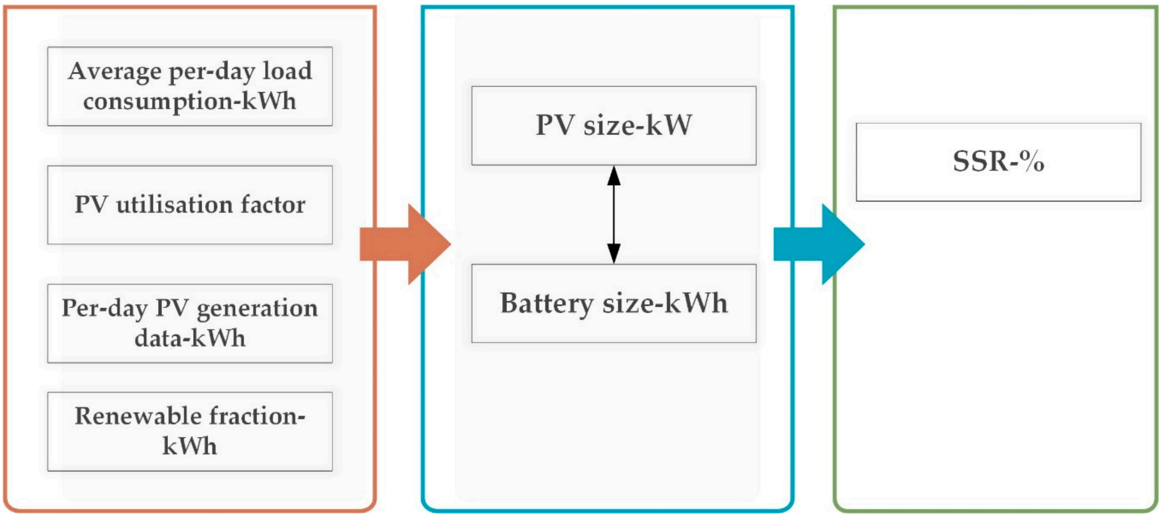

Figure A2. Estimation process of varying battery sizes on SSR.

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Energy Allocation Strategies for Common Property Load Connected to Shared Solar and Battery Storage Systems in Strata Apartments

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Abstract: Common property (CP) is a significant consumer of electricity in apartment buildings. Although some apartments in Australia have adopted shared microgrid configurations to offset grid consumption, the characteristics and load patterns of CP are rarely discussed due to lack of available data. As common areas normally constitute part of owner corporations, energy distribution in these premises requires attention. This paper presents empirical analysis of the CP load connected to shared solar and battery storage for three apartment complexes located in Perth Australia. Load patterns for CP over a defined dataset period were analyzed, and grid usage reduction was examined by implementing and comparing three energy allocation strategies based on surplus energy utilization. The findings indicated significant grid usage reduction for CP load in different apartments after implementation of three strategies. Instantaneous consumption decreased 72%, and surplus allocation strategy reduced 91%, while consumption-based allocation reduced 76%, of grid electricity. Moreover, consumption-based allocation offered improved cost benefits compared to the other two strategies. The results further revealed the usefulness of energy allocation and effectiveness of surplus energy utilization. Based on outcomes, the strategies provide consolidation with conventional energy trading mechanisms and broadly link to the virtual power plant concept for coordinating energy flows between multiple generators.

Keywords: solar PV; battery storage; shared microgrid; apartments; common areas; energy allocation; grid reduction

1. Introduction

In recent years, attention has been paid to the reduction of residential electricity consumption driven by motivations, such as bill cost reduction and abatement of carbon emissions. Carbon emission mitigation has mainly become a global objective for achieving energy transition from fossil fuel-based power sources to distributed renewable energy resources (DRES). Environmental concerns have led to large augmentation of DRES, including solar photovoltaic (PV) and wind in the global energy market. The share of global installed PV capacity in 2019 reached approximately 580 GW [1] which is expected to grow to 1320 GW by 2029 [2]. In this context, several market trials of grid connected PV microgrids have been demonstrated due to this increased penetration. Despite the large potential of electricity generation, PV and wind are highly dependent on weather conditions; hence, intermittency is a major challenge due to irregular generation. To overcome the intermittency issue, stable storage technology is required for balancing energy supply and demand. Energy storage technology has been acknowledged to provide flexibility services to improve grid stability by providing operating reserves and time shifting to match load and generation [3,4]. In terms of long-term balancing of supply and demand, large scale storage technologies, such as battery storage, pumped hydro-storage, flywheel, and compressed air storage, hold primary interest (ibid). With the decline of battery costs, small size, low maintenance, and high efficiency, it is becoming the most feasible storage option for co-location with PV and wind.

With the majority of its energy still derived from fossil-fuel based sources, Australia is at a critical stage of energy transition supported by its favorable geophysical condition to broadly adopt DRES [5]. Soaring electricity bills in conjunction with the decline in prices of PV and battery storage have caused the domestic uptake of DRES in Australia and provided energy autonomy to consumers, thereby reducing reliance on utility grid network. The South West Interconnected System (SWIS) is an islanded electricity network in Western Australia, which relies on its own domestic power generation to maintain supply and demand without the assistance of other regional networks. The massive uptake of renewable energy has pushed the Wholesale Electricity Market in the SWIS network into a renewable energy transition, which is similar to other national and global transitions [6]. Most notably, the excessive daytime PV generation in Western Australia can jeopardize the viability of baseload generators [7]. It is anticipated that solar PV generation capacity in Western Australia will reach 1500 MW by 2030 [7].

DRES can also support local energy markets in terms of ancillary services whilst providing additional capacity. At present, ancillary services, such as voltage and frequency control, are supported by synchronous generators. If DRES are controlled and aggregated, they can leverage ancillary services not only at the distribution level but also by providing dynamic balancing to resolve demand and supply and peak management issues. On the other hand, in the event of any network failure, the distributed resources can feed power to the main infrastructure. In the medium term, this rapid uptake will result in the decommissioning of coal-based power plants, being replaced by distributed rooftop PV, large PV plants, and wind energy.

A significant proportion of consumers living in the approximately 2 million houses in Australia have access to PV generated electricity. Apartment buildings contribute to one third of all residential housing approvals [8], and, indeed, apartments are a prime utilizer of electricity. Notwithstanding the fact that PV and battery energy storage system (BESS) have been fitted mostly on freehold dwellings [9–14], widespread adoption of PV-BESS on apartment buildings have seen less installations. Detached houses have adequate roof space to accommodate PV panels, and the systems are straightforward to design and install. Energy from a grid or PV-BESS is generally distributed through a single meter connection for a single dwelling, so there is no complexity in energy accounting for the building. In contrast, there are many constraints when it comes to the deployment of PV-BESS systems in multi-residential buildings, particularly apartments. Apartments carry less roof-space to power maximum households through PV in a vertical spaced area, and individual PV connections demand complex technical retrofits. Under Australian strata law, the apartment roof containing solar panels is a shared resource managed by a legal committee known as Owners Corporation (OC) [15]. The OC governs the building ownership management, such as controlling the utility, asset maintenance, and billing, for common property (CP) areas. The OC also normally owns the CP electricity. Hence, for installation of a new PV-BESS or retrofit in the building, an agreement or bylaw is generally needed from the OC. Difficulties occur when some residents wish to install an individual PV system in a shared space, while others opt out creating inequitable distribution of the solar resource. In tandem with this, there is no clear business model for commissioning PV-BESS in apartments, while network constraints and regulatory issues have also impeded the uptake of renewable energy in strata titled apartment buildings [4,16].

Consequently, consumers living in multi-residential buildings are deprived of the energy and cost benefits enjoyed by detached house residents. Only a few studies have demonstrated the impact of PV-BESS on apartment buildings [4,15–17]. The studies [15,16] emphasized that a shared microgrid for apartment buildings can be more effective as it offers techno-economic benefits by reducing grid imported electricity during peak periods while storing excess energy during the daytime. Common areas (The terms common property and common areas are interchangeably used in this paper.) in apartments are also known as common property (CP) in Australia, common hold in the UK and commodious in the U.S. and Canada and hold prime importance in terms of high electricity usage [15]. Strata title apartments contain properties sold to more than one owner having ownership of a residential unit, as well as common areas [17]. Much like residential units in apartments, it follows that measures are needed to solve the electricity cost problem resulting from common areas energy usage, such as the installation of solar PV modules and BESS.

Study Objective

Despite the large-scale rollout of PV installations in detached residential houses, a steady decline and in some cases, abandonment of the feed-in-tariff subsidy has reduced the incentives for consumers. These incentives are gained from exporting surplus PV to the utility. However, high-rise apartments still face an existing barrier of a relatively small rooftop area, which avoids them covering their energy demand through solar PV alone [18]. Although battery storage and demand response strategies can be added to optimize energy usage [19], through increasing self-consumption and self-sufficiency, a practical solution to utilize excess exported solar energy among apartment units is still under exploration.

Integration of PV-BESS to an existing grid connected system can power apartment and common area electricity needs through energy management strategies, which fairly allocate and distribute energy from both sources. This is important if certain innovative solutions are envisaged in order to incentivize consumers. Although the techniques require advanced metering equipment and a dynamic communication infrastructure, the pathway to a dynamic energy system demands the incorporation of such mechanisms for a cost-effective low carbon outcome. On the apartment scale, the methodologies can be effective within the building for strata management or a local aggregator. Data related to PV generation, apartment consumption, and therewith CP usage holds utmost importance. Regardless of whether the split-incentive issue can be resolved through a shared embedded microgrid [4,20], the energy accounting of excess renewable energy shared between consumers and the CP load needs further investigation.

Considering the elements of common areas grid electricity reduction and excess energy distribution, this paper undertakes an empirical analysis of CP loads connected to a shared microgrid with PV and BESS in three apartment complexes in the White Gum Valley (WGV), Perth, Australia. For a rigorous analysis of the CP load, a large sample would be required from a variety of apartment complexes; however, there is scant literature support when it comes to the usage of PV and BESS specially to offset CP grid electricity usage. Only a few studies [21,22] have discussed the CP consumption with PV. However, to the best of our knowledge, except Reference [4,21], the academic literature does not consider the role of deployed battery storage with PV in meeting the CP load demand. Similarly, there is a lack of published work on the CP load behavior of Australian apartment buildings. This work also fills the gap of data scarcity pertaining to common areas of Australian apartments by demonstrating CP load consumption trends for each site, as well as a comparison of three strategies, which allocate and distribute excess renewable energy in order to lower CP consumption from the grid. The study differs from any conventional peer-to-peer trading mechanism, such as auction-based approaches [23–25], blockchain based algorithms [26], or game theory [27,28]. Alternatively, we first show CP load patterns in apartment buildings and then include three strategies to illustrate the grid usage reduction in meeting CP demand. This removes sophisticated forecasting models used for energy trading. Moreover, we also discuss the empirical results from surplus energy gained by apartment units and further recommend the energy trading algorithms to be implemented.

The paper is structured as follows:

- ➢ Section 2 discusses electricity consumption in common areas and includes a literature review on energy allocation and distribution in multi-residential buildings.

- ➢ Section 3 presents the methodology and analysis in detail. Initially, CP load characteristics at WGV are presented, followed by information about the shared microgrid configuration, as well as CP load consumption patterns from three apartments. Thereafter, three energy allocation strategies are explained.
- ➢ Section 4 presents the results post implementation of the three strategies.
- ➢ Lastly, Section 5 concludes the paper, highlighting major findings and recommendations for future research.

2. Electricity Consumption in Common Areas

Multi-residential strata buildings vary in terms of design and construction. Apart from the residential units, the CP load generally includes carpark lights, sensors supply, ventilation fans, pumps, foyers and vertical transportation, such as lifts [18,29,30]. Each Australian state applies their own legislation for management of strata developments [14]. In Western Australia, there are many approaches to managing common areas and individual ownership. Individuals can own the inside, as well as outside, sections of the buildings. However, for a general understanding, common area is specified here as the premises jointly owned by owners in a strata titled scheme, i.e., owners as tenants in common [18].

There has been a reporting range in the literature regarding the amount of electricity consumption in common areas. This variance is due to the variety of factors, such as number of stories, floor area, and number or type of appliances [15,31]. For these reasons, there may be a difference in energy consumption between household electricity and common areas [32]. In a study of Australian virtual apartment buildings, the average annual CP ratio in different characteristic buildings varied between 33% and 57% of the total load. Another study [33] examining three housing forms found that electricity use in medium and high-density housing increased as floor area (comprising common areas) was expanded. Common areas electricity consumption of medium to high-rise buildings in a Japanese region [34] documented an annual 886 kWh energy usage/dwelling, equivalent to 10% of the multi-dwelling unit. Close to this result, another study [30] stated the average annual common areas electricity usage of 1026 kWh. A residential apartment building in Italy [29] reported annual common services energy usage of 2114 kWh. Apartment buildings with old construction and vertical transportation contribute to higher electricity consumption. Monthly common areas usage in a 40-unit Canadian condominium building [35] was found to be large at 26,715 kWh. Similarly, a 16-story apartment building in Lithuania [22] consumed 28,390 kWh of energy usage annually from the common areas. There are certain factors to be considered before deploying common area load, such as shape factor and specific energy usage. Specific final energy use (kWh/m^2), as explained in Reference [36], was found to be four times lower than apartment areas. Although increasing the common area size might decrease the final energy use of the building, it will inevitably increase the energy usage of the building.

Regardless of rules and regulations, the overall CP load is observed to be higher than total apartment loads in medium and high-rise buildings [20,21,37]. Hence, meeting the CP load demand through renewables becomes a critical part of offsetting high electricity bills and carbon emission reductions. Indeed, several solutions can be implemented for enhancing the operation of appliances in common areas [18], such as the replacement of energy efficient lights [38], placement of motion sensors to activate the lights, or particular function only in the presence of human, timers, and usage of energy efficient devices [39]. However, it is a normal observation that electricity use in common areas requires nonstop operation, and, if the location is the basement, the majority of load comes from lighting [29,40,41]. Although the above-mentioned literature draws attention to electricity use in common areas, the appliances have been mostly grid supplied. There is lack of data and literature related to PV-BESS implementation in common areas, and withal utilization of surplus PV for powering common areas has not yet been discussed.

Energy Allocation and Distribution in Multi-Residential Buildings

Distribution of energy among apartment and CP loads from shared PV-BESS still requires research. Shared PV and BESS has been installed in apartments [16] where metered CP load provides a much better understanding of the diurnal and monthly electricity usage. Although CP usage as a rule of thumb can be billed equally among the residents, equitable allocation of CP load demand with the majority of load met by renewable sources is still a challenging issue. In a shared microgrid, there is no demarcation between energy utilized from the grid or imported through PV-storage on a single bus. This occurs in non-optimized systems with no PV export control nor utilization; thus, the only way to assess the net consumption of a particular unit or CP is through multiplying instantaneous load by the overall shared percentage of grid or renewable. Thus, considering higher CP loads of apartment buildings, energy flows should be investigated for grid reliance reduction.

A significant literature has recently addressed energy sharing problems in the form of trading methodologies and energy allocation mechanisms to examine benefits for consumers living in a shared space. Energy and price allocation issues in apartment buildings were addressed in Reference [23] by developing two models maximizing the welfare of the dwelling, as well as increase of revenue. In both models, consumer preferences were driven by certain objectives, such as emission mitigation, cost, and onsite generation. The findings concluded that both models optimize energy allocation fairly based on price auction.

A simulation of peer-to-peer energy trading was performed in Reference [27] using game theory. The authors used a four-layer architecture to categorize the involved elements in the "Elecbay" trading process. The results demonstrated the energy reduction between the utility sourced electricity and distributed generators. A two-stage aggregated battery control was proposed in Reference [42] to simulate peer-to-peer energy sharing in a community microgrid. An external arbitrator controlled the prosumers' renewable system, which was developed for energy sharing. Energy sharing resulted in 30% cost savings as compared to other peer-to-peer trading tools.

To achieve maximum profit through energy sharing, a system model was designed in Reference [28] to address the problem by considering the prosumer perspective. Moreover, the authors proposed an optimal pricing model based on Stackleberg game, in which microgrid operators served as masters, while prosumers acted as slaves. The model saw a positive effect on microgrid energy profile. A simulated peer-to-peer bidding mechanism was introduced in Reference [24] for supplier and consumer nodes for energy trading. Two different price modes were used for buying and selling subject to change in different time periods. Simulation outcomes suggested the effectiveness of the proposed method in improving the efficiency and cost savings from local decentralized consumption compared to centralized systems. A dual energy sharing strategy was proposed in Reference [43] to reduce energy costs and encourage renewable utilization for a prosumer community. The strategies included intra and inter community energy sharing in a day ahead stage. The framework was fast and efficient and provided practical application recommendations. In Reference [44], the impact of peer-to-peer trading was assessed using sensitivity analysis in view of network constraints. The article gave an explicit focus to measure the impact of exported and imported power in peer-to-peer exchange using double auction. The proposed model decreased electricity costs, while maintaining the demand and supply balance.

A peer-to-peer blockchain based energy-sharing platform was proposed in Reference [26]. The optimization of energy exchange prices by game theory proved more effective and profitable than non-game theory. Similarly, a multi-story apartment building in the UK was simulated in Reference [45] to propose a novel aggregator service for providing billing and distribution benefits. A model predictive control algorithm optimized the renewable system. A comparison of different tariffs suggested effectiveness of aggregator service in terms of bill savings, load shifting, and energy exchange. Peer-to-peer energy trading was applied in Reference [46] on a community microgrid using three different market models of bill sharing, mid-market rate, and auction-based pricing.

Different PV-penetrations were tested to analyze cost reductions. The model demonstrated a 30% cost reduction from various levels of demand.

A co-simulation methodology was presented in Reference [25] analyzing distribution networks and peer-to-peer energy trading. An open source simulator was used to model the distribution network, which was interfaced with a peer-to-peer energy exchange simulator. The P2P energy simulator employed a double-auction mechanism based on blockchain. The proposed co-simulation demonstrated the ability of measuring the distributed network voltage effects on peer-to-peer trading. A case study of peer-to-peer energy trading in low voltage networks was presented in Reference [47]. The study particularly considered network constraints for energy trading models. The simulation demonstrated the usefulness of considering network constraints for future peer-to-peer trading as consumers received financial benefits.

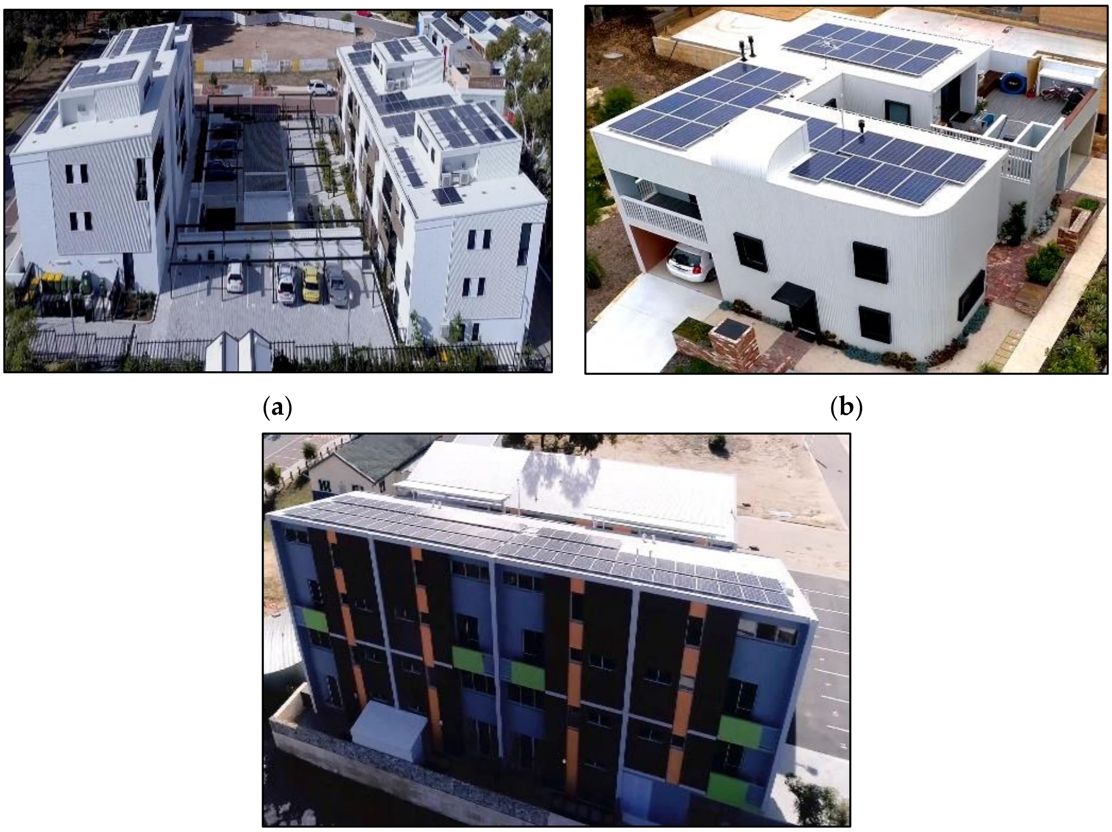
Lastly, a transactive energy trading framework was proposed in Reference [48] for the community microgrid with PV and BESS in 15 apartment buildings. The framework traded excess energy with non-contributing owners via a transactive energy sharing game, while the profits were shared with contributing owners and also their renters. Simulation results revealed the benefits of the trading framework for all participants as grid reliance was significantly mitigated.

While the literature collated above has considered energy allocation and trading for multi-residential settings, there is still a lack of information regarding common area electricity exchange within the apartment building. To reduce costs from high CP grid electricity usage in apartments, utilization of DRES with the conventional grid is also instrumental. In terms of dispatching excess PV energy, the allocation strategies for apartment buildings can be intertwined with a sub-virtual power plant to coordinate energy flow between multiple PV generators, battery storage, and loads. Moreover, the surplus export solutions can be profitable for the local market as they can be interconnected to other markets within the same distribution network in order to share excess energy at times of load demand. Strategists and policy designers may also take advantage of energy trading and allocation strategies from consumers with PV and BESS to incentivize customers without it, on one hand, while backing up the grid with ancillary support.

3. Methodology and Analysis

3.1. Common Property Loads at WGV

The WGV development is a 2.2-hectare development, located in the city of Fremantle, Perth, Australia. The project site embeds three multi-residential apartment buildings known as Evermore [49], Generation Y (Gen Y) [50], and Sustainable Housing for Artists and Creatives (SHAC) [51], as shown in Figure 1. The WGV research project exhibited the use of solar PV and BESS in these multi-residential strata developments to demonstrate a governance model that enables the effective sharing of the energy and costs benefits between households, developers, owners, and utilities. The three apartment buildings differ in size and construction. Evermore consists of 24 one, two, and three-bedroom apartments. Gen Y is a two-story triplex apartment building built on an area of 250 m^2. SHAC is affordable apartments built for artists and creatives, which contains three 3-bedroom townhouses, eight 2-bedroom units, one 1-bedroom unit, and two communal artist studios. Although the three apartments differ in construction, we do not specify individual dwelling characteristics in this study, such as floor area, household size, and thermal features. Rather, we concentrate on analyzing energy consumption in common areas and effects of the PV-BESS on load demand.



(**a**) (**b**)

(**c**)

Figure 1. Apartment complexes investigated in this study: (**a**) Evermore (24 apartments), (**b**) Gen Y (3 apartment units), and (**c**) SHAC (12 apartments, 2 studios).

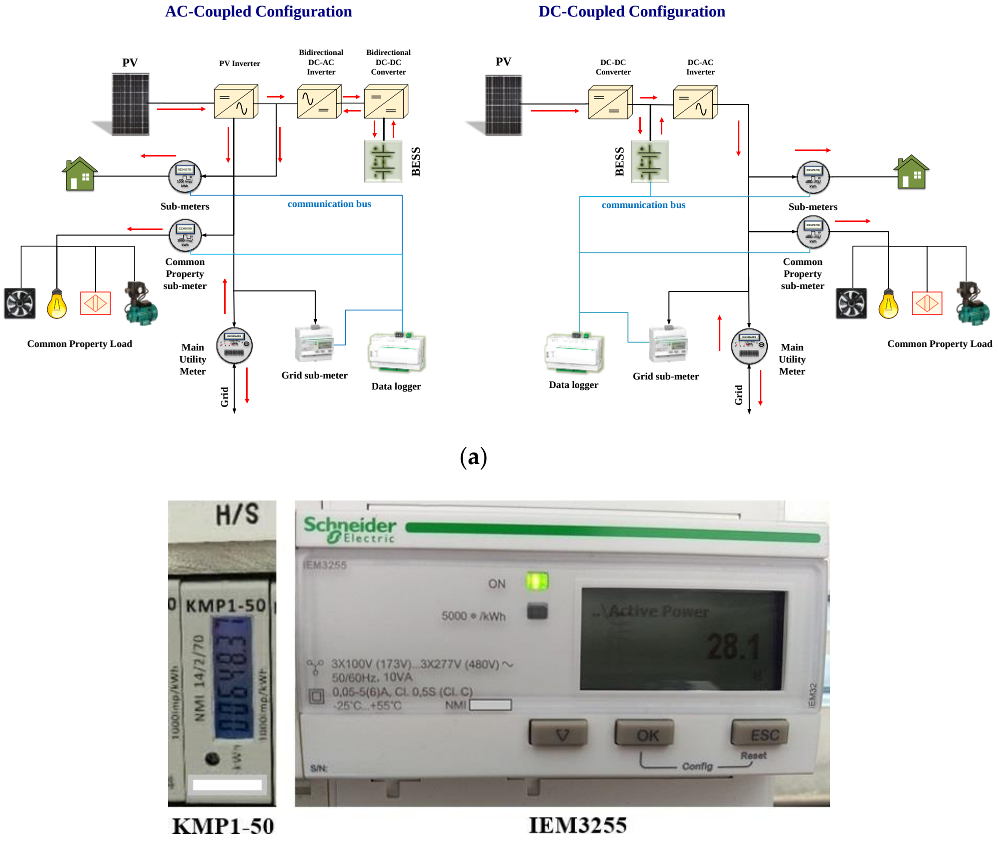
Conventionally common areas of each apartment complex differs in dimension according to the requirements and capacity of the building. The CP loads at the three sites of WGV do not contain any community pools, vertical transportation and space-heating requirements except the air conditioner used in the Evermore battery room. All car parks are open spaced; hence, the only ventilation needed was in the battery room. The absence of large load presumes a lower energy consumption from common areas. Table 1 includes three site characteristics, type of CP loads and renewable system installed. A PV energy distributed model for the apartment buildings was mainly comprised of a common utility sharing model [52] where PV generation supplies CP load. This is the simplest model, which ensures an equity in energy sharing. In the WGV apartment complexes, CP load is part of the shared microgrid, which connects to the centralized PV-BESS and grid. In the Gen Y and Evermore apartments, the PV and BESS are co-owned by apartment owners and managed by the strata company with authorization of the developers, whereas the developer manages the system at SHAC [53]. The battery technology used in the BESS is lithium iron phosphate, a type of lithium ion battery, which is among the most stable of lithium ion technologies. Lithium ion batteries provide high efficiency, high energy density, large power capability, and improved life cycle [3,4]. It is hoped that with addition of battery storage, this study expands the functionality of CP load demand coverage through PV and grid. Although the size of common areas and electricity usage is quite site specific, the jurisdictions with similar characteristics must be considered before scaling the results.

Table 1. Apartment site characteristics.

Site	Storeys + Units	Type of CP Loads	Renewable Size	Configuration
Evermore	3 + 24	Walkway, entrance and car park lights, electric gate opener and sensor, ventilation fan and air conditioner for battery room.	54.6 kWp, 150 kWh Lithium-ion	AC-coupled
Gen Y	2 + 3	Walkway lights, entry sensor lights, rainwater pump	9 kWp, 10 kWh Lithium-ion	AC-coupled
SHAC	3 + 14	Carpark lights, switchboard room electricity, ventilation fan for battery room.	19.6 kWp, 40 kWh Lithium-ion	DC-coupled

3.2. *Shared Microgrid Configurations*

Generally, the shared microgrid consists of a centralized BESS, PV source, and metering network connected to the apartment loads [4,16,54]. This also includes the CP load, which forms an integral part of the shared network. A counterpart to this is the separate connection of PV to supply CP or individual apartment loads. Typically, the apartments and communities deploy these two connection arrangements. The connection diagram of shared loads along with CP in the three apartments is shown in Figure 2. Usually, there are two types of PV-BESS configurations in residential applications, Alternating current (AC) coupled and Direct current (DC) coupled. In this study, Evermore and Gen Y implemented AC-coupled systems, whereas SHAC installed DC-coupled systems [16].



(**a**)

KMP1-50 **IEM3255**

(**b**)

Figure 2. (**a**) Common property (CP) load connection to AC- and DC-coupled configurations. (**b**) Pulse meters used for measuring CP demand.

The primary rationale for selecting these configurations are based on the following particular preferences: (1) Storing PV generation in batteries; (2) covering apartment load demand according to available PV-BESS capacity; (3) export excess generation to the local aggregator for implementation of energy trading and allocation; and (4) export the remaining surplus to the utility. AC-coupled systems have the advantage of connecting to multiple AC sources without complexity, e.g., grid and PV. In a DC-coupled system, PV connects on a DC bus, whilst the inverter input links to the DC bus, and its output supplies the load. DC coupling generally demands one conversion and hence requires less power converting equipment. Each configuration holds pros and cons in terms of efficiencies and operation, which is endorsed by the literature with mixed opinion. Some articles [55,56] have claimed higher efficiency of AC-coupled systems than DC-coupled systems. On the other hand, DC-coupled systems have improved performance and longevity in terms of technical performance [57]. Although the basic difference between the two configurations is the connection of electrical bus to the loads, the common objective is to offset grid usage electricity and utilization of excess energy for trading and energy allocation. In the WGV project, the secondary reason for choosing these two configurations by stakeholders and developers was also contingent to cost savings.

The connection schematic in Figure 2a shows individual apartment load connected and metered separately alongside common property load, and this is often termed a Shared Energy Microgrid [16] and embedded network [20]. As indicated earlier, the AC-coupled system links to the AC bus via the bidirectional DC-AC inverter and DC-DC converter. Additionally, a PV inverter also links to the AC bus; hence, the load is supplied from the BESS via a bidirectional converter, PV inverter, and grid. On the other side, in the DC-coupled system, the battery inside the BESS is first charged via the DC-DC converter and then converted to AC via the inverter.

As shown in Figure 2b, the pulse sub-meters used for CP at the three sites are KMP1-50 (from K-Mac Powerheads) and IEM3255 (from Schneider), in particular KMP1-50 at Gen Y and IEM3255 at Evermore and SHAC. The measurement data from these meters is recorded by a data-logger, which employs a communication method as given in Reference [16] to forward information for data analysis. Due to the multi-load connection of CP (lights, fans, and ancillaries), obtaining an appliance-based breakdown of common areas electricity was not possible; however, the pulse metering reads energy and power consumption measurements at 15-min resolution. This granularity facilitates in accumulating measurements to understand temporal CP demand.

3.3. CP Load Patterns

Figure 3 shows the average day common property load demand from common areas of the 3 apartment buildings. The temporal data consists of 15-min interval values averaged over the period of one year (from January–December 2019). It is noteworthy that, for the three sites, Evermore, Gen Y, and SHAC differ in common area sizes, appliances type and time of operation. For instance, the Gen Y plot illustrates a rather flatter response over the diurnal period whilst Evermore usage peaks around midday and in the evening (around 9:00 p.m.). The Gen Y CP load, contrary to large developments and the other two apartments in this study, is relatively small. The load patterns of Gen Y CP load exhibit an identical pattern with little variation in amplitude due to a fixed appliance operation [4].

The walkway lights operate in the evening until early morning, whilst the control supply provide uninterruptible power to sensors. The pattern of CP load at SHAC gives a more usual operation of common area electricity usage, which peaks in the evening until the next morning [29]. This is due to switching on of lights in that particular period. However, as mentioned earlier, the CP load usage may vary according to the location and construction of the building. In some cases, daytime CP load is higher [15], which is evident from the Evermore plot in Figure 3. The large battery in Evermore required a separate switchboard room for battery storage and inverter operation; hence, heat caused by electronic switching required temperature maintenance controlled by the use of a ventilator fan and air-conditioner. Moreover, the battery storage switchboard room was located in an open space in common areas at a distance from the residential units; thus, it received direct sunlight, which also contributes inward heat in the battery switchboard room. The battery rooms at Gen Y and SHAC, on the other hand, were located on the ground floor with adequate wind passage; thus, ventilator fans were sufficient for temperature control. Therefore, the daytime consumption at SHAC remained lower than evening. Nevertheless, the plot in Figure 3 reveals an interesting challenge of meeting CP load demand through the use of renewables at different times of the day. In the case of Evermore, it becomes easier as the majority of load demand can be covered through solar PV. However, in cases similar to SHAC, the developments depending solely on PV would need additional battery storage if they want to reduce high electricity costs from the grid in the evening.

The electricity data used in Figure 3 was further individualized to reveal weekend CP load consumption in Figure 4; however, no such difference was observed between the normal weekday and weekend profiles [32,41], thus demonstrating a fixed operation of common areas in three apartment buildings (ibid).

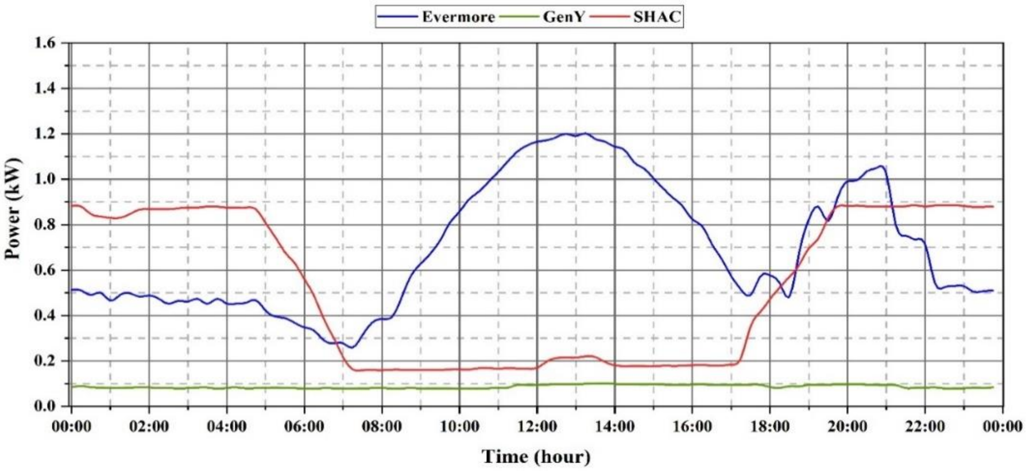


Figure 3. CP diurnal load profile averaged over the period of available data for each site.

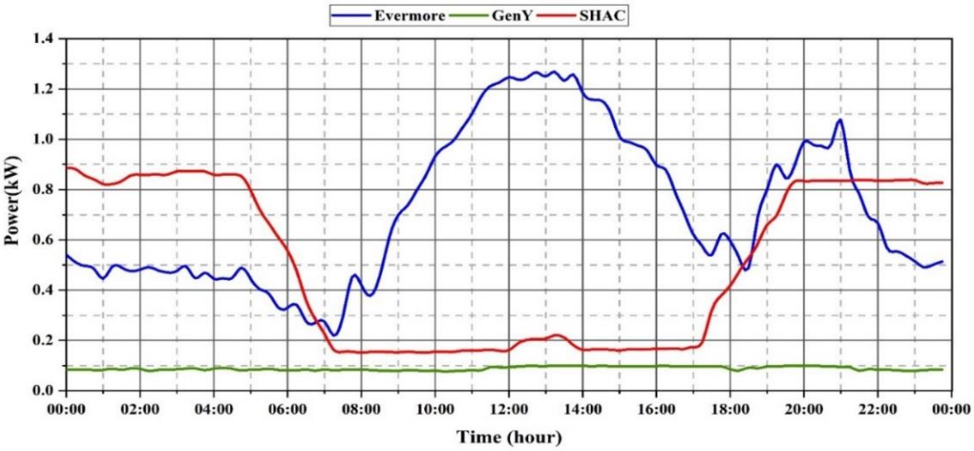


Figure 4. CP diurnal weekend load profile averaged over the period of available data for each site.

Similarly monthly consumption in Figure 5 illustrates homogeneous consumption over the full data period in SHAC and Gen Y, whilst no seasonal variation effect on CP load was observed. In Evermore, the summer months illustrate a high electricity usage due to the space-cooling consumption inside the battery switchboard room, as described earlier in Figure 3. As indicated earlier, CP load varies according to the load requirement of an individual apartment building, its coverage area, and time of use. In a similar manner, the monthly measurements in high-rise apartments may have a significant impact on common energy use with high heating and cooling requirements. Moreover, high-rise apartments may have vertical moving conveyance, such as lifts. Similarly, low-rise stretched buildings may have a large underground carpark requiring nonstop ventilation and lights. The overall apartment to CP load ratio in Table 2 implies a small size of CP load in three dwellings, which has elsewhere been reported as large, and may be more than the sum of individual apartment usage [21].

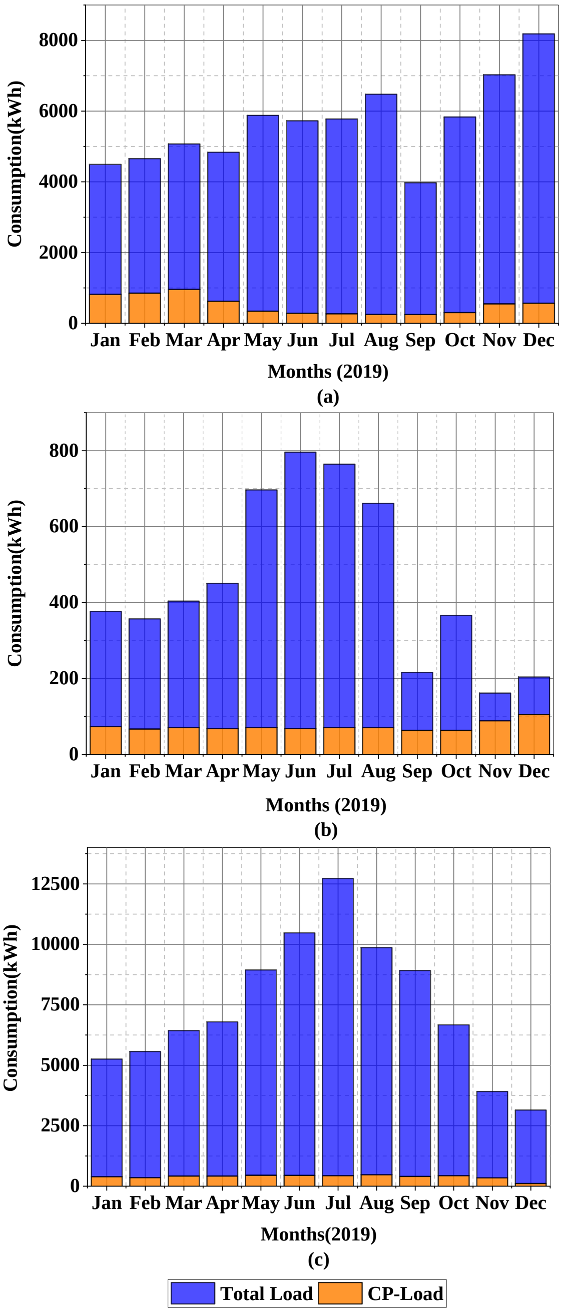


Figure 5. Monthly consumption proportion of total apartment load and CP for each site: (**a**) Evermore, (**b**) Gen Y, and (**c**) SHAC.

Table 2. CP load to total load proportion in three apartment buildings.

Site	Total Load (kWh)	Common Property Load (kWh)	CP-Proportion (%)
Evermore	67,936.188	6071.057145	8.93
Gen Y	5452.007	878.793	16.11
SHAC	108,154.9	5977.335	5.52

Regardless of the relatively small CP load in this study, the main intent has been to scrutinize how solar PV and battery storage reduces the grid reliance when covering CP demand. This is an important case for the majority of developments lacking PV and battery storage deployments and heavily relying on wholesale market electricity. Based on the CP load details given above, the shared microgrid of Figure 2, and the load patterns details given in Figures 3 and 5, we now proceed to explore the strategies to analyze energy allocation, as well as the results of the CP load consumption with apportionment of PV-BESS and grid.

3.4. Energy Allocation Strategies

The investigation of the energy allocation can be carried out by careful consideration of energy flows; this is through a virtual mechanism considered alongside tangible operation. For managing the market arrangement for energy flows, a middle body, such as an aggregator, or, in strata, OC, can leverage the execution of a virtual trading mechanism. Often, these methods rely on physical sub-metering with advanced communication infrastructure [58], which provide a deep understanding of load profiles and renewable generation [27], and sub-metering has also been shown to reduce electricity usage [35].

The prevailing models allocate a portion from the shared energy system to a unit at each time interval. If energy consumption is lower than production, it is either stored in a battery or fed back to the grid. A conventional implementation of an energy trading mechanism is shown in Figure 6. After allocating an equal portion of local energy generation to an apartment unit, the process verifies if energy consumption falls within the allocation, and then local energy trading occurs via a virtual trading mechanism. As stated earlier in the literature review section, these mechanisms usually rely on blockchain based algorithms or peer-to-peer trading techniques. Although this energy distribution method is still viable in many cases, the drawback lies in the limitation of excess exports to the grid in the case that the electricity consumption remains well under the allocated energy portion. With the low feed-in-tariff in Western Australia, this will provide less cost benefits to the local energy market dealing with the energy trade [16].

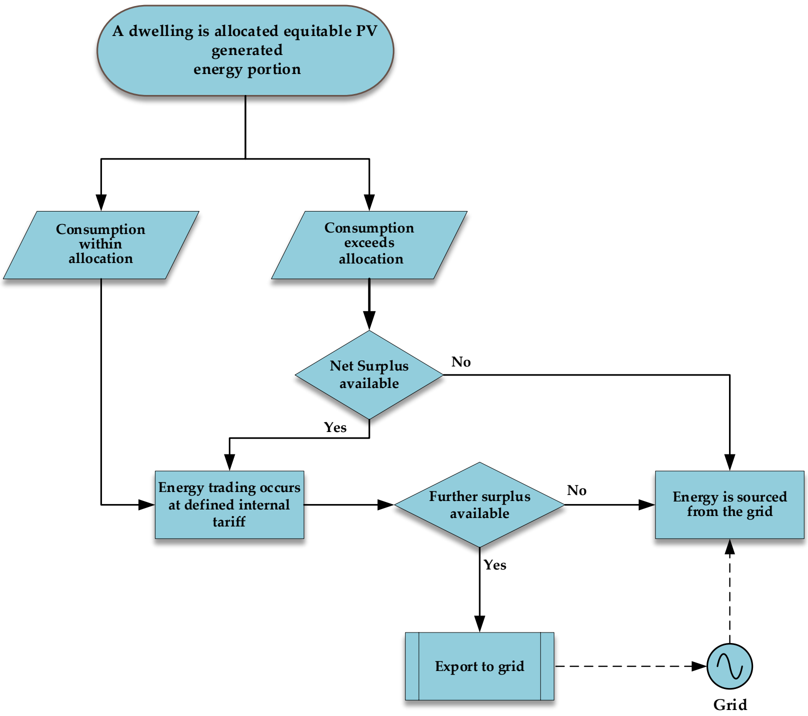


Figure 6. Conventional energy trading in a multi-residential building with grid connected renewable system.

The inevitable existence of CP load in apartment buildings implies that there is a good opportunity to use the excess available energy to meet the load demand of common areas instead of exporting back to the grid. In the event of large consumption from apartments, CP load demand normally draws energy from the grid, whilst billing costs are equally shared between consumers as part of OC.

Using real time data from the three apartment buildings, we propose this alternative approach of using excess allocated energy for CP loads, and we then compare three methods to demonstrate results in terms of grid energy savings and cost benefits achieved by consumers. Our proposed strategies can be intertwined with techniques that share excess energy with multiple residents in the same microgrid at an internal retail rate defined by the local aggregator. In so doing, the efficiency increases as excess energy would be shared between consumers, as well as supplied to the CP load, which, in existing models, is exported back to the grid at low tariff. Figure 7 maps the three strategies in the form of flowcharts. The three strategies included in this study are Instantaneous consumption (IC), Surplus Allocation (SA), and Consumption-based Allocation (CA). The strategies rely on real time 15-min resolution data from WGV apartments. The dataset is largely comprised of cumulative values; therefore, in order to get the output, we need the delta difference of two intervals, i.e., the present and the previous, as shown in Equation (1) [4].

$$\Delta A_n = B_n - B_{n-1}, \quad (1)$$

where n represents particular interval, and A, B are output and cumulative values, respectively. It is important to note that the strategies calculate generation, load demand, and allocation parameter for the next interval using the previous interval delta.

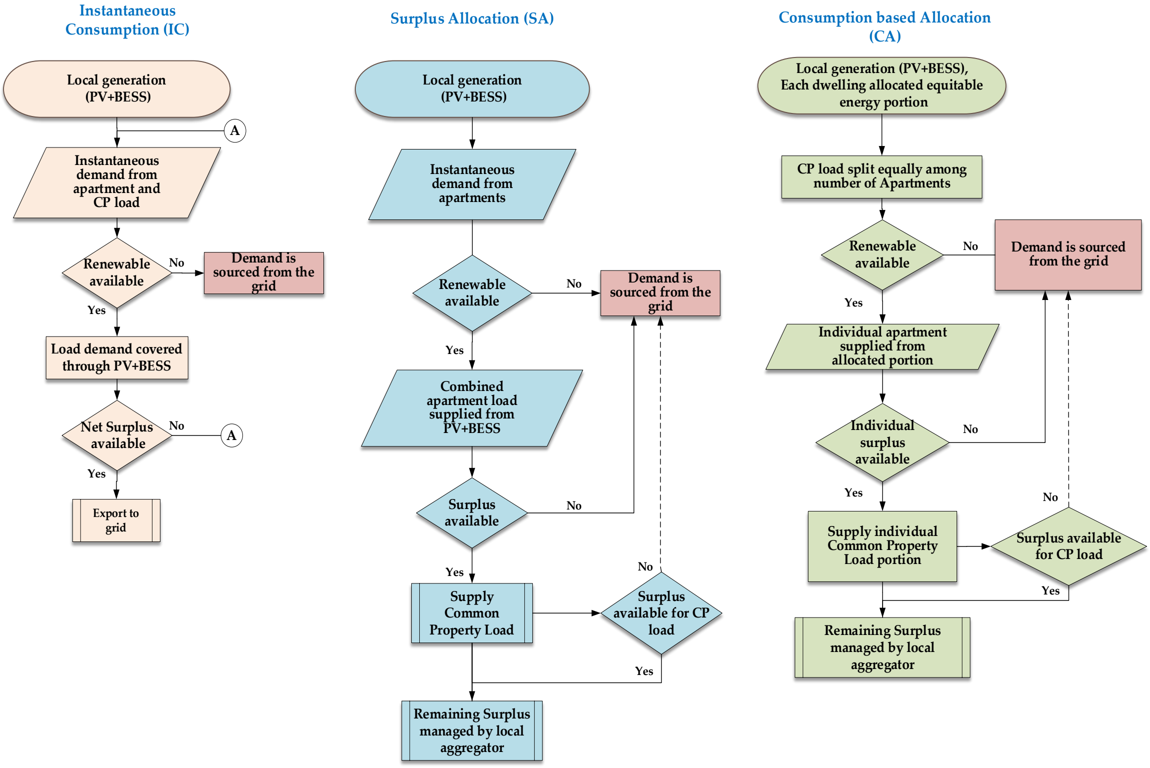


Figure 7. Energy allocation strategies workflow for offsetting CP load demand.

3.4.1. Instantaneous Consumption

IC is the current methodology applied for meeting overall load demand through grid connected shared configurations in WGV apartments. The amount of consumption from each residential unit including CP load is supplied by PV-BESS depending on the available generation and storage capacity.

For AC-coupled systems, the demand is fulfilled from the PV and BESS simultaneously, whereas, in DC-coupled systems, the battery inverter supplies the instantaneous demand after charging by solar PV. The surplus generation from the system is exported to the grid. In the event of low PV and BESS capacity, the system draws power from the grid.

A simple way to elucidate this phenomenon can be given as in Equations (2) and (3) [4].

$$\text{Source } (\%) \;=\; \sum\nolimits_{t=0}^{95} [\text{Load consumed}]_t (\text{kWh}) / [\text{Total Load}]_t (\text{kWh}) * 100, \tag{2}$$

$$\text{IC (kWh)} = \text{Source } (\%) * \text{Unit Consumption (kWh)}. \tag{3}$$

Here, load consumed is the contribution of source (either grid or PV-BESS) in meeting load demand, whereas t denotes a 15-min interval, which makes per day 96 iterations based on 15-min data resolution. The unit consumption in Equation (3) defines any apartment or CP load. The above method can be useful to implement in a shared cooperative scheme where consumers and strata agree to equally earn benefits from the shared system based on their electricity usage. It is clearly observed that the apportioned CP load consumption is congruent to the monthly fraction of PV-BESS and grid. However, where energy trading and optimization are applied, the methodology needs improvement in energy resource allocation to gain further benefits.

3.4.2. Surplus Allocation

SA initially prioritizes apartment instantaneous load demand supplied from renewable generation (E_G) and any surplus ($Surplus_{SA}$) remainder is used to cover CP load before being exported to the local aggregator for energy management. The process follows temporal computations on measured data from meters, which is presented here in Equation (4) [28,42,46].

$$Surplus_{SA} (\text{kWh}) \;=\; \sum\nolimits_{t=0}^{95} [E_{G,t} - E_{apt,t}(n)]; \tag{4}$$

Here, n represents a particular apartment.

If the above, Equation (4), returns a positive value (i.e., surplus energy), and then the energy will be used to supply CP load (E_{cp} as written in Equation (5) [54]. The local aggregator would manage any excess energy remaining after supplying CP load shown as Excess.

$$\begin{array}{l} \text{If } Surplus_{SA} > \; 0 \; CP_{calc} \;=\; \sum_{t=0}^{95} \left(Surplus_{SA,t} \;-\; E_{cp,t}\right) \\ \text{If } CP_{calc} < \; 0; \text{ supplies from grid } CP_{calc} \;>\; 0; \text{ Excess.} \end{array} \tag{5}$$

3.4.3. Consumption Based Allocation

For CA, a uniform renewable generation capacity (E_{GA}) is allocated to each apartment unit (except CP load) for each 15-min time interval. Additionally, the CP load consumption (E_{cp}) is also split proportionally between numbers of apartments to keep uniformity for net energy exchange. Each apartments' consumption is then netted off from its allocated portion of renewable energy. Any surplus available ($Surplus_x$) after utilization of allocated energy [28,42,46] is then dedicated to meet the individual portion of CP load demand (CP_x) [54]. Here, subscript x represents a particular apartment. Should an individual unit consume more than its allocated portion, then the grid fulfils the remaining demand. Even though each residential unit is allocated a fixed energy portion, the real distributed energy could deviate from the allocated energy. If a customer energy trading mechanism (such as peer-to-peer) is applied here, then the unit consuming more energy receives the benefit of importing shared energy at a cheaper rate from the immediate neighborhood in the same microgrid. The individual excess energy after covering CP demand ($CP_x > 0$) is then received by the local aggregator to leverage subsequent monetary benefit or further use for energy trading purposes. A similar analogy was discussed in Reference [52], where an apartment unit with a positive value difference was titled a prosumer, whilst a unit with negative value becomes a consumer. Equations (6)–(8) determine the values for the CA strategy.

$$E_{CP,ca}(\text{kWh}) = \sum_{t=0}^{95}\left(\frac{E_{cp,t}}{number\ of\ apartments}\right), \tag{6}$$

$$Surplus_x(\text{kWh}) = \sum_{t=0}^{95}\left(E_{GA,t} - E_{apt,t}(x)\right). \tag{7}$$

If $Surplus_x > 0$,

$$CP_x = \sum_{t=0}^{95}\left(Surplus_{x,t} - E_{cp,ca,t}\right). \tag{8}$$

If $CP_x < 0$, supplies from grid; and if $CP_x > 0$, Excess energy.

We will further show utilization of this Excess in Section 4.2.

4. Results and Discussions

4.1. Instantaneous Consumption

Referring to Figures 3–5, we now discuss the impact of CP load integration into a shared microgrid. As mentioned previously, the IC strategy is currently implemented in the studied shared microgrid that distributes renewable and grid electricity based on instantaneous consumption of a particular load. A detailed chart of the CP renewable fraction and grid consumption in three apartment complexes is illustrated in Figure 8. On the left, the energy fraction over the dataset period (January 2019–December 2019) from PV-BESS and grid are displayed in pie charts as percentages. Subsequently, the monthly distribution of CP load apportioned according to the monthly percentage of PV-BESS and grid are shown on the right side. This energy percentage from the PV-BESS can also be defined in terms of self-sufficiency [16].

Evermore and Gen Y, despite having different household and system capacity, show a similar annual energy fraction and grid imported electricity (66% and 33%, respectively) whilst SHAC relied 53% on grid and 47% on PV-BESS. The CP monthly energy distribution chart shows monthly consumption bar charts on the left axis compared to monthly consumption percentages from PV-BESS and grid on the right axis. Monthly bar charts illustrate CP load usage covered by both sources based on instantaneous consumption. For each of the three sites, seasonal variation affected the load consumption in the winter months (May to August), which is most likely due to high utilization of heating appliances inside apartments and concurrently low PV generation, resulting in less battery storage in evening hours [4,16]. Since all loads share energy from a centralized microgrid, the lowered availability of renewable energy demands more energy from the grid. On the other hand, during the summer months (December to March), we learned that the greater proportion of energy demand was supplied by the PV-BESS due to the large availability of PV.

Based on the load patterns presented in Figure 3, we can clearly see CP usage at SHAC increases during the evening period. Hence, we can deduce that we need more battery storage for meeting the majority of the CP load demand in SHAC as compared to Evermore and Gen Y. Nevertheless, it seems obvious that, regardless of the load patterns, it is critical for a system to retain adequate PV size and battery storage capacity in order to cover the bulk of total load consumption.

In the case of strata developments where CP load consumption is usually higher than apartment units, this strategy would indeed require optimization to allocate renewable energy from the shared microgrid to common areas compared to residential units. Moreover, seasonal effects due to low PV production might be overcome by introducing hydrogen-based or other storage solutions for common areas [59].

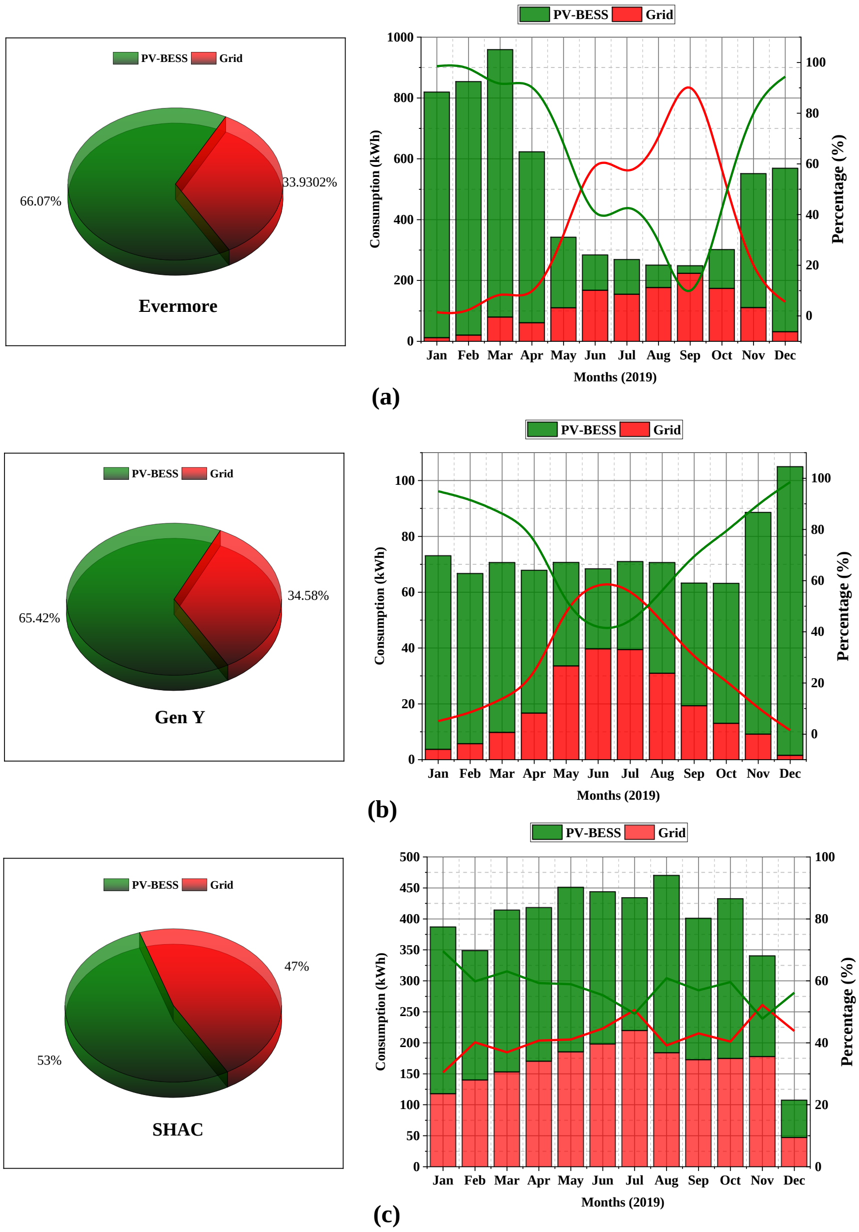


Figure 8. Pie chart of total renewable and grid fraction for CP load at three sites with monthly bar chart of CP instantaneous load distribution according to the Instantaneous consumption (IC) strategy, (**a**) Evermore (**b**) Gen Y (**c**) SHAC.

4.2. Comparison of Strategies

We will now proceed to compare the three strategies IC, SA, and CA applied to different datasets for the three apartment buildings and analyze monthly grid reduction. The dataset chosen for Gen Y was similar to the previous plots (Figure 8), whereas, for Evermore and SHAC, we chose most recent ones (i.e., December 2019 to August 2020).

From Figure 9, we can see that overall SA achieved the lowest grid consumption with 91% for CP load at Evermore, followed by CA 76% and IC 72%. Similarly, for Gen Y, SA reduced grid usage by 82%, IC reduced to 72%, and then CA by 70%. In SHAC, the grid usage remained higher, and we have stated the reasons of this large usage to be the undersized PV-BESS system, as well as high consumption by the apartments [16]. At SHAC, the greatest grid reduction was attained by IC (24%), 14% by CA, and only 9% by SA. It is interesting to see that the three strategies achieved grid usage reduction differently in all three developments, except SA, which remained the largest contributor in

Evermore and Gen Y. From the analyzed data, we did not find any seasonal dependency of high grid reduction at Evermore, albeit, in Gen Y and SHAC, the highest consumption by all three strategies occurred in winter (May to August). It can be assumed that the high grid reduction by SA at Evermore and Gen Y was due to excess energy availability. In SHAC, SA contributed the lowest in grid usage mitigation due to low production and high electricity consumption. Tables A1, A3 and A5 list the detailed numeric monthly distribution.

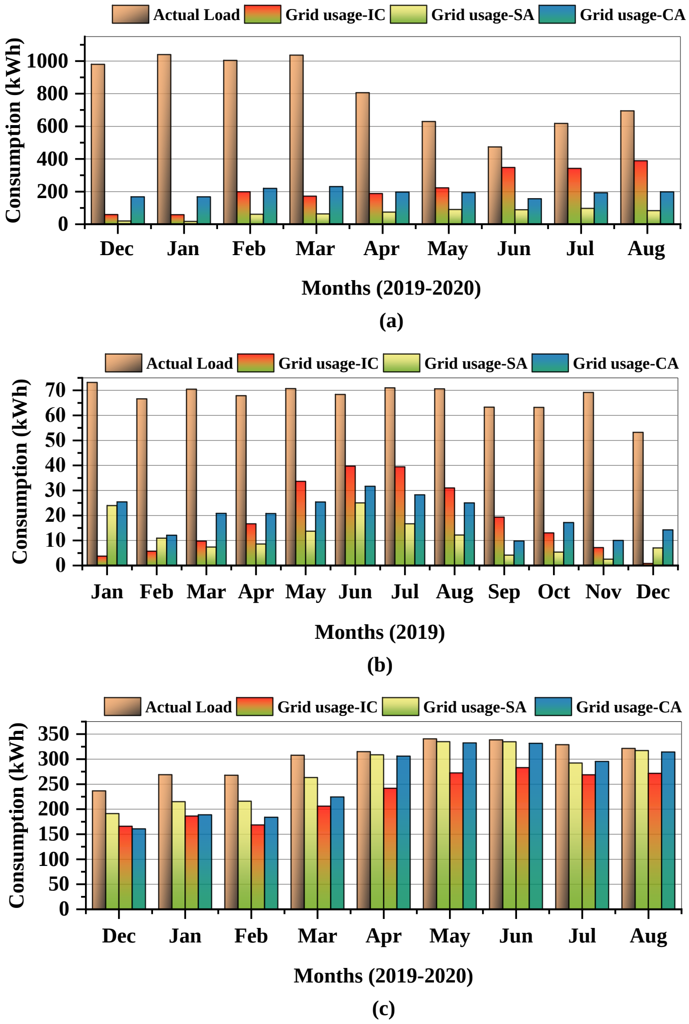


Figure 9. Comparison of actual CP load consumption with three strategies to analyze grid usage reduction: (**a**) Evermore, (**b**) Gen Y, and (**c**) SHAC.

On the other hand, if we consider seasonal variation, the excess generation from PV is expected in summer (December to March). The residual PV generation after application of one of the three strategies would also depend on the amount of electricity consumed by apartments, which will influence the CP load demand through renewables. Figure 10 illustrates the excess energy acquired after all temporal energy exchanges were performed by the three strategies. This meant that renewable energy was utilized by the apartment and CP loads at each time interval; therefore, we aggregated the remainder as excess energy. We have also shown the cost credits due to this monthly excess energy on the right axis. We assume the internal tariff rate of 15 cents/kWh for excess energy. We define excess energy plainly as "Excess", followed by each strategy's acronym. The associated costs from the three strategies are calculated as given in Equations (9)–(11) below:

For IC: If exported energy to the grid = Excess-IC (kWh), then,

$$\text{Cost IC (\$)} = \text{Excess-IC (kWh)} \times 0.15. \tag{9}$$

For SA: If $CP_{calc} > 0$; CP_{calc} = Excess-SA (kWh), then,

$$\text{Cost SA (\$)} = \text{Excess-SA (kWh)} \times 0.15. \tag{10}$$

For CA: If $CP_x > 0$; Sum of all CP_x = Excess-CA (kWh), then,

$$\text{Cost CA (\$)} = \text{Excess-CA (kWh)} \times 0.15. \tag{11}$$

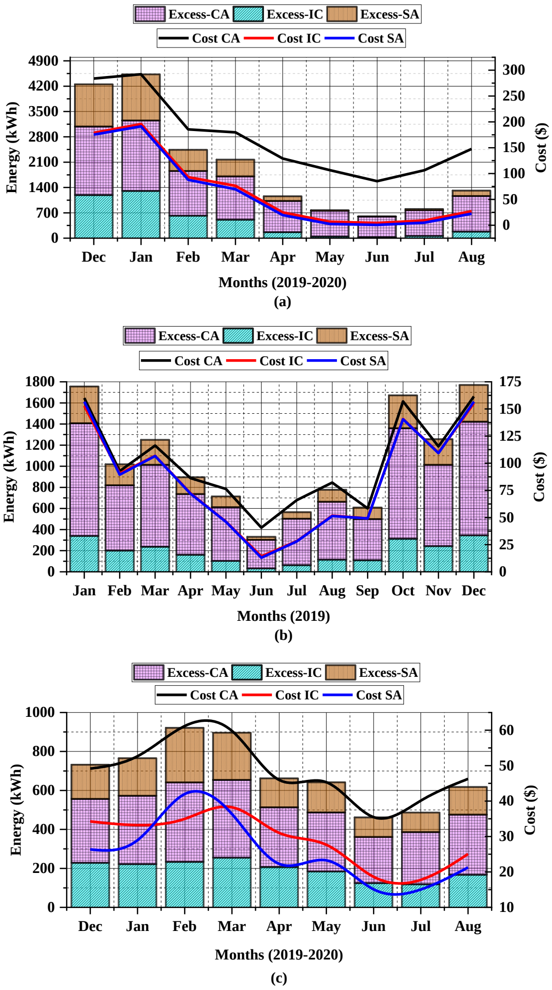


Figure 10. Excess energy gained after implementation of the three strategies and associated cost benefits. (**a**) Evermore, (**b**) Gen Y, and (**c**) SHAC.

As we already pointed out, the summer period generates more excess energy, this is also reflected in the chart where the December–February period gave the highest surplus energy. It is apparent from Figure 10 that, by comparing the three strategies, we see that the CA strategy congregated more surplus energy and thus costs throughout the dataset in all sites, i.e., 8086.20 kWh ($1212.93) at Gen Y, 10,106.26 kWh ($1519.9) at Evermore, and 2906.12 kWh ($435.9) at SHAC. Meanwhile, excess energy and cost from the other two strategies remained lower than CA. SA collected 3827.3 kWh ($574) at Evermore, 2264.16 kWh ($1018.8) at Gen Y, and 1537.12 kWh ($230.5) at SHAC, whereas IC gathered 4111.9 kWh ($616.78) at Evermore, 2262 kWh ($1017.9) at Gen Y, and 1738.8 kWh ($260.8) at SHAC.

Table A2, Table A4, and Table A6 list monthly figures of excess energy and costs for Evermore, Gen Y, and SHAC, respectively. We can relate the difference in results to the fact that, in both IC and SA, the available energy is netted from total apartment load (with the exception of CP load exclusion from the total load in SA). The assumption is different in CA, where renewable energy and the portion of CP load usage is allocated to each unit.

We further analyze excess energy obtained from CA in Figure 11 and demonstrate the annual contribution of energy from each apartment unit for the three sites. This reveals the excess energy generated by each unit after meeting the individual load demand and its allocated CP usage. Consequently, the apartment, which utilizes least electricity or displays efficient load consumption is credited with high excess energy and cost benefits. A similar convention is shown in Reference [52], where the apartment residents are considered as prosumer and consumer based on their energy consumption with the energy efficient user receiving more cost incentives. The apartment residents in Figure 11 are alphabetically named PX (where x = apartment). The chart only highlights minimum and maximum energy attained by individual units in three apartment sites by color bars. Consumer PO collated more excess energy (550 kWh) among all the residents at Evermore, PY (3043 kWh) at Gen Y, and PB (334 kWh) at SHAC, respectively. Apartment unit PQ (234 kWh) at Evermore, conversely, retrieved less energy due to large energy consumption, PX (2314 kWh) at Gen Y, and PD (136 kWh) at SHAC. Individual cost benefits retrieved after applying the CA strategy for the three sites have been included in the Appendix A (Figure A1). Comparing the three sites, we note the high excess energy generated by Gen Y and Evermore residents, while values from SHAC remained lower. It could be asserted that an adequately sized renewable system would prove effective in incentivizing consumers if excess energy is properly managed. Likewise, the surplus energy and potential cost benefits derived from the results provides a good opportunity for implementing an energy trading system within these apartment complexes.

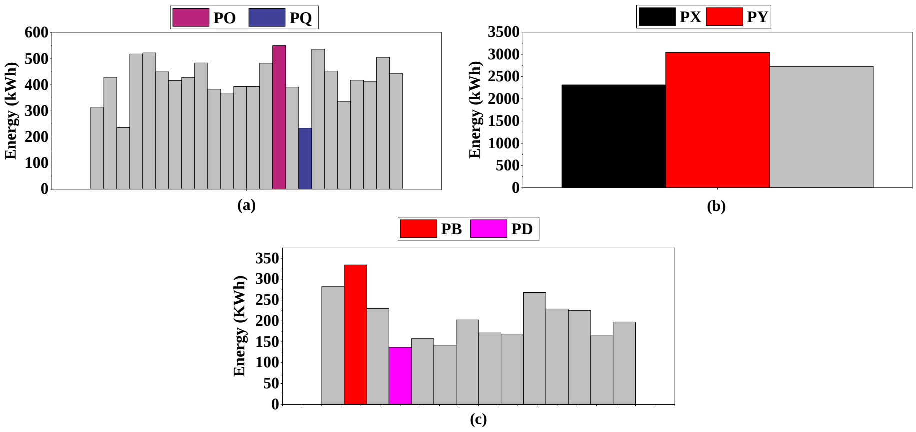


Figure 11. Minimum and maximum excess energy obtained by individual apartments from Consumption-based Allocation (CA) strategy: (**a**) Evermore, (**b**) Gen Y, and (**c**) SHAC.

Table 3 summarizes merits and demerits of three strategies. Although complete abatement of grid electricity usage for CP load could not be achieved, we still suggest for future studies to implement the CA strategy. The integration of the current methodology of shared system with energy trading mechanisms entails an energy efficient system where excess energy may be redistributed to further decrease CP load from the grid; thus, increasing self-sufficiency or the excess energy could even be available for user interaction in the form of energy trading with other consumers in neighborhood microgrids. Although the current study limits its focus to the energy effects of the shared system on CP loads, it will be informative to discern results from peer-to-peer trading among residents in similar shared microgrid settings with CP load.

Table 3. Advantages and disadvantages of the three strategies.

Title	Advantage	Disadvantage
Instantaneous Consumption (IC)	Useful in a shared setup where consumers and strata body agree to earn benefits from the shared PV-BESS based on individuals' electricity usage.	Renewable energy is not allocated therefore consumers are not conscious about their energy consumption.
	A particular unit or common area may utilize maximum renewable energy in case other apartment units are not consuming.	Energy fraction distribution depends entirely on individual unit's consumption.
		Excess PV energy is exported to the grid.
		Individual cost benefits are not explicitly discerned as exported energy is unallocated.
Surplus Allocation (SA)	CP load can be supplied from renewable surplus remained after apartments' utilization.	Dependent on apartment load consumption. If renewable generation is equal or less than total apartment load, CP load will be supplied by grid.
	CP may utilize maximum renewable energy in case apartment units are not consuming.	Individual cost benefits are not explicitly discerned as exported energy is unallocated.
	Can achieve high grid usage reduction at sites where ample excess generation is available.	
Consumption Based Allocation (CA)	A uniform portion of renewable generation is allocated to each apartment unit along with proportionate consumption of CP load allocated to all apartments.	Fixed allocated portion of renewable energy. If allocated energy portion runs out, then CP load imports grid electricity.
	An allocated share of renewable means consumers will remain conscious of their energy consumption.	
	Possibility of peer-to-peer trading between consumers and monetary benefits in case a particular unit consumes less than allocated portion.	
	Can aggregate high excess energy and cost benefits as compare to other two strategies.	

5. Conclusions

This article investigated the application of a shared microgrid for mitigating grid usage of CP load. By including CP load profiles from apartment buildings, the study contributed to the scarce literature and data regarding common areas electricity usage in Australian Apartment buildings that are connected to a shared microgrid with PV and BESS. The load profiles from three apartment buildings confirmed that common areas load patterns are highly building specific; however, they are usually invariable in terms of daily usage due to fixed operation of appliances. Contrary to conventional apartment complexes, where common areas serve the major portion of load consumption, the monthly and annual CP to apartment load ratio in this study remained lower. By utilizing real time data from three apartments, we implemented three allocation strategies to evaluate grid usage reduction for CP load and its resultant cost effectiveness. The first strategy IC utilized PV-BESS supply to cover instantaneous load demand from CP and apartments. The other two strategies (SA and CA) were based on the approach of employing excess PV energy to supply for CP load instead of exporting back to the grid.

IC strategy has usefulness of utilizing maximum PV-BESS energy by any apartment unit in a shared microgrid, wherefore the residential unit or CP at any interval may benefit by consuming a maximum amount of renewable energy given its load demand is higher than the other unit. Unavailability of PV, on the other hand, puts a high electricity consumer in energy debit, as all energy consumed would be imported from the grid. A drawback of this strategy is non-reservation-based energy distribution, in which a consumer may only gain maximum profit when renewable generation is available, and the resident has appliances to run. Nonetheless, the IC strategy overall achieved grid reduction of 72% at Evermore, 72% at Gen Y, and 24% at SHAC.

SA supplements IC strategy by utilizing the remainder of the excess energy by apartments to cover CP load demand. The benefits and downsides are very similar to IC, however; the utilization of excess energy instead of grid export is the major advantage. It would be valuable to employ this strategy in jurisdictions where the renewable system generates ample surplus energy with less feed-in tariffs; hence, the utilization of excess energy could be more productive. The SA strategy achieved grid usage reduction of CP load by 91% at Evermore, 82% at Gen Y, and 9% at SHAC. Absence of energy allocation would mean that the cost benefits obtained from excess energy in two strategies are aggregated but could not be accorded to any individual consumer.

A uniform portion of renewable energy was allocated to apartments in the CA strategy, which presented more benefits than the previous two strategies. Firstly, an allocated share of renewable implies a responsible electricity usage by consumers in order to avoid grid electricity imports. Secondly, total CP load consumption is proportionally distributed among apartment units; hence, cost benefits are contingent on self-electricity usage and ability to cover maximum CP load demand. Lastly, the strategy can easily be interlinked with peer-to-peer trading mechanisms to share excess power with other consumers in a microgrid. Overall, CA collected more surplus energy than the other two strategies. Similarly, CA resulted in higher cost benefits as compared to the other two strategies. The strategy achieved overall grid reduction of 76% at Evermore, 70% at Gen Y, and 14% at SHAC. Notwithstanding the fact that a complete reduction of grid usage for CP could not be achieved, it is worth considering that the investigated strategies attained cost benefits by reduced grid usage (through SA), while gaining excess energy and cost benefits (through CA).

There was a marked effect of seasonal variations noticed during the winter period, especially with IC strategy (Figure 9). These adversities might be addressed by installing seasonal storage technologies with the current system [59]. Since energy allocation and consumption in the right time frame have high relevance for energy efficiency, consumer behavior should also not be overlooked in this regard. A balanced utilization of energy could imply net benefits. The findings from this study also indicated cost and surplus energy provision for consumers utilizing less energy (Figure A1). On an individual basis, consumers may benefit from these strategies by remaining conscious of their energy consumption. This could be enabled by linking the system output with visualization platforms providing feedback to consumers of their energy consumption and exchanges.

In apartment buildings, where common areas generally contribute a majority of energy consumption, application of shared microgrid with energy allocation strategies could be an effective solution. With the large availability of excess energy in apartments, like Evermore and Gen Y, it would be a good practice in future studies to orchestrate these strategies with energy trading mechanisms to incentivize consumers. This will require supervision of energy flows and grid export by a strata body or local aggregator to handle the process virtually. The mechanisms could be similar to peer-to-peer trading or, on a larger scale, may link with virtual power plants for apartment precincts. Considering the global upswing of apartment living concentrated in urban areas, the uptake of DRES, including PV and BESS, in these buildings is of paramount importance to reduce high billing costs from the utility and mitigate carbon emissions that would have incurred due to high usage of grid electricity. Against this backdrop, the energy transition to DRES in future can accelerate phase-out of fossil-fuel plants in regional networks, like SWIS, and similar global utility networks.

