THESIS

Bidding Strategy for a Virtual Power Plant for Trading Energy in the Wholesale Electricity Market

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Abstract

Virtual power plants (VPPs) are an effective way to increase renewable integration. In this PhD research, the concept design and the detailed costs and benefits of implementing a realistic VPP in Western Australia (WA), comprising 67 dwellings, are developed. The VPP is designed to integrate and coordinate an 810kW rooftop solar PV farm, 350kW/700kWh vanadium redox flow batteries (VRFB), heat pump hot water systems (HWSs), and smart appliances through demand management mechanisms.

This research develops a robust bidding strategy for the VPP to participate in both load following ancillary service (LFAS) and energy market in the wholesale electricity market in WA considering the uncertainties associated with PV generation and electricity market prices. Using this strategy, the payback period can be improved by 3 years (to a payback period of 6 years) and the internal rate of return (IRR) by 7.5% (to an IRR of 18%) by participating in both markets. The daily average error of the proposed robust method is 2.7% over one year when compared with a robust mathematical method. The computational effort is 0.66 sec for 365 runs for the proposed method compared to 947.10 sec for the robust mathematical method.

To engage customers in the demand management schemes by the VPP owner, the gamified approach is adopted to make the exercise enjoyable while not compromising their comfort levels. Seven gamified applications are examined using a developed methodology based on Kim's model and Fogg's model, and the most suitable one is determined. The simulation results show that gamification can improve the payback period by 1 to 2 months for the VPP owner.

Furthermore, an efficient and fog-based monitoring and control platform is proposed

for the VPP to be flexible, scalable, secure, and cost-effective to realise the full capabilities and profitability of the VPP.

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Declaration

I, Behnaz Behi, declare that this thesis submitted in fulfilment of the requirements for the conferral of the degree Doctor of Philosophy, from Murdoch University, is wholly my own work unless otherwise referenced or acknowledged. This document has not been submitted for qualifications at any other academic institution.

Behnaz Behi

June 2022

List of Publications

I. **Behnaz Behi**, Ali Baniasadi, Ali Arefi, Arian Gorjy, Philip Jennings, and Almantas Pivrikas, "Cost–benefit analysis of a virtual power plant including solar PV, flow battery, heat pump, and demand management: A Western Australian case study," Energies, vol. 13, pp. 2614, 05/21, 2020, https://doi.org/10.3390/en13102614.

II. **Behnaz Behi**, Ali Arefi, Philip Jennings, Arian Gorjy, and Almantas Pivrikas, "Advanced monitoring and control system for virtual power plants for enabling customer engagement and market participation," Energies, vol. 14, no. 4, 2021, https://doi.org/10.3390/en14041113.

III. **Behnaz Behi**, Philip Jennings, Ali Arefi, Ali Azizivahed, Almantas Pivrikas, SM Muyeen, Arian Gorjy, "A Robust Participation in the Load Following Ancillary Service and Energy Market for a Virtual Power Plant in Western Australia," under review in Energies.

IV. **Behnaz Behi**, Ali Arefi, Philip Jennings, Almantas Pivrikas, Arian Gorjy, Arindam Ghosh, "A robust bidding strategy for VPPs including gamified customer engagement," 2021 31st Australasian Universities Power Engineering Conference (AUPEC); 2021 26-30 Sept. 2021, doi: 10.1109/AUPEC52110.2021.9597759.

V. **Behnaz Behi**, Ali Arefi, Philip Jennings, Almantas Pivrikas, Arian Gorjy, and PS Catalao, "Consumer engagement in virtual power plants through gamification," 2020 5th International Conference on Power and Renewable Energy (ICPRE); 2020 12-14 Sept. 2020, doi: 10.1109/ICPRE51194.2020.9233110 **(BEST PAPER AWARD)**.

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This thesis has been written in the format of thesis by compilation. Chapters 3 and 7 of this thesis have been published in a scientific journal. Also, Chapter 6 has been submitted for publication and is under review with another scientific journal. Chapters 4 and 5 are published in the proceedings of two power and energy conferences. These chapters represent a collaborative work. I hereby confirm that following statements of contribution are a true representation of my work with validation from the Principal Supervisor of this thesis.

____________________ Behnaz Behi June 2022	____________________ Prof Philip Jennings June 2022

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Author's Name	Contribution	Overall Percentage (%)
Behnaz Behi	Data Collection, Conceptualization, Methodology, Formal Analysis, Software, Validation, Investigation, Resources, Writing Original Draft, Visualization, Funding Acquisition	70
Other co-authors	Validation, Resources, Supervision, Administration, Funding Acquisition, Review and Editing	30

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List of Abbreviations

AC	Air conditioner
AEMC	Australian Energy Market Commission
AEMO	Australian Energy Market Operator
AER	Australian Energy Regulator
AMS	Advanced microgrid solution
API	Application programming interface
ARENA	Australian Renewable Energy Agency
ARIMA	Autoregressive integrated moving average
AUD	Australian Dollar
BLE	Bluetooth Low Energy
CAPEX	Capital expenditure
CHP	Combined heat and power
CRF	Capital recovery factor
DEIP	Distributed Energy Integration Program
DER	Distributed energy resources
DG	Distributed generations
DoD	Depth of discharge
DR	Demand response
DSS	Dispatch support service
EMIS	Energy management information system
EMS	Energy management system
EV	Electric vehicle
EWH	Electric water heater
GA	Genetic algorithm
GAMS	General Algebraic Modelling System
GDP	Gross domestic product
HWS	Hot water system
ICT	Information and communications technology

IRCR	Individual reserve capacity requirement
IRR	Internal rate of return
LEY	Less Energy Empowers You
LFAS	Load following ancillary service
LGC	Large-scale generation certificate
LRET	Large-scale renewable energy target
LRRAS	Load rejection reserve ancillary service
LTE	Long-Term Evolution
NPV	Net present value
PDF	Probability density function
PEM	Point estimate method
PSO	Particle swarm optimisation
PV	Photovoltaic
RCC	Reserve capacity credit
RES	Renewable energy source
SD	Standard deviation
SOC	State of charge
SPINE	Smart premises interoperable neutral message exchange
SRAS	Spinning reserve ancillary service
SRES	Small-scale renewable energy scheme
SRS	System restart service
STC	Small-scale technology certificate
TOU	Time of use tariff
VPP	Virtual power plant
VRFB	Vanadium redox flow battery
WA	Western Australia
WEM	Wholesale electricity market

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Chapter 1 Introduction

1.1 Background

A virtual power plant (VPP) consists of multiple small generators, both renewable and conventional, energy storage, and controllable demand [1]. A VPP generally refers to an aggregation of resources including demand flexibilities, coordinated using software and communications technology to deliver services to the consumers, power grids, electricity markets and other players, as depicted in **Figure 1.1** [2, 3]. Those services have traditionally been provided by conventional power plants.

In recent years, environmental concerns have led to increased penetration of renewable energy sources (RES) into several power systems worldwide [4, 5]. The concept of VPP has attracted widespread attention as a result of the prevalence of distributed generations (DGs) [6, 7] and the world is beginning to use DGs for greater energy efficiency and renewable sources, as an alternative to traditional and fossil fuel-based generations [8]. The implementation of VPPs is an efficient and economical way of increasing the penetration of renewable-based DG [7].

Some of the major electricity industry players, including the Australian Energy Market Operator (AEMO), the Australian Renewable Energy Agency (ARENA), the Australian Energy Market Commission (AEMC), the Australian Energy Regulator (AER), and members of the Distributed Energy Integration Program (DEIP) are working together to develop a regulatory framework and operational process [9, 10], so that distributed energy resources (DERs), through VPPs, can be effectively integrated into the Wholesale Electricity Market (WEM), maximising value to consumers while also supporting power system security and local utility requirements.

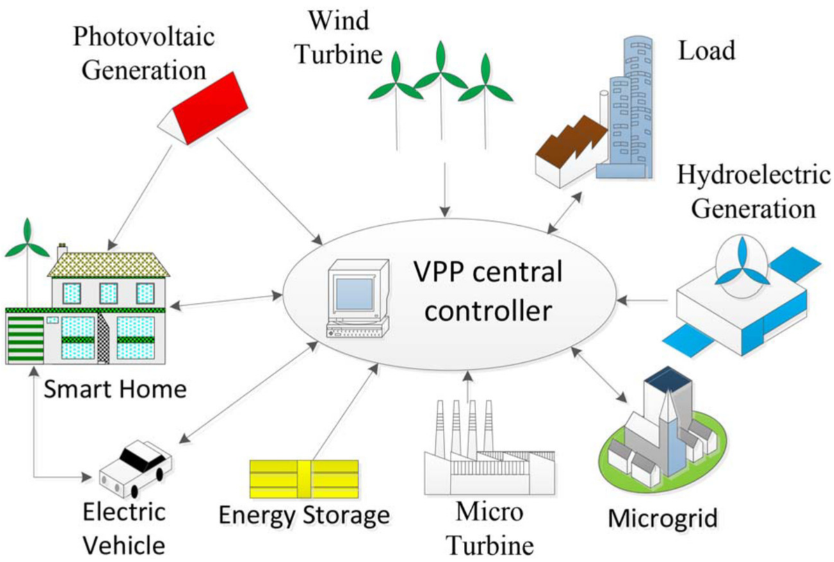

Figure 1.1. Components of VPP [3].

As the levelized cost of energy generated by renewable sources is decreasing in Australia as shown in **Figure 1.2** [11], the VPPs can utilize renewable energy and participate in the wholesale markets in order to maximise the VPP's profit on day-ahead and real-time bases. Various types of services can be delivered by VPPs, such as participating in markets for both energy and ancillary services, as well as entering into network support agreements with utilities. All of these services will add value for consumers through decreasing the cost of electricity and improving renewables integration [2]. One of the requirements for participating in the electricity market is the ability to participate at different times and different levels of energy for various services. The bidding strategy is a critical tool for the operators of VPPs for maximising their benefit and providing a sustainable growth path for renewables.

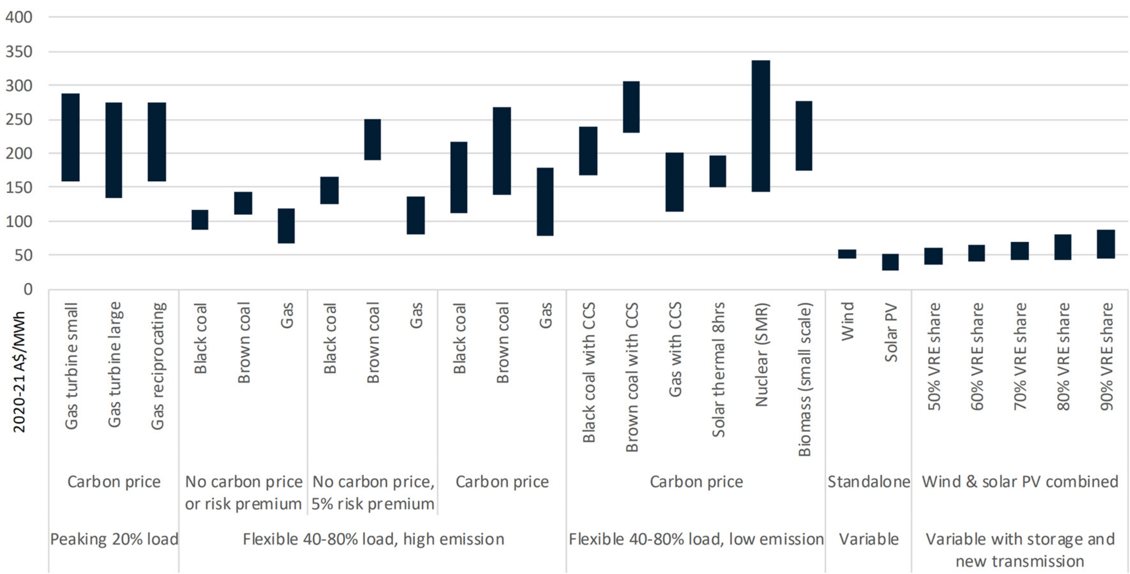

Figure 1.2. The levelized cost of energy at different levels of renewables penetration; VRE: variable renewable energy [10]

1.2 Motivation

The establishment of a VPP and its participation in the WEM is only profitable if the VPP is able to bid its services in the market properly. This bidding process includes how much and when energy should be sold to and bought from the WEM and also when to participate in ancillary service market. At the moment, there is no regulatory and financial structure in place in Western Australia (WA) to examine the profitability of the participation of VPPs in the WEM. Without an effective bidding strategy framework, the establishment and growth of VPPs in the private sector will be limited [10].

Another critical problem for VPPs is how to value their participation in the electricity market. If a VPP is forced to sell its produced energy at a very low price to the WEM, the profit of the VPP could be very low or even negative. Therefore, the wrong bidding strategy for VPPs results in the waste of investment and time for VPPs, which would be not a sustainable business strategy for the VPPs' owners. Consequently, an optimal bidding strategy is very important for VPPs to participate in the wholesale electricity market to clearly reflect their expenses and profits and on the other hand to satisfy the requirements of consumers.

Even with the establishment of regulatory frameworks, VPPs cannot be effectively engaged in the WEM due to the lack of bidding strategies for VPPs for how to participate effectively in the electricity market. Therefore, the **main research question** of this PhD project is: **“What is the optimal bidding strategy for a realistic VPP?”** This bidding strategy is the enabling tool for the VPP when participating in the WEM for energy trading and available ancillary service provision.

1.3 Research Aim and Significance

The *main aim* of this research is to develop the tools to reduce the cost of the electricity for consumers and to make a reasonable profit for the VPP owner through an effective design of the VPP with active customer engagement and a robust bidding strategy to participate in the wholesale electricity market.

To realize this aim, it is necessary to develop a realistic modelling of expenses and revenues of VPPs, to engage customers in an attractive way, to discover an effective bidding strategy, and to propose an enhanced control and communication platform.

This research project is significant as it could produce enormous benefit to the communities and VPP’s owners. Some key benefits of this research are listed below:

- **Reducing the Electricity Prices**

Electricity prices have doubled in the past ten years, which is a major financial burden for many Australians, especially for those with lower incomes. It is important to know that 3 million Australians are living under the poverty line, including 1 million children.

- **Attracting Private Investment**

By developing an effective VPP design and a robust bidding strategy for the VPP owner, the VPP investment becomes profitable enough to attract private investment, which would be great enabler for increasing the number of jobs and specialized knowledge in this domain.

- **Enhancing Renewable Integration**

By enabling more VPPs, aggregated renewable generators can participate in the electricity market to improve their added value in different aspects by providing services to AEMO and the local utility.

- **Gamified Customer Contribution**

Traditional demand response programs have failed due to the significant administrative burden. Using a gamified approach within a VPP, the customer engagement should increase, as this new approach encourages customers to participate in demand response in an enjoyable way, without stress or anxiety.

1.4 Methodology and Innovations

The innovations and contributions of this project in order to achieve the main aim of this research are as follows:

- **Developing an affordable concept design for residential VPPs**

In this research, an affordable concept design for residential VPPs is developed. In this work, the VPP is designed to integrate and coordinate rooftop solar photovoltaic panels (PV), vanadium redox flow batteries (VRFB), heat pump hot water systems (HWSs), and demand management mechanisms.

- **Developing a realistic and detailed modelling of revenues and expenses of the VPP**

For developing an efficient bidding process, when participating in the wholesale electricity market, the expenses and revenues of VPPs should be modelled as accurately as possible. These costs are associated with the following aspects:

1. VPP investment: such as investment on PVs, batteries, measurement and control infrastructure,
2. Wholesale Market costs: these are the costs associated with participating in the energy and ancillary market such as energy purchase, market fees, loss factor, clean energy regulations, network charge, individual reserve capacity requirement (IRCR), and ancillary service costs.

The revenues of a VPP will include energy sold to the wholesale electricity market and the revenue from selling energy to consumers within the VPP and revenue from the provision of ancillary services. These revenues and expenses should be modelled to evaluate the net profit and the total net present value (NPV) of a VPP.

- **Developing a simple, robust, and effective bidding strategy**

In this research, a simple, robust, and effective bidding strategy for participation in the energy and ancillary service market considering a gamified approach for customer engagement is developed. The aim is to find the bidding strategy for available resources in the VPP into the electricity market to maximise the profit of the VPP while reducing the cost of electricity for the customers.

For a profitable VPP, the aim is to provide this effective method for optimum bidding in the WEM, considering customer engagement. This method should be simple as it is critical for private investors to understand the logic behind the bidding strategy easily in order to have an enough confidence in the long-term profitability of the VPP. However, the methodologies implemented for bidding are usually based on complicated mathematical and/or heuristic methods. Also, the method should be robust in order to provide for profitable bidding considering the uncertainties associated with the market prices and PV generations.

- **Proposing an effective gamification-based approach for engaging consumers**

One of the most ancient ways of learning is through games that not only entertain people but also change their behaviour. Traditional demand response programs have not been very successful due to the administrative overhead and impact on customers' comfort. To engage consumers within a VPP, a smart way is required to be attractive and result in a long-term behavioural change of consumers. Therefore, in this thesis, we propose a gamification approach for VPPs to provide some motivations to consumers to engage effectively with the commands from the VPP owner, while socializing with others and learning about energy systems and sustainability and not compromising their level of comfort.

- **Developing a cloud-based monitoring and control system platform**

To implement and operate a VPP efficiently, an effective monitoring and control platform is required. Therefore, a practical concept design for the monitoring and control of residential VPPs, which is flexible and scalable and interacts with different energy resources such as rooftop PV, battery, and appliances is developed. Also, a detailed monitoring and control system for customer engagement within a VPP is proposed. Furthermore, an effective fog-based platform for hosting computing and forecasting systems is developed to maximise the benefits to the consumers and the VPP owner by participating in the wholesale electricity market and customer engagement.

1.5 Thesis Structure

The structure of the thesis is provided in **Figure 1.3**. As shown, Chapter 3 presents an affordable concept design for residential VPPs and also provides a complete formulation for modelling of costs and benefits of such VPPs. Chapter 4 discusses various gamification approaches for customer engagement in demand response initiatives. This Chapter provides a comparison amongst different methods and platforms of gamification to evaluate the suitability of them for the application of the VPP. Chapter 4 presents a proposed simple and robust bidding strategy for the energy market in the WEM in which the amount of energy purchased from, and sold to, the market is optimally determined. In the proposed bidding strategy, charging and discharging of the flow battery is also scheduled, considering the uncertainties of PV generation and energy prices in the market.

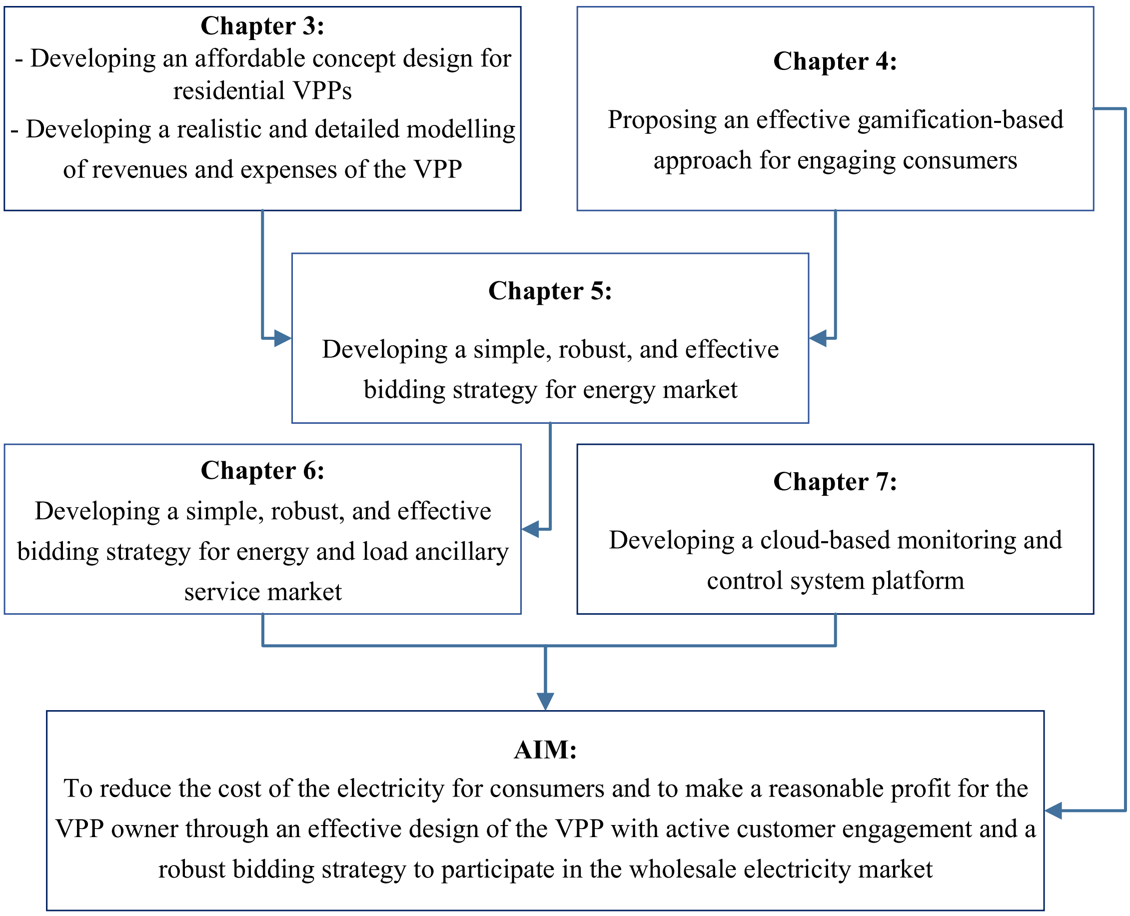

Figure 1.3. The structure of the thesis

Chapter 6 develops an optimal bidding strategy for participation in both the energy and ancillary service markets in the WEM. The ancillary service in the WEM in WA that a VPP can participate in, is the load following ancillary service (LFAS), as discussed in detail in Chapter 6.

Also, Chapter 7 proposes a scalable and flexible platform for a cloud-based monitoring and control system to support the smooth operation of the VPP. All of these chapters contribute to the main aim of this research, which is to reduce the cost of electricity for consumers and make a reasonable profit for the VPP owner through an effective design of the VPP via active customer engagement and a robust bidding strategy for participation in the wholesale electricity market.

1.6 Thesis Outline

Chapter 1 provides the background, aims and research question for this project. **Chapter 2** provides a comprehensive literature review of relevant research works. The concept design of residential VPPs including the detailed modelling of their expenses and revenues when participating in WEM is provided in **Chapter 3**. **Chapter 4** discusses and compares different gamification approaches and applications to evaluate the applicability of them in the context of the proposed VPP. **Chapter 5** develops a robust yet simple bidding strategy for participating in the energy market in the WEM, considering the uncertainties and customer engagement. **Chapter 6** extend the bidding strategy for a VPP to participate in both the energy and ancillary services markets in the WEM, resulting in a much better payback period and rate of return for the VPP. **Chapter 7** proposes a cloud-based monitoring and control system for the VPP which is scalable and flexible. **Chapter 8** provides some concluding remarks and suggestions for future research work.

Chapter 2 Literature Review

This Chapter investigates the literature related to case studies of virtual power plants (VPPs) and the costing formulation of VPPs, along with the different approaches to bidding strategies for VPPs. After reviewing the cases studies on VPPs, the aspects of customer engagement, demand response and gamification are discussed. Then, the components of expenses and revenues of a VPP when participating in an electricity market are presented, followed by reviewing different bidding strategy algorithms for VPPs in the electricity market.

2.1 Introduction

Reducing the carbon footprint and improving the sustainability of energy systems are some of the main goals of many countries. To achieve these goals, many nations are planning for increasing renewable energy integration, for which they set some targets such as the contribution of 23.5% renewable generation by 2020 in Australia, which it has already achieved [12]. To speed up renewable integration, the governments provide some level of incentives to investors and end-users for the installation and use of renewable-based energy resources such as photovoltaics (PV) and wind and also energy storages [13].

Considering the increase of electricity prices in Australia, by 200% during last decade, which brings financial difficulties to many people, it is critical that the use of renewable energy resources and energy storages reduces the cost of electricity for people. Energy aggregators such as VPPs have a great potential to achieve the goal of reduced electricity price for end-users. VPPs can integrate and coordinate all available energy resources and load flexibility in one place to harmonize the use of energy in order to reduce the cost of electricity by proper planning of energy usage, electricity market participation and customer engagement [7, 14].

To realize all the potential benefits of a VPP, the VPP should be carefully designed and should be managed optimally to be able to produce a profit for the VPP owner and reduce the cost of electricity for the customers [14, 15]. In this Chapter, the previous relevant works and research on VPPs, customer engagement and electricity market participation are discussed, as shown in **Figure 2.1**.

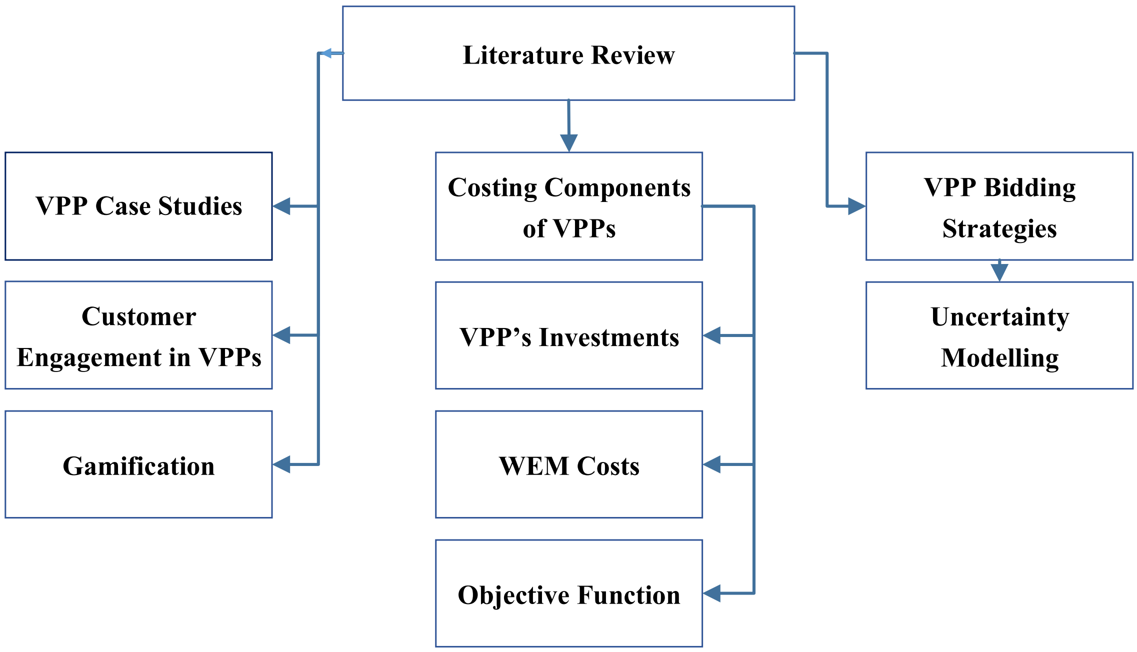

Figure 2.1. The components of the literature review

2.2 VPP Case Studies

There are many studies that investigate different aspects of VPPs. For example, [16] evaluates the role of VPPs in encouraging the customers within the VPP to use energy efficient appliances. This study on a 63 MW VPP shows a significant energy reduction of 273 GWh/year when high-efficiency devices are installed.

The affordability and technical aspects of VPP implementation through multiple revenue streams are discussed for a university campus [17]. This research shows that a VPP within the university can be a successful business case in urban areas for the owner however the detailed formulation of the expenses is not provided. A VPP has the ability to coordinate the flexibilities from loads for a larger gain in providing services to an electricity market or grid. The Next Kraftwerke is an example for this capability of VPPs, in which customers, regardless of their locations, can sign up to participate in this VPP, commit to the program and share the benefits generated by the VPP [18]. Also, a VPP can aggregate specific devices such as micro combined heat and power (CHP) modules. For example, in Germany, 25 CHPs are integrated and the effectiveness of that for Germany is investigated [19].

There are some categories of VPPs such as community VPP or commercial VPP. Community VPP generally refers to a coordination of neighbour residential customers and some community service utilities such as parks and aged cares. The practical cases for community VPP are in Ireland, Belgium and the Netherlands [20]. Commercial VPP, on the other hand, coordinates commercial and industrial customers for example in a large shopping centre or in an industrial park. A case study of a commercial VPP in Scotland shows that more than 10% increase in the VPP profit has been achieved by a proper management of renewables and interaction with the electricity market [21].

VPPs can be used to maximise the self-supply such as the case in Spain, in which the VPP is designed to be self-sufficient, as much as possible, while contributing to the electricity market and local grids [22]. In some VPP cases, some economic metric such as gross domestic product (GDP) per capita and unemployment rate are taken into account to evaluate the benefits of establishing VPPs on different aspects of social, economic and environmental factors [23]. It is observed for example that a high level of renewable integration can influence the prices in the electricity market significantly [24]. The case study of VPP participation in the electricity market in Germany shows a good economic outcome. For example, the revenue of the VPP increased by 11% [25]. Also, short-term techno-economic analysis of VPPs has been conducted to evaluate the effect of load dynamics, which cannot be used for the cost benefit assessment of a VPP [26]. Islanded VPPs which are not connected to the grid, are also considered as an option for renewable integration but their effectiveness is limited as they do not participate in the electricity market [27].

A summary of the comparison of literature topics is provided in **Table 2.1**.

Table 2.1. The comparison of recent papers on VPP cases

Ref. #	DR	PVs	Energy storage	Heat pump	Electricity market	Detailed modelling	Gamified DR	WA context
[16]	×	√	×	×	√	√	×	×
[17]	√	√	√	√	√	×	×	×
[18]	√	√	√	×	√	×	×	×
[19]	√	√	√	√	×	×	×	×
[20]	√	√	√	×	√	×	×	×
[21]	×	√	×	×	√	√	×	×
[22]	√	√	√	√	√	×	×	×
[23]	√	√	√	×	√	×	×	×
[24]	√	√	√	√	√	×	×	×
[25]	√	√	√	×	√	√	×	×
[26]	√	√	√	×	√	×	×	×
[27]	√	√	√	√	×	√	×	×
[28]	×	√	√	×	×	√	×	×
[29]	×	√	√	×	√	√	×	√

The Australian Energy Market Operator (AEMO) along with other Australian government bodies introduced the VPP demonstration in 2019. The aim of this demonstration is to study the tasks, capacities, and challenges for the implementation of VPPs in Australia. Some of the main tasks that AEMO intends to investigate in the VPP trials are [30]:

- Participation in the electricity market to provide different services such as energy and ancillary services such as frequency regulation and grid voltage control,
- Provision of operational visibility for better understanding of VPPs' benefits,
- Enhancement of customers' satisfaction and experiences,
- Evaluation of the requirement of cyber security.

The locations and sizes of the VPP participants in this demonstration are provided in **Figure 2.2**. As shown, all participants are located outside Western Australia and consequently, there is not any case to examine technical and financial aspects of VPPs in WA in this demonstration. The total size of all VPPs add up to 31 MW, and mainly PVs and batteries are considered as the participants in these trials [28].

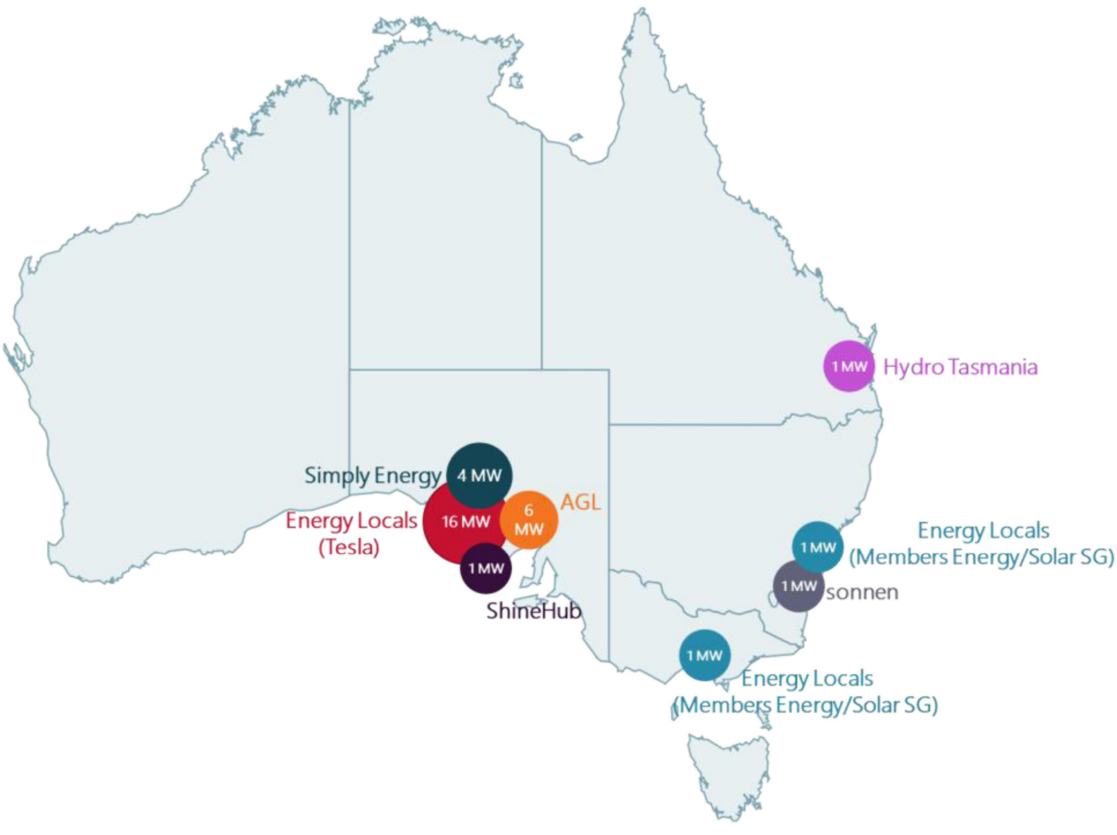

Figure 2.2. The location and size of VPPs in the AEMO's VPP demonstration [28]

In WA, in addition to a project in South Lake, two other projects on VPPs are considered. One project is called “Project Symphony”, in which the homes in the suburbs of Harrisdale, Piara Waters and Forrestdale in WA will form a VPP. 50% of homes in these suburbs have rooftop PVs, which contribute to the VPP, along with the batteries, and some appliances such as air conditioners and hot water systems. This project, that is supported by Synergy, Western Power and AEMO, is in its early stages and is planned to finish in mid-to-late 2023 [31]. There are no more details about how this project would be implemented. Another project in WA is the “Schools VPP Pilot Project”, in which 17 schools are participating. PVs and batteries will be installed in schools with the goal that the battery can contribute to the reliability and security of local grids, while improving the sustainability of energy supply at schools. Based on the available information, there is no WEM participation from these schools’ VPPs and they are designed to work as a community VPP [29].

2.3 Customer Engagement in VPPs

Customers can be engaged with VPPs in different ways such as controlling their consumption, via air conditioners, hot water systems, pool pumps, and smart appliances or actively managing their energy production from solar rooftop PV systems and energy storage. These contributions are usually categorised as demand response (DR), or more generally, customer engagement. To realise these contributions, an active arrangement between customers and the VPP owner should be in place [32]. This arrangement will enable the VPP to intervene in energy-related behaviour of customers in order to change it to the required model. One of the effective platforms is smart energy management systems (EMS), which can be configured for engaging customers. EMS includes smart meters, communication, control system, user-friendly dashboard, and the appropriate hardware and software, which will be discussed in this thesis. The inclusion of game design elements into EMS provides a great opportunity for energy-related behaviour change. The gamification approach facilitates active participation and engagement of consumers with the identified values of a VPP [33].

Demand response that is sometimes called load profile shaping, contributes flexibility. VPPs can use this flexibility to participate in the day-ahead, balancing, or ancillary service market in order to maximise their benefit, resulting in reducing the cost of electricity for consumers [34]. In a VPP with different sources of energy, both renewable and conventional, and controllable loads, one of the main objectives is to introduce a framework that optimises the response of demand to different signals such as electricity prices, PV generation, and temperature. The demand response is generally categorised in two forms as follows [2]: a) load curtailment/turn on, and b) load shift.

In the case of load curtailment/turn on, a load can be switched on or off without any requirement for utilising that load again during the timeframe. For example, a pool pump can be turned off for the whole day due to a rise in electricity price. An example of load shift is a washing machine, for which the user of this appliance can shift the use to the defined interval. In addition, considering different types of appliances, the time interval of DR is different, which is usually defined as short–term interval DR or long-term interval DR.

For the short-term interval DR, appliances such as electric water heaters (EWH) and air conditioners (AC) are considered to contribute. These or similar appliances can be turned off for a maximum of 10 to 20 minutes, considering the comfort level of the customer, temperature, and all settings from consumers. Where these appliances are interrupted, they will not receive any signal for DR for the next period of time, depending on the setting of consumers, which could be 10 minutes to 1 hour [35, 36].

Long-term interval DR is associated with the DR intervals for several hours, for example, 2 hours. Appliances such as dishwashers, washing machines, pool pumps, driers, and electric vehicles (EVs) can be programmed to fit into this scheme. Customers will set their requirements for each of these appliances to make sure that their comfort levels are met. For example, they can put the constraints on washing machines and dishwashers that the washing cycle should be finished before applying the DR command [37, 38].

In order to facilitate the decision for customers about whether to participate in DR and nominate one or some of their appliances, a framework is necessary to consider the uncertainties in the load, PV, and electricity market, cost of load curtailment or shift for them, and time of use tariffs (TOUs) [39]. Also, the variation of the load profile of customers should be studied by the VPP owner to make sure it satisfies the VPP's constraints. Some DR loads can be nominated to participate in the electricity market, and some DRs contribute to congestion management of local electric grids. In this case, the grid operator can send a command for controlling these types of loads to stay below the thermal limit of equipment or grid voltage violations [40]. Flexible loads can contribute to the operation of VPPs. For example, a VPP with 46% flexible loads was studied to evaluate the effectiveness of DR programs and the comfort levels of the resident [41]. Such load flexibilities from VPPs can contribute to the reduction of peak load and the investment on pole and wire in distribution networks [42].

In some cases, customers use combined heat and power generation in order to generate power and heat from the recovery process simultaneously. This technology can be utilised in DR programs to adjust the electricity and heat load together, which can reduce the risk of participation in DR schemes for VPPs, if programmed effectively [14]. A VPP, including a CHP should optimise the heat storage and boiler operation in order to effectively participate in a DR program, then a scheduling decision is provided for participating in WEM.

Although demand responses are considered as one of the sources of flexibilities for VPPs, which potentially could improve the profit of the VPP [43, 44], the problem with traditional DR programs is that they are less effective due to the significant administrative burden or due to violating the comfort level of customers. Gamified DR in the other hand will provide a platform for customers to engage in DR programs in enjoyable ways while keeping the level of comfort that they desire.

2.4 Gamification

Games are one of the ancient ways of effective learning. People not only can learn through games but also can enjoy the whole process, resulting in the desirable behaviour change for the designed purpose. For effective customer engagement, a behavioural change associated with the use of energy needs to happen in which customers can willingly react and accept the DR commands from the VPP owner. Also, the customers can reject or accept any types of participation in DR programs or program EMS through auto response to the desirable events. The value created by the gamified DR programs will contribute to the electricity price reduction for the customers, to VPP profit increase, and to some services to the WEM and grid.

There are some energy-related applications which work based on gamified approaches. The applications that are studied in this thesis are Ecogator, Social Power Game, Makahiki, Power House, Less Energy Empowers You (LEY), Wattsup, enCOMPASS and Funergy [45]. These applications can also be used for energy efiiciency/saving if programmed properly [33].

EcoGator application can provide energy efficiency advice when a person wants to buy appliances. Also, it can compare two appliances and give insights to the customer about the sustainability of products [45]. The app will give the users some points and increase their level of involvement as they are using the functions of the application more. Also, the users of the app can receive and share some energy efficiency tips [46].

Social Power Game is designed to provide a collaborative platform amongst neighbors so they can participate in teams for completing a task then receiving some points. This constructive competition amongst teams of neighbours will result in awareness improvement related to energy consumption and realistic energy savings for households while they enjoy the social interaction between neighbours [45].

Makahiki is an application for programming any type of gaming platform. For example, a sequence of activities and actions can be designed for evaluating the energy consumption at home or evaluating the DR events to encourage faster and more accurate decision making. The players can earn points by doing certain actions. The app can provide data visualization on energy consumption and other data [47].

The Power House application can read the energy consumption of a home and use it for giving rewards to each user in an online environment. In this platform, neighbours can enhance their social reputation by adjusting their energy-related behaviours [48].

Less Energy Empowers You (LEY) is a gaming platform that challenges the users by encouraging them to use energy optimally and in return getting maximum points. Also it provides some quizzes that if completed by the user, some additional points will be awarded [49]. Wattsup is a Facebook-based application which provides ranking, rewards, and comparison amongst friends considering their energy consumption [50].

The enCompass and Funergy is another gamification platform for energy saving which comprises data collection sensors including user data, data analytics, action recommendations, and a programmable gamification system [51]. The collected data can be compared with some reference data or other users' data to provide some insights to the users about their levels on the ladder and to give some recommendations on the appropriate use of energy [45, 52].

A detailed comparison and evaluation of the suitability of gamified applications in the VPP context are discussed in Chapter 4.

2.5 Costing Components and Objectives for VPPs

The cost modelling for VPPs is critical to understand whether the VPP arrangement is profitable. In this section, the expenses and revenues of a VPP are discussed and the associated costing formulation is reviewed.

2.5.1 VPP's Investments

One part of the costs of a VPP is its investments in PVs, energy storages, smart appliances, and electrical system infrastructure to participate effectively in the electricity market and engage customers [53]. Monitoring, and control infrastructure is also essential to collect the relevant data for justifying the benefits of an implemented system, for which Government incentives will assist in some cases [54].

When modelling the cost of infrastructure, the net present value (NPV) of the equipment over the lifetime period is calculated. Therefore, it is important to know the lifetime of equipment, operation and maintenance costs, and any cost of replacement. For batteries, the lifetime is reported as the number of cycles of charging and discharging (e.g. 10,000 cycles) or the amount of energy produced by the battery such as energy throughput. Therefore, in the costing model, such parameters should be taken into account. To calculate the NPV of the cost C in year n, considering the interest rate of i, the following formula is utilised.

$$NPV = \frac{C}{(1+i)^n} \tag{2.1}$$

Also, for finding the levelised annual cost, based on the net present value, the capital recovery factor (CRF) is used as below.

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{2.2}$$

2.5.2 Wholesale Electricity Market Costs

An accurate modelling of the wholesale electricity market (WEM) is required for VPP owners to evaluate the affordability of their participation in the market. Some of the main objectives of an electricity market are as follows [55]:

i. to promote the economically efficient, safe and reliable generation and supply of electricity and electricity related services in the interconnected system.
ii. to stimulate a fair competition among generators and retailers in the grid, including by facilitating efficient entry of new competitors.
iii. to avoid discrimination in that market against particular energy options and technologies, including renewables options and technologies related to the reduction of overall greenhouse gas emissions.
iv. to minimise the long-term cost of electricity supplied to customers from grids.
v. to manage the electricity amount used and when it is used.

These costs, associated with participating in a market, are set out below:

- **Purchasing energy from WEM**

The wholesale electricity price is determined by the supply and demand in the market. These prices are available online from AEMO through a dashboard, as shown in **Figure 2.3**, for example [32]. The energy purchased from the electricity market is multiplied by the real-time price to determine the cost of electricity purchased from the market. As shown in **Figure 2.3**, the forecast electricity price is also available in order to enable participants to bid their generation in the WEM.

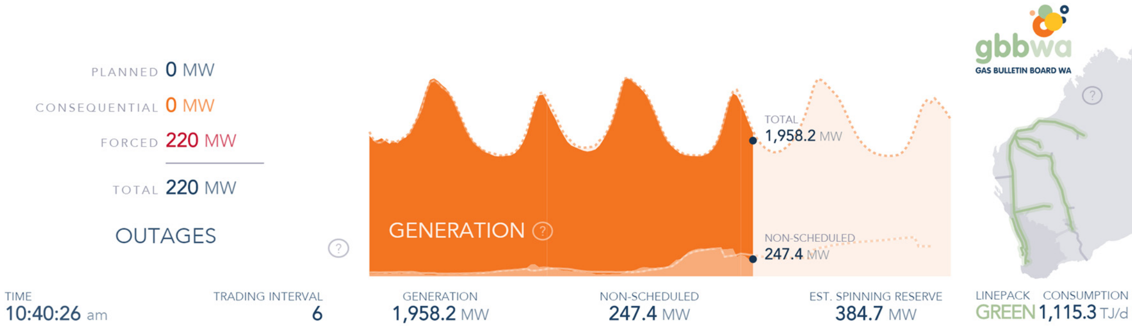

Figure 2.3. The dashboard for the wholesale electricity prices for Western Australia [32]

- **Market fees**

Based on the wholesale electricity market rules, AEMO charges participants a market fee in order to handle the costs associated with market operation services, market administration services and system planning services. These costs are categorised below and calculated, based on the wholesale electricity market rules [55].

i. Market Fees, System Management Fees and Regulator Fees,

ii. Application Fees,

iii. Reassessment Fee.

- **Loss factor**

Each participant in the market will pay the costs associated with the share of energy loss in distribution and transmission lines. The cost is calculated in accordance with section 4.1 of the market procedure for determining loss factors [55]. The average distribution loss factor is evaluated, based on losses in substation transformers, transmission and distribution feeders, and distribution transformers, where relevant [56]. Individual loss factors are calculated by AEMO for all participants including Scheduled Generator, Non-Scheduled Generator, Interruptible Load, Dispatchable Load, and Non-Dispatchable Load. For VPPs also, this loss factor will be determined by AEMO.

- **Individual reserve capacity requirement (IRCR)**

There is an IRCR for each market customer, which is calculated based on the individual's peak responsibility. The IRCR for each market customer is published by AEMO to support participants in providing the reserve capacity in the wholesale market.

- **Clean energy regulator and ancillary service fee**

The large-scale renewable generators with the capacity of more than 100 kW are able to request Large-scale Generation Certificates (LGCs) and pay the associated costs of them. For renewable generators under the Large-scale Renewable Energy Target (LRET), one megawatt hour of generation above a specified baseline is equivalent to one LGC [57]. To support the renewable integration and also ancillary service to the WEM, large market participants need to pay a fee to the AEMO for this purpose.

The detailed formulations of expenses and revenues for a VPP participating in the WEM are provided Chapter 3.

2.5.3 Objective Function

The profit function or objective function that should be maximised by a VPP when participating in the WEM is defined below:

$$\begin{aligned} Objective\ Function &= Total\ NPV\ Profit \\ &= Total\ NPV\ Revenue - Total\ NPV\ Expenses \qquad (2.3) \end{aligned}$$

The revenues of a VPP include different components including services to the electricity market, such as selling energy and ancillary services, and also selling energy to customers within the VPP [1, 4]. In some cases, there are some incentives and grants from Government for implementing renewables that can be considered as part of the revenue.

The expenses of a VPP will include the cost of purchasing energy from the electricity market, the NPV costs of investment, the operational costs of PVs and energy storages, and the costs associated with participating in the WEM. There are several cost components in the expenses of a VPP, which should be modelled clearly. The costs associated with the technological possibilities, commercial and economic opportunities and regulatory frameworks, have the greatest impact on the design and viability of a VPP. Sometimes, VPPs participate in the market through an affiliated retailer. Therefore, the costs associated with this affiliation should be considered [9]. Also, the participation in the electricity market sometimes has some constraints [6, 8], including the following:

a. WEM constraints including minimum and maximum of energy and/or power contribution and their rates at each interval,
b. VPP constraints including generation and energy storage operational and load balancing constraints,
c. Consumers' constraints including comfort levels and the settings of appliances.

The details of formulations for expenses and revenues of VPPs in the WEM are provided in Chapter 3.

To achieve the commercial and economic goals for a VPP owner within the regulatory constraints, information and communications technology (ICT) technologies play a vital role in establishing the required communications, control and management system. It is critical for ICT within a VPP to be scalable and flexible. Also, it needs to provide uninterrupted monitoring to support bidding strategies and fault detection to avoid any major financial issues [1, 4]. The details of the concept design of the control and monitoring system is provided in Chapter 7 of this Thesis.

2.6 VPP Bidding Strategies

For providing an optimal bidding strategy, all required data including weather, market prices, generation, and load are collected via defined ICT interfaces by the VPP, including historical data as empirical data for consolidation of forecast data. Using such data, a bidding of available energy resources will be conducted by the VPP to determine the amount of selling and buying at different time intervals, for which different aspects of technical, economic and social requirements will be considered [25]. The requirement of the electricity market is also defined, based on what the VPP produces and the biddings for several time interval, for which the VPP will be paid or needs to pay, based on the clear price, determined by the AEMO. In such a market, for example, if the bidding price of VPPs is lower than the forecasted price of market, the VPP will win the optimal amount [58].

A good bidding strategy is the result of carefully planning the usage of available resources within a VPP, such as demand flexibilities, PV generation, charging and discharging of energy storage, and electric vehicle integration [34]. Each VPP owner needs to make sure to implement a bidding strategy that maximises the profit of the VPP while satisfying the requirement of the systems and reducing the cost of electricity for the customers. The problem is formulated as below:

$$Objective\ function = VPP's\ profit = NPV\ revenue - NPV\ expenses$$

$$Subject\ to: \begin{cases} VPP's\ constraints \\ Consumers'\ constraints \\ Market\ constraints \end{cases} \tag{2.4}$$

The decision variables for this optimisation could be the hourly bidding amount for energy and power for the next day, hourly consumers' contribution in demand response, and charging/discharging of energy storage owned by the VPP. There are different approaches to solve this objective function, such as mathematical-based methods including linear programming or mixed-integer programming [37, 59, 60]. Another category of methods is the heuristic-based methods such as particle swarm optimisation (PSO), and genetic algorithm (GA) [2, 61].

Sometimes the problem is formulated as multi-objective cost functions where there are diverse objectives in the formulation. These objectives are joined together through optimisation and multiple solutions, identified using selection algorithms such as the Pareto principle [34]. As only one solution will be implemented in practice, it is recommended to focus on a single-objective problem and explore the uncertainty of parameters more comprehensively.

It is important to note that a VPP that only accepts the price from the electricity market is called a price taker while those VPPs that participate in bidding the price as well, will be called a price maker. Most VPPs, at the moment, are considered as the price takers in WA, so the focus of this research would be on this type of VPPs.

A mixed-integer linear programming model is adopted to maximise the weekly profit of the VPP by providing a bidding strategy, subject to the long-term bilateral contracts and technical constraints [62]. In addition, a bidding strategy that does not need any pre-assumptions on the PDF of random variables, using combined optimisation is studied in [63]. Another benefit of combined optimisation is the lower computational effort compared to other algorithms that evaluate uncertainties such as stochastic optimisation.

The robust and combined optimisation algorithms, which are deterministic and non-parametric, consider the VPPs' profit performance in several scenarios. Therefore, computational efforts for these optimisations are lower than the stochastic optimisation. Generally, a lower computational effort for finding the optimal solution for bidding can be achieved by deterministic optimisation algorithms [5, 63]. Robust optimisation algorithms aim to find the optimal solution even with uncertainties in the problem, and stochastic optimisers will examine many scenarios to find the optimum solution [56]. There are some approaches that provide hybrid stochastic/robust optimisation [64] to get the benefits of both approaches.

Further, a multistage adaptive robust optimisation has been developed to determine the robust bidding strategy for a VPP. In this optimisation algorithm, firstly, the bidding prices, DRs, charging/discharging patterns are initiated. The second step is to find the availability of PV generation, so the variables in the first step are updated. This algorithm iterates until the convergence criteria are met [65]. Moreover, it is critical to consider the comfort levels of customers in temperature, humidity, and light, which can be modelled in the gamification approach or in the constraints in the bidding strategy [66]. Moreover, a two-stage procedure, based on robust optimisation, is proposed in [3]. The bidding amounts are determined in the first stage. When the actual scheduling in the day-ahead market is decided, in the second stage, the hourly bidding prices are decided in the real-time market for the day. Robust optimisation is utilised to address uncertainties in wind-power production and market prices, which are modelled by their confidence bounds.

Also, stochastic programming is used for the self-scheduling procedure within a VPP. The uncertainty of the wind power and solar power generation is addressed by the use of pumped hydro storage and a conventional power plant as a backup in order to provide flexible and smooth operation [67]. Also, a non-linear maximization formulation for the optimisation of the bidding strategy is developed with constraints to maximise the profit of the VPP, while satisfying the customers' expectations. In this approach, an operational optimisation of resources including DRs and PVs, using the VPP control system, is modelled and simulated using GAMS software [68]. Another method is the information gap theory, which is used to schedule different energy resources within a VPP [69]. In addition, the uncertainties in electricity prices and renewable resources are modelled through a robust coordination of energy resources in [70]. Also, a two-level robust dispatching model for available resources in a VPP can be designed to reduce the costs of the VPP [71].

Another approach to finding a solution for the bidding strategy, is defining many constraints and using a what-if approach to solve the problem. For example, these constraints can be the surplus energy to store, battery discharge when PV generation is not enough, or the electricity price is high and DR activation when there is a lack of energy resource [53]. The benefit of this approach is the speed of the process, but it may converge to a local optimal solution. A heuristic dynamic game theory can be used to find the bidding price, while considering the uncertainties associated with electricity prices [59]. A fuzzy-based decision-making procedure, which incorporate a novel "insecurity" metric based on human psychology, is also developed for the bidding strategy [72]. This multi-agent system tries to minimise emissions and/or total energy cost, considering an aggregation structure with the electricity market. The operational flexibility of the VPP's resources is measured by the "insecurity factors", which are converted to numerical values through fuzzy logic. Considering external price signals, the VPP's constraints, and short-term forecasts, the system is able to create an optimal bidding strategy to participate in the electricity market [2]. Also, the heuristic algorithm of the grasshopper optimisation algorithm is utilized for the frequency control as an ancillary service by a VPP [73]. As discussed in [17, 74], participation of a VPP in the energy market and ancillary service can potentially result in a better payback period for the owner of the VPP. A conditional value-at-risk approach is used for the optimal bidding strategy for participation of a VPP in the electricity market for aggregating EVs [75]. The autoregressive integrated moving average (ARIMA) models are used to forecast the electricity market parameters. To model the uncertainties in the ancillary service prices in the electricity market, the fuzzy set theory is used.

There are many ancillary services in the WEM, which are managed by AEMO. These ancillary services, as described in the "wholesale electricity market rules" [74], are spinning reserve ancillary services (SRAS), load rejection reserve ancillary services (LRRAS), load following ancillary service (LFAS), dispatch support service (DSS), and system restart service (SRS). In the WEM, only LFAS is run by AEMO within a market environment available, and other ancillary service are procured by lateral contracts. The details of LFAS definition and rules are provided in Chapter 6.

2.6.1 Uncertainty Modelling

As there are uncertainties in demand profiles, renewable generations, and electricity prices, they need to be considered in the bidding strategy. Generally there are two approaches for modelling uncertainties which are a) scenario, and b) mathematical modelling [76].

In scenario modelling, different scenarios for the combination of uncertainties are identified and then each scenario is evaluated individually. The result of each scenario is assessed separately and also in combination with other scenarios' results to find the overall objective function. Different methods such as Monte Carlo analysis used in stochastic optimisation or scenario generation in dynamic programming, are based on scenario modelling [3, 77].

Mathematical modelling sometimes called probabilistic modelling, is based on creating probability density functions (PDFs) of the uncertain parameters for electricity market prices and PV generation outputs. Then using a mathematical formulation, these parameters are related to the objective function in order to form its PDF. The PDF of the objective function is evaluated against criteria and constraints. For example, the point estimate method (PEM) can be utilised to construct different PDFs [34, 78]. To handle the uncertainty problem, the VPP coordinates DRs, energy production and storage units to reduce the total risks for the VPP and to maximise the VPP's profit. In other words, the proposed bidding strategy should be robust in respect to the available uncertainties to ensure that even in the worst cases, the bidding strategy is optimum for the VPP [39, 59].

The issue with the scenario-based and mathematical modelling is that they are not generally computationally efficient, which means that it takes some time for the control system to decide on the optimum bidding values, considering the uncertainties. Therefore, in this thesis, we propose a simple yet robust bidding strategy which is understandable to industrial partners and also much faster than the mathematical methods.

2.7 Research Gaps

Based on the literature review, there are some significant research gaps in the topic of VPPs. Firstly, an affordable concept design for VPPs is required in order to reduce the cost of electricity for consumers and generate a reasonable profit for the VPP owners to encourage the private investment. Secondly, how the VPP in the context of WA can effectively participate in the WEM in order to be profitable and reliable for industry. Thirdly, there is a gap in gamified customer engagement so that the VPP's owner can consider more seriously the contribution of load flexibilities. In this thesis, all of these research gaps are studied, and innovative solutions are developed and discussed.

2.8 Conclusions

This review of the literature reveals that VPPs can integrate and coordinate renewable energies, energy storage, and customers' flexibilities in a cost-effective way. VPPs have the potential to reduce emissions, improve power quality and reliability, and reduce electricity prices. Based on previous research works, VPPs can produce value in the wholesale electricity market by selling energy during periods of high electricity price or contributing to other ancillary services such as frequency control. To integrate VPPs into the WEM, an optimal VPP concept design for Western Australia needs to be developed. Also, a robust and optimal bidding strategy is required to optimise the use of PVs, energy storage, and DRs to maximise the VPP's profit. There are some algorithms for optimisation of a VPP's objective function including mathematical and heuristic approaches. However, a realistic modelling of DR implementation, realistic modelling of the expenses and revenue of a VPP and the associated constraints in the WEM context are not provided in the literature. Also, the speed of optimisation and decision making is another critical aspect of an optimal bidding strategy that should be addressed. In addition, a monitoring and communication platform for the VPP, which is scalable, flexible, and reliable needs to be proposed. These issues will be addressed in this thesis in the following Chapters, considering a realistic case of a VPP in WA.

Chapter 3 Cost Benefit Analysis of a Virtual Power Plant including Solar PV, Flow Battery, Heat Pump, and Demand Management: A Western Australian Case Study[1]

3.1 Summary

Achieving the renewable energy integration target will require the extensive engagement of consumers and the private sector in investment and operation of renewable-based energy systems. Virtual power plants are an efficient way to implement this engagement. In this Chapter, the detailed costs and benefits of implementing a realistic virtual power plant (VPP) in Western Australia, comprising 67 dwellings, are calculated. The VPP is designed to integrate and coordinate rooftop solar photovoltaic panels (PV), vanadium redox flow batteries (VRFB), heat pump hot water systems (HWSs), and demand management mechanisms. An 810 kW rooftop solar PV system is designed and located using the HelioScope software. The charging and discharging of a 700 kWh VRFB is scheduled for everyday use over a year using an optimisation algorithm, to maximise the benefit of it for the VPP owners and for the residents. The use

[1] This chapter is based on the published journal paper of: Behnaz Behi, Ali Baniasadi, Ali Arefi, Arian Gorjy, Philip Jennings, and Almantas Pivrikas, "Cost–benefit analysis of a virtual power plant including solar PV, flow battery, heat pump, and demand management: A Western Australian case study," Energies, vol. 13, pp. 2614, 05/21, 2020, https://doi.org/10.3390/en13102614.

of heat pump HWSs provides a unique opportunity for the residents to save energy and reduce the total cost of electricity along with demand management on some appliances. The cost and benefit analysis shows that the cost of energy will be reduced by 24% per dwelling in the context of the VPP. Also, the internal rate of return for the VPP owner is at least 11% with the payback period of about 8.5 years, which is a promising financial outcome.

3.2 Introduction

The integration of renewable energy resources into energy systems is one of the aims of nations to reduce their carbon footprint and improve the sustainability of energy delivery. Therefore, some renewable energy targets are defined to enhance the speed of this integration. For example, in Australia, the contribution of renewables to electricity generation by 2020 is set as 23.5%, which is already achieved [12]. To this aim, the governments try to encourage investors and end-users to invest and use renewable resources such as solar and wind as their source of energy. In Australia, there are two schemes, which are the Large-scale Renewable Energy Target (LRET) for high energy users and the Small-scale Renewable Energy Scheme (SRES) for incentivizing individuals to install more renewable-based systems such as PV and heat pumps [13]. Considering the variability of renewable resources, the integration of a high level of green resources into the grids is very challenging in order to satisfy the technical and security requirement of the grids.

Energy aggregators such as virtual power plants (VPPs) can play a fundamental role in encouraging consumers to participate in investment and operation of renewable energy systems. VPPs are normally defined as a coordinated combination of different kinds of energy sources and flexible load demands. These resources include PV, wind, solar thermal/storage, electric vehicles, different types of electricity storage such as batteries, fuel cells, and capacitors along with some demand response capabilities, which are all monitored and controlled by an advanced ICT platform [14]. VPPs can create a platform that incentivizes the use of renewable energies by reducing the cost of energy delivery to them and by facilitating the use of controllable appliances to facilitate demand response. In addition, VPPs are able to fill the information and technology gap in the electricity market and utilities for better incorporating the end-user participants into the wholesale market and addressing technical issues in the network. VPPs can contribute to demand shaping and reducing the peak load, security and frequency control, and local power quality improvement [79]. Therefore, a VPP demonstration has been established in Australia from 2019 by the collaboration of the Australian Energy Market Operator (AEMO), the Australian Renewable Energy Agency (ARENA), the Australian Energy Market Commission (AEMC), and the Australian Energy Regulator (AER) to investigate the capabilities and effectiveness of VPPs in different ways with a forecast of total installed VPP capacity of 700 MW by 2022 [30].

VPPs can help to reduce energy consumption by encouraging the use of highly efficient appliances as discussed in [16], which shows a saving of 273 GWh per year for a VPP with the capacity of 63 MW. Although a proper modelling of energy efficiency for VPPs is provided in this reference, demand shifting, battery, and heat pumps are not considered. The Next Kraftwerke is another platform for VPP for facilitating the aggregation of customers and coordinating the available flexibilities in demand [18]. Every consumer can join this VPP regardless of its location on the network, however, there are some limitations on the benefits generated by the whole VPP. However, a detailed modelling of how this system can benefit both the owner and the consumers is not presented for this platform. The community-based VPP is also discussed and explored in [20] with the practical cases in Ireland, Belgium and the Netherlands. This research has identified four key components of VPP which are the community, the community operation rules, the portfolio of aggregated energy resources, and the coordinated roles of community members. This research focuses on the concept of a VPP and no detailed formulation on expenses and benefits for consumers and the VPP is provided. Moreover, a commercial VPP was studied in Scotland and the resource management in relation to the market price was scheduled, demonstrating an increase of 12% in VPP profit compared to the operation of a renewable plant without the establishment of VPP [21]. This research only addresses a commercial VPP not a residential one without modelling the use of heat pumps, battery and demand management. In [23], a study was conducted to provide a quantification for the economic, environmental, and social benefits of a microgrid using the economic metrics of a society, such as GDP per capita and unemployment rate. However, a framework to evaluate the affordability of a microgrid or VPP business is presented. A model of a VPP based on the electro-economical concept was proposed to integrate the dynamics of different players in a VPP in the short term [26] but it has a limitation for the long-term cost and benefit analysis of the VPP. Further, there is some literature focusing on the economics of VPPs using Homer software [27], however, these studies did not consider any connection to the wholesale electricity market as generally the corresponding VPPs were islanded microgrids.

Deferrable loads, including air conditioners and heat pumps can provide some flexibilities in VPPs; for example, a commercial building with about 46% of such flexible loads was investigated to use this capability in a DR event while keeping the comfort level of people within the standard levels [41]. This demand response from a VPP can greatly contribute to peak load shaving and therefore reduce the capital investment in pole and wire distribution networks [42]. Further, a techno-economic analysis of a VPP for a university campus was investigated in [17] and different avenues of revenue and flexibility were discussed, showing a positive business case for VPPs in urban areas. Although a suitable formulation of revenues for a VPP which interacts with the electricity market is presented in that research, no detailed analysis and formulation is provided for the residential consumers and how the VPP can benefit them. Also, the economic evaluation of VPPs in the German energy market shows that the VPP's revenue can increase by 11% to 30% by 2030 when they are engaged in the electricity market [25]. However, the role of technologies, such as flow batteries and heat pumps, are not discussed in that paper. It was also shown that a high number of renewable-based VPPs can contribute actively to the prices in the electricity market, so VPPs can play a critical role in future energy delivery systems [24]. Moreover, the impact of VPPs was analysed in Spain with the aim of maximization of self-supply and revenue from the market, showing that VPPs can greatly contribute to electricity grid and VPP operation [22]. But, in this work also, no detailed costs and benefits analysis is provided for the consumers. The aggregation of 25 micro combined heat and power devices (mCHP) within a VPP was investigated in [19] for Germany, which shows the effectiveness of this technology for cold-weather regions, but no assessment of the market-related costs and revenues is provided.

Although there is some literature on the economics of VPPs, there is a lack of detailed analysis of costs and benefits of VPP, which is specific to the situation of a country. This Chapter provides a detailed quantification of a realistic VPP, comprising 67 residential dwellings, under construction in Western Australia (WA). To the best of the authors' knowledge, there is no other study that provides such study, which is very critical for growing VPP businesses. Specifically, the contributions of this Chapter are as follows:

- Developing an affordable concept design for residential VPPs, which include a rooftop solar farm, flow battery, heat pump hot water systems, and demand management.
- Providing a detailed model for the expenses associated with a deployment of a VPP in WA including the expenses pertaining to the wholesale electricity market and to the capital expenditure.
- Developing a detailed model for the revenues of a VPP in WA including the revenues obtained by selling electricity to the wholesale electricity market and to the residents of the VPP.
- Developing an effective system for controlling battery, heat pumps, and residential demands in order to optimize the benefits for both the VPP owner and the residents.
- Investigating and modelling the economics of a real-world VPP comprising 67 residential dwellings in WA including all of the above-mentioned aspects for a VPP.
- Providing recommendations for VPP businesses and policy makers under similar market and economic situations.

This Chapter is organized as follows. Section 3.2 provides the architecture of the proposed VPP in WA. Section 3.3 presents the load modelling within the VPP. Section 3.4 discusses the methodology for the detailed formulation of expenses and revenues for the VPP. The battery and demand management algorithms are discussed in Section 3.5. Section 3.6 presents the required input parameters and assumptions for the simulation. The simulation results are provided in Section 3.7. All of the conclusions are summarized in Section 3.8.

3.3 The Proposed Architecture of the VPP

The proposed VPP comprises 67 residential dwellings in WA, with a rooftop PV farm, smart appliances, and heat pump hot water. A centralized vanadium redox flow battery (VRFB) is also installed in the VPP in order to store energy during high PV generation and low electricity market prices. Smart appliances for each home include a dishwasher, dryer, washing machine, and heat pump, which can be controlled and shifted to a planned time. There is no gas in the complex and all appliances are electric. For each home also, there is a monitoring system that measures electrical parameters of different circuits within that home. These monitoring systems collect and store data on consumptions in the cloud. These data are available to the operator of the VPP and also to the external regulators through an application programming interface (API), which is a scalable and flexible ICT configuration for VPPs [80]. The VPP control system that decides on the load, PV and battery control is also located on the cloud, which has access to PV forecasting, the AEMO wholesale market, and the weather forecast APIs. The control system manages this complex as a VPP through the proposed cloud-based data system, aggregating different energy resources to minimise the cost of electricity for residents.

Figure 3.1 shows the architecture of the proposed VPP in Berrigan Dr, South Lake, WA, next to the Lakeland Senior High School. This architecture is the simplified overview of different components in the VPP. The details for each component in this proposed structure of VPP are explained in Chapter 7. As part of the Future Market Design within the work stream of the Energy Transformation Strategy, the aggregators can be registered as a VPP in WA. The framework and requirement of registration and participation in the wholesale electricity market (WEM) are also established [81].

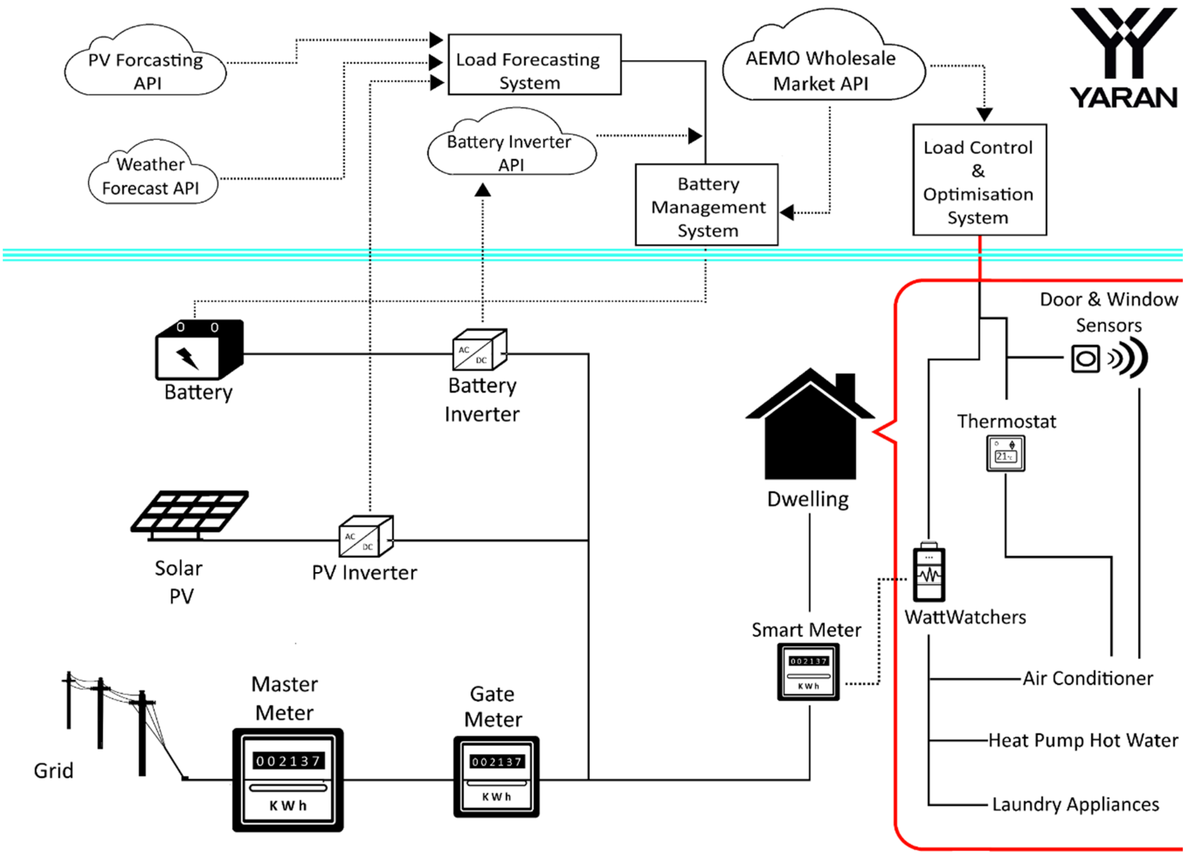

Figure 3.1. The proposed architecture of the VPP in WA.

3.3.1 Rooftop Solar Farm

In order to be a carbon negative development, the maximum rooftop solar PV is considered to be installed, which is in alignment with the benefit maximization of the VPP. The maximum rooftop installation is calculated using the HelioScope software. The simulation has shown that approximately 810 kW capacity of PV can be installed on the rooftop of the dwellings and carports, which is about one 12 kW PV system per each premise. In this design, the roof pitching is also considered to maximise PV production and minimise the shading loss. The location of PV systems for the whole complex from the simulation results by HelioScope is provided in **Figure 3.2**. The total PV generation during a year within the VPP is 1,190,689 kWh, with the most monthly generation during summer and spring months, for example, in November, December and January as shown in **Figure 3.3**. In order to validate the PV generation simulation by HelioScope, the real

PV output data measured from the two nearest available sites [82] to the VPP in WA were averaged as shown in **Figure 3.3**. As can be seen, the simulation of PV generation is very close to the real data but a bit less than real data in most of the months. The difference is mainly due to the orientation of dwellings in the VPP, so not all of PV panels are oriented in the optimal direction to maximise the PV output. The type of PV module utilised in this project is the Canadian Solar, CS6K-305MS with the nameplate of 305W power output. The yearly average Global Horizontal Irradiances (GHI) for clear sky and for the shaded case are 161.2 and 160.8 kWh/m^2, respectively.

In this analysis, the environmental condition is based on the data collected from the Jandakot Airport station, provided from www.weatherspark.com. The average daily high temperature during the hot season (from 19 December to 20 March) is above 28°C with February as the hottest month. The average daily high temperature during the cool season (from 26 May to 26 September) is below 20°C with July as the coldest month. The average wind speed during windier months (from 31 October to 21 March) is more than 20.7 km/h with January as the windiest month of the year with an average hourly wind speed of 22.6 km/h (South). Also, the average wind speed during calmer months (from 21 March to 31 October) is 19.7 km/h with April as the calmest month of the year with the wind speed of 18.9 km/h (East). The wind speed is measured at 10m above the ground. The total area of the site is about 28,000 m^2.

The PV system of the complex is designed as a fully embedded network, whereby energy generated by any of the houses' PV systems can be used by all dwellings within the development. Also, the VPP operator can decide on charging the battery using excess PV generation or exporting energy to the WEM depending on the situation and the electricity price.

Figure 3.2. The proposed architecture of the VPP in WA

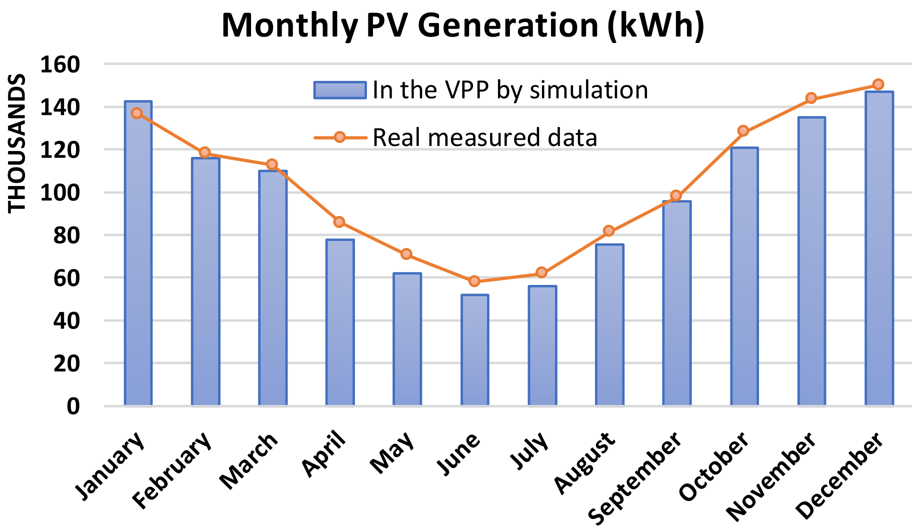

Figure 3.3. The PV generation during a year within the VPP compared to the real data measured in WA.

3.3.2 Vanadium Redox Flow Battery (VRFB)

The use of energy storage will improve the integration of renewable energy as it provides an opportunity for storing the energy and exporting when needed [83]. VRFB is an electrochemical energy storage which is based on a reversible chemical reaction within a sealed electrolyte, in which energy is stored in a liquid vanadium electrolyte, a mixture of distilled water, vanadium salts and sulphuric acid [84]. The liquid that carries energy, will be pumped between two tanks through electrochemical cells. The larger tanks are able to store more energy and they are organized in cells and cell stacks within the VRFB. The energy is charged or discharged in the electrolyte based on the level of applied voltage.

The VRFB has favourable specifications such as long lifetime, e.g. 20,000 cycles, at a reasonable price and fast charging and discharging capabilities that help contribute to grid security and reliability [85, 86]. At the end of a VRFB's nominal lifetime, it is just required to replace the liquid instead of replacing the whole battery system, which is another advantage of this battery compared to lithium-ion or lead-acid batteries. Moreover, the energy and power of the installed VRFB is scalable independently, which is usually not the case for the other types of batteries. Further, the electrolyte is not explosive or flammable, and can be recycled easily at the end of its lifetime. VRFB can achieve 100% charge level with negligible self-discharge inside the battery, which is a limitation for most Li-ion or lead-acid batteries. Also, the life cycle of VRFBs is more environmentally friendly than that of Li-ion or lead-acid batteries, as 100% recycling of vanadium electrolyte can be achieved while there are severe environmental impacts for the lead and lithium technologies [87]. Another advantage of VRFB over other types of battery is very low degradation, so it is possible to maintain the same capacity as the original capacity. In addition, the VRFB is also more affordable for longer duration of storage than Li-ion or lead-acid batteries [87]. Considering all the benefits and specifically the longer lifetime of VRFB, (e.g. 20 years or the equivalent cycles, compared to other types of lithium- or nickel-based batteries or lead-acid batteries, normally 10 to 15 years), the manufacturers can provide a longer term warranty for VRFBs, which is very important for the economic feasibility of the VPP.

Therefore, VRFB was chosen for electricity storage in this project. The size of VRFB in the VPP, considering the available budget, was chosen to be 700 kWh, 350 kW. The technical requirements are satisfied with the chosen size of VRFB

3.3.3 Heat Pump Hot Water System

A heat pump hot water system (HWS) can transfer heat from air, water, or underground to the water stored in its tank. The heat available in the outdoor air is extracted by a heat exchanger/evaporator and transferred to a refrigerant [88]. Then using a compressor, the temperature of the refrigerant will be increased for heating up the water in the tank. The compressor does not consume a lot of energy, so using one unit of consumed electrical energy, it is possible to transfer up to five units of environmental energy for heating purposes. Therefore, compared to other technologies of hot water such as electric or gas HWS with storage or instant option, a heat pump provides better energy efficiency [89]. Also, investment on both electricity and thermal storage can reduce the total life cycle cost of energy delivery significantly, for example by 40% [90].

The suitable control of the heat pump in conjunction with the PV generation will bring benefits to the VPP in terms of energy efficiency, energy cost reduction for consumers and interaction with electricity grids [91, 92]. The use of heat pumps for storing energy at the lower electricity price in the electricity market also shows another benefit of this technology for the VPP [93]. Considering the benefits of heat pump HWS for the VPP operator and for the resident, in this project, a heat pump is provided for each dwelling. A size of 220 litres was selected for each HWS after considering the average usage of hot water in the area [94]. This system can generate average heating output of 1.6kW at the ambient temperature between -5 to 42^{O}C while the electricity consumption of the unit is only 0.55kW.

3.4 Load Modelling

This section provides the load modelling of 67 residential homes in the VPP. A detailed modelling of different loads including the power consumption and hours of working, considering the situation in Australia, is prepared for this VPP [94-97]. **Table 3.1** to **Table 3.4** show the electricity loading of different appliances and also major loads in different seasons.

In order to generate the annual load profile for the households in the VPP, load uncertainties of non-controllable appliances are considered and modelled using Monte Carlo Simulation (MCS). MCS can provide daily load profiles based on the information in **Table 3.1** to **Table 3.4** and the level of uncertainties set in the simulation.

Figure 3.4 shows the load profile and PV production for a sample week in summer, generated by MCS. Also, **Figure 3.5** illustrates the contributions of different appliances and their variation in different seasons.

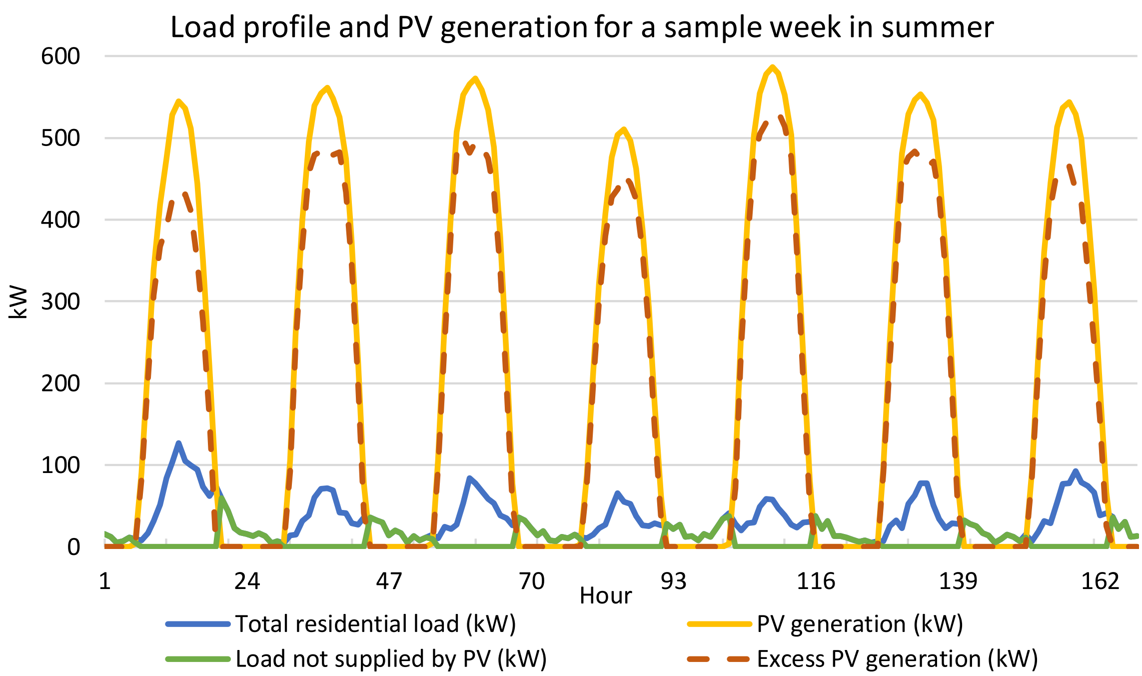

Figure 3.4. The load profile and PV production for a sample week in summer, Excess PV generation is equal to PV generation minus the total load.

Table 3.1. Daily appliance consumption in weekdays and weekends

Appliance	Weekday	Weekend	Usage time	Watts
Coffee maker	40% at 6-10am 30% at 4-7pm	40% at 8-10am 30% at 4-7pm	10min	900-1400
Microwave	40% at 7-10:30am; 20% at 12-2pm; 20% at 6-8pm	40% at 7-10:30am; 20% at 12-2pm; 20% at 6-8pm	5min	750-1100
Toaster	50% at 6-10:30am; 10% at 11.30-1pm; 10% at 6-8pm	50% at 8-10:30am; 10% at 11.30-1pm; 10% at 6-8pm	3min	800-1400
Iron	5% at 7-8am; 5% at 10-11am; 5% at 6-8pm	5% at 10-11am; 5% at 6-8pm	15min	1000-1800
Stereo system	10% at 9am-1pm; 20% at 4-10pm	20% at 9am-4pm; 40% at 4-10.30pm	30-90 min†	65-225
Hair dryer	30% at 5.30-9:30am; 10% at 11.30-1pm; 30% at 8-10pm	10% at 11.30-1pm; 40% at 7.30-10.30pm	5min	1200-2000
Laptop	50% at 10.30am-2am	50% at 10.30am-2am	90-180 min†	50
PC/monitor	30% at 9.30am-9pm	40% at 9.30am-9pm	90-180 min†	150
Television	30% at 9.30am-2am 20% at 6-11pm	30% at 9.30am-2am 50% at 6-11pm	90-180 min†	65-175
Refrigerator, Freezer	100% All time (thermostatically controlled)	100% All time (thermostatically controlled)	*Cont.*	100-200
Vacuum	10% at 9am-5pm	15% at 9am-5pm	30min	600-1800
Deep Fryer	10% at 11-2pm 15% at 5-8pm	10% at 11-2pm 15% at 5-8pm	18min	600-1000
Oven	20% at 10.30am-12.30am 25% at 5.30-8.30pm	30% at 10.30am-12.30am 25% at 5.30-8.30pm	44min	1000-1800
Kettle	30% at 7:30-10.30am 40% at 1.30-4.30pm 10% at 6-8pm	30% at 7:30-10.30am 40% at 1.30-4.30pm 10% at 6-8pm	3min	2000-2500
Stove	20% at 7-9am 20% at 10.30am-1.30pm 20% at 5.30-8.30pm	10% at 7-9am 20% at 10.30am-1.30pm 20% at 5.30-8.30pm	30min	1000-2000
Dishwasher*	40% at 10.30am-3.30pm	60% at 10.30am-3.30pm	20-60 min†	1200-2400
Washing machine*	10% at all time except 3-9pm	20% at all time except 3-9pm	20-60 min†	500-1300

* the timing is different whether demand management is applied to the appliances or not.
† the time is randomly chosen between the minimum and maximum values in each day.

