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*Review*

# Grid-Forming Virtual Power Plants: Concepts, Technologies and Advantages

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**Abstract:** Virtual Power Plants (VPPs) are efficient structures for attracting private investment, increasing the penetration of renewable energy and reducing the cost of electricity for consumers. It is expected that the number of VPPs will increase rapidly as their financial return is attractive to investors. VPPs will provide added value to consumers, to power systems and to electricity markets by contributing to different services such as the energy and load-following services. One of the capabilities that will become critical in the near future, when large power plants are retired, is grid-forming capability. This review paper introduces the concept of grid-forming VPPs along with their corresponding technologies and their advantages for the new generation of power systems with many connected VPPs.

**Keywords:** virtual power plant; grid-forming inverters; renewable energy; energy storage; review

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## 1. Introduction

Global warming has reached a point where it is causing serious climate change, and this has focused the world's attention on reducing the use of fossil fuel-based sources to generate electrical power [1]. In addition to this, fossil fuels are being seriously depleted, and some believe that they should be preserved for high-value applications and future generations. As a result, the use of renewable energy sources (RESs) such as solar and wind has experienced a sharp increase in recent years. Initially, large-scale RESs were integrated into distribution networks by utilities with different objectives [2,3]. For example, the authors of [4] advocated RESs to enhance the power quality of distribution networks. Likewise, reliability enhancement was another application of the integration of RESs into the power distribution grid [5]. From this, it is clear that RESs not only decrease the considerable amount of pollution derived from power generation, but also bring advantages such as loss minimization and reliability improvement.

Similarly, consumers have attempted to reduce their electricity costs and cut their $CO_2$ emissions by installing photovoltaic (PV) panels on their house roofs [6]. Although this mechanism often helps to decrease their electricity bills, there remain some unresolved issues. Firstly, their additional generation may be partially wasted because they cannot participate effectively in the wholesale electricity market, because their generation is not significant enough to allow them to have an active role in the market. Another problem of such standalone systems is that they experience more power outages due to natural disasters, like hurricanes, earthquakes and storms. In order to tackle these problems related to rooftop PV, the concept of a virtual power plant (VPP) has been introduced [7]. Generally speaking, VPP means combining dispersed small-scale generators to create a unified system, resulting in increasing their ability to participate in the wholesale electricity market as well as increasing the stability of the grid. VPPs can be easily formed based on existing systems and they can decrease public expenditure on additional transmission lines.

Some review papers are present in the literature which pertain to this topic. To begin with, the authors of [8] reviewed the challenges of uncertainties in the operation of VPPs. Similarly, in [9], a review was provided on transforming microgrids to VPPs. VPP management strategies were reviewed in [10]. The participation of VPPs in the energy market was another challenge that has been reviewed in the European Union by the authors of [11].

To the best of the authors' knowledge, there is no review of grid-forming VPPs and grid-forming inverters. Accordingly, this paper focusses on this topic, and the concept of VPPs and grid-forming is illustrated by a simulation of a real grid-forming VPP in Western Australia.

The structure of this article is summarized as follows. VPPs are reviewed in Section 2. A summary about grid-forming inverters is provided in Section 3. In Section 4, the concept of grid-forming VPPs is discussed. The problem formulation associated with grid-forming VPPs is developed in Section 5. The simulation results of a grid-forming VPP in a real case in Western Australia are discussed in Section 6. In Section 7, the main results and conclusions of this review are presented.

## 2. Virtual Power Plants (VPPs)

VPPs are becoming appealing at the present time due to combining dispersed energy resources into a unified power plant which can supply the local demand as well as connecting to the main grids [12]. This section 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 case 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 a review of different bidding strategy algorithms for VPPs in the electricity market.

### 2.1. General Overview

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 have set some targets, such as the contribution of 23.5% renewable generation by 2020 in Australia, which it has already achieved [13]. 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 for energy storage [14].

Considering the increase in electricity prices in Australia by 200% during the last decade, which brings financial difficulties to many people, it is critical that the use of renewable energy resources and energy storage reduces the cost of electricity for people. Energy aggregators such as VPPs have a great potential to achieve this goal of reduced electricity prices 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 [15,16].

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 [16,17]. In this paper, the previous relevant works and research on VPPs, customer engagement and electricity market participation are discussed, as shown in Figure 1 [18].

### 2.2. VPP Case Studies

There are many studies that investigate different aspects of VPPs. For example, [19] 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 [19].

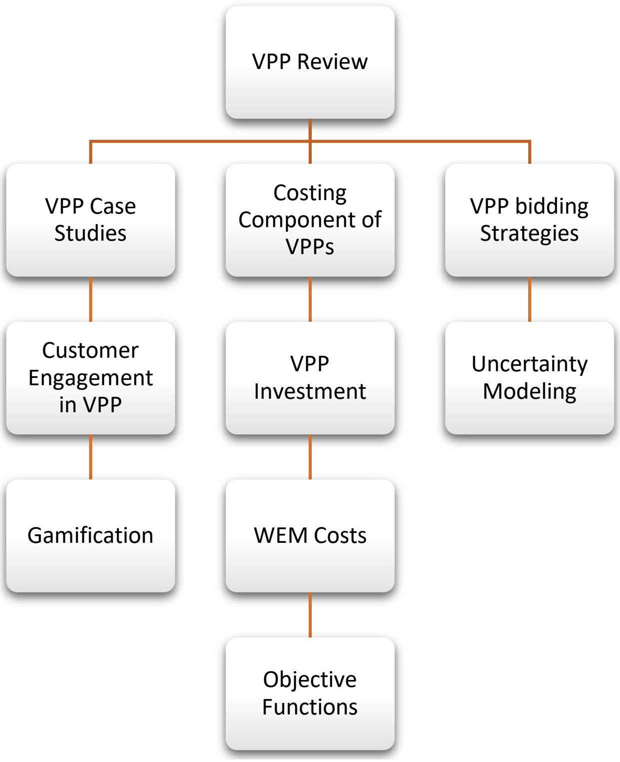


**Figure 1.** The components of the literature review in this article.

The affordability and technical aspects of VPP implementation through multiple revenue streams are discussed for a university campus in [20]. This research shows that a VPP within a 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 of this capability of VPPs; 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 [21]. 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 in [22].

There are several categories of VPPs, including community VPP or commercial VPP. Community VPP generally refers to a coordination of neighbouring residential customers and some community service utilities such as parks and aged care facilities. Practical cases of community VPP exist in Ireland, Belgium and the Netherlands [23]. 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 a 10% increase in the VPP profit has been achieved by good management of renewables and interaction with the electricity market [24].

VPPs can be used to maximise the self-supply, such as the case in Spain, in which the VPP is designed to be as self-sufficient as possible while contributing to the electricity market and local grids [25]. In some VPP cases, some economic metric such as gross domestic product (GDP) per capita, unemployment rate, etc., are taken into account to evaluate the benefits of establishing VPPs on different aspects of social, economic and environmental criteria [26]. It is observed, for example, that a high level of renewable integration can significantly influence the prices in the electricity market [11]. A case study of VPP participation in the electricity market in Germany shows a good economic outcome [27]. For example, the revenue of the VPP increased by 11% [27]. 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 [28]. 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 [29].

A summary of the comparison of literature topics is provided in Table 1.

**Table 1.** A comparison of recent papers on VPP case studies. (√: considered, ×: not considered, and #: reference number).

| Ref. # | DR | PVs | Energy Storage | Heat Pump | Electricity Market | Detailed Modelling | Gamified DR | WA Context |
|---|---|---|---|---|---|---|---|---|
| [19] | × | √ | × | × | √ | √ | × | × |
| [20] | √ | √ | √ | √ | √ | × | × | × |
| [21] | √ | √ | √ | × | √ | × | × | × |
| [22] | √ | √ | √ | √ | × | × | × | × |
| [23] | √ | √ | √ | × | √ | × | × | × |
| [24] | × | √ | × | × | √ | √ | × | × |
| [25] | √ | √ | √ | √ | √ | × | × | × |
| [26] | √ | √ | √ | × | √ | × | × | × |
| [11] | √ | √ | √ | √ | √ | × | × | × |
| [27] | √ | √ | √ | × | √ | √ | × | × |
| [28] | √ | √ | √ | × | √ | × | × | × |
| [29] | √ | √ | √ | √ | × | √ | × | × |
| [30] | × | √ | √ | × | × | √ | × | × |
| [31] | × | √ | √ | × | √ | √ | × | √ |

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 capabilities, capacities and challenges for the implementation of VPPs in Australia. Some of the main capabilities 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 customer satisfaction and experience;
- Evaluation of the requirement of cyber security.

The locations and sizes of the VPP participants in this demonstration are provided in Figure 2. As shown, all participants are located outside Western Australia (WA); consequently, there is not any case data to examine technical and financial aspects of VPPs in WA in this demonstration. The total size of all VPPs adds up to 31 MW, and PVs and batteries are mainly involved as the participants in these trials [30].

In WA, in addition to a project in South Lake, two other projects on VPPs are underway. 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, which is supported by Synergy, Western Power and AEMO, is in its early stages and is planned to finish in mid-to-late 2023 [32]. 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 school VPPs, and they are designed to work as a community VPP [31].

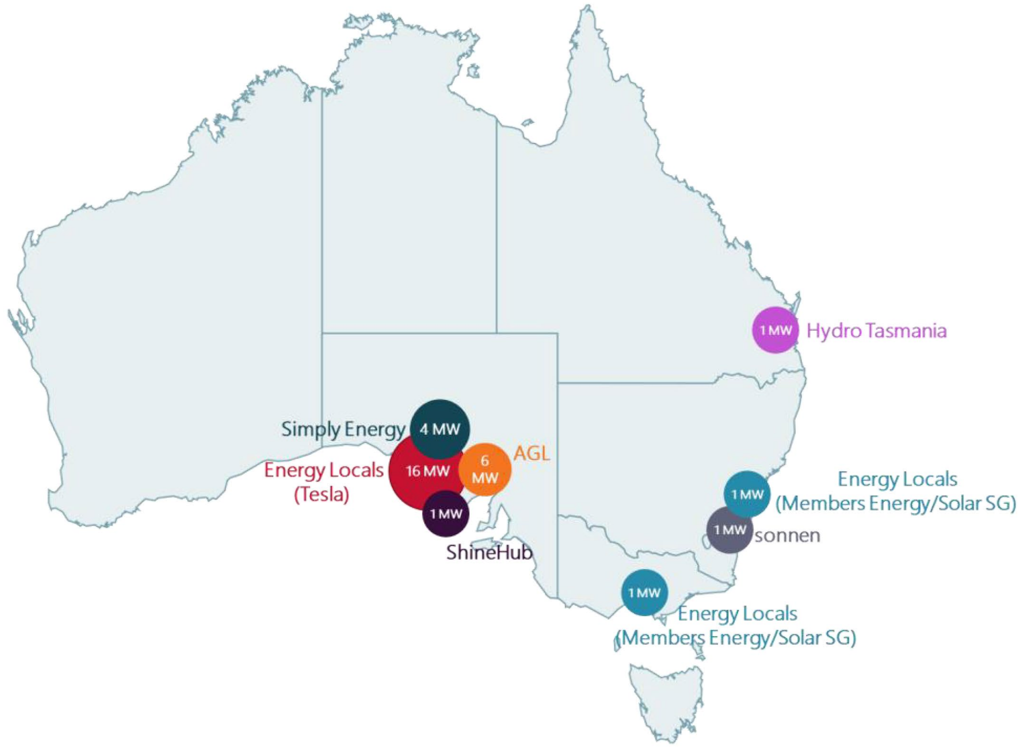


**Figure 2.** The location and size of VPPs in the AEMO's VPP demonstration [30].

### 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, 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 [33]. 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. 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 [34].

Demand response (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 [35]. 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 to demand from different signals such as electricity prices, PV generation, temperature, etc. The demand response is generally categorised in two forms as follows [36]: (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. This 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 min, 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 settings of consumers, which could be 10 min to 1 h [37,38].

Long-term interval DR is associated with DR intervals of several hours, for example, 2 h. 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 constraints on washing machines and dishwashers that the washing cycle should be finished before applying the DR command [39,40].

In order to facilitate the decision for customers about whether to participate in DR and nominate one or more of their appliances, a framework is necessary to consider the uncertainties in the load, PV, electricity market, cost of load curtailment or shifts for them and time-of-use tariffs (TOUs) [41]. 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 [42]. 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 residents [43]. Such load flexibilities from VPPs can contribute to the reduction of the peak load and the investment in poles and wires in distribution networks [44].

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 [16]. A VPP that includes a CHP should optimise the heat storage and boiler operation in order to effectively participate in a DR program, and then a scheduling decision is provided for participating in the WEM.

Although demand responses are considered as one of the sources of flexibilities for VPPs, which potentially could improve the profit of the VPP [45,46], 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, on 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 that work based on gamified approaches. The applications that are reviewed in this paper are Ecogator, Social Power Game, Makahiki, Power House, Less Energy Empowers You (LEY), Wattsup, enCOMPASS and Funergy [47]. These applications can also be used for energy efficiency/saving if programmed properly [34].

The 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 [47]. The app will give the users some points and increase their level of involvement the more they use the functions of the application. Users of the app can also receive and share energy efficiency tips [48].

Social Power Game is designed to provide a collaborative platform amongst neighbours so that they can participate in teams for completing a task while receiving points for doing so. 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 [47].

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 visualisation on energy consumption and other data [49].

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 [50].

Less Energy Empowers You (LEY) is a gaming platform that challenges the users by encouraging them to use energy optimally in order to obtain maximum points. It also provides some quizzes that award additional points if completed by the user [51].

Wattsup is a Facebook-based application which provides ranking, rewards and comparison amongst friends on the basis of their energy consumption [52].

The enCompass and Funergy are other gamification platforms for energy saving which utilise data collection sensors including user data, data analytics, action recommendations, and a programmable gamification system [53]. 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 [47,54].

### *2.5. Costing Components and Objectives for VPPs*

The cost modelling for VPPs is critical to understanding 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 Investments

One part of the costs of a VPP is its investments in PVs, energy storage, smart appliances and electrical system infrastructure to participate effectively in the electricity market and engage customers [55]. Monitoring and control infrastructure are also essential to collect the relevant data for justifying the benefits of an implemented system, for which government incentives will assist in some cases [56].

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 $i$, the following formula is utilised.

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

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

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{2}$$

2.5.2. 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 [57]:

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 when and how much electricity is used.

The 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 3, for example [33]. 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 3, the forecast electricity price is also available in order to enable participants to bid their generation into the WEM.

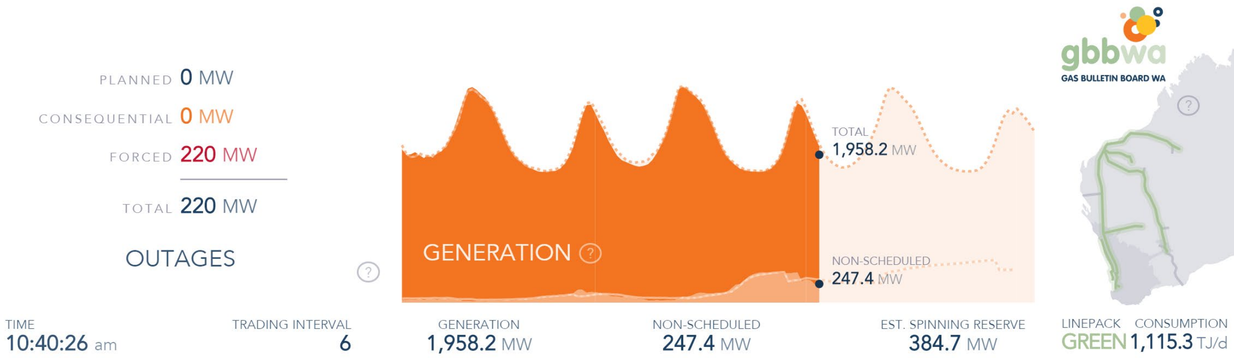


**Figure 3.** The dashboard for the wholesale electricity prices for Western Australia [33].

- 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 [57]:

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 the market procedure for determining loss factors [57]. The average distribution loss factor is evaluated based on losses in substation transformers, transmission and distribution feeders and distribution transformers, where relevant [58]. 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, this loss factor will also 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 a 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 [59]. To support the renewable integration and the 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 in 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:

$$\begin{aligned} Objective\ Function &= Total\ NPV\ Profit \\ &= Total\ NPV\ Revenue - Total\ NPV\ Expenses \end{aligned} \tag{3}$$

The revenues of a VPP comprise different components, including services to the electricity market, such as selling energy and ancillary services, and also selling energy to customers within the VPP [60,61]. In some cases, there are some incentives and grants from the 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 storage, 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 [62]. Also, the participation in the electricity market sometimes has some constraints [63,64], 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 [27].

To achieve the commercial and economic goals for a VPP owner within the regulatory constraints, information and communications technology (ICT) plays 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 [60,61]. The details of the concept design of the control and monitoring system are provided in [65].

*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 [27]. The requirement of the electricity market is also defined based on what the VPP produces and the biddings for several time intervals 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 the market, the VPP will win the optimal amount [66].

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, etc. [35]. 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:

$$\begin{gathered} Objective\ function = VPP's\ profit = NPV\ revenue - NPV\ expenses \\ Subject\ to\ : \begin{cases} VPP's\ constraints \\ Consumers'\ constraints \\ Market\ constraints \end{cases} \end{gathered} \tag{4}$$

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, etc. [39,67,68]. Another category of methods is the heuristic-based methods such as particle swarm optimisation (PSO), genetic algorithm (GA), etc. [36,69].

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 and identified using selection algorithms such as the Pareto principle [35]. 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 VPP.

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 [70]. In addition, a bidding strategy that does not need any pre-assumptions on the PDF of random variables, using combined optimisation, is studied in [71]. 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 [71,72]. 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 [58]. There are some approaches that provide hybrid stochastic/robust optimisation [73] 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 and 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 [74]. 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 [75] Moreover, a two-stage procedure, based on robust optimisation, is proposed in [76]. 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.

Moreover, stochastic programming is used for the self-scheduling procedure within a VPP. The uncertainty of 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 [77]. Also, a non-linear maximisation 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 [78]. Another method is the information gap theory, which is used to schedule different energy resources within a VPP [79]. In addition, the uncertainties in electricity prices and renewable resources are modelled through a robust coordination of energy resources in [80]. Moreover, a two-level robust dispatching model for available resources in a VPP can be designed to reduce the costs of the VPP [81].

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 resources [55]. 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 [66]. A fuzzy-based decision-making procedure, which incorporates a novel "insecurity" metric based on human psychology, is also developed for the bidding strategy [82]. 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 [36]. Moreover, the heuristic algorithm of the grasshopper optimisation algorithm is utilised for the frequency control as an ancillary service by a VPP [83]. As discussed in [20,84], 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 [85]. 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 [85].

There are many ancillary services in the WEM, which are managed by AEMO. These ancillary services, as described in the "wholesale electricity market rules" [84], 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 services are procured by lateral contracts.

### 2.7. Uncertainty Modeling

As there are uncertainties in demand profiles, renewable generation 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 [86].

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 [76,87].

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 [35,88]. 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 optimal for the VPP [41,67].

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.

## 3. Grid-Forming Inverters

As discussed previously, the number of distributed energy resources such as renewable resources, energy storage systems and electric vehicles experienced a sharp increase in recent times [89]. These distributed energy resources produce/draw direct current (DC), and they require a device for converting DC to alternating current (AC) in order to connect to existing networks. Inverters are the usual interface for interconnecting distributed energy resources with the network [90]. Generally speaking, in the past, grid-following (GFL) inverters were used to interconnect such resources with the network [91]. Although GFLs provide high-quality power to the network, they suffer from several operational restrictions. One of the challenges associated with GFLs is the zero-inertia characteristics that make controlling them difficult, which decreases the inertia of the entire network. If the inertia of the network decreases, the reliability and stability of the network decreases [92]. In order to compensate for the limitations of GFL, Grid-forming (GFM) inverters have been recently introduced. GFM inverters are developed based on voltage source inverters, which threaten the inertia of the network less because GFMs can regulate their voltage and frequency. It means that GFMs possess a self-synchronisation which leads to supporting the voltage, frequency and inertia of the whole network [93]. Table 2 provides a comparison of the capabilities of GFM and GFL.

**Table 2.** The capabilities of GFL versus GFM [92].

| GFL Inverters | GFM Inverters |
|---|---|
| Current-based inverters | Voltage-based inverters |
| Phase angle and current regulation. | Regulating the voltage's frequency and amplitude |
| Conforming to network | Tweaking the network's voltage and frequency |
| The management of both active and reactive powers | Immediate load balancing |
| - | Functioning with a weak grid and in islanding mode |
| - | System inertia is supported by this |
| - | Ability to start in black box |

From Table 2, it can be deduced that VPPs should be handled by GFM inverters because of several reasons which are discussed as follows. To begin with, VPPs are operated in both islanded and grid-connected modes, so GFM facilitates the implementation of these modes. In addition, in the grid-connected mode with VPP participation in energy markets, GFM inverters do not jeopardise the main network inertia and even strengthen the inertia of the network. As a result of these tremendous advantages, GFM inverters are the preferred alternative for grid-forming VPPs.

## 4. Concept of a Grid-Forming VPP

As discussed in the previous section, grid-forming inverters are used to connect dispersed resources into a unique resource and convert it to Alternating Current (AC). The design of a grid-forming inverter is illustrated in Figure 4 [94]. As can be seen, the PV modules generate direct current power by receiving energy from the Sun. The generated power may have a low/high level of voltage which can be controlled by DC-DC inverters [95]. Then, the regulated voltage from the DC-DC inverters is connected to DC-AC inverters in a DC link [96]. Eventually, the AC power is transmitted to the power grid by step-up transformers. This GFM inverter enables us to simultaneously convert DC to AC and inject/absorb reactive power into the network.

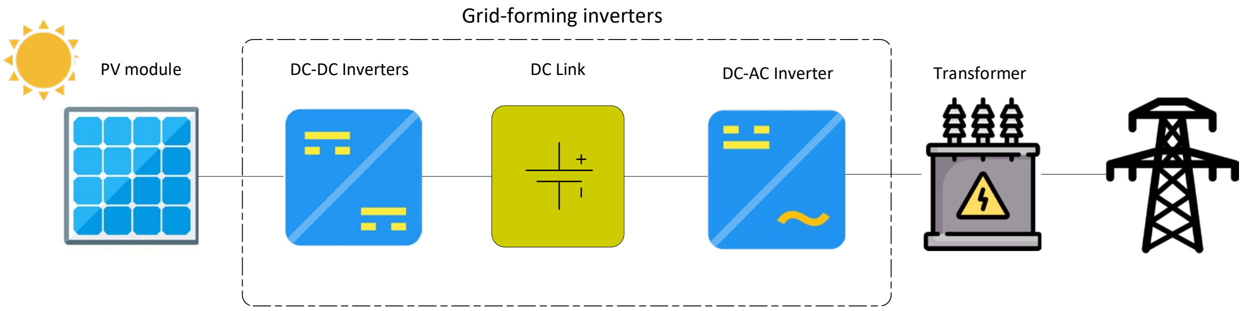


**Figure 4.** Schematic of grid-forming inverters.

The above diagram, for a grid-forming inverter, can be extended to develop a grid-forming VPP. A schematic is illustrated in Figure 5. As can be seen from this procedure, houses are equipped with solar panels. The generation of these panels is connected to the VPP control center by means of a grid-forming inverter. Inverters convert the DC power generated by the PV sources into AC form. The AC power is used to supply consumers, and extra power is sold to the main grid. It should be noted that the GFM inverter can also absorb/inject reactive power into the network.

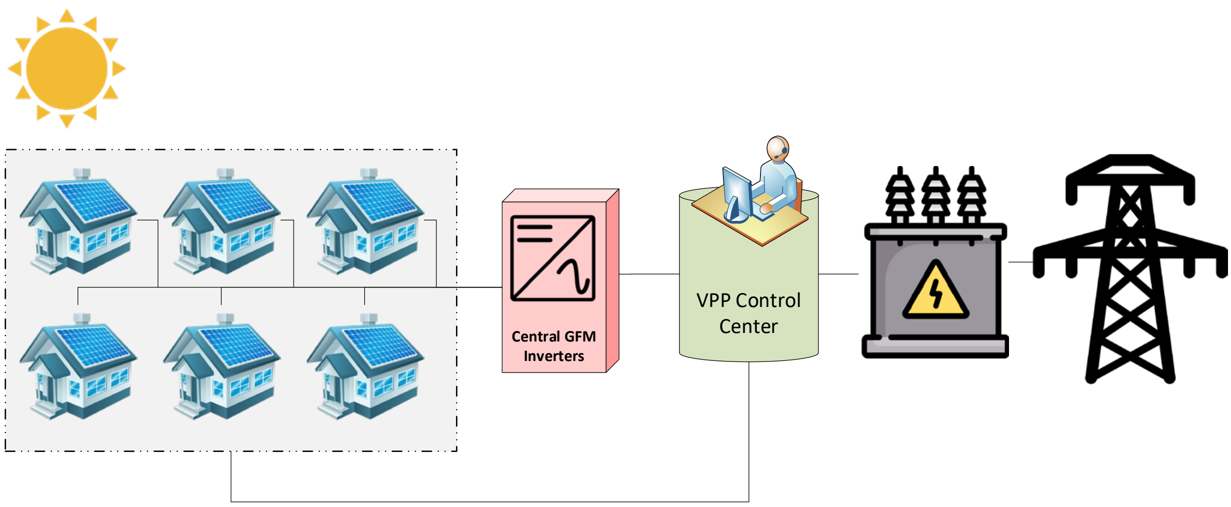


**Figure 5.** Schematic of a grid-forming VPP without energy storage.

It is notable that PVs have intermittent generation, meaning that they only generate over specific times, for roughly 8–18 h each day. Accordingly, energy storage systems can also be integrated into the network in order to increase the flexibility and stability of the VPP. Figure 6 illustrates a grid-forming VPP in the presence of an energy storage system. This is an example of a clean VPP. It should be noted that diesel generators could also be integrated to increase the flexibility and reliability of the VPP. However, they produce greenhouse emissions, so their use should be minimised and they should only be used as a backup source for emergency situations.

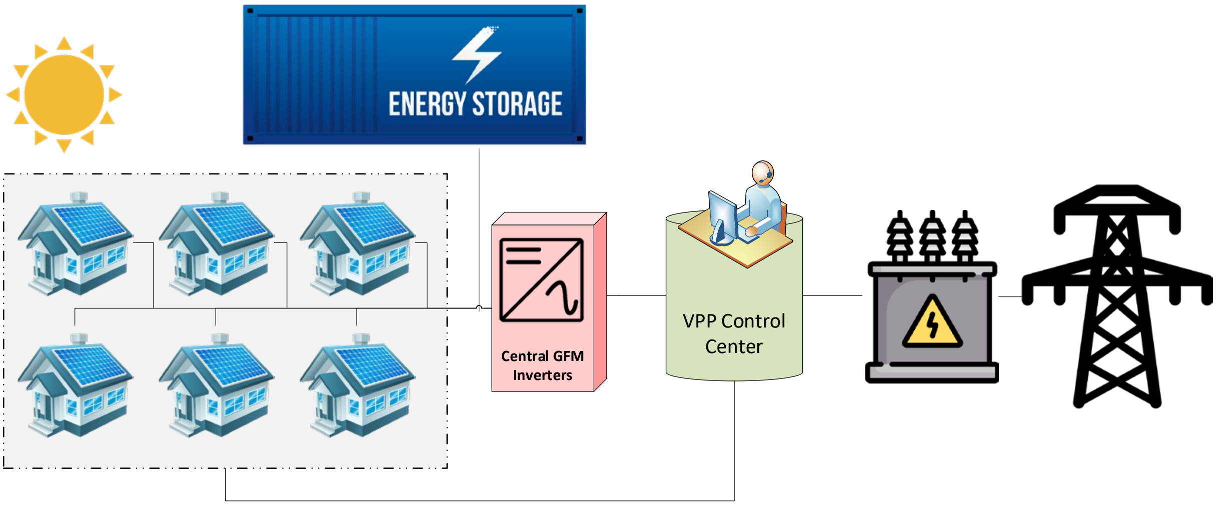


**Figure 6.** Schematic of a grid-forming VPP with energy storage.

It is worth noting that recently, grid-forming inverters have become available in various sizes and could easily be used to create a grid-forming VPP. For example, Tesla has provided utility-scale inverters which can facilitate the design of grid-forming VPPs.

## 5. Problem Formulation

The aim of VPPs is to maximize their profit, and this can be considered via an objective function as follows. Equation (5) illustrates this objective function, which is revenue minus the operational costs. The revenue is also calculated by Equation (6), which is the amount of energy sold to the market minus the purchased energy from the market. The operational costs can be calculated by Equation (7), which is the operational cost of the distributed generation resources and energy storages [97,98].

$$Maximize\ [profit] = Revenue - Operation\_Cost \tag{5}$$

$$Revenue = \sum_{t\in\Omega_{time}} C^t_{DA} P^t_{sell} - \sum_{t\in\Omega_{time}} C^t_{DA} P^t_{buy} \tag{6}$$

$$Operation_{Cost} = \sum_{t\in\Omega_{time}} C^t_{OC} P^t_{PVs} + \sum_{t\in\Omega_{time}} C^t_{DA}\left(P^t_{ch,ess} - P^t_{dis,ess}\right) \tag{7}$$

where $C^t_{DA}$ is the day-ahead market price. $P^t_{sell}$ and $P^t_{buy}$ are respectively the amount of energy sold and bought from the market. $C^t_{OC}$ is the operational cost of PVs. $P^t_{PV_s}$ represents the energy generated by the solar panels.

Along with the aforementioned objective functions, some constraints must be satisfied for secure operation of VPPs. Constraints in Equations (8) and (9) demonstrate the boundaries of reactive power which PV inverters can provide. Energy storage also has some constraints, such as the rate of charge/discharge, which are satisfied by Equations (10)–(14).

Power balance is also another item which is considered in this investigation by Equations (15) and (16), respectively [99].

$$Q_{PV}^{p,t} \leq \sqrt{\left(S_{PV}^{p}\right)^{2} - \left(P_{PV}^{p,t}\right)^{2}},\ \forall t \in \Omega_{time},\ \forall p \in \Omega_{PV} \tag{8}$$

$$Q_{PV}^{p,t} \geq -\sqrt{\left(S_{PV}^{p}\right)^{2} - \left(P_{PV}^{p,t}\right)^{2}},\ \forall t \in \Omega_{time}, \forall p \in \Omega_{PV} \tag{9}$$

$$ESS^{e,t} = ESS^{e,t-1} + \eta_{ch} P_{ch,ess}^{e,t} \Delta t - \left(\frac{1}{\eta_{dis}}\right) P_{dis,ess}^{e,t} \Delta t\ \ ,\ \forall t > 1,\ \forall e \in \Omega_{ess} \tag{10}$$

$$ESS^{e,min} \leq ESS^{e,t} \leq ESS^{e,max},\ \forall t \in \Omega_{time},\ \forall e \in \Omega_{ess} \tag{11}$$

$$P_{ch,ess}^{e,min} \leq P_{ch,ess}^{e,t} \leq P_{ch,ess}^{e,max},\ \forall t \in \Omega_{time}, \forall \mathrm{e} \in \Omega_{ess} \tag{12}$$

$$P_{dis,ess}^{e,min} \leq P_{dis,ess}^{e,t} \leq P_{dis,ess}^{e,max}, \forall t \in \Omega_{time}, \forall \mathrm{e} \in \Omega_{ess} \tag{13}$$

$$ESS^{e,\mathrm{initial}} = ESS^{e,\mathrm{final}},\ \forall initial,\ final \in \{0,\ 24\}, \forall \mathrm{e} \in \Omega_{ess} \tag{14}$$

$$P_{PV}^{p,t} + P_{buy}^{t} + P_{dis,ess}^{e,t} = P_{ch,ess}^{e,t} + P_{L}^{t} + P_{Sell}^{t} +\ \ , \forall t \in \Omega_{time}, \forall p \in \Omega_{PV},\ \forall e \in \Omega_{ess} \tag{15}$$

$$Q_{PV}^{p,t} = Q_{L}^{t}\ , \forall t \in \Omega_{time}, \forall p \in \Omega_{PV} \tag{16}$$

$$V_{b}^{n,t} = V_{b}^{m,t} - \frac{\left(R_{L}^{mn,t} P_{flow}^{mn,t} + X_{L}^{mn,t} Q_{flow}^{mn,t}\right)}{\mathrm{V}_{0}},\ \forall t \in \Omega_{time},\ \forall n, \mathrm{m} \in \Omega_{bus} \tag{17}$$

$$\left(V_{b}^{min}\right) \leq V_{b}^{n,t} \leq \left(V_{b}^{max}\right),\ \forall t \in \Omega_{time},\ \forall n \in \Omega_{bus} \tag{18}$$

$$\left(P_{flow}^{mn,t}\right)^{2} + \left(Q_{flow}^{mn,t}\right)^{2} \leq \left(S_{flow}^{Max}\right)^{2},\ \forall t \in \Omega_{time},\ \forall n, m \in \Omega_{bus} \tag{19}$$

In the above expressions, $Q_{PV}^{p,t}$ is the reactive power of PV inverters. $S_{PV}^{p}$ shows the rating of PV inverters. $P_{PV}^{p,t}$ denotes the forecasted active power of PVs. $ESS^{e,t}$ is the state of charge of the energy storage. $\eta_{ch}$ and $\eta_{dis}$ signify the efficiency of charge and discharge, respectively. $P_{ch,ess}^{e,t}$ and $P_{dis,ess}^{e,t}$ are the amount of power charged/discharged, respectively. The boundaries of state of charge are represented by $ESS^{e,min}$ and $ESS^{e,max}$. Similarly, $P_{ch,ess}^{e,min}$ and $P_{ch,ess}^{e,max}$ illustrate the acceptable amount of battery charging. The battery discharge is also limited by $P_{dis,ess}^{e,min}$ and $P_{dis,ess}^{e,max}$. $ESS^{e,\mathrm{initial}}$ is the state of the charge of the battery at time 0. $ESS^{e,\mathrm{final}}$ is the state of the charge at hour 24. The voltage of the network is also modeled by Equations (17)–(19).

GFVPP also brings benefits for power system dynamics [100–103]. In particular, the use of grid-forming VPPs has a major impact on the dynamics of the power system, with a high level of renewable integration. Renewable energy resources contribute to the uncertainties in power generation and to the reduction of inertia in power systems. These two critical factors increase the chance of instability of renewable-rich power grids. Grid-forming VPPs provide a solution to both of these problems. GFVPPs can reduce the uncertainties associated with renewable generation by effectively using internal demand and energy storage, so that they smoothen the fluctuations from such resources. Moreover, GFVPPs add to the inertia of the grid by providing more energy storage to the grid with smart scheduling control systems, which reduce the chance of instability in power systems.

## 6. Simulation Results

Figure 6 illustrates a VPP which has PV generation and central energy storage. This VPP has been connected to the market and can interact with the network. A typical load demand of a VPP located in Western Australia is utilised. The load demands for different seasons are shown in Figure 7. The daily market price is also depicted in Figure 8. The forecasted PV generation is shown in Figure 9, which is linked to the VPP by an inverter with 1 MVA rating. The PV inverter is utilised to supply the demand shown in Figure 7. An energy storage with a rating of 500 kWh is also included. The information associated with this VPP is provided in Table 3. The results are provided for four seasons as follows.

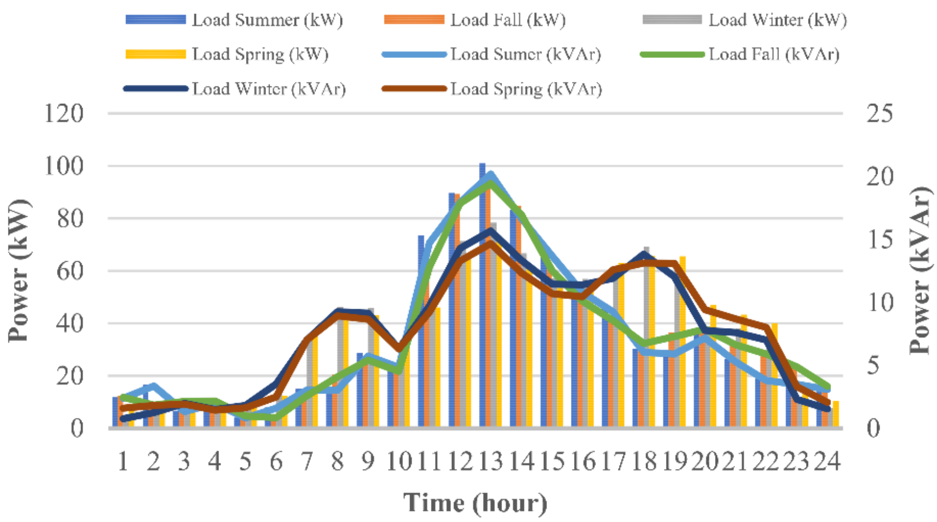


**Figure 7.** The daily load demand for 4 seasons.

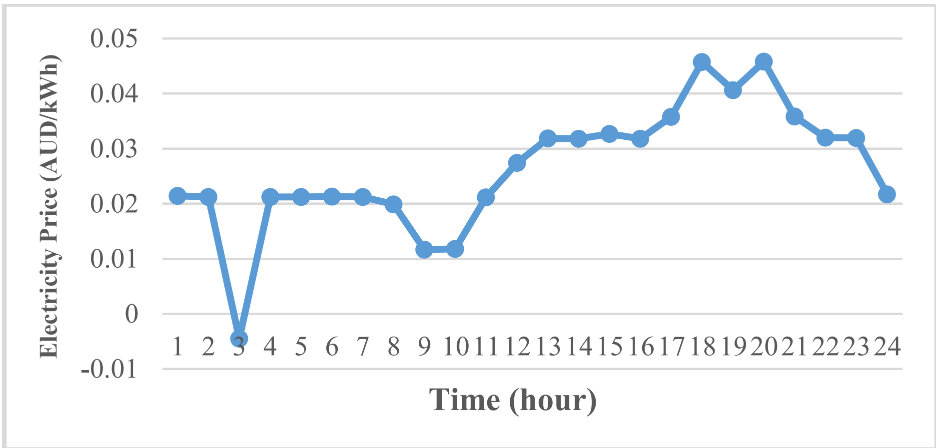


**Figure 8.** The wholesale market electricity price.

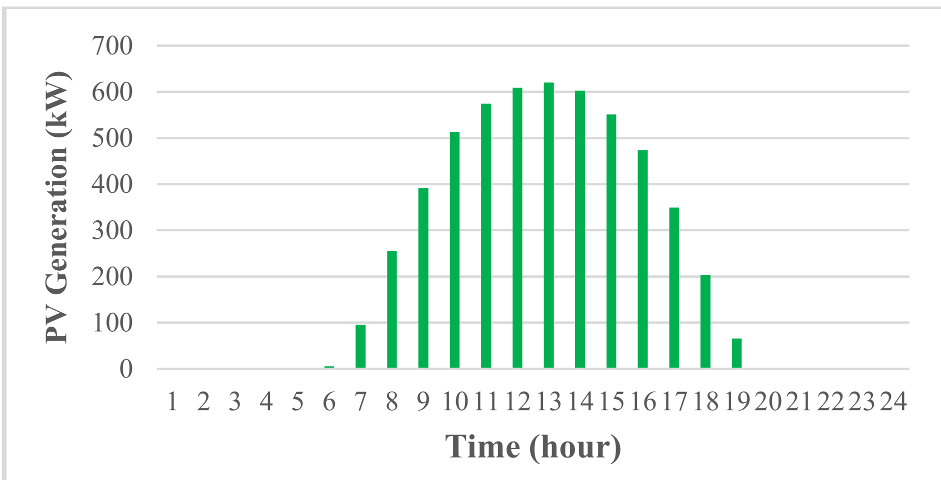


**Figure 9.** The daily PV generation.

**Table 3.** Description of the single bus grid-forming VPP.

| | |
|---|---|
| PV size | 810 kW |
| Inverter size | 1 MVA |
| Battery size | 500 kWh |
| Forecasted values of PV | Provided in Figure 7 |
| Energy price | Provided in Figure 8 |
| Forecasted load | Provided in Figure 9 |

The daily bidding power for the summer load profile is shown in Figure 10. As can be seen from this figure, the VPP sells the excess power to the main grid in [8–18] hours interval. In other words, the surplus power from PV at hours [8–18] is sold to the grid. In addition, the battery is also charged in the intervals where the price is low and then released at hours where the market price is high. This, in turn, could help to increase the profitability of the VPP.

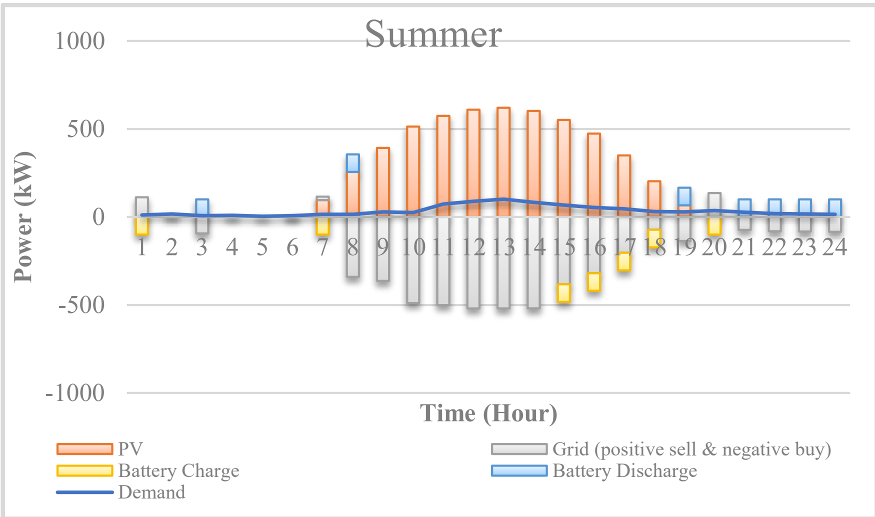


**Figure 10.** The bidding power of the VPP in summer.

Reactive power support by means of PV inverters is also another variable which is optimised based on the VPP requirement. The amount of inverter power provided by the inverter for summer is illustrated in Figure 11. It is clear that the reactive power demand of the VPP is completely met by the PV inverter.

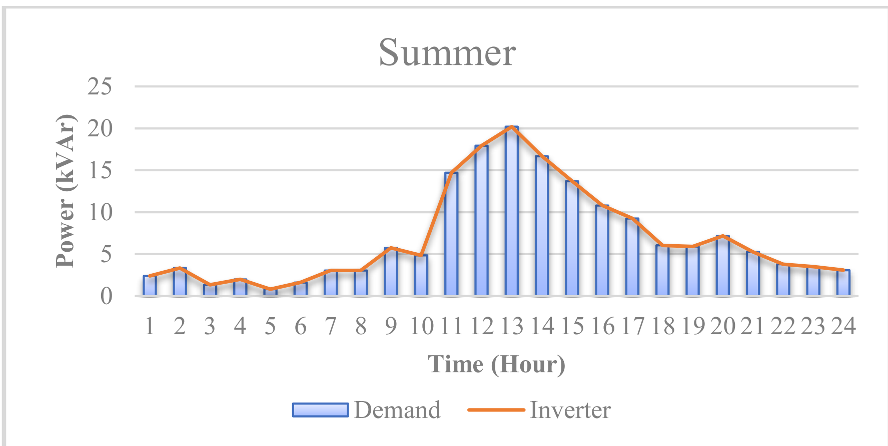


**Figure 11.** The reactive power support by smart inverters in summer.

Figure 12 displays the daily bidding power for the fall season. This bar chart illustrates how the VPP sells extra electricity to the main grid at intervals, when it has extra generation. To put it differently, the grid buys the extra electricity generated by PV during hours [8–18]. Batteries are additionally charged during intervals when the price is lower and then released during periods when the market price is higher. This can therefore contribute to raising the VPP's profit.

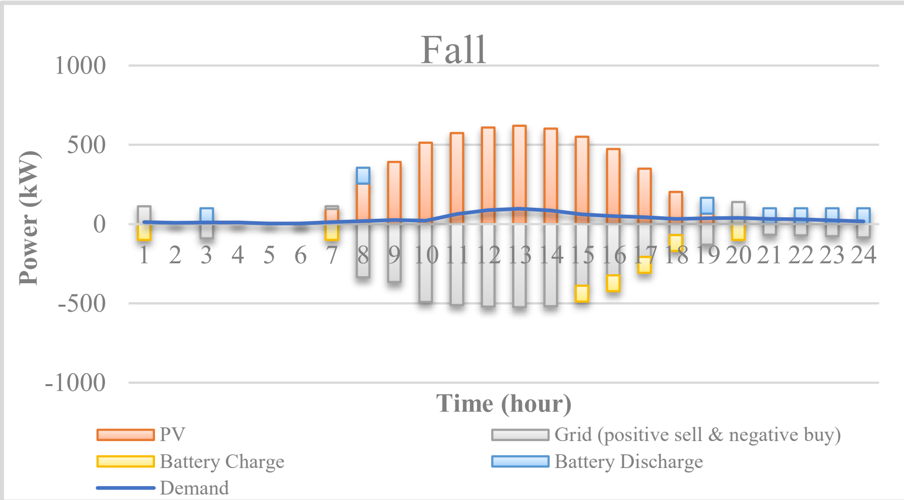


**Figure 12.** The bidding power of the VPP in fall.

Another variable that is optimised based on the VPP need is reactive power support via PV inverters. Figure 13 shows the provided reactive power from the PV inverter. From this, it is clear that all reactive demand is supported by the PV inverters.

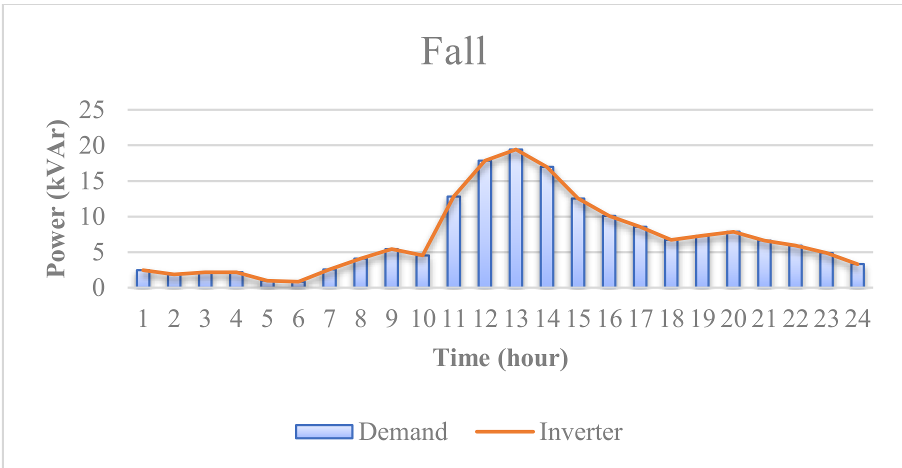


**Figure 13.** The reactive power support by smart inverters in fall.

The daily bidding power for the winter season is shown in Figure 14. This bar graph demonstrates how the VPP periodically sells additional power to the main grid due to extra generation. In other words, the grid purchases any excess power produced by PV during the hours [8–18]. During times when the price is lower, batteries are charged and then released during times when the market price is higher. Therefore, this may contribute to increasing the VPP's profit.

Reactive power support through PV inverters is another factor that is optimised depending on the VPP's need. Reactive power from the PV inverter for winter is shown in Figure 15. It is clear from this that PV inverters support the entire reactive power demand.

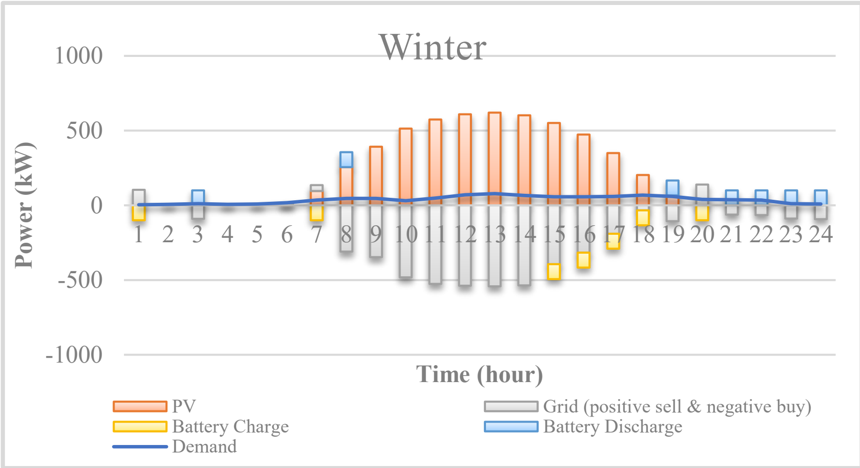


**Figure 14.** The bidding power of the VPP in winter.

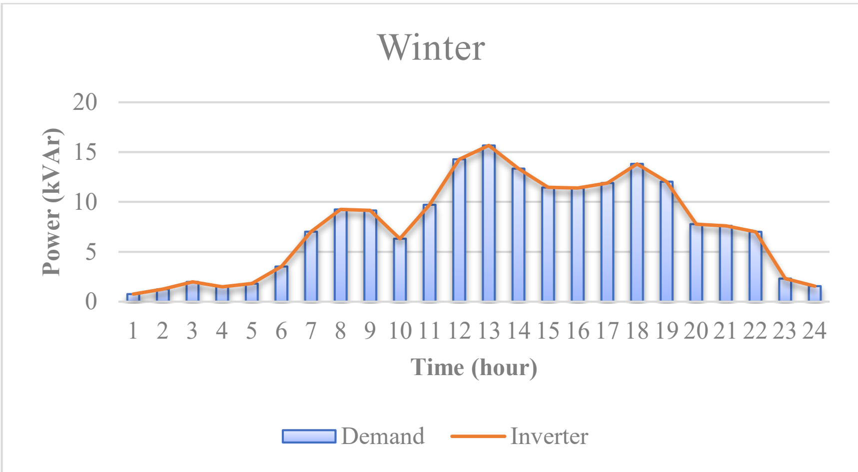


**Figure 15.** The reactive power support by smart inverters in winter.

Figure 16 illustrates the daily bidding power over the spring season. This bar graph illustrates how the VPP offers more power to the main grid as a result of increased generation. In other words, the grid buys any extra energy generated by PV throughout the [8–18] hour period. Batteries are also charged during periods of low market price and then released during periods of high market price. As a result, this assists the VPP to generate more income.

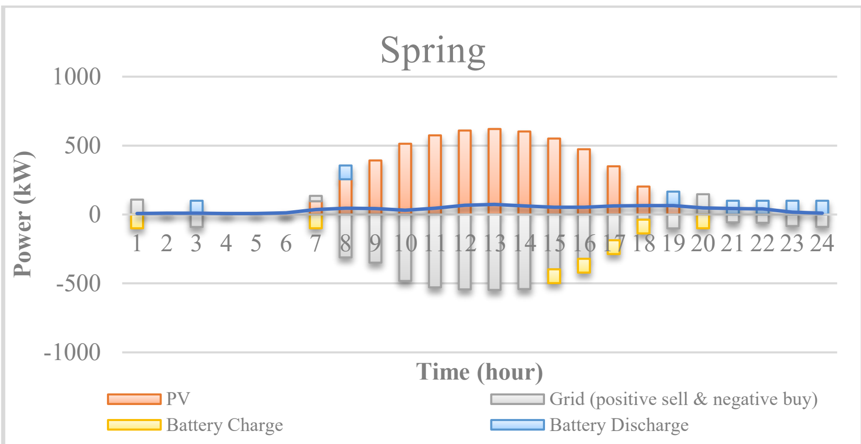


**Figure 16.** The bidding power of the VPP in spring.

Another aspect that is optimised depending on the VPP's need is reactive power assistance provided by PV inverters. Figure 17 displays the PV inverter's reactive power over the spring. This shows that the full reactive power demand is supported by PV inverters.

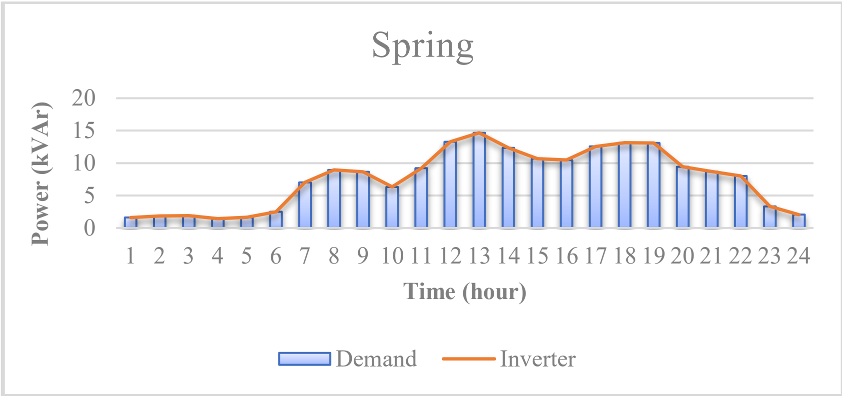


**Figure 17.** The reactive power support by smart inverters in spring.

The amount of profit which a VPP can achieve is summarised in Table 4. As can be seen from this table, the model VPP could achieve a daily profit of $115/day. In other words, it can be approximately $40 k over a year. From this it can be concluded that VPPs bring a lot of advantages, such as reactive power support, profit maximising, etc.

**Table 4.** The summation of profit of the model VPP for different seasons.

| Seasons | Summer | Fall | Winter | Spring |
| --- | --- | --- | --- | --- |
| Summation of Profit over day ($/day) | 118.7 | 118.2 | 115.9 | 115.6 |

The effect of the PV inverter on the voltage profile of the network is also investigated here. In order to recognise what impact the PV inverter may have on the controlling voltage, the reactive power demand is increased at some hours. The voltage profile of the VPP is illustrated to distinguish it from the controlling voltage of the PV inverters. Here, the reactive power demand of the VPP rises/decreases at hours 5, 10 and 15. The results for summer are provided in Figures 18 and 19. From these figures, it is clear that the voltage at each of these points leveled out over the period, meaning that PV inverters can maintain the voltage of the VPP within acceptable ranges by injecting/absorbing reactive power, as shown in Figure 19.

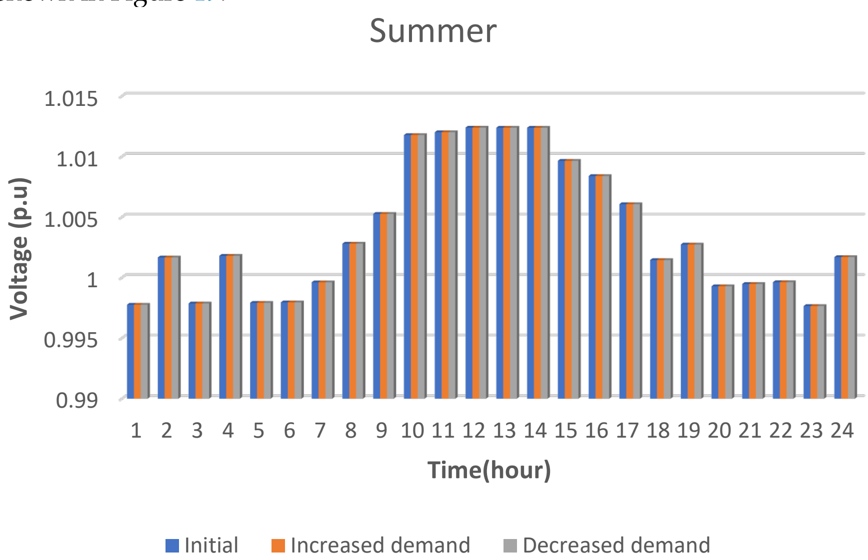


**Figure 18.** The voltage of the VPP in summer.

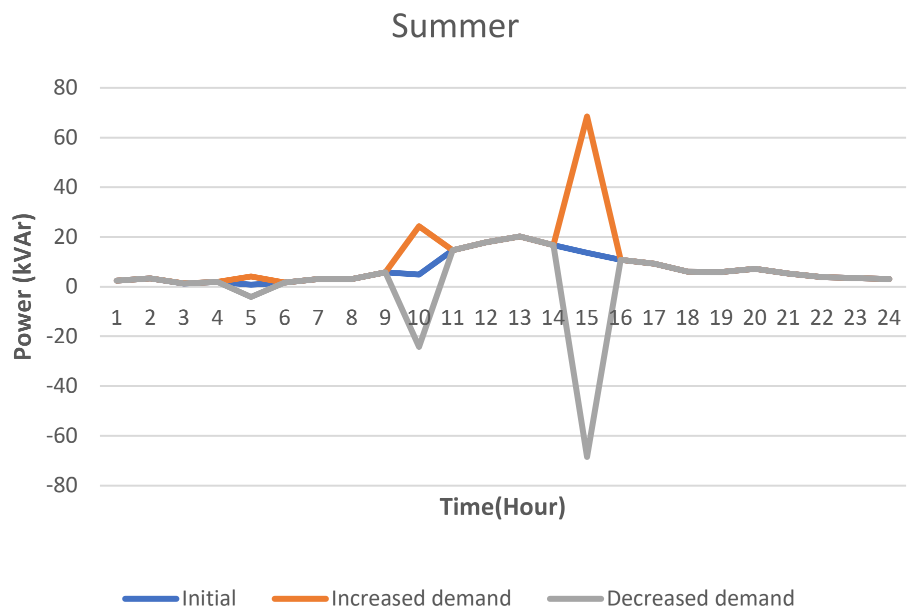


**Figure 19.** The reactive power provided by smart inverters in summer when demand varies.

## 7. Discussion and Conclusions

Power systems are undergoing a revolution due to the introduction of new technologies, concepts and designs. Recently, by realising the merits of VPPs, this is becoming much more appealing around the world. This paper, consequently, has provided a comprehensive review of this emerging technology. In addition, the concept of grid-forming virtual power plants was also introduced, meaning that solar energy is integrated into the network by smart inverters. Smart inverters enable VPP operators to support the reactive power of the VPP as well as inverting the DC current to the AC form. After that, the problem formulation with the aim of profit maximization for the VPPs has been developed in the presence of smart inverters. Finally, the concept was simulated for a VPP in Western Australia. From this investigation, some conclusions can be derived, as listed below:

- The reactive power demand of a VPP can be completely supplied by smart inverters;
- The profit of a VPP is maximized by selling the surplus power to the main grid;
- The energy storage was charged in intervals when the market price was less and then released in times when the price was high.

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 work, 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.

In this investigation, a grid-forming VPP was considered so that a large number of PV panels could be combined though an inverter. Although the main goal of a PV inverter is to invert DC to AC power, it can also be used as a reliable reactive power source to support the network. In other words, PV inverters could supply the reactive power demand as well.

After developing the grid-forming VPP concept, a bidding strategy was developed. The results implied that the VPP could maximise its profit by selling excess power into the main grid. In addition, central energy storage had a vital role in charging at a lower price and selling at a higher price.

There are several other topics in terms of grid-forming VPPs which need further research, including:

- The bidding strategy for VPPs under uncertainties is an open topic which needs to be investigated to reveal how much profit is decreased/increased if uncertain parameters violate their forecasted values;
- Power quality-oriented VPP operation is also another important factor needing further investigation;
- Reliability-based grid-forming VPPs are another important area for further investigation.

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