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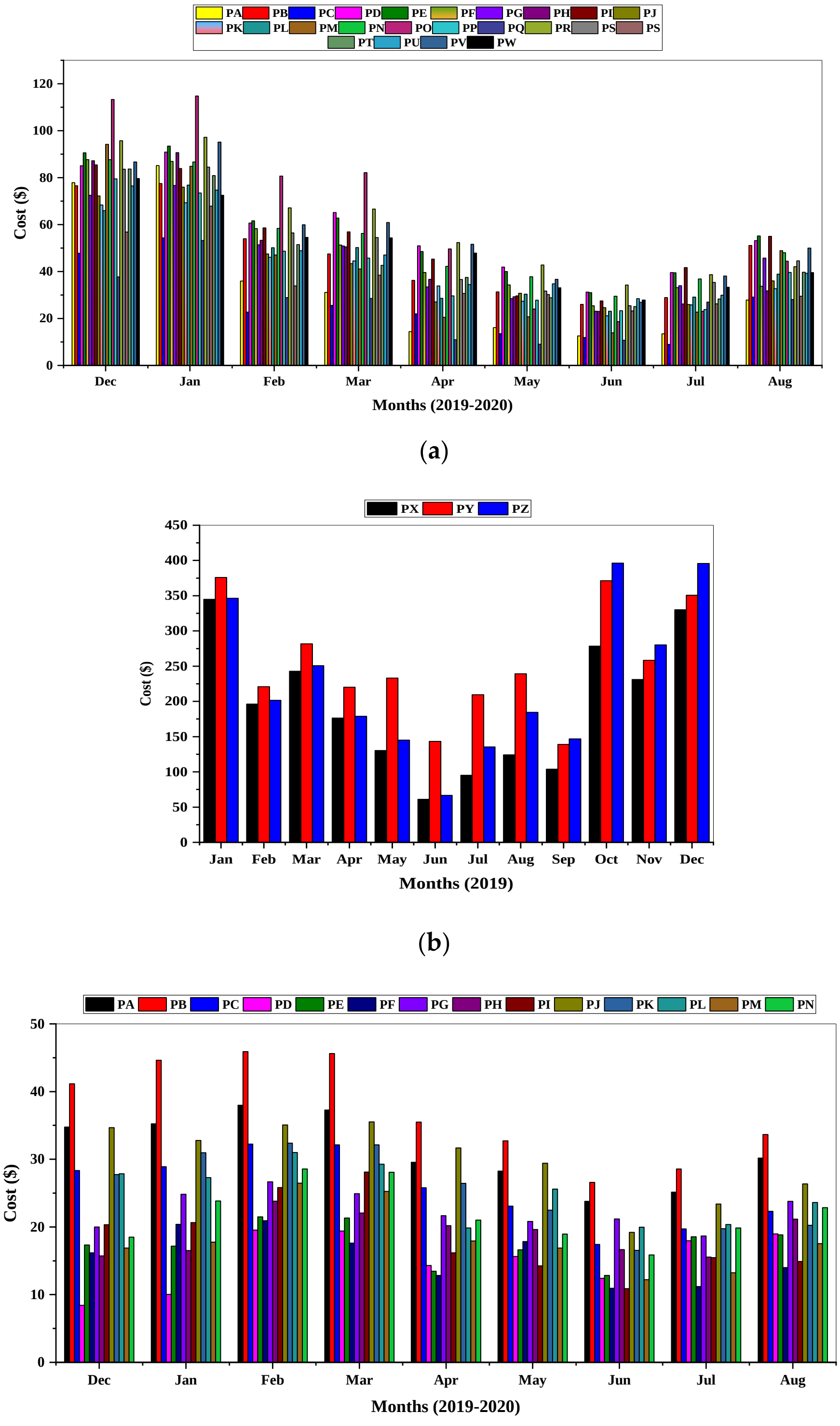
Nomenclature

ΔA_n	Delta difference output between two intervals
B_n	Cumulative value of current interval
B_{n-1}	Cumulative value of previous interval
CP_{calc}	Excess energy after supplying CP load in SA
CP_x	CP load demand covered for individual apartment
$E_{CP,ca}$	The CP load consumption split proportionally between numbers of apartments in CA
E_G	Renewable generation
E_{GA}	Renewable generation capacity allocated to each apartment unit
E_{apt}	Energy consumption of apartment
E_{cp}	CP energy consumption
$Surplus_{SA}$	Surplus remainder after subtracting apartment load from renewable generation in SA strategy
$Surplus_x$	The surplus available after utilization of allocated energy
AC	Alternating Current
BESS	Battery Energy Storage System
CA	Consumption based Allocation
Cost CA	associated costs from CA strategy
Cost IC	associated costs from IC strategy
Cost SA	associated costs from SA strategy
CP	Common Property
DC	Direct Current
DRES	Distributed Renewable Energy System
Excess-CA	excess energy obtained from CA strategy
Excess-IC	excess energy obtained from IC strategy
Excess-SA	excess energy obtained from SA strategy
GW	Gigawatts
IC	Instantaneous Consumption
kWh	kilowatt-hours
OC	Owner Corporation
PV	Photovoltaics
SA	Surplus Allocation
SWIS	South West Interconnected System
WGV	White Gum Valley

Appendix A



(**a**)

(**b**)

(**c**)

Figure A1. Monthly associated costs from excess energy retrieved by individual. Apartment units at (**a**) Evermore, (**b**) Gen Y, and (**c**) SHAC.

Table A1. Monthly grid usage reduction for CP load using three strategies at Evermore.

Months	**Actual Load (kWh)**	**Grid Usage-IC (kWh)**	**Reduction (%)**	**Grid Usage-SA (kWh)**	**Reduction (%)**	**Grid Usage-CA (kWh)**	**Reduction (%)**
Dec	979.58	59.15	93.97	19.98	97.97	167.89	97.97
Jan	1040.02	58.29	94.4	17	98.37	167.91	98.37
Feb	1003.95	198.87	80.2	61.43	93.89	219.87	93.89
Mar	1036.58	172.5	83.36	63.38	93.89	230.67	93.89
Apr	806.2	188.08	76.68	74.4	90.78	197.25	90.78
May	629.16	223.18	64.53	90.26	85.66	194.28	85.66
Jun	473.43	347.61	26.58	88.72	81.27	156.4	81.27
Jul	617.97	341.93	44.67	96.98	84.31	193.06	84.31
Aug	694.69	389.07	44	83.23	88.03	198.35	88.03

Table A2. Total monthly excess energy and costs obtained from three strategies at Evermore.

Months	**Excess-IC (kWh)**	**Excess-CA (kWh)**	**Excess-SA (kWh)**	**Cost IC ($)**	**Cost SA ($)**	**Cost CA ($)**
Dec	1192.09	1892.14	1168.32	178.82	175.25	283.83
Jan	1305.68	1947.34	1274.92	195.86	191.24	292.11
Feb	620.81	1236.24	585.6	93.13	87.84	185.44
Mar	509.02	1198.1	463.98	76.36	69.6	179.72
Apr	166.07	860.65	131.19	24.91	19.68	129.1
May	45.53	710.36	16.34	6.83	2.46	106.56
Jun	29.36	567.85	4	4.41	0.6	85.18
Jul	62.32	709.68	33.26	9.35	4.99	106.46
Aug	181.08	983.95	149.74	27.17	22.47	147.6

Table A3. Monthly grid usage reduction for CP load using three strategies at Gen Y.

Months	**Actual Load (kWh)**	**Grid Usage-IC (kWh)**	**Reduction (%)**	**Grid Usage-CA (kWh)**	**Reduction (%)**	**Grid Usage-SA (kWh)**	**Reduction (%)**
Jan	73.15	3.72	94.93	25.42	65.25	23.96	67.25
Feb	66.61	5.7	91.46	12.09	81.86	10.91	83.64
Mar	70.46	9.75	86.17	20.83	70.45	7.37	89.55
Apr	67.86	16.67	75.44	20.75	69.43	8.57	87.39
May	70.7	33.62	52.45	25.39	64.1	13.7	80.63
Jun	68.37	39.71	41.93	31.68	53.67	25.01	63.43
Jul	71.02	39.45	44.46	28.25	60.23	16.67	76.53
Aug	70.62	30.97	56.15	25.02	64.58	12.2	82.74
Sep	63.27	19.33	69.46	9.79	84.54	4.12	93.51
Oct	63.21	13.04	79.38	17.14	72.89	5.36	91.53
Nov	69.18	7.14	89.69	10.01	85.55	2.51	96.38
Dec	53.24	0.8	98.5	14.22	73.3	7	86.86

Table A4. Total monthly excess energy and costs obtained from three strategies at Gen Y.

Months	Excess-IC (kWh)	Excess-CA (kWh)	Excess-SA (kWh)	Cost IC ($)	Cost SA ($)	Cost CA ($)
Jan	339.7	1067.31	348.24	152.87	156.71	160.1
Feb	201.28	618.58	198.81	90.58	89.47	92.79
Mar	237.53	775.19	236.93	106.89	106.62	116.28
Apr	160.7	575.45	159.99	72.32	72	86.32
May	102.76	508.55	102.27	46.25	46.02	76.29
Jun	31.56	270.94	28.77	14.2	12.95	40.64
Jul	62.77	440.06	62.23	28.25	28	66.01
Aug	114.96	548.04	114.19	51.73	51.39	82.21
Sep	109.46	389.69	109.24	49.26	49.16	58.46
Oct	312.8	1046.13	312.37	140.76	140.57	156.92
Nov	243.54	769.73	242.96	109.6	109.33	115.46
Dec	345.02	1076.6	348.24	155.26	156.71	161.49

Table A5. Monthly grid usage reduction for CP load using three strategies at SHAC.

Months	Actual Load (kWh)	Grid Usage-CA (kWh)	Reduction (%)	Grid Usage-IC (kWh)	Reduction (%)	Grid Usage-SA (kWh)	Reduction (%)
Dec	236.43	160.53	32.11	165.83	29.87	190.99	19.23
Jan	268.89	188.55	29.88	186.18	30.77	214.8	20.12
Feb	267.72	183.6	31.42	168.48	37.07	215.69	19.44
Mar	307.72	224.33	27.1	205.96	33.07	263.11	14.5
Apr	314.92	305.78	2.91	241.54	23.31	308.47	2.05
May	340.41	332.36	2.37	272.35	20	334.71	1.68
Jun	338.46	331.53	2.05	282.89	16.42	334.63	1.14
Jul	328.73	295.28	10.18	268.56	18.31	292.17	11.13
Aug	321.38	314.25	2.22	271.59	15.5	317.08	1.34

Table A6. Total monthly excess energy and costs obtained from three strategies at SHAC.

Months	Excess-IC (kWh)	Excess-CA (kWh)	Excess-SA (kWh)	Cost IC ($)	Cost SA ($)	Cost CA ($)
Dec	228.37	327.81	175.62	34.26	26.35	49.18
Jan	221.41	350.99	193.06	33.22	28.96	52.65
Feb	233.24	407.83	279.92	34.99	41.99	61.18
Mar	254.91	398.69	242.37	38.24	36.36	59.81
Apr	206.72	306.41	148.47	31.01	22.27	45.97
May	184.42	302.15	155.05	27.67	23.26	45.33
Jun	124.23	236.51	100.6	18.64	15.09	35.48
Jul	118.48	267.42	100.27	17.78	15.04	40.12
Aug	167.11	308.43	141.81	25.07	21.28	46.27

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Publication IV

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Review

A Rapid Review on Community Connected Microgrids

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Abstract: As the population of urban areas continues to grow, and construction of multi-unit developments surges in response, building energy use demand has increased accordingly and solutions are needed to offset electricity used from the grid. Renewable energy systems in the form of microgrids, and grid-connected solar PV-storage are considered primary solutions for powering residential developments. The primary objectives for commissioning such systems include significant electricity cost reductions and carbon emissions abatement. Despite the proliferation of renewables, the uptake of solar and battery storage systems in communities and multi-residential buildings are less researched in the literature, and many uncertainties remain in terms of providing an optimal solution. This literature review uses the rapid review technique, an industry and societal issue-based version of the systematic literature review, to identify the case for microgrids for multi-residential buildings and communities. The study describes the rapid review methodology in detail and discusses and examines the configurations and methodologies for microgrids.

Keywords: rapid review; microgrid; community; solar PV; battery storage; utility grid; inverter; energy sharing

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1. Introduction

Electricity produced from non-renewable power plants can experience power disruptions because of extreme weather conditions, which may sometimes result in huge financial losses [1], estimated at USD 44 billion annually, as reported in the US [2]. At the same time, the recent upsurge of solar photovoltaic (PV) penetration worldwide, coupled with the climate agenda of carbon emissions mitigation, have also disrupted the monopoly of fossil fuel-based power plants, thus transitioning towards a new renewable power regime.

Following the suppression of socio-economic activity induced by COVID-19, there was a decline of 6.4% in global greenhouse gas (GHG) emissions in 2020 relative to 2019, equivalent to 2.3 billion tonnes [3]. Although this reduction is promising, GHG emissions are expected to surpass previous figures when the ongoing pandemic situation comes to an end. Of the reported 33 billion tonnes of global GHG emissions for the 2019 season [4], along with other active sources of emissions, the building sector is a key contributor; it has been reported that the building sector is responsible for 19% of carbon emissions, 51% of global electricity consumption and 32% of global energy consumption [5,6].

It is commonly acknowledged that the main drivers of electricity consumption of buildings are heating and cooling appliances. Although modification in construction design can modulate these loads, such high consumption offers an excellent opportunity for the abatement of GHG emissions and costs by utilising distributed renewable energy sources (DRESs).

It is financially difficult to accomplish net zero energy in existing residential buildings, but there are approaches to offset grid-imported electricity, with innovative building construction designs emerging. The concept of net zero energy buildings (NZEBs) has been adapted widely in the research community and projects. NZEBs generate the energy they consume from DRESs, mainly PV and battery storage. Today, the utility network offers dynamic tariffs for scheduling consumers' electricity usage. Energy management systems (EMSs) and arbitrage allow users to charge their electric vehicle (EV) during low-tariff periods. These innovative measures contribute to net zero sustainable buildings. It is, however, equally important to identify which building type (detached houses, multi-residential communities or high-rise apartments) requires an identified mode of technology if the energy transition is to accelerate.

Though attractive in theory, "net zero" as such is not the cornerstone of an ideal sustainable building; rather, this lies in the combined specifics of maintaining smooth electricity supply, frequency and voltage stability, backup generation during blackouts and meeting peak demand that must be contemplated in the selection process of DRESs. For instance, diesel generators are still regarded in many applications as the most orthodox backup option to provide electricity during outages and are often combined with battery storage. However, rapid infrastructure transformation and increasing tariffs foster the need for a new electricity paradigm to deliver power, with microgrids being the product of this new required distributed transformation. Microgrids contain a group of loads and poly-generation sources (e.g., PV and battery storage) operating in a single management system connected to the grid or isolated.

The increased penetration of DRES, principally PV, into utility grids poses various challenges such as the management of excess energy flow, voltage fluctuation, frequency distortion, system stability and protection issues [7]. Further, the efficient utilisation of renewable energy is also imperative on both residential and commercial scales. Microgrids offer various benefits when integrated with the grid, including (i) energy quality, (ii) system reliability, (iii) peak power reduction, (iv) ancillary services provision such as voltage and frequency regulation, (v) reactive power support through the injection of power into the grid, (vi) backup supply in case of grid failure, (vii) electricity infrastructure replacement, (viii) contribution to GHG abatement and (ix) providing autonomy to consumers by giving them control over modifying their energy use through demand response strategies.

The massive rollout of small-scale distributed microgrids with PV and battery storage systems can curtail the levelized cost of energy and, in some cases, cause grid parity situations [8]. The deployment of battery storage from static packs to mobile EVs can also minimise energy costs and ensure the smooth supply of power.

Indeed, various multi-objective control and optimisation techniques can be applied to model microgrids [9]. In the same manner, several forms of DRESs can be integrated with microgrids, such as fuel cells, hydrogen, wind turbines and various forms of energy storage. Technological developments and decreasing costs of DRESs favour microgrid deployment globally; however, many regulatory and policy barriers across certain domains exist, which should also be surveyed. It appears that multi-residential buildings, communities and apartments have received less attention when it comes to the applicability of DRESs, in line with their complexity in design, regulations and scalability.

After the careful review of scientific articles on the topic, it appears that there are several ways of implementing a microgrid for multi-residential buildings and communities; we define such microgrid schemes as community connected microgrids (CCMs). It is worth noting that the terms community grid, community microgrid and multi-residential communities are used interchangeably with CCM in this study without the actual meaning being affected.

The aim of this study is to contribute to existing knowledge from the perspective of a rapid review and provide an effective methodology taking into account CCMs. The scholarship is compiled through configurations or topologies related to CCM, their characteristics, methodologies, pros and cons and barriers to the operationalisation of such microgrids.

The next sections cover the methodology used to conduct the rapid review, followed by a description of the selected articles, a synopsis of configurations, methodologies, opportunities and barriers in microgrid implementation, and finally, a conclusion.

2. The Rapid Review Methodology

Rapid review methodology and manuscripts accelerated over the year 2020, partly due to the emergence and prevalence of COVID-19 around the world. The principles of this methodology are based on the systematic review method, which seeks to identify the conclusions and analyses of multiple research resources, but so that the results obtained can be implemented for policymaking within shorter timeframes. To keep the research predefined and well organised, certain inclusion and exclusion criteria are set with the aim of extracting only published literature reviews from authentic and reliable resources for further evaluation.

Rapid reviews differ from standard literature reviews as such studies can be completed within shorter timeframes as compared with traditional systematic literature reviews (SLRs), which are often conducted within one to two years [6,10]. They have been predominantly conducted in the medical science research, and there is not much evidence that they have been applied in the field of renewable energy. Rapid reviews, much like SLRs, minimise the risk of bias [6]. Factors such as specific database selection, set timeframes and review article proclivity confines the length of rapid reviews. Rapid reviews implicitly synthesise a wide literature through original reviews without these being singularly studied. Consequently, the conclusions are much shorter; the findings, however, are substantial and unbiased as compared with narrative reviews.

We take the example of the "AGILE" model used in Lagisz et al. [11] to describe the rapid review process, in which each step is recurrent and interconnected to the following step. Although AGILE was originally developed drawing on a different motivation, it is still appropriate for use in this study, which follows the steps as shown in Figure 1. To expedite the process, we have excluded the team communication step, which often requires stakeholder consultation and interviews, from the AGILE model.

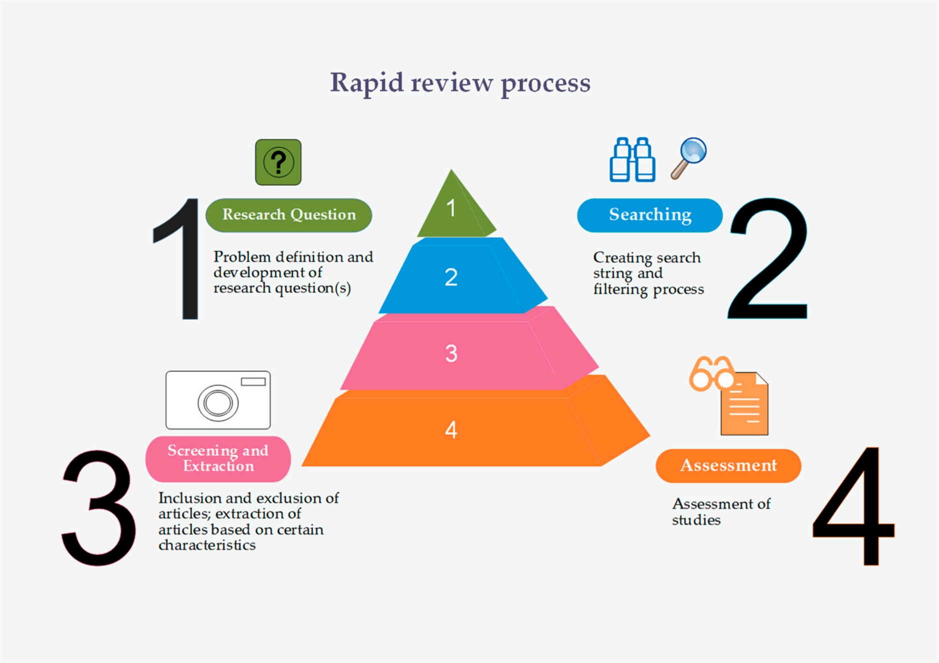

Figure 1. Rapid review process diagram.

The rapid review methodology (see Figure 1) follows the following steps:

1. Research question;
2. Search criteria and filtering method;
3. Screening, eligibility criteria and extraction;
4. Quality assessment of selected studies.

We now discuss each step.

2.1. Research Question

The fundamental research questions have been designed for this rapid review in such a way that they provide a quick overview of microgrids, including configurations, methodologies used and typical challenges that the system encounters and resolves on implementation. Research questions developed before formulating the review comprise the following:

5 Which type of configuration(s) in microgrids is mainly used with DRES within CCM? What are the characteristics, benefits and technical challenges involved?
6 Which control methodologies and optimisation were applied in CCM?
7 What are the main barriers to the implementation of CCM?

These research questions are not exhaustive, and the review may contain information in much more detail. As indicated earlier, our focus has been on microgrids for community and multi-residential housing. Although this article reviews without specificity regarding location, any narrative review or grey literature concentrating on a particular area and passing the assessment criteria is included in this study.

2.2. Search Criteria and Filtering Method

Four reliable trans-disciplinary databases—namely, Scopus, Web of Science, ProQuest and IEEE—were selected for this research. The year selection ranges from 2010 to 2020. A separate search was also conducted through Google and Google Scholar to generate results based on grey academic literature (e.g., reports and articles) that might be relevant and may not have been discovered if running only the usual academic database search. Since Google prioritises search results by number of citations, initial result pages were preferred. Publications were selected in accordance with their scope and the eligibility criteria (listed in Section 2.3), and emphasis was given to documents that contained reviews.

The criterion for the year selection was set to include only recent research studies relevant to research topic, so that the current scenario and rapidly changing technology trends and the situation regarding microgrids within multi-residential buildings could be thoroughly analysed and investigated.

The search string was tested on 15 March 2021 using the abovementioned academic databases and the results were blended to address the research questions. The search string process given in each database looks visually different; however, they follow a common sequence of steps, which are:

- Boolean operator usage to combine different queries, e.g., OR, AND.
- Exact search term or approximate words (with wildcard characters, e.g., "*").
- Word stemming to retrieve both singular and plural form of words.

The search method was applied to filter article titles, keywords and abstracts; other selection parameters included articles in English language, peer-reviewed academic publications, and strictly review articles.

The search string applied to the databases consisted of the following words:

(("solar" OR "solar PV" OR "PV" OR "solar*" OR "photovoltaic*" OR "microgrid" OR "microgrid*" OR "distributed*" OR "integrated") AND (batter* OR battery OR storage OR "energy storage" OR "battery storage") AND ("building*" OR "multi-residential" OR "apartment*" OR community OR "communit*" OR "dwelling*" OR "storey" OR "multi-family" OR "condos" OR "suite*" OR "villa*" OR "multi-unit") AND ("systematic review" OR "systematic literature review" OR review OR "meta analysis" OR "meta-analysis"))

Appendix A lists the search string and filters applied to the different academic databases.

2.3. Screening, Eligibility Criteria and Extraction

The accumulated results from the database search criteria and Google/Google Scholar were forwarded to Endnote reference management, which applied the duplicate removal process followed by manual screening for filtering the abstracts and titles that were most relevant. Articles that qualified for the rapid review consisted of literature review articles and grey literature that addressed the research question; more specifically, the selected publications fell into one of the following categories:

- Studies that provided a thorough review on microgrids in communities and multi-residential buildings.
- Studies that explored energy system configurations and discussed opportunities as well as challenges of deploying CCM.

The relevant articles, as revealed by the abstract and title screening, were studied in detail and synthesised following the same relevancy criteria discussed previously. Among the total of 327 identified search results, after the search, filtering and eligibility process, 13 articles were considered relevant for rapid review. Figure 2 outlines the search and screening processes based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) diagram.

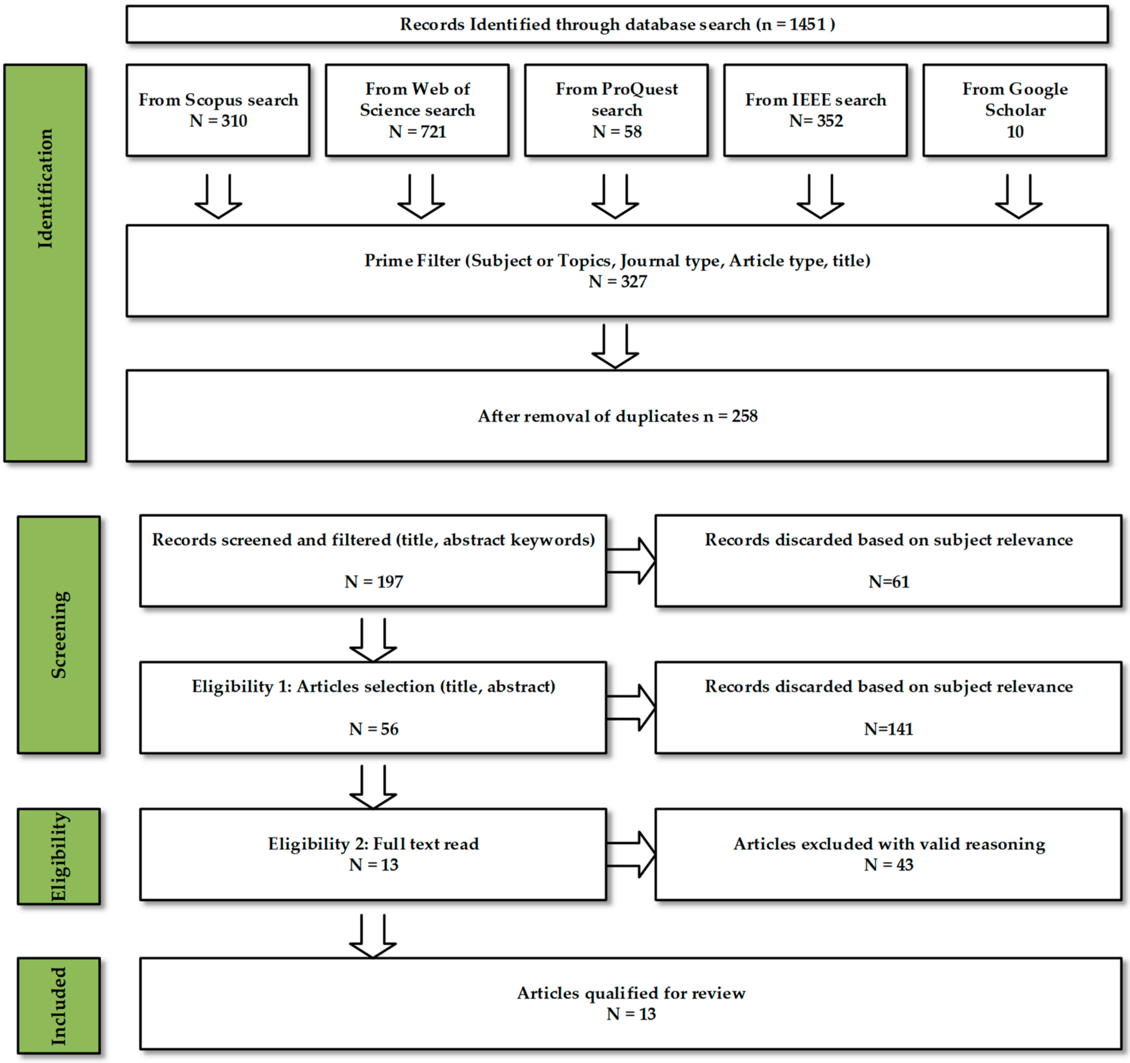

Figure 2. Article selection using the PRISMA approach to the rapid review.

2.3.1. Extraction and Composition

Similar to other types of review, the rapid review can be synthesised qualitatively and quantitatively depending on the characteristics of the articles [6]. Although the reviewed papers are of a technical nature, this rapid review is described qualitatively.

The following attributes were identified for each article included in this rapid review: publication year, paper title, review type, number of reviewed articles, building type, funding and study scope. Research question data concerning microgrid configurations, methodologies and challenges were derived and synthesised.

Content included reasons for different components and configurations used for microgrids in communities, their strengths and shortcomings, challenges (technical as well as regulatory), optimisation control methodologies and future recommendations. Microgrids for communities generally operate on AC-type DRESs with or without battery storage, with the main objective of obtaining low-carbon, cheap electricity and autonomy for consumers by facilitating energy sharing and trading. At the niche level, the process involves technologies used in microgrids for power conversion, control, protection, monitoring and grid interaction. From an administrative point of view, energy management considering load demand and grid connection is also vital, as is discussed below.

2.3.2. Quality Evaluation

A quality evaluation of the selected publications is imperative to provide insightful results and rapid review authentication. The evaluation was conducted through A Measurement Tool to Assess Systematic Reviews version 2 (AMSTAR2) [12], which contains 16 questions to be addressed for every article (see Appendix B). The questions included in AMSTAR2 discuss search strategies, methodologies, risk of bias (RoB) evaluation and results interpretation quality. To visually validate the quality of the articles, Table 1 with answers for the 16 questions is included with colour coding: blue-accent-1 colour represents a "yes" answer, orange-accent-2 colour represents a "no" answer and yellow indicates "unsure". Articles displaying more blue fields indicate high quality and involve lower RoB. Questions 11, 12 and 15 were not applicable and hence excluded.

2.4. *Quality Assessment of Selected Studies*

An SLR aims to collate academic evidence that meets predefined eligibility criteria for the purpose of addressing a particular research question. In comparison with narrative reviews, SLRs are considered high quality with minimal RoB. Narrative reviews, in contrast, exhibit random criteria regarding article selection, thus limiting the search methodology. Moreover, the literature selected in narrative reviews is self-selected, and hence has a high RoB.

Adhering to the eligibility criteria, all publications included in this rapid review are literature reviews (12), with one qualitative analysis report. The characteristics of each review are distinct as, among the 12 articles, only one claims to be a systematic review while 11 are narrative reviews of academic or grey literature. The AMSTAR2 risk assessment tool conducted for the 12 articles in Table 1 shows that publications included scored an average of 3.1 (out of 13 questions), implying an overall medium quality.

The highest score, achieved by Ceglia et al. (2020), was 5 (38.4%). According to question four of Table 1, most studies did not record satisfactory information regarding their comprehensive literature search strategy and data extraction procedures. Moreover, a majority disregarded the quality and RoB of the examined reviews.

Table 1. Quality evaluation of questions from the AMSTAR 2 checklist. The character "Q" in "Q1–Q16" of Table 1 denotes question number.

Author (Year)	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q13	Q14	Q16	Overall Score
Zou, Mao [13]	1	0	0	0	0	0	0	0.5	0	0	0	0.5	1	3
Burmester, Rayudu [14]	0.5	0	0	0	0	0	0	0.5	0	0	0	0.5	1	2.5
Hannan, Faisal [15]	1	0	0	0	0	0	0	0.5	0	0	0	1	1	3.5
Planas, Andreu [16]	1	0	0	0	0	0	0	0.5	0	0	0	0.5	1	3
Parra, Swierczynski [17]	1	0	0	0	0	0	0	0.5	0	0	0	0.5	1	3
Huang, Zhang [18]	1	0	0.5	0	0	0	0	0.5	0.5	0	0	0.5	1	4
Koirala, Koliou [19]	1	0.5	0.5	0	0	0	0.5	0.5	0.5	0	0	0.5	0	4
Neves, Silva [20]	1	0	0.5	0	0	0	0	0.5	0.5	0	0	0.5	1	4
Rosado and Khadem [21]	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0.5
Ceglia, Esposito [22]	1	0.5	1	0.5	0	0	0	0.5	0	0	0	0.5	1	5
Roberts, Bruce [23]	1	0	0	0	0	0	0	0.5	0	0	0	0.5	1	3
Olgyay, Coan [24]	0.5	0	0	0	0	0	0	0.5	0	0	0	0.5	1	2.5

Huang, Zhang [18] claimed to be a systematic review; however, it neither followed a literature strategy nor defined any exclusion criteria, and only partially discussed RoB assessment. Koirala, Koliou [19] performed a database search, but without explaining further steps of a systematic review. Only one article [22] discussed the selection criteria of the study design and review method; a few other studies discussed this in vague terms. Three articles partially discussed RoB. Ceglia, Esposito [22] mentioned more than two databases and keywords for the article search, but nevertheless lacked information usually presented in a thorough systematic review. The majority of the selected articles discussed summarised results based on scholarship retrieved from review articles, albeit without considering RoB. Taking all these limitations into account, this rapid review discusses the important and relevant outcomes and conclusions.

3. Study Characteristics

The papers reviewed in this rapid review were published between 2010 and 2020; altogether, they reviewed approximately 1700 research articles, case studies and grey literature. They were written globally, spanning Europe, Asia, Africa, Australia and North America. The main theme of the reviewed articles was microgrid configurations or energy systems for communities and multi-residential buildings.

Table 2 lists the study characteristics of the reviewed articles. Four articles [13,14,16,25] explicitly investigated microgrids, particularly in the domain of energy management, configurations, control topologies and design and modelling challenges. The remaining articles focused on DRESs for community setup.

Table 2. Characteristics of the reviewed articles.

Author	Title	Article Type	Study Scope	Building Type	Location	Number of Reviewed Studies	Research Funding	Conflict of Interests
Zou, Mao [13]	A Survey of Energy Management in Interconnected Multi-Microgrids	Narrative review	Review of surveys regarding energy management systems (EMSs) in multi-microgrids and review on the optimisation algorithm.	Interconnected households	Researchers are based in China and the US; article locations not specified	Not explicitly stated	NSF China, Central Universities of China, US NSF and WEREC, Auburn University US	None
Burmester, Rayudu [14]	A Review of Nanogrid Topologies and Technologies	Narrative review	Reviews the nanogrid, its control topologies and usefulness within supply and demand domain.	Multiple loads	Researchers are based in New Zealand; article location is not specified	Not explicitly stated	Victoria University Wellington	None
Hannan, Faisal [15]	A Review of Internet of Energy (IoE) Based Building Energy Management Systems: Issues and Recommendations	Narrative review	Review of an IoE-based BEMS for improving the future generation building performance and energy utilisation.	NZEB	Researchers are based in Malaysia, Australia and Denmark; article locations not specified	Not explicitly stated	Universiti Tenaga Nasional	None
Planas, Andreu [16]	AC and DC Technology in Microgrids: A Review	Narrative review	Detailed analysis of parameters for AC and DC microgrids for the purpose of identifying available substitutes for designing and configuring a microgrid.	General buildings	Researchers are based in Spain; article locations not specified	Not explicitly stated	Department of Education, Universities and Research of the Basque Government and the Government of the Basque Country within the research program ETORTEK as part of project ENERGIGUNE12	None
Parra, Swierczynski [17]	An Interdisciplinary Review of Energy Storage for Communities: Challenges and Perspectives	Narrative review	Analysis of community energy system (CES) technologies, applications and the role of stakeholders in the deployment of CES.	Communities	Researchers are based in Switzerland, the UK and Denmark; article locations not specified	Not explicitly stated	Commission for Technology and Innovation in Switzerland within the Swiss Competence Centre for Energy Research in Heat and Electricity Storage.	None

Table 2. *Cont.*

Author	Title	Article Type	Study Scope	Building Type	Location	Number of Reviewed Studies	Research Funding	Conflict of Interests
Huang, Zhang [18]	A Technical Review of Modeling Techniques for Urban Solar Mobility: Solar to Buildings, Vehicles, and Storage (S2BVS)	Systematic review	Systematic review of solar mobility research along with newly developed energy concepts and techniques. The study discussed the conventional solar mobility scope from the solar to buildings, vehicles and storage (S2BVS) perspective. Moreover, detailed modelling of each configuration in the S2BVS model and related advanced controls is presented.	Residential and commercial buildings	Researchers are based in Sweden, China and the UK; article locations not specified	Mostly Europe, the US, the UK and East Asia (China and Japan)	This research was funded by the EU Horizon 2020 EnergyMatching project, the UBMEM project of the Swedish Energy Agency and the J. Gust. Richert foundation in Sweden	None
Koirala, Koliou [19]	Energetic Communities for Community Energy: A Review of Key Issues and Trends Shaping Integrated Community Energy Systems	Narrative review	Presents the concept of ICES. Reviews the recent energy trends and the related technological, socio-economic, environmental and institutional problems forming the development of ICESs. It discusses the role of local systems to incorporate DRESs while engaging local communities.	Communities	Researchers are based in the Netherlands, Spain and Germany; article locations not specified	Not explicitly stated	Erasmus Mundus Fellowship	None
Neves, Silva [20]	Design and Implementation of Hybrid Renewable Energy Systems on Micro-communities: A Review on Case Studies	Narrative review of case studies	Reviews the design of Hybrid Renewable Energy Systems (HRESs) in isolated micro-communities, particularly on islands. Discusses systems configuration, electricity demand characteristics and dynamics, and complexities in implementation.	Micro-communities on islands	Researchers are based in Portugal and the US; article locations are based in Europe, Asia, Africa, Oceania and North America	42 island case studies and 7 remote villages	Foundation of Science and Technology of Portugal	None

Table 2. *Cont.*

Author	Title	Article Type	Study Scope	Building Type	Location	Number of Reviewed Studies	Research Funding	Conflict of Interests
Rosado and Khadem [21]	Development of Community Grid: Review of Technical Issues and Challenges	Narrative review	Reviews the technical issues related to the community grid scenario and approaches to solutions required for the purpose of making the community grid highly renewable and sustainable.	Community based	Researchers are based in Ireland; article locations are based in Europe, Asia, Africa, Oceania and North America	Not stated	Not given	None
Ceglia, Esposito [22]	From Smart Energy Community to Smart Energy Municipalities: Literature Review, Agendas and Pathways	Narrative review	Examines the theoretical approach of smart energy community and discussed incentives of smart energy community applications in smart localities.	Community based	Researchers are based in Italy; location of every article is not given, however, some articles are based in Japan and Europe.	Not explicitly stated but only 10 energy communities mentioned in a table	Regione Campania, within the framework of the GeoGRID ProjecT	None
Roberts, Bruce [23]	Opportunities and Barriers for Photovoltaics on Multi-unit Residential Buildings: Reviewing the Australian Experience	Narrative review	Reviews opportunities and barriers to increasing PV deployment in apartment buildings.	Apartments	Researchers are based in Australia; content locations are mostly Australian	Combination of 44 articles, several survey reports and regulatory documentation	Energy Consumers Australia), Co-operative Research Council for Low Carbon Living and an Australian Government Research Training Program Scholarship	None
Olgyay, Coan [24]	Connected Communities: A MultiBuilding Energy Management Approach	Technical report	Explores various factors influencing the development and operation of connected communities and assesses their potential value.	Multi-buildings	Researchers are based in the US; project location based in the US	Not explicitly stated	Department of Energy Office of Energy Efficiency and Renewable Energy Building Technologies Office	None
Fontenot and Dong [25]	Modelling and Control of Building-integrated Microgrids for Optimal Energy Management—A Review	Narrative review	Provides an outline of microgrids, its components, significance to utility grid and building holders. It also discusses technical and modeling challenges. Additionally, reviews various data-driven forecasting methods for microgrid controls.	General buildings	Researchers are based in the US; article location is not specified	Approximately 177	CPS Energy and the US National Science Foundation	None

Hannan, Faisal [15] reviewed IoE-based building energy management system (BEMS) technologies such as DRESs, storage and communication interfaces for upgrading the proposed building energy operation. Community energy storage (CES) was reviewed by [17], with a strong focus on technologies used for end-user applications, techno-economic analysis and socio-environmental assessments of CES; this paper also provided a viewpoint on CES from the utility network, policy and consumers perspectives. Huang, Zhang [18] reviewed solar mobility concepts and discussed the modelling of solar to building, vehicle and storage (S2BVS). Koirala, Koliou [19] presented the concept of integrated community energy systems (ICESs) and studied issues of ICES from technical, socio-economic, environmental and institutional perspectives. Neves, Silva [20] reviewed Hybrid Renewable Energy Systems (HRESs) design for micro-communities and discussed technological configuration, electricity demand and the intricacies of system commissioning.

The concept of a community grid (CG), including grid and distributed energy sources and participation of energy trading, was presented by Rosado and Khadem [21]. The authors also presented technical issues associated with a CG and discussed solutions for developing a sustainable network. Ceglia, Esposito [22] studied smart energy systems (SESs) for smart energy communities and reviewed prospective applications in smart localities. A review by Roberts, Bruce [23] identified the scope of PV deployment in multi-residential apartment buildings and investigated opportunities and barriers for the uptake of PV systems, especially from an Australian perspective. Finally, a technical report by Olgyay, Coan [24] presented connected communities and explored several factors affecting their functionality. Nearly all articles discussed CCM, identified gaps and proposed future research directions. A summary of key findings from the reviewed articles is given in Appendix C.

4. Community Connected Microgrids

DRESs include distributed generators (DGs), power inverters/converters and energy storage systems (ESSs), which create a microgrid capable of feeding distributed loads. The combined effect of these components in the microgrid allows for the adequate exploitation of available resources (such as solar, wind and biomass) while improving the stability, power quality and reliability of a microgrid [16]. This section of this rapid review focuses on components of the microgrid, and configurations referred to in the review articles.

4.1. Components of a Microgrid

In addition to the main DRES elements stated above, other components also perform critical functions in the microgrid, including the point of common coupling (PCC), distribution, control circuit, protections and monitoring. The components of a microgrid can be operated based on different types of power source, such as AC and DC networks. Each power source offers distinct characteristics, with certain advantages and disadvantages. The microgrid can be connected and disconnected from the main grid through the PCC, which employs power converters and switchgears to perform this switchover [16].

4.1.1. Transmission and Distribution

AC-based microgrids consist of different types of wiring distribution contingent on the application (i.e., single, three-phase without neutral and three-phase with neutral, with three-phase being the common system for power transmission). From the regulatory point of view, the existing standards support AC microgrids for the reason that AC microgrids are ubiquitous and have broad applications, which is not the case for DC microgrids.

DC microgrids also fall into three types—mono-polar, bipolar and homo-polar—and can be designed with multiple buses in order to obtain high reliability. They rely on high voltage direct current (HVDC) technology, acknowledged for its high power density, absence of short-circuit issues and high stability [16]. Prominent examples of the HVDC transmission system include the Rio Madeira system in Brazil—the longest HVDC installation, stretching over 2375 km—and the Jinping-Sunan installation in China, which, with 7800 kV ultra-HVDC [16] and a capacity of 7.2–7.6 GW, is considered the most powerful transmission line in the world.

DC distribution lines are useful when compared with AC distribution lines due to the absence of reactive power, which results in lower power losses, less voltage drop and an increased power capacity of the electrical transmission. These benefits bring about reliable and high-quality DC power output and allow a larger stretch to the network for the same capacity of load. Generally, DC/AC conversion includes electrical losses [14], while many modern sources and loads such as PV panels, batteries, compressors, fans, servers and EVs operate on DC power; hence, few studies [14,18] have recommended the utilisation of DC microgrids instead of AC microgrids.

There are some instances of DC microgrid applications covered in the literature. A DC microgrid on a 350 V bus was proposed to introduce large PV generation in [18], which similarly reported a DC microgrid with an energy-hub for power sharing (operated at 760 V) that converted and controlled energy flow between the DC and AC grid. A DC/DC converter was designed to step down the 760 V DC grid voltage to 120–400 V (the voltage generally required by DC loads). Thus far, the major applications of DC distribution are limited to specific areas, such as network telecommunication equipment, transportation, ships, and motors.

4.1.2. Power Converters

The power converters in microgrids are selected based on technical parameters such as AC or DC sources, voltage levels, the direction of power flow and, most importantly, the type of load (AC or DC). Additionally, galvanic isolation is added by using transformers. Power converters usually inject and absorb reactive power and further participate in voltage stability [17,21,25]. Moreover, in some cases, commercially available grid-connected PV inverters also support voltage stability, reactive power and anti-islanding functions [16].

AC systems require a controlled DC–AC inverter designed from insulated-gate bipolar transistors (IGBT), DC–DC converters and DC link capacitors for maintaining constant reference voltage at the input of inverters. Matrix converters that enable bidirectional power flow can also be used through two-way switches without the inclusion of reactive components. AC microgrids with battery storage deploy bidirectional DC–DC converter topology coupled with a three-phase transformer-based inverter [16] or, in some cases, a three-phase inverter with LC filter [21]. In DC systems, the AC source output is first converted into DC through rectifiers. Conversion is performed through a three-phase inverter coupled with a high-frequency transformer and then a three-phase rectifier. Similarly for flywheel systems, permanent synchronous generators are placed at the input of DC and AC systems.

In all DC/AC, AC/DC and DC–DC converters, the voltage amplitude of the converters can be lower or higher than the input voltage. This variation takes effect through reactive elements (inductors or capacitors) and switching components (IGBTs). Generally, buck and boost converters are used for this purpose. Component switching is performed through pulse width modulation signals, which can also be changed by feeding back the reference voltages and currents [14].

Since DC microgrids are not generally implemented, standard power converters configurations to couple DGs into them are rare; nevertheless, they require fewer components than three-phase AC topology [16]. Furthermore, the available DC topologies utilise multilevel inverters and high-frequency transformers, which in comparison are smaller in size and lighter in weight than low-frequency transformers.

Overall, AC lines offer better conversion efficiencies than DC lines for residential systems; however, in the case of fuel cell or other DC generators, conversion efficiencies could be superior to AC. Inverters/converters deliver non-linear characteristics and carry harmonics at PCC [15,21].

The presence of harmonics in the current can directly occur from converter switching, which degrades the performance of the grid because of unbalanced load conditions. Such harmonics can be mitigated using active and passive filters or controlling the main source of distortion. Similarly, resonances are created by the shunt capacitors in the grid. This problem is mostly found in three-phase and single-phase distribution grids. To reduce resonance, the capacitor size could be increased when designing filters [21].

Current ripple and harmonics are reduced in the DC case because of reverse polarity protection, and the ripples generated by various devices are not synchronised. Power converter/inverter topologies for PCC are proposed in [14,16].

4.1.3. Monitoring

To ensure balanced demand and supply, a rigid monitoring structure with a communication network is indispensable and may facilitate to apply energy management strategies. There are different monitoring interfaces used for AC and DC microgrids, as identified by [16]. One of these is a framework based on the service-oriented architecture. This interface connects different service applications via communication interfaces. A number of services can communicate with each other by either passing data or coordinating with other services. In addition, “universal monitoring, protection, and control units” considered similar to intelligent electronic devices provide efficient system monitoring, as they collect measurement data from appliances and devices. Another possibility to monitor different microgrids is via “phasor measurement units” that leverage accurate data about the power system and allow efficient management of the system.

In Hannan, Faisal [15], a BEMS is shown to incorporate data using meters and different sensors. The data are then used to analyse energy management system performance. Similarly, the field and enterprise zone of smart grid architecture in [18] consists of metering and communication equipment for the control and monitoring of electricity networks as well as power scheduling for utilities and energy traders. Metering has also been reported as one factor that has broad application in demand-side management (DSM) [19].

One of the objectives of smart communities is digital interconnectedness. This is heavily dependent on the availability of energy data flowing from cloud-based services, sensors and smart meters; however, the technical setup incurs higher installation and management costs [22]. Moreover, to incentivise consumers, measurement of parameters such as self-consumption is critical and, combined with smart metering rollout and installation in embedded networks [23], new developments are taking up metering and communication. Notwithstanding, smart metering data also raise questions of customer privacy and security of a microgrid [25]. Technology-wise, the installation of DC microgrid monitoring systems are straightforward as compared to AC microgrids due to absence of frequency and reactive power elements.

4.1.4. Protection Schemes

Microgrids require sophisticated protection schemes to ensure safe operation. Like transmission, protections can be based on AC and DC sources. The core criteria for selecting the proper protection systems for microgrids are sensitivity, response time and security level. The protection schemes originate from several DGs installed, and the short-circuit current availability in the islanded mode [14].

Utility standards require the implementation of anti-islanding protection schemes for power converters connected to the distribution grid. Anti-islanding schemes detect loss of utility power in a short time period and switch off the inverter in microgrid. Anti-islanding schemes may impact network performance and need enhancements to mitigate excessive trips; on the other hand, the impact of increasing PV generation can also degrade the microgrid performance with the utility network [21]. In [21], islanding detection schemes are summarised into four categories:

8. Passive: this is based on measuring the electrical magnitudes.
9. Communication-based algorithms: fast communication is provided between the grid protection and DG.
10. Active: analyses the system response while injecting the electrical current.

11 Hybrid scheme: combines the active and passive techniques.

The protection design for DC microgrids takes a different approach than for AC microgrids because AC systems must include ground fault detection; also, since the current in DC systems omits zero crossing, short-circuit current interruption in DC systems is harder to pick up as compared with AC systems [16]. Nonetheless, protection system costs in AC microgrids are lower than in DC microgrids [16].

From a system perspective, there are protections inside inverters/converters to save the system operation; [15] mentioned fault detection and diagnosis (FDD), an automatic method of sensing and isolating faults for the protection of a BEMS.

Although IEEE set standards for protection schemes, an Australian study identified that, for bigger systems, there were no national standards for protections, and it was left to network operators to reinforce additional protection requirements for network safety [23].

4.2. Microgrid Configurations

Microgrids can be configured subject to the requirements of a particular site. The following subsections discuss different application-dependent configurations (mostly communities) of microgrids covered in the review articles.

4.2.1. Behind-the-Meter Systems

Behind-the-meter (BTM) systems are PV-based microgrids installed by an owner behind the main grid for offsetting the household electricity load. A study by [23] discussed the opportunities and barriers in implementing PV systems in apartment complexes, specifically within the Australian context. Table 3 lists the apartment installation models and the descriptions as discussed in [23].

Nevertheless, there are prevailing regulatory and governance issues associated with the adoption of shared BTM systems and shared microgrids with battery storage systems, as mentioned in [23]. The physical limitations of roof space on apartments and split incentives to proportionally distribute the incentives between the owner and renter are major governance issues. From a financial point of view, raising levies and funds for multi-residential/strata complexes and setting up internal tariffs for solar utilisation also pose challenges. Moreover, there is less data availability and knowledge gaps in research and engineering groups regarding shared BTM.

On the network side, no such retail and technical regulations exist on how to manage BTM installations. Given the applicability of shared BTM in multi-residential housing, configuration can take advantage of different governance models implemented in commercial setups, strata buildings and communities and facilitate peer-to-peer trading.

The standard configuration for PV-BTM is implemented on shared roof space of apartments to supply common property (CP) demand connected behind the grid meter [26].

Table 3. PV implementation models for apartment buildings.

PV Implementation Models	Description
Individual PV connected to apartments	Does not involve shared governance and is the simplest arrangement in which a PV system can be installed behind the meter.
Shared PV	Installation is simple and the common arrangement in shared PV is to use the shared generation resource to supply CP demand.
Distributed arrangement to apartments using PV in an embedded network	Network configured with parent and child metering arrangement using an embedded network.
Local energy trading technique to promote energy trading in apartments using shared PV distribution	Energy is distributed using the local energy trading or virtual net metering method.
PV distribution to apartment using the behind-the-meter approach	This approach involves connecting a shared PV system behind the meter of all apartments.

4.2.2. Nanogrids

Burmester, Rayudu [14] discussed the existing literature related to nanogrids, and the techniques and control topologies that could intelligently control nanogrids. A nanogrid is defined as a power distribution system for a small building or single house with the characteristics of connecting and disconnecting from other power sources using a gateway. A local production system in nanogrid manages the control system and also utilizes energy storage. The major components of a nanogrid are shown in Figure 3. The local power source in a nanogrid could be chosen from DRESs such as wind, solar and non-renewable energy resources such as fuel cells or diesel generator. The nanogrid controller coordinates with multiple sources to optimise power and deliver it to the loads. The loads mainly consist of residential appliances such as electric heaters, ovens and televisions.

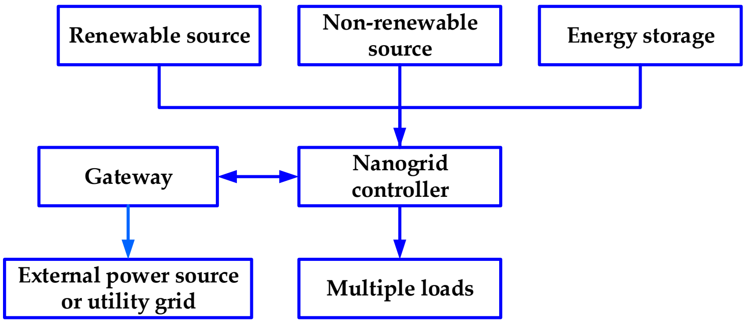

Figure 3. Components of a nanogrid.

Bidirectional flow between the nanogrid, power grid and microgrid is provided by the gateway, which also handles the communication between power networks. Finally, an ESS could be integrated as an optional element in line with its ability to stabilise the network.

