# Role of Aggregator in Coordinating Residential Virtual Power Plant in "StoreNet": A Pilot Project Case Study

Mohamed Bahloul, Liam Breathnach, Jerry Cotter, Mohamed Daoud (SMIEEE), Aziz Saif, and Shafi Khadem (SMIEEE)

Abstract-Towards the development and demonstration of an innovative business model where the value proposition for consumers/prosumers, aggregators and network operators are well maintained, this study assesses the performance of different aggregation control strategies for a distributed energy storage based residential virtual power plant (VPP). A special focus is given on the social welfare and network strength and their relation to energy storage capacity and power budgets allocation. The study is based on a real-life demonstration project, StoreNet where the basic self-consumption (SB-SC) control strategy has already been deployed. Analysing one-year measured data, it is observed that the implemented SB-SC approach allows 16%-19% electricity cost-saving, whereas the proposed VPP-bill minimisation approach can benefit from 37%-42% cost saving. This is also 7%-8% higher than the single home bill minimisation approach where the community does not participate in the VPP model. In contrast, the peak shaving approach is more favourable for the network operator. It reduces the load peak by 46.5%-64.7% and also drastically reduces the benefits for the customers and aggregator. Based on these studies and learning, some recommendations are made addressing the integration aspect of residential VPP and the future development of this concept for the local and wholesale energy markets.

*Index Terms*—Virtual power plant, aggregator, energy management system, MILP programming, StoreNet pilot project.

NT	
NOMENCL	ATURE

CVPP:	Commercial virtual power plant
DER:	Distributed energy resources
DSO:	Distribution system operators
DSR:	Demand-side response
EMS:	Energy management system
ES:	Energy storage
LL:	Load levelling
MILP:	Mixed Integer Linear Programming
PS:	Peak shaving
PSDT:	Peak shaving during the daytime
RES:	Renewable energy systems
SB-SC:	StoreNet basic self-consumption
SH-BM:	Single house bill minimisation
TSO:	Transmission system operators
TVPP:	Technical virtual power plant
VPP:	Virtual power plant
VPP-BM:	Virtual power plant bill minimisation

# I. INTRODUCTION

The roll-out of smart meters, demand response, and dynamic pricing is driving advancement in the energy system decarbonisation and market participation. The challenges faced by the utility providers include facing the demands of power production, both in monitoring and forecasting. The integration of virtual power plants (**VPP**) can help alleviate any potential grid volatility by providing a granular response to demand. A VPP may be able to help with

the intermittency of renewables, reduce consumption at times of peak demand and provide a reserve of power [1], [2], [3].

To develop and manage the VPP, the aggregator plays the most important role as a mediator between the consumers, who sell their self-generated excess clean energy and demand flexibilities (modifications in consumption), and the markets where the aggregator sells these flexibilities for use by other electricity system and market players. These activities of market participation and system management and support for VPP are considered respectively as commercial and technical activities. Thus the concepts appear as commercial VPP (CVPP) and technical VPP (TVPP) [4], [5]. The functionality of CVPP mainly includes (i) trading in the wholesale energy market, (ii) balancing of trading portfolios and the provision of services that are not location-specific to the system operator. On the other hand, TVPP provides (i) local system management for distribution system operators (DSO), (ii) system balancing and ancillary services to transmission system operators (TSO). There can, however, be a commercial value associated with the provision of such grid services.

The energy management system (EMS) presents the core of the VPP concept. Its main functionality consists of ensuring an optimal dispatch of the VPP resources while scheduling the electricity production and consumption of different VPP resources. Indeed, it plays a crucial role in collecting, storing, and analysing the various forms of data from VPP resources and coordinating the control of remote monitoring devices. Usually, a certain number of subfunctionalities are implemented to ensure robust and coordinated operation of the control system, such as forecasting the DER generation and loads, power flow coordination among the different VPP components, management of energy storage (ES) unit, flexible load unit, etc. The EMS dispatch concept is to accomplish certain technical and/or commercial objectives for the VPP operation, such as reducing greenhouse emissions, maximising profit, minimising network losses, reducing energy cost, etc. To this end, different approaches have been developed [6]. These approaches could be split into analytic or heuristic methods. The literature review shows that the most adapted algorithms in the deterministic category are mixed-integer linear programming, dynamic programming, and nonlinear programming. Researchers usually refer to stochastic or robust optimisation methods to count model, measurement, or forecast uncertainties. Heuristic methods are showing an increasing potential for EMS VPP design and especially using the genetic algorithm and particle swarm optimisation method [7], [8], [9].

The recent development of IoT and smart meter technologies has promoted the smart integration of residential houses into the electricity system. Residential prosumers will play a key role in decarbonising the electricity system and promoting demand-side response (**DSR**) programs [10], [11]. The potential of residential consumers in participating in flexibility management has been assessed via different pilot projects [10], [12]. Along with the recent development of house EMS [8], [13], the VPP concept has a pivotal role in smoothing the transition towards decarbonising the building/residential sector and maximising the social welfare of residential distributed energy resources (DER) [1], [14]. In [7], the authors have proposed a coordination control approach to reducing the electricity bills of smart houses in a neighbourhood. They have also analysed the impact of control on the average peak reduction. The authors in [14] have proposed a day ahead control algorithm for residential VPP and investigated the economic impact of ES and distributed PV on the residential aggregator. An optimal approach for maximising the residential VPP income via participating in the energy and local flexibility markets has been investigated in [3]. In [15], the authors proposed a demand response algorithm for residential aggregated load peak shaving. The described case study showed that the proposed approach reduces the aggregated load by 33% during peak hours.