Table 3.2. Major load variations in spring/autumn

Appliance	Weekday	Weekend	Watts
Lighting	70% at 6pm-11pm 10% at 5-7.30am 10% at 8pm-3am	70% at 6pm-11pm 25% at 8pm-1am	10-100
Heat pump HWS	75% at 9.30am-4pm	75% at 9.30am-4pm	550
Air conditioner	60% at 6am-10am 65% at 5pm-10pm 50% other	60% at 6am-10am 65% at 5pm-10pm 55% other	1000- 3000

Table 3.3. Major load variations in summer

Appliance	Weekday	Weekend	Watts
Lighting	70% at 7pm-11pm 10% at 5-7.30am 10% at 8pm-3am	70% at 7pm-11pm 25% at 8pm-3am	10-100
Heat pump HWS	70% at 9.30am-4pm	70% at 9.30am-4pm	550
Air conditioner	60% at 11am-4.30pm 80% at 4.30pm-10pm 50% other	70% at 11am-4.30pm 85% at 4.30pm-10pm 55%other	1000- 3000

Table 3.4. Major load variations in winter

Appliance	Weekday	Weekend	Watts
Lighting	70% at 5pm-11pm 10% at 5-7.30am 10% at 8pm-1am	70% at 5pm-11pm- 20% at 8pm-1am	10-100
Heat pump HWS	80% at 9.30am-4pm	80% at 9.30am-4pm	550
Air conditioner	60% at 6am-5pm 70% at 5-12pm 55% other	70% at 6-5am 80% at 5-12pm 60% other	1000- 3000

3.4.1 Air Conditioning Load

The heating and cooling load for a building is determined based on the ambient temperature, solar radiation, building thermal mass, internal heat gain, thermal load disturbance, and the comfort level of residents. Indoor temperature is regulated by using thermostats. The state of the on/off relay can be determined by the hysteresis control rule in cooling mode as follows [98]:

$$\mathbb{U}(t) = \begin{cases} 0, & if\ \mathbb{U}(t - \Delta t) = 1, \quad T_{in} < T_{in,min} \\ 1, & if\ \mathbb{U}(t - \Delta t) = 0, \quad T_{in} > T_{in,max} \\ \mathbb{U}(t - \Delta t), & otherwise \end{cases} \tag{3.1}$$

where T_{in} is the indoor temperature which is function of outdoor temperature, solar radiation, internal heat gain, and building thermal mass. $T_{in,max}$ and $T_{in,min}$ are upper and lower boundaries of temperature set-point. $\mathbb{U}$ is the discrete state of the relay which switches the heat distributor on and off; according to the hysteresis control rule.

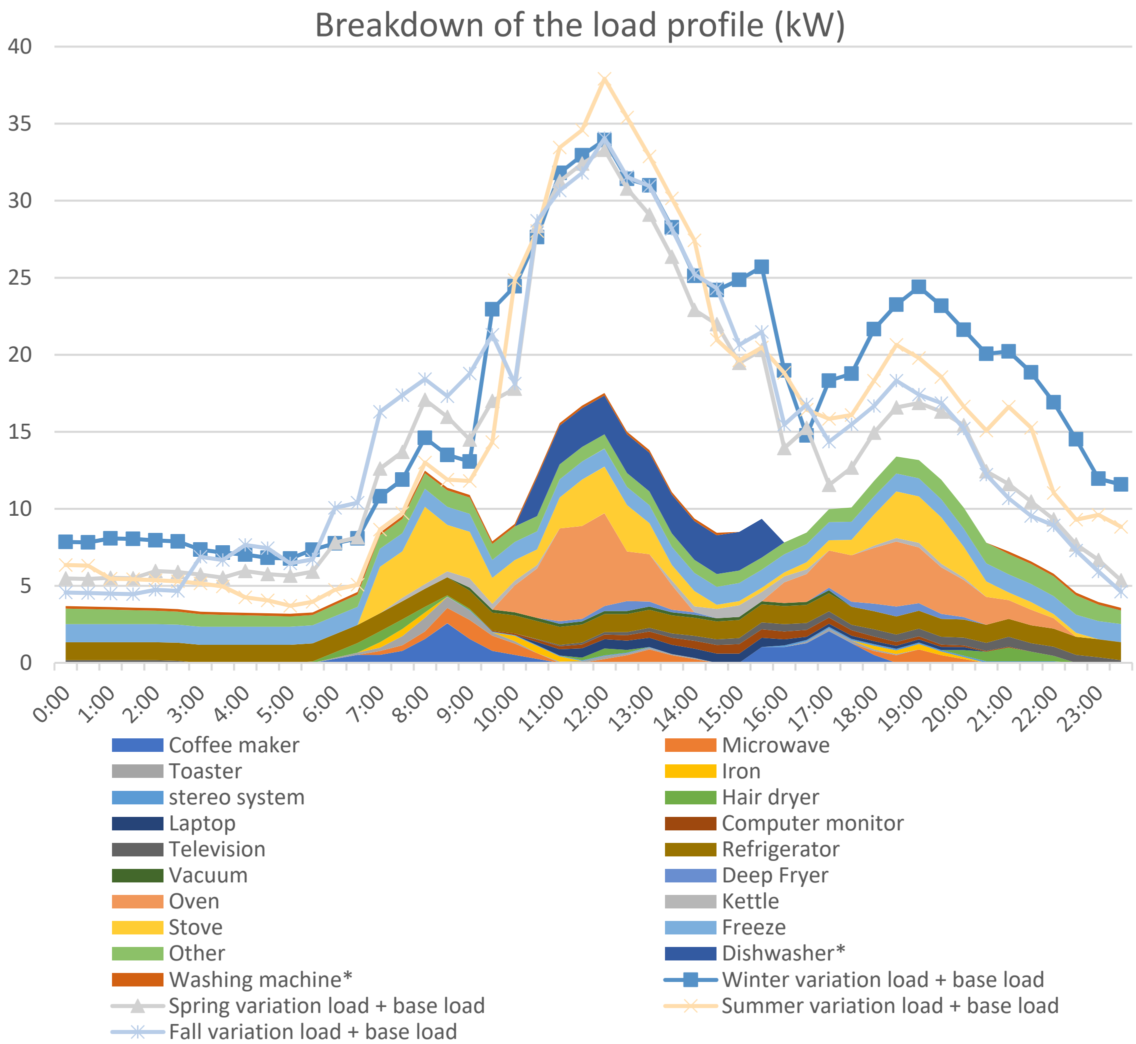

Figure 3.5. The simulated load profiles and the variations in different seasons.

Buildings are modeled by the heat dynamic state space model [90, 92]:

$$\begin{bmatrix} \dot{T_l} \\ \dot{T_{in}} \end{bmatrix} = \begin{bmatrix} \frac{-1}{R_{in}C_l} & \frac{1}{R_{in}C_l} \\ \frac{1}{R_{in}C_{in}} & -(\frac{1}{R_{io}C_{in}} + \frac{1}{R_{il}C_{in}}) \end{bmatrix} \begin{bmatrix} T_l \\ T_{in} \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{1}{C_l} \end{bmatrix} \mathbb{U} Q_a + \begin{bmatrix} 0 & 0 & 0 \\ \frac{-1}{R_{in}C_l} & \frac{-1}{R_{in}C_l} & \frac{-1}{R_{in}C_l} \end{bmatrix} \begin{bmatrix} T_o \\ S_r \\ I_g \end{bmatrix} \tag{3.2}$$

where R_{in}, C_l, C_{in} and R_{il} are thermal parameters of the building, and Q_a is the heat transfer rate of the air conditioner. The daily thermal demand is calculated based on the building model, as presented in (3.2). In each time step, the updated indoor temperature ($\dot{T_{in}}$) and building lumped thermal mass temperature ($\dot{T_l}$) are calculated based on the present temperatures, solar radiation (S_r), outdoor temperature (T_o), and the heat gain (I_g).

In this VPP complex, the comfort temperatures for occupants are considered as 24-26^{O}C degree for summer and 20-22^{O}C for winter. For each of 67 homes in this VPP, a split air conditioner of 2.7 kW with a coefficient of performance (COP) of 3 is considered. Then the annual load profile is generated for the air conditioning load, as shown in **Figure 3.6**. Note that the number of active air conditioners is determined based on **Table 3.2** to **Table 3.4**.

3.5 The Formulation of Expenses and Revenues

3.5.1 The Expenses of the VPP

This section provides a detailed list and formulation of expenses for the VPP. The total net present value (NPV) of expenses over the period of planning (horizon year) is formulated as below:

$$C_{tot} = C_{WEM} + C_{CAPEX} \tag{3.3}$$

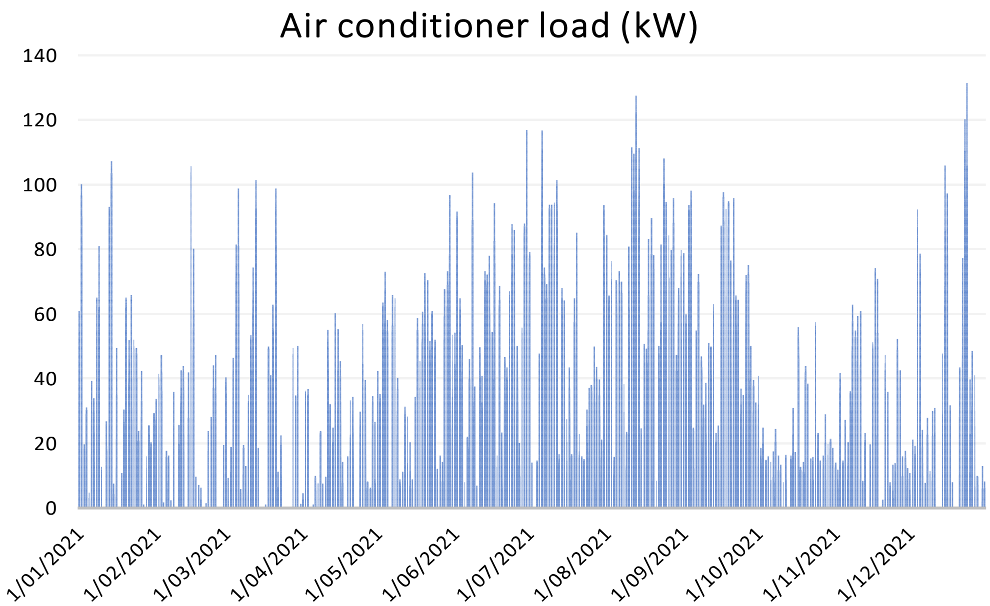

Figure 3.6. The simulated air conditioner load profile

where C_{WEM} is the total NPV of WEM-related expenses and C_{CAPEX} is the total NPV of capital expenditure (CAPEX) expenses.

The total NPV of WEM-related and CAPEX-related expenses are formulated as below:

$$C_{WEM} = \sum_{y=1}^{HY} C_{WEM}^{y,NPV} = \sum_{y=1}^{HY} C_{E,in}^{y,NPV} + C_{Ret,in}^{y,NPV} + C_{Ret,out}^{y,NPV} + C_{TC}^{y,NPV} + C_{LF}^{y,NPV} + C_{CER}^{y,NPV} + C_{AS}^{y,NPV} + C_{MF}^{y,NPV} + C_{SC}^{y,NPV} \quad (3.4)$$

$$C_{CAPEX} = C_{PV}^{NPV} + C_{VRFB}^{NPV} + C_{HP}^{NPV} + C_{Trans}^{NPV} + C_{Meters}^{NPV} + C_{Design}^{NPV} \quad (3.5)$$

The definition of the WEM-related expenses and costs are provided as below [99]:

- $C_{WEM}^{y,NPV}$ is the NPV of the WEM-related expenses at yth year;
- HY is the horizon year and y is the index for the year;
- $C_{E,in}^{y,NPV}$ is the NPV cost of purchasing energy from the WEM balancing market at

yth year, which is formulated as:

$$C_{E,in}^{y,NPV} = \frac{1}{(1+i)^y} \sum_{h=1}^{8760} E_{in}^{y,h} \pi^{y,h} \quad (3.6)$$

where $E_{in}^{y,h}$ is the purchased energy from WEM and $\pi^{y,h}$ is the WEM electricity price at hth hour of yth year, i is the interest year. The coefficient $\frac{1}{(1+i)^y}$ is applied here to convert the cost at year y to the net present value.

- $C_{Ret,in}^{y,NPV}$ is the NPV cost of the retailer margin expense associated with the purchase from the WEM. This cost is calculated as a percentage, namely α^y in this Chapter, of the cost of purchasing energy from the WEM and formulated as:

$$C_{Ret,in}^{y,NPV} = \alpha^y C_{E,in}^{y,NPV} \quad (3.7)$$

- $C_{Ret,out}^{y,NPV}$ is the NPV cost of the retailer margin expense associated with the export from the VPP to the WEM. This cost is also calculated as a percentage (α^y) of the NPV of the revenue from selling energy to the WEM, namely $R_{WEM}^{y,NPV}$ here, and formulated as:

$$C_{Ret,out}^{y,NPV} = \alpha^y R_{E,WEM}^{y,NPV} \quad (3.8)$$

- $C_{TC}^{y,NPV}$ is the NPV of the energy tariff charge, which is calculated based on the tariff that is applied to the VPP. In this case the applied tariff is RT16 [100], which is for the business customers with the time of use (TOU) bi-directional service, and it is formulated as below. $\omega^{y,h}$ is the energy tariff price at the hour h of year y.

$$C_{TC}^{y,NPV} = \frac{1}{(1+i)^y} \sum_{h=1}^{8760} E_{in}^{y,h} \omega^{y,h} \quad (3.9)$$

- $C_{LF}^{y,NPV}$ is the NPV cost of the loss factor, which is calculated as a constant coefficient (β^y equal to 0.0603 for 2019-2020) times the NPV of the network charge in each year, which is :

$$C_{LF}^{y,NPV} = \beta^y C_{TC}^{y,NPV} \quad (3.10)$$

- $C_{CER}^{y,NPV}$ is the Clean Energy Regulator fee, which is applied to the big customers, proportional to the energy imported from the grid. The fee is γ^y AUD per kWh purchased from the grid in each year, namely E_{in}^y, and formulated as below. γ^y is 0.02256 AUD per kWh for 2019-2020.

$$C_{CER}^{y,NPV} = \frac{1}{(1+i)^y} \gamma^y E_{in}^y \tag{3.11}$$

- $C_{AS}^{y,NPV}$ is the ancillary service fee, which is a constant percentage of the energy imported from the grid. The fee is δ^y AUD per kWh purchased from the grid in each year and formulated as below. δ^y is 0.00372 AUD per kWh for 2019-2020.

$$C_{AS}^{y,NPV} = \frac{1}{(1+i)^y} \delta^y E_{in}^y \tag{3.12}$$

- $C_{MF}^{y,NPV}$ is the market fee, which is a constant percentage of the energy imported from the grid. The fee is $\theta^y = 0.001029$ AUD per kWh for 2019-2020.

$$C_{MF}^{y,NPV} = \frac{1}{(1+i)^y} \theta^y E_{in}^y \tag{3.13}$$

- $C_{SC}^{y,NPV}$ is the daily supply charge, which is a constant daily charge as per the tariff of RT16. This charge is $\vartheta^y = 2.9958$ AUD per day for 2019-2020, which is applied for all 365 days of a year.

$$C_{SC}^{y,NPV} = \frac{1}{(1+i)^y} \vartheta^y \times 365 \tag{3.14}$$

The formulation of CAPEX-related costs is also presented here.

- C_{PV}^{NPV} is the cost associated with the PV system during the project, including the cost of PV panels ($C_{PV,panel}^{NPV}$), inverter ($C_{PV,inverter}^{NPV}$), installation and commissioning ($C_{PV,inst}^{NPV}$), and PV panel maintenance ($C_{PV,OM}^{NPV}$) such as annual washing and cleaning. $R_{PV,STC}^{NPV}$ is the small-scale technology certificate (STCs) rebate calculated based on [101], which is granted as an incentive to those who install solar systems. Although this is revenue for the VPP, it is located here with other costs of PV for the sake of clarification. If the horizon year is no longer than the lifetime of the PV panels, the NPV cost of PV panels and the associated installation cost are equal to the investment cost at the beginning of the project. As the lifetime of inverters, e.g. 12 years, is shorter than the lifetime of PV panels, e.g. 20 years, it is required to replace the inverters during the life of the project. In this case, we need to consider the cost of the inverter in year 12 for example and calculate the corresponding NPV cost. $\mu_{PV,OM}^{y}$ is the maintenance cost of PV panels per dwelling in year y

$$C_{PV}^{NPV} = C_{PV,panel}^{NPV} + C_{PV,inverter}^{NPV} + C_{PV,inst}^{NPV} + C_{PV,OM}^{NPV} - R_{PV,STC}^{NPV}$$

$$C_{PV,OM}^{NPV} = \sum_{y=1}^{HY} \frac{1}{(1+i)^{y}} \times 67 \times \mu_{PV,OM}^{y} \tag{3.15}$$

- C_{VRFB}^{NPV} is the cost associated with the VRFB system, including the cost of the battery ($C_{VRFB,batt}^{NPV}$), the cost of maintenance ($C_{VRFB,OM}^{NPV}$) and the cost of installation ($C_{VRFB,inst}^{NPV}$) such as designing and constructing a slab and foundations for the battery. The 20 year warranty is included in the price of the VRBF. $\varphi_{VRFB,OM}^{y}$ is the maintenance cost of the VRFB in year y.

$$C_{VRFB}^{NPV} = C_{VRFB,batt}^{NPV} + C_{VRFB,inst}^{NPV} + C_{VRFB,OM}^{NPV}$$

$$C_{VRFB,OM}^{NPV} = \sum_{y=1}^{HY} \frac{1}{(1+i)^{y}} \times \varphi_{VRFB,OM}^{y} \tag{3.16}$$

- C_{HP}^{NPV} is the cost of heat pump HWS for 67 dwellings. The government provides a rebate for the use of heat pumps as well [102] so the cost is adjusted based on this incentive. Also, the difference between the cost of heat pump and instantaneous electric HWS is considered in the NPV calculations;

- C_{Trans}^{NPV} is the cost of the power transformer and associated cabling and protection system that connects the VPP to the grid;
- C_{Meters}^{NPV} is the cost of the smart meters for 67 dwellings including the cloud storage for monitoring, auditing and control purposes;
- C_{Design}^{NPV} is the cost of design of the embedded network, communication and electrical design.

3.5.2 The Revenues of the VPP

The revenues of the VPP come from selling energy to the WEM, R_{WEM}, and also to the residents, R_{RES}, which is formulated as below:

$$R_{tot} = R_{WEM} + R_{RES} \tag{3.17}$$

$$R_{WEM} = \sum_{y=1}^{HY} R_{WEM}^{y,NPV} = \sum_{y=1}^{HY} R_{WEM,RC}^{y,NPV} + R_{E,WEM}^{y,NPV}$$

$$R_{E,WEM}^{y,NPV} = \frac{1}{(1+i)^y} \sum_{h=1}^{8760} E_{out}^{y,h} \pi^{y,h} \tag{3.18}$$

$$R_{WEM,RC}^{y,NPV} = \frac{1}{(1+i)^y} \rho_{RCC}^{y} P_{RCC}^{y}$$

where $R_{WEM}^{y,NPV}$ is the NPV of the revenue from selling energy to the WEM, $E_{out}^{y,h}$ is the the energy exported to the WEM at hour h of year y. $R_{WEM,RC}^{y}$ is the reserve capacity revenue calculated based on the reserve capacity credit (RCC), namely P_{RCC}^{y}, assigned to the VPP and the price (ρ_{RCC}^{y}) AUD/MW/year associated with it. For 2019-2020, the price of RCC is 146,994.24 AUD/MW/year [103].

R_{RES} is the NPV of the revenues from selling energy to the 67 dwellings, which comprises of two revenues; resident supply charge and energy consumption charge. This revenue is formulated as:

$$R_{RES} = \sum_{y=1}^{HY} R_{RES}^{y,NPV}$$

$$= \sum_{y=1}^{HY} \frac{1}{(1+i)^{y}} \times 365 \times (67 \times \sigma_{RES,SC}^{y} + \sum_{h=1}^{24} E_{RES}^{y,h} \tau_{RES,E}^{y,h}) \quad (3.19)$$

Where $\sigma_{RES,SC}^{y}$ is the resident supply charge in AUD/day at the yth year, $E_{RES}^{y,h}$ is the total energy consumption by 67 dwellings and $\tau_{RES,E}^{y,h}$ is the price of electricity sold to the residents at hth hour of the yth year. The price of electricity to the residents is considered at the lower price compared to the other electricity providers in the region.

Using the revenue of R_{RES}, the average electricity cost per dwelling can also be calculated as below:

$$C_{RES}^{ave} = \frac{R_{RES}}{67} \quad (3.20)$$

3.5.3 The Profit of the VPP

After calculating the total NPV of expenses and revenues of the VPP, the net NPV profit of the VPP operator is expressed as:

$$B_{tot} = R_{tot} - C_{tot} \quad (3.21)$$

3.6 Battery and Demand Management

3.6.1 Demand Management

As the major appliances of the dwellings in this VPP are smart and can controlled, some of those presented in **Table 3.5** are considered for demand management (DM). These appliances can be programmed in order to manage at which hours they are available for normal working. The residents have the right to override the rules that the appliances are already programmed for.

Table 3.5. Manageable/Shiftable loads

Appliance	Working time
Dishwasher	Between 10 and 16 hours
Dryer and washing machine	Any time except 15-21 hours
Heat pump HWS	Between 9 and 17 hours

3.6.2 Battery Management

In order to maximise the benefit achievable from the battery for the VPP and the residents, an efficient charging and discharging of the VRFB is important. To achieve this aim, it is critical to identify whether charging from excess PV is beneficial or not and whether discharging at which hour is more effective.

First, two parameters are defined here:

a) the revenue per kWh of selling excess PV to WEM at hth hour of yth year, which is equal to the opportunity cost of not selling excess PV to WEM, which is defined as below:

$$rev/kWh^{y,h} = \frac{E_{out}^{y,h}\pi^{y,h} - C_{Ret,out}^{y,h}}{E_{out}^{y,h}} = \frac{E_{out}^{y,h}\pi^{y,h} - E_{out}^{y,h}\pi^{y,h}\alpha^{y}}{E_{out}^{y,h}} = \pi^{y,h}(1-\alpha^{y}) \tag{3.22}$$

b) the cost of purchasing one kWh energy at the hth hour of the yth year for charging the battery at non-PV hours, which is equal to the avoided cost of not purchasing energy from the grid at RT16, which is calculated as:

$$cost/kWh^{y,h} = \frac{C_{E,in}^{y,h} + C_{Ret,in}^{y,h} + C_{TC}^{y,h} + C_{LF}^{y,h} + C_{CER}^{y,h} + C_{AS}^{y,h} + C_{MF}^{y,h}}{E_{in}^{y,h}}$$

$$= \frac{E_{in}^{y,h}\pi^{y,h} + \alpha^{y} E_{in}^{y,h}\pi^{y,h} + E_{in}^{y,h}\omega^{y,h} + \beta^{y} E_{in}^{y,h}\omega^{y,h} + \gamma^{y} E_{in}^{y,h} + \delta^{y} E_{in}^{y,h} + \theta^{y} E_{in}^{y,h}}{E_{in}^{y,h}}$$

$$= \pi^{y,h}(1+\alpha^{y}) + \omega^{y,h}(1+\beta^{y}) + \gamma^{y} + \delta^{y} + \theta^{y} \tag{3.23}$$

It is assumed that the daily forecast of electricity price is available through the corresponding API from the AEMO [104]. Also, it is considered that state of charge

(SOC) of the battery is zero at the beginning and the end of each day because the VRFB technology that enables the battery to discharge 100% is available, and now more manufacturers are providing this capability (For example, the VRFBs by the VSUN company in Australia, https://vsunenergy.com.au/technical-info/). It means that one full charge and one full discharge is scheduled every day. For example, if the opportunity cost of not selling excess PV to the WEM ($rev/kWh^{y,h}$) < cost of purchasing energy for charging the battery at hours without PV generation, namely non-PV hours, ($cost/kWh^{y,h}$): The VRFB is charged from excess PV. In the case of multiple hours with excess PV, which satisfies this condition, this is sorted based on their $rev/kWh^{y,h}$ and the VRFB is scheduled for charging at the lowest $rev/kWh^{y,h}$. **Figure 3.7** shows the opportunity costs during PV generation and the cost of charging during non-PV hours. Also, it shows the priority of hours for charging from 1 to 10. As seen, the cheapest hours for charging are 7am, 8am, and 12pm, in which the battery is charged using excess PV. If there is not enough PV excess in the priority hours, then the battery can be charged in non-PV hours. It is important to note that not all PV hours are suitable for charging as, for example, the cost of hours 1pm to 3pm during PV generation is higher than the cost of charging at 1am to 3 am. The VRFB is also discharged when the total revenue is maximised, which is formulated as the revenue gained from the avoided cost of not purchasing k_1 units of energy from grid at RT16 to supply the load + selling k_2 units to the WEM, which is equal to $k_1 cost/kWh^{y,h} + k_2 rev/kWh^{y,h}$.

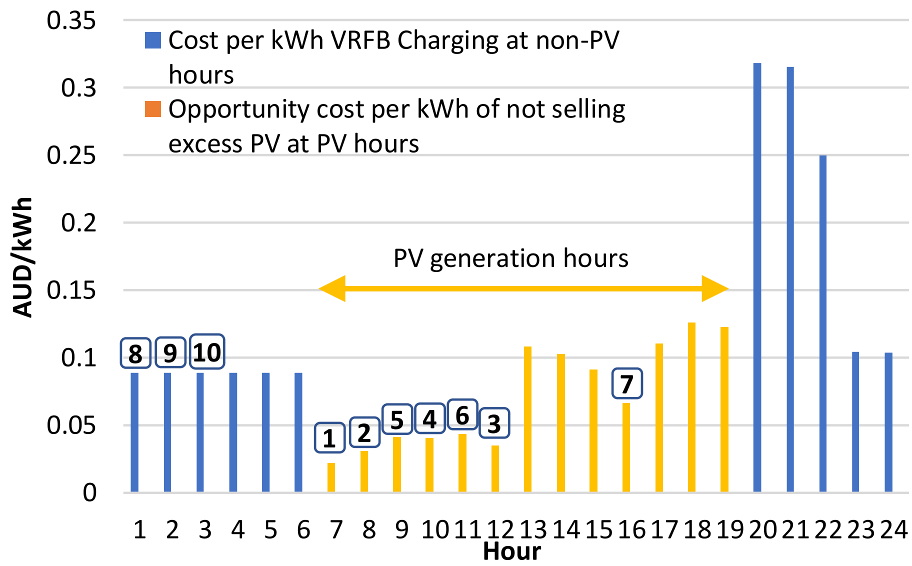

Figure 3.7. The charging hour priority for the VRFB for a sample day

In order to maximise the benefit of VRFB, charging and discharging, the charging/discharging scheduling needs to be optimized for each day. The optimisation problem is formulated as below in which the total cost of daily charging/discharging is minimised. In this formulation, $x^{y,h}$ is the VRFB power at the hth hour and yth year for which the positive and negative signs represent charging and discharging, respectively.

$$minimize \left(\sum_{h=1}^{24} HourPrice^{y,h}\right), \qquad \forall y$$

$$HourPrice^{y,h} = \begin{cases} x^{y,h} rev/kWh^{y,h} & x^{y,h} > 0 \; during \; PV \; hours \\ x^{y,h} cost/kWh^{y,h} & x^{y,h} > 0 \; during \; non-PV \; hours \\ k_1 cost/kWh^{y,h} + k_2 rev/kWh^{y,h} & x^{y,h} < 0 \end{cases} \tag{3.24}$$

$$k_1 = \min\left(EnPV_{RES}^{y,h}, |x^{y,h}|\right), \qquad k_2 = |x^{y,h}| - k_1$$

Constraints:

$$\sum_{h=1}^{24} x^{y,h} = 0 \;, \;\; \forall y$$

$$\sum_{h=1}^{hour} x^{y,h} \geq 0 \ , \qquad \forall \ hour = 1 \dots 24 \ , \forall y$$

$$\sum_{h=1}^{24} \left| x^{y,h} \right| \leq 2E_{VRFB}^{max} \ , \forall y$$

$$-P_{VRFB}^{max} \leq x^{y,h} \leq P_{VRFB}^{max} \ , \forall y$$

where E_{VRFB}^{max} and P_{VRFB}^{max} are the maximum allowable stored energy and charging/discharging power for the VRFB. and $EnPV_{RES}^{y,h}$ is the dwelling load that is not supplied by PV. The charging/discharging problem is optimised by the *fmincon* function in MATLAB, whose parameters are provided in **Table 3.6**.

Table 3.6. The parameters of the *fmincon* function in Matlab

Parameter	Value
Algorithm	SQP
Constraint Tolerance	1e-20
Optimality Tolerance	1e-20
Step Tolerance	1e-20
Max Iterations	1000
Max Function Evaluations	50,000

3.7 Input Parameters and Assumptions

The WEM electricity price for one year is obtained from the AEMO website. In the simulation, the noise of price forecast is considered to be 10%. The costs of major equipment are provided in **Table 3.7**. Also, the costs of the RT16 tariff are presented in **Table 3.8** [100]. The tariff of the VPP for the residents is based on the TOU tariff considering the local electricity retailer. However, this tariff is customised by providing an incentive to the customers within the VPP, which is that the cost of electricity between 10 am and 2pm is zero, as indicated in **Table 3.9**. The major loads, including washing machines, dryers, dishwashers, and heat pumps can run during this time. This tariff structure in other Chapters such as in Chapters 5 and 6 is different, in which the flat tariff is considered in those Chapters to evaluate different types of tariff structure within the VPP and to assess the viability of that for the customers and for the VPP owner.

The STC rebate for PV and heat pump are calculated to be about 414,000 AUD and 70,000 AUD, respectively. The horizon year is 20 years.

Table 3.7. The costs of the equipment

Equipment	AUD
PV, 810kW	530,000 (life time = 25 years)
Inverters for 810kW PV	124,000 (replacement at year 11)
PV installation	500,000
VRFB, 350kW, 700kWh	600,000, Payable in 4 instalments over 4 years (calendar lifetime = 25 years)
Battery installation	30,000
67 x Heat pump HWS, 220 litre	165,000

Table 3.8. The costs of the RT16 tariff

Fixed cost (cents/day)	Peak (cents/kWh): 8am to 10pm, Monday to Friday	Off-peak (cents/kWh): 10pm to 8am, Monday to Friday and All times on Saturday and Sunday
299.580	15.954	3.646

Table 3.9. The tariff of the VPP for the residents

Fixed cost (cents/day)	Peak (cents/kWh): 4pm to 10pm	Shoulder (cents/kWh): 8am to 4pm	Off-peak (cents/kWh): 10pm to 8am	Free electricity: 10am to 2pm
103.3263	54.81	28.71	15.10	0.00

3.8 Simulation Results

In this Section, the simulation of the proposed VPP in WA is described, and the expenses and the revenues of the VPP in four different cases are discussed. The case studies are defined as:

Case I: the VPP with heat pump and DM

Case II: the VPP with heat pump without DM

Case III: the VPP without heat pump (instead instant electric HWS is used.) with DM for dishwasher, dryer, and washing machine

Case IV: the VPP without heat pump and without DM

3.8.1 Comparison of different Cases

Figure 3.8 shows the average annual energy cost per dwelling with and without VPP in AUD.

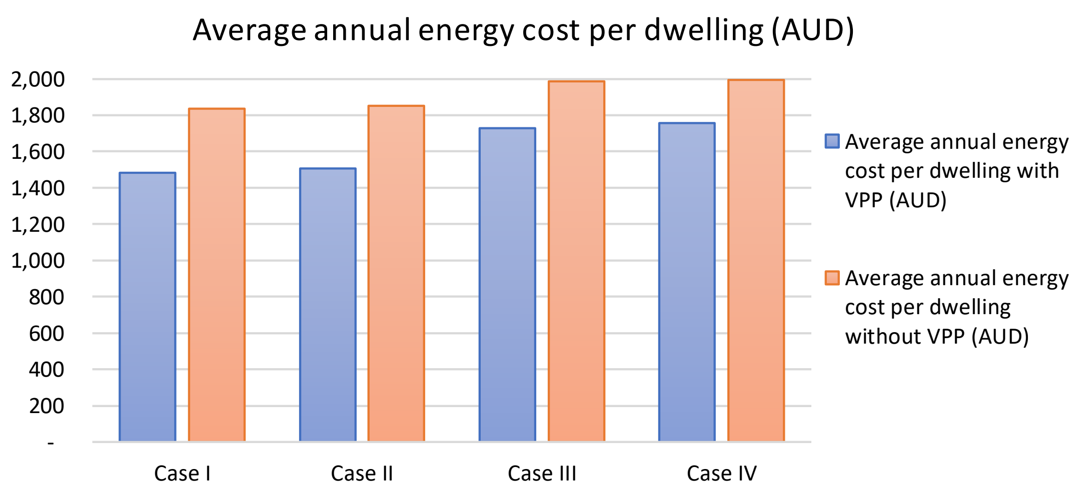

Figure 3.8. The average annual energy cost per dwelling with and without VPP (AUD)

As seen, the cost of electricity with VPP in Case I is lower than all other cases as energy efficient heat pumps and demand management are implemented in this case. For example, the annual cost to residents in Case I is less than the Cases II, III, and IV by 2%, 16%, and 18%, respectively with VPP. Also in Case I, the cost of electricity without VPP is about 24% higher than the cost within the context of a VPP, which shows a competitive energy advantage for customers in VPPs. Within VPP, the customers can have guaranteed free electricity between determined hours and there is no need to pay for the maintenance of PV, battery and the control system.

The cash flow for 20 years is illustrated in **Figure 3.9**. As seen the payback period on investment for all different cases is about 8.5 years. The internal rate of return (IRR) is also 11.2%, 11.4%, 12.1%, and 12.5% for Case I to IV, respectively. Case IV has a higher IRR compared to other cases as there are more high consumption appliances such as an instant HWS installed. Although the IRR for Case IV is higher than for Case I (by 1.3%) which makes Case IV is more attractive for the VPP owner, the cost of electricity per dwelling in the Case IV is 18% higher than that for the Case I. Therefore, to move towards affordable and sustainable housing and to make the energy option attractive for the residents, Case I is prioritized for the VPP.

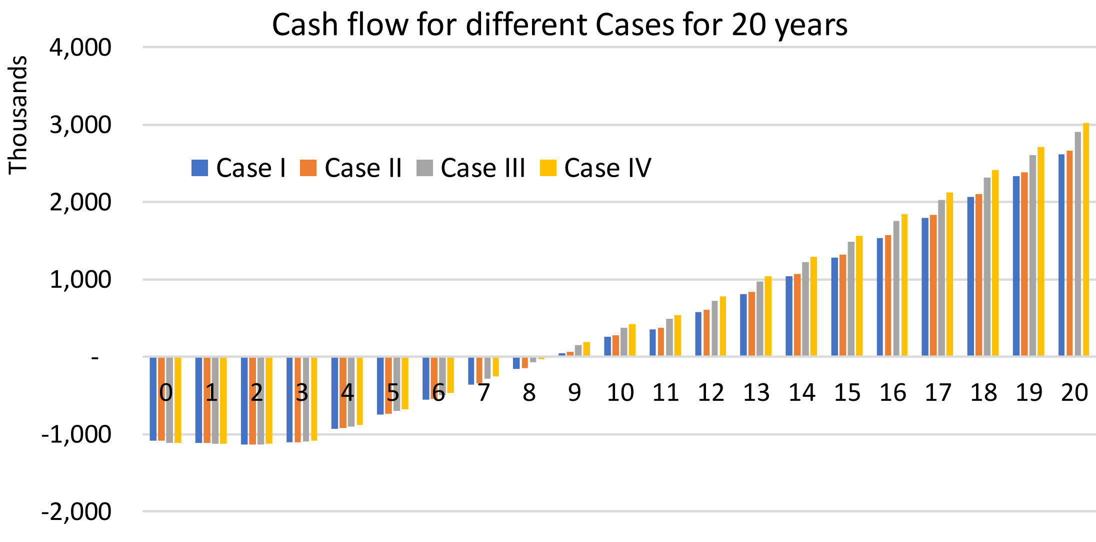

Figure 3.9. The average annual energy cost per dwelling with and without VPP (AUD)

Figure 3.10 also shows the breakdown of the NPV revenue in AUD streams over 20 years for the VPP in four cases. As seen, about one third of the revenue comes from selling energy from the PV and battery to the WEM. Moreover, between 40 and 45% of the revenue is obtained by selling energy to the residents. Further, no more than 14% of the revenue is received from the supply charge for the dwelling. And, the revenue associated with the reserve capacity credit forms only 13 to 15% of the total revenue over 20 years.

As shown in the Case I, the revenue from selling to residents is less than other cases but the revenue from the interaction with the WEM is higher than other cases.

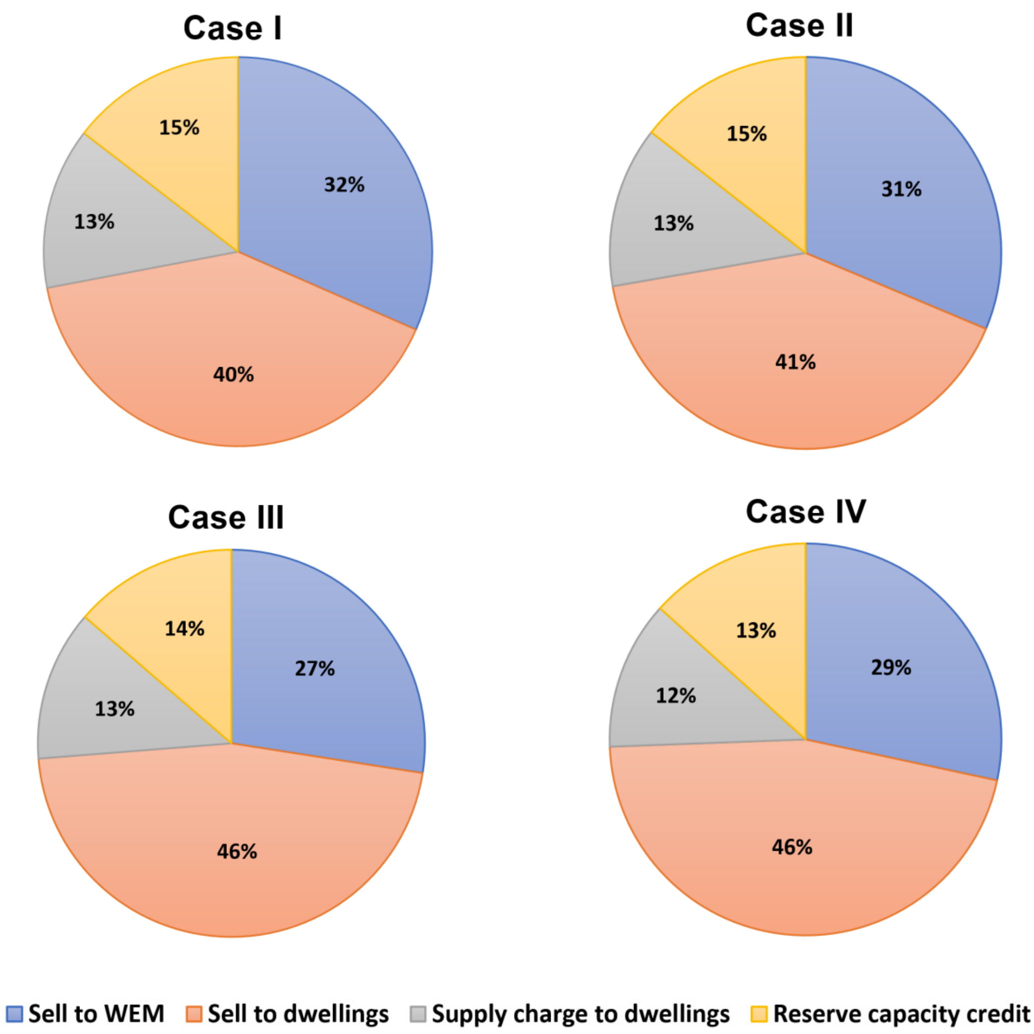

Figure 3.10. The breakdown of NPV revenue (AUD) over 20 years for the VPP in four Cases

The breakdown of the NPV operational cost of the VPP over 20 years is illustrated in **Figure 3.11**. In this figure, the investment costs are not shown in order to have a better view of the operational costs. As seen, the costs of maintenance for PV and VRFB make up about 50% of the total expenses. Therefore, it is critical for a VPP owner to keep the maintenance costs as low as possible. One of the approaches is to purchase the components from a provider that can provide long-term warranty on the equipment. Also, purchasing from the WEM and the retailer involve marginal expenses of about 12% each.