Similar to microgrids, nanogrids can be either AC coupled or DC coupled. The DC nanogrid employs a DC-to-DC converter to interface with the DC load. The gateway is based on a bidirectional AC-to-DC converter. On the other hand, the AC nanogrid consists of a DC–AC inverter that takes the DC voltage as an input from the source converter and outputs 230 V. Although the majority of existing loads in both homes and factories are AC, DC nanogrids have the advantage in terms of efficiency and performance factors, though DC nanogrids also have protection issues. The damaging faults which include ground fault and circuit line fault can arise at switching devices, loads and output terminals. They can be curtailed by installing arcing-type circuit breaker protection [14]. A network of nanogrids “Plico project” in western Australia is a good example of community-focused microgrids. It aims to develop a virtual power plant based on residential PV and battery storage systems [27].

4.2.3. Community Grids

A CG [21] involves DRES integration to the utility grid together with consumer engagement to facilitate an energy trading mechanism. The architecture of a CG is based on a central community grid controller (CGC), which manages and operates the virtual microgrid. The key aim of the deployment of a CG is to reduce electricity consumption from the grid by utilising more power from DRESs. The focus, however, is on the penetration of DRESs for micro-generation systems and distributed systems without comprising power grid stability [21,24]. Moreover, consumers can actively become energy active citizens and exchange energy within their CG, and also potentially with the transmission grid.

Nonetheless, CGs are also associated with technical problems including generation intermittency, voltage fluctuation, stability, resonances, harmonic distortion, islanding operation and network protection [21]. The voltage fluctuations and generation variability directly affect the active power flow in the distribution networks, both in terms of direction and magnitude. Further, the variation in active and reactive power also affects the voltage profile in the distribution feeders. This problem can be resolved using static synchronous compensators (STATCOMs), tap changers, PV inverters, power inverters and energy storage [21].

Stability problems can occur with large or small signal surges. Larger surges are by interactions between different items of equipment in a slowly changing event, while small surges are generated by sudden changes in operating conditions. Unstable behaviour in the distribution grid can cause serious equipment disconnection and disturbances. The impedance criterion in this case can be used to determine small signal instability. The proper selection of protection schemes is also essential for the stable operation of community microgrids. Reasons for improper selection include relay malfunctioning while mis-operations are caused by erroneous operation of the fuse, unsynchronised closing and loss of coordination [21].

4.2.4. Integrated Community Energy Systems

A study by Koirala, Koliou [19] explored the development of integrated community energy systems (ICESs) which integrates different combinations of DRESs as an alternate energy system for the transition of the local energy landscape. ICESs are multiproduct and multisource and fulfil the requirements of the energy of the local communities by establishing better synergy between different communities and by integrating the energy sectors. The energy system for ICESs consists of different technological artefacts and decision-making groups and are governed by energy policymakers. They also facilitate energy-related services for large-scale systems, network services and operating reserves using the interconnection and can provide superior community engagement with self-reliance, energy independence and security. The technical challenges discussed in [19] related to the ICESs are highlighted in Table 4.

Table 4. Technological issues of ICESs.

Challenges	ICESs Role
Intermittency of DRESs, demand response	Mitigation of the effect of peaks, load balancing in power, activation of demand and generation
Load and grid defection	Local balancing using local energy system
Storage	Collective purchasing of community energy storage and household storage devices
Energy efficiency	Collective purchasing of insulated energy-efficient appliances and materials
Local balancing of demand and supply	Diversity in supply and demand
Impact on larger energy system	Load balancing and ICESs increase the penetration of renewables

4.2.5. Smart Energy Systems

Connected communities can also take advantage of an SES to improve the quality of supply and reliability, the use of local participation of citizens as well as the reduction in cost in terms of energy vectors procurement [22]. SESs can address various socio-technical issues including energy poverty in rural areas and energy autonomy to maintain balance in energy flow between storage and import. It promotes renewable uptake by managing electricity peak demands and reduces GHG emissions. From a technical point of view, an SES addresses demand prediction and data-related issues by placing accurate sensors and loggers for measuring energy demand. Further, SESs can be developed by the approaches outlined below:

Multi-energy approach: This uses various DRESs such as hydrogen, biogas and fossil fuels for electricity cooling/heating loads.

Sharing approach: Multiple users locally share a single energy system through central microgrids powered by different renewable sources that allow the system to use them more efficiently.

Energy storage: Energy storage stores the excess amount of thermal/electric energy produced.

EV integration: The surplus energy from renewable systems can also be stored in EVs in the smart energy community (SEC) and can be further provided to final users through vehicle to home technology.

NZEB: The NZEB approach allows a high energy performance building to fulfil most energy demands through local DRES.

4.2.6. Interconnected Multi-Microgrids

Interconnected multi-microgrids (IMMGs) incorporate multiple individual microgrids closely located and connected to an electrical distribution bus. IMMGs can operate in either the grid-connected mode or the islanded mode. IMMGs also facilitate energy trading with microgrids situated in close proximity, thus avoiding large distance transmission losses. One of the major advantages IMMGs offer is the distributed structure of microgrids, which improves the reliability of the distribution network [13].

The three topologies usually used in IMMGs are radial or star, mesh and daisy chain. In the radial topology, the multi-microgrids form a star arrangement where each microgrid is connected to the main grid directly through a distribution bus at point of energy exchange. One of the key challenges with the radial topology is management of energy and power sharing capability. If the energy exchange with a utility grid is overloaded, the power distribution line can become congested. In daisy chain configuration, the energy flows bidirectionally between the main grid and the microgrid, and also between adjacent microgrids. The energy sharing with other microgrids leads to additional challenges in designing the energy schedule and optimisation techniques with network constraints. Microgrids in mesh topology are interconnected using a communication network and a transmission line. The structure is complex compared with the daisy chain and radial technologies; thus, more intelligent coordination and energy-sharing techniques are required.

4.2.7. Hybrid Renewable Energy Sources

Communities can also be connected using HRESs which are specifically built for island and remote village communities. In HRESs, the diesel power plant is the main source of supply (39%), while the mainland grid contributes 25% and others 36%. Consequently, hybrid systems based on diesel/wind play a significant role as a source of power (18%) [20]. A list of hybrid system characteristics for remote villages and islands discussed in [20] are provided in Table 5.

Table 5. Micro-community hybrid grid projects.

Main Activities	Remote Village	Islands
Major hybrid system configuration	Batteries/PV/private diesel generator	Wind/diesel power plant/PV
Grid connections	86% isolated	71% isolated
Major backup	Batteries	Diesel
Renewable penetrations	For yearly demands up to 100%, lower than 2000 kWh/household	For yearly demands up to 80%, lower than 20,000 MWh
Demand	[1.3–245.3] MWh/year based on evening hours	Different with geographic sites [111–754,000] MWh/year; peak high demand—24 h requirements
Number of houses and demand	Less than 50 MWh/year of demand for 60 houses	When inhabitants increase above 10,000, the relation of demand is non-linear
Common configurations	PV/PDG coupled with batteries	Wind/PV/DPP

5. Energy Storage for Community Microgrids

A community microgrid configuration necessitates the adoption of ESSs as this offers various benefits. From a technical perspective, load demand aggregation generates fewer spikes in load profile in comparison with an individual house, which reduces the battery discharge rate and also decreases the optimum battery capacity. Most importantly, energy storage becomes crucial when the primary source of power is from DRESs, and therefore, to cover the rest of the night demand, more storage is needed if grid consumption is to be avoided [21]. In the case of off-grid CCMs, this implies a large amount of storage. ESSs can address the issue of intermittent generation; hence, efficient storage is still a significant challenge for future microgrids.

The adoption of CES provides power quality, stability to the grid, voltage control, peak demand management and demand load management. From a socio-economic point of view, and along with distributed wind and solar power resources, CES addresses issues of energy efficiency, affordability and mitigation of GHG emissions linked to individual households and communities [17]. Further, utility companies can optimise CES systems for the benefits of the electricity network and wholesale electricity markets. However, the existing CES models (through battery) are costly. CES can open new approaches for energy transition as the community scale introduces electrochemical technologies such as batteries and can increase the awareness of users and communities regarding energy usage and environment.

Several energy storage technologies are discussed by the selected reviews. Conventional lead–acid batteries are the most widely available storage in the market and mainly used in automotive applications and in uninterrupted power supplies for residential and commercial purposes [16,17,19,25]. The major benefits of lead–acid are low cost, high efficiency (70–80%) and long lifetime (5–10 years). However, cycle-lifespan is short (i.e., 500–2000 cycles), which limits the charging capability and provides poor temperature handling [17,19].

Lithium-ion (Li-ion) technology is by far the most rapidly growing and adoptable technology for stationary applications [19,24,25]. The success factors are high efficiency (90–95%), high energy density (75–200 Wh/kg), long life and operating cycles, low maintenance, high power capability and better temperature management (−25 °C to 55 °C) [16,18,19,24,25]. The most common identified downside of Li-ion technology is high cost [17,18]; however, this is estimated to drop within next decade in line with massive manufacturing. Similarly, flow batteries are used in high-power, large-scale commercial-based systems and offer better efficiency (80–85%) [17].

Thermal storage systems offer efficient storage with 30–60% efficiency, better energy density (80–250 Wh/kg) and low energy consumption and GHG emissions [15–19,25]. Thermochemical heat storage systems have high energy density with minimal loss; however, thermochemical materials incorporated in storage systems for buildings have the drawback of high cost, unsuitable temperature and discharge power [15,19,25].

Hydrogen is also considered a promising technology for mid- to long-term storage because of its high specific energy density (33kWh/kg) and energy and power ratings [17]. The process usually involves converting surplus electricity into hydrogen and oxygen through electrolysis; hydrogen can then be used to charge fuel cells. Higher costs of electrolysers and supporting material are disadvantages of this technology [17,20,25]. Moreover, water needed, and logistics costs make it an expensive investment. For short-term standby applications, flywheels are also considered promising [19]; these can stabilise intermittent generation from solar and wind.

Further storage technologies such as compressed air energy storage and pumped hydro storage, regardless of their poor efficiency, carry high capacities with longer lifespans [16,19,25]. Superconducting magnetic energy storage yields high efficiency; however, it is still in the demonstration and testing phase [16].

6. Control and Optimisation Methodologies

Microgrids require different control tasks to guarantee the correct operation of the system. The optimisation of CCMs is no different than conventional microgrids and have also been broadly examined in the literature that focuses on load demand, economic efficiency, GHG emission reduction and control optimisation.

Controls in AC and DC microgrids consist of a hierarchical structure which executes tasks on the basis of multi-agent control [16,25]. There are three outer to inner levels of controls; namely, grid, management controller and field [16,25]. At the grid level, a distribution network operator and a market operator are usually functional. At the management level, a microgrid controller manages functions such as frequency regulation, voltage control, grid synchronism, blackouts and optimisation operations. Similarly, at the field level, local controllers are placed in each component of the microgrid (DGs, storage or loads). Local controllers for DGs normally consist of the droop control method, which offers high reliability and does not demand a communication network between DRESs. For intermittent DRESs, non-linear droop control is implemented. Local controllers for storage control the charge and discharge of a battery or other source. One such control method mentioned in [16] is the state of charge (SOC)-based adaptive droop.

In DC microgrids, there are no frequency control or reactive power flow requirements, which makes the grid interfacing task easier. Conversely, frequency must be controlled in AC microgrids, and power electronic components should be synchronised with the grid for stable operation. Phase locked loops are the most common method for AC system synchronisation with the grid.

The voltage balancing requirement is also crucial for microgrids. This is controlled in AC microgrids using reactive compensation devices such as static var compensators or STATCOMs.

AC microgrids' stability is typically affected by the operational mode (on grid/off grid), control topologies, type of DRES and network parameters. The main stability issues identified by [16] include small signal stability, transient stability and voltage stability. Most of these issues can be resolved through improvement in control methodologies for DGs, storage and load.

The following subsections present various control methodologies and their characteristics discussed in the reviewed articles.

6.1. Energy Management Systems

Energy management systems (EMS) in IMMGs are used for controlling generation and energy consumption. Each individual microgrid consists of a renewable source, ESS, residential/commercial loads and EMS, which autonomously controls and manages energy. Additionally, the microsource controllers are responsible for controlling the ESS, and the load controllers for managing controllable loads. All of these components are interconnected using a rigid communication infrastructure [13].

Distributed optimisation EMS techniques for IMMGs include dual decomposition (DD), game theory and the alternating direction method of multipliers (ADMM). In a DD optimisation technique, the microgrid and distributed system operator (DSO) are owned by different groups and, based on their objectives and policy, schedule non-renewable and renewable DGs.

Game theory provides a strong tool to attain cooperative and non-cooperative power control strategies in interconnected microgrids. This approach uses each microgrid to attain more benefits than operating alone under well-designed policies. In IMMGs, a cooperative approach is usually preferred. The literature in [13] covered various game theory algorithms proposed in order to gain benefits for microgrids. Nash bargaining is used for effective and fair energy trading between IMMGs. Similarly, coalitional game theory optimises energy sharing and trading in smart households while also decreasing the total cost of microgrids. In non-cooperative game theory, the Nash equilibrium involves competition among purchasing microgrids for every microgrid with a diverse energy demand in the IMMG. It is generally applicable in situations where all microgrids in the network simultaneously share energy on an equal basis.

In contrast, the ADMM algorithm carries superior convergence properties while achieving an optimal power schedule and can be used for distributed microgrids. ADMM, like other strategies, was used by various studies to optimise power flow and real-time energy management.

6.2. Building Energy Management System

A BEMS uses a complex method to monitor and control the building energy usage. A BEMS may include controllers that read input parameters such as weather information, building insights, renewable system and other parameters to regulate the whole system to bring maximum efficiency. Decisions for efficiency are made based on energy consumption and cost factors. To ensure the integrity of BEMSs, FDD methods are also used to sense and isolate faults and to protect BEMSs from further damage or loss. FDD processes are usually categorised into model-based FDD, signal-based FDD, knowledge-based FDD, active FDD and hybrid FDD.

Presently, the control strategies such as on–off control, proportional integral derivative (PID) control and rule-based control, as stated in Hannan, Faisal [15], exhibit drawbacks in terms of stability. Therefore, a model-based control system in a BEMS is implemented in which control parameters of the building are processed mathematically. A model predictive control (MPC) approach for a BEMS was also studied and the three aspects of MPC identified were problem formulation, control architecture and implementation type.

IoE technology in BEMS controllers regulates bidirectional information and electricity flow. The IoE blends the characteristics of smart grid and the Internet of Things (IoT) [15]. The IoT has several real-life applications that require telemetric assistance, while a smart grid specifically provides bidirectional communication between BEMS and the grid, and also controls and monitors energy generation. Since the IoE establishes communication between these two aforementioned units, it also utilises information from the metering. The IoE has various control nodes and routers that can be used for network solutions. The possible system architecture of the IoE posits a control centre in the middle and other objects such as DRESs, sensors and storage are connected to the controlling object through the internet, which then makes decisions based on inputs and commands.

There are several challenges that are noteworthy with regard to BEMSs, including the unreliability of renewable system operation, internet security, scalability and cost. Monitoring data from the BEMS may have corrupted and be missing data values; thus, advanced deep learning techniques may be implemented to predict future estimated values. Similarly, security and privacy techniques such as blockchain in the EMS can be utilised to secure the network. Optimisation techniques for energy efficiency, energy storage materials, non-linear electronics interfaces and power quality issues are other future research directions to be explored [15].

6.3. Nanogrid Controllers

The topology for nanogrids uses a centralised controller [21], which receives values from sensors and performs actions for optimising the power. In the decentralised approach, nodes communicate to each other and operate independently from a centralised controller. The hybrid distributed control has combined characteristics of centralised and distributed control. The few control techniques for nanogrids mentioned in the studies are given below:

Ad hoc nanogrid: This is a type of distributed control is used where there is no access to a national power grid.

Cost function: Uses a central control and takes advantage of fluctuations in power grid prices for implementing the DSM.

Predictive control: A hybrid central control makes decisions based on historical information.

Flattening peak electricity demand: Assists to reduce the amount of power purchased from a power grid.

Droop control: A technique used for controlling the level of voltage on the demand and supply management sides.

Further, a nanogrid network can be used to connect multiple nanogrids to form a microgrid, creating a larger power system. The nanogrid focuses on the hierarchical approach to distribute power from the nanogrid to a microgrid to the utility grid. One of the advantages of this approach is that it can handle intermittent power outages. In addition, bidirectional power sharing balances the grid and the communication layer, making the network more secure, and it can collect statistics on power usage. These advantages lead to overall financial benefits and grid stability; however, the central control unit makes the system susceptible to failure and makes it dependent on high bandwidth communication architecture.

6.4. Building-Integrated Microgrids

The objective of the building-integrated microgrid control is to minimise operational costs while satisfying constraints such as grid reliability and equipment stability. The centralised control collects data from microgrid components and applies an optimisation algorithm to achieve optimal control decisions in the central unit. In distributed control, there is no central agent, and the optimisation algorithm is applied locally. Centralised control has good performance in small-scale microgrids, and the decentralised approach operates well for large-scale microgrids [25]. The control strategies of building microgrids and optimisation techniques given in [25] are summarised below.

Rule-based control: These are based on conditional commands, based on IF–THEN statements and are easy to implement because of simplicity in syntax. Applications of rule-based control given in [25] consist of a commercial building automation system and ESS-based microgrids. Rule-based control has the convenience of implementation without control; however, it does not perform effectively compared with advanced and intelligent control systems.

Optimal control and multi-objective optimisation: Control decisions in optimal control are made by resolving an optimisation issue and applying the optimal control outcome. Optimisation problems are solved within the framework of a large control scheme; for example, MPC. The objective of optimal control generally is to decrease the total operational cost of the microgrid. On the other hand, multi-objective optimisation is beneficial when there are two separate objectives: for instance, total cost and reduction in GHG emissions.

Decision variables: These variables imply parameters that can be referenced by a controller to make an operational decision. Examples include battery charging/discharging power, reactive power from DG, SOC, controllable loads and temperature baselines.

Agent-based control: This is a decentralised approach based on multiple agents that is worthwhile to implement in microgrid energy management. Moreover, it is useful in conditions where a fully formulated optimisation problem becomes unfeasibly difficult, or there is no knowledge of the full system model.

MPC: This widely used control strategy in microgrids depends totally on the system dynamic model. The model utilised is a linear dynamic model. MPC has the capability to forecast future events and perform on that information in the present.

Optimisation techniques were also covered by Fontenot and Dong [25], as given below.

Linear programming: In this optimisation technique, a linear objective function is minimised over a group of decision variables within a group of linear constraints. It is restricted to cost functions and constraints that are linear in the decision variables.

Non-linear programming: In this, neither constraints nor objective functions are linear in terms of decision variables. Non-linear programming can be significantly more complex to solve than linear programming, particularly if the objective function and constraints are non-convex.

Dynamic programming: The optimisation problem in dynamic programming is distributed into sub-problems in a recursive manner. In microgrids, where each system state depends on the former state, sub-problems may be resolved in reverse, commencing with the known state, until the initial (desired unknown) state is resolved.

Stochastic programming: This integrates random variables into optimisation problems so as to identify uncertainties in model data. For instance, stochastic programming can account for irregularities in load demand, DRES generation and energy costs.

Metaheuristics: Metaheuristics is a high-level method designed to discover processes that can lead to satisfactory results to optimisation issues. Metaheuristics are highly useful in situations when system information is not available, or where the solution set to a problem is unrealizably huge.

6.5. Advanced Controls for Energy Storage and EVs

The current literature has also focused on advanced control methods for enhancing building energy performance with battery storage and EVs. These advanced controls can be classified into individual and coordinated controls that emphasise the optimisation of a single building and multiple buildings, respectively.

In an individual control approach, the process of individual building energy storage or charging rates of EVs are optimised independently. After that, the individual energy storage or EV charging loads are aggregated to obtain the aggregated level of performance. However, this aggregated performance is not optimised. Different methods for optimisation such as an MPC approach, a mixed-integer non-linear programming algorithm and a multi-objective non-linear inversion-based control strategy were discussed for individual controls [18].

The coordinated control approach can further be categorised into bottom–up and top–down approaches. In a bottom–up approach, the optimisation of processes of individual energy storage and the individual EV charging rates are executed in sequential succession based on the aggregated results of the previously optimised energy storage or EVs. In a top–down approach, the optimisation objective encompasses aggregate level performance. To attain the acquired performance at the aggregated level, the operations of individual energy storage or the individual EV charging rates are coordinated.

Some of the methods mentioned in [18] for coordinated control include Deep Reinforcement (DR) Learning to learn the optimal behaviour via a trial and error-based method, collaborative DR control, an adaptive bi-level decision model, a two-stage adaptive robust optimisation-based collaborative operation approach, a coordinated charging method and the MPC method. One drawback of the coordinated approach is that computational complexity rises with the increasing quantity of energy storage devices or EVs.

6.6. Hybrid Systems Controllers

Investigation of the load interval curves illustrates that load levels remain intermediate normally for the greater part of the year. However, high peaks are encountered less often and survive for relatively short intervals. CCMs have advantages of handling short-interval high peaks; however, long duration peaks would require large storage systems, which are not economically viable [17]. In such cases, a combination of technologies (i.e., hybrid systems) can be preferred as they can meet community energy requirements at much lower costs than individual systems. Solutions of an exemplar hybrid system could be collated from these technologies based on system requirements: flywheels/super capacitors for high power, lead–acid/Li-ion batteries for stable power and energy, and flow batteries/hydrogen for energy storage. One downside of this method is that technical configurations and optimization processes for hybrid systems can be considerably more complicated than for a single-technology design.

Moreover, in a community setup, the CGC in [21] overviews grid operation, performs power and energy matching, stabilises and controls the amplitudes of different parameters and facilitates the interaction of prosumers and the utility operator in energy trading.

7. Energy Sharing: A Major Incentive for Community

Energy sharing inside the community or a cluster of buildings improves the self-consumption rate while mitigating electricity demand from the grid. To unlock the benefits of energy sharing, a specific energy-sharing solution is required for the transfer of the energy equivalent from one prosumer to another. Based on existing technology, this sharing is implemented mainly on AC networks; however, researchers also recommend sharing on DC microgrids in line with the large availability of DC-powered appliances [18]. In its simplest form, the basic configuration for energy sharing in a CCM connects to a number of buildings where surplus renewable energy or energy from a central storage is shared between buildings or communities that are low in demand and also exported to the main grid [13,14,19,22]. This process is often metered to maintain transactions and billing for incentivising prosumers [23]; other sharing configurations include embedded networks and BTM. The roof space for accommodating PV panels can belong to the owners' corporation, the owner or the construction developer. Based on these shared configurations, there are different forms of energy trading, most notably blockchain, tariff-based and energy leasing. Moreover, surplus PV energy can be shared using local energy trading, a basic form of peer-to-peer trading calculated via the reconciliation of total exported and grid-imported energy [23]. To amplify this community energy trading, it is desirable to have a graphical user interface platform for ease of use.

In a multi-owned building with a CCM, issues such as cost and benefit allocation might appear. Similarly, the capital cost of shared systems in a CCM could be complex because of its different distribution nature among consumers, building owners, utility companies and third-party companies.

Scaling up energy storage for multiple buildings or units increases value. For instance, in a multi-residential building or community where loads are usually asynchronous, shared storage capacity could be less than the sum of individual storages in the case where each user installs their own battery. The literature mainly considers active sharing; however, research should consider reactive power behaviour to improve system reliability. Moreover, energy management schemes can be highly suitable for energy sharing. The literature identified few projects with implemented energy trading between consumers; in the NEXT21 project, end-users are able to share and trade energy with each other [22].

In the solar to buildings (S2B) mobility model [18], surplus PV energy is shared between several buildings to reduce dependency on the main grid and efficiently utilise overall PV energy. The buildings in the S2B mobility model are connected to a central sharing microgrid that delivers the excessive PV energy from one building to other buildings with high consumption. This shared microgrid is also connected to the main grid in the case of insufficient PV generation. Research conducted by [18] reviewed extensions of the conventional S2B model to solar to buildings, vehicles and storage (S2VBS).

The adoption of EVs that rely on solar mobility models can also contribute effectively to reducing GHG emissions. The solar to vehicle functions through the concept of combining a standard grid-connected PV system with EVs. A local controller manages the energy flow between solar, grid and EV. In some instances, the integration of buildings and EV could work perfectly following a standard method. Electricity produced by rooftop PV panels primarily supplies the house loads and then charge the EV batteries. In the case of surplus generation, energy is exported to the grid. In models with building, storage and EVs, the EV batteries are allowed to feed electricity to the building or utility grid.

Further, plug-in hybrid electric vehicles (PHEVs) could minimise a building's total energy costs by scheduling and optimising the charging–discharging of batteries. In other examples, a retired EV battery (REVB) model was investigated on the basis of the fading capacity model of lithium battery, and a multi-objective algorithm non-dominated sorting genetic algorithm II (NSGA-II,) generated the Pareto set of optimal solutions. This developed NSGA-II method in a residential building indicated that a hybrid energy system with PV–hydrogen–REVB is a satisfactory way to display REVBs' residual capacities. In addition, a building-to-vehicle-to-building model enables the bidirectional exchange of electricity between EV batteries and buildings. In this model, the application of bidirectional EV charging and discharging enables PV energy sharing among a cluster of buildings. Such methods for energy sharing significantly improve PV power utilisation and brings financial and environmental benefits.

The metrics mainly used for evaluating the performance of a S2VBS model are environment, energy and economy. Energy performance is assessed using various parameters including loss of power supply possibility (LPSP) and potential energy waste possibility (PEWP). The LPSP assesses the possibility of whole energy system power loss among commonly used metrics. The PEWP evaluates the energy usage efficiency of the modelled renewable energy system. The capacity factor analyses PV power generation. The economic performance assessment of PV systems is carried out using the simplest economic indicator, which is cost of energy. Similarly, the net present value ascertains the investment profitability. Further, the payback period is another generally used indicator for economic analysis. The profitability index estimates the investment profitability by quantifying the amount created per unit of investment. Lastly, environmental performance is assessed using GHG emissions and carbon intensity.