The integration of ES potentially enhances VPP market uptake and grid integration scalability and sustainability. Indeed, ES can reduce the investment needed in upgrading the network to be able to cope with the significant peaks and troughs in the flow of electricity [2], [3], [16]. As well as benefits to the network, the successful development of commercial ES can accelerate the shift to a low carbon economy [17]. Moreover, in VPP, the ES solution can help the owners of renewable energy systems (RES) capture the value of flexibility [18], increase the value of assets through the markets, reduce the financial risk through aggregation, and improve the ability to negotiate commercial conditions. The benefits for network operators (TSO and DSO) includes increased visibility of RES units for consideration in network operation, control flexibility of RES units for network management, improved use of grid investments, improved coordination between DSO and TSO, mitigate the complexity of operation (caused by the growth of inflexible distributed generations) [19], [20]. The suppliers and aggregators have many advantages, such as new offerings for consumers/prosumers and DERs (such as EV, ES, microgeneration systems, flexible loads, HP etc.) suppliers, mitigating commercial risk, and proposing/extending new business opportunities [21].

# A. Motivation

Few VPP projects were developed worldwide to assess the technoeconomic viability of this novel VPP concept in a real case. Indeed in the US, ConEdison VPP manages ES and PV installed in residential houses. The Australian SA VPP project presents a good learning VPP paradigm. More information about these projects and previous ones could be found in [22]. This ongoing effort enabled building a better understanding of the VPP and the concept they are created for and encouraged financial and funding institutions to participate in the VPP future. However, there is still a lot of learning to bring this technology as a mature product to the market. For instance, there is less understanding among decision-makers and stakeholders about the best relationship framework to establish between the aggregator and the network operator and utility suppliers. Usually, if the aggregator belongs to the utility, then the objectives of the aggregator will stand at the utility side to maximise the benefits of the utility. On the other hand, if the aggregators are a third-part profit entities, they will generally be scanning for maximising their profit. But, how about maximising the benefit of the customers

or society? What objectives can be considered, and how can the control policies impact this? Many other research questions are still required to answer as: What kind of control strategy can be adapted for residential VPP? What are the impacts of the aggregator control approach on VPP and network operation? What is the impact of the popularisation of residential VPP on the future operation of the electric network? How can the ES sizing affect the aggregator control strategy and its economic benefits? However, a very important question arises again here - How sensitive is the control approach to the stable and economic operation of VPP? In practice, it means will it be beneficial if the number of VPP houses increases, or/and an allocation of part of the ESs power and capacity budget to provide other services to the community or the grid?

## B. Paper contribution

Motivated by the above, the StoreNet pilot project contributes to the VPP state of the art, demonstrates the viability of a VPP as an aggregation platform of distributed resources for the stakeholders' benefits, and analyses potential policy and actions to support efficient VPP deployment in the energy transition. This paper uses the StoreNet pilot project facilities, data, and outputs to address some research gaps related to VPP control strategy performances and their impact on VPP performances. The key contributions of this paper to current to state of the art are summarised as follows

- Five different control strategies for aggregators operating the StoreNet demo side are proposed, and the impact of each control approach on the VPP and network operation is assessed through a daily and monthly analysis; these strategies are not new, but their implementation through residential VPP control is new and did not practiced/implemented yet,
- The impact of ES sizing on the aggregator control strategy and its economic benefits is studied, along with the interaction aspect with a day-night tariff scheme and the impact due to the consumption pattern. This will give the aggregator a better idea of improving the VPP management and operation. Moreover, it will provide a framework for the DSO, utility supplier, and market operator (aggregator) to develop an appropriate remuneration scheme that will shape the future of the local energy market and its contribution to grid stability, thus demonstrating the way to easing DERs integration and grid decarbonisation,
- Based on the performed analysis in this paper, some recommendations are proposed addressing the integration and the future development of residential VPP in the local and wholesale energy markets. Initially, a VPP bill minimisation (VPP-BM) control strategy is proposed. The main aim here is to optimise the load and resources management to maximise economic benefits for consumers at the community level. A zero feed-in tariff is considered here to align with the Irish policy. Hence, the algorithm considers here the VPP as a central controller to exchange energy between different houses but does not benefit from any feed-in tariff scheme. The impact of the aggregation concept is investigated through the design of a single house bill minimisation (SH-BM) approach. This algorithm offers similar functionality to VPP-BM; however, it focuses on self-optimisation for each house rather than considering it as a community. From a network point of view, peak shaving (PS) and load levelling (LL) algorithms have been designed. The

latter strategies (PS and LL) are more beneficial for the system operator. The main aim is to study the impact of providing such a service to the grid operator on the revenue stream and mainly the electricity bill. A peak shaving during the daytime (**PSDT**) algorithm is also assessed. This strategy is developed to concretise the grid operator requirement of minimising the peak during the daytime to enhance network flexibility. The total consumption is usually very high in peak times and can trigger some power quality issues. The performances of each algorithm mentioned above are described and compared with the StoreNet basic self-consumption (**SB-SC**) algorithm developed and applied by the aggregator for the initial operation design of the StoreNet platform.

Moreover, we assess the impact of ES power and capacity budget on the economic viability of the different control strategies. This is to investigate the ES deployment by each control strategy and a potential role of the VPP in providing other energy and flexibility services, as secondary ones, in the market, and generate accordingly additional benefits for customers.

The rest of this paper is organised as follows; in sections II, the design methodology of the algorithms is described, a Mixed Integer Linear Programming (**MILP**) formulation is considered. Section III presents case studies for different scenarios; a sensitivity analysis is also assessed to investigate the revenue stream from the ES capacity and power budget allocation. Moreover, an analysis of the implemented and proposed algorithms is described showing the impact of each approach and the adopted day-night tariff scheme on the saving and consumption pattern. In section IV, key findings and recommendations, based on this study and StoreNet learnings, are given that address the future development of VPP in the local and whole energy markets. Finally, section V concludes this paper.

# II. STORENET VPP CONTROL

"StoreNet" is an industry-led, collaborative project of the International Energy Research Centre with Solo Energy (aggregator), Electric Ireland (utility supplier), and ESB Networks (network operator).

The StoreNet VPP demonstration is located in the Dingle peninsula in the southwest of Ireland and is controlled by the aggregator in Cork. Twenty (20) houses host each a 10kWh/3.3kW peak Sonnen lithium-ion **battery ES**. Nine (9) of those houses also have installed rooftop 2.4kW PV panels, and all of the houses are on smart meters with a day/nighttime tariff scheme. Fig. 1 shows the StoreNet demonstration site, the location of the participating houses and a system installation example. In the StoreNet concept, the VPP is designed to create value for both the VPP operator and the participants in the scheme – usually through sharing of the financial benefits that the VPP creates. The VPP participant will receive the electricity bill from the VPP operator rather than the electricity supplier in this case. The VPP billing will consider the contribution of the house to the total saving.

The StoreNet control architecture consists of a central controller that specifies the power exchange between the ESs, the houses, the PV generators, and the grid. The customer locations are noted by the red dots. The overall VPP cloud control architecture is also presented in Fig. 2.

The SB-SC algorithm has been developed by Solo Energy (aggregator) to control the battery ES. According to the ES existing



Fig. 1. StoreNet VPP Demonstration site and Network



Fig. 2. VPP Control architecture

control method, the implemented algorithm aims at maximising the PV generation self-consumption at the household level. It uses a day ahead control approach using a forecast of generation and consumption (Fig.3). Further details of the algorithm and ES functionalities are described in [23]. The authors, in this case, have full access to onsite outputs but not the algorithm script to replicate the system for offline analysis.



Fig. 3. Screenshot of Sonnen Dashboard

In the remainder of this section, five different control approaches

for StoreNet VPP aggregator are described. A day ahead control approach is considered. It computes the charging and discharging battery ES reference signals based on the day ahead generation and consumption forecast (Fig. 4). A Mixed Integer Linear Programming (MILP) algorithm is used to design the reference signal for the power conversion system to ensure optimal system management to fulfil specified criteria or a so-called objective function. The algorithm considers the characteristics of the system components in each house and the design objective to synthesise the optimal control scenario. The MILP constraints and objective functions are described as follows



Fig. 4. StoreNet Control Layout

# A. StoreNet VPP control - General constraints

1) *PV constraints:* For the rest of this study, the upper cases ^ and ^ are used to denote the AC and DC signals, respectively.

First, let's define  $P_{PVGeni,k}^-$  as the maximum DC output power of  $i^{th}$  PV generator ( $PVG_i$ ) at a specified time interval k as:

$$P_{PVGeni,k}^{-} = P_{PVi,k}^{-} + P_{PVi,k}^{F-}, \forall i,k$$
 (1)

 $P_{PVi,k}^{-}$  denotes the amount of power used by the VPP for its operation and should satisfy the constraint (2).

$$P_{PVi,k}^{-} \le P_{PVGeni,k}^{-}, \forall i,k \tag{2}$$

 $P_{PVi,k}^{F-}$  is the additional amount of power that will not be used by the VPP controller. According to the DSO and service provider feeding strategies, this amount of power could be curtailed or injected into the grid. Since there is no feed-in tariff in Ireland, a power curtailment strategy is considered in this case.

According to the VPP operation,  $P_{PVi,k}^-$  could be split into three parts as described in (3). The first part  $P_{PVi/Hi,k}^{\sim}$  will feed the load of the house  $(House_i)$  The second part  $P_{PVi/G,k}^{\sim}$  will be injected into the grid and transferred to other VPP loads. However, the last part  $P_{PVi/Bi,k}^-$  will be used to charge the local battery i  $(Bat_i)$ .

$$P_{PVi,k}^{-} = \frac{1}{\eta_{PVi}^{\sim}} P_{PVi/Hi,k}^{\sim} + \frac{1}{\eta_{PVi}^{\sim}} P_{PVi/G,k}^{\sim} + \frac{1}{\eta_{PVi}^{\sim}} P_{PVi/Bi,k}^{\sim}, \forall i,k$$
(3)

 $\eta_{PVi}^{\sim}$  is the conversion efficiency index of the *i*<sup>th</sup> DC/AC inverter installed in  $House_i$  and ensuring the power conditioning between the PV and the House. The same efficiency index is considered here to count the power losses of the DC/AC inverter. And  $\eta_{PVi}^{-}$  denotes the efficiency index of the DC/DC conversion system.

2) Battery ES constraints: The *i*<sup>th</sup> battery charging and discharging powers (respectively  $P_{Bi,k}^{C-}$  and  $P_{Bi,k}^{D-}$ ) can be described by (4) and (5):

$$P_{Bi,k}^{C-} = \eta_{Bi}^{C} P_{G/Bi,k}^{\sim} + P_{PVi/Bi,k}^{-}, \forall i,k$$
(4)

$$P_{Bi}^{D-} = \frac{1}{\eta_{Bi}^{D\sim}} P_{Bi/G,k}^{\sim} + \frac{1}{\eta_{Bi}^{D\sim}} P_{Bi/H,k}^{\sim}, \forall i,k$$
(5)

 $P_{G/Bi,k}^{\sim}$  is the  $Bat_i$  AC charging power from the grid.  $P_{Bi/G,k}^{\sim}$ , and  $P_{Bi/H,k}^{\sim}$  respectively are the AC discharging power outputs of  $Bat_i$  that is injected into the grid and  $House_i$ .  $\eta_{Bi}^{C}$  and  $\eta_B^{D}$  are respectively the charging and discharging efficiency of the battery bidirectional AC/DC inverter.

Due to the technical specifications of the battery and in order to minimise the losses of the power conversion system,  $P_{Bi,k}^{C-}$  and  $P_{Bi,k}^{D-}$  should be bounded by specific values as [17], [9]:

$$\chi_{i,k}^{C}\underline{P_{Bi}^{C-}} < P_{Bi,k}^{C-} < \chi_{i,k}^{C}\overline{P_{Bi}^{C-}}, \forall i,k$$
(6)

$$\chi_i^D \underline{P_B^{D-}} < P_{Bi,k}^{D-} < \chi_i^D \overline{P_{Bi}^{D-}}, \forall i,k$$
(7)

 $P_{Bi}^{C-}$  and  $P_{B}^{D-}$  (respectively  $\overline{P_{Bi}^{C-}}$  and  $\overline{P_{Bi}^{D-}}$ ) represent the minimum (respectively maximum) charging and discharging DC power.  $\chi_{i,k}^{C}$  and  $\chi_{i,k}^{D}$  are binary variables that describe respectively the charging and discharging status of  $Bat_i$ . In order to avoid the simultaneous charging and discharging operating modes, the following constraint should be satisfied:

$$\chi_i^C + \chi_i^D \le 1, \forall i, k \tag{8}$$

It should be noticed that the battery can charge/discharge a limited amount of energy, and the available stored energy, at specified time interval k, is determined by the state of the charge of the battery as:

$$SoC_{i,k} = SoC_{i,0} + \sum_{t=0}^{k} \left( P_{Bi,k}^{C-} - P_{Bi,k}^{D-} - P_{Bi}^{SD} \right) \Delta k \qquad (9)$$

where  $\Delta k$  is the sampling period. The terms  $SoC_{i,0}$  and  $P_{Bi}^{SD}$  denote respectively the initial SoC and the self discharge power of the  $Bat_i$ 

Usually, the SoC of an ES can vary from 0% to 100%; however, in order to maintain a good operating condition of the battery and preserve its capacity lifetime, the SoC should be maintained within a certain range [24]. Thus, the constraint (10) is introduced:

$$SoC_i < SoC_{i,k} < \overline{SoC_i}, \forall i,k$$
 (10)

where  $\underline{SoC_i}$  and  $\overline{SoC_i}$  denote the upper and the lower bounds of  $Bat_i$ .

3) VPP and load constraints: According to the VPP operation, the load demand of  $i^{th}$  house  $(P_{Li,k}^{\sim})$  will be supplied by the grid, the local PV generator  $(PVG_i)$ , and the local battery  $Bat_i$  as:

$$P_{Li,k}^{\sim} = P_{G/Hi,k}^{\sim} + P_{PVi/Hi,k}^{\sim} + P_{Bi/Hi,k}^{\sim}, \forall i,k$$
(11)

It is to be noticed that  $P^{\sim}_{G/Hi,k} \geq 0$  and  $P^{F-}_{PVi,k}$  (in 1) is non remunerated, hence 12 holds:

$$P_{PVi/Hi,k}^{\sim} + P_{Bi/Hi,k}^{\sim} \le P_{Li,k}^{\sim}, \forall i,k$$
(12)

Then, the total load of the VPP, at a time k,  $P_{VPP,k}^{\sim}$  can be defined as:

$$P_{VPP,k}^{\sim} = \sum_{i=1}^{n_{H}} P_{Li,k}^{\sim} + P_{G/Bi,k}^{\sim} - P_{PVi/Hi,k}^{\sim} - P_{Bi/Hi,k}^{\sim} - (1-\xi)P_{Bi/G,k}^{\sim} - (1-\xi)P_{PVi/G,k}^{\sim}, \forall i,k$$
(13)

where  $n_H$  is the number of houses in the VPP.  $\xi$  presents the grid losses coefficient. This term is introduced to count the energy losses due to the energy transfer within the participating houses under the VPP operation.

Since there is no grid feed-in tariff, no power will be injected into the grid, or there will be curtailment for the overall excess self-generation power; hence we assume that  $P_{VPP,k}^{\sim}$  will be positive for all time. Then the constraint (14) should be accounted.

$$P_{VPP,k}^{\sim} \ge 0, \forall k \tag{14}$$

In order to ensure a smooth transition between the two consecutive decision horizons and the new control sequence, the final  $Bat_i$  SoC value for decision horizon  $h(SoC_{i,hk_T})$ , is imposed when computing the optimisation algorithm (as described in 15). In this study, this value is considered to be equal for each decision horizon  $(SoC_{i,Hk_T})$ , to be used as an initial SoC value to design the control sequence of the next decision horizon.

$$SoC_{i,k_T} = SoC_{i,hk_T} = SoC_{i,Hk_T}$$
(15)

#### B. StoreNet VPP control - Objective function

The objective functions of the EMS algorithms depend on the stakeholders' requirements/benefits; customer, VPP aggregator, utility supplier, and the network operator. These will offer the aggregator the flexibility to deal with different scenarios and to compare their technical-economic impacts on the network and the end-users.

1) Single house bill minimisation (SH-BM): The controller considers each house as a single entity. The role of the aggregator is then to design a battery charge-discharge controller that maximises the economic benefits of each house independently. The benefits are generated by purchasing energy from the grid to charge the battery at nighttime or excess PV energy when available and then using it during the daytime to feed the load. The DERs, in this case, are not optimally deployed in favour of the community since they are controlled as a separate unit to maximise the individual profits without being able to share these resources with the other VPP customers. The objective function used to design the *i*<sup>th</sup> house battery charge-discharge controller ( $J_{SH-BMi}$ ) is described as:

$$J_{SH-BMi} = min \sum_{k=0}^{k_T} \Psi_k \Big( P_{Li,k}^{\sim} + P_{G/Bi,k}^{\sim} - P_{Bi/Hi,k}^{\sim} \Big)$$
$$i = 1 \cdots n_H \tag{16}$$

where  $k_T$  is the horizon decision interval and  $\Psi_k$  is the electricity price of a time interval k.

2) VPP bill minimisation (VPP-BM): The control algorithm, in this case, optimises the DERs in favour of all the VPP customers. It enables sharing of DERs among customers and creates a cooperative energy exchange framework between the households in the community. The main aim of this VPP is to generate the maximum benefits from the use of batteries and PV generators through the minimisation of the total electricity bills from aggregating the loads, the PV generation, and the batteries use of the different houses [25]. This objective can be guaranteed through the minimisation of the following objective function:

$$J_{VPP-BM} = \min \sum_{i=1}^{n_{H}} \sum_{k=0}^{k_{T}} \Psi_{k} \Big( P_{Li,k}^{\sim} + P_{G/Bi,k}^{\sim} - P_{PVi/Hi,k}^{\sim} - P_{Bi/Hi,k}^{\sim} - (1-\xi) P_{Bi/G,k}^{\sim} - (1-\xi) P_{PVi/G,k}^{\sim} \Big)$$
(17)

3) Peak shaving (PS): Peak Shaving is one of the potential VPP applications in the smart grid network [15], [26]. It aims at reducing the peak demand to avoid the installation/operation of additional generation, distribution, and transmission capacities to secure the supply during the peak period. Usually, this peak can appear either in the early morning or early evening time. This offers a good feature for the TSO/DSO to control their network and minimise the future grid support investment. However, this may impact the direct economic benefits of end-users. Then a compensation scheme for using this feature should be placed. The mathematical formulation of the peak shaving objective function can be described by (19) as

$$J_{PS} = min(P_{VPP,max}) \tag{18}$$

where  $P_{VPP,max}^{\sim}$  is the maximum aggregated load such that:

$$P_{VPP,max}^{\sim} > P_{VPP,k}^{\sim} \forall, k$$
 (19)

Note that this service can be considered by the DSO only for an aggregated load since a single house peak shaving will not get the same impact as an aggregator can do.

4) Peak shaving during daytime (PSDT): PSDT is another control approach that combines peak shaving and a kind of energy bill minimisation. This will especially be applicable where the day-night tariff system exists, such as in Ireland. Usually, the daytime electricity tariff is much higher than that of the nighttime. A peak demand appears in the daytime (mostly in the late afternoon and early evening time), making the DSO feel concerned about the ability of their facilities to respond to the peak demand. This approach is different from PS since minimising the peak during the nighttime (early morning) is not considered here in the VPP control. Also, using this approach will lead to less energy demand from the grid in the daytime, and more energy demand will be shifted to the nighttime, mainly for charging the ES during the nighttime

6

low grid tariff. While considering the ToU tariff characteristics, thus shifting the demand to the nighttime will reduce the electricity bill. The objective function is described by:

$$J_{PSDT} = min(DP_{VPP,max}) \tag{20}$$

where:

$$DP_{VPP,max} > DP_{VPP,k} \forall,k$$
 (21)

and

$$DP_{VPP,k} = \sum_{i=1}^{N_H} \Upsilon_k \Big( P_{Li,k}^{\sim} + P_{G/Bi,k}^{\sim} - P_{PVi/Hi,k}^{\sim} - P_{Bi/Hi,k}^{\sim} - (1-\xi)P_{Bi/G,k}^{\sim} - (1-\xi)P_{PVi/G,k}^{\sim} \Big)$$
(22)

 $\Upsilon_k$  is a daytime interval index.

5) Load levelling (LL): The load levelling approach aims at reducing the fluctuation in electricity demand by minimising the gaps between the on-peak and the off-peak values [26]. The aggregator may use the batteries to store the electricity excess during low demand and use it during the high demand period so that the imported electricity from the grid maintains nearly a constant level throughout the day-night period. This approach presents many advantages for TSO/DSO and system operators to manage the upstream generation and the electric network. The objective function is given by (23) as

$$J_{LL} = min \left( P_{VPP,max}^{\sim} - P_{VPP,min}^{\sim} \right)$$
(23)

where  $P_{VPP,max}^{\sim}$  is described by (19) and  $P_{VPP,min}^{\sim}$  is the minimum aggregated load such that:

$$P_{VPP,min}^{\sim} < P_{VPP,k}^{\sim} \forall, k \tag{24}$$

# **III. CASE STUDIES**

This section presents three groups of case studies. The first group considers the nominal case where the full capacity of the storage units are utilised (20 batteries), and the performances are evaluated based on the daily profile. The second group presents a comparative analysis of the different control approaches in terms of savings (compared to the initial load demand base case with no PV and ES contribution at the consumer-end) and peak consumption on a monthly basis. The third group shows sensitivity analysis of the VPP-BM total saving for battery capacity and power allocation and investigates the system performances while considering 20% - 100% of the total energy and power capacities of the batteries. The day-time in this study is 10 am - 10 pm. The electricity tariffs are proposed based on the Irish electricity market for 2019 (9.1 cents/kWh for nighttime and 19.4 cents/kWh for daytime) [27], [28]. Other design parameters are given in the Appendix. The aggregator control dashboard provides forecasted and real measured data of each house's load and PV generation. Moreover, the real measurement of the batteries charging and discharging control signal is available for the implemented SB-SC algorithm. Thus, for the sake of comparison, we use the real data in spite of the forecasted one to compute the proposed algorithms and compare the obtained results with the SB-SC outputs.

# A. Full capacity storage utilisation – daily analysis

This case study presents detailed results of the SH-BM, VPP-BM, PS, PSDT, and LL algorithms considering 30 min (sampling period) time-series data for a day.

Fig. 5 presents different EMS outputs. The load (blue lines) represents the real-life measured data combined for 20 customers. The obtained results show that compared to the single house optimisation (SH-BM, Fig. 5a), the combined/VPP optimisation (VPP-BM, Fig. 5b) allows 9.42% more return on a typical day. This preliminary result shows the advantage of aggregating DERs to generate higher revenue. Moreover, it can be observed that in term of saving, the VPP-BM and PSDT offer a close performance; the PSDT also offers more peak reduction than that of the VPP-BM (grid - red lines). It is also observed that the saving from the StoreNet SB-SC is even less (23.72%) than that of SH-BM (36.41%), VPP-BM (45.83%), and PSDT (43.63%). The analysis of the results also shows that there is a huge difference in savings between PS (15.3%)and PSDT (43.63%). This can be explained by the fact that while using PS, there is less room for the battery to charge energy from the grid at nighttime and discharge in the daytime when the electricity price is high. However, for PSDT, there are less constraints for the battery to be fully charged before the daytime begins and then use this energy to minimise the peak and the load at the time.

The PS and LL algorithms exhibit almost the same peak reduction (grid). Moreover, both present similar savings that are close to 15%. The differences between these PS and LL can be obtained more clearly in the case of monthly performance. Hence, deeper analysis has also been performed to get insights into the overall performances considering the seasonal and monthly scenarios. Thus, the second group of case studies is presented in the next section. It includes extensive simulations of the different proposed control strategies implementing 1 year of real measured data where SB-SC outcomes are from the real-life performance.

# B. Savings and peak consumption study – monthly analysis

This section presents comparative studies on the performance of the newly proposed and developed EMS algorithms and the applied SB-SC algorithm. The performance is evaluated in terms of monthly electricity cost savings and the peak consumption in VPP aggregation mode. Simulations were carried out using 1h sampling period for the 1st and the 2nd then 15th and 16th of each month. Real data gathered from July 2019 to June 2020 were used. Afterwards, the mean value is computed and presented. The decision horizon is 24h. Noting that the reduced sampling time for the daily analysis is proposed to give more insights into the dynamics of the control, as described in Figure 5. However, the monthly analysis is more static, and hence to reduce the computation burden and complexity, the 1h sampling time is proposed for this study.

Fig. 6a shows the possible monthly savings if the proposed algorithms are implemented and the existing day-night tariff scheme is considered. It is clearly observed that the VPP-BM can be the best approach in terms of savings. PSDT is in the second rank, followed by SH-BM, and SB-SC is in the fourth rank. The LL here offers a minor saving ratio and can even lead to close to zero and negative values for some periods (July – Dec). To assess the impact of different control algorithms on the consumption waveform, the peak values are plotted in Fig. 6b. It shows that SB-SC and SH-BM exhibit



Fig. 5. Different EMS output for a typical day (100% capacity utilisation)

the highest peak value (despite neither of the algorithms showing a considerably best saving ratio).VPP-BM and PSDT show almost the third and the fourth-highest peaks. The PS is the best approach here in terms of reducing the peak, followed by the LL showing almost similar peak values, but the savings are comparatively very low.

# C. Sensitivity analysis

In this group of case studies, a sensitivity analysis is performed to investigate the impact of batteries power and capacity budget on the economic viability of the VPP. As the initial objective of the StoreNet VPP is to reduce the VPP community bills and previous analysis also show that VPP-BM or PSDT strategy can be the best choices, this analysis is extended further to study how the battery power and capacity variation can impact other control performances and compare this with the VPP-BM algorithm outputs. The extensive simulations have been performed using 30 min time series data while considering the same simulation conditions as it is done in the previous case studies.

The main results are plotted in Fig. 7. It can be observed that the capacity budget has more impact on the savings rather than the increasing power ratio. For a fixed power ratio between 0.2 and 1, the economic saving is linearly dependent on the capacity budget. The maximum saving can be achieved at around 0.7 - 0.8 capacity ratio and a power ratio of 0.2 - 0.3 (20% - 30% of the nominal power). The maximum saving value here is around 46% (as described in the first case study, Fig. 5b), and it is higher than the mean value of the year as shown in Fig. 5a (in the second case study). The saving value is due to batteries usage. It can be concluded that the batteries utilisation factor, in this case, is very low. This can impact the profitability of the battery investment. Further development on the utilisation of the batteries' budgets should be considered. Indeed, in this case, at least 70%-80% of the total power budget and 20%-30% of the total capacity budget can be used to perform other VPP services without impacting the VPP-BM economic performances.

To give more insight into the impact of batteries power and capacity budget variation on the other control strategies, simulations have been performed considering 20% of the battery capacity and power, respectively. Table I shows the main outputs while considering the five different proposed algorithms. The obtained results show that VPP-BM, in this case, is an energy-oriented



(a) Saving (%) for different control algorithms from July 2019-June 2020



Fig. 6. Saving vs peak consumption analysis



Fig. 7. EA Saving for different capacity and power ratios

application. The saving shows high volatility when reducing the capacity budget (26.5% saving, for 20% capacity) compared to allocating less power budget (43.4% saving, for 20% power). The SH-BM and PSDT exhibit similar high sensitivity to capacity budget; however, both algorithms are too sensitive also to power budget allocation compared to VPP-BM. The saving ratios of applying PS and LL algorithms have almost the same values. This can be justified by the aggregated storage units' large capacity and power budgets compared to the total aggregated load.

### IV. KEY FINDINGS AND RECOMMENDATIONS

In response to the research questions, as outlined in the motivation section (1.1), the main takeaways from these case studies

TABLE I BILL SAVING FOR DIFFERENT BATTERIES CAPACITY AND POWER RATIOS

	SH-	VPP-	PS	PSDT	LL	SB-
	BM	BM	(%)	(%)	(%)	SC
	(%)	(%)				(%)
20% Power	26.76	43.42	15.30	24.17	15.25	
20% Capacity	16.18	26.45	15.33	18.04	14.86	
Nominal	36.41	45.85	15.30	43.63	15.39	23.72
Annual Average	31.89	39.358	13.16	36.90	0.54	17.59

are as follows:

- Among all these control strategies, VPP-BM will bring the maximum economic benefits for consumers and the aggregator.
- 2) Compared to the non aggregated control strategy (SH-BM), the VPP aggregation concept in VPP-BM and PSDT can help to reduce the peak. For the above control approaches, the aggregated peaks are still much higher than the original peak. These strategies dramatically can shift the peak load from daytime to nighttime, which may harm the grid operation.
- The LL and PS strategies can contribute to peak shaving and thus very much grid supportive, but may not be the good solutions for the consumers and aggregator.
- 4) Optimal sizing of the aggregated storage is also crucial to maximise the benefits. All strategies can be implemented at different capacity and power budgets, which will bring some economic benefits, but the VPP-BM shows more stability in economic performance and also can be securely extended

for multi-service provision in future. New control strategies can be developed in future.

5) Results show that VPP-BM can be the best economic choice for the consumers and aggregators, but in the long run, with the presence of high number storage and capacity, the network daily profile could be changed with nighttime or multiple peaks. This will hedge the grid from some kind of cobra phenomenon [29] relating to the fast development of VPP aggregation and the quick transition of the local and wholesale energy market. Both the regulator authority and policymakers need to carefully consider these findings for future market development. Further work deserves the development of improved control strategies to maintain the benefits of consumers, aggregators and network operators in one frame. A new business model should also be adopted for this.

To alleviate the gap between the technical and economic benefits of the above-mentioned algorithms, another possible solution can be to develop a novel consumption tariff scheme to enhance the synergy between local energy market development and grid support. Indeed, to engage prosumers more in the future local electricity market, an attractive consumption tariff is to be applied to justify the initial prosumers' investment. However, the scheme can also include a kind of awards or penalties based on network requirement compliances.

# V. CONCLUSION

Five different control approaches for a residential VPP platform integrating rooftop PV and battery ES have been analysed in this paper. The controller has been synthesised through the resolution of the MILP problem formulation for a horizon decision interval that considers PV generation and load demand forecast.

Extensive simulation studies have been carried out using the time series real measured data from a real-life demonstration project. Moreover, a sensitivity analysis has also been presented to assess the impact of reducing the battery power and capacity budgets on the control outputs and economic returns. The Irish day-night tariff scheme is used to evaluate the techno-economic impact of each algorithm, and a zero feed-in tariff is considered in compliance with the Irish regulation for residential PV systems.

The sensitivity analysis has also shown that the capacity of batteries mainly drives VPP-BM economic saving. An optimal financial incentive can be gained while considering only a small portion of the power budget. This will give a potential asset to the VPP to participate in other applications, mainly the power one, and create an additional revenue stream to support their business model. In this case, ancillary services markets to reserve markets can be attractive options. A design of a sophisticated optimisation algorithm will play a key role here, and the aggregator needs to develop good flexibility to operate in both local and wholesale energy markets and coordinate its operation in both markets.

# APPENDIX

# ACKNOWLEDGMENT

This work is part of StoreNet project and the authors acknowledge the support from both the Department of the Environment, Climate and Communications and the Industry partners.

#### REFERENCES

- K. Bruninx, H. Pandžić, H. Le Cadre, and E. Delarue, "On the interaction between aggregators, electricity markets and residential demand response providers," *IEEE Transactions on Power Systems*, vol. 35, no. 2, pp. 840–853, 2019.
- [2] M. Di Somma, G. Graditi, and P. Siano, "Optimal bidding strategy for a der aggregator in the day-ahead market in the presence of demand flexibility," *IEEE Transactions on Industrial Electronics*, vol. 66, no. 2, pp. 1509–1519, 2019.
- [3] C. A. Correa-Florez, A. Michiorri, and G. Kariniotakis, "Optimal participation of residential aggregators in energy and local flexibility markets," *IEEE Transactions on Smart Grid*, vol. 11, no. 2, pp. 1644–1656, 2020.
- [4] T. Xu, W. Wu, Z. Wang, and T. Zhu, "Coordinated optimal dispatch of vpps in unbalanced adns," *IET Generation, Transmission Distribution*, vol. 14, no. 8, pp. 1430–1437, 2020.
- [5] Z. Ullah, G. Mokryani, F. Campean, and Y. F. Hu, "Comprehensive review of vpps planning, operation and scheduling considering the uncertainties related to renewable energy sources," *IET Energy Systems Integration*, vol. 1, no. 3, pp. 147–157, 2019.
- [6] N. Naval, R. SÃ; nchez, and J. M. Yusta, "A virtual power plant optimal dispatch model with large and small-scale distributed renewable generation," *Renewable Energy*, vol. 151, pp. 57 – 69, 2020.
- [7] B. Celik, R. Roche, D. Bouquain, and A. Miraoui, "Decentralized neighborhood energy management with coordinated smart home energy sharing," *IEEE Transactions on Smart Grid*, vol. 9, no. 6, pp. 6387–6397, 2018.
- [8] E. Yao, P. Samadi, V. W. S. Wong, and R. Schober, "Residential demand side management under high penetration of rooftop photovoltaic units," *IEEE Transactions on Smart Grid*, vol. 7, no. 3, pp. 1597–1608, 2016.
- [9] Y. Huang, L. Wang, W. Guo, Q. Kang, and Q. Wu, "Chance constrained optimization in a home energy management system," *IEEE Transactions on Smart Grid*, vol. 9, no. 1, pp. 252–260, 2018.
- [10] A. Soares, O. De Somer, D. Ectors, F. Aben, J. Goyvaerts, M. Broekmans, F. Spiessens, D. van Goch, and K. Vanthournout, "Distributed optimization algorithm for residential flexibility activation - results from a field test," *IEEE Transactions on Power Systems*, vol. 34, no. 5, pp. 4119–4127, 2019.
- [11] F. Elghitani and W. Zhuang, "Aggregating a large number of residential appliances for demand response applications," *IEEE Transactions on Smart Grid*, vol. 9, no. 5, pp. 5092–5100, 2018.
- [12] J. Kiljander, D. Gabrijelčič, O. Werner-Kytölä, A. Krpič, A. Savanović, Ž. Stepančič, V. Palacka, J. Takalo-Mattila, and M. Taumberger, "Residential flexibility management: A case study in distribution networks," *IEEE Access*, vol. 7, pp. 80 902–80 915, 2019.
- [13] J. Leitao, P. Gil, B. Ribeiro, and A. Cardoso, "A survey on home energy management," *IEEE Access*, vol. 8, pp. 5699–5722, 2020.
- [14] B. Celik, S. Suryanarayanan, R. Roche, and T. M. Hansen, "Quantifying the impact of solar photovoltaic and energy storage assets on the performance of a residential energy aggregator," *IEEE Transactions on Sustainable Energy*, vol. 11, no. 1, pp. 405–414, 2019.
- [15] S. Bahrami, Y. C. Chen, and V. W. S. Wong, "Deep reinforcement learning for demand response in distribution networks," *IEEE Transactions on Smart Grid*, vol. 12, no. 2, pp. 1496–1506, 2021.
- [16] B. Behi, A. Baniasadi, A. Arefi, A. Gorjy, P. Jennings, and A. Pivrikas, "Cost benefit analysis of a virtual power plant including solar pv, flow battery, heat pump, and demand management: A western australian case study," *Energies*, vol. 13, no. 10, 2020.
- [17] M. Bahloul and S. K. Khadem, "An analytical approach for techno-economic evaluation of hybrid energy storage system for grid services," *Journal of Energy Storage*, vol. 31, p. 101662, 2020.
- [18] M. Bahloul, A. Majumdar, M. Daoud, and S. Khadem, "Energy storage system: A potential flexibility resources to accelerate the decarbonisation of smart grid network," *IET Conference Proceedings*, pp. 14–20, January 2021.
- [19] S. Riaz and P. Mancarella, "On feasibility and flexibility operating regions of virtual power plants and tso/dso interfaces," in 2019 IEEE Milan PowerTech, 2019, pp. 1–6.
- [20] S. Wang and W. Wu, "Aggregate flexibility of virtual power plants with temporal coupling constraints," *IEEE Transactions on Smart Grid*, vol. 12, no. 6, pp. 5043–5051, 2021.
- [21] W. Kong, F. Luo, Y. Jia, Z. Y. Dong, and J. Liu, "Benefits of home energy storage utilization: An australian case study of demand charge practices in residential sector," *IEEE Transactions on Smart Grid*, vol. 12, no. 4, pp. 3086–3096, 2021.

- [22] X. Wang, Z. Liu, H. Zhang, Y. Zhao, J. Shi, and H. Ding, "A review on virtual power plant concept, application and challenges," in 2019 IEEE Innovative Smart Grid Technologies - Asia (ISGT Asia), 2019, pp. 4328–4333.
- [23] Sonnen. Operating instructions for operators sonnenbatterie eco 9.43. [Online]. Available: https://midsummerwholesale.co.uk/pdfs/sonnen-943-user-manual. pdf
- [24] M. A. Hannan, M. M. Hoque, A. Hussain, Y. Yusof, and P. J. Ker, "Stateof-the-art and energy management system of lithium-ion batteries in electric vehicle applications: Issues and recommendations," *IEEE Access*, vol. 6, pp. 19362–19378, 2018.
- [25] S. Monie, A. M. Nilsson, J. Widén, and M. Åberg, "A residential communitylevel virtual power plant to balance variable renewable power generation in sweden," *Energy Conversion and Management*, vol. 228, p. 113597, 2021.
- [26] Y.-G. Park, J.-B. Park, N. Kim, and K. Lee, "Linear formulation for short term operational scheduling of energy storage systems in power grids," *Energies*, vol. 10, p. 207, 02 2017.
- [27] CRU, "Commission for regulation of utilities :electricity and gas retailmarkets report q1 2019," 2019 [Online]. [Online]. Available: https://www.cru.ie/wp-content/uploads/2019/08/ CRU19101-Q1-2019-Retail-Markets-Report.pdf
- [28] SEAI, "Sustainable energy authority of ireland :understanding the factors that affect energy prices is important for ireland. it helps businesses, householders and policymakers to respond appropriately." 2022 [Online]. [Online]. Available: https://www.seai.ie/data-and-insights/seai-statistics/key-statistics/prices/
- [29] S. Nykamp, M. G. Bosman, A. Molderink, J. L. Hurink, and G. J. Smit, "Value of storage in distribution grids - competition or cooperation of stakeholders?" *IEEE transactions on smart grid*, vol. 4, no. 3, pp. 1361–1370, 2013.



Jerry Cotter is a Technical Manager for Solar PV and Battery storage within Electric Ireland. He is Solar Power (PV) Expert with a demonstrated history of working in the Renewable Energy industry. He is a specialist in Solar Power Installations, Energy Efficiency, Project Management, Energy Storage, and Off-grid Power Solutions



Mohamed Daoud (SM'19) received the B.Sc. and M. Sc. degrees in electrical engineering from Alexandria University, Egypt, in 2009 and 2013, respectively, and the Ph.D. degree in Electrical Engineering from Politecnico di Torino, Italy. He was with the International Energy Research Centre (IERC), Ireland, from 2019 to 2021. He is currently with Siemens Energy, Germany. His research interests include energy conversion, renewable energy, control systems, and electric machines.



Mohamed Bahloul joined the IERC team in March 2017 as a researcher. He is involved in projects related to the smart grid, storage systems and renewable energy systems. He received the master's degree in modelling information and systems from the University of Picardie Jules Verne, Amiens, France, the M.Sc. degree in international business management from ESIEE and ESC, Amiens, France, and the Ph.D. degree in electrical and system control engineering from the National School of Engineer Sfax, Sfax, Tunisia, in 2015. He was a Postdoctoral Researcher and a Teaching Assistant with

the University of Sfax, from 2015 to 2017. He was also a Visiting Researcher with the University of Picardie Jules Verne, Amiens, and the Federal University of Technology of Parana, Brazil. His research interests include robust control, adaptive control, fuzzy logic control, states and parameters estimation, optimisation techniques and their applications for real-time control of electrical machine, power conversion systems, renewables, energy storage systems, and other mechatronic systems.



Aziz Saif received the double M.Sc. degree in power engineering from the Royal Institute of Technology, Sweden, and the Eindhoven University of Technology (TU/e), Eindhoven, The Netherlands, in 2014. He is currently working as a Research Associate with the International Energy Research Centre, Tyndall National Institute. His research interests include the operation of power grid with high renewable generation, local electricity markets in distribution grids, power system dynamics and stability, and demand response.



Liam Breathnach holds an M.Sc degree in Applied Computing for Technologies, 2012, from DIT, Ireland. He is actually a Technology Director, Grid Scale Energy Storage at SMS plc. He is a specialist in the modelling and analysis of power systems with over fifteen years of prior experience working in the power system studies field at ESB International. He has undertaken numerous transmission and distribution projects both in Ireland and internationally.



Shafi Khadem (M'11, SM'21) received a Ph.D. degree in electrical and electronic engineering in 2013. Since 2015, he has been a Senior Researcher and leads the Embedded and Distributed Generation Systems (EDGE) Group at the IERC. He is research active in smart grids with a special focus on grid stability, power quality, microgrids, virtual power plants, and local electricity markets. He is active in IEEE PES, Smart Grids and Smart Cities Societies and serves as an Associate Editor for IEEE Access, MPCE.