The optimisation algorithm in this Chapter has provided an algorithm for optimizing this purchasing amount. Other fees such as the Clean Energy Regulator, ancillary service and market fees are about 9% of total expenses. Also, the costs associated with the RT16 tariff, including the supply charge would be about 13%.

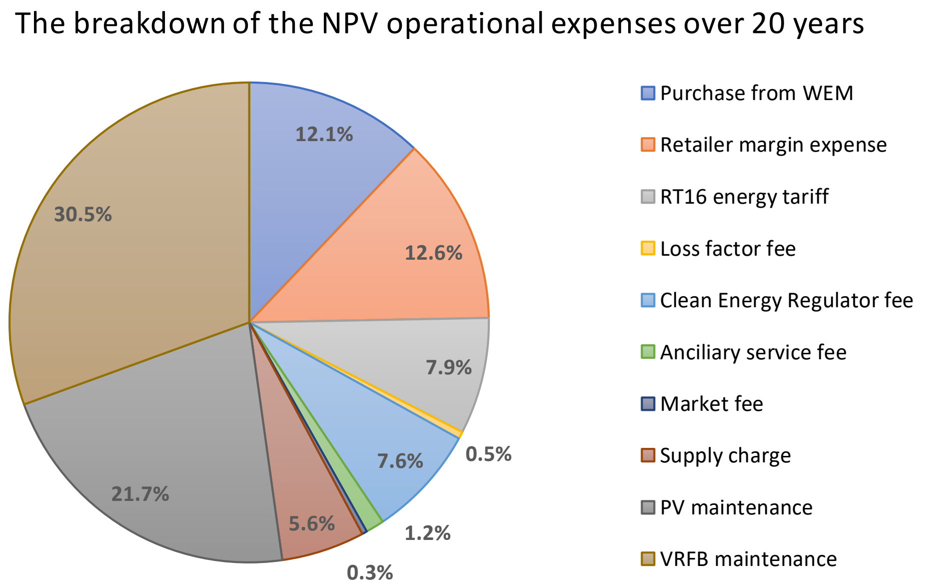

Figure 3.11. The breakdown of NPV revenue (AUD) over 20 years for the VPP in Case I

Figure 3.12 shows the scheduling of charging and discharging of the VRFB obtained from the optimisation algorithm for a sample day for Case I. Also, in this figure, the charging cost and the discharging revenues in AUD for the corresponding hours are presented. As the cost of charging is low during PV generation, in this case, the battery is charged based on the priority given during optimisation. In this case, the charging hour priority is 7am, 8am, 12pm, and 10am. The charging power at 7am and 8am is limited to the excess PV, and at 12pm is limited to the maximum power of the VRFB, which is 350kW. The discharging is also scheduled, based on the output of the optimisation. In this case, the discharging occurred to supply the load during the evening, when the RT16 tariff value is high. The algorithm through the optimisation looks for the higher WEM prices to discharge the battery during these hours. As shown, the discharge power will supply the load during the hours of 20 to 22, when there is no PV generation. Also, the VRFB is scheduled to discharge at hours of 18 and 19 as the WEM price is high, although there is an excess PV during this time.

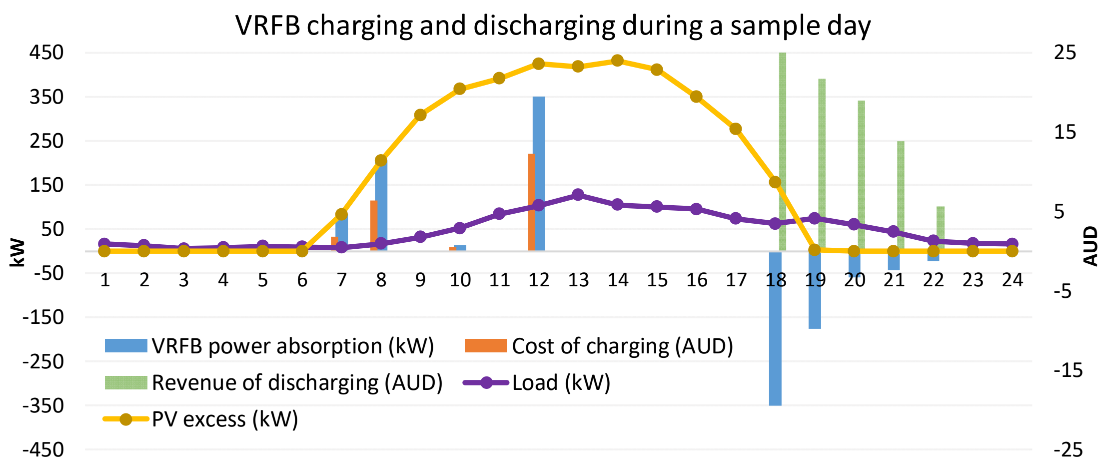

Figure 3.12. The charging and discharging of VRFB during a sample day in Case I

3.8.2 Recommendations

Based on the study conducted in this Chapter, the following recommendations are made to provide some insights for VPP businesses and policy makers:

- **Long-term planning of VPPs:**

The successful and sustainable rollout of VPPs requires reliable long-term planning including investment and operational analysis for 20 years, for example. This assessment gives both the VPP owners and policy makers a better understanding of affordability of such a structure in the long-term and the required logistic and regulatory supports. Through this planning exercise, the costs and benefits of the VPP is determined and possible future revenues are investigated.

- **Wholesale electricity market interaction:**

The involvement of VPPs in WEM requires extensive development of the regulations and procedures related to this interaction. The preparation of such guidelines has been initiated in some countries such as Australia. It is critical that the costs and benefits for VPP owners are considered in these rules and guidelines in order to minimise the costs of VPP implementation for the business. Also, the regulations should facilitate multiple revenue streams for VPPs to make the business sustainable in the long term. For example, in addition to the energy market, VPPs can participate in a demand response market or a frequency control market, which need an appropriate setup and regulation. Participating in multi-markets will reduce the payback period of investment for VPP owners and encourage more investors to enter this business.

- **Incentivizing VPP projects:**

The governments and policy makers need to incentivize different configurations of VPPs and different locations to evaluate the cost/benefits and barriers to VPP implementation in the real-world. Using this approach, they can collect required technical and financial data from a realistic VPP to use in regulation and procedure development. Also, these incentives will encourage more investors to invest in VPPs, so the government can achieve the goal of renewable integration and customer engagement in a shorter period of time.

- **Batteries and PVs:**

The costs of batteries are still high for investors. Also, the cost of VRFBs and PV maintenance is high. Therefore, the regulators should plan for and incentivize the research and development of low cost VRFBs and PVs, including investment and maintenance costs. In addition, the VPP owners can evaluate other options, such as leasing batteries for a period of time, which may be be more profitable for them.

- **Data availability:**

Although there are very good resource data on the WEM, environment and generation, the evaluation and implementation of a VPP requires a wider range of data including the costs associated with environmental factors, customer behaviour, the load profile of different categories of consumers, and also economic factors. Therefore, policy makers should facilitate the creation and development of the required data for VPP implementations. Incentivizing VPP development is one way to speed up the preparation of such data.

- **Forecasting tools:**

The performance of a VPP in controlling PV, battery, and demand is mainly dependent on the reliable forecasting of WEM, weather, PV output and electricity load. VPP owners should pay significant attention to the selection of the most accurate forecasting tools, which in many cases result in a higher investment cost for the VPP owner. Therefore, the policy maker can facilitate the use and development of such forecasting tools by encouraging and incentivizing the research in that domain and developing the right specifications for those tools.

- **ICT, data storage, and security**

One of the important prerequisites of long-term profitability of a VPP is a stable, scalable and cost-effective ICT connectivity amongst different components within the VPP including PV, battery, demand, control system, and forecast tools. For controlling and forecasting purposes, an efficient and secured, cloud-based, storage platform for data should be established. Also, the ICT system should be secure enough for communication and control signals and for different types of data including consumers' data. All these aspects require the right knowledge for the VPP owners to choose the correct and cost-effective ICT, storage and security systems. Obviously, such arrangements will increase the cost of investment for VPP owners, and the policy makers need to facilitate the consultation service to VPPs about this matter. Incentivizing a VPP project will again help reduce the associated costs of ICT, storage, and security.

- **Enhancing the community knowledge and involvement:**

A VPP needs to have a very good market for its services. In other words, a VPP owner should have enough customers to use the energy delivered by the VPP. Therefore, it is very critical that the community's knowledge is increased about the advantages of a VPP, to encourage them to be involved in a VPP. The enhancement of community awareness is a collaborative task between the governments and the VPP investors. The government and policy makers should promote the use of services provided by VPPs. On the other hand, VPP owners should provide attractive packages for the customers to encourage them to become involved in the VPP. If the VPP owner is successful in engaging customers in the investment and operation of the VPP, this collaboration will unlock many more benefits to the customers and the VPP owner.

- **Local utility interaction:**

An establishment of a VPP requires some local utility approvals for the connection of the facility to the local grid. These approvals are usually time and money consuming, which adversely affects the affordability of a VPP by deferring its operation. Policymakers can develop some guidelines and procedures to facilitate such approvals for VPPs. Also, the VPPs can contribute to the local voltage control in the grid, for which VPP owners can receive a signal from the local utility about how to react in order to satisfy the voltage grid standard. To achieve this aim, a contractual framework is necessary, and the policy makers should play a very active role in developing it.

- **Energy trading amongst VPPs:**

Another revenue stream for the VPPs would be energy trading amongst neighbourhood VPPs in the future. A VPP can decide to purchase energy from the wholesale market or from another VPP nearby that provides more cost-effective energy. This arrangement enables purchasing local energy from another VPP without going through the electricity market arrangement and paying extra fees associated with the operation of the market. However, a network charge will be applied by the local utility for the use of the network. Policy makers need to provide the required regulations and procedures for such local trading.

3.9 Conclusions

This Chapter investigates the detailed financial analysis of implementing a virtual power plant in Western Australia, which includes 67 residential dwellings. This VPP uses a cloud-based platform for analysing the data and controlling the VPP which includes rooftop solar photovoltaic (PV), vanadium redox flow battery (VRFB), heat pump hot water systems (HWSs), and management of some appliances such as washing machines, dishwashers and dryers. The size of the rooftop solar farm is calculated and designed at 810kW using the HelioScope software. Also, the optimum charging and discharging of the 700kWh, 350kW VRFB is demonstrated using the proposed optimisation algorithm. The study shows that the cost of energy is reduced for consumers by up to 24%, where they are engaged within the VPP. Also, the implementation of the VPP provides at least an 11% rate of return for the owner with less than 9 years for the payback period.

Chapter 4 Consumer Engagement in Virtual Power Plants through Gamification[1]

4.1 Summary

Virtual power plants (VPPs) are defined as an aggregator of different types of energy resources and flexibility, coordinated by VPP owner through a smart control system. A correct establishment of a VPP will result in reduced electricity costs for the consumers within the VPP. One of the key aspects of VPP's success is the consumer engagement in order to manage their flexibilities effectively. Gamification is an efficient way of learning and engagement, which can efficiently change the behaviour of consumers towards participating in programs provided by VPPs for energy cost reduction. In this Chapter, a gamification-based approach for consumer engagement is proposed and a methodology based on Fogg's behaviour model and Kim's model on player types is developed to examine the suitability of available gamification applications for energy saving/efficiency in the context of a VPP. Seven gamification applications are analysed and evaluated based on the developed methodology and the results are provided.

4.2 Introduction

Electricity prices have doubled in the past eight years [105] which has become a major

[1] This chapter is based on the published paper of: Behnaz Behi, Ali Arefi, Philip Jennings, Almantas Pivrikas, Arian Gorjy, and PS Catalao, "Consumer engagement in virtual power plants through gamification," 2020 5th International Conference on Power and Renewable Energy (ICPRE); 2020 12-14 Sept. 2020, doi: 10.1109/ICPRE51194.2020.9233110.

financial burden for those on lower incomes who are already suffering from a housing affordability crisis. These factors have contributed to three million Australians considered to be living under the poverty line, including one million children.

Tenants of new properties could benefit from reduced electricity prices supplied by photovoltaic (PV) and energy storage within a microgrid, however residential developers are avoiding investment in renewable energy technologies due to uncertainties around financial feasibility, business model, and technology required to create a smart virtual power plant (VPP), especially where an effective interaction with other parties such as the Australian Energy Market Operator (AEMO) becomes critical. Without an affordable integration of renewables and storage, the expansion of new technologies on these sites will be questionable.

VPPs are usually defined as an integration of diverse kinds of energy and flexibility resources. These resources can consist of wind, solar, hydrogen and thermal units, electric vehicles, fuel cells, batteries and capacitors, different types of energy storages such as thermal or pumped storage PVs and storage units combined with demand flexibilities, combined heat and power (CHP), flexible loads known as demand response (DR), and sometimes traditional resources such as diesel generators [14].

Based on the capabilities of VPPs, it is forecasted that over one million residential batteries will be installed to form VPPs over the coming years [54]. This level of VPP implementation requires effective incentive mechanisms from VPP owners or government to realise the capabilities of majority of batteries and VPPs. Also, it is essential to explore the demand side contributions, metering and control capabilities for the benefit of customers and the grid [54].

VPPs can potentially provide some important roles to community and consumers such as below [7]:

- CO_2 emissions reduction due to the integration of renewable energies into the grid;
- Improvement of renewable penetration by realising the benefits of them;
- offering cost-effective electricity production to consumers by incentives;
- lower cost of energy delivery to the market by providing an optimal bidding strategy;
- reliability improvement of supply of electricity by providing local electricity generation;
- deferral of network investment by the participation and control of VPPs;

When there are many consumers within a VPP, there are many challenges on how to manage the benefits and constraints of consumers, the VPP owner, and the electricity market. Some of these challenges are how to provide the best bid for the energy produced by a VPP; how to optimize individual household energy consumption via incentives, how to manage PV generation; how to produce and store energy in electricity/thermal storage; and how to satisfy AEMO's and the utility's requirements. All of these questions require research and innovative solutions. Further, no complete solution exists in the wholesale market and peer-to-peer market [106] to provide the platform to integrate storage and smart appliances (i.e. heat pump hot water systems, air-conditioners, and washing machines), PV inverters, smart meters and to optimize these based on real time wholesale market prices and the grid condition [8].

Consumers' flexible demands, PV and storage have the potential to provide energy where the electricity price is high and contribute to stable and efficient operation of the electricity grid. However, electricity generation is dictated by resource availability – that is, when the sun is shining, or the wind is blowing. Increased uptake of intermittent energy resources has caused a reduction in daytime energy generation supplied by the grid, while peak loads after sunset are increasing. This requires peaking power stations that must be maintained despite being sparsely active. This issue, commonly referred to as the "duck curve”, is a major concern for grid operators. Increasing penetration of PVs also leads to some challenges in power systems such as frequency and voltage regulation. Effective integration of storages, PVs and demand response (DR) in order to address the grid side concerns is challenging, especially in the context of affordable building development to make a sustainable long-lasting solution to consumers.

In order to realise DR and customer engagement, an energy-related behaviour change should happen, which can be identified through a human behaviour change model. A combination of game design elements can fulfil the requirement of customer engagement. The customer participation is guaranteed by recognizing a value stream for the customers when using a gamification-based solution. Also, the value stream should bring some benefits to the VPP owner, the WEM, and the whole energy supply in order to achieve a sustained engagement of customers. Another application of game-based participation is energy efficiency improvement [33].

To address these issues, the available resources within a VPP should be managed optimally in order to participate effectively in the WEM and to manage efficiently the consumers’ contributions as well [14, 15]. In order to engage consumers within a VPP, a smart and efficient way is required to be attractive and in a long-term guarantee the behavioral change of consumers. One of the most ancient ways of learning is through games that not only entertain people but also change their behaviour. Gamification provides some motivation for consumers of VPPs to learn to save energy and to reduce the cost of energy through sustainability and an environmentally friendly method. The purpose of gamification is mainly to engage consumers in energy efficiency, self-managing consumption and demand response programs.

There are some approaches for energy saving/efficiency through gamification such as Ecogator, Social Power Game, Makahiki, Power House, Less Energy Empowers You

(LEY), Wattsup, enCOMPASS and Funergy [45]. This Chapter investigates the gamification approaches and applications to evaluate the strengths and weaknesses of those platforms in the context of VPPs.

4.3 Gamification approaches

In this section, some applications of gamifications in energy-related studies are presented.

4.3.1 EcoGator

EcoGator is a smart phone application, which advises on efficiency and focuses on efficient energy consumption. This application has two modes of operation, which are presented as follows [46]:

- the shopping mode for identifying the most efficient appliances at sale points for customers with the following features:
    - scanning the appliances energy labels, which help calculate the yearly running cost of the appliance and the total life-time cost of the product based on the efficiency indicators of the appliance;
    - comparison between two scanned products as a decision-making tool for the customer.
- the day-to-day mode for increasing awareness of sustainable and efficient use of products, which provides advice on how to efficiently use the appliances and how to save money.

There are some gamification aspects to this application, including the awarding of points for the users when they are using the application, for example, scanning appliance labels, using the comparison tool or calculation functions, reading tips and sharing tips in social media. Also, earning points allows users to go forward to in different levels. Within each level, the knowledge of users is tested through quizzes and some challenges. After passing each level, the awarding system will allow the user to enter in a prize contest. The feedback shows that this application is very useful in shopping for appliances but not very encouraging in raising awareness [45].

4.3.2 Social Power Game

Social power game is another game-based mobile application for changing the users' behaviour in a long-term move towards sustainable energy consumption. The application focuses on social learning through a collaborative and action-oriented model in the context of a challenging neighbourhood-based energy-saving contest. Connecting to neighbourhoods facilitates the collaboration and exchange of information amongst people. The application can provides visual electricity consumption trend over time and the effect of user actions, including visualization of team challenges to promote collaboration and competition [107].

The gamification aspects of this application are categorized in two dimensions: household dimension and social dimension. When users register to join the game, they are assigned to one team with a challenge or goal. There are some collaborative and cooperative tasks that should be completed through coordination with others. The participants receive some points by completing any of those tasks and get information about how to make efficient use of the shared resources to improve awareness of the energy use in their surroundings. There would be some competitions amongst teams through visual comparison of their points, average consumptions, and the individual player's contribution to the corresponding team. Badges are awarded to players for their individual achievements and also for continuous or outstanding contributions to their teams. The first results of a study of this application show that 75% of the households participating in the project reduced their consumption to some degree between 1% and

25% [45].

4.3.3 Makahiki

This gaming engine is an open-source game which aims to enhance the awareness about energy conservation through education of a subject or training on a skill. This application facilitates the implementation of "serious games", which motivates players to learn about energy issues, to improve their understanding about energy consumption, and to teach them how to use energy efficiently in their life. Watt Depot is integrated into this engine to collect and store the energy consumption of users and to provide near real-time consumption tracking. Google visualizations is also incorporated to dynamically visualize the consumption data in an understandable way [47].

To promote energy consumption awareness, Makahiki supports the creation of a sequence of actions, including commitments and daily energy goals. For example, replacing a light bulb in a home or attending meetings about energy efficiency are defined as actions. Also, it allows the comparison among floors or buildings and the players get points for any of these actions. The players can define daily, monthly, or yearly goals as well with the corresponding tasks, which can be individual or collaborative goals. To earn points, players should perform certain actions and make public commitments to adopt more sustainable behaviours. In this platform, the player experience is improved by creating focus group and usability evaluations, which requires a good, planned and intensive communication strategy for its adoption. Moreover, incentivising social influencers can create a positive impact in the adoption of this platform. Further, it is very difficult to find the best incentives where the player population is diverse, so prizes and incentives should to be carefully analysed [45].

4.3.4 Power House

Power House is an online game that promotes improved real-world energy behaviours by connecting home smart meters and social networks.

After tracking users' energy consumption by its local energy provider, the data is sent back to the game environment for impacting player in-game behaviour towards rewards and social reputation. Players' energy consumption during the last 24 hours is visualized in a dashboard for reviewing their scores and virtual credits and competition results with other players and teams. Virtual credits can be used on in-game items, or on real world products provided by the VPP or utility [48].

The gamification aspect of this tool is earning virtual credits and a leader board for showing the individual or team achievements and comparing them with the achievements of others. Furthermore, the players can compete against their neighbours in energy saving competitions by keeping track of the activities of every member of the family to reduce waste and improve efficiency. The points system is based on the ability to minimise the amount of electricity consumed by the family. The results of an experiment illustrates that this game-based tool positively improves the efficient use of energy by turning off the appliances after the gaming period [45].

4.3.5 Less Energy Empowers You (LEY)

To understand domestic energy usage, LEY proposes a persuasive pervasive-based serious game to help people change their energy-related habits. The three main components of the platform are: a sensor platform, a supporting web-based information system and a mobile game application. Real time data is provided by the sensor platform, then data along with the game rules are stored in the web application, which is equipped with visualization aspects as well. The two gaming modes of this tool are [49]:

- The single mode, in which players are challenged to enhance their energy consumption to an optimal level for getting the maximum points. In this mode, players are ranked based on the official European energy efficiency rating, which presents the energy efficiency of residences on a scale of A (most efficient) to G (least efficient).

- The completion mode, in which the players challenge other players in an energy-based quiz competition. The ranks and points are awarded at the end of competition.

The house avatar is another game feature of the LEY application, through which the household consumption can be monitored [45].

4.3.6 Wattsup

The aim of Wattsup, which is a Facebook-based application, is to encourage energy saving by using live and historical energy feedback in a social-normative context. Wattsup shows data for energy consumption and CO_2 emission to give the participants the ability to compare household data with their friends.

This platform uses Wattson Sensors to collect and store the consumption data of the households. The data is then transmitted to a server connected to a desktop application and a Facebook gamified application. This information is illustrated on Facebook in three different ways: a) individual consumption, b) Friends can compare the consumption against a selected friend, c) Rankings is based on their daily consumption in a leader board [50].

Results of two tests on this platform show that social interaction can effectively motivate consumers to optimize their household energy consumption as they are spending time on the rankings interface, viewing and commenting on the rankings table.

4.3.7 enCOMPASS and Funergy

The Encompass platform is another system for an holistic socio-technical gamification for energy saving with the following components, as shown in **Figure 4.1** [51]:

- Sensors data acquisition: for conversion of acquired parameters (temperature, humidity, and luminance) to data and communication with a centralized data centre to integrate those data into all components of the platform.

- User data acquisition: Using a gamified mobile app for household consumers and the associated appliances to engage users within the collaborative platform.
- Data analysis and user modelling: Algorithms are used for extracting data from applications for different purposes such as user behaviour to measure energy consumption. Classification techniques and advanced analysis to extract from data divided into two main classes of visual and thermal comfort.
- Adaptive in-context action recommendation: Activity patterns in the building control system and the consumer app recommended to improve energy saving.
- Engagement engine with adaptive gamification: Making the gamification model adaptive and flexible impacts on energy consumption behaviour of users, such as users' location and activity, indoor climate and interaction history [52].

This system will benefit consumers with a cloud-based applications programming interface (API) through enCOMPASS APIs. The components of the enCOMPASS platform are presented in **Figure 4.1**. The enCOMPASS provides a gamified web application via a PC or mobile phone, which offers an interactive visualization of energy consumption. Through this platform, consumers can explore their consumption profiles by time granularity (e.g., on a daily, weekly or monthly basis), by consumption source, by user context, and activity type. The system can compare the consumption against a reference values or neighbours to provide warnings to above-average consumers with personalized suggestions on how to reduce consumption. Players are encouraged by two gamified elements [45, 52]:

- Gamified rewards (points, badges, achievements, tangible prizes) which can be received through different types of mechanisms such as achieving goals, social comparison and social collaboration.

- Funergy, which is a serious game through which points are awarded. This is a simple cooperative game where players try to reach the best final score by collaborating with each other. This game is a combination of a physical board-game with a digital app.

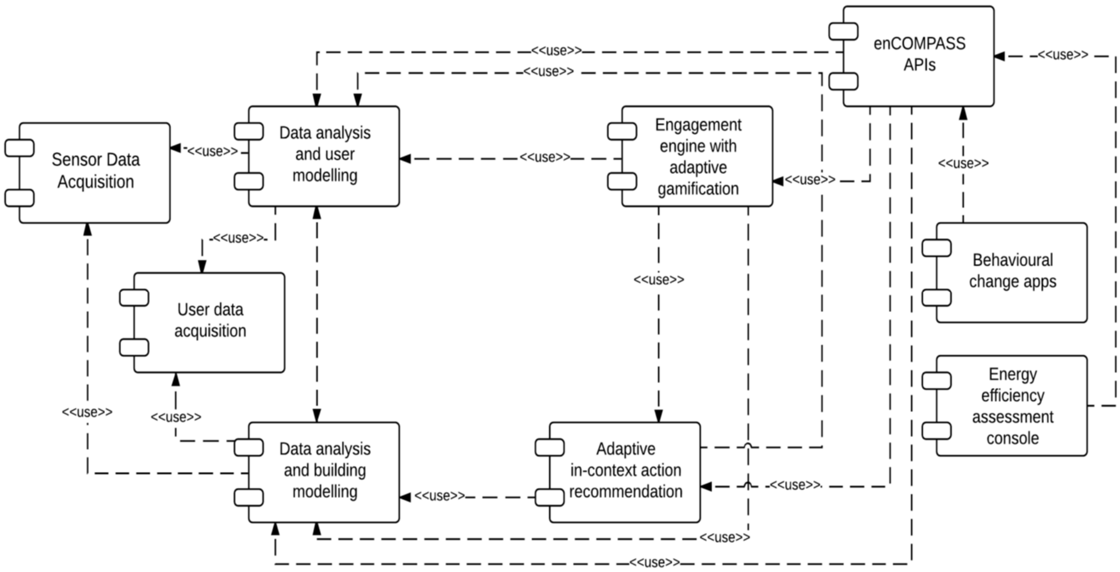

Figure 4.1. The components of the enCOMPASS platform [51, 52]

4.4 Methodology

As discussed in the last Section, some relevant tools have been developed to incorporate gamification into consumers' engagement with VPPs by targeting their interests, including motivations related to economic, environmental, and social issues. Based on the Fogg's model for the behaviour change [108] shown in **Figure 4.2**, three elements should be available to facilitate the achievement of target behaviour. These three elements for behaviour (B) change are motivation (M), ability (A), and trigger (T), which is summarized in: B = M A T.

In this model, by an increasing motivation and ability, the likelihood of happening of behavioural change will increase. However, Fogg claims in addition to a strong motivation and high ability, an appropriate trigger align with the corresponding change of behaviour is essential. Such triggers should generally satisfy three conditions, which are: a) users should be aware of triggers, b) addressing the target behaviour, and c) timely introduced when both the motivation and the ability are at their maximum. Based on this theory, Fogg has provided some thresholds that ability and motivation should be above those values in order to make triggers effective. As seen in **Figure 4.2**, there are some sub-components for each element, for example, pleasure, hope, and acceptance are the components of motivation that are considered when designing a gamification approach

It is critical to know that the abilities and motivations of different people are different. Players can be categorized into four roles, which are Achievers, Explorers, Socializers and Express, as per Kim's model [109]. Players who like to compete are identified as achievers. Those players who prefer collaboration are known as socialisers. On the other hand, explorers like to explore applications, tools' capabilities, contents, and people, who are motivated by information and access and knowledge. Finally, express players are those motivated by self-expression, as they want to express their abilities and showcase their creativity.

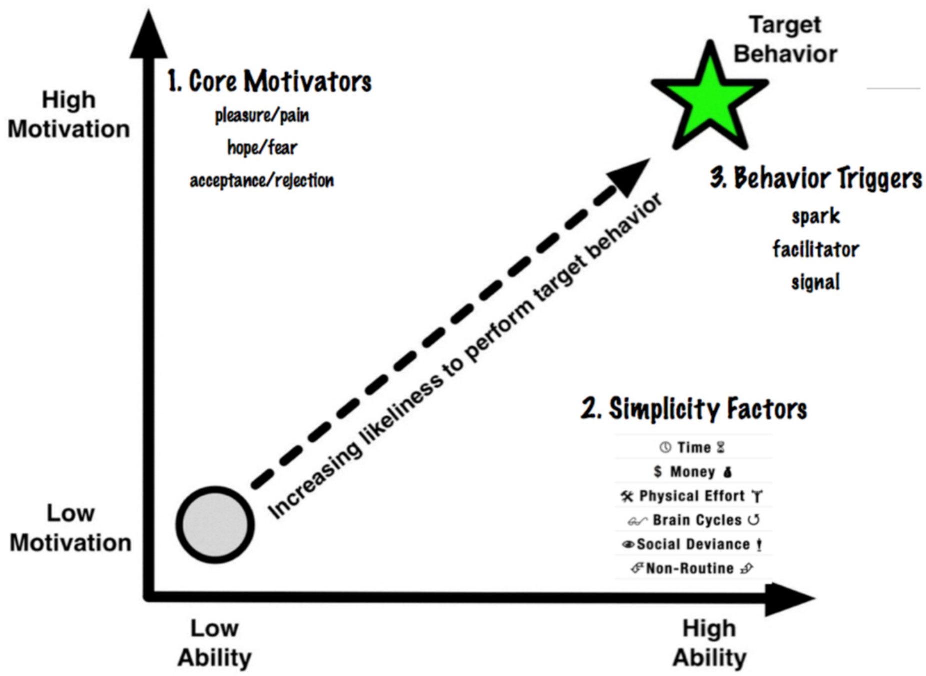

Figure 4.2. Elements of Fogg's model for behavioural change [108].

Amongst these players with different attitudes, collaboration is one of the most influential approaches for engaging many users. On average, the players' population is distributed as 80% socialisers, 50% explorers, 40% achievers, and 20% express [109].

Therefore, the gamification approach for the engagement of the customers should provide motivation to consumers and enhance their ability towards achieving the targeted behaviour. Also, the gaming strategy should consider the range of different types of players as discussed here. To achieve this aim, a gaming system should be established to increase the awareness and knowledge of consumers regarding their possible contribution to the economy and the environment in order to enhance the uses' abilities. This system needs to protect the privacy of users while providing a user-friendly interface. This system should be fun for users as this is a very important characteristic of gamification for triggering their involvement.

Based on consumers' energy consumption behaviour, a rewarding system as a motivation offers a number of discounts, points and credits to participants to increase the satisfaction of residential customers. By using a private platform based on the web and a mobile device, customers can communicate in on-line gaming and share their problem solving. This collaborative system, that is attractive for more than 80% of players, scores consumers on the basis of energy reduction, for instance, while it encourages participants to compete to gain more credit or points [33].

The user interface will also provide the opportunity to customers to control and decide when and how to reduce their electricity consumption. Consequently, it has the most positive effect on customers. This is achieved through a stimulating and enjoyable engagement program such as dashboards, progress bar and message box. The performance status is another dimension of gamification that improves the motivation of consumers. Attribution and behaviour scores of residential customers can be followed through the application process. For instance, when a customer acts in an energy application, the achievement of badges and points appears, and the way of behaving is changed as a consequence.

Figure 3 shows the whole methodology and the relationship amongst the Fogg's model and Kim's model in order to introduce the gamification capabilities. This Chapter considers the parameters shown in **Figure 4.3** to explore the capabilities and effectiveness of available applications for gamification within a VPP context.

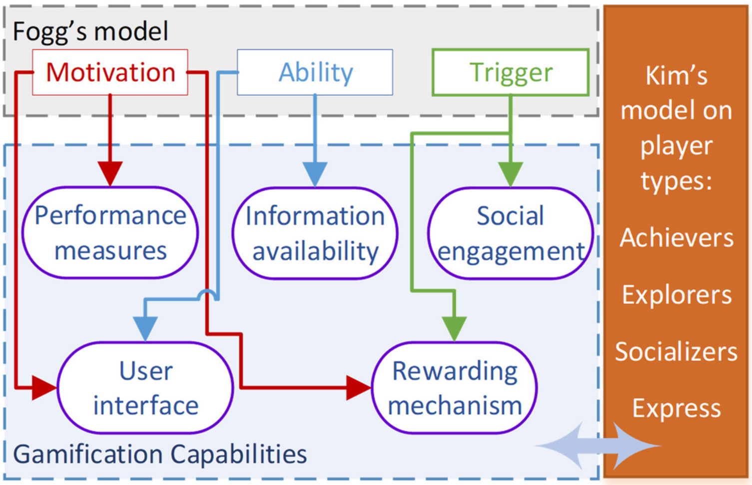

Figure 4.3. Parameters for the evaluation of gamification applications

4.5 Evaluation of Gamification Approaches

The characteristics of available gamification applications suitable for consumers' engagement in a VPP in Western Australia are explored in this Section. There is an intention to develop VPPs in Western Australia, comprising many single storey residential dwellings with a rooftop PVs and controllable storages and loads.

This VPP will be managed as a VPP through a cloud-based data system, aggregating different energy resources to minimise the cost of electricity for residents through participating in the electricity market. Within a VPP, residents may need to respond to the signals from the VPP's owner for turning on/off their appliances or charging/discharging energy storages. In another words, demand response aspects of the energy consumption are the most important behaviour, for which the gamification application should be designed.

The main residents of the VPPs are families with average/lower band of income, as the energy efficiency is more important to these categories of consumers. Therefore, the gamification applications reviewed in [45] are filtered, based on the fact that they are targeting families, as shown in **Table 4.1**. Included in this criterion, the cyber security of the applications is also considered.

Another important feature of the gamification application is the proper user interface, resulting in customer satisfaction. The interface has to enable user to work on a mobile platform, as an available platform for many family members including parents and teenagers. Consequently, only those applications are appropriate to be able to provide this feature, as presented in **Table 4.1**. As discussed, social engagement is another important aspect of gamification that can be attractive for more than 80% consumers.

Therefore, **Table 4.1** shows which applications can support multiplayer and social collaboration and competition.

Performance measures are the vital part of the gamification for providing the right feedback to consumers and motivating them to change their behaviour.

All applications in **Table 4.1** can provide some sort of performance measures such as consumption reduction, the number of times using the app, and number of games they played. However, the 'Social Power Games' and 'enCOMPASS' can provide more statistics and comparison against individual and teams to make the game more collaborative and competitive.

Information availability is suitable almost for all gamification algorithms. However, those applications with a capability of social connection can provide knowledge sharing amongst neighbours and/or team members. Therefore, the ranking of those applications would be higher as illustrated in **Table 4.1**.

The last capability of a gamification approach is establishing a rewarding mechanism. As seen in **Table 4.1**, some applications provide an approach for rewarding such as virtual credit, tangible rewards, or points/badges that are converted to some level of incentives. Among the applications in **Table 4.1**, 'Power House' and 'enCOMPASS' have a better built-in mechanism for rewarding and incentivizing consumers for their actions and behaviour change, so the ranking of these two applications is higher than others in this matter.

By analysing different aspects of capability of gamification application, the suitability of them for the use in a VPP platform is inferred. As seen in **Table 4.1**, the column of 'Overall evaluation: suitability' will provide a ranking for the application in this table in terms of suitability for VPP. As illustrated, the suitability of 'ecoGator' and 'Makahiki' is low as they do not provide a social connection amongst consumers, cannot accommodate a rewarding system, or support mobile devices.

In addition, 'Power House' is not a family-oriented application that cannot support social connection and mobile devices, so its ranking for the use in VPP context is very low. The suitability of 'Wattsup' and 'LEY' are medium as there are some drawbacks in these applications such as not family-oriented or no strong social connection. However, there are some possibilities for upgrading these applications in future in order to satisfy all criteria. 'Social Power Game' is a suitable gamification approach for VPPs as it can cover all required aspects for a VPP, so it ranked here as 'high' suitability.

Amongst all applications discussed in **Table 4.1**, 'enCOMPASS' has the 'very high' suitability for VPPs. As presented in previous Section, the enCOMPASS platform is a system of gamification for energy savings and behavioural change with the components of sensors data acquisition, user data acquisition, data analysis and user modelling, adaptive in-context action recommendation, engagement engine with adaptive gamification. The adaptive in-context action recommendation in this platform is an excellent way for monitoring the activity patterns of consumers in the building of an efficient control system. Also, data analysis and user modelling algorithms are used for extracting data from this application for different purposes, such as user behaviour, to incentivize consumers accordingly. As the VPP is being established in Western Australia, the realistic data about the implementation of gamification method will be discussed in future publications.

Table 4.1. The Comparison of Gamification Applications in Terms of Different Capabilities Necessary for VPPs

Gamification Application	Families as the targeted audiences	User interface platform: Mobile phone	Social engagement	Performance measures	Information availability	Rewarding mechanism	Overall evaluation: suitability
ecoGator	√	√	×	√	√	×	low
Social Power Game	√	√	√	√√	√√	√	high
Makahiki	×	×	√	√	√√	√	low
Power House	×	×	×	√	√	√√	very low
Less Energy Empowers You (LEY)	√	√	×	√	√	√	medium
Wattsup	×	√	√	√	√√	√	medium
enCOMPASS and Funergy	√	√	√	√√	√√	√√	**very high**

4.6 Conclusions

Virtual power plants (VPPs) are a promising framework for reducing the cost of electricity by the use of more renewable energies and the engagement of consumers to purchase energy from the wholesale market when it is very cheap. To coordinate the flexibilities of consumers through demand response programs, an appropriate customer engagement system is required. This Chapter proposes a gamification-based approach for consumer engagement in VPPs and develops a methodology for evaluating different applications in this area. Seven gamification applications, which are available in the market, are examined using the proposed methodology. The results showed that the 'enCOMPASS' application is the most suitable application in the context of VPP.

Chapter 5 A Robust Bidding Strategy for VPPs Including Gamified Customer Engagement[1]

5.1 Summary

Virtual power plants (VPPs) are becoming critical parts of energy systems to increase renewable energy integration and to reduce the cost of electricity. To maximise the benefits to customers and VPP owners, the consumers' engagement is important for adding flexibility to the electricity load of the VPP. In this Chapter, the impact of customer contributions into a VPP energy management system through gamification is studied. To this aim, the contribution of customers within a realistic VPP of 67 dwellings in Western Australia is modelled. This model is included in a robust optimized procedure to maximise the profit of a VPP owner over a year. In this platform the uncertainties associated with renewable energy generation and market electricity are considered to find the optimum solution for the worst-case scenario of uncertainties. The simulation results show that the gamified customer involvement has positive impacts on increasing the profit of the VPP.

[1] This chapter is based on the published paper of: Behnaz Behi, Ali Arefi, Philip Jennings, Almantas Pivrikas, Arian Gorjy, Arindam Ghosh, "A robust bidding strategy for VPPs including gamified customer engagement," 2021 31st Australasian Universities Power Engineering Conference (AUPEC); 2021 26-30 Sept. 2021, doi: 10.1109/AUPEC52110.2021.9597759.

5.2 Introduction

Virtual power plants (VPPs) are becoming an attractive investment option for private investors in energy systems. This trend is associated with the lower prices of photovoltaics (PVs) and energy storage as well as available control and communication technologies to optimally operate the VPP [30]. Studies show that the payback period of VPP investments is reduced dramatically to about 8.5 years in recent years, while the customers within the VPP can enjoy about 24% of energy saving [110]. On the other hand, the policies and renewable energy targets in countries motivate increasing interest in PV and battery installation, which is a promising situation for VPPs [12].

For a profitable VPP, it is essential that the VPP has an optimum and robust buying and selling, namely bidding, strategy with the wholesale electricity market (WEM). For providing an optimal bidding strategy, all required data including electricity prices, PV generation, and load are collected via information and communications technology (ICT) interfaces by the VPP, including forecast data through the available application programming interfaces (APIs) [111]. Then, the energy bidding strategy takes place to schedule the use of available resources and to determine the optimal bidding amount by the VPP to the WEM. This procedure will occur in specified time intervals considering economic, technical, contractual, and forecast data [25]. A VPP considers its investments, PV availability and energy storage levels, along with the expectations of customers, to schedule the demand response, storage of energy and bidding amount for participation in the electricity market [34]. For economic operation of a VPP it needs an economic bidding strategy and optimal dispatching of the available resources and customer flexibilities to maximise the benefits, subject to satisfying the constraints [112]. Generally, the methodologies implemented to solve this objective function are classified into two main categories:

- Mathematical: based on mathematical approaches such as mixed-integer linear programming (MILP), and stochastic linear programming MILP [37, 59, 60].
- Heuristic: based on nature-inspired algorithms such as the genetic algorithm (GA), fuzzy systems, game theory, and particle swarm optimisation (PSO) [2, 61].

An electric vehicle-based aggregator/VPP is studied in [75] to participate in the electricity market by an optimal bidding strategy, based on the conditional expectation optimisation model, which is formulated as the minimisation of an expectation problem with conditional value-at-risk constraints. The combined optimisation is utilised in [63] for bidding the energy price. Deterministic optimisation requires a lower computational effort amongst these optimisation algorithms [37, 59, 60]. Hybrid stochastic/robust optimisation is proposed in [64] in order to realise the advantages of both algorithms. Robust optimisation ensures the optimality for the algorithm, considering uncertainties, while stochastic optimisation will explore many scenarios within the research space [113]. A decision making approach for bidding prices is developed in [72] based on fuzzy logic, which tries to minimise total energy cost, considering an aggregation structure with the electricity market. Although the use of customer flexibilities is discussed in some literature, the robust and optimum use of gamification for customer engagement is not considered in these references. Gamification for customer engagement is a promising approach to improve the knowledge of customers while adjusting their behaviour to maximise the profit for the VPP and consumers [114].

The aim of this Chapter is to provide a simple, robust, and effective method for optimum bidding in the day-ahead market considering a gamified approach for customer engagement. It is critical for private investors to understand the logic behind the bidding strategy in order to have an enough confidence in the long-term profitability of the VPP. Although the mathematical and heuristic optimisation algorithms give a good solution for the bidding task, they are very complicated so investors would not have a good understanding of the principles on which those algorithms are providing a solution. This is the motivation of this Chapter to provide a simple, understandable procedure for the bidding strategy to provide an optimum solution. Another benefit of the proposed strategy in this Chapter is the high speed of this method compared to the time-consuming mathematical or heuristic methods. The computational effort is more important when the VPP wants to run the bidding program multiple times during a day in real-time.

The Chapter is organised as follows. Section 5.3 develops the problem formulation. Section 5.4 presents the bidding strategy. In Section 5.5, the simulation results are provided, and the concluding remarks are presented in Section 5.6.

5.3 Problem Formulation

The aim of the bidding strategy is to find the optimum hourly bidding of energy into the electricity market to maximise the profit of the VPP. The objective function over one day is presented in (5.1).

$$maximize\ (R_{tot} - C_{tot})$$
$$\text{Constraints: } \begin{cases} VRFB\ charging\ and\ discharging\ constrains \\ Customer\ preferences \end{cases} \tag{5.1}$$

The terms of this optimisation problem are described below.

5.3.1 The total revenue of the VPP

The revenue (R_{tot}) of the VPP owner is formulated in (5.2).

$$R_{tot} = R_{Fix} + R_{Var} = R_{Fix} + \sum_{h=1}^{24} E_{out}^{d,h} \pi^{d,h} + \sum_{h=1}^{24} E_{RES}^{d,h} \tau_{RES,E}^{d,h}$$
$$E_{out}^{d,h} = \begin{cases} E_{PV}^{d,h} - E_{RES}^{d,h} - E_{VRFB}^{d,h} & if\ \left(E_{PV}^{y,h} - E_{RES}^{y,h} - E_{VRFB}^{y,h}\right) > 0 \\ 0 & otherwise \end{cases} \tag{5.2}$$

where R_{Fix} is the fixed revenue for that year, which is converted to the daily revenue, such as the income associated with the allocated reserve capacity credit (RCC) for this VPP at a defined price (AUD/MW/year) [103]. R_{Var} includes two terms, which are:

- $\sum_{h=1}^{24} E_{out}^{d,h}\pi^{d,h}$: the daily revenue from selling $E_{out}^{y,h}$ to the electricity market at h-th hour of d-th day at the market price of $\pi^{d,h}$, and
- $\sum_{h=1}^{24} E_{RES}^{d,h}\tau_{RES,E}^{d,h}$: the daily revenue from selling $E_{RES}^{d,h}$ to the customers within the VPP at h-th hour of d-th day at the market price of $\tau_{RES,E}^{d,h}$.

When $E_{out}^{d,h}$ is positive, then it is equal to the whole energy generated by the PV system, $E_{PV}^{d,h}$, minus the energy stored in the vanadium redox flow batteries (VRFB), $E_{VRFB}^{d,h}$, minus customers' energy consumption, $E_{RES}^{d,h}$. The base tariff for the customers within the VPP is presented in **Table 5.1**, which is equivalent to 10% discount compared to the flat tariff by the local utility, as an incentive for all customers. The detailed formulation of R_{tot} is provided in [110].

Table 5.1. The Base Values of Electricity for the Residents; 10% discount compared to the local utility's tariff

Fixed cost (cents/day)	Any hour: flat tariff (cents/kWh)
94.63	26.39

5.3.2 The total expenses of the VPP

The cost of the VPP (C_{tot}) for day d is presented in (5.3)

$$C_{tot} = C_{Fix} + (1+\alpha^y)\sum_{h=1}^{24} E_{in}^{d,h}\pi^{d,h} + \alpha^y \sum_{h=1}^{24} E_{out}^{d,h}\pi^{d,h} + (1+\beta^y)\sum_{h=1}^{24} E_{in}^{d,h}\omega^{d,h} + (\gamma^y + \delta^y + \theta^y)\sum_{h=1}^{24} E_{in}^{d,h} \quad (5.3)$$

$$E_{in}^{d,h} = \begin{cases} E_{PV}^{d,h} - E_{RES}^{d,h} - E_{VRFB}^{d,h} & if\ (E_{PV}^{d,h} - E_{RES}^{d,h} - E_{VRFB}^{d,h}) < 0 \\ 0 & otherwise \end{cases}$$

where C_{Fix} is the fixed part of the expenses associated with the capital expenditure

(CAPEX) including the costs of PV, VRFB, electrical and communication systems. This fixed cost can be excluded from the operational daily optimisation. The other terms for the expenses are as below:

1. $\left(1+\alpha^{y}\right)\sum_{h=1}^{24} E_{in}^{d,h}\pi^{d,h}$: the total energy of $E_{in}^{d,h}$ purchased at the price of $\pi^{d,h}$ at h-th hour of d-th day from the electricity market through the retailer at the retailer margin of α^{y};
2. $\alpha^{y}\sum_{h=1}^{24} E_{out}^{d,h}\pi^{d,h}$: The retailer commission when the VPP sells to the electricity market.
3. $\left(1+\beta^{y}\right)\sum_{h=1}^{24} E_{in}^{d,h}\omega^{d,h}$: the local utility tariff costs at the price of $\omega^{y,h}$in h-th hour and d-th day [100].
4. $(\gamma^{y}+\delta^{y}+\theta^{y})\sum_{h=1}^{24} E_{in}^{d,h}$: The fees associated with the Clean Energy Regulator, the ancillary service, the market at the margins of γ^{y} , δ^{y} , and θ^{y}, respectively.

$E_{in}^{d,h}$ has non-zero value when the VPP is purchasing energy. The detailed formulation is described in Chapter 3 [110].

5.3.3 The modelling of gamified customer engagement

The engagement of customers is through a game, in which the customers are the owner of a virtual home in the game. At the beginning of each day, a specific amount of energy points is given to all players. These points decrease during a day if the customer does not accept the requested demand change by the VPP operator. The remaining points are accumulated in the game for each player in the game. Using these points, the customers can unlock some energy efficiency products or bonuses then purchase and install them in their virtual home in the game, resulting in a more energy efficient home and higher points each day. The flowchart of the game is provided in **Figure 5.1**. Based on this gamification approach, the energy consumption by residents in *h-th* hour of *d-th* day, $E_{RES}^{d,h}$, is:

$$E_{RES}^{d,h} = E_{RES,def}^{d,h} - \vartheta^h \tau^h E_{RES,def}^{d,h} \tag{5.4}$$

where $E_{RES,def}^{d,h}$ is the default load profile of the customers, ϑ^h is the electricity reduction factor due to gamification at hour h and τ^h is the factor representing how many percentages of customers are participation in the gamified approach.

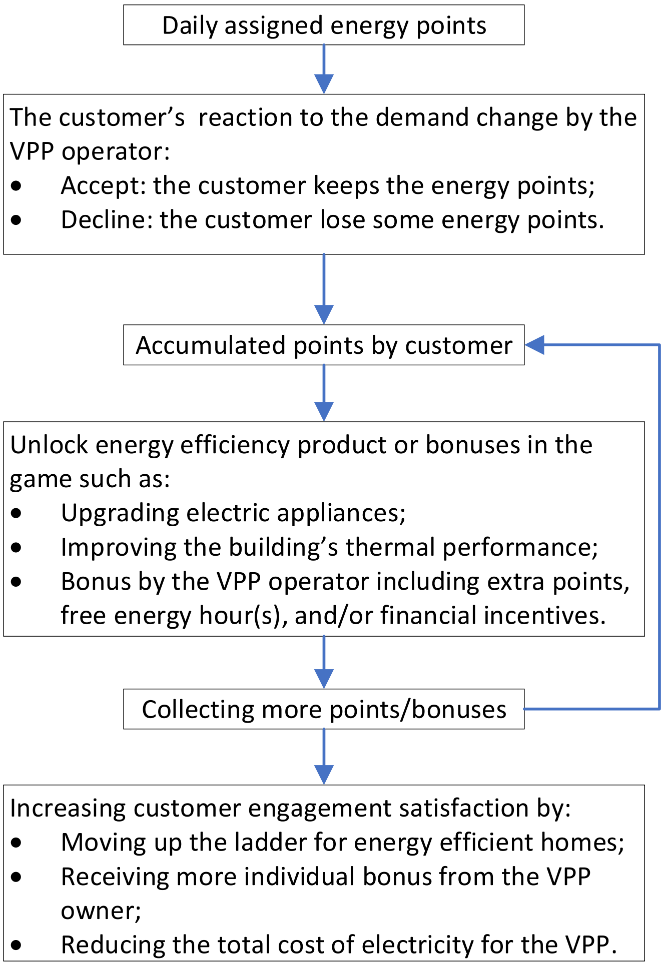

Figure 5.1. The flowchart of the gamified customer engagement

The parameters ϑ^h and τ^h are empirical parameters based on some realistic implementation of gamified customer engagement and realistic results. In this VPP setup, all customers' engagement has a pre-program setup, in which the VPP operator can control some loads in the dwellings such as washing machine, dryer, heat pump, air conditioner, and dishwasher. The control of these appliances can be withdrawn by customers based on their preferences as described in Section 5.3.4. This automatic arrangement means that the probability of customer engagement in the gamified customer participation is very high compared to the manual cases, such as the experiment conducted in [115], showing the contribution of around 40% to the program. In this Chapter, we will run a sensitivity analysis on the customer participation percentage, τ^h.

In addition, it can be calculated from [115] that the average electricity consumption per customer is reduced by about 11%. As in this VPP in WA, only electricity is consumed, the reported effect on gas and electricity in [115] is combined to represent the electricity reduction. Moreover, in the VPP in WA, major appliances are remotely controllable, so the energy reduction is likely to be much higher and between 30% to 70%.

5.3.4 The constraints of the optimisation

In this Section, the constraint formulations for the battery charging/discharging and customer preferences are provided.

- **VRFB charging/discharging constraints**

The constraints on battery charging/discharging are presented in (5.5).

$$\sum_{h=1}^{24} E_{VRFB}^{d,h} = 0 \ , \quad \forall d$$

$$0 \leq \sum_{h=1}^{hour} E_{VRFB}^{d,h} \leq E_{VRFB}^{max} \ , \forall \ hour = 1 \dots 24 \ , \forall d \tag{5.5}$$

$$-P_{VRFB}^{max} \leq E_{VRFB}^{d,h} \leq P_{VRFB}^{max} \ , \forall d, h$$

where P_{VRFB}^{max} is the maximum charging/discharging power for the battery and E_{VRFB}^{max} is the maximum stored energy of the battery. $E_{VRFB}^{d,h}$ is positive when the battery is charging. It is considered that the battery does a complete cycle of charging and discharging during a day. This assumption is the same as the one introduced in Chapter 3.

- **Customer preference constraints**

Customer preferences are pre-set values by them to determine whether they are willing to contribute to the gamified customer engagement program or not. To achieve this aim, $CP_{l,n}^{d,h}$ is defined in (5.6) to represent this contribution of customer n on d-th day and h-th hour for l-th appliance.

$$CP_{l,n}^{d,h} = \begin{cases} 1 & customer\ contributes \\ 0 & customer\ does\ not\ contribute \end{cases} \tag{5.6}$$

The controllable appliances, option l, are washing machine, heat pump, air conditioner, and dishwasher. The customer preferences for the appliances are integrated into the model of the VPP load profile as in (5.7).

$$\begin{aligned} E_{RES}^{d,h} = E_{RES,nonCon}^{d,h} \\ + \sum_{n=1}^{67} CP_{WM,n}^{d,h} E_{WM,n}^{d,h} + CP_{HP,n}^{d,h} E_{HP,n}^{d,h} + CP_{AC,n}^{d,h} E_{AC,n}^{d,h} \\ + CP_{DW,n}^{d,h} E_{DW,n}^{d,h} \end{aligned} \tag{5.7}$$

where $E_{RES,nonCon}^{d,h}$ is the non-controllable portion of the load profile, $E_{WM,n}^{y,h}$, $E_{HP,n}^{y,h}$, $E_{AC,n}^{y,h}$, $E_{DW,n}^{y,h}$ are respectively the energy consumption by washing machine, heat pump, air conditioner, and dishwasher at hour *h* by the *n-th* dwelling.

The voltage profile is not considered as the site will be connected to a very strong network nearby, so the amount of power generated or absorbed by the battery does not affect the voltage profile. Also, the VPP does not have any contract with the local utility for the voltage control at the moment. Power balance constraints are satisfied during the optimisation where the amount of power from the grid is calculated based on (5.12).

5.4 Bidding Strategy

In this Section, the approach for solving the developed optimisation problem is explained. Although there are some mathematical and heuristic approaches to solve the optimisation problem, here, a simple, fast, and effective approach is developed to find the optimum bidding strategy for each day. First, the following four parameters are defined:

a) the revenue per kWh: This parameter represents the revenue of selling excess PV to the electricity market at h-th hour of d-th day as in (5.8). Also, this parameter is considered as the opportunity cost of not selling excess PV to the market for internal use.

$$rev/kWh^{d,h} = \pi^{d,h}(1-\alpha^{y}) \tag{5.8}$$

b) the cost of purchasing one kWh energy: This parameter determines the cost of a purchased energy unit from the electricity market for provision to dwellings or charging the battery at the *h-th* hour of the *d-th* day, as defined in (5.9). Also, this cost is equivalent to the avoided cost of not purchasing energy from the market.

$$\begin{aligned} &cost/kWh^{d,h} = \\ &\pi^{d,h}(1+\alpha^{y}) + \omega^{y,h}(1+\beta^{y}) + \gamma^{y} + \delta^{y} + \theta^{y} \end{aligned} \tag{5.9}$$

The details of working out these two parameters are provided in Chapter 3 [110].

c) the battery charging cost for one kWh: this parameter shows the cost of charging the battery during non-PV hours by purchasing energy from the electricity market or the opportunity cost of charging the battery during PV hours by excess PV and not selling that excess PV to the market. This parameter is formulated as (5.10).

$$\begin{aligned} &BatteryChargingCost/kWh^{d,h} \\ &= \begin{cases} rev/kWh^{d,h} & during\ PV\ hours \\ cost/kWh^{d,h} & during\ non-PV\ hours \end{cases} \end{aligned} \tag{5.10}$$

The hours associated with the lowest values of the $BatteryChargingCost/kWh^{d,h}$ are chosen for battery charging during a day. There are usually some hours during PV hours with smaller $rev/kWh^{d,h}$ than the $cost/kWh^{d,h}$ in non-PV hours, therefore, charging the battery would be optimum to be conducted during PV hours.

d) the battery discharging revenue for one kWh: this value evaluates the benefit of discharging the battery in a certain hour and is formulated as in (5.11). The amount of discharging power that supplies the load that is not supplied by PV, namely $E^{d,h}_{RES-PV}$, is valued at $cost/kWh^{d,h}$, because it avoids purchasing energy from the market to supply the demand. The value of the extra discharging power beyond the load will be calculated at $rev/kWh^{d,h}$. For the purpose of finding the revenue associated with discharging, we consider the maximum discharge power of the battery.

$$\begin{aligned} &BatteryDischargingRev/kWh^{d,h} \\ &= [E_{RES-PV}^{d,h} cost/kWh^{d,h} + (E_{VRFB}^{max} - E_{RES-PV}^{d,h}) rev/kWh^{d,h}]/P_{VRFB}^{max} \end{aligned} \tag{5.11}$$

Finally, the optimum bidding power for *h-th* hour and *d-th* day, $BiddingkWh^{d,h}$, is calculated using (5.12).

$$BiddingkWh^{d,h} = E_{RES}^{d,h} + E_{VRFB}^{d,h} - E_{PV}^{d,h} \tag{5.12}$$

The positive and negative signs of the bidding kWh at each hour means purchasing and selling to the electricity market, respectively. The flowchart of the algorithm for maximising the profit of the VPP is provided in **Figure 5.2**. During scheduling of charging and discharging of the battery, the constraints of that are also considered.

5.4.1 The robustness of the optimisation

The proposed approach is robust, which means that the obtained bidding strategy is optimum for the worst case of uncertain parameters [64]. The uncertainties here are associated with the electricity price and the PV generation, which are varying between a high and a low boundary. The worst case under which the optimisation needs to be solved is presented in **Table 5.2**.

Table 5.2. The worst case for bidding

	PV generation	Electricity price
The VPP is **selling** to the market	low	low
The VPP is **buying** from the market	low	high

5.5 Simulation Results

In this Section, the simulation results for a realistic VPP in WA under development are presented.

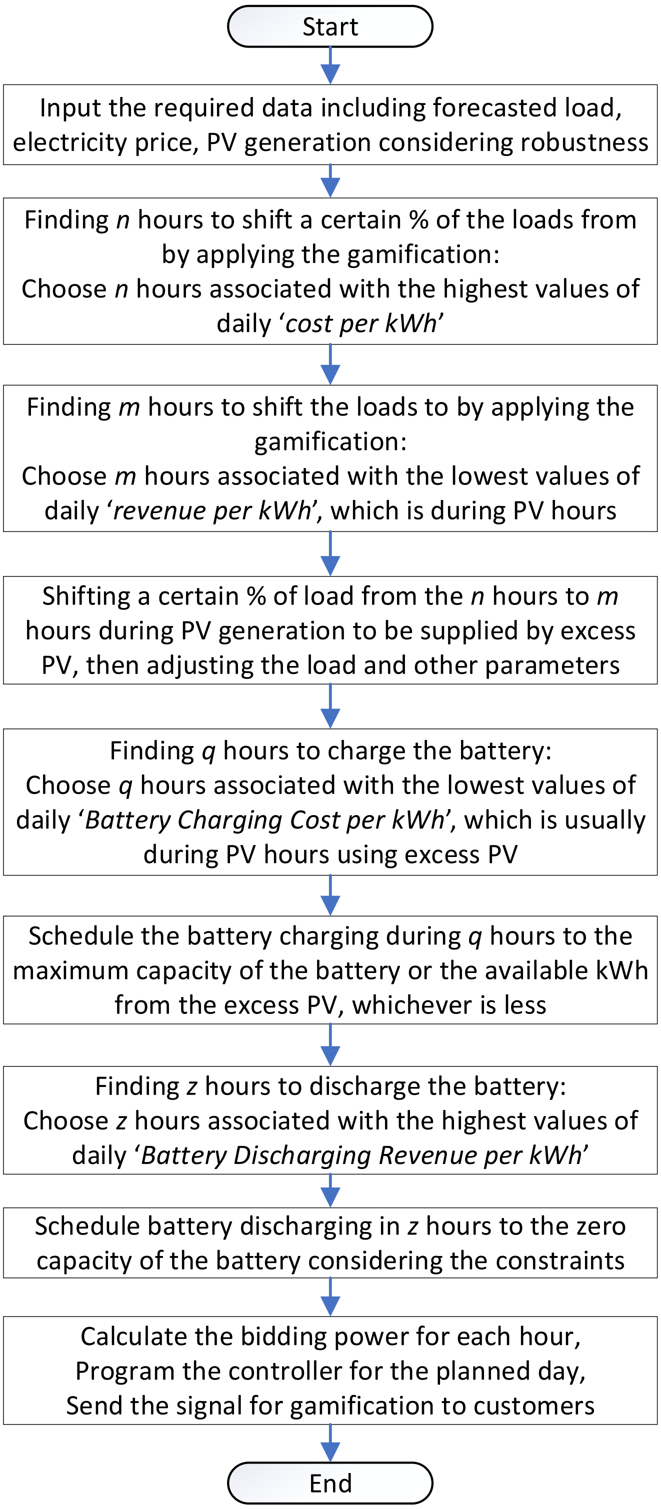

Figure 5.2. Flowchart of optimised robust bidding strategy

5.5.1 The realistic VPP in WA

The 67 dwellings in South Lake, WA are designed to form a VPP, including 810kW of rooftop solar PV and a 700kWh, 350kW VRFB. Each dwelling is designed to be equipped with controllable appliances including heat pump hot water systems, washing machine, air conditioner, and dishwasher with EEBUS protocol. The detailed information on the design of this VPP is provided in [110]. The typical load profiles for different seasons are provided in **Figure 5.3**.

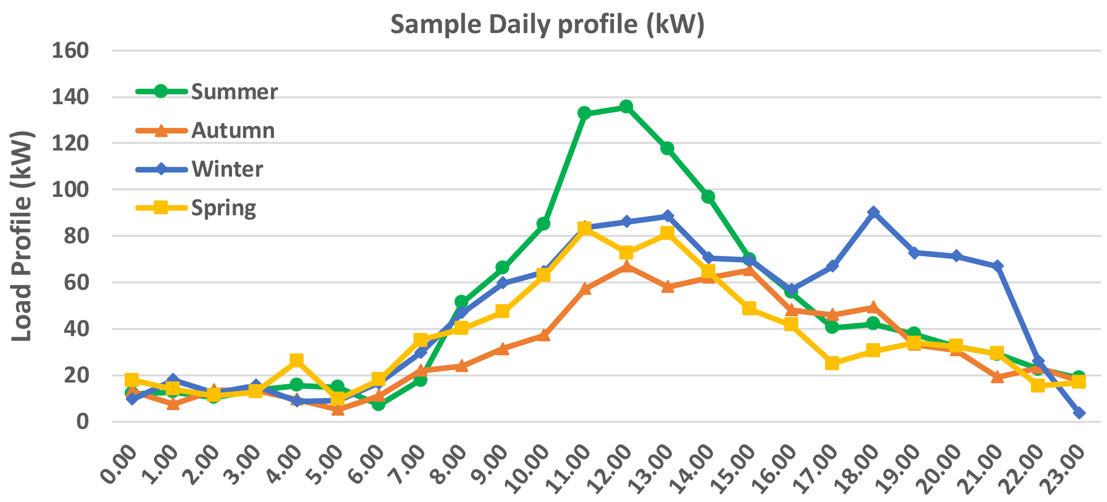

Figure 5.3. Sample daily profile of the VPP for different seasons

5.5.2 Assumptions

In this simulation, it is assumed that the uncertainty of PV generation and electricity price is 10%. Also, the electricity reduction factor due to gamification, ϑ^h, is 30% and the percentage of customer participation in the gamified approach, τ^h, is 80%. It is assumed that the VPP is registered to trade directly with the electricity market, therefore, the retailer's margin, α^y , is zero. In this VPP, we allow for generating PV as much as the solar panels can generate, therefore, PV curtailing is not recommended here to maximise the VPP's profit. As the VPP already gives 10% discount for all consumers, the gamification's effect is considered mainly through social interaction, collaboration and competition.

5.5.3 VPP bidding on different days

Figure 5.4 shows the bidding power, battery charging, PV generation, load amount including gamification, and the electricity price on 1 January. As can be seen, the battery is charged using excess PV when the electricity price is low and discharged during non-PV hours when the electricity price is high. During hours 11 to 19, the excess PV is sold to the market to maximise the profit of the VPP. The electricity price at hour 3 is negative but, considering the purchase fees, the cost of buying electricity at that time is not cheaper than those hours already selected by the proposed algorithm here. The gamification approach enables customer engagement to shift some controllable loads including heat pumps, washing machines, dishwashers, and dryers to the hours with less energy cost for the VPP. As illustrated in **Figure 5.4**, 30% of loads from hours 18-23 are shifted to hour 9. It is important to mention that the load and gamified responses are probabilistic measures, which means that the contributions from customers are not necessarily equal.

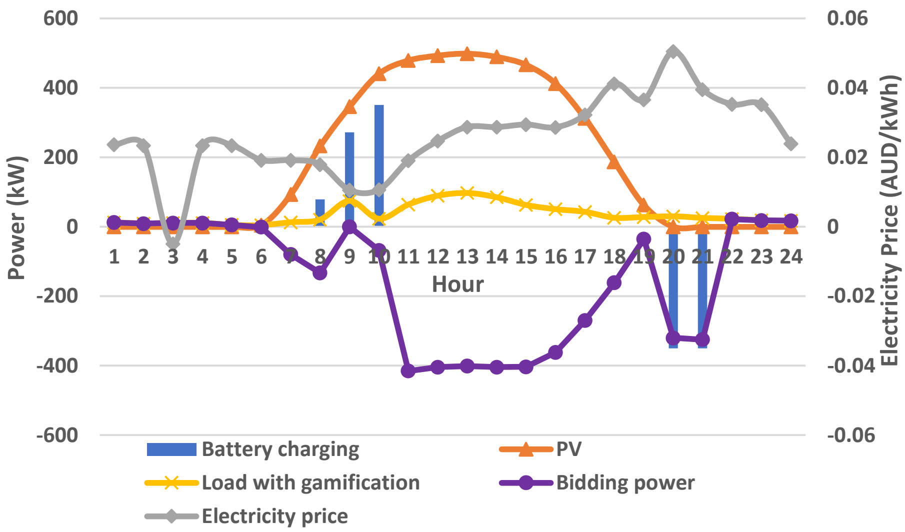

Figure 5.4. Bidding power of the VPP and other parameters on 1 January; negative bid means selling to the market

Figure 5.5 shows the optimised bidding power of the VPP during peak load on 14

January. As seen, the price of electricity during hours 14 and 15 is maximum, therefore, the algorithm has decided to discharge power from battery for selling to the market. Also, through gamification, 50% of customer loads from hours 13 to 17 are shifted to hour 8 to maximise the profit of the VPP. In this case, the loads are shifted within the PV hours to increase the profit of the VPP.

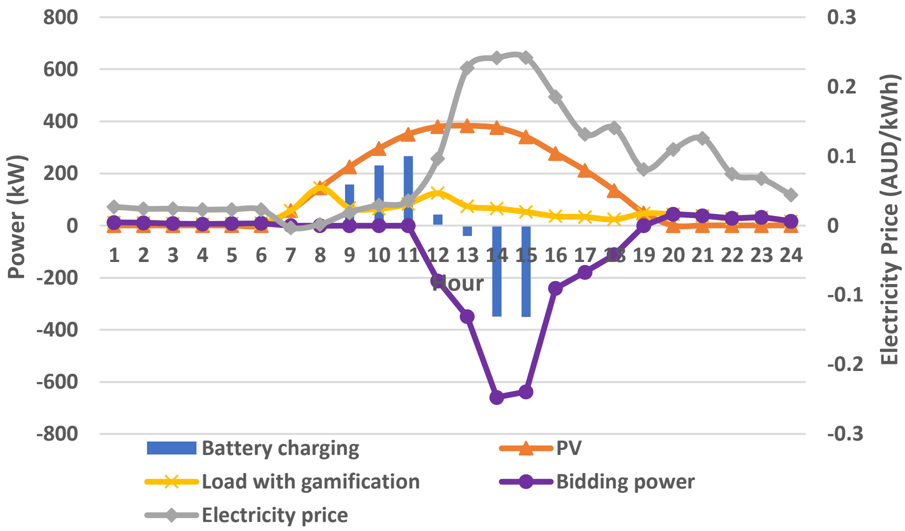

Figure 5.5. Bidding power of the VPP during peak load on 14 January

Bidding power and other parameters are presented in **Figure 5.6** for 5 October when PV generation is maximum. As can be seen, the battery is charged during PV hours when the electricity price is low, and also the load is shifted to that hour in order to maximise the profit of the VPP.

On cloudy days also, the proposed algorithm can provide a robust solution for VPP's bidding as shown in **Figure 5.7**. As demonstrated, the load is shifted during PV hours as much as possible as the electricity price is very low. In addition, the battery is charged using excess PV during PV generation, then discharged when the electricity price is high to cover the load and to sell to the electricity market.

For some days such as 25 May where there is not any excess PV, the gamification and battery charging/discharging will not be implemented.

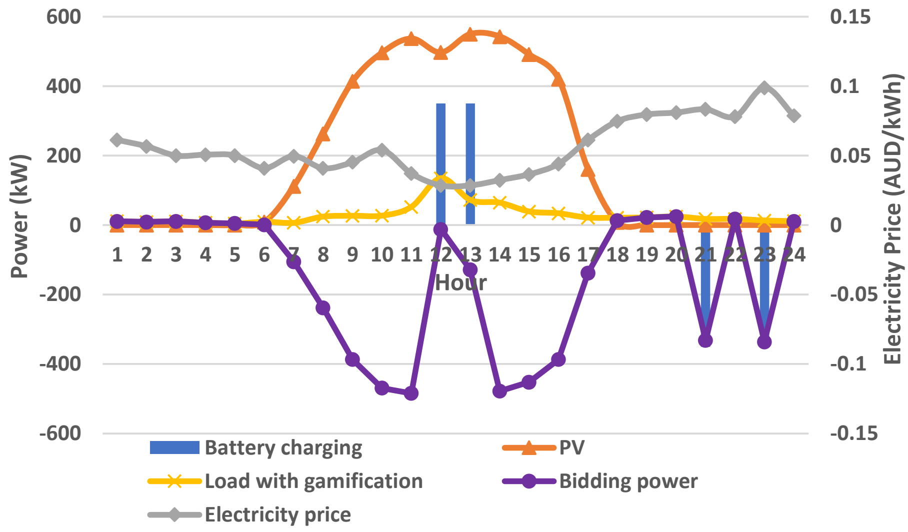

Figure 5.6. Bidding power of the VPP and other parameters during peak PV generation on 5 October

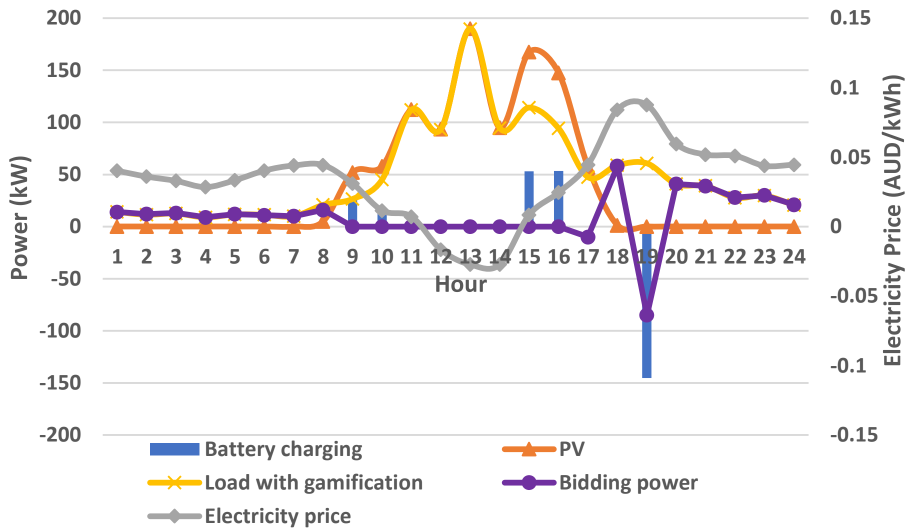

Figure 5.7. Bidding power of the VPP and other parameters during a cloudy day with intermittent PV generation on 17 June

5.5.4 VPP profit on different days

Table 5.3 shows the daily profit of the VPP with and without using gamification for demand management. As seen, on all days, there is a positive profit for the VPP owner with differing amounts. The amount of saving depends on the pattern of PV generation, electricity price and load profiles all together. If there are low electricity price hours during PV generation, this would be a good opportunity to shift the load during these hours to reduce the cost of the VPP such as the case in the peak load on 14 June.

Table 5.3. The daily profit of the VPP with and without using gamification (AUD/day)

	14 June Peak load	**5 Oct Max PV**	**17 Jun Cloudy day**
With gamification	889	493	422
Without gamification	849	486	419
AUD improvement	39	6	3

The total profit of the VPP over a year with and without implementation of the gamification at different levels of load management is presented in **Figure 5.8**. These results are obtained by simulation of the VPP performance over a year, while the results for different days are obtained by simulation of that day. As can be seen, there is an increasing profit by increasing the level of load shifting capabilities. These levels of load management are achievable in the VPP in WA as many appliances including heat pump, washing machine, dishwasher, and dryers are remotely controllable. Also, there are different circuits at each dwelling, supplying different zones of the house, which are separately controllable remotely. As discussed in this Chapter, residents through engaging in the gamification process will likely accept the change in their load pattern but this will be up to the decision of the resident. In all cases, the participation of customers is considered to be at 80%.

5.5.5 Customer electricity cost saving

As the tariff for the dwellings within the VPP is 10% lower than the tariff presented by the local utility, there is 10% saving for each dwelling within the VPP. The average electricity cost per dwelling within the VPP per year is AUD 1,571, which shows AUD 175 saving per year for the energy for each house. This expense would be AUD 1,746 if the houses are supplied by the local utility. On top of this, the residents within the VPP have access to the gamification app through which they can socialise and learn about topics related to energy.

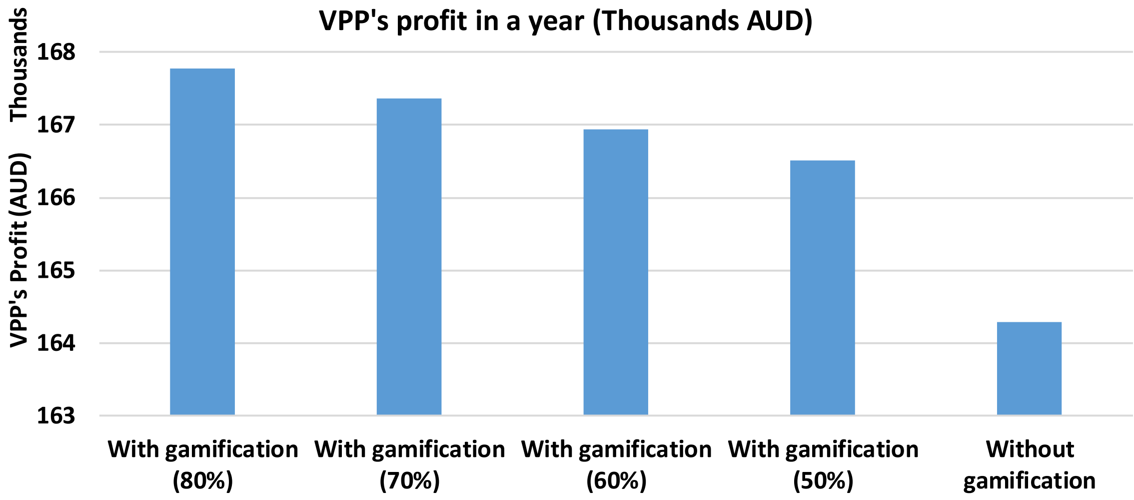

Figure 5.8. The total profit of the VPP in a year with and without gamification

5.5.6 Different uncertainty on PV and electricity price

If the uncertainties associated with the PV generation and electricity price increase, the profit of the VPP decreases as it needs to have a conservative optimum plan in place in all uncertain situations. For example, if the uncertainties increase from 10% to 20% for both PV generation and electricity price, the VPP's profit for the peak load on 14 June decreases from AUD 889 to AUD 718 on that day, which is about 19% reduction compared to 10% uncertainty. As seen, the profit decreases more than uncertainty increase.

5.6 Conclusions

A robust bidding strategy is developed in this Chapter, which is a simple and understandable procedure considering gamification for customer engagement. The procedure is simulated for a realistic VPP in WA, and the simulation results show that the bidding strategy can provide a robust bidding in different situations including peak load, cloudy day, and different levels of PV. Also, it demonstrates that increase of profit by using gamification and the robust algorithm.

Chapter 6 A Robust Participation in the Load Following Ancillary Service and Energy Market for a Virtual Power Plant in Western Australia[1]

6.1 Summary

Virtual power plants (VPPs) are an effective platform for attracting private investment and customer engagement to speed up the integration of green renewable resources. In this Chapter, a robust bidding strategy to participate in both energy and ancillary service market in the wholesale electricity market is proposed for a realistic VPP in Western Australia. The strategy is accurate and fast, so the VPP can bid in a very short period of time. To engage customers in the demand management schemes by the VPP owner, the gamified approach is adopted to make the exercise enjoyable while not compromising their comfort levels. The modelling of revenue, expenses and profit for the load following ancillary service (LFAS) and the energy market is provided, and the effective bidding strategy is developed. The simulation results show a significant improvement in the financial indicators of the VPP when participating in both the LFAS and energy market. The payback period can be improved by 3 years to the payback period of 6 years and the

[1] This chapter is based on the submitted journal paper of: Behnaz Behi, Philip Jennings, Ali Arefi, Ali Azizivahed, Almantas Pivrikas, SM Muyeen, Arian Gorjy, "A Robust Participation in the Load Following Ancillary Service and Energy Market for a Virtual Power Plant in Western Australia," under review in Energies.

internal rate of return (IRR) by 7.5% to the IRR of 18% by participating in both markets. The accuracy and speed of the proposed bidding strategy method is evident when compared with a mathematical method.

6.2 Introduction

The emission of greenhouse gases is causing the Earth's temperature to rise, and if we don't take immediate action, we will see catastrophic consequences. Achieving zero net emissions by 2050 is now a goal for many nations, including Australia , and it will require the use of renewable resources [116]. Renewables like solar and wind are abundant and can be used without emitting any significant pollution. Such renewable energy sources are becoming more popular, but they can't always generate power when we need it because the sun is not shining, or the wind is not blowing. This is a problem because we need to rely on renewable energy to help us reduce our reliance on fossil fuels and stop climate change. Energy storage is the key to making renewables reliable [117]. By storing energy when the sun is shining and the wind is blowing, we can use that energy when we need it most and keep our renewable systems running smoothly.

Therefore, the world is moving towards renewable energy and energy storage, but the process is slow. Also, utilities are struggling with the technical issues associated with the increase of rooftop PV systems and large renewable plants. Virtual power plants (VPPs) are an effective way of coordinating different sources of energy and attracting private investments, which help make renewables the norm [118]. By investing in VPPs, the investors are not only helping the environment, but they are also getting a great return on their investment, i.e. 8.5 years payback for an Australian VPP [119]. An analysis of a VPP in Malaysia, which includes PVs and energy storage, also shows a 10 to 11 year payback period.[120]. In addition, a study in Japan shows that the payback period of a

VPP can be around 15 years when they get a discount on energy storage in a large scale system [121]. Another study shows that heating, ventilation, and air-conditioning units can create a VPP for a residential community [122]. VPPs are becoming more and more popular, especially when they realize they can increase their revenue by participating in the wholesale electricity market (WEM).

The WEM is a competitive market, operated by the Australian Energy Market Operator (AEMO) where generators sell their electricity and services to the grid at a price that will make them the most profit. By participating in the WEM, VPPs can optimise their contributions in different markets to maximise their profits. Also, VPPs can provide ancillary services such as a load following service to the grid and get paid for it. This can result in significantly increased profits for VPPs. Different strategies are proposed for optimizing the participation of VPPs in electricity markets, which are different essentially because of the difference in rules of operating markets around the world. For example, information gap theory is utilized for scheduling resources in a VPP [69]. Also, a robust coordination of energy resources is discussed to consider the uncertainties in electricity prices and renewable resources [70]. Heuristic algorithms such as the grasshopper optimisation algorithm are also used for controlling frequency by a VPP [73]. Further, a coordinating system was evaluated for congestion management using multiple VPPs [123]. A two-level robust dispatching of resources in a VPP results in around 20% cost reduction for the VPP [71]. A Dirichlet process mixture model can also be used to optimise the operation of a VPP robustly [124]. A Nash-Harsanyi Bargaining Solution can also innovatively developed to fairly allocate the profit of participating in frequency regulation [125]. In addition, participation of a VPP in ancillary service [74] and the energy market can result in a payback period of around 10 years [17]. However, the engagement of customer to the operation of VPPs is very critical and needs to be considered in a way to be enjoyful for the customers, which is not investigated in details in these literature.

Demand management is considered as a source of flexibility within a VPP that increases the profit of a VPP [43, 44]. However, traditional demand response and management has been not very effective. Therefore, a gamified approach is studied for customer engagement within a VPP [114]. Using this gamification approach, the customers will participate more in the demand flexibility of the VPP. Also, a robust bidding strategy considering gamified consumer contributions is studied [114]. Although the participation in the market is discussed in the literature, a detailed framework for a bidding strategy for Western Australia (WA), which includes gamified customer engagement and is fast and understandable for industry has not previously been provided.

6.2.1 Ancillary Services in WEM

In addition to the energy market, there are several ancillary services, which are being procured by AEMO for the reliable and secure operation of the power grid in WEM. These ancillary services are load following ancillary service (LFAS), spinning reserve ancillary services (SRAS), load rejection reserve ancillary services (LRRAS), dispatch support service (DSS), and system restart service (SRS), as explained in the "wholesale electricity market rules" [74]. Among all these services, AEMO runs the ancillary market only for LFAS, and other ancillary service are secured using bilateral contracts with large generators, specifically with Synergy. *Therefore, in this Chapter, only participation in the LFAS market is considered for the VPP.*

LFAS is the service to continuously balance supply and demand to regulate the frequency of the WEM power grid within the normal range, which is from 49.8 to 50.2 Hz for 99% of the time. To this aim, the participants in the LFAS market can provide two forms of upwards LFAS and downwards LFAS. Upwards LFAS is provided for increasing frequency by increasing the power generation of the participant, while downwards LFAS is provided to decrease frequency. LFAS is enabled in response to any frequency violations from the normal condition, for which the power generation of the enabled participant in the LFAS market changes based on commands from an automatic generation control (AGC) system.

As per the WEM rules, the AEMO must forecast the upwards LFAS and the downwards LFAS quantities for each 30-miniute trading interval in the next trading day, however, these estimates can be modified before the trading interval. A participant in the LFAS market can submit a LFAS amount for their facilities for any or all trading intervals in the balancing horizon and before the gate closure for those trading intervals. The balancing horizon is a 43-hour period from 1pm of each trading day to the end of 8am on the next trading day

An example of LFAS bidding and enablement over four trading intervals is shown in **Figure 6.1**. As can be seen, in the trading interval 1, the enabled LFAS power is upwards and less than the bidding amount of this participant. In the 2nd interval, the enabled LFAS amount is downwards and near the downwards LFAS bidding. There is no enablement in the third interval. However, in the fourth trading interval, both upwards and downwards are enabled, and the bidding amount for the downwards LFAS is also enabled.

The LFAS requirement approved for the WEM in 2020-21 has increased to 105 MW (from the planned 85 MW) for upwards and downwards LFAS between 5:30am and 7:30pm, and to 80 MW (from the planned 50 MW) for both upwards and downwards LFAS between 7:30pm and 5:30am for each trading interval. These increased amounts for LFAS requirements are due to the expected connection of 520MW of additional intermittent non-scheduled generation, especially roof top PV panels. It is expected that LFAS requirements have increased due to adding more volatile rooftop PVs. The actual average upwards and downwards LFAS quantities enabled between 5:30am to 7:30pm during 25 September 2020 up to 30 April 2021 are 111 and 117 MW, respectively, which shows some levels of backup LFAS have also been activated [126].

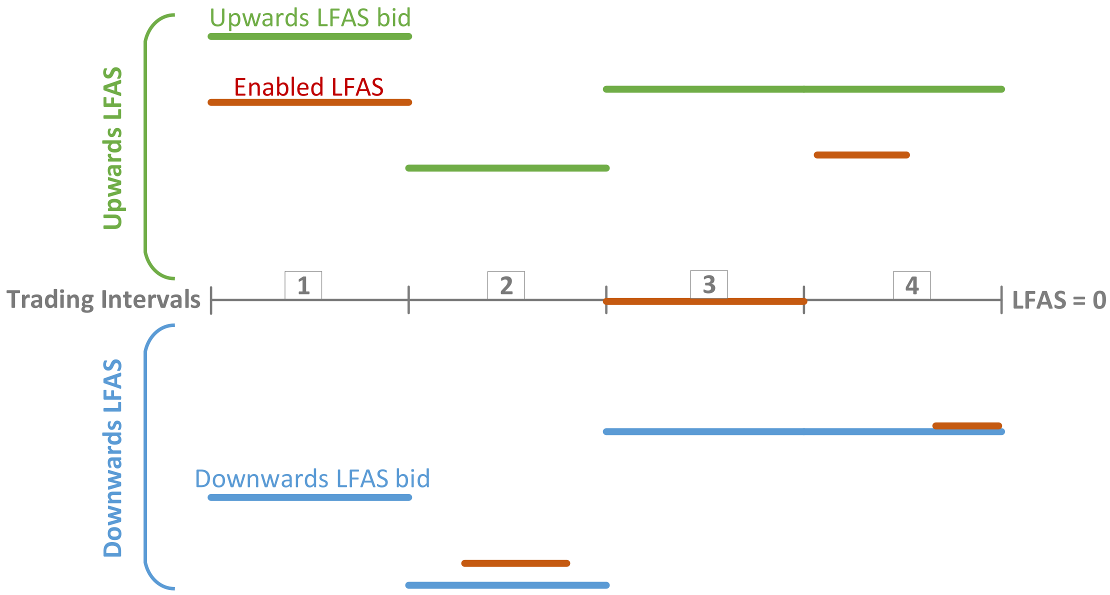

Figure 6.1. An example of LFAS bidding and enablement over four trading intervals. Green: bidding power for upwards LFAS; Blue: bidding power for downwards LFAS; Brown: the enabled power by AGC.

6.2.2 Contributions of the Chapter

This Chapter develops a framework for a bidding strategy, which maximises the profit for the VPP owner, reduces the cost of electricity for the dwellings and also provides a service to the Western Australian grid by provision of energy and load following ancillary service. The proposed framework also includes the gamified customer engagement model developed by [114]. Based on the best knowledge of authors, there is not any previous research that jointly considers the gamification approach along with the participation in LFAS market. Additionally, the proposed method is fast, as it uses an expert method for bidding, which enables a VPP to decide on the optimal bidding in a very short period of time. Using this strategy, the VPP is also able to change its bidding right before the gate closure to maximize the profit. Another benefit of this higher speed is to reduce the computational efforts and the required memory for attaining an optimal bid for a VPP. Furthermore, the logic of the proposed expert bidding strategy is simple and understandable, so it can be easily implemented in different practical platforms.

A realistic VPP is studied in this Chapter, as this is being built in Western Australia, including 67 dwellings, an 810 kW rooftop solar farm, 350 kW/700 kWh vanadium redox flow batteries (VRFB), heat pump hot water systems (HWS), and demand management. The contribution of this Chapter is as follows:

- Developing an expert model for a fast and robust bidding strategy in the LFAS and energy markets, considering PV generation, energy storage scheduling and a gamified contribution of consumers to maximize the profit of the VPP and reduce consumers' energy costs.
- Analysis of the economic viability of the realistic VPP when participating in the LFAS and energy markets, including the payback period, internal rate of return, cash flow, and profit, over the lifetime of the project.
- Comparison of the proposed fast bidding strategy with a traditional robust mathematical approach to show the effectiveness of the proposed strategy for deciding or changing the bidding values in a short period of time.

This Chapter is organised as follows. The next Section provides the problem formulation for the VPP's profit. Section 6.4 develops a robust bidding strategy for participation in the LFAS and energy markets. Section 6.5 discusses the simulation results. Concluding remarks are provided in Section 6.6.

6.3 Problem Formulation

The goal of participation in the WEM and managing customers' loads is to maximise the profit of the VPP, while reducing the cost of electricity for the customers from what they should pay to the local utility. Therefore, the objective function of the problem is formulated as in (6.1) over a day, which is the total revenue minus the total expenses for the VPP.

In all equations the indices *d,h* represent the values of the corresponding parameter at *h-th* hour of *d-th* day.

$$maximize\ (R_{tot} - C_{tot})$$
$$\text{Constraints: } \begin{cases} Energy\ storage\ charging/discharging \\ Customer\ preferences\ constraints \end{cases} \tag{6.1}$$

$$R_{tot} = R_{Fix} + R_{Var}$$
$$= R_{Fix} + \sum_{h=1}^{24} E_{out}^{d,h}\pi^{d,h} + \sum_{h=1}^{24} E_{RES}^{d,h}\tau_{RES,E}^{d,h} + \sum_{h=1}^{24} P_{LFAS,UP}^{d,h}\zeta_{LFAS,UP}^{d,h} + \sum_{h=1}^{24} P_{LFAS,DOWN}^{d,h}\zeta_{LFAS,DOWN}^{d,h} \tag{6.2}$$

$$E_{out}^{d,h} = \begin{cases} E_{PV}^{d,h} - E_{RES}^{d,h} & if\ \left(E_{PV}^{y,h} - E_{RES}^{y,h}\right) > 0 \\ 0 & otherwise \end{cases} \tag{6.3}$$

$$C_{tot} = C_{Fix} + \left(1 + \alpha^{y}\right)\sum_{h=1}^{24} E_{in}^{d,h}\pi^{d,h} + \left(1 + \beta^{y}\right)\sum_{h=1}^{24} E_{in}^{d,h}\omega^{d,h} + (\gamma^{y} + \delta^{y} + \theta^{y})\sum_{h=1}^{24} E_{in}^{d,h} \tag{6.4}$$

$$E_{in}^{d,h} = \begin{cases} E_{PV}^{d,h} - E_{RES}^{d,h} & if\ \left(E_{PV}^{d,h} - E_{RES}^{d,h}\right) < 0 \\ 0 & otherwise \end{cases} \tag{6.5}$$

where R_{tot} and C_{tot} are the total revenue and expenses of the VPP, respectively, R_{Fix} is the fixed revenue, and R_{Var} is the variable revenue, which includes three terms; the daily revenue from selling $E_{out}^{y,h}$ to the electricity energy market ($\sum_{h=1}^{24} E_{out}^{d,h}\pi^{d,h}$) at the market price of $\pi^{d,h}$, the daily revenue from selling $E_{RES}^{d,h}$ to the customers ($\sum_{h=1}^{24} E_{RES}^{d,h}\tau_{RES,E}^{d,h}$) at the agreed price of $\tau_{RES,E}^{d,h}$, and the daily revenue from selling $P_{LFAS,UP}^{d,h}$ to the upwards LFAS market ($\sum_{h=1}^{24} P_{LFAS,UP}^{d,h}\zeta_{LFAS,UP}^{d,h}$) at the weighted average price of $\zeta_{LFAS,UP}^{d,h}$ and selling $P^{d,h}_{LFAS,DOWN}$ to the downwards LFAS market at the weighted average price of $\zeta^{d,h}_{LFAS,DOWN}$. $E^{d,h}_{PV}$ is the energy generated by the PV system, $E^{d,h}_{RES}$ is the customers' energy consumption. The electricity tariff for the customer is 94.63 cents/day for the fixed cost and 26.39 cents/kWh for energy usage at any hour, which is provided at a 10% discount compared to the local utility tariff [127]. The tariff structure is the flat tariff, which is similar to the assumption in Chapter 5. The actual LFAS prices are not published by the AEMO, therefore, we can only use the weighted average prices for LFAS, which is published by the AEMO. Also, the input data for PV generation, electricity prices, and LFAS prices are adjusted as per the robustness consideration, as discussed in Section 6.4.3.

C_{tot} is the total expenses of the VPP for a day, C_{Fix} is the fixed part of the expenses like CAPEX, $E^{d,h}_{in}$ is the total energy purchased from the WEM at the price of $\pi^{d,h}$ through a retailer with the margin of α^{y}, $\omega^{y,h}$ is the local utility tariff costs [100], γ^{y} , δ^{y} , and θ^{y}, respectively are the fees associated with the Clean Energy Regulator, the ancillary service, and the market. The detailed formulation and explanation of costs and expenses is provided in [110].

6.3.1 The Modelling of Gamification for Customer Engagement

The gamification approach proposed here is based on a virtual home system owned by each dwelling. By increasing the efficiency of this virtual home system, the participants can compete with each other and get more benefits, prizes, and badges. The details of the gamified approach for customer engagement are presented in [127]. Based on this effective approach, the energy consumption by dwellings, $E^{d,h}_{RES}$, is:

$$E^{d,h}_{RES} = E^{d,h}_{RES,def} - \vartheta^{h} \varrho^{h} E^{d,h}_{RES} \tag{6.6}$$

where $E^{d,h}_{RES,def}$ is the default load profile of the dwellings and ϑ^{h} and ϱ^{h} are the electricity reduction factor and the percentage of customer participation in the gamified approach, respectively, as described in Chapter 5

6.3.2 The Constraints

The constraint for the energy storage, VRFB, is as follows. In this formulation, it is considered that the energy storage is dedicated to participation in LFAS market.

$$
\begin{gathered}
0 \leq SOC_{VRFB}^{d,h} \leq SOC_{VRFB}^{max} \quad , \quad \forall d,h \\
0 \leq P_{LFAS,UP}^{d,h} \leq P_{VRFB}^{max} \ , \qquad 0 \leq P_{LFAS,DOWN}^{d,h} \leq P_{VRFB}^{max}
\end{gathered}
\tag{6.7}
$$

where $SOC_{VRFB}^{d,h}$ and SOC_{VRFB}^{max} are the state of charge (SOC) at day *d* and time interval of h and the maximum state of charge, and P_{VRFB}^{max} is the maximum charging/discharging power of the VRFB. As $P_{LFAS,UP}^{d,h}$ is for the upwards LFAS, which is for increasing frequency, so the energy storage should inject power to the grid, which reduces the SOC of the energy storage, therefore, $P_{LFAS,UP}^{d,h}$ comes with a negative sign in the SOC calculation. However, $P_{LFAS,DOWN}^{d,h}$ is for the downwards LFAS, resulting in charging the energy storage.

Another constraint is the customer preference constraints, which are pre-defined values by residents to satisfy their comfort levels. Every command for customer participation in demand change can be withdrawn by a customer or can be programmed by them for which times and dates and for which appliances, the VPP commands can or cannot be applied. The detailed formulation of the customer preference constraints is provided in [127].

6.4 A Robust Bidding Strategy for LFAS and Energy Market

In the case of the realistic VPP in this Chapter, which is in a medium size range, considering the size of the energy storage of 350kW/700kWh and 810kW of rooftop PVs, the following expert method of bidding strategy is used:

- The VRFB is dedicated to participating in the LFAS market.
- The excess PV generation is sold to the energy market after covering the customer's load during PV generation.

For this bidding strategy, the customer's load is shifted through the gamification approach from expensive energy hours during non-PV hours to non-expensive energy hours during PV hours to maximise the profit of the VPP, based on the gamification method in [127]. Most major appliances in this VPP such as heat pump HWS, dishwasher, dryer and washing machine are controllable and planned to response to the commands from the VPP controller to run mostly during PV generation as discussed in [119].

This bidding strategy is simple but effective, as it is based on the expert model, which is understandable and accepted by the industry. The rationale behind this strategy is that, at the moment, only scheduled generators, such as the VRFB, are accepted by the AEMO in WA to participate in the LFAS market. Also, the reward for participating in the LFAS market is higher than participating in the energy market only, most of the time. Therefore, major part of flexibility in the VPP, which is energy storage, is dedicated to the LFAS. The overall structure of the proposed bidding strategy method is provided in the flowchart in **Figure 6.2**. As seen, after collecting the required data, the bids for the LFAS are obtained. Then independently, the gamification is run, and the bidding amount for energy is calculated, as discussed in this section.

6.4.1 Bidding Model in LFAS Market

The LFAS market is run for each 30 minutes (trading interval) in the WEM. The bidding into the LFAS market depends on the SOC of the VRFB at the end of the last trading interval, and the efficiency of the VRFB. However, the amount of power bidding is also limited to the maximum power. The LFAS bids are proposed in (6.8) to (6.9).

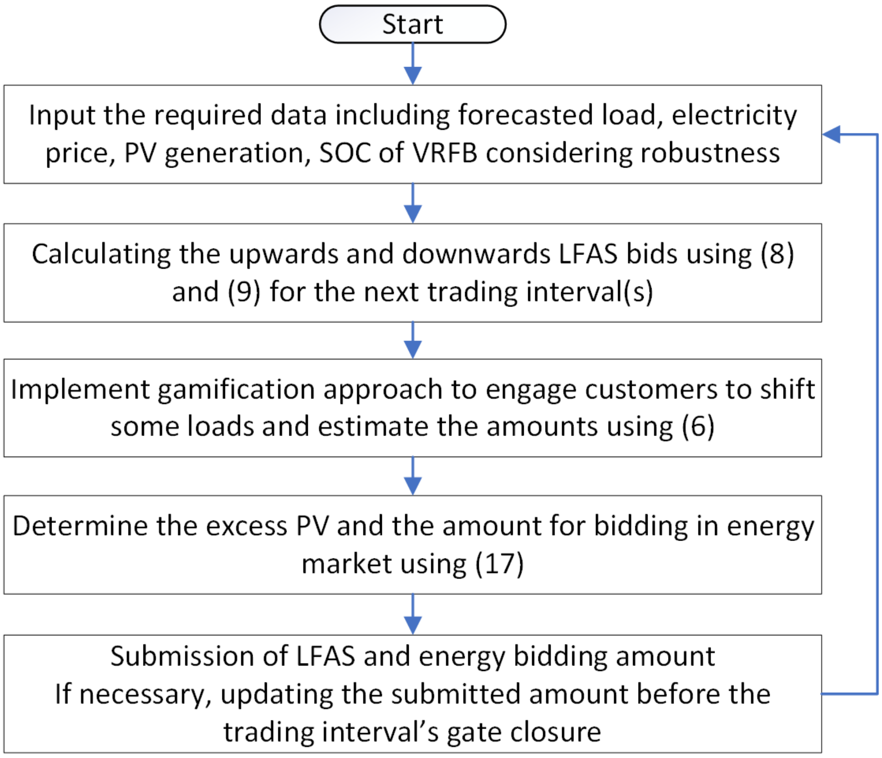

Figure 6.2. The flowchart for the bidding strategy in LFAS and energy market.

The amount of bidding for the upwards LFAS is calculated based on the SOC divided by the trading interval ($T_{trading}$) for the LFAS market, multiplied by the roundtrip efficiency (η_{VRFB}^{eff}) of the VRFB, as seen in (6.8). This bidding amount is capped by the maximum power capability of the VRFB. The efficiency of the VRFB is only considered in conjunction with upwards LFAS, as it is the roundtrip efficiency. Based on a similar concept, (6.9) provides the bidding value for downwards LFAS. Here, it is assumed that if the AEMO needs LFAS from this VPP, it enables the upwards or downwards LFAS bidding values to be determined as in (6.8) and (6.9).

In reality, the downwards and upwards LFAS are enabled for a shorter period of time within $T_{trading}$, which are defined as $t_{LFAS,DOWN}^{d,h}$ and $t_{LFAS,UP}^{d,h}$, respectively. These times are modeled as random values, as in (6.13) and (6.14), because they depend on many parameters at the time of LFAS enablement including grid situation. The duration of

LFAS usage depends on the balance of load and generation including roof top PV generation, which is very volatile, therefore, the best modelling for this duration is a random number. Also, there is a lack of available data on the enablement of LFAS in each trading interval as they are not published by the AEMO. For the same reason, the command (Cmd_{LFAS}) by the AGC on the enablement of upwards, downwards, or both LFAS services during the corresponding trading interval, has random behaviour, so in the simulation, the command for LFAS enablement is generated randomly for each trading interval. For example in (13), if the downwards LFAS is not activated, $t_{LFAS,DOWN}^{d,h}$ is zero, and if enabled, $t_{LFAS,DOWN}^{d,h}$ is a random number uniformly distributed between 0 and $T_{trading}$.

$Enable_{LFAS}^{d,h}$ is the enablement rate of the LFAS service for the VRFB. In practice, not in all intervals, the LFAS are enabled, which is modelled as a random variable here, and a sensitivity analysis is conducted on the enablement rate in Section IV. $random(0, T_{trading})$ is a uniformly distributed random number between 0 and $T_{trading}$. $round()$ is the round function.

$Profit_{LFAS}^{d}$ is the daily profit from participation in the LFAS market. Although there are some costings associated with participation in the LFAS market in the WEM, the detailed costings of the contracts are only available internally to AEMO and not to the public. The AEMO has published the weighted average prices for upwards and downwards LFAS, $\zeta_{LFAS,UP}^{d,h}$ and $\zeta_{LFAS,DOWN}^{d,h}$ which are used in this Chapter, as shown in **Figure 6.3** [126]. These prices include the weighted average all revenue and expenses and can be used as representative of the profit of participation in the LFAS market.

$EnergyThroughPut_{VRFB}^{d}$ is the "energy throughput" of the battery for d-th day, which is the amount of energy that can be delivered by the VRFB. Although in some cases, the curve of depth of discharge (DoD) vs lifetime of energy storages is used for estimating their lifetimes, this approach is not very effective when we have a volatile PV generation and load. In this Chapter, we are using the energy throughput parameters for estimating the remaining lifetime of the VRFB. This method is increasingly being adopted by more manufacturers, and they now guarantee the amount of energy throughput for their energy storages [128].

$$P_{LFAS,UP}^{d,h} = \min\left(\frac{SOC_{VRFB}^{d,h-1} \times \eta_{VRFB}^{eff}}{T_{trading}}, P_{VRFB}^{max}\right) \ , \quad \forall d,h \tag{6.8}$$

$$P_{LFAS,DOWN}^{d,h} = \min\left(\frac{SOC_{VRFB}^{max} - SOC_{VRFB}^{d,h-1}}{T_{trading}}, P_{VRFB}^{max}\right) \tag{6.9}$$

$$\begin{aligned} SOC_{VRFB}^{d,h} = SOC_{VRFB}^{d,h-1} + P_{LFAS,DOWN}^{d,h} t_{LFAS,DOWN}^{d,h} / \eta_{VRFB}^{eff} \\ - P_{LFAS,UP}^{d,h} t_{LFAS,UP}^{d,h} \ , \quad \forall d,h \end{aligned} \tag{6.10}$$

$$Profit_{LFAS}^{d} = \sum_{h=1}^{24} P_{LFAS,UP}^{d,h} \zeta_{LFAS,UP}^{d,h} + \sum_{h=1}^{24} P_{LFAS,DOWN}^{d,h} \zeta_{LFAS,DOWN}^{d,h} \tag{6.11}$$

$$EnergyThroughPut_{VRFB}^{d} = \sum_{h=1}^{24} P_{LFAS,UP}^{d,h} t_{LFAS,UP}^{d,h} \tag{6.12}$$

$$t_{LFAS,DOWN}^{d,h} = \begin{cases} 0 & Cmd_{LFAS}^{d,h} = UP \quad or \quad No\ cmd \\ random(0, T_{trading}) & Cmd_{LFAS}^{d,h} = DOWN \\ random(0, T_{trading}/2) & Cmd_{LFAS}^{d,h} = UP\ \&\ DOWN \end{cases} \tag{6.13}$$

$$t_{LFAS,UP}^{d,h} = \begin{cases} random(0, T_{trading}) & Cmd_{LFAS}^{d,h} = UP \\ 0 & Cmd_{LFAS}^{d,h} = DOWN \ \ or\ No\ cmd \\ random(0, T_{trading}/2) & Cmd_{LFAS}^{d,h} = UP\ \&\ DOWN \end{cases} \tag{6.14}$$

$$Cmd_{LFAS}^{d,h} = \begin{cases} UP & Rnd\_Cmd_{LFAS}^{d,h} = 1 \\ DOWN & Rnd\_Cmd_{LFAS}^{d,h} = 2 \\ UP\ \&\ DOWN & Rnd\_Cmd_{LFAS}^{d,h} = 3 \\ No\ command & Rnd\_Cmd_{LFAS}^{d,h} = 0 \end{cases} \tag{6.15}$$

$$Rnd\_Cmd_{LFAS}^{d,h} = \begin{cases} round(random(1,3)) & random(0,1) \le Enable_{LFAS}^{d,h} \\ 0 & random(0,1) > Enable_{LFAS}^{d,h} \end{cases} \tag{6.16}$$

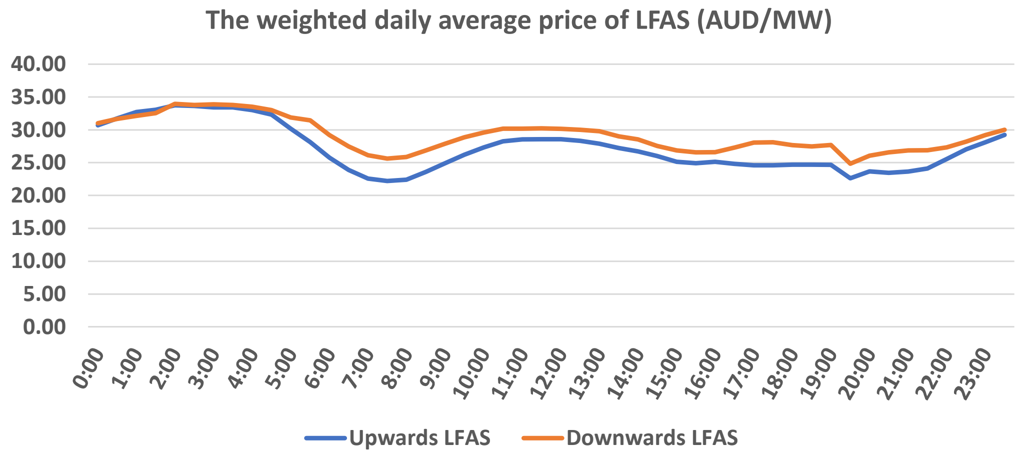

Figure 6.3. The weighted daily average price for upwards and downwards LFAS in the WEM.

6.4.2 Bidding Model in Energy Market

As the battery is utilised in the LFAS market in this section, the only source of energy to participate in the energy market is the excess PV generation after covering the demand. $E_{RES}^{d,h}$ is the demand considering demand management through the gamified approach, as discussed in Section 6.3.1.

$$E_{Energy}^{d,h} = E_{RES}^{d,h} - E_{PV}^{d,h} \tag{6.17}$$

where $E_{Energy}^{d,h}$ is the bidding amount in the energy market and $E_{PV}^{d,h}$ is the PV generation in the *h-th* hour and *d-th* day. $E_{Energy}^{d,h}$ is negative when selling to the WEM and positive when buying from the market.

6.4.3 Robustness Consideration

Robust optimisation means that the values of the decision variables obtained from the algorithm are optimum for the worst case of uncertain parameters [64]. Therefore, the robust algorithm tries to get the optimum results, even for the worst-case scenarios, for which they need to find the worst-cases first. The uncertainty of participation in the LFAS market is the price of upwards and downwards LFAS. The electricity price and the PV generation are the uncertain parameters in the energy market. These uncertain input parameters are modelled as variables between a low and high boundary. In order to satisfy the requirement of robust optimisation, the worst-case scenarios are provided in **Table 6.1**. It is important to mention that considering the worst-case scenario in the method does not mean that the algorithm is conservative, but it does guarantee the robustness of the proposed method.

It is also assumed that when the LFAS service is enabled in any trading interval, the amount of bidding power for LFAS is used for the period of the LFAS provision, which is considered as the worst-case for the use of energy storage.

Table 6.1. The worst-case scenario for participation in LFAS and energy market

	PV generation	**Electricity price**	**LFAS price**
The VPP is **selling energy** to the energy market	low	low	-----
The VPP is **buying energy** from the energy market	low	high	-----
The VPP is participating in **LFAS** market	-----	-----	low

6.4.4 A Robust Bidding Strategy for the Energy Market Only

When participating only in energy market, the energy storage is also utilized for bidding in the energy market. A fast and robust method for this case is detailed in [127], and the strategy is not repeated here. However, in this Chapter, we provide a comparison against a traditional mathematical-based optimisation algorithm to show the effectiveness of this proposed algorithm.

6.5 Simulation Results

In this section, the simulation results of participation of the VPP in the LFAS market and the energy market in the WEM is discussed. The case study is the realistic VPP, comprising 67 residential homes in South Lake in WA, which includes a 350 kW/700 kWh VRFB and an 810 kW solar system, installed on the roofs of the dwellings. The detailed information on the design of this VPP is provided in [110]. Controllable appliances using EEBUS protocol with automatic and manual control platforms based on a cloud are also proposed for each home [111].

6.5.1 Assumptions

The costings of CAPEX such as solar system, VRFB, inverters, and also the coefficient of market expenses are provided in [119]. Other input parameters are provided in **Table 6.2**. The uncertainty levels are modelled as a band interval. For example, 10% uncertainty of PV generation means that the PV generation changes within ±10% of the mean value of PV generation at a specific time.

Table 6.2. Input parameters for simulations

Parameters		**Value**
Uncertainty levels (%)	PV generation	10%
	Electricity price	10%
	LFAS price	20%
Gamification parameters	Electricity reduction factor	50%
	Customer participation	80%
VRFB	Efficiency (%)	85%
	Maximum energy throughput	13,000,000 kWh
Discount for customers		10%
Interest rate		5%
Horizon year (years)		20

6.5.2 Economic comparison

As the duration of LFAS bidding when participating in LFAS market, is a random process, to have a better understanding of economic parameters such as profit and payback period, a Monte Carlo simulation with 100 runs was used. Each run includes a complete year of simulation for every trading interval. For each trading interval, the bidding values are calculated based on the strategy provided in Section 6.4.1. After obtaining the outcome of 100 runs, the mean and standard deviation of parameters are calculated for comparison. The Monte Carlo simulation has been run for a case in this paper for 1,000 times, the difference between the output data and those from 100 runs is almost negligible, therefore, 100 runs for the Monte Carlo simulation is justifiable. The program has been run 100 times and the mean and standard deviation of parameters are obtained for comparison. The net present values (NPVs) of total revenue, expense, and profit for the duration of the project study (20 years) is provided in **Figure 6.4**.

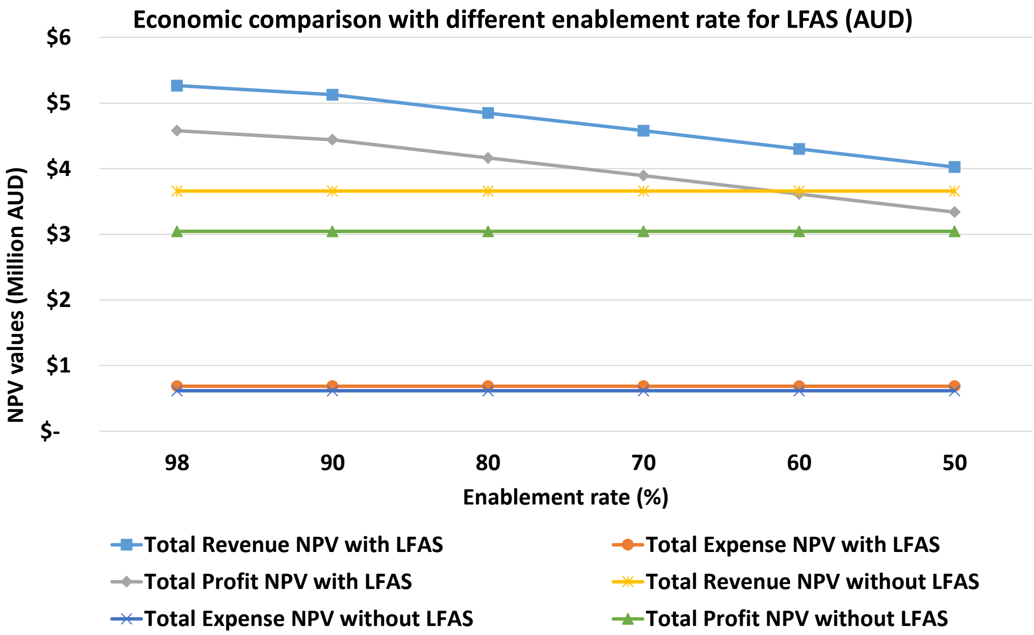

Figure 6.4. The average NPV values of total revenue, expense, and profit with different levels of enablement rates (%) for the LFAS market and without the LFAS market.

As seen in **Figure 6.4**, the total profit of the VPP is reduced by decreasing of enablement of LFAS service. The profit is about AUD 4.6m for the enablement of 80%

and decreases to about AUD 3.3m for the enablement of 50%, which is about 28% reduction in the profit of the VPP. In realistic operation, we are expecting the enablement of more than 80%, as there are many volatile rooftop PV generators connected to the grid and they are increasing with time. Also, the battery is much faster than traditional rotating generators so they can response to any frequency deviation faster, which means that the LFAS services by the VRFB can be enabled faster and with a higher probability.

Also, **Figure 6.4** shows that that the profit of VPP with LFAS is higher than the profit without LFAS and only participating in energy market. The profit with LFAS at the enablement of 90%, for example, is about AUD 1.4m higher than the profit when participating only in the energy market, which shows a significant improvement of around 45% in profit by participating in the LFAS market. There are no major differences in the NPV of the expenses, as the enablement influences the operation of the energy storage, and the investment is about the same.

The standard deviation (SD) of the parameters including the NPV of profit and revenue is around 0.5%, which shows a consistent outcome across 100 different runs of the Monte Carlo simulation.

The payback periods and internal rates of return (IRRs) for different levels of enablement rates (%) for the LFAS market and the comparison with the financial parameters without LFAS market are presented in **Figure 6.5**.

As can be seen the figures for the payback periods and IRRs are much better in the case with LFAS participation. The payback period shows a significant improvement to about 6 years for the enablement of more than 90% of LFAS compared to about 9 years without LFAS participation, which is a very good incentive for private investors to invest in VPPs. Also, the IRR is about 18% with LFAS with the enablement of more than 90% while the IRR is around 10% when the VPP is designed to only participate in the energy market, which is a major improvement in the financial outcome when considering the LFAS market. As can be seen, the payback period increases from 6 to 8 years and the IRR decreases from 18% to 12% when the enablement rate decreases from 98% to 50%. The main reason is that the revenue from the LFAS market reduces by the decrease of the enablement rate while the investments on the CAPEX are about the same for both cases

The SD of the IRR and payback period is around 0.6%, which shows a robust outcome across all 100 runs of the Monte Carlo simulation.

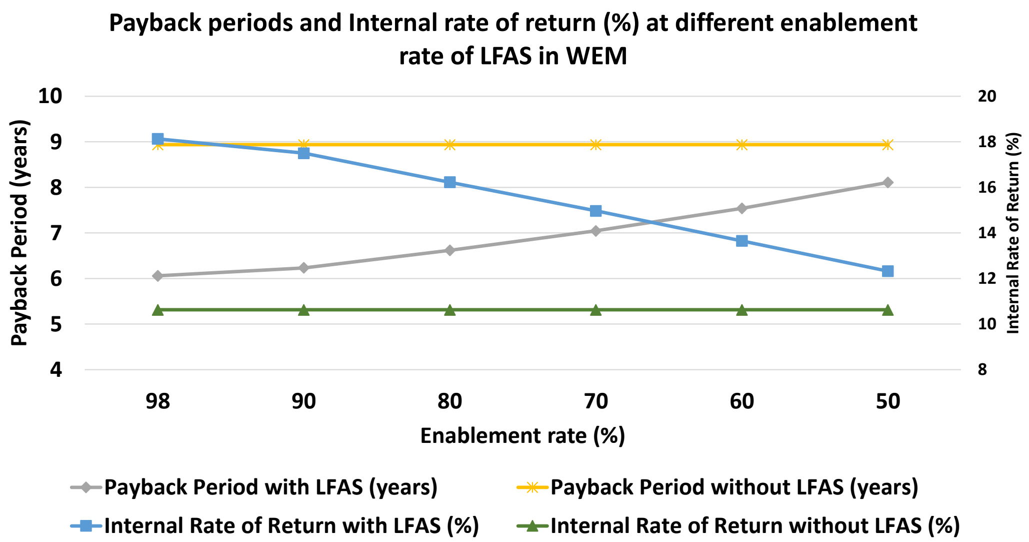

Figure 6.5. The payback periods and internal rates of return for different levels of enablement rates (%) for the LFAS market and without the LFAS market.

6.5.3 Energy throughput and lifetime of VRFB

When participating in the LFAS market, we charge and discharge the VRFB more often, so we need to investigate the lifetime of the battery at different levels of enablement, as seen in **Figure 6.6**.

As can be seen, the energy throughput by the VRFB increases with the higher level of enablement, resulting in a reduction in the useful lifetime of the battery. If the enablement rate of LFAS is less than 80%, the useful lifetime of the VRFB is its calendar lifetime, which is 25 years. The useful lifetime of the VRFB is less than 25 years when the enablement rate is more than 80%. However, the useful lifetime of the battery is still more than 20 years when the enablement is higher than 80%, which is more than the horizon year for the analysis of this project (20 years). Therefore, the VRFB can be used at the highest enablement rate, and it is expected to deliver LFAS service during the lifetime of the project, which is another advantage of the VRFB compared to other types of energy storages.

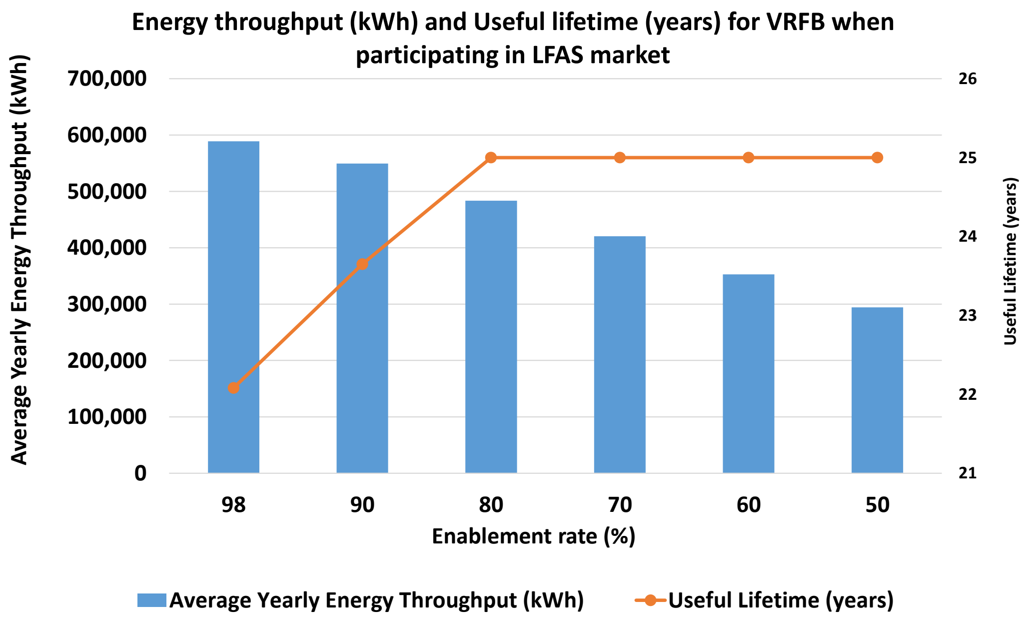

Figure 6.6. The energy throughput and useful lifetime of VRFB at different levels of enablement rates (%) for the LFAS market.

6.5.4 Cash Flow Analysis

Another financial indicator for a project is the cash flow. The cash flow with different enablement rates is depicted in **Figure 6.7**. As shown, the investment in year 0 is almost the same for all cases of the enablement. However, the amount of income is much higher in later years when the enablement rate for LFAS activation is higher. For example, the cash flow in year 20 with the enablement of 90% is about AUD 1.5m higher than the case with the enablement of 50%. Also, the cash flow graph shows the payback period of the cases with the higher enablement is lower, because the VRFB is participating more in the

LFAS market when the enablement is higher.

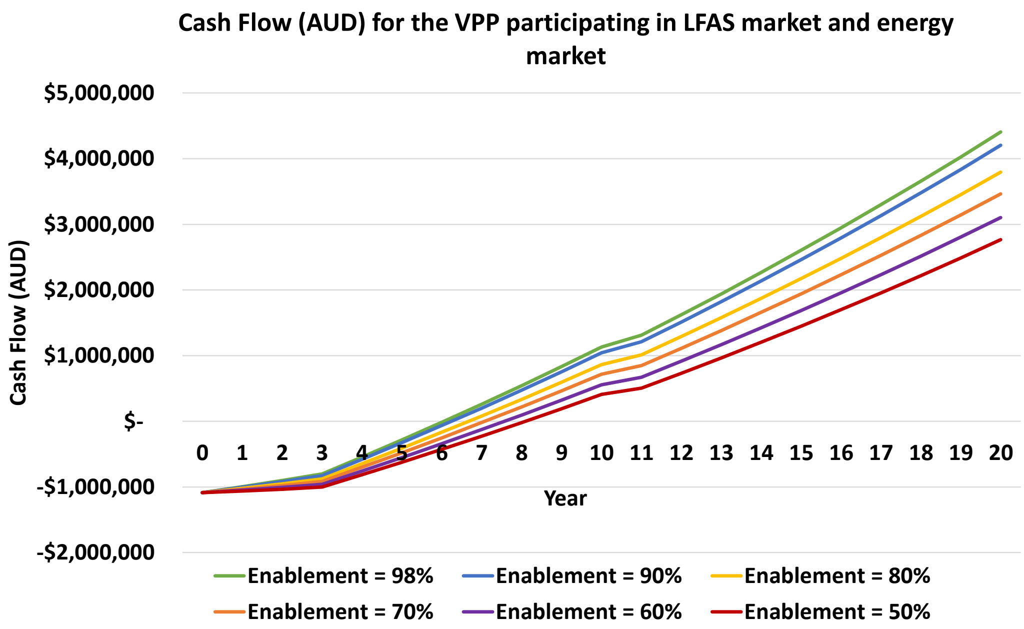

Figure 6.7. The cash flow for the VPP at different levels of enablement rates (%) when participating in LFAS market and energy market.

6.5.5 The Impact of Gamification

It is desirable for the VPP investor to see the impact of gamification for customer engagement on the financial parameters of the VPP. Here, we discuss some aspects of this effect, for example, the revenue and profit at different enablement with and without gamification is provided in **Figure 6.8**. As shown in this figure, the total profit is higher with the gamification as this approach encourages customers to participate in demand management through an enjoyable and gamified system while not compromising their comfort levels.

The increase in the total profit due to gamification when participating in both the LFAS and energy market is about AUD 80,000, which is an improvement in the total profit. The improvement is relatively low as the number of dwellings is not very high and the peak load of the customers (~140kW) compared to the size of PV (810kW) and battery capacity

(700kWh) is low. If the VPP expands in future and includes more customers, this improvement will also be enhanced. If the VPP participates in the energy market only, the improvement is about AUD 54,000 with gamification. This shows that the gamification is also more effective when the VPP is participating both LFAS and the energy market compared to the case of only the energy market.

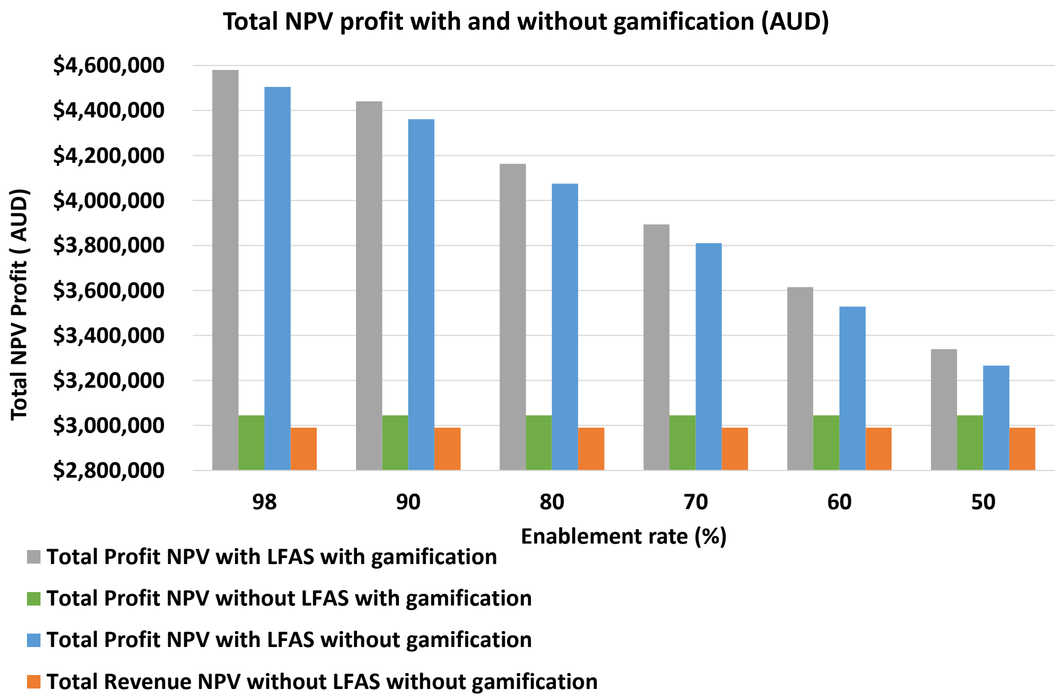

Figure 6.8. The total NPV profit of the VPP project with and without gamification at different levels of enablement rates (%).

Also, **Figure 6.9** shows that the payback period is higher without considering gamification, which is a fraction of a year improvement with gamification. In this simulation, just one run of the program is considered to show indicative results for the payback periods and profits.

The improvement of performance due to gamification is not relatively very high as the number of dwellings is not very high and the peak load of the customers (~140kW) compared to the size of PV (810kW) and battery capacity (700kWh) is low. If the VPP expands in future and includes more customers, this improvement will also be enhanced. To prove this, the simulation is run with 5 times larger load, in which the profit of the VPP increases by about AUD 220,000 with gamification compared to without gamification. This shows that the number of customers and the level of loading has a great impact on the gamification approach for customer engagement.

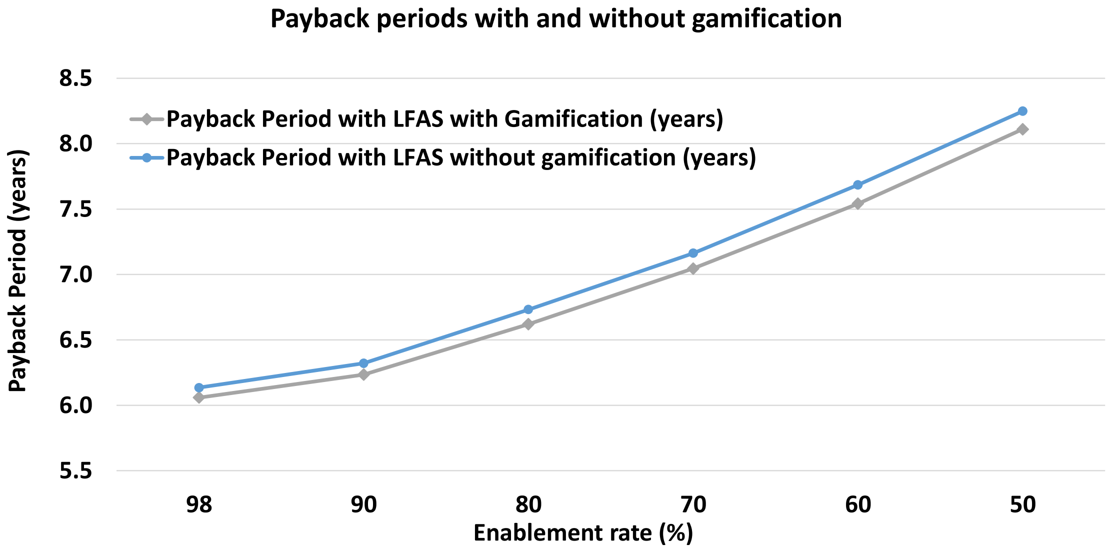

Figure 6.9. The payback period of the VPP project with and without gamification at different levels of enablement rates (%).

6.5.6 The Components of the NPV Revenues and Expenses

The components of revenues and expenses are detailed in this Chapter and in [119]. **Figure 6.10** and **Figure 6.11** show the components of the NPV revenue and the NPV expenses, respectively.

As can be seen in the revenue graph, the component of the LFAS revenue decreases by the reduction of the enablement of LFAS. This LFAS revenue does not exist in the revenue component of the case, in which the VPP participates only in the energy market. Also, the reserve capacity credit is a revenue when the VPP is not participating in the LFAS, as the VPP can apply for and receive a credit for the development of capacity in the WEM. However, when the battery is dedicated to the LFAS market, the VPP cannot get a measurable reserve capacity credit for it. As can be seen in **Figure 6.10**, the amount of energy sold to the WEM in the case of no LFAS is higher than the cases with the LFAS participation, as in this case, the VRFB is also charged and discharged optimally to sell energy to the WEM. The figures provided in this section were obtained by one simulation run to show indicative values of revenues and expenses.

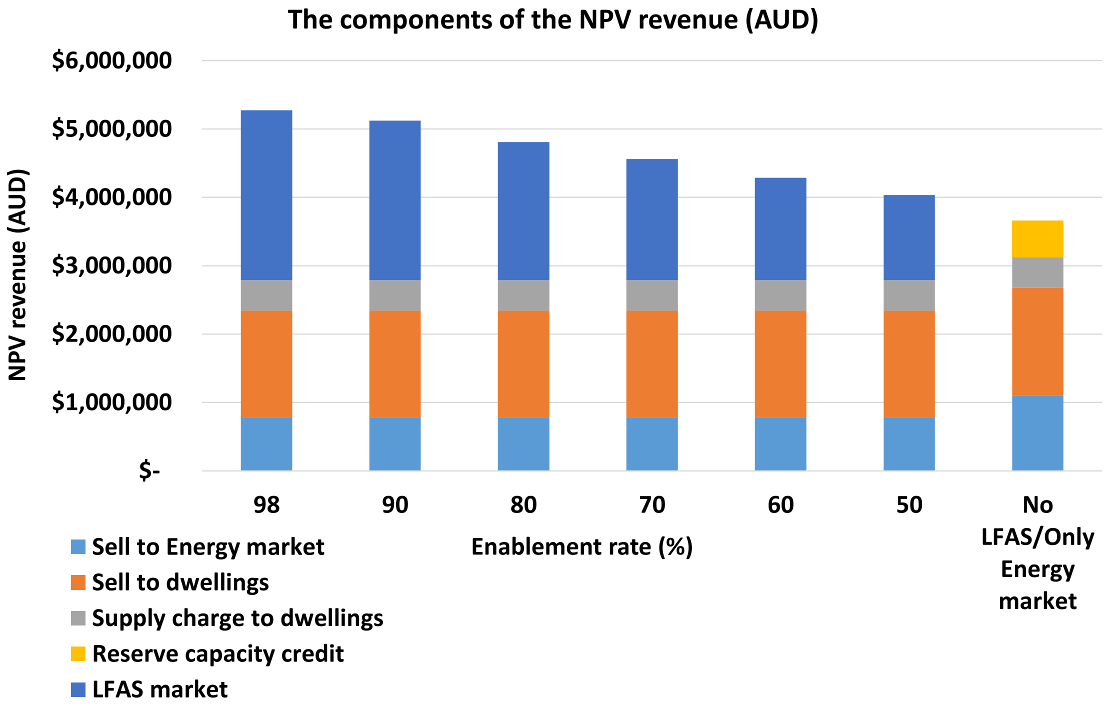

Figure 6.10. The components of the NPV revenue with and without participation in LFAS market.

As the expenses for different levels of the enablement are about the same, only one representative example of the expense's components is provided in **Figure 6.11**. As can be seen, the amount of energy purchased from the WEM in the case with LFAS is higher than the case without LFAS, as the energy storage is working towards optimal energy transaction in the case of no LFAS. Also, it is evident that the major expenses are associated with the maintenance of the VRFB and PV panels.

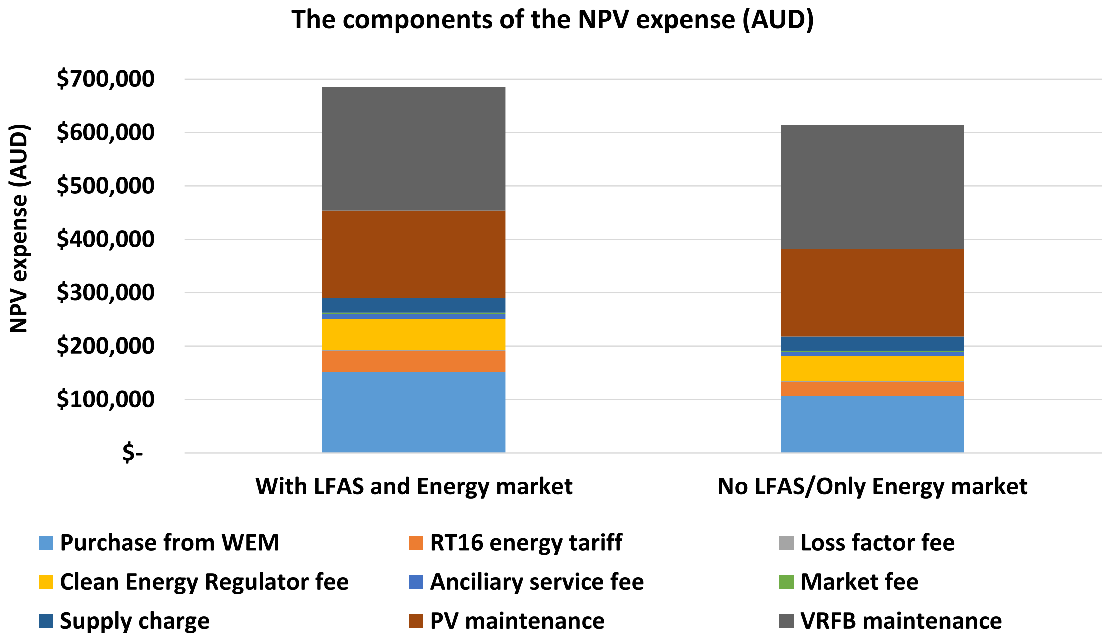

Figure 6.11. The components of the NPV expense with and without participation in LFAS market.

6.5.7 Customer Benefit

As discussed in Section 6.3, the tariff for the customer within the VPP is provided 10% cheaper compared to the tariff of the local utility. This provides a 10% reduction in the costs of electricity for each dwelling. The average cost of electricity per home within the VPP per year is about AUD 1,504 considering the assumptions in this simulation. This electricity cost could be AUD 1,671 if the customers are not a part of the VPP. In addition, the customer can benefit from participating in the gamified app to socialize and compete for obtaining more discounts in energy consumption.

6.5.8 Comparison with a Robust Mathematical Algorithm

To verify the effectiveness of the simplified and robust bidding strategy, we examine it in one market, which is energy market [127] in comparison with a robust mathematical algorithm, detailed in [129]. **Figure 6.12** shows the daily profit optimized using both the proposed robust method and the mathematical method. As can be seen the difference between the outcome of these two algorithms is very small. The average daily error for the profit over a year is 2.7% and the SD of the error is 3.1%, which shows the accuracy of the proposed robust and simple method.

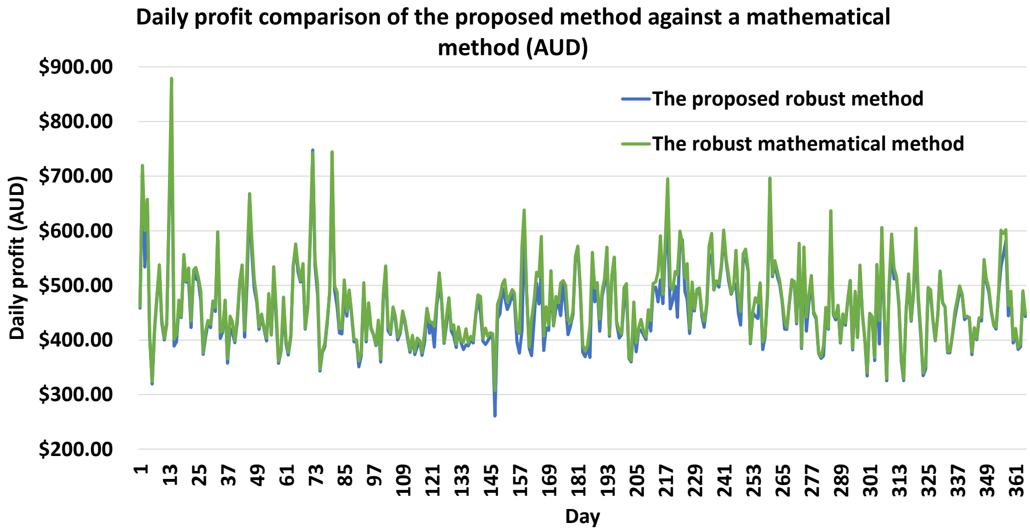

Figure 6.12. The daily profit comparison between the proposed robust method and the mathematical robust method for participating in only energy market.

Figure 6.13 illustrates the yearly revenue, expense and profit obtained using the proposed method and the mathematical algorithm. As seen the difference over a year also very minor with the error of 2.9%, 4.1%, 2.7% for the yearly revenue, expense, and profit, respectively. These errors over a year are very small compared to the benefits of the proposed robust bidding strategy including being understandable and fast.

The computational time taken for finding a solution by the bidding strategy for 365 runs over a year based on the proposed method and the mathematical method is presented in **Table 6.3**. As seen, the difference between the running time is significant, which is critical when the VPP wants to evaluate the bidding values upon receiving new data just before the gate closure. In such cases, the VPP can run the bidding strategy to find better values for the bids to improve the profit. Also, in some cases, the VPP is required to run more sensitivity analysis with respect to the uncertainties of input data in a short period of time, e.g. major weather events or a fault in the VPP, to revise the bidding in order to enhance the reliability and also the profit of the VPP. In this case also the speed of the proposed expert method is essential. Another benefit of the proposed fast method is that the amount of required memory for the proposed expert method is much less than the robust mathematical method, as it does not require a lot of iterations to solve the bidding problem.

The abovementioned evidence shows the significance of the proposed method over traditional mathematical methods. The platform for simulating these methods is MATLAB on a machine with a 2.9 GHz CPU and 16 GB RAM.

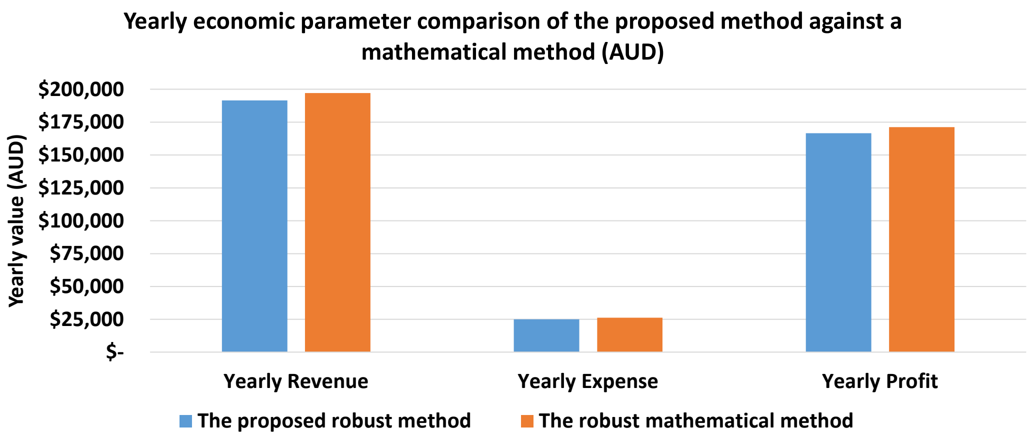

Figure 6.13. The yearly revenue, expense, and profit comparison between the proposed robust method and the mathematical robust method for participating in only energy market.

Table 6.3. Computational Time for 365 Runs

The proposed robust method	The robust mathematical method
0.66 sec	947.10 sec

6.6 Conclusions

A robust and fast bidding strategy for participation of VPPs in the load following ancillary service (LFAS) and energy market in the WEM is proposed. To study the effectiveness of the proposed bidding strategy, a realistic VPP comprising 67 dwellings in WA is studied. The simulation results show that participation in both LFAS and the energy market gives a better financial return including payback period and internal rate of return (IRR). For example, the payback period of the VPP system is improved from 9 to 6 years and the IRR from 10.5% to 18% by participating in both the LFAS and energy market. This improvement is achieved without compromising the useful lifetime of the energy storage very much over the period of the project as the VRFB, chosen for this VPP, has a longer life and much higher energy throughput compared to other battery technologies.

In this VPP, the customers are also participating in a demand management scheme by the VPP owner through a developed gamified approach. In this arrangement, the customers accept the command by the VPP through an enjoyable and socialised gaming platform while not compromising their comfort levels. All customers will benefit by participating in the VPP as their electricity costs are at least 10% lower than when not being in the VPP.

The comparison of the proposed robust bidding strategy with a robust mathematical method shows the effectiveness of the proposed method. The accuracy of the proposed method is very high with the daily average error of 2.7%. However, the computational effort for the proposed method is much lower, which is 0.66 seconds compared to 947.10 seconds for the mathematical methods. Future work could include the trading among multiple VPPs in addition to the WEM.

Chapter 7 Advanced Monitoring and Control System for Virtual Power Plants for Enabling Customer Engagement and Market Participation[1]

7.1 Summary

To integrate large scale renewable energy into energy systems, an effective participation from private investors and active customer engagement are essential. Virtual power plants (VPPs) are a very promising approach. To realize this engagement, an efficient monitoring and control system needs to be implemented for the VPP to be flexible, scalable, secure, and cost-effective. In this Chapter, a realistic VPP in Western Australia is studied, comprising 67 dwellings, including a 810 kW rooftop solar photovoltaic (PV) system, a 700 kWh vanadium redox flow battery (VRFB), a heat pump hot water system (HWS), and demand management mechanisms. The practical and detailed concept design of the monitoring and control system for EEBUS-enabled appliances, and also for the PV and VRFB system, with smart inverters, is proposed. In addition, a practical fog-based storage and computing system is developed to enable the VPP owner to manage the PV, VRFB, and EV charging station for maximizing the benefit

[1] This chapter is based on the published paper of: Behnaz Behi, Ali Arefi, Philip Jennings, Arian Gorjy, and Almantas Pivrikas, “Advanced monitoring and control system for virtual power plants for enabling customer engagement and market participation,” Energies, vol. 14, no. 4, 2021, https://doi.org/10.3390/en14041113.

to the customers and the VPP owner. Further, the proposed cloud-based applications enable customers to participate in gamified demand response programs for increasing the level of their engagement while satisfying their comfort level. All proposed systems and architecture in this Chapter have the capability of being implemented fully and relevant references for practical devices are given where necessary.

7.2 Introduction

To reduce the pollution associated with fossil fuels and to enhance the sustainability of energy systems, many countries have established policies, rules, and incentives to boost the use of renewable energy resources. If the governments only invest in the integration of renewable energies, it will take a long time and high cost to replace the use of traditional energy resources. Therefore, many nations are providing frameworks for the contribution of the private sector and customers to the integration of renewable energy [130]. VPPs are one of those frameworks that encourage customers and business owners to invest in renewable-based energy systems. For example, in Australia, the Australian Energy Market Operator (AEMO), along with other government agencies such as the Australian Energy Market Commission (AEMC), the Australian Renewable Energy Agency (ARENA), and the Australian Energy Regulator (AER) has implemented a VPP demonstration to evaluate the regulation and effectiveness of VPPs in several circumstances [30]. It is forecasted that the total installed VPP capacity in Australia by 2022 would be 700 MW. The associated regulations, requirements and procedures for participation of VPPs in the wholesale electricity market (WEM) are now in place in Western Australia (WA) [81] and investors can register their VPP through this system. This framework will speed up the process of renewable energy integration in Australia to possibly achieve 100% renewable integration by 2050. At the moment, the target is 23.5%

of renewable integration by 2020, which is already achieved [12]. Along with the framework, there are incentives for renewable generation in Australia, such as the Large-scale Renewable Energy Target (LRET) for large scale installations and the Small-scale Renewable Energy Scheme (SRES) for small customers for the utilization of renewable-based systems such as photovoltaics (PV) and heat pumps [13].

VPPs are usually a combination of several kinds of renewable-based distributed energy resources (DERs) and engage customers through demand management, coordinated through a central or distributed control system based on an advanced information and communication technology (ICT) platform [14]. Energy resources such as solar and wind, along with storage technologies, such as batteries, fuel cells, capacitors, and solar thermal/storage can be included in a VPP, depending on the situation and the associated cost/benefit analysis. Smart appliances and electric vehicles (EVs) are part of such VPPs in order to enable a VPP to participate effectively in the electricity market. One of the main reasons for establishing VPPs by the private sectors is to benefit from incentivized green resources and technology to reduce the cost of energy to the customers within the VPP and to make a good marginal profit for the VPP owner. To achieve this aim, a detailed analysis of the cost and benefit of different technologies and platforms needs to be conducted like the case study of the VPP in WA [110]. As seen in this reference, the cost of energy per dwelling is reduced by 24% within the VPP when compared with the case without the VPP. Also, the VPP owner can receive an internal rate of return of at least 11% with a very promising payback period of about 8.5 years. Moreover, the use of highly-efficient appliances within VPPs can reduce energy consumption by 273 GWh per year for a 63 MW VPP [16]. Further, the operation of a renewable plant within a VPP context can produce 12% more profit for the VPP owner in Scotland [21]. Also, the cost and benefit analysis of VPPs in Germany demonstrate an increase of 11% to 30% by 2030 in the VPP's revenue by participating in the electricity market [25]. Moreover, renewable-based VPPs can affect the price of electricity in the WEM in the long-term [24] and contribute to the efficient operation of the electricity grid [22].

Local energy communities have a great potential for being a platform for VPPs. The consumers within these communities can produce and store energy, shift their loads, and share the produced energy and the installed infrastructure. Several methods are used to plan such energy communities and coordinate loads and resources to maximise the benefit of that to all participants. Community energy planning including PV, energy storage, and demand response using smart home automation is implemented in the Municipality of Berchidda, Italy, which shows a reduction in energy purchased from the grid and in the energy costs to the consumers [131]. Also, a fair method is proposed for the cost/profit allocation of shared infrastructure in a local energy community [132, 133]. The method is applied to a community with PV and hydroelectric energy resources and shows a fair distribution of costs and revenues amongst customers. To optimize and control the resources and customer contributions, a decentralized market, based on a genetic algorithm, is developed to facilitate the expansion of local energy communities [134]. By optimising the load profile of customers within a community, there is an opportunity to enhance the self-consumption of PV generation, as discussed in [135]. In addition, day-ahead operational planning of a local energy community using the alternating direction method of multipliers shows that the cost to customers decreases and the revenue to providers increases compared with when they are interacting with the local utility [136]. In addition, trilateral bilevel stochastic mixed-integer programming is proposed to plan storages and PV supply while handling the operational complexity with regard to the wholesale market [137]. The outcomes of this approach illustrate good planning of the community energy system with optimal operation. Also, neighbourhood trading amongst a local community shows a positive effect in reducing the total costs of community planning [138]. Moreover, to handle uncertainties of PV and load for community energy planning, robust optimisation methods are very useful to handle such uncertainties [139].

Investing in different technologies in a VPP is only beneficial where the customers within the VPP interact with them and participate in demand management. Therefore, the VPP needs to provide an attractive information and technology platform to the customers to facilitate the aggregation of their flexibilities [18] and to encourage them to engage with the requests from the VPP owner for demand shaping, appliances control, security and frequency control, and local power quality improvement [79]. This will help the VPP to participate effectively in the WEM to maximise the benefits to the customers and the VPP owner. Controllable loads such as heat pumps and air conditioning systems can provide flexibility to the customer to participate in demand response (DR) programs, which will contribute to the electricity cost reduction to the customers [41] and to the reduction of capital investment in the local utility [42]. One of the effective ways of engaging customers in DR programs is through the gamification of participation as discussed in detail in [114]. Customers can learn, collaborate and compete using an appropriate gamification application while they are engaging in the demand management programs scheduled and proposed by the VPP's owner.

To realize the customer engagement and market participation of the VPPs, a robust platform that coordinates and controls different resources and communicates with the market operator is essential. For example, Advanced microgrid solutions (AMS) provides the SigmaOne platform for optimizing the revenue of the VPP owner. [140]. This platform can provide a cloud-based probabilistic forecast and stochastic optimisation to maximise the benefit when participating in the WEM. However, this platform does not provide a clear roadmap and solution for customer participation. The Sunverge Energy platform is another application specially designed for the utilities, to monitor and control rooftop PVs and to enable customers to see their consumption and manage that. This platform can communicate also with the home management system (HMS) to control some devices but no direct solution is provided for market participation by the customers through VPP [141]. The characteristics of a smart energy management information system (EMIS) for the built environment are discussed in [142] for improving energy efficiency and interior climate for a resident. In this work, different platforms such as Wi-Fi, Bluetooth Low Energy (BLE), Sigfox, Narrowband IoT, and also LTE and LoRa, which are Long-Term Evolution and Long Range, respectively, along with their specifications and applications are discussed. The characteristics of a smart EMIS include data storage, customizable reporting, scalability, interaction with devices, accessibility, security, and knowledge discovery [142]. There are also several energy/building management systems available in the market [143] that can satisfy some of these criteria for a smart EMIS. Universal Microgrid Controller™ is another platform with the capabilities of flexibility, scalability, security, real-time monitoring, and optimisation of microgrid operation [144]. OATI GridMind is another platform for microgrid/VPP monitoring and optimisation that can provide a smooth control system for multiple energy resources within a VPP [145]. The DER Optimisation Software is a cloud-based and scalable management software for monitoring, communicating with, controlling, and optimizing the economics of energy resources within a VPP [146]. The GridMaster Microgrid Control System is another robust and secure platform for optimum operation of a microgrid or VPP, which is equipped with a military-grade cyber security protocol to protect the system from the growing threat of cyberattacks and to provide a user-friendly interface and scalability [147]. There is another cloud-based platform; the Prescient U10 Controller for optimizing the lifetime of DERs and supporting the power quality as well [148]. However, a detailed demand engagement approach for consumer engagement is not provided on these platforms.

Although there is some literature on the platforms for monitoring and controlling VPPs, there is a lack of detailed architecture of such systems for both market participation and customer engagement for a real case. This Chapter provides a detailed monitoring and controlling system for a real VPP, being established in WA, which includes 67 residential households. Based on the knowledge of the authors, there is no other study that provides such analyses, which is so important for VPP businesses. The specific contributions of this Chapter are as follows:

- Developing a practical concept design for the monitoring and control system of residential VPPs, which is flexible and scalable and interacts with different energy resources such as rooftop PV, battery, and appliances.
- Providing a detailed monitoring and control system for customer engagement within a VPP including the EEBUS protocol and gamification applications.
- Providing a detailed monitoring and control system for a rooftop solar farm and battery energy storage.
- Developing an effective fog-based computing and forecasting system to maximise the benefits of the consumers and the VPP owner by participating in the wholesale electricity market and customer engagement.

The Chapter is organized as follows. Section 7.3 provides the concept design configuration of the proposed VPP in WA. Section 7.4 presents the load monitoring and control of appliances in dwellings including customer engagement in the VPP. Section 4.5 discusses the monitoring and control of PV and battery systems for the VPP. The fog-based data storage and computing systems are discussed in Section 7.6. The relevant conclusions are summarized in Section 7.7.

7.3 The Concept Design of the Proposed VPP

The proposed VPP comprises 67 residential houses located in WA, equipped with smart appliances for each home, including a washing machine, dishwasher, dryer, and heat pump, whose electricity consumptions are controllable and shiftable during the day. On the rooftop of each dwelling, there is a 12 kW PV, which contributes to the PV farm of 810 kW, as calculated using the HelioScope software, including PVs installed on carports' rooftops, as shown in **Figure 7.1**. 1,190,689 kWh is the total PV generation during a year in this VPP based on the simulation considering the roof pitching, the orientation of dwellings, and the shading loss [82, 110]. The energy generated by any of the dwelling's PV systems can be used by all dwellings within the VPP. The technologies selected for this VPP, will provide an affordable energy system for both the customers and the owner of the VPP as discussed in Chapter 3 [110]. It is expected that in future each household uses an EV as well. As EVs integration level is not very high at the moment, the participation of EVs, charging and discharging of them are not considered in the previous Chapters, however, in this Chapter for the purpose of monitoring and control system, EVs are considered.

To store energy during low electricity market prices and high PV generation and to increase the integration of renewables, centralized energy storage based on vanadium redox flow, namely VRFB, is utilized here. The size of VRFB in the VPP, considering the available budget and the optimum use of the battery, was chosen to be 700 kWh, 350 kW. The VRFB is electrochemical energy storage in which energy is stored in a liquid vanadium electrolyte and is based on a reversible chemical reaction [84]. The liquid is pumped between two tanks whose sizes determine the size of the VRFB.

Figure 7.1. The proposed location of the VPP in WA

The reasons for the use of VRFB, that make it affordable in this VPP compared with other storage technologies, are as follows:

- The long lifetime, e.g. 20,000 cycles equivalent to 20 years, at a reasonable price. Also, it is only necessary to change the liquid inside of the battery after the nominal lifetime of the VRFB. It is not required to replace the whole battery system if it is needed for a longer period of time [83].
- The fast charging and discharging capabilities that can play a positive role in the electricity network security and reliability [85, 86]. Also, it can be charged to 100% of its capacity level with negligible self-discharge.
- The VRFB is comparatively environmentally friendly and safe technology as the electrolyte is not explosive or flammable and can easily be 100% recycled at the end of its lifetime [87].
- The energy and power at the VRFB technology is scalable independently, which makes it easier for the VPP owner to scale up the business as required.

- The VRFB has a very low degradation, so over a long time, it maintains the same capacity.

Another technology that is utilized in this VPP for energy efficiency is the heat pump hot water system (HWS), which extracts the heat available in the outdoor air using a heat exchanger and transfers it to a refrigerant [88]. The compressor increases the temperature of the refrigerant, which is used for heating the water in the HWS. As the heat pump can produce five units of energy using one unit of energy in the compressor, it has a much higher energy efficiency [89]. Moreover, the total life cycle energy cost can be reduced, for example by 40%, when using both electricity and thermal storage [90]. The VPP can enhance the energy efficiency of households and can benefit from the interaction with the local utility by coordinated control of PV systems and the heat pumps [91, 92]. Moreover, heat pumps can store thermal energy at a lower electricity price, which brings another advantage to the VPP [93]. In the VPP project in WA, a 220-litre heat pump HWS is installed for each dwelling to maximise the benefits for the consumers and the VPP owner. The size of HWS is chosen based on the average consumption of hot water in that area [94]. The proposed HWS has an electricity consumption of 0.55kW, which can provide heating of 1.6 kW on average to water at the ambient temperature between -5 to 42^{O}C. The efficiency of the heat pump, like any other equipment, is not greater than 100%, as demonstrated in **Figure 7.2**, the electrical energy here is used for moving the heat not for converting electricity to heat. As seen, the 0.55 kW compressor can move 1.05 kW of heat from the air plus the electricity converted through the compressor to the other side for heating water. In this schematic, the efficiency of all equipment is considered 100% just for the demonstration of the concept of the heat pump, but in practice that efficiency is not achieved, and for example, we need more kWh of heat from the air to provide 1.6 kWh of heat energy to the water.

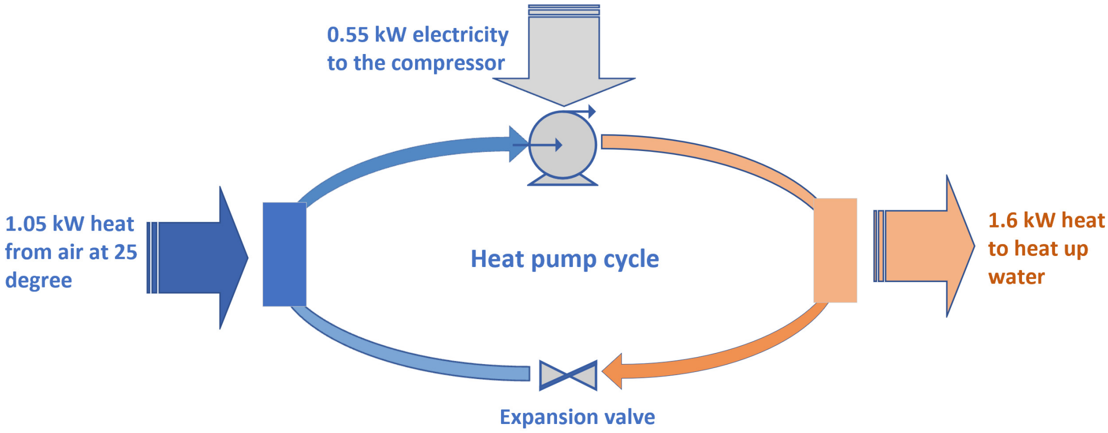

Figure 7.2. The schematic of energy movement in a heat pump.

Furthermore, the VPP is connected to the electricity grid and there is no gas in the complex. **Figure 7.3** shows the overall configuration of the proposed VPP in WA. As seen in **Figure 7.3**, There is the main loop of 400V low voltage network, but operated in radial, with controllable switches for maximizing the reliability of power supply. There are two main distribution transformers to improve the reliability of supply and also to enable the electrification of stage-by-stage development of the VPP. Smart meters are installed at the secondary of each transformer to measure the active and reactive power in four quadrants. These meters collect power quality data including harmonics, sag and swell for any further study in the future on the quality improvement and diagnosis of faults in the network. Moreover, there are monitoring systems for each household, including the HMS and their controllable appliances, which are compatible with EEBUS protocol, as discussed in Section 7.4. In addition, an EV charging station is provided within the VPP network for electric vehicles, which is connected using inverters to the 400V network. The inverter communicates with the cloud to send consumption data and to receive the required commands. As demonstrated in the figure, the connection of rooftop PVs for each of the 67 dwellings is separated from the cable service (main supply) of the house as the PVs are the asset of the VPP owner and this configuration enables the operator of the VPP to access the PVs in a timely manner for any service or troubleshooting without disturbing the residents. Also, there is a centralized VRFB connected to the main ring of the LV network of the VPP, as presented in Section 7.5.

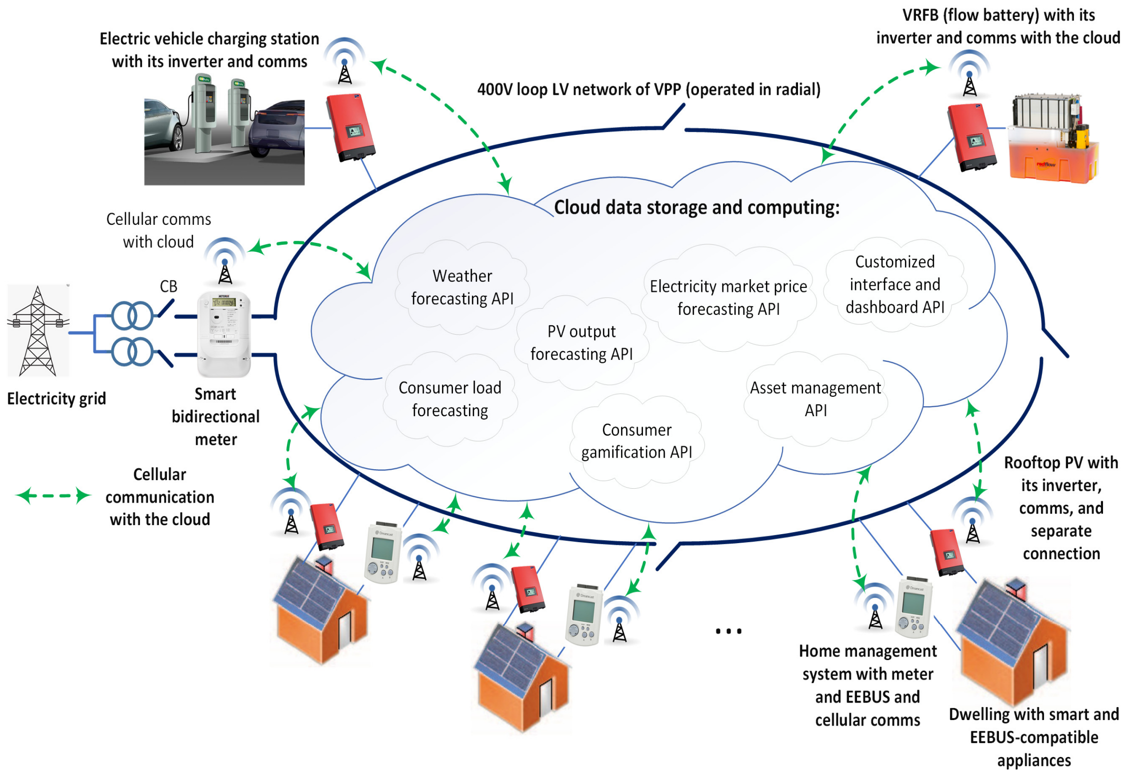

Figure 7.3. The proposed architecture of the VPP in WA.

Storage of data collected from all electric devices is managed in a fog-based storage system, as discussed in Section 7.6. All devices have a standalone cellular communication link to the cloud, as illustrated in **Figure 7.3**. We need a flexible and scalable ICT platform here to make the collected data available to the VPP operator and other third parties in contract with the VPP. To achieve this aim, the right approach this to use application programming interfaces (APIs) [80].

In the proposed configuration, the monitoring and control system is located on the cloud with access to different APIS such as electricity price forecast and weather forecast. This system will optimize the battery charging/discharging and the customer load scheduling to maximise the benefits to the consumers and to the VPP owner, as discussed in Section 7.6.

7.4 Consumer Load Monitoring, Control and Engagement

This section describes the consumer load monitoring system and how to engage customers in demand management.

7.4.1 Consumer Load Monitoring

In order to provide a clear picture of consumption within each of the 67 residential homes in the VPP, suitable monitoring and control protocol is necessary. This protocol needs to support the coherency, flexibility and scalability of this energy system. Amongst different technologies, EEBUS, or Smart Home IP, provides advanced and intelligent integrity and network among appliances [149]. EEBUS is a standardized language of energy, which is manufacturer-independent, that every appliance and device can use and communicate through it. EEBUS is licence-free and can be implemented by any developer or any manufacturer. Through this protocol, the devices within each dwelling are connected to the local energy management system such as the home management system (HMS) for the home and then to the VPP management system. There are also available HMS manufacturers that provide the EEBUS protocol support. Using EEBUS, the VPP owner can communicate with the appliances to develop its own energy management strategy in order to maximise the total benefit to the consumers and to the owner.

Figure 7.4 shows the configuration of the monitoring and control system within each dwelling. The modelling of load profile and the demand management capacity in this VPP is studied in detail in Chapter 3 [110]. Based on this research, appliances such as a washing machine, dryer, air conditioner, and heat pump HWS are connected through

EEBUS to a local HMS for each dwelling. All load data are monitored, and the associated data are collected through EEBUS protocol by the HMS, then HMS sends data to the cloud using the dedicated cellular link. In addition, the energy management comments from the cloud are transmitted through the HMS to the appliances. Nowadays, there are increasing numbers of appliances manufacturers that adopt the EEBUS protocol for their products such as Bosch, Stiebel Eltron, AEG, and Siemens. As discussed, EEBUS will enable scalability and flexibility of the monitoring and control system. For example, if one appliance is off-line or faulty, other appliances will continue their communication properly and independently. Also, if another appliance is added in the future for monitoring and control, this will be easily implemented through the EEBUS protocol. The full specification of EEBUS is available online in [150]. The associated data model for EEBUS is explained and defined, based on the Smart Premises Interoperable Neutral Message Exchange (SPINE) specification, which is standardized by TC 59 WG 7 in CENELEC in the prEN 50631-1 specification [149, 151]. The user applications of SPINE for different types of appliances and purposes are provided by the EEBUS initiative discussed in [149].

The incoming meter is also in communication with the local HMS through EEBUS, as shown in **Figure 7.4**. There are some products that combine the HMS capabilities and incoming smart electricity meter together so there is no need for a separate meter at each dwelling, which is a recommended approach in this project. However, for the clarity of the concept, the HMS, and the smart meter are shown separately in **Figure 7.4**.

In order to improve the reliability of data handling, a fog-based storage system for data is proposed here, in which there is a local storage of data within HMS/smart meter and a cloud-based storage combined. The capacity of local storage is recommended to be for one-month's worth of all data collected for the defined measurement time interval. The

HMS/smart meter has the capability of storing data locally in real-time and then send it to the cloud, as illustrated in **Figure 7.4**. This configuration is more reliable than just local storage or only cloud storage. For example, if at some point there is not a reliable connection link to the cloud, no data will be missed but it is stored locally and sent out to the cloud when the connection is established. The communication link between the HMS and the cloud is based on a cellular link. This medium is chosen due to the higher reliability and being standalone compared with other platforms such as WiFi and LoRa.

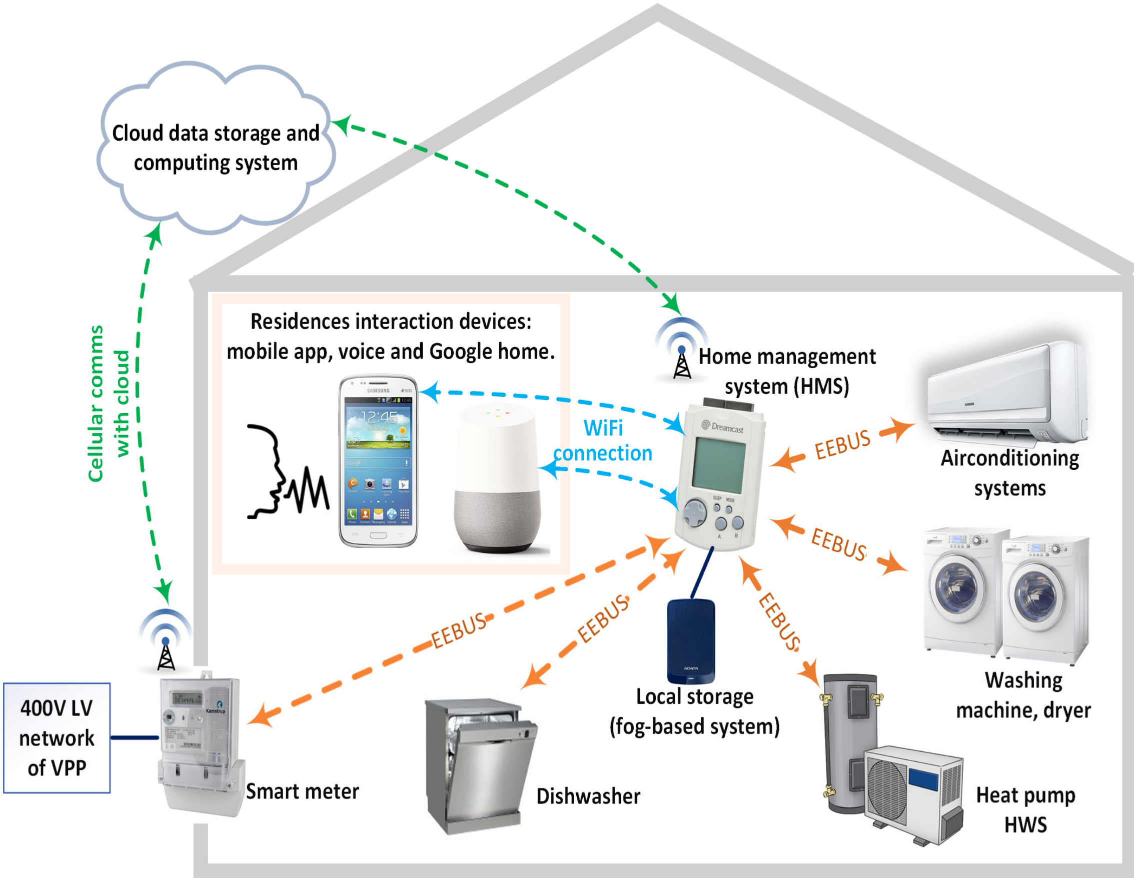

Figure 7.4. The proposed configuration of the monitoring and control system within each dwelling in the VPP.

7.4.2 Consumer Engagement in Demand Management

To encourage consumers to participate in demand management (DM) activities, research has been conducted to work out the efficient and effective approach, as detailed in [114]. As shown in that research, the gamification approach is the best method of engaging the customers for changing their behaviour. Therefore, the required hardware and applications should be in place. To achieve the goals of gamification, a mobile application in which the consumers can get the score, badges, and credits for their energy-related activities is considered. The most appropriate application for the VPP is identified as enCOMPASS and Funergy as detailed in [114]. The specifications of the proposed gamification application can be summarized as below:

- User data collection for consumer engagement through the gamified mobile app.
- Appliances and sensor data collection for evaluating the current status of the appliances and to assess the healthiness of the internal environment of dwellings.
- Algorithms for the load and user behavior modelling for providing adaptive action recommendations to the consumers, which would be a cloud-based application.
- Adaptive and flexible gamification application to engage consumers in the DM events using gamified rewards (points, badges, achievements, tangible prizes) through social collaboration and comparison.

A practical framework for the gamified customer engagement is proposed in **Figure 7.5**. As seen, the optimisation API on the cloud, as discussed in Section 5, will find the optimal status of the appliances, whether each controller device in each dwelling needs to be on/off and for which period of the day. These data go to the consumer gamification API for updating the components of the gamified customer engagement to encourage them to accept the optimal commands from the optimisation API. The customers, as the players, are classified as socialisers, explorers, achievers, and express, as defined and explained in [114], so the gamified approach should be able to target all types of players to maximise the engagement. As presented in **Figure 7.5**, a collaborative/competitive game will be updated online for all users in which they need to accept the optimisation

API commands in order to help others and/or proceed faster ahead of others. This task will target specifically socialisers and achievers. Also, an exciting story about the contribution of customers and the effect on the community and the world will be updated to engage explorers. In addition, to encourage express players, a story-telling challenge will be announced in which the participants record a short video online to show how they are excited about their contribution to the demand management. Based on the participation of customers in each scheme, the API will calculate the points, badges, and update the ladder in the application, as shown in **Figure 7.5**. The customers can participate in all these gamified schemes and collect more points.

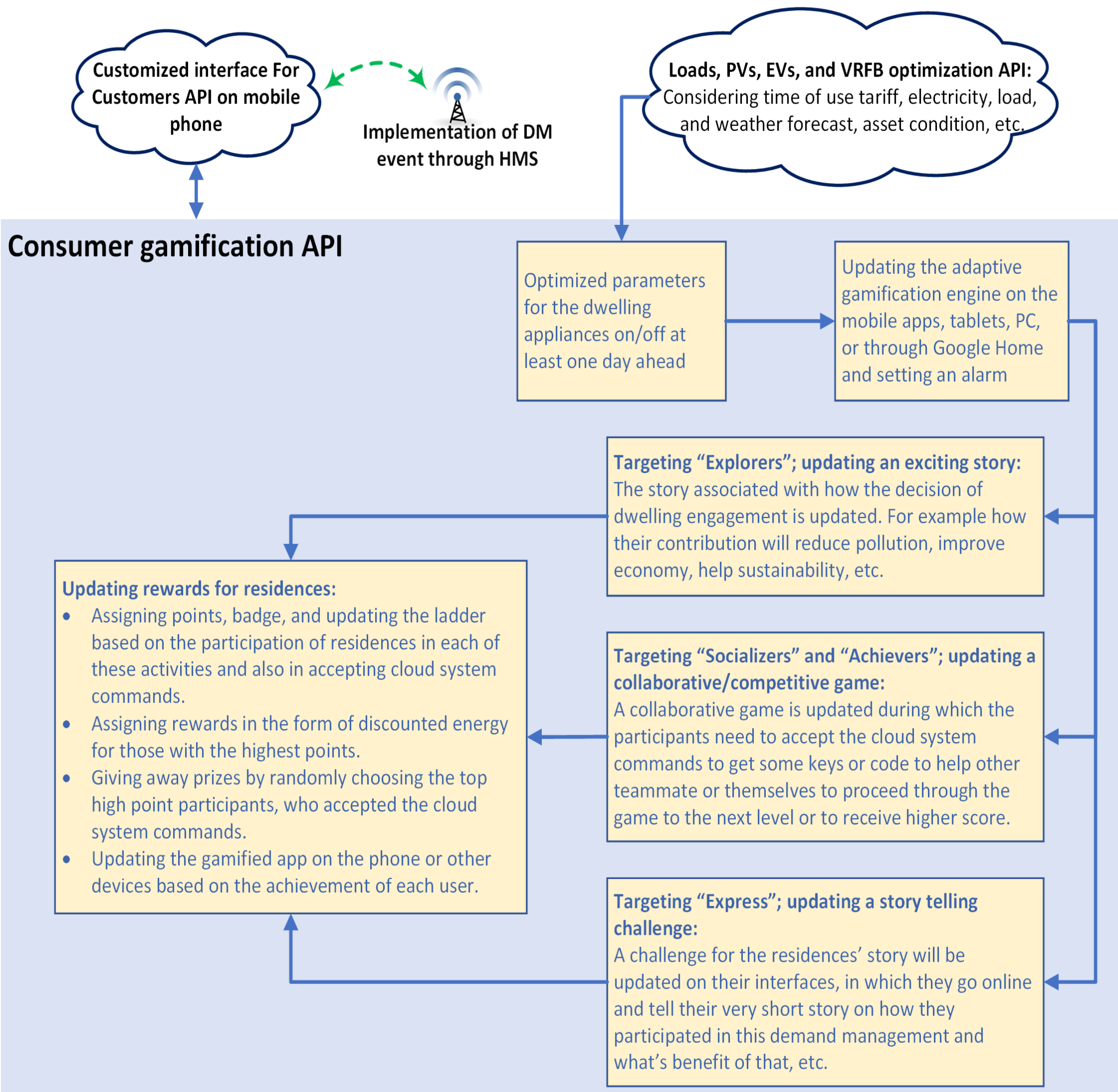

Figure 7.5. The proposed framework for the gamification system for customer engagement.

Each home is equipped with a speaking-interface device such as Google Home which is relevant for those people that prefer to communicate their commands through speaking or those people with a disability. As mentioned, the appliances such as a dishwasher, dryer, washing machine, air conditioner, and heat pump are studied as suitable options for participation in demand management in the first stage in the VPP. The initial settings for the time of use of these appliances are presented in **Table 7.1** as discussed in [114]. These settings can be changed through the gamification application or the Google Home device by the residents. The DM events are determined by the VPP owner through the optimisation process, discussed in Section 5 and sent to the consumers through the gamification app beforehand. The consumers are able to see the events and the corresponding incentives in order to decide to participate in that DM event or not. The residents are able to activate the automatic acceptance of some offers with some conditions.

Table 7.1. Manageable/Shiftable loads

Appliance at the dwelling	Initial setting
Dishwasher	Working between 10am and 4pm
Washing machine/Dryer	Not working between 3pm and 9pm
Heat pump HWS	Working between 9am and 5pm
Air conditioner	Working between 10am and 4pm

7.5 PV and VRFB Monitoring and Control System

The PV system and VRFB are connected to the VPP electric network through inverters. These inverters should have the capability to communicate with a cloud-based management system for optimal control.

In this VPP, one inverter is considered for each PV system on the rooftop of each dwelling in order to improve the reliability and scalability of the overall VPP system.

Also, since the PV systems are the asset of the VPP owner, this approach will make the maintenance and diagnosis of PV systems easier. Another configuration would be to put a DC bus to collect DC energy from PV systems across all dwellings then convert them using a centralized inverter from DC to AC for connection to the VPP network. Both configurations, considering the available technologies for AC and DC systems, are technically feasible. We can build both AC and DC networks and both DC-AC and DC-DC converters are available for different ranges of power. While the AC configuration needs a DC-AC inverter for each PV system at each dwelling, the DC configuration needs a DC-DC converter for each PV system as they cannot be connected directly to the DC bus, and each PV system output voltage needs to be regulated separately. This means that in both configurations, the same number of converters are required, but different types are required, which results in similar costs of inverters and the maintenance costs for the converters. However, in the DC system configuration, we need extra investment and operation/maintenance costs for the DC bus all over the community and a centralized inverter for converting DC to AC, which means that the DC system in this case is not economic. Also, in the case of failure of an inverter in the centralized case, a high proportion of the energy production will not be delivered, whereas in the distributed case, only a small proportion of the produced energy will not be exported in the case of inverter failure. The configuration of PV systems and their inverters is provided in **Figure 7.6**.

As seen in **Figure 7.6**, each PV inverter at each dwelling has a communication link to the cloud through a cellular link. In the communication platform also, a distributed system is proposed in which each inverter can independently communicate to the cloud using an independent cellular communication platform. This configuration will ensure the reliability and scalability of the system. For example, if another PV system is added, it can be integrated easily into the current platform, or if a PV system is out of service, other

PV systems can continue their monitoring and control safely. Also, the PV generation from each dwelling can be monitored separately and diagnosis can be conducted. The storage system is designed to be a fog-based system, in which there is local storage in the inverter for a period of time, for example 1 month, and then the collected data will be transmitted to the cloud.

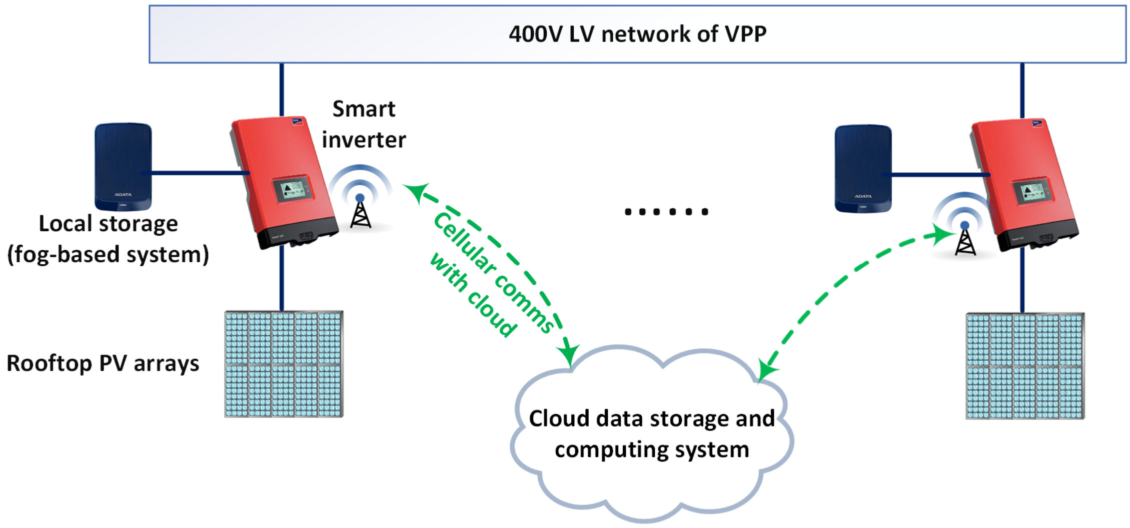

Figure 7.6. The proposed configuration of the monitoring and control system for PV systems in the VPP.

The minimum number of signals that usually need to be collected and sent to the clouds are listed in **Table 7.2**. These signals are recorded by the advanced and recent inverters available on the market and they have internal memory for storing these data for a period of time that can be adjustable as per the project's needs. These parameters are required for analysing the performance and healthiness of the PV systems including inverters using the corresponding application and also for monitoring the energy delivered by the solar system. The inverter can receive commands for changing the AC output characteristics including the voltage, frequency and power factor.

The interface of the 700 kWh/350 kW VRFB is also bi-directional DC/AC inverters. For this project, two inverters in parallel are designed in order to improve the reliability and accessibility to the battery in the case of inverter failure. Another configuration would be one inverter with an additional switching leg as a reserve in the case of failure of one leg. Other specifications are the same as for the PV system inverters.

Table 7.2. The signals necessary to collect and send to the cloud from the inverters of PV and battery systems

Electrical power signals	
Active input and output power of inverter	Output reactive power/power factor of inverter
Input and output voltage/current	Output THD and the highest harmonic magnitude
MPPT setting	Output fundamental frequency
The status of protection signals	
Input/output disconnection device	Overcurrent protections
DC PV array string fault	DC/AC surge arresters
Power electronic parts failures	Environmental condition: Temperature, humidity, and illuminance

7.6 Fog-based Data Storage, Computing and Forecasting for Market Participation

In order to reduce the cost of the communication link to the cloud and also enhance the speed of computation, a fog-based data storage and computing system is designed for the VPP. As discussed in the previous sections, each item of equipment has its own local controller and storage, which is acting as a fog agent. For example, each inverter for PV and VRFB has its own control system for regulation of voltage and frequency at its setpoints and also has a local storage. Each fog agent will communicate through cellular communication directly to the cloud, in which the management system and other applications are located.

The details of a practical fog-based system for dwellings are depicted and explained in

Figure 7.7. the corresponding standard for a fog-based storage and computing system is developed by OpenFog Consortium and adapted as the standard by IEEE 1934-2018 [152]. As seen in **Figure 7.7**, the fog device, which is a locally located device in each dwelling, is the HMS device for each home that communicates with devices through EEBUS as described in Section 7.4. The HMS is responsible for controlling and responding to urgent and time-sensitive tasks such as file/smoke or climate change inside a dwelling, including temperature, humidity, and lighting. Also, the fog-device needs to store the historical data for a limited period, for example for a month, and communicate data and commands to/from the cloud monitoring and control system.

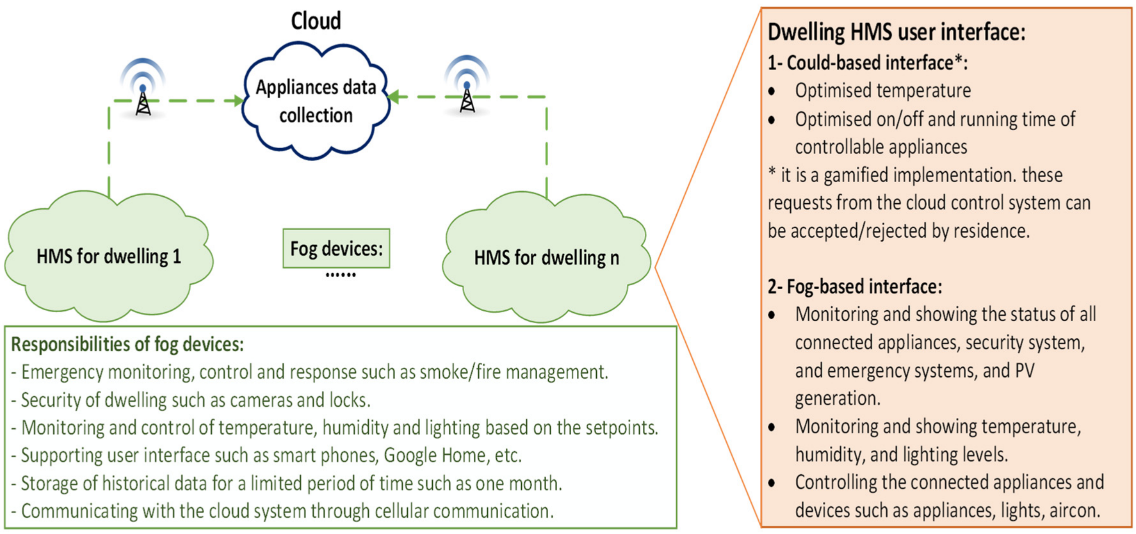

Figure 7.7. The proposed fog-based configuration and user interface for dwellings.

The interface of the HMS is set up on a smart phone, tablet, or PC. Also, the HMS is able to communicate through voice with those with a disability. There are two main sections on the interface of this HMS; one is the fog-based interface, and another is the cloud-based interface. The fog-based interface will show the status of the appliances, security and emergency devices. Also, the user can change the setting of devices and control temperature, lighting, and humidity. The cloud-based interface shows the optimized commands that have been received from the cloud control system. These commands, including the change of status of controllable appliances, can be accepted or rejected by the user. The user can set the HMS to automatically accept all commands from the cloud or manually decide on them. The gamification approach, described in Section 7.4.2, will encourage all types of users to engage with the system and accept the commands as much as possible.

The schematic of the proposed cloud-based control and management system is presented in **Figure 7.8**.

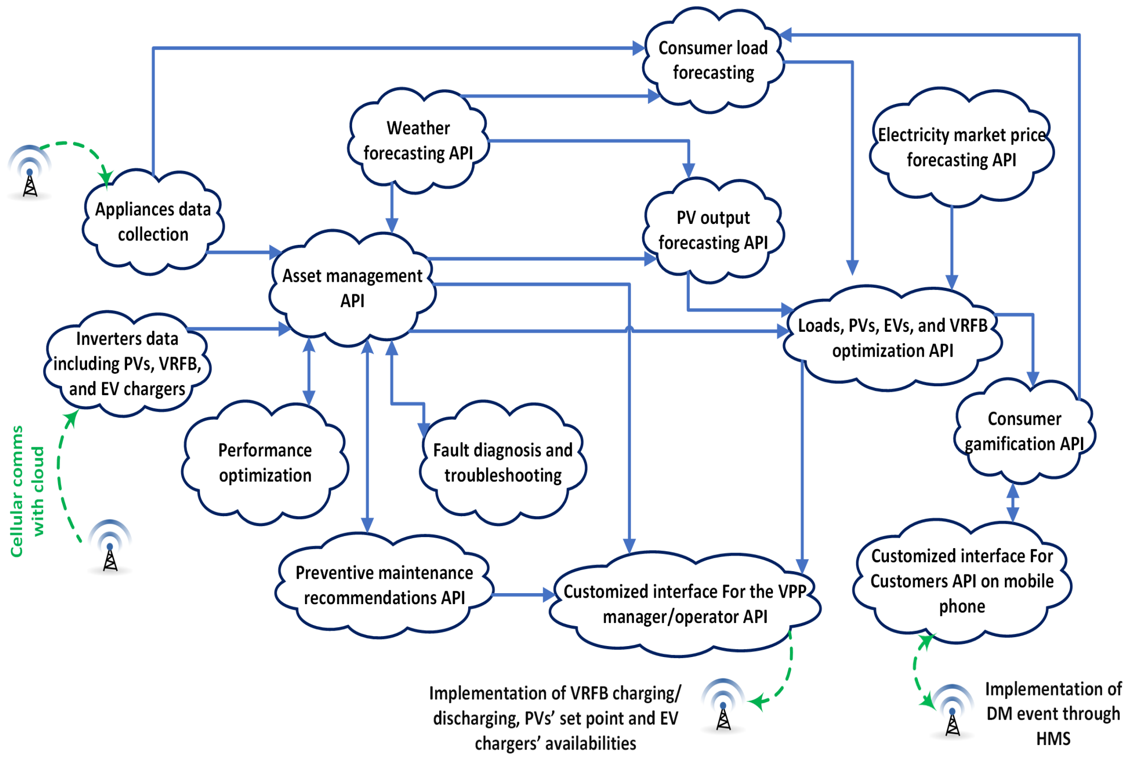

Figure 7.8. The proposed configuration of the cloud-based monitoring and control system APIs for the VPP.

As seen, the following APIs are introduced and utilized in this management system:

- Weather forecasting API: This application will feed in the forecast data from the corresponding institute for example Bureau of Meteorology (BOM) in Australia. The data are used to predict the load profile of the consumers, to manage the assets and to diagnose the faults.

- PV output forecasting API: This application will determine near future data for PV generation considering the weather condition and the status of the assets. If the sky camera device is installed in the area of the VPP, it will improve the accuracy of PV prediction.
- Electricity market price forecasting API: Electricity market regulators, for example AEMO in Australia, can provide the market price forecast. The data are fed into the optimisation algorithm for the battery and PV contributions and also used for demand management within the VPP.
- Consumer load forecasting: this forecasting tool will predict near future demand considering temperature and the gamification system in place within the VPP. There are some advanced tools that can forecast net customer load including PV as well [153].
- Consumer gamification API: this API will collect all history of activities by consumers on energy saving and demand management and also the preferred settings for the time of use of appliances and their settings. These data are necessary for predicting the load profile of consumers.
- Asset management API: This application uses a data analytic approach to find out the healthiness of the assets including the appliances, PV systems and VRFB including their inventors. Considering the status of the assets, this application can provide recommendations on how to improve the performance. Also, it can diagnose some faults and provide preventive maintenance recommendations.
- Customized interface and dashboard API for the VPP manager or residents: Consumers will be aware of the demand management events for their appliances through their gamification API. The corresponding dashboard for gamifications will be available as a mobile application for the consumers. The dashboard for the VPP

manager should also show all the optimized variables for the demand management, VRFB, and PVs. Also, the manager needs to see the status of the assets and any recommended maintenance for implementation.

7.6.1 Optimisation Application

The detailed formulation of the objective, revenues and expenses are discussed in the previous Chapters. However, here we briefly revie the application of the optimisation algorithm. In order to maximise the benefits to the VPP's owner and residents, a cloud-based optimisation application is used to schedule the optimal charging/discharging of the battery and consumption patterns. In this optimisation, the default aim for the PV system is to maximise the PV active power generation, except if there is a requirement from the local utility on the reactive power injections.

The optimisation objective function and its constraints are formulated as below:

$$maximize\ (R_{tot} - C_{tot} - C_{DM})$$
$$\text{Constraints: } \begin{cases} VRFB\ charging\ and\ discharging\ consraints \\ Customer\ the\ use\ of\ appliances\ constraints \\ PV\ system\ generation\ constraints \end{cases} \tag{7.1}$$

$$\begin{aligned} R_{tot} &= R_{Fix} + R_{Var} \\ &= R_{Fix} + \sum_{h=1}^{24} E_{out}^{y,h} \pi^{y,h} + \sum_{h=1}^{24} E_{RES}^{y,h} \tau_{RES,E}^{y,h} \\ &+ \sum_{h=1}^{24} P_{LFAS,UP}^{d,h} \zeta_{LFAS,UP}^{d,h} \\ &+ \sum_{h=1}^{24} P_{LFAS,DOWN}^{d,h} \zeta_{LFAS,DOWN}^{d,h}, \quad y\ is\ fixed \end{aligned} \tag{7.2}$$
$$E_{out}^{y,h} = \begin{cases} E_{PV}^{y,h} - E_{RES}^{y,h} - E_{VRFB}^{y,h} & if\ \left(E_{PV}^{y,h} - E_{RES}^{y,h} - E_{VRFB}^{y,h}\right) > 0 \\ 0 & otherwise \end{cases}$$
$$E_{RES}^{y,h} = E_{RES,Fix}^{y,h} + \sum_{n=1}^{67} E_{WM,n}^{y,h} + E_{HP,n}^{y,h} + E_{AC,n}^{y,h} + E_{DW,n}^{y,h}$$

$$\Rightarrow R_{tot} = R_{Fix}^{*} + \sum_{h=1}^{24} E_{out}^{y,h} \pi^{y,h}$$

$$+ \sum_{h=1}^{24} \left\{ \tau_{RES,E}^{y,h} \sum_{n=1}^{67} E_{WM,n}^{y,h} + E_{HP,n}^{y,h} + E_{AC,n}^{y,h} + E_{DW,n}^{y,h} \right\}$$

$$C_{tot} = C_{Fix} + \left(1 + \alpha^{y}\right) \sum_{h=1}^{24} E_{in}^{y,h} \pi^{y,h} + \alpha^{y} \sum_{h=1}^{24} E_{out}^{y,h} \pi^{y,h}$$

$$+ \left(1 + \beta^{y}\right) \sum_{h=1}^{24} E_{in}^{y,h} \omega^{y,h} + \left(\gamma^{y} + \delta^{y} + \theta^{y}\right) \sum_{h=1}^{24} E_{in}^{y,h} \quad (7.3)$$

$$E_{in}^{y,h} = \begin{cases} E_{PV}^{y,h} - E_{RES}^{y,h} - E_{VRFB}^{y,h} & if\ \left(E_{PV}^{y,h} - E_{RES}^{y,h} - E_{VRFB}^{y,h}\right) < 0 \\ 0 & otherwise \end{cases}$$

$$C_{DM} = \sum_{n=1}^{67} k_1 \Delta E_{WM,n}^{y,h} + k_2 \Delta E_{HP,n}^{y,h} + k_3 \Delta E_{AC,n}^{y,h} + k_4 \Delta E_{DW,n}^{y,h} \quad (7.4)$$

where,

- R_{tot}: is the total revenue of the VPP owner for the next day including selling energy to the WEM and also to the residents. Also, R_{tot} includes the reserve capacity revenue by the VPP based on the allocated reserve capacity credit (RCC) for this VPP and the associated price (AUD/MW/year) [103]. The detailed formulation of R_{tot} is provided in [110]. The base tariff for which the VPP sells energy to the dwelling is presented in **Table 7.3**. As seen, from 10am to 2pm, the electricity is free for the consumers within the VPP, which is a very strong incentive for them to manage their electricity use and to participate in the demand management events, scheduled by the VPP owner. The timing of the tariff can be changed depending on the season as well, such as being flat tariff, as considered in Chapters 3 and 5. For the sake of simplicity, R_{tot} can be written as (7.2), where R_{Fix} represents all fixed terms in the revenue of the VPP during a year and can be excluded from the optimisation process in a specific year. In (7.2), the exported energy to the electricity market at the *h*-th hour is $E_{out}^{y,h}$ with the price of electricity at that hour equal to $\pi^{y,h}$. The total consumed energy by 67 dwellings is $E_{RES}^{y,h}$ at the price of $\tau_{RES,E}^{y,h}$ for the hour

h in year y. this electricity price is provided by the WEM price forecasting API on the cloud. $P_{LFAS,UP}^{d,h}$ and $P_{LFAS,DOWN}^{d,h}$ are the power sold to the upwards and downwards LFAS market at the prices of $\zeta_{LFAS,UP}^{d,h}$ and $\zeta_{LFAS,DOWN}^{d,h}$, respectively. $E_{WM,n}^{y,h}$, $E_{HP,n}^{y,h}$, $E_{AC,n}^{y,h}$, $E_{DW,n}^{y,h}$ are respectively the energy consumption at hour h by the washing machine, heat pump, aircon, and dishwasher of the n-th dwelling. As seen in (7.2), the variable parameters are whether these controllable appliances are working or not. Another variable parameter is the amount of energy charged in the battery, namely $E_{VRFB}^{y,h}$. In (7.2), $E_{PV}^{y,h}$ is the amount of energy generated by the whole PV system, which is forecasted by the weather forecasting API and the asset management API on the cloud.

Table 7.3. The TOU tariff of the VPP for the residents

Fixed cost (cents/day)	**Peak (cents/kWh): 4pm to 10pm**	**Shoulder (cents/kWh): 8am to 10am / 2pm to 4pm**	**Off-peak (cents/kWh): 10pm to 8am**	**Free electricity: 10am to 2pm**
103.3263	54.81	28.71	15.10	0.00

- C_{tot}: are the total expenses of the VPP owner for the next day, which includes the WEM-related expenses and the capital expenditure (CAPEX) expenses. The CAPEX is the fixed cost, so it is not considered in the operational optimisation. The compact formula is presented in (7.3), and the detailed formulation is provided in Chapter 3 [110]. The WEM-related expenses consist of the following:

1. $E_{in}^{y,h}$, which is the cost of energy purchased from the electricity market.
2. The retailer margin expenses when the VPP purchases energy from the electricity market, which is obtained by applying the coefficient of α^{y} to the purchased energy, $E_{in}^{y,h}$.

3. The retailer margin expenses when the VPP exports/sells to the WEM, which is calculated using the coefficient of α^{y} applied to the sold energy.
4. The energy tariff charge, which is the local utility tariff applicable to the VPP, represented by $\omega^{y,h}$ in h-th hour and y-th year [100].
5. The cost of the loss factor obtained using the parameter of β^{y}.
6. The Clean Energy Regulator fee, the ancillary service fee, the market fee, which are calculated respectively using the parameters γ^{y}, δ^{y}, and θ^{y}.

The definition and values of the above-mentioned coefficient are provided in [110]. The CAPEX-related costs also include the following items; however, they are not considered in the optimisation process. The costs of installed capital expenditure like PV panels and VRFB are calculated based on the NPV cost, then converted to daily costs.

1. The cost of the PV systems, including the cost of PV panels, inverters, structures, installation and commissioning, and the associated maintenance such as cleaning.
2. The cost of the VRFB, including the cost of the battery, designing, foundation, installation, and operation and maintenance costs.
3. The cost of the heat pumps HWS for 67 dwellings including the government rebate for the use of heat pumps. The costs of other appliances, including those equipped with EEBUS technology, are not included here as they are considered in the price of the dwelling or the associated rental expenses.
4. The cost of the internal network, distribution transformer, cabling and protection system.
5. The cost of the fog devices including HMSs and smart meters for 67 dwellings, also the cost of design and implementation of the communication system for the purpose of advanced monitoring and control of the VPP.

- C_{DM}: is the cost of demand management, which includes the additional incentives payable to the consumers when they receive high ranks and badges in the gamification application by participating in DM events scheduled by the VPP owner or competing/collaborating with others for some setup energy saving/management goals. This cost can be included in the total costs of the VPP, as formulated in Chapter 3 but here, we consider a separate term for that for the clarification of such costs. Also, the costs of the gamification application can be considered in this cost. These will be determined by the VPP owner depending on the effectiveness of the DM goals. The equation for this cost is provided in (4), in which k_1 to k_4 are the values of incentives per kWh for different customer contributions. Δ represents the changes in the consumption of each appliance. For example, if the command is turning off the air conditioner, and the customer accepted that, the $\Delta E_{AC,n}^{y,h}$ becomes positive and equal to the change in the energy consumption of the appliance.

There are some mathematical optimisation applications on the cloud for solving such a problem in a manageable time, like the high-performance computing platform by Azure [154]. As an example, the simulation results of optimisation including the detailed formulation for the VRFB is provided and discussed in [110]. Also, Azure IoT can provide a secure and scalable platform for data management of several devices on the cloud, which is a solution for the proposed fog-based data storage and computing system for the VPP [155]. In addition, Azure artificial intelligence can provide the necessary tools for forecasting the load, customer behaviour and PV output, as proposed in this Chapter [156].

7.7 Conclusions

This Chapter proposes a concept design for the monitoring and control system of a virtual power plant in Western Australia, which includes 67 residential dwellings. This study shows that a fog-based platform is an affordable, scalable, and reliable approach for collecting and analysing the data to optimally manage controllable appliances in dwellings, rooftop photovoltaic (PV), and a vanadium redox flow battery (VRFB). For example, the proposed system is affordable because it proposes the use of cloud storage and cloud computing instead of a large computing centre. It is proven in many cases that the cloud-based system will increase the reliability of access to the information and computation. Also, when we want to scale the system, the cloud-based system is easy to scale compared to the traditional storage and computing centres. For even better reliability, we proposed here a fog-based system in which a small capacity of storage along with the meters with built-in computing capacities is distributed to each dwelling with home management systems. The various cloud-based applications necessary for the operation of a VPP are proposed, including weather, PV output, and customer load forecast and also gamification, asset management, and optimisation algorithm.

Also, the main power transformer is designed as two parallel transformers, so it allows for stage-by-stage development of the VPP, and at the same time, increases the reliability of grid supply. Furthermore, the PV systems are connected through separate inverters to the AC bus, which is a more affordable and reliable option compared to a DC bus, as discussed in Section 7.5. In addition, the communication system for the PV systems, dwellings, and the battery are designed to be standalone and independent from each other, and to communicate directly with the cloud. This configuration is more cost-effective compared to the LAN network or any other centralised communication system, and at the same time, increases the reliability of the communication system. It is proposed that the relevant data from the corresponding inverters are also transferred directly to the cloud through cellular communication. The fog devices for inverters are the internal processor and memory of those inverters as well.

Further, at the consumer level, we have proposed the use of appliances with built-in EEBUS and the use of HMS with EEBUS protocol to avoid any extra investment on the installation of separate control and communication devices for each appliance. This demonstrates that the system is more affordable and also more reliable as it uses fewer components in the proposed system. For encouraging customers to engage with the optimized commands from the cloud-based optimisation system, the gamification application is the most effective approach in which people can collaborate and compete for getting prizes and badges. This research enables communities and industry to establish a cost-effective, reliable, and scalable VPP to provide sustainability at the lower cost of energy for the residents. Future work will include the investigation of price maker VPPs and bidding strategies.

Chapter 8 Conclusions and Suggestion for Future Work

8.1 Conclusions

This thesis presents the results and outcomes of the research conducted on the development of concept design, formulation, and bidding strategy for residential virtual power plants (VPPs) in Western Australia (WA). VPPs are a combination multiple energy resources including PVs, energy storages and load flexibilities, coordinated and managed by a control system for efficient use of energy and effective participation in the wholesale electricity market (WEM).

The main aim of this research has been achieved, which is to develop an effective design for the VPP with a robust bidding strategy to participate in the WEM along with active customer engagement to make a reasonable profit for the VPP owner. Such effective arrangement of the VPP not only attracts private investors to invest in VPPs but also reduces the cost of the electricity for consumers, which again makes the VPP a desirable option for customers.

In this thesis, the detailed financial analysis and formulation of costs and benefits for a realistic VPP in WA is developed and presented. The realistic VPP, which is being built in South Lake, WA, includes 67 residential homes. The rooftop PV system is designed and sized using HelioScope software with the size of 810 kW, which can generate 1,190,689 kWh per year. Further, the vanadium redox flow battery (VRFB) is chosen as the energy storage system because of numerous benefits of this technology, such as lifetime and environmental impacts, compared to others such as Lithium-ion energy storage. The size of the VRFB designed for the VPP is 700 kWh/350 kW.

Also, smart appliances for better management of devices and heat pump hot water systems (HWSs) for improving the efficiency of HWSs are considered in the design of this VPP. A detailed load modelling for different appliances is developed and using Monte Carlo simulation, a simulated yearly load profile is constructed. The optimum energy bidding strategy along with the optimum charging and discharging of the VRFB to maximise the benefit of the VPP, when participating in the energy market only, is formulated as a linear programming problem and solved by MATLAB. To reduce the cost of electricity for the consumers, a customised time-of-use (TOU) tariff is developed, in which the electricity would be free between 10am and 2pm for the customers within the VPP. The analysis shows that the cost of electricity is decreased for each dwelling by 24% within the VPP compared to when they are connected with the local utility. Also, the internal rate of return for the VPP owner is at least 11% with the payback period of 9 years, which is a promising financial outcome for the investors.

As the VPP utilises load flexibilities through demand response programs, the customer engagement in a enjoyable way is crucial. This thesis has developed a gamified approach for customer engagement in the VPP, in which residents will contribute to demand response programs activated by the VPP owner through a gamified application. Through this approach, not only is the comfort level of customers not compromised but also an improved social engagement is provided to them via interaction in the gamification app. A methodology for assessing the suitability of different gamification applications in the context of a VPP is proposed in this thesis based on Fogg's behaviour model and Kim's model on player types. Using this proposed method and analysing seven gamification applications, "enCOMPASS" is demonstrated to be the most appropriate app for the VPP.

For a sustainable business model for the VPP owner, the operation of the VPP should be profitable over the long run, for which an optimum control system and participation in the electricity market is required. In this thesis, a robust and fast bidding strategy for participation in the energy market and in the load following ancillary service (LFAS) in the WEM is proposed and examined. For participating in the energy market only, four parameters are defined including the revenue per kWh, the cost of purchasing one kWh, the battery charging cost for one kWh, and the battery discharging revenue for one kWh. Using these parameters, a fast and robust energy bidding strategy for the WEM is developed considering the uncertainties associated with PV generation and electricity price. In this research, a flat tariff is considered for the customers, that shows 10% reduction of electricity cost over a year for the customers within the VPP.

Further, an optimal bidding strategy for participation in both LFAS and energy market is also developed. Using this strategy, the VPP can achieve a payback period of 6 years with IRR of 18%, while not compromising the useful lifetime of the energy storage when participating in the load following service in the WEM. In such an arrangement, the consumers are also participating in a gamified DR program in an enjoyable and sociable way while not compromising their comfort levels. The gamification approach will also improve the payback period for the VPP owner by about two months. This improvement is much more if the number of customers is larger within the VPP. The cost of electricity for customers within the VPP is also reduced by 10% over a year, compared to the situation of not being within the VPP.

The proposed robust and simple bidding strategy for the VPP in WA is fast and accurate, evident by the detailed comparison between this algorithm and a robust mathematical method. The daily average error of the proposed robust method compared to the robust mathematical method is 2.7%, which demonstrates a very high accuracy of the proposed method. The effectiveness of the proposed bidding strategy is highlighted when comparing its the speed with that of the other algorithm. The computational effort for 365 runs for the proposed robust bidding strategy is 0.66 seconds compared to 947.10 seconds for the robust mathematical methods.

To coordinate and manage all energy resources, an affordable, scalable, and reliable monitoring and control system is essential. In this thesis, a concept design of such platform is developed, and the specification of the system is proposed. In the proposed platform, all smart appliances are connected through the EEBUS protocol to the home management system (HMS), which communicates via a cellular connection with the fog-based control system. The PV systems and energy storage also have direct cellular communication with the cloud-based system. The fog-based control system has local and cloud-based storage and processing units to collect and manage data, to run the optimisation algorithm, and to send command to multiple resources including energy storages and the gamification app. Many cloud-based applications are proposed to be included in the monitoring and control platform including PV output forecast, load forecast, and gamification to help improve the efficiency of the proposed platform.

In summary, the main findings of this thesis are as follows:

- It is found that an affordable concept design for an effective residential VPP in WA can be developed including rooftop solar farm, vanadium redox flow battery, heat pump hot water system, and smart appliances along with a gamified customer engagement and a scalable cloud-based monitoring and control platform.
- It is discovered that a robust bidding strategy for the energy and LFAS markets for the VPP is achievable and that it is a simple, fast, and understandable procedure for industry and private investors considering gamification for customer engagement.

- The accuracy of the proposed robust method is very high with the daily average error of 2.7%. However, the computational effort for the proposed method is much lower at 0.66 sec for 365 runs compared to 947.10 sec for the mathematical methods.
- The average electricity cost per dwelling within the VPP per year is at least 10% cheaper compared to the cost of buying from the local retailer. This cost reduction could be up to 24% when considering a customised TOU tariff for the customers, but the payback period for the VPP owner would be longer.
- By participation in both LFAS and the energy market, the VPP owner will get a better financial return. For example, the payback period of the VPP system is improved from 9 to 6 years and the IRR from 10.5% to 18% by participating in both the LFAS and energy market.
- A methodology to evaluate the suitability of applications for the gamified customer engagement in a VPP is developed, and the best right applications for a realistic VPP in WA are selected. The gamification can improve the payback of the VPP by a fraction of a year, while customers are participating in the program with interest and enjoyment.
- A cost-effective, reliable, flexible, and scalable monitoring and control platform for the VPP is proposed to provide sustainability at the lowest cost of energy for the residents and a robust control of the system by the VPP owner.

8.2 Suggestions for Future Work

There are some research topics that researchers can consider for the future work. The outcome, methodologies, and findings in this thesis will help foster the knowledge and develop new ideas in the following aspects:

- **Central cooling and heating system**: the heating and cooling system is considered for each dwelling in this thesis, following the discussion with the VPP owner. The centralised cooling and heating system could potentially improve the efficiency of the system, if it is designed carefully, and can be used as a thermal energy storage when participating in the WEM. Therefore, it is suggested as one of the future works for researchers who are interested in this domain.

- **PV/Thermal hybrid units**: another technology is the PV/thermal unit that generates PV and at the same time it can generate warm water or air. Such technologies are becoming available and can be used for increasing the temperature of water or air to be used in the hot water system or air conditioning system, respectively. Evaluating the viability of PV/thermal hybrid units within a VPP is another subject of near future research.
- **Trading among multiple VPPs**: by increasing the number of VPPs in future, there will be possibility of energy transactions amongst VPPs. Therefore, it is encouraging that researchers are investigating this topic to develop a platform for trading energy and services amongst multiple VPPs.
- **Multiple ancillary service integration**: in the near future, VPPs can participate in multiple ancillary services not only the LFAS market. Therefore, it is appropriate to develop a bidding strategy to integrate the bidding for the energy market with multiple ancillary services in the WEM.
- **The impact of electric vehicles**: The rise in the number of EVs is imminent. EVs within VPPs can be considered as the moving energy storage which can sell energy to the VPP or transfer energy among VPPs. Consequently, investigating the energy and money transactions including the appropriate platform for EVs within VPPs will become important.
- **The LFAS and energy markets in the national electricity market (NEM):** The

research in this thesis is focussed on the implementation of VPP in WA with its own market rules in the WEM. It is recommended to further research the affordable VPP design, gamification, and bidding strategy in the NEM, which has different rules for both energy and ancillary markets.

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