Figure 4 presents a summarised illustration of CCM components, features and functionalities. Moreover, a list of CCM projects included in review articles is also included in Appendix D.

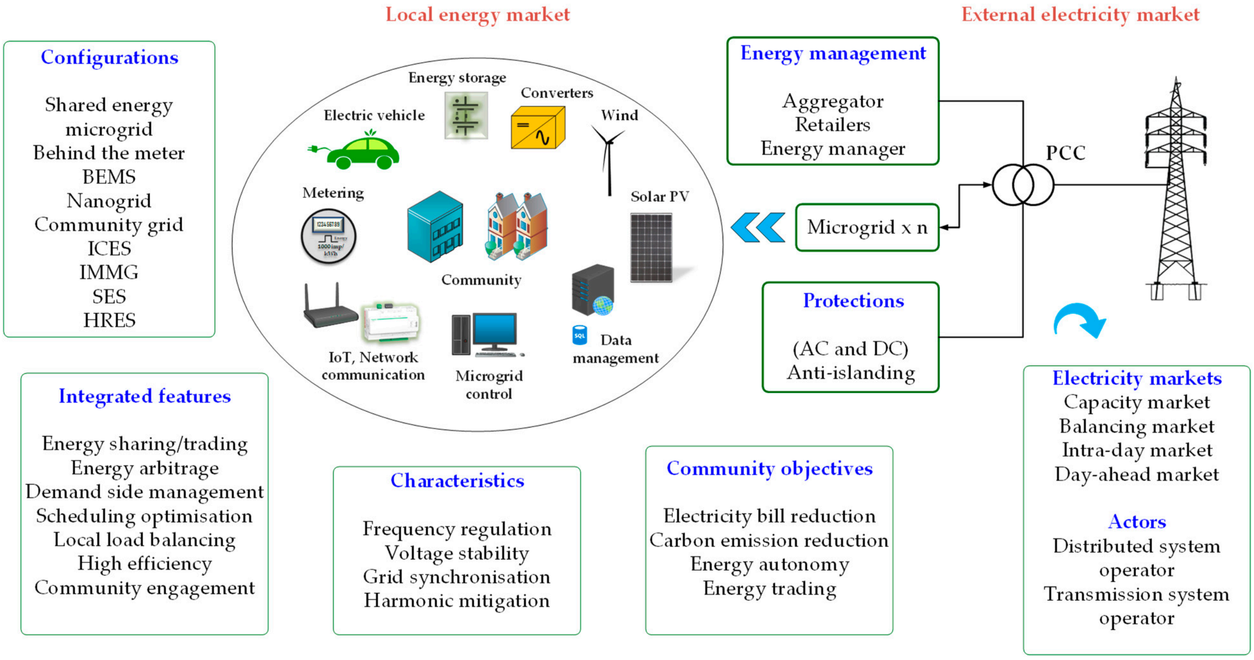

Figure 4. Features and functions of CCMs based on included studies.

8. Barriers and Opportunities

8.1. Regulatory Issues

Regulatory frameworks for CCMs necessitate a set of supportive rules and principles to address socio-techno-economic and institutional issues to pave the way for successful microgrid implementation. Most often, profitability from DRESs is highly dependent on regulatory frameworks of a particular dominion [23], coupled with consumer engagement [17,24]. Nevertheless, the major barrier in deployment of CCMs is incumbents supporting centralised systems. However, considering distributed systems beyond PCC, energy management between microgrids and DSOs becomes complex in line with the interconnectedness of individual microgrids, and synchronous operation with active/reactive power flows between microgrids, varying loads and grids [13]. Varying levels of power generation intermittency because of weather can be harmful for the network, owing to the inadequacy of monitoring, diagnosing and maintaining the system [15]. Moreover, the penetration of renewables in the grid causes voltage fluctuations and resonances [15,21]. Alongside these, the other main factors hindering the proliferation of community microgrids include high grid interconnection costs, additional protection requirements considering large PV integration, feed-in-tariffs and islanding issues [16,19,23]. Moreover, the shortage of public and/or private locations to install power units also presents challenges for community microgrids.

Actors in the energy market, including households, have diverse interests; for example, end-users expect low-cost efficient energy. Energy service providers benefit from energy-efficient operation and management of local generation. Meanwhile, aggregators envisage business models that optimise profits and flexibility in the capacity markets. Regulators, which generally include governments, transmission system operators (TSOs), DSOs and policymakers, seek to maintain a low-carbon, low-cost balance of supply and demand for consumers while also distributing energy to the residential network and grid [19].

In terms of development consent, installing PV storage systems in established jurisdictions requires permission from the state or the council and, in some cases, restrictions may apply due to shading from newly constructed buildings [23]. Similarly, for the purpose of revenue generation, the strata company or owners' corporation, which manage energy trading, are required to be registered as service providers/retailers. This entails a series of operational and cost restrictions that may discourage the adoption of DER, especially in multi-residential apartments [23].

To achieve an energy-efficient and sustainable system, price design is also pivotal for providing subsidies; ancillary services, and services-based markets such as capacity markets, balancing markets as well as day-ahead energy markets [19]. Community systems supported by DSOs are often restricted by regulators from operating DGs and ESSs to inhibit them from competing with independent generators in the wholesale electricity market [17,22]. Regulators want service providers to enter the capacity market while strata or owners consider a much cheaper and cleaner community solution [23].

From another perspective, the installation of an embedded system or shared energy microgrid [28,29] can affect the revenue stream for the network because the fee is charged for energy distributed at one connection point rather than several individual connections through large tariffs.

Similarly, on the policy side, incentives such as subsidies and feed-in tariffs can boost the uptake of renewables that may participate in ancillary services [17,22,23], whereas taxes and levies on CCMs conversely could affect installations [17,18,23]. In some instances, the lack of consumption data to implement optimised energy planning should not be overlooked [22].

Emphasis should be given to consolidate universal standards; for instance, in terms of technical rules, IEEE 1547 (DRES interconnection with the grid) is considered the gold standard for microgrids. Similarly, regulations are needed for DC microgrids. The existence of regulatory frameworks, and a good understanding of such, are essential for the effective commissioning of microgrids [16,19,22,23]. Global examples mentioned in [24] enjoy the full value proposition due to the absence of market and regulatory frameworks; however, techno-economic challenges remain. If grid support services are ensured, projects such as gridSMART in the US, which provides a distributed management controller and aggregated setup, could be a better model of utility scale community projects [17,25].

To unlock the full potential of microgrids, a shared learning platform should be practiced to coalesce community groups, policymakers and regulators and decipher the policies and regulatory frameworks that may help in overcoming the barriers [17,19,22].

8.2. Opportunities

One of the major advantages after installation of CCM is that it reinforces the economics in various ways. Imported grid electricity is reduced by the integration and utilisation of DRESs and due to this, there are always open opportunities for new businesses. If a grid is properly managed, it may result in incentives as well as cost savings which can be relayed to the level of consumers.

CCMs can facilitate a utility grid during peak demand. Advanced control methodologies discussed in Section 6 with the help of system monitoring can shave peak loads, reducing peak hour costs, and can also defer pricey maintenance and upgrades to transformers and distribution feeders. Aggregated power generation by CCMs could also support ancillary services, for instance, voltage and frequency regulation, which may further generate revenue possibilities.

CCMs can offer cheap electricity costs, a resilient microgrid and may also supply energy in emergency situations. Through highly resilient and highly reliable systems, energy-related businesses such as data centres and high-tech industries can be attracted.

9. Conclusions and Future Directions

This review presents a guideline and summary for the researchers on existing microgrids, configurations and technologies used and sets forth future recommendations helpful for policymakers and industries, who are laying the groundwork for commissioning CCMs. Notably, the rapid review methodology was applied to the research area of microgrids, which play a key role in the abatement of global GHG emissions and dependence of communities on utility grids—two burning issues of this decade.

Existing microgrids, either AC or DC, operate using a centralised approach (storage and control), which performs well for small microgrids. AC microgrids have numerous advantages at the PCC. Similarly, DC microgrids offer several benefits, especially for long-distance transmission and lower costs of controllers and metering. On the other hand, AC protection systems are more economical than DC protections. The existing protection schemes for microgrids are designed for a customised solution; more research is needed to design protection schemes for universal microgrid design. Since microgrids are becoming more advanced and complex, the performance of the centralised approach is increasingly unstable. Thus, there is a need for further exploration of the decentralised approach.

The intermittent and volatile characteristics of the DRES with dynamic loads in the CCM present new challenges in designing optimal control and scheduling techniques in power systems. Load demand and DRES selection in building intelligent microgrids vary across consumers and utilities; therefore, these bilateral requirements must be managed through the energy system. Further, optimisation techniques for resolving stochasticity, energy efficiency, storage materials, non-linear communication and power quality issues including reactive power flow are critical future research directions. In terms of energy trading, focus has been given to active trading and sharing; nevertheless, reactive power should also be considered an essential element of calculations for gaining overall stability.

For efficient load operation, optimisation methods such as online algorithms have importance in energy scheduling; these online algorithms should reduce computational complexity. IoE-based BEMSs offer energy savings and GHG reductions but pose several challenges, including internet security, scalability and cost. Moreover, missing data points, spurious values and discrepancies can interfere with the energy management process, particularly as concerns security and privacy. Central control systems (at the multibuilding scale) are a critical component of CCMs, providing maximum benefits to the grid, dwelling owners and consumers, whereas decentralised control offers “plug-and-play” performance. Intriguingly, nanogrid controllers may act as decentralised controllers, share energy and facilitate DSM techniques, and can also form a microgrid in an interconnected topology.

Designing and orchestrating storage technologies is a significant challenge in terms of economics and efficiencies; thus, future research should develop cost-effective highly efficient ESSs technologies [20]. Li-ion technology is expected to be a widely adopted battery technology for CCMs. For community setup, CES as a model can open new doors for the energy transition as community-scale microgrids will incorporate storage technologies such as batteries and increase awareness across users and communities regarding energy consumption and environmental aspects. Community batteries can essentially reduce capacity by half in comparison with individual battery systems, owing to the favourable impact of demand aggregation. Battery storages with HRESs for remote villages are a good choice on technical and economic grounds. Nevertheless, the existing models running on battery storage are expensive, and other forms of hybrid sources are required to fulfil at least 50% of the energy demand. It is also evident from implemented examples that DC microgrids are a gradually emerging technology and could be much more efficient than AC microgrids. However, the design of DC microgrids requires further exploration to develop advanced systems for large-scale deployment.

CCMs enable engagement between local communities by means of mutual purchasing, combined ownership arrangements and the integration of various sectors such as electricity, heating, cooling and gas. CCMs may significantly enhance future energy systems if there is an assurance of financial incentives and a consensus between different actors; notably, regulatory authorities, policymakers, government and community.

Notwithstanding, future research should incorporate advanced building coordinated controls and optimisation algorithms such as agent-based modelling and occupancy models in microgrids for optimising energy usage to obtain improved self-sufficiency and maximum economic gains.

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Nomenclature

AC	Alternating current
ADDM	Alternating direction method of multipliers
AMSTAR2	A Measurement Tool to Assess Systematic Reviews version 2
B2V	Building to vehicle
BEMS	Building energy management system
BTM	Behind the meter
CCM	Community connected microgrids
CES	Community energy storage
CGC	Community grid controller
COVID-19	Coronavirus disease 2019
CP	Common property
DC	Direct current
DD	Dual decomposition
DG	Distributed generators
DR	Deep Reinforcement
DRES	Distributed renewable energy systems
DSM	Demand-side management
DSO	Distributed system operator

EMS	Energy management system
ESS	Energy storage systems
EV	Electric vehicles
FDD	Fault detection and diagnosis
GHG	Greenhouse gas
HRES	Hybrid Renewable Energy Systems
HVDC	High voltage direct current
ICES	Integrated community energy systems
IEEE	Institute of Electrical and Electronic Engineers
IGBT	Insulated-gate bipolar transistors
IMMG	Interconnected multi-microgrids
IoE	Internet of Energy
IoT	Internet of Things
LC	Inductance–Capacitance
Li-ion	Lithium-ion
LPSP	Loss of power supply possibility
MPC	Model predictive control
NSGA-II	Non dominated sorting genetic algorithm II
NZEB	Net zero energy buildings
PCC	Point of common coupling
PEWP	Potential energy waste possibility
PHEV	Plug-in hybrid electric vehicles
PID	Proportional integral derivative
PRISMA	Preferred Reporting Items for Systematic reviews and Meta-Analyses
PV	Photovoltaic
REVB	Retired EV battery
RoB	Risk of bias
S2B	Solar to buildings
S2BVS	Solar to building, vehicle and storage
SEC	Smart energy community
SES	Smart energy systems
SLR	Systematic literature reviews
SOC	State of charge
STATCOMs	Static synchronous compensators
TSO	Transmission system operators
US	United States

Appendix A

Table A1. Search String and Filters Applied to the Academic Databases.

Database	Search String	Filters Applied
Scopus	TITLE-ABS-KEY(“solar” OR “solar PV” OR “PV” OR “solar*” OR “photovoltaic*” OR “microgrid” OR “microgrid*” OR “distributed*” OR “integrated”) AND TITLE-ABS-KEY(batter* OR battery OR storage OR “energy storage” OR “battery storage”) AND TITLE-ABS-KEY(“building*” OR “multi-residential” OR “apartment*” OR community OR “communit*” OR “dwelling*” OR “storey” OR “multi-family” OR “condos” OR “suite*” OR “villa*” OR “multi-unit”) AND TITLE-ABS-KEY(“systematic review” OR “systematic literature review” OR review OR “meta analysis” OR “meta-analysis”))	AND DOCTYPE(re) AND PUBYEAR > 2009 AND PUBYEAR < 2021 AND (LIMIT-TO (SUBJAREA,”ENER”) OR LIMIT-TO (SUBJAREA,”ENGI”) OR LIMIT-TO (SUBJAREA,”MULT”)) AND (LIMIT-TO (EXACTSRCTITLE,”Renewable And Sustainable Energy Reviews”) OR LIMIT-TO (EXACTSRCTITLE,”Applied Energy”) OR LIMIT-TO (EXACTSRCTITLE,”Energy And Buildings”) OR LIMIT-TO (EXACTSRCTITLE,”Renewable Energy”) OR LIMIT-TO (EXACTSRCTITLE,”Energies”) OR LIMIT-TO (EXACTSRCTITLE,”Energy”) OR LIMIT-TO (EXACTSRCTITLE,”Energy Conversion And Management”) OR LIMIT-TO (EXACTSRCTITLE,”International Journal Of Energy Research”) OR LIMIT-TO (EXACTSRCTITLE,”Journal Of Energy Storage”) OR LIMIT-TO (EXACTSRCTITLE,”Solar Energy”) OR LIMIT-TO (EXACTSRCTITLE,”Sustainability Switzerland”) OR LIMIT-TO (EXACTSRCTITLE,”Sustainable Cities And Society”) OR LIMIT-TO (EXACTSRCTITLE,”Building And Environment”) OR LIMIT-TO (EXACTSRCTITLE,”Journal Of Power Sources”) OR LIMIT-TO (EXACTSRCTITLE,”Wiley Interdisciplinary Reviews Energy And Environment”) OR LIMIT-TO (EXACTSRCTITLE,”Advances In Building Energy Research”) OR LIMIT-TO (EXACTSRCTITLE,”Building Simulation”) OR LIMIT-TO (EXACTSRCTITLE,”Buildings”) OR LIMIT-TO (EXACTSRCTITLE,”Electronics Switzerland”) OR LIMIT-TO (EXACTSRCTITLE,”Energy And Environment”) OR LIMIT-TO (EXACTSRCTITLE,”Energy And Environmental Science”) OR LIMIT-TO (EXACTSRCTITLE,”International Journal Of Electrical Power And Energy Systems”) OR LIMIT-TO (EXACTSRCTITLE,”International Journal Of Low Carbon Technologies”) OR LIMIT-TO (EXACTSRCTITLE,”Journal Of Cleaner Production”)) AND (LIMIT-TO (EXACTKEYWORD,”Solar Energy”) OR LIMIT-TO (EXACTKEYWORD,”Energy Storage”) OR LIMIT-TO (EXACTKEYWORD,”Energy Efficiency”) OR LIMIT-TO (EXACTKEYWORD,”Energy Utilization”) OR LIMIT-TO (EXACTKEYWORD,”Renewable Energy Resources”) OR LIMIT-TO (EXACTKEYWORD,”Building”) OR LIMIT-TO (EXACTKEYWORD,”Solar Power Generation”) OR LIMIT-TO (EXACTKEYWORD,”Sustainable Development”) OR LIMIT-TO (EXACTKEYWORD,”Energy Conservation”) OR LIMIT-TO (EXACTKEYWORD,”Renewable Energies”) OR LIMIT-TO (EXACTKEYWORD,”Renewable Energy Source”) OR LIMIT-TO (EXACTKEYWORD,”Energy Management”) OR LIMIT-TO (EXACTKEYWORD,”Renewable Energy”) OR LIMIT-TO (EXACTKEYWORD,”Smart Power Grids”) OR LIMIT-TO (EXACTKEYWORD,”Solar Power”) OR LIMIT-TO (EXACTKEYWORD,”Performance Assessment”) OR LIMIT-TO (EXACTKEYWORD,”Solar Buildings”) OR LIMIT-TO(EXACTKEYWORD,”Energy Storage Systems”) OR LIMIT-TO (EXACTKEYWORD,”Optimization”) OR LIMIT-TO (EXACTKEYWORD,”Photovoltaic System”) OR LIMIT-TO (EXACTKEYWORD,”Smart Grid”) OR LIMIT-TO (EXACTKEYWORD,”Literature Reviews”)

Table A1. *Cont.*

Database	Search String	Filters Applied
		OR LIMIT-TO(EXACTKEYWORD,”Renewable Energy Systems”) OR LIMIT-TO (EXACTKEYWORD,”Renewable Resource”) OR LIMIT-TO (EXACTKEYWORD,”Demand-side Management”) OR LIMIT-TO (EXACTKEYWORD,”Electricity Generation”) OR LIMIT-TO (EXACTKEYWORD,”Review”) OR LIMIT-TO (EXACTKEYWORD,”Reviews”) OR LIMIT-TO (EXACTKEYWORD,”Storage”) OR LIMIT-TO (EXACTKEYWORD,”Sustainability”) OR LIMIT-TO (EXACTKEYWORD,”Building Applications”) OR LIMIT-TO (EXACTKEYWORD,”Demand Analysis”) OR LIMIT-TO (EXACTKEYWORD,”Demand Response”) OR LIMIT-TO (EXACTKEYWORD,”Energy”) OR LIMIT-TO (EXACTKEYWORD,”Intelligent Buildings”) OR LIMIT-TO (EXACTKEYWORD,”Power Generation”) OR LIMIT-TO (EXACTKEYWORD,”Electric Batteries”) OR LIMIT-TO (EXACTKEYWORD,”In-buildings”) OR LIMIT-TO (EXACTKEYWORD,”Micro Grid”) OR LIMIT-TO (EXACTKEYWORD,”Photovoltaic”) OR LIMIT-TO (EXACTKEYWORD,”Photovoltaic Systems”) OR LIMIT-TO (EXACTKEYWORD,”Renewable Energy Generation”) OR LIMIT-TO (EXACTKEYWORD,”Residential Building”) OR LIMIT-TO (EXACTKEYWORD,”Use Of Renewable Energies”) OR LIMIT-TO (EXACTKEYWORD,”Zero Energy Buildings”) OR LIMIT-TO (EXACTKEYWORD,”Battery Storage”) OR LIMIT-TO (EXACTKEYWORD,”Building Energy Consumption”) OR LIMIT-TO (EXACTKEYWORD,”Community Energy”) OR LIMIT-TO (EXACTKEYWORD,”Design Method”) OR LIMIT-TO (EXACTKEYWORD,”District Energy Systems”))
Web of Science	((TOPIC: ((((((((”solar” OR “solar PV”) OR “PV”) OR “solar*”) OR “photovoltaic*”) OR “microgrid”) OR “microgrid*”) OR “distributed*”) OR “integrated”) AND TOPIC: ((((batter* OR battery) OR storage) OR “energy storage”) OR “battery storage”)) AND TOPIC: (((((((((((”building*” OR “multi-residential”) OR “apartment*”) OR community) OR “communit*”) OR “dwelling*”) OR “storey”) OR “multi-family”) OR “condom”) OR “suite*”) OR “villa*”) OR “multi-unit”)) AND TOPIC: ((((”systematic review” OR “systematic literature review”) OR review) OR “meta analysis”) OR “meta-analysis”))	Refined by: WEB OF SCIENCE CATEGORIES: (GREEN SUSTAINABLE SCIENCE TECHNOLOGY OR ENGINEERING ELECTRICAL ELECTRONIC OR MANAGEMENT OR AUTOMATION CONTROL SYSTEMS OR ENGINEERING ENVIRONMENTAL OR ENGINEERING MULTIDISCIPLINARY OR ENVIRONMENTAL STUDIES OR MULTIDISCIPLINARY SCIENCES OR EDUCATION EDUCATIONAL RESEARCH OR EDUCATION SCIENTIFIC DISCIPLINES OR ENGINEERING MANUFACTURING) AND DOCUMENT TYPES: (REVIEW) AND SOURCE TITLES: (RENEWABLE SUSTAINABLE ENERGY REVIEWS OR RENEWABLE ENERGY OR CLEAN TECHNOLOGIES AND ENVIRONMENTAL POLICY OR JOURNAL OF MODERN POWER SYSTEMS AND CLEAN ENERGY OR SUSTAINABLE CITIES AND SOCIETY OR SUSTAINABILITY OR CSEE JOURNAL OF POWER AND ENERGY SYSTEMS OR JOURNAL OF CLEANER PRODUCTION OR CURRENT OPINION IN GREEN AND SUSTAINABLE CHEMISTRY OR ENERGY EDUCATION SCIENCE AND TECHNOLOGY PART A ENERGY SCIENCE AND RESEARCH OR BUILDING AND ENVIRONMENT OR ENVIRONMENTAL PROGRESS SUSTAINABLE ENERGY OR IET GENERATION TRANSMISSION DISTRIBUTION OR IEEE ACCESS OR ADVANCED SUSTAINABLE SYSTEMS OR INTERNATIONAL JOURNAL OF ELECTRICAL POWER ENERGY SYSTEMS OR SMART SCIENCE OR INTERNATIONAL JOURNAL OF PRECISION ENGINEERING AND MANUFACTURING GREEN TECHNOLOGY OR INTERNATIONAL JOURNAL OF RENEWABLE ENERGY DEVELOPMENT IJRED) Timespan: 2010-2020. Indexes: SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH, BKCI-S, BKCI-SSH, ESCI, CCR-EXPANDED, IC.

Table A1. *Cont.*

Database	Search String	Filters Applied
ProQuest	(“solar” OR “solar PV” OR “PV” OR “solar*” OR “photovoltaic*” OR “microgrid” OR “microgrid*” OR “distributed*” OR “integrated”) AND (batter* OR battery OR storage OR “energy storage” OR “battery storage”) AND (“building*” OR “multi-residential” OR “apartment*” OR community OR “communit*” OR “dwelling*” OR “storey” OR “multi-family” OR “condos” OR “suite*” OR “villa*” OR “multi-unit”) AND (“systematic review” OR “systematic literature review” OR review OR “meta analysis” OR “meta-analysis”)	AND stype.exact(“Conference Papers & Proceedings” OR “Reports” OR “Working Papers” OR “Scholarly Journals”) AND at.exact(“Literature Review” OR “Review”) AND la.exact(“English” OR “English”) AND (pub.exact(“Energy, Sustainability and Society” OR “Clean Technologies and Environmental Policy” OR “Sustainability” OR “Journal of Modern Power Systems and Clean Energy” OR “Frontiers in Energy” OR “Sustainability Science” OR “Current Sustainable/Renewable Energy Reports” OR “Energies” OR “European Journal of Information Systems”) AND at.exact(“Literature Review”) AND subt.exact(“literature reviews” OR “reviews” OR “sustainability” OR “systematic review” OR “energy” OR “energy storage” OR “sustainable development” OR “optimization” OR “renewable energy” OR “technology”) AND la.exact(“ENG”) AND pd(20100101-20201027) AND PEER(yes))
IEEE	(“All Metadata”:”solar” OR “solar PV” OR “PV” OR “solar*” OR “photovoltaic*” OR “microgrid” OR “microgrid*” OR “distributed*” OR “integrated”) AND “All Metadata”: batter* OR battery OR storage OR “energy storage” OR “battery storage”) AND “All Metadata”:”building*” OR “multi-residential” OR “apartment*” OR community OR “communit*” OR “dwelling*” OR “storey” OR “multi-family” OR “condos” OR “suite*” OR “villa*” OR “multi-unit”) AND “All Metadata”:”systematic review” OR “systematic literature review” OR review OR “meta analysis” OR “meta-analysis”)	Filters Applied: JournalsIEEE AccessProceedings of the IEEEIEEE Communications Surveys & TutorialsEngineering & TechnologyIEEE Transactions on Industry ApplicationsIEEE Transactions on Power ElectronicsIEEE Transactions on Industrial ElectronicsDesign Issuesreviewsdata analysispower gridsdistributed power generationpower convertors2010–2020

Appendix B

Table A2. AMSTAR2 Assessment Checklist.

Questions	Decision Rules and Comments
Question 1. Have reviewers clearly described research questions and inclusion criteria?	1 = yes = components of PICO (Population, Intervention, Comparator group, and Outcome).
	0.5 = unsure/moderately = undecided between yes and no, drawing on the information given in the review.
	0 = no = no such information explicitly given.
Question 2. Did the article explicitly state about design of review methods before it was initiated and did the article vindicate any variation from the protocol?	1 = yes = protocol was written by the authors that consisted of ALL of the following: search technique, review question, inclusion/exclusion method, RoB evaluation.
	0.5 = unsure/moderately = protocol was written by the authors that consisted of ALL of the following: search technique, review question, inclusion/exclusion method, RoB evaluation.
	0 = no = not included any systematic review design.
Question 3. Did the review authors elucidate their study selection?	1 = yes = reasons of the study selection provided in the review.
	0.5 = unsure/moderately = multiple online sources or single online source. Undecided between yes and no, drawing on the information given in the article.
	0 = no = just a single online source OR no search additionally conducted.
Question 4. Was literature search technique applied by the review authors?	1 = yes = searched minimally 2 databases, keyword and/or search technique included, applied filtered on, e.g., language, country AND checked the references/bibliography, searched for grey literature, searched under 24 months of review completion.
	0.5 = unsure/moderately = searched at least 2 databases, keyword and/or search technique included, applied filtered on, e.g., language, country.
	0 = no = no relevant information given.
Question 5. Had authors independently carry out study selection?	1 = yes = any of these: minimum of two reviewers independently agreed on the selection of articles and decided on which articles to incorporate OR two authors chosen a specimen of article and accomplished at least 80% consensus, with the rest chosen by another author.
	0.5 = unsure/moderately = undecided between yes and no, drawing on the data given in the article.
	0 = no = exclusively one author performed study selection or no details of authors' participation in study selection.
Question 6. Had authors independently carry out data extraction?	1 = yes = any of these: minimum of two reviewers agreed to extract data from the articles OR two authors performed data extraction from articles and accomplished at least 80% consensus, with the rest chosen by another author.
	0.5 = unsure/moderately = undecided between yes and no, drawing on the data given in the article.
	0 = no = one author selected the articles or no details of authors' participation in extracting the data.
Question 7. Had authors provided details of the excluded articles and reasons for excluding the article?	1 = yes = presented details of all potentially excluded articles from the review AND for each article, provided reasons for article exclusion.
	0.5 = unsure/moderately = provided details of all excluded studies from the review but for each study, did not provide reasons for excluding articles from the review. 0 = no = no list of excluded studies.
Question 8. Had authors delineate the embedded articles sufficiently?	1 = yes = components of PICO (Population, Intervention, Comparator group, and Outcome).
	0.5 = unsure/moderately = components of PICO (Population, Intervention, Comparator group, and Outcome) concisely explained, or with little information. Undecided between yes and no, drawing on the data given in the article.
	0 = no = no, or incomplete details of the included articles.

Table A2. *Cont.*

Questions	Decision Rules and Comments
Question 9. Had authors employ an acceptable technique for assessing the RoB in articles incorporated in the review?	1 = yes = RoB assessment was explicitly mentioned in the included articles.
	0.5 = unsure/moderately = undecided between yes and no, drawing on the data given in the articles. RoB referred OR not adequately analysed (e.g., more than one source of bias was found; however, not all were analysed).
	0 = no = RoB assessment was not mentioned in included articles.
Question 10. Had authors provided the information on funding source for the articles?	1 = yes = provided information on funding sources for individual articles.
	0.5 = unsure/moderately = funding sources given for articles included in the review, or provided details on few articles. Undecided between yes and no, drawing on the data given in the article.
	0 = no = no description on the funding sources for individual articles.
Question 11. Had authors provided suitable methods for statistical combination of results, If meta-analysis was performed?	1 = yes = the authors provided reasons for integrating the data using meta-analysis AND employed a suitable method to collate outcomes and amended any heterogeneity AND researched the reasons of any diversity or amended any heterogeneity or contradiction.
	0.5 = unsure/moderately = conditions for yes only moderately completed. Undecided between yes and no, drawing on the data given in the article.
	0 = no = no clarification of meta-analysis or improper statistical techniques were employed for quantitatively collating and data analysis, moreover heterogeneity was not analysed.
	N/A = not applicable = meta-analysis was not performed.
Question 12. Had authors evaluate the probable effects of RoB in individual articles on the meta-analysis results If meta-analysis was performed?	1 = yes = selected only low RoB studies.
	0.5 = unsure/moderately = undecided between yes and no, drawing on the information given in the article.
	0 = no = the probable effect of RoB not assessed.
	N/A = not applicable = meta-analysis was not performed.
Question 13. Had authors elucidated RoB in individual articles when explaining the review results?	1 = yes = merely low RoB articles were included OR potential impact of RoB on the results were discussed.
	0.5 = unsure/moderately = undecided between yes and no, drawing on the data given in the article.
	0 = no = no clarification of the likely effect of RoB in individual articles.
Question 14. For any heterogeneity noticed in the results, did authors provide a discussion or satisfactory interpretation?	1 = yes = heterogeneity in the results had no potential OR in the case heterogeneity was found, the reviewers investigated those sources and explained the effect on the results.
	0.5 = unsure/moderately = undecided between yes and no, drawing on the data given in the article.
	0 = no = no elaboration or explanation of heterogeneity.
Question 15. Had authors conduct sufficient investigation of article bias and explained its potential effects on the results If performed quantitative analysis was performed?	1 = yes = the authors performed statistical or graphical experiments for publication bias and explained the prospects and extent of effects of publication bias.
	0.5 = unsure/moderately = multiple online sources without additional sources OR a single online source and one additional source. Undecided between yes and no, drawing on the data given in the article.
	0 = no = tests for publication bias was not performed and neither potential impact of publication bias was explained.
	N/A = not applicable = meta-analysis was not performed.
Question 16. Had authors mention any likely root of conflict of interest, including any funding they received for performing the review?	1 = yes = no competing interests were reported by the authors OR the reviewers declared their sources of funding and how the authors arranged probable conflicts of interest.
	0.5 = unsure/moderately = undecided between yes and no, drawing on the data given in the article.
	0 = no = statement on competing interests and sources of funding were not provided, neither how authors arranged probable conflicts of interest.

Appendix C

Table A3. Summary of Key Findings from Reviewed Articles.

Author	Key Findings	Recommendations
Zou, Mao [13]	• IMMGs generate better results in distributed architecture, along with energy trading facilitation within adjacent microgrids whilst mitigating transmission losses. Consequently, the grid operates under less stress conditions. • Depending upon locality, IMMGs can work both in islanded or grid-connected mode.	• Optimal scheduling techniques are challenging due to the intermittent characteristics of DRESs alongside dynamic loads in the microgrids. • IMMGs should handle varying load characteristics from the consumers' and utilities' end. • Reactive power besides active power should also be considered in optimization scheduling techniques to enhance the robustness and reliability of the power system.
Burmester, Rayudu [14]	• Nanogrids operate on a reduced capacity than conventional microgrids; nevertheless, several nanogrids can be coupled through gateway controllers to form a large microgrid. • They facilitate energy trading between consumers/prosumers and various nanogrids. • DC nanogrids have an edge over AC microgrids in terms of efficiency due to less power conversion steps. DC nanogrids can be highly adaptable since the majority of electronic appliances are DC powered.	• More demonstrational projects are required to test nanogrids to understand consumer centric incentives. Moreover, nanogrid research may help energy retailers to strategize demand-side management.
Hannan, Faisal [15]	• Key technologies used in IoE-based BEMSs are energy routers, battery storage and plug-and-play interfaces. • Low energy efficiency, environment, storage materials and power quality are major issues in commissioning of IoE-based BEMSs. • Significant energy savings and GHG emission reduction can be achieved from an IoE-based BEMS.	• IoE-based BEMSs require scalable, stable, and localized systems for the future improvement of building energy utilization. • An efficient BEMS also demands an advanced system for processing large amounts of data and the maintenance of privacy. • An IoE-based BEMS has significant potential for future development depending on the integration of cost-effective and energy-efficient DRESs.
Planas, Andreu [16]	• The AC microgrids provide better protection at PCC whilst they are more economical than DC protections. • DC microgrids provide low-cost metering and better power quality considering long-distance transmission. • For decreasing installation costs, AC microgrids are economical for big loads (e.g., industries and power plants) whilst DC microgrids work better for locations with more DC loads (e.g., offices).	• At present, small microgrids are designed with centralized control. However, as technology progresses, the new systems are getting more complex; therefore, a centralized approach may cause instability. Research is required to investigate decentralize options. Existing protection schemes are modelled for a customized system design; therefore, universal protection schemes for microgrids should be introduced.

Table A3. *Cont.*

Author	Key Findings	Recommendations
Parra, Swierczynski [17]	• Energy efficiency characteristics such as self-consumption, electricity demand load shifting and management are key drivers of CES rollout. • PV generation produces more economic value than demand load shifting due to the difference in retail and wholesale electricity tariffs. • The successful implementation of CES also ensures absolute energy management, incentive-based community engagement, community rights over grid ownership and a stable policy framework.	• For a significant role in future energy systems, interaction among different actors, authorities and governments are required. The adoption of CES may also be escalated by the provision of economic incentives and improved regulatory frameworks formed by policymakers. • Battery technology is still expensive; therefore, CES should rely on energy-efficient technology.
Huang, Zhang [18]	• With the integrated operation of shared microgrids, PV, ESSs, EVs and design of advanced controls, S2BVS mobility models can provide optimal performance including increased self-consumption and energy autonomy. Moreover, energy sharing is a key characteristic of the S2BVS model, which can exploited by employing the better coordination of buildings, storage and vehicles.	• The existing methods seldom incorporate EV control in building energy management. This includes the charging/discharging of EV batteries. Future studies are required to design advance control for integrating EVs with electrical storage. • Advanced DC systems for large scale systems are needed in future research. • Buildings clusters must be well designed to capitalize the full potential of energy sharing.
Koirala, Koliou [19]	• ICESs leverage advanced community engagement with autonomous energy, power reliability and security. Moreover, using the interconnection, they also enable network services and operating reserves. • ICESs influence various actors as they interact with different systems. Therefore, policies need to be designed in agreement with all stakeholders for equal distribution of costs and incentives.	• Challenges in centralized energy systems (socio-economic, technical, environmental and institutional) should be overcome. Therefore, well-designed business models, institutional factors and regulatory frameworks are required before the integration of ICESs. • Using different demonstrational projects, quantitative assessment using empirical data is recommended to increase the adaption of ICESs.
Neves, Silva [20]	• The standard configuration of hybrid systems in islands and remote communities is wind/photovoltaic/DPP and photovoltaic/PDG coupled with battery storage in villages. • For island applications, the design of an ESS is a big challenge from economics and efficiencies perspectives.	• Accurate facts and figures are required for demand estimation and power security. • System optimisation requires design methodology and tools considering real investments projections. • Renewable autonomy of 50% will be hard to achieve, unless storage technology is standardised for HRESs.
Rosado and Khadem [21]	• Much higher DRES penetration will be required in future community grids. This penetration can be enabled by coordinated microgrid operation, energy storage to mitigate DRES intermittency, microgrid protection and the usage of sophisticated controllers. • Impactful communication between the community grid controller and distribution network is important for neutralizing the disturbance from the distribution network.	• Advanced protections systems need improved communication interfaces with new functionalities such as grid parameters detection and synchronization.

Table A3. *Cont.*

Author	Key Findings	Recommendations
Ceglia, Esposito [22]	• The community considers the collective interest by prioritizing the location of resources confined to a specific location and also keeping a socio-technical network. • Generally, the DRES for energy production at a particular region is not shared with the population. Therefore, in the SEC modelling strategy, community acceptance is a major problem to address. • The absence of appropriate energy laws may result in consumer dissatisfaction.	• Future studies should evaluate and focus on the legislative context of energy communities' experimental proposals from various geographical and economic perspectives. • Energy community design can achieve a grid of communities which may improve the energy market management and environmental benefits of a particular jurisdiction.
Roberts, Bruce [23]	• PV installation in apartments needs considerable coordination between prosumers and actors to share cost incentives from BTM or embedded network configurations. • Despite regulatory, governance and financial barriers, practical models for multi-residential apartments exist; however, a shared consortium can aid prosumers in determining feasible opportunities.	• Generally, communities have unanimity over joint decisions; other actors and policymaking bodies should also line up with communities' interest. • A dearth of energy data in apartments is still an obstacle to discern the PV installations. From the regulatory point of view, data availability could be essential in the decision-making process.
Olgyay, Coan [24]	• An efficient and reliable grid-connected system with PV with an ESS generating low GHG emissions can be obtained using CCs. • CCs can achieve high reliability, reduce the capacity requirements and provide various value streams in energy bill reduction and cost savings.	• The diversity in building type and load with DRESs will facilitate multiple value streams. • Shared resources (e.g., shared PV and energy storage) connected to multiple buildings could possibly offer improved lifecycle costs than single dwelling due to low maintenance costs and high resource utilization.
Fontenot and Dong [25]	• Due to the intermittency of DRESs and consumer occupancy behavior scheduling, the optimization of a microgrid becomes complex. • The complexity of a given model ensures the accuracy while it also increases computational load. Moreover, smart meter data have consumer privacy and microgrid security issues.	• Rigid optimization strategies will become imperative as design models of microgrids are becoming complex. Agent-based modeling, occupancy models and integration of building-to-grid systems need to be integrated in microgrid.

Appendix D

Table A4. List of Community Microgrid Projects across the Globe.

Project	Country	System	Description
Seasons at Ontario	United States	140 kW solar PV on rooftop of 80 unit multi-family buildings. PV generation is allocated to the common areas and benefits are shared between the building owner and tenants.	A near-zero-energy building was demonstrated that integrates solar PV with the motivation to decrease energy costs and operational expenses by increasing energy efficiency and demand response strategies.
Lancaster Virtual Power Plant	United States	10 MW PV and 5 MW energy storage fitted on schools, homes and other facilities. The expanded construction development would install a 125 kW/500 kWh flywheel system fucntioning as a virtual power plant.	A virtual power plant which aims to optimise DRESs to obtain reveneue generation, increase cost savings, and acheive grid stability.
Peña Station NEXT	United States	A microgrid with 1 MW PV, 2 MWh battery; 1.6 MW DC grid-connected solar carport system installed in a 100-building mixed-use community built on 382 acre land. The microgrid enables multiple stakeholders to share the assets and the incentives from PV-BESS.	The installed microgrid improves system stability by offering frequency and voltage regulation, whilst energy storage and demand response decreases existing grid infrastructural costs.
Reynolds Landing	United States	800 kW PV, 600 kWh battery microgrid instlaled on 62 single-family dwellings.	A microgrid with the help of controller, home energy management system and DRESs provides grid service and efficient performance for customers.
FortZED project	United States	4 MW PV, combined heat and power and conventional generators installed in a mixed-use community on 2 square miles of land; includes several stakeholders.	A central controller virtually connects the building automation system and DRESs that establishes communication between the distributed generators and building automation.
Isle au Haut	United States	250 kW solar PV array, 1000 kWh battery storage; diesel generator and thermal storage capability installed in an island.	Project incorporates a blockchain-based energy network supported by a metering system.
Alkimos Beach	Australia	250 kW PV and 1.1 MWh battery storage installed on more than 100 residential homes.	The retail model demostrates that the integration of DRESs with digital technologies give benefits to consumers, energy retailers, housing developers and network operators.
gridSMART project	United States	25 kW PV and 25 kWh Li-ion battery storage as well as 1 MW PV with 6 MWh sodium sulphur battery installed on a 150 square mile area.	Alongside DRESs, the microgrid incorporates different components such as community battery, reactive control and metering, which will be integrated with data centre, demand response, dynamic pricing as well as plug-in hybrid vehicles.
Kelsterbach	Germany	50 kW and 135 kWh Li-ion battery storage installed on individual houses.	The microgrid increases self-consumption and optimises combined heat and power storage.

Table A4. *Cont.*

Project	Country	System	Description
CES for Grid Support	United States	25 kW PV and 50 kWh Li-ion battery storage installed on 20 units of individual houses.	The project showcases a microgrid with peak shaving capability, as well as voltage support and remote monitoring when integrated to the grid.
Feldheim	Germany	81.1 MW wind, 2.25 MWp solar and a 500 kWe/500 kWt biomass plant for district heating and storage; battery storage of 10 MWh built for providing frequency control services to a TSO and powers up to 37 households.	The system meets all of its local load demand and sends the remaining generation back to the grid.
NEXT21	Japan	100 kW combined heat and power based on fuel cells installed in 18 households.	The project demonstrates energy sharing and trading between consumers.
Smart Energy City	Japan	27,000 kW PV and 2000 EVs installed in 4000 smart houses with A home energy management system.	This community microgrid supplies residential demand through DRESs and meets 80% of the net load demand.
Wiltshire Wildlife Community Energy	Switzerland	Ground mounted 1 MW and 9.1 MW PV system powering approximately 500 houses.	The project promotes sustainability by introducing DRESs in the microgrid.
Sifnos Island Cooperative	Greece	2 MW PV and 6.9 MW wind farm.	By utilising DRESs, the project demostrates an autonomous renewable system and sustainable future for the energy community.
The Leaf Community Project	Italy	The system inlcudes 5 PV systems, two mini-hydroelectric plants, a ground source heat pump, condensing boiler, fuel cell storage, and EVs.	This project involved a wide community of engineers, scholars and public managers whilst aiming to achieve sustainability and social responsibility objectives.
Kalbarri Microgrid	Australia	1.6 MW supplied by wind farm, 1 MW from rooftop PV panels whilst 3.5 MW will be supplied by battery storage (capacity of 4.5 MWh).	One of Australia's biggest microgrids installed in the coastal town of Kalbarri which operates entirely in renewable mode, drawing energy from wind farm and residential PV panels.
Plico Project	Australia	Nanogrids and microgrids for 250+ homes with 6.6 kW PV and 7.2 kWh battery storage systems.	On reaching 1000 households, the virtual power plant will be able to provide 6.5 MW peak solar, 9.6 GWh/year and mitigate 7 kilo tones of GHG emissions every year.

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Appendix A

Co-authors’ statements of contributions

As a first author Moiz Masood Syed, contributed to the publication:

Performance of a shared solar and battery storage system in an Australian apartment building

Contribution components include:

Conceptualization, methodology, software, validation, Formal analysis, Investigation, data curation and analysis, writing—original draft preparation, writing—review and editing, visualization.

Signature of Candidate: **Date:** 28/04/2021

I, as a co-author, endorse that the level of contribution by the candidate indicated above is appropriate.

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As a first author Moiz Masood Syed, contributed to the publication:

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

Contribution components include:

Conceptualization, methodology, software, validation, Formal analysis, Investigation, data curation and analysis, writing—original draft preparation, writing—review and editing, visualization.

Signature of Candidate: **Date:** 28/04/2021

I, as a co-author, endorse that the level of contribution by the candidate indicated above is appropriate.

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As a first author Moiz Masood Syed, contributed to the publication:

Energy Allocation Strategies for Common Property Load Connected to Shared Solar and Battery Storage Systems in Strata Apartments

Contribution components include:

Conceptualization, methodology, software, validation, Formal analysis, Investigation, data curation and analysis, writing—original draft preparation, writing—review and editing, visualization.

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As a first author Moiz Masood Syed, contributed to the publication:

A rapid review on community connected microgrids

Contribution components include:

Conceptualization, methodology, software, validation, Formal analysis, Investigation, data curation and analysis, writing—original draft preparation, writing—review and editing, visualization.

Signature of Candidate: **Date:** 12/05/2021

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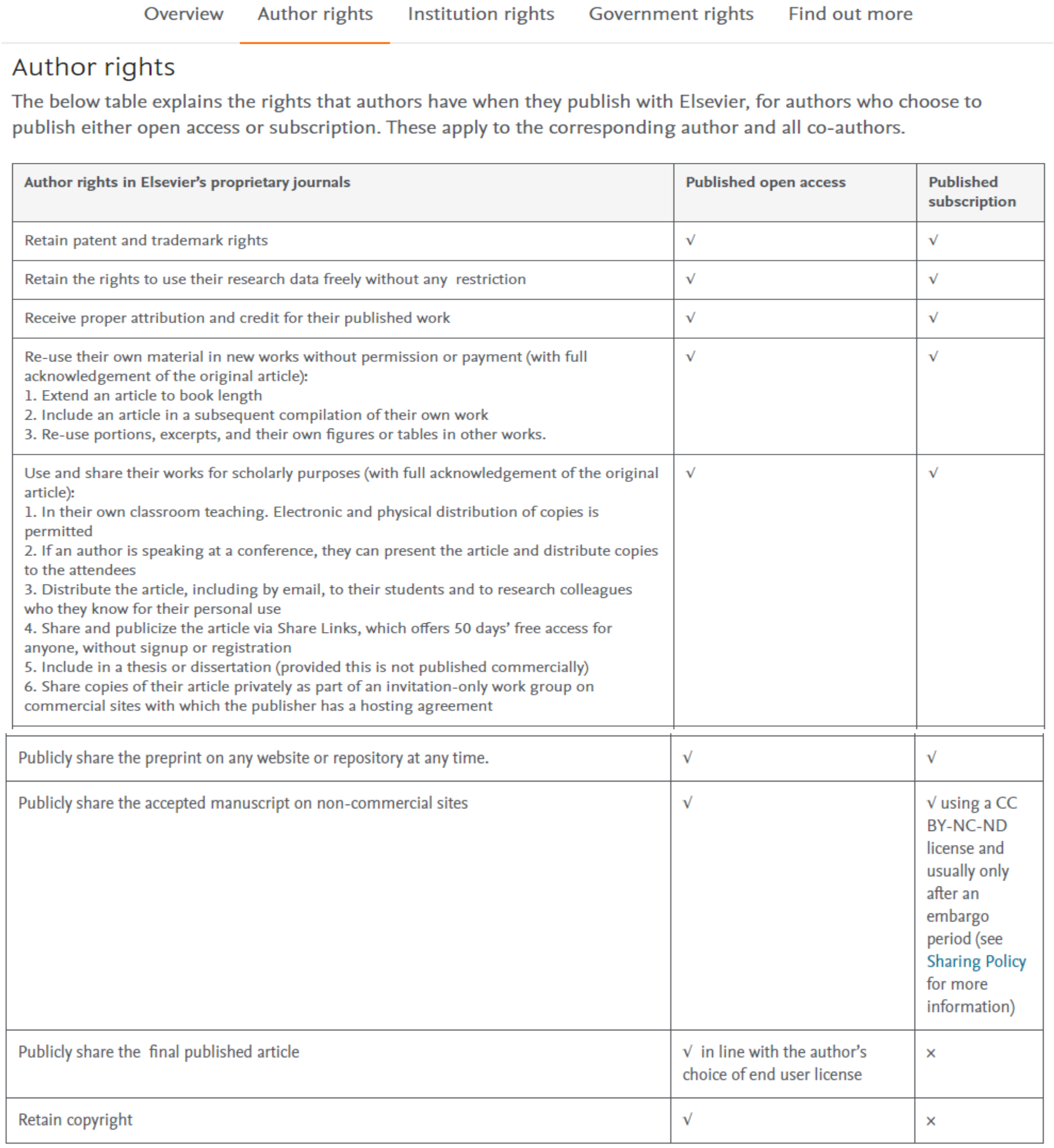

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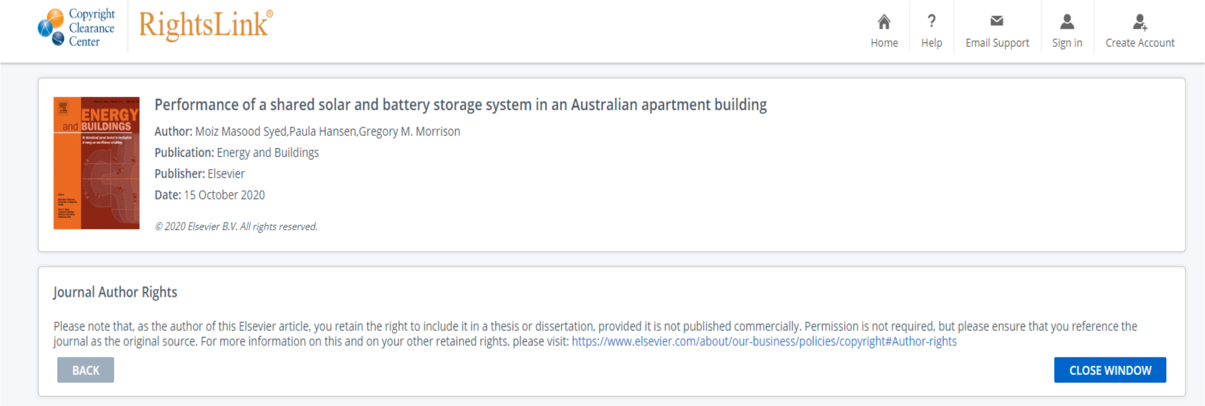

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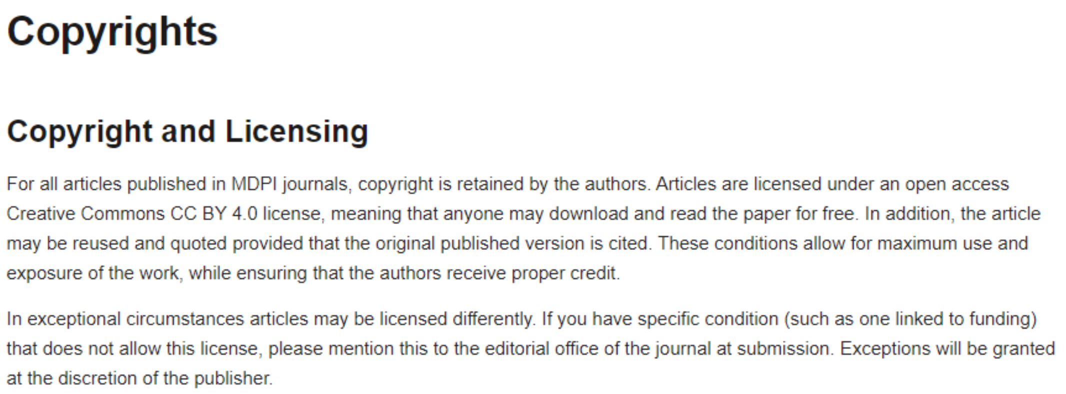

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