# Design and Field Implementation of a Hierarchical Control Solution for Residential Energy Storage Systems

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***Abstract*—This paper presents an innovative approach to the design and real-life field implementation of a hierarchical control solution for a residential ESS (energy storage system) for consumers/prosumers. The proposed control solution minimises residential prosumers' electricity bill. It consists of an offline controller (secondary level) implemented in the cloud, which works in total synergy with a local real-time controller (primary level) at the ESS. The offline controller proposes an optimal day-ahead energy management strategy using the forecasted demand and PV generation; whereas the local real-time controller is responsible for the management strategy in the best suitable way while dealing with the system real-time constraints and forecast uncertainties. Distributed implementation and demonstration of the solution have been performed through a cloud control platform, operated by an aggregator. Moreover, an offline analysis has been carried out to assess the performances of the real-life implementation outputs and verify the effectiveness of the proposed approach. The obtained results show promising performances of the overall system and implementation approach. This will further ease the integration process of consumer/prosumer with the future virtual power plant or local electricity market operator. The main concept has been developed to be implemented within the StoreNet pilot project platform.**

***Index Terms*—Energy management system, hierarchical control, residential EES, StoreNet pilot project, virtual power plant, local electricity market.**

## NOMENCLATURE

| | |
|---|---|
| $P_{L,k}^{\sim}$: | House total load |
| $P_{G/B,k}^{\sim}$: | Grid to battery AC power |
| $P_{B/H,k}^{\sim}$: | Battery to the house AC power |
| $P_{PV/H,k}^{\sim}$: | PV to house power AC power |
| $k_T$: | decision horizon |
| $\Psi_k$: | Time of use tariff |
| $P_{H,k}^{\sim}$: | Total household consumption |
| $P_{PV/B,k}^{\sim}$: | PV to the battery AC power |
| $P_{PVGen,k}^{-}$: | Total DC power PV generation |
| $\eta_{PV}^{\sim}$: | DC/AC PV conversion efficiency |
| $\eta_{PV}^{-}$: | DC/DC PV conversion efficiency |
| $P_{C,k}^{Ref-}$: | Reference battery charging |
| $P_{D,k}^{Ref-}$: | Reference battery discharging |
| $\overline{P_B^{-}}$: | Maximum DC Battery power output |
| $\underline{P_B^{-}}$: | Minimum DC Battery power output |
| $\overline{SoC}$: | Maximum battery SoC value |
| $\underline{SoC}$: | Minimum battery SoC value |
| $SoC_k^{Ref}$: | Battery reference state of charge |
| $\eta_B^{C\sim}$: | Battery AC charging efficiency |
| $\eta_B^{D\sim}$: | Battery AC discharging efficiency |
| $SoC_0$: | Initial battery SoC |
| $P_{B,k}^{SD}$: | Battery self discharge |
| $SoC_{k,t}^{Ref}$: | Real-time t battery reference state of charge |
| $SoC_{r,t}$: | Measured battery SoC |
| $P_{Lr,t}$: | Measured load at the time t |
| $P_{Reg,t}$: | SoC regulation power signal |
| $P_{Cr,t}^{-}$: | Real-time battery charging control signal |
| $P_{Dr,t}^{-}$: | Real-time battery discharging control signal |

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## I. INTRODUCTION

NOWADAYS, residential consumers are increasingly engaged in taking part in the technological and environmental challenges facing electricity system modernisation. Residential consumers are becoming prosumers, participating in reshaping the way of operation and management of the electricity system, and introducing new segments in the energy market [1], [2].

It is to be noted that, in 2016, consumers worldwide spent an estimated $67 billion [3], which is projected to be $189.5 billion by 2023 [4], on smart home hardware, services, and installation to make their homes more energy-efficient, secure, and comfortable. Investing in rooftop PV generation is one of the main households' interests. It presents a big portion of the consumers' investments. Rooftop solar photovoltaic incentive programmes have been widely deployed and have been very effective in many countries. Compared to 2020, the residential solar installations in the U.S. were raised by 13% in 2021 [5]. This enables the consumers to reduce their energy bills, increase their efficiency and self-consumption indices, and participate in the climate change action.

Moreover, the sharp decrease in energy storage system (ESS) cost has bent the consumer barrier of battery deployment at the residential level. Indeed residential ESSs are getting more interest and end-user acceptance. Furthermore, it plays a major role in reducing electricity bills, especially in the case of the deployment of dynamic electricity tariffs at the consumer level. According to [6], the global residential ESS market is estimated to achieve a 22.88% compound annual growth rate between 2019 – 2024. The global market value is estimated to reach 17.5 billion $ by 2024, compared to an estimated value of 6.3 billion in 2019.

It is very much possible that PV and ESS will be the integral part of the smart and energy efficient residential houses in the coming days. Aggregation of these resources for a better and efficient operation of the distribution network are being considered now-a-days and this will also increase the prosumer's benefits, such as bill minimisation. Two major aggregator models for residential prosumer/consumers can be distinguished in the literature. In the first model, the aggregator creates a new market framework. The prosumers, in this case, will develop their own strategy to maximise their output in the new framework. The aggregator plays the role of the electricity supplier. This model is very ambitious and exhibits high flexibility for citizen engagement in the energy transition. However, the concept is still at an early stage and requires more assessment to be implemented within the actual energy market. The model proposed in [7] is a relevant example here. The aggregator in the latter paper decides the electricity pricing based on the day-ahead wholesale market and consumers' forecasted consumption and preference. In the second model, the aggregator takes the role of a facilitator [8], [9]. The main objectives are 1) to help the prosumers optimally manage their local resources for achieving different kinds of objectives, 2) to ease the integration of residential prosumers into different existing electricity market layers. This model is adequate for immediate implementation, and the technology readiness shows increasing potential in the market. Our paper deals with this second model. It will assess the implementation of a complete solution for residential prosumer equipped with battery energy storage and rooftop PV generator to minimise electricity bills in a day/night time of use (TOU) electricity tariff scheme framework.

Residential consumers exhibit different objectives and preferences as: minimising day-ahead operation costs [1], achieving autonomous power supply and consumption [10], improving the economical benefits/efficiency [11], [12], supporting grid quality operation [13], [14], etc. Hence, different scheduling and control techniques have been developed. Noting that the design of a control solution / residential management system is not a trial task. It has been attracting a huge interest recently.

Dealing with real-time operational constraints and minