

Article

Advanced Monitoring and Control System for Virtual Power Plants for Enabling Customer Engagement and Market Participation

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Abstract: 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 paper, 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), an electric vehicle (EV) charging station, 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 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 paper have the capability of being implemented fully and relevant references for practical devices are given where necessary.

Keywords: photovoltaic generation; monitoring system; virtual power plant; control system; flow battery; EEBUS; distribution network; heat pump; demand side management; cloud-based computing; fog-based computing



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1. 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 [1]. Virtual power plants (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 [2]. It is forecasted that the total installed VPP capacity in Australia by 2022 would be 700 MW. The associated regulations, requirements and procedures for the participation of VPPs in the wholesale electricity market (WEM) are now in place in Western Australia (WA) [3] 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 has already been achieved [4]. 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 [5].

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 [6]. 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 [7]. 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. The VPP owner can also 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 [8]. Further, the operation of a renewable plant within a VPP context can produce 12% more profit for the VPP owner in Scotland [9]. The cost and benefit analysis of VPPs in Germany also demonstrates an increase of 11% to 30% by 2030 in the VPP's revenue by participating in the electricity market [10]. Moreover, renewable-based VPPs can affect the price of electricity in the WEM in the long-term [11] and contribute to the efficient operation of the electricity grid [12].

Local energy communities have a great potential to be platforms 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 maximize 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 in Italy, which shows a reduction in energy purchased from the grid and in the energy costs to the consumers [13]. Also, a fair method is proposed for the cost/profit allocation of shared infrastructure in a local energy community [14,15]. 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 contribution, a decentralized market based on a genetic algorithm is developed to facilitate the expansion of local energy communities [16]. By optimizing the load profile of customers within a community, there is an opportunity to enhance the self-consumption of PV generation, as discussed in [17]. 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 [18]. 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 [19]. The outcomes of this approach illustrate good planning of the community energy system with optimal operation. Neighbourhood trading amongst a local community also shows a positive effect in reducing the total costs of community planning [20]. Moreover, to handle uncertainties

of PV and load for community energy planning, robust optimization methods are very useful to handle such uncertainties [21].

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 [22] and to encourage them to engage with the requests from the VPP owner for demand shaping, appliance control, security and frequency control, and local power quality improvement [23]. This will help the VPP to participate effectively in the WEM to maximize 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 [24] and to the reduction of capital investment in the local utility [25]. One of the effective ways of engaging customers in DR programs is through the gamification of participation as discussed in detail in [26]. 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) provide the SigmaOne platform for optimizing the revenue of the VPP owner [27]. This platform can provide a cloud-based probabilistic forecast and stochastic optimization to maximize 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 also communicate with the home management system (HMS) to control some devices but no direct solution is provided for market participation by the customers through VPP [28]. The characteristics of a smart energy management information system (EMIS) for the built environment are discussed in [29] for improving energy efficiency and interior climate for a residence. In this work, different platforms such as Wi-Fi, Bluetooth Low Energy (BLE), Sigfox, narrowband Internet of Things (NB-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 [29]. There are also several energy/building management systems available in the market [30] 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 optimization of microgrid operation [31]. OATI GridMind is another platform for microgrid/VPP monitoring and optimization that can provide a smooth control system for multiple energy resources within a VPP [32]. The DER Optimization Software is a cloud-based and scalable management software for monitoring, communicating with, controlling, and optimizing the economics of energy resources within a VPP [33]. 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 cybersecurity protocol to protect the system from the growing threat of cyberattacks and to provide a user-friendly interface and scalability [34]. There is another cloud-based platform; the Prescient U10 Controller, for optimizing the lifetime of DERs and supporting the power quality as well [35]. 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 paper 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 paper 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 maximize the benefits of the consumers and the VPP owner by participating in the wholesale electricity market and customer engagement.

The paper is organized as follows. Section 2 provides the concept design configuration of the proposed VPP in WA. Section 3 presents the load monitoring and control of appliances in dwellings including customer engagement in the VPP. Section 4 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 5. The relevant conclusions are summarized in Section 6.

2. 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. It is expected that each household uses an EV as well. 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 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 [7,36]. 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 [7].

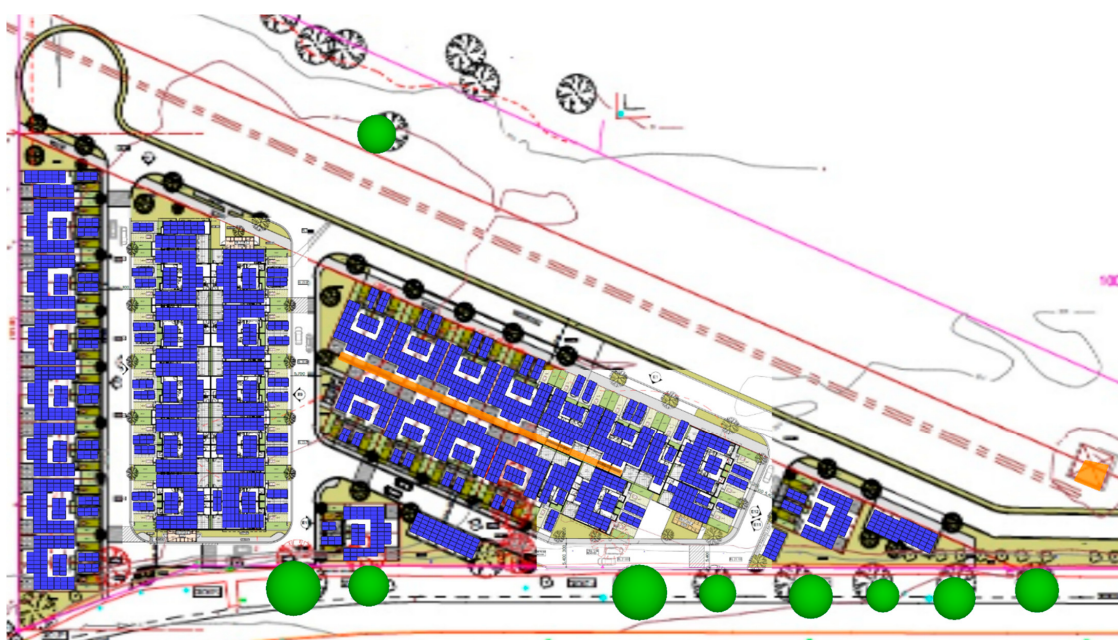


Figure 1. The proposed location of the virtual power plant (VPP) in Western Australia (WA).

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 [37]. The liquid is pumped between two tanks whose sizes determine the size of the VRFB. 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. It is also 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 [38].
- The fast charging and discharging capabilities that can play a positive role in the electricity network security and reliability [39,40]. It can also be charged to 100% of its capacity level with negligible self-discharge.
- The VRFB is a 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 [41].
- 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 [42]. 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 [43]. Moreover, the total life cycle energy cost can be reduced, for example by 40%, when using both electricity and thermal storage [44]. 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 [45,46]. Moreover, heat pumps can store thermal energy at a lower electricity price, which brings another advantage to the VPP [47]. In the VPP project in WA, a 220-L heat pump HWS is installed for each dwelling to maximize 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 [48]. The proposed HWS has an electricity consumption of 0.55 kW, which can provide heating of 1.6 kW on average to water at the ambient temperature between -5 to 42 °C. It seems that the efficiency is more than 100%, however, as demonstrated in Figure 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.

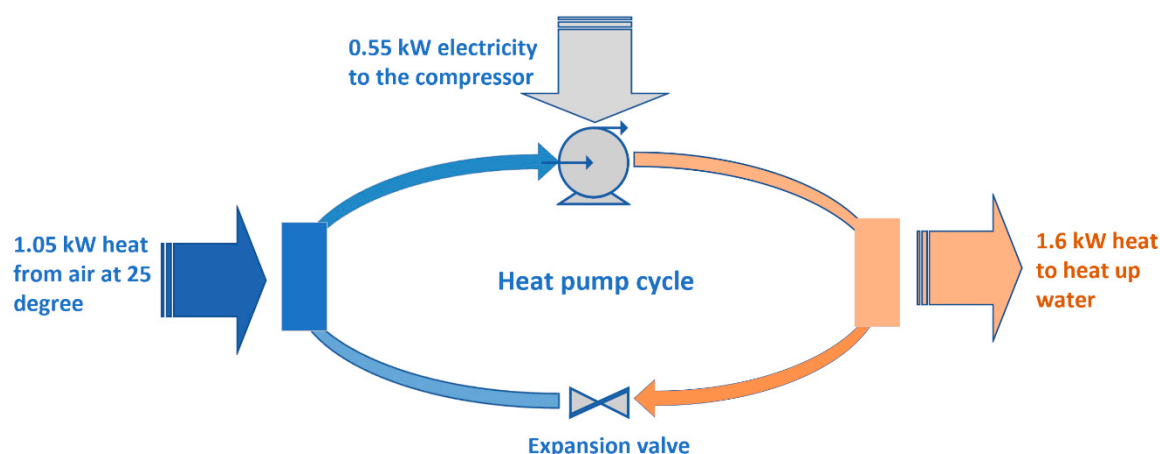


Figure 2. The schematic of energy movement in a heat pump.

Furthermore, the VPP is connected to the electricity grid and there is no gas in the complex. Figure 3 shows the overall configuration of the proposed VPP in WA. As seen in Figure 3, there is the main loop of 400 V low voltage (LV) network, but operated in radial, with controllable switches for maximizing the reliability of the 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 3. 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 residences. There is also a centralized VRFB connected to the main ring of the LV network of the VPP, as presented in Section 4.

Storage of data collected from all electric devices is managed in a fog-based storage system, as discussed in Section 5. All devices have a standalone cellular communication link to the cloud, as illustrated in Figure 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 is to use application programming interfaces (APIs) [49].

In the proposed configuration, the monitoring and control system is located on the cloud with access to different APIs such as electricity price forecast, weather forecast, etc. This system will optimize the battery charging/discharging and the customer load scheduling to maximize the benefits to the consumers and to the VPP owner, as discussed in Section 5.

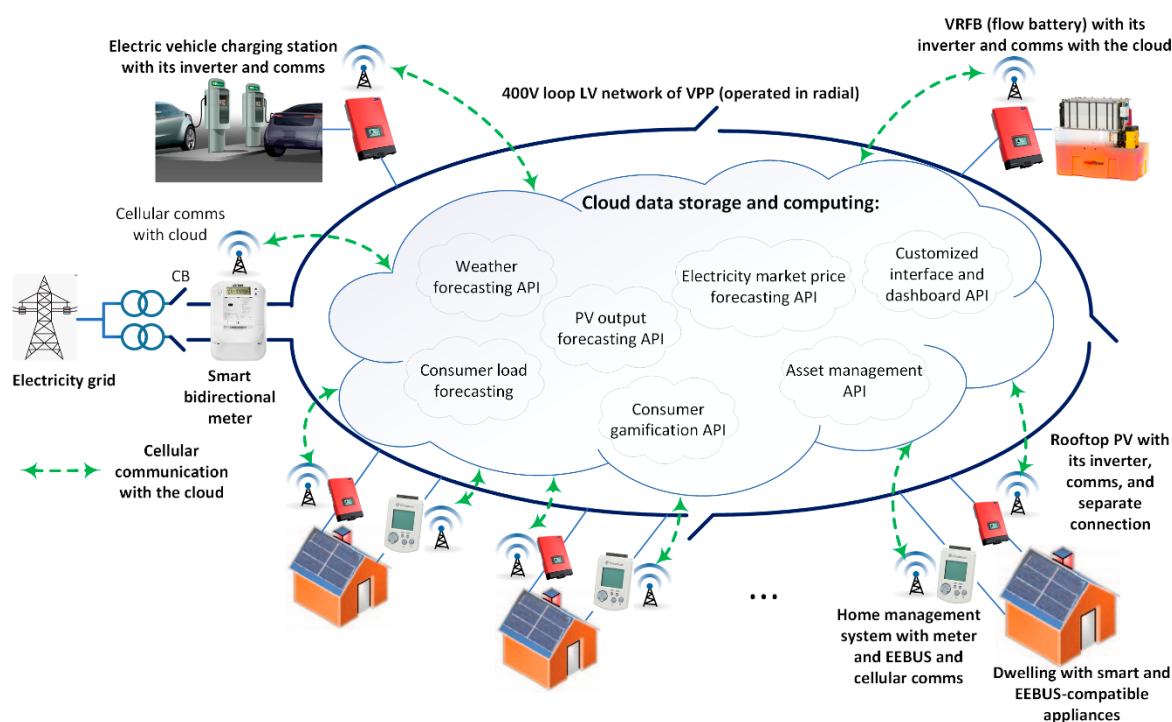


Figure 3. The proposed architecture of the VPP in WA. VRFB: vanadium redox flow battery; PV: photovoltaic; API: application programming interfaces (CB—Circuit breaker).

3. Consumer Load Monitoring, Control and Engagement

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

3.1. 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 [50]. 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 maximize the total benefit to the consumers and to the owner.

Figure 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 [7]. 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. If another appliance is added in the future for monitoring and control, this will also be easily implemented through the EEBUS protocol. The full specification of EEBUS is available online in [51]. 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 the European Committee for Electrotechnical Standardization (CENELEC) in the prEN 50631-1 specification [50,52]. The user applications of SPINE for different types of appliances and purposes are provided by the EEBUS initiative discussed in [50].

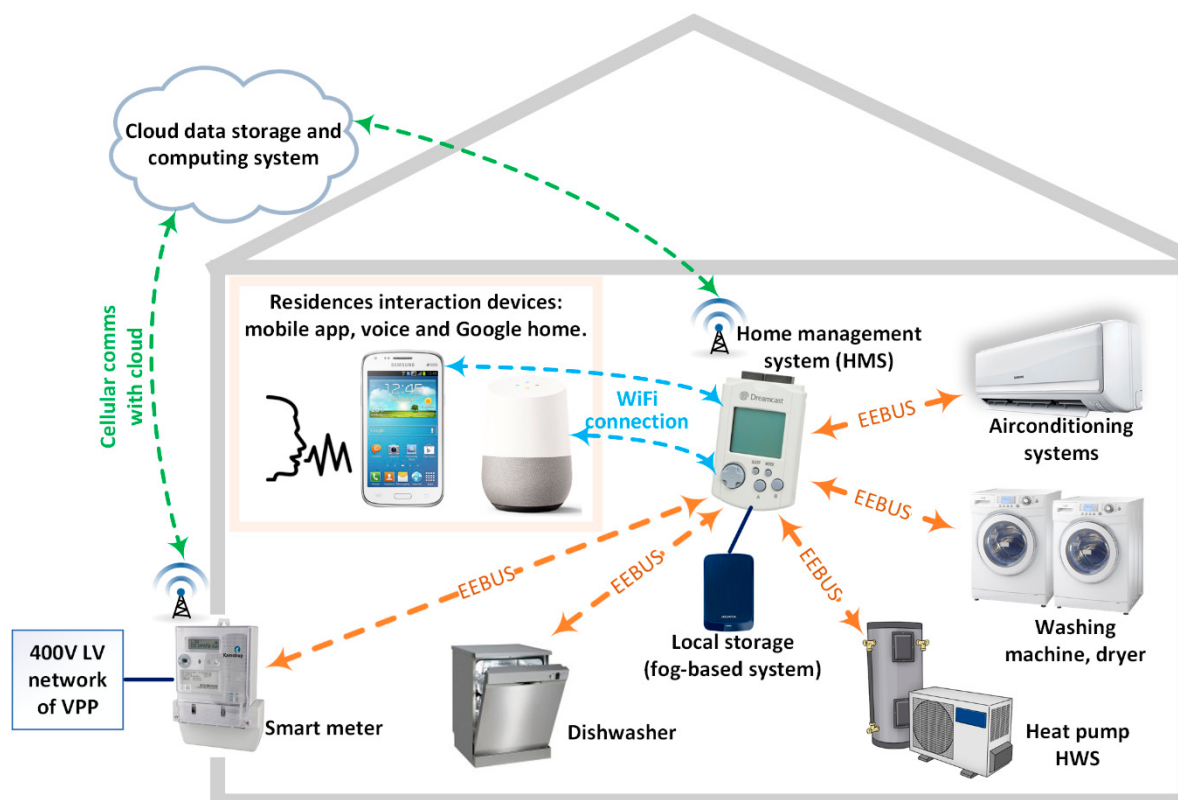


Figure 4. The proposed configuration of the monitoring and control system within each dwelling in the VPP. HWS: hot water system.

The incoming meter is also in communication with the local HMS through EEBUS, as shown in Figure 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 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 the HMS/smart meter and a cloud-based storage combined. The capacity of local storage is recommended to be for one-months' 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 sending it to the cloud, as illustrated in Figure 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 they are 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, LoRa, etc.

3.2. 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 [26]. 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 obtain 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 [26]. 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 behaviour 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 5. As seen, the optimization 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 optimization API. The customers, as the players, are classified as socializers, explorers, achievers, and express, as defined and explained in [26], so the gamified approach should be able to target all types of players to maximize the engagement. As presented in Figure 5, a collaborative/competitive game will be updated online for all users in which they need to accept the optimization API commands in order to help others and/or proceed faster ahead of others. This task will target specifically socializers and achievers. An exciting story about the contribution of customers and the effect on the community and the world will also 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 5. The customers can participate in all these gamified schemes and collect more points.

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 (TOU) of these appliances are presented in Table 1 as discussed in [26]. 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 optimization process as 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 whether to participate in that DM event or not. The residents are able to activate the automatic acceptance of some offers with some conditions.

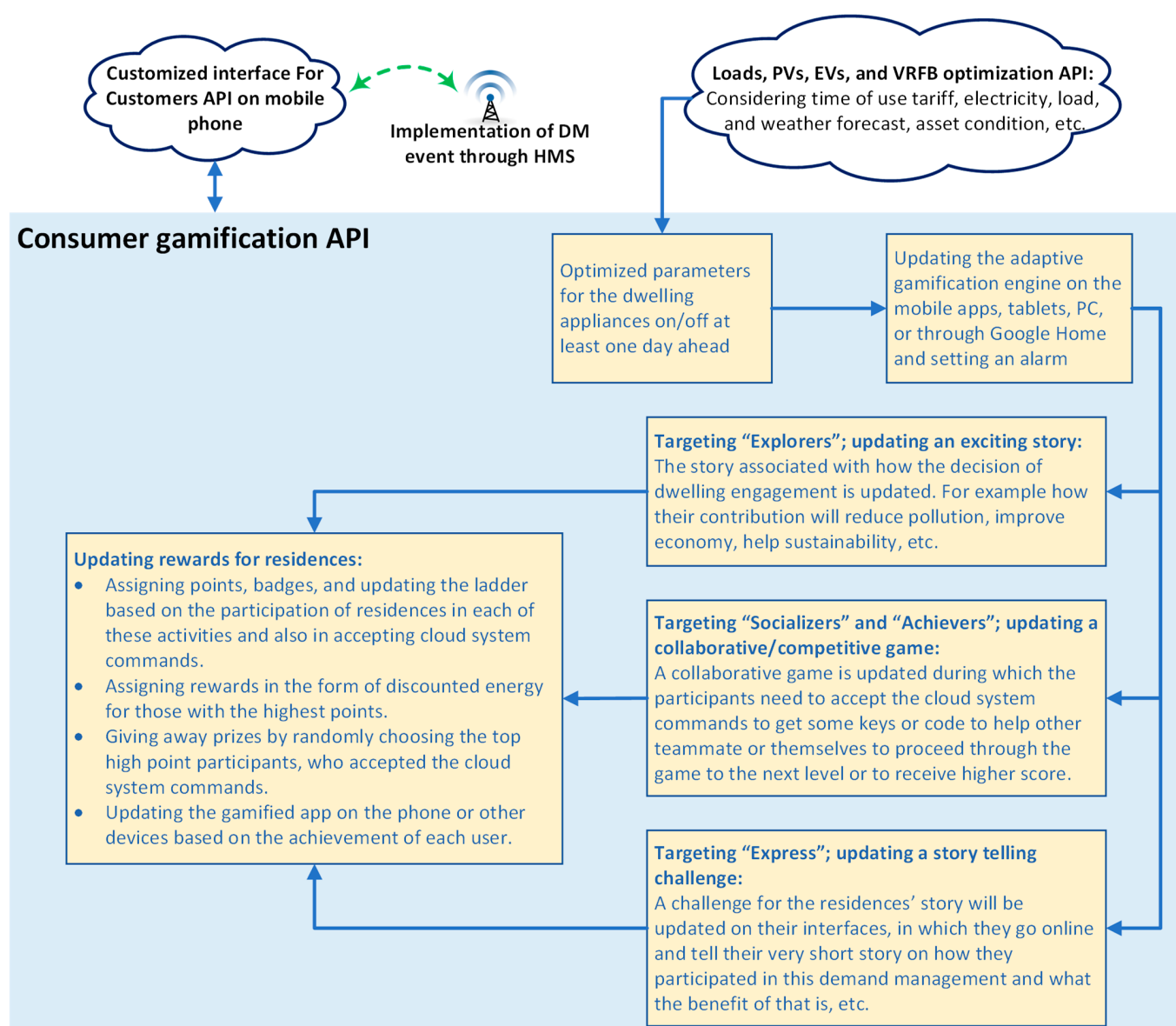


Figure 5. The proposed framework for gamification system for customer engagement. DM: demand management.

Table 1. Manageable/shiftable loads.

Appliance at the Dwelling	Initial Setting
Dishwasher	Working between 10 a.m. and 4 p.m.
Washing machine/Dryer	Not working between 3 p.m. and 9 p.m.
Heat pump HWS	Working between 9 a.m. and 5 p.m.
Air conditioner	Working between 10 a.m. and 4 p.m.

4. 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. Since the PV systems are the asset of the VPP owner, this approach will also 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. 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 Table 2.

Table 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 total harmonic distortion (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, etc.

As seen in Figure 6, each PV inverter at each dwelling has a communication link to the cloud through a cellular link. In the communication platform, a distributed system is also 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. The PV generation from each dwelling can also 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.

The minimum number of signals that usually need to be collected and sent to the clouds are listed in Table 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.

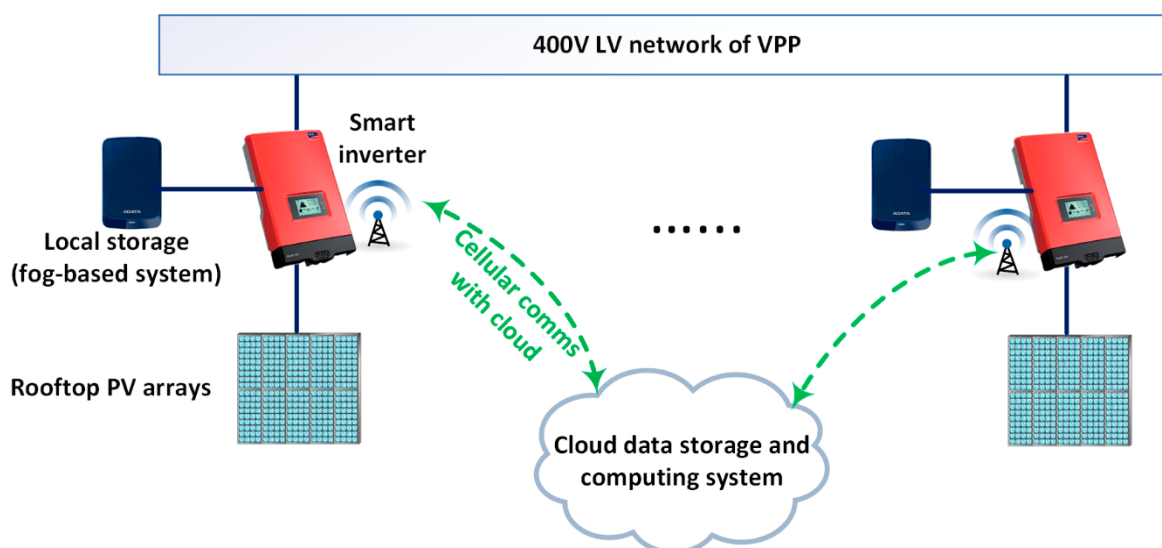


Figure 6. The proposed configuration of the monitoring and control system for PV systems in the VPP.

5. 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 the 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. 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 [53]. As seen in Figure 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 3. The HMS is responsible for controlling and responding to urgent and time-sensitive tasks such as fire/smoke or climate change inside a dwelling, including temperature, humidity, and lighting. The fog-device also 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.

The interface of the HMS is set up on a smartphone, tablet, or PC. The HMS is also 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. The user can also change the setting of devices and control temperature, lighting, etc. 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/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 3.2, will encourage all types of users to engage with the system and accept the commands as much as possible.

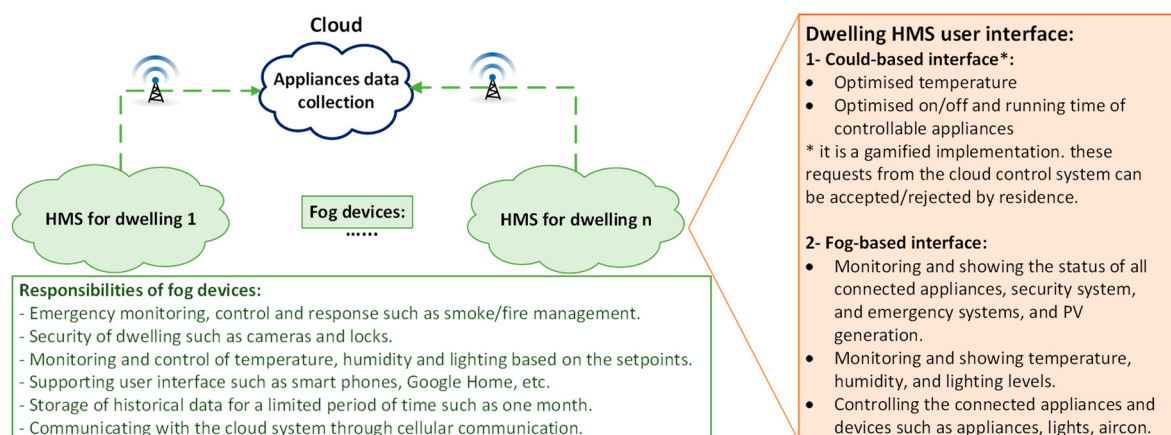


Figure 7. The proposed fog-based configuration and user interface for dwellings.

The schematic of the proposed cloud-based control and management system is presented in Figure 8. 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 optimization 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 [54].
- **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. It can also 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. The manager also needs to see the status of the assets and any recommended maintenance for implementation.

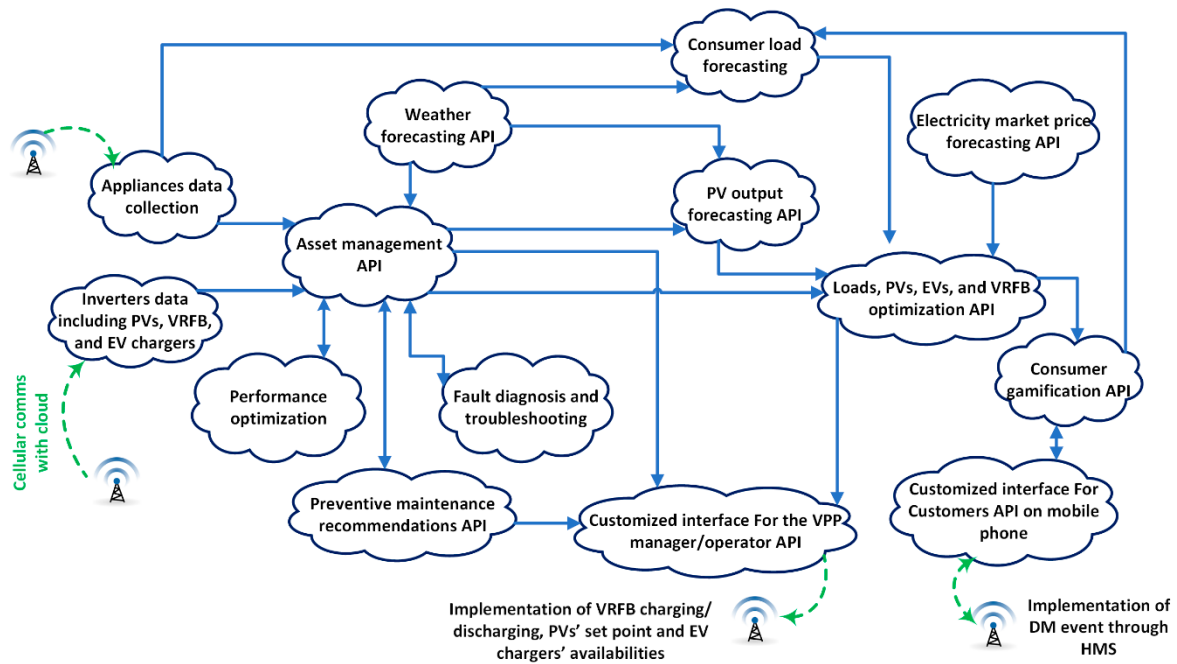


Figure 8. The proposed configuration of the cloud-based monitoring and control system APIs for the VPP. EV: electric vehicle.

Optimization Application

In order to maximize the benefits to the VPP's owner and residences, a cloud-based optimization application is used to schedule the optimal charging/discharging of the battery and consumption patterns. In this optimization, the default aim for the PV system is to maximize the PV active power generation, except if there is a requirement from the local utility on the reactive power injections.

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

$$\text{maximize } (R_{tot} - C_{tot} - C_{DM})$$

Constraints :

$$\begin{cases} \text{VRFB charging and discharging constraints} \\ \text{Customer the use of appliances constraints} \\ \text{PV system generation constraints} \end{cases} \quad (1)$$

$$\begin{aligned} R_{tot} &= R_{Fix} + R_{Var} \\ &= R_{Fix} + \sum_{h=1}^{24} E_{out}^{y,h} \pi^{y,h} \\ &\quad + \sum_{h=1}^{24} E_{RES}^{y,h} \tau_{RES,E}^{y,h} \quad y \text{ is fixed} \\ E_{out}^{y,h} &= \begin{cases} E_{PV}^{y,h} - E_{RES}^{y,h} - E_{VRFB}^{y,h} & \text{if } (E_{PV}^{y,h} - E_{RES}^{y,h} - E_{VRFB}^{y,h}) > 0 \\ 0 & \text{otherwise} \end{cases} \\ E_{RES}^{y,h} &= E_{RES,Fix}^{y,h} + \sum_{n=1}^{67} E_{WM,n}^{y,h} + E_{HP,n}^{y,h} + E_{AC,n}^{y,h} \\ &\quad + E_{DW,n}^{y,h} \\ \Rightarrow R_{tot} &= R_{Fix} + \sum_{h=1}^{24} E_{out}^{y,h} \pi^{y,h} \\ &\quad + \sum_{h=1}^{24} \left\{ \tau_{RES,E}^{y,h} \sum_{n=1}^{67} E_{WM,n}^{y,h} + E_{HP,n}^{y,h} + E_{AC,n}^{y,h} + E_{DW,n}^{y,h} \right\} \end{aligned} \quad (2)$$

$$\begin{aligned}
C_{tot} = & C_{Fix} + (1 + \alpha^y) \sum_{h=1}^{24} E_{in}^{y,h} \pi^{y,h} \\
& + \alpha^y \sum_{h=1}^{24} E_{out}^{y,h} \pi^{y,h} \\
& + (1 + \beta^y) \sum_{h=1}^{24} E_{in}^{y,h} \omega^{y,h} + (\gamma^y \\
& + \delta^y + \theta^y) \sum_{h=1}^{24} E_{in}^{y,h} \\
E_{in}^{y,h} = & \begin{cases} E_{PV}^{y,h} - E_{RES}^{y,h} - E_{VRFB}^{y,h} & \text{if } (E_{PV}^{y,h} - E_{RES}^{y,h} - E_{VRFB}^{y,h}) < 0 \\ 0 & \text{otherwise} \end{cases}
\end{aligned} \quad (3)$$

$$\begin{aligned}
C_{DM} = & \sum_{n=1}^{67} k_1 \Delta E_{WM,n}^{y,h} + k_2 \Delta E_{HP,n}^{y,h} + k_3 \Delta E_{AC,n}^{y,h} \\
& + k_4 \Delta E_{DW,n}^{y,h}
\end{aligned} \quad (4)$$

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. R_{tot} also 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) [55]. The detailed formulation of R_{tot} is provided in [7]. The base tariff for which the VPP sells energy to the dwelling is presented in Table 3. As seen, from 10 a.m. to 2 p.m., 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 slightly depending on the season as well. For the sake of simplicity, R_{tot} can be written as (2), where R_{Fix} represents all fixed terms in the revenue of the VPP during a year and can be excluded from the optimization process in a specific year. In (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. $E_{WM,n}^{y,h}$, $E_{HP,n}^{y,h}$, $E_{AC,n}^{y,h}$, $E_{DW,n}^{y,h}$ 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 (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 (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.
- 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 optimization. The compact formula is presented in (3), and the detailed formulation is provided in [7]. 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 [56].
 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 .

Table 3. The TOU (time of use) tariff of the VPP for the residents.

Fixed Cost (cents/day)	Peak (cents/kWh): 4 p.m. to 10 p.m.	Shoulder (cents/kWh): 8 a.m. to 10 a.m./ 2 p.m. to 4 p.m.	Off-Peak (cents/kWh): 10 p.m. to 8 a.m.	Free Electricity: 10 a.m. to 2 p.m.
103.3263	54.81	28.71	15.10	0.00

The definition and values of the above-mentioned coefficient are provided in [7].

The CAPEX-related costs also include the following items; however, they are not considered in the optimization process. The costs of installed capital expenditure such as PV panels and VRFB are calculated based on the NPV cost, then converted to daily costs.

7. The cost of the PV systems, including the cost of PV panels, inverters, structures, installation and commissioning, and the associated maintenance such as cleaning.
 8. The cost of the VRFB, including the cost of the battery, designing, foundation, installation, and operation and maintenance costs.
 9. The cost of the heat pump 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.
 10. The cost of the internal network, distribution transformer, cabling and protection system.
 11. 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. 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 optimization applications on the cloud for solving such a problem in a manageable time, such as the high-performance computing platform by Azure [57]. As an example, the simulation results of optimization including the detailed formulation for the VRFB is provided and discussed in [7]. Azure IoT can also 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 [58]. In addition, Azure artificial intelligence can provide the necessary tools for forecasting the load, customer behaviour and PV output, as proposed in this paper [59].

6. Conclusions

This paper 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). It also proposes that

the EEBUS-enabled appliances are the best way to communicate and control the customer load. For encouraging customers to engage with the optimized commands from the cloud-based optimization system, the gamification application is the most effective approach in which people can collaborate and compete for getting prizes, badges, etc. It is shown that an AC system is more economic compared to a DC system for the internal network of the VPP. It is proposed that the relevant data from the corresponding inverters of these systems are transferred directly to the cloud through cellular communication. In this research, home management system devices are defined as fog devices for dwellings to collect the data of appliances and residence settings and then to transfer them to the cloud. The fog devices for inverters are the internal processor and memory of those inverters as well. The various cloud-based applications necessary for the operation of VPP are proposed, including weather, PV output, and customer load forecast and also gamification, asset management, and optimization algorithm. 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 residences. Future work will include the investigation of price maker VPPs and bidding strategies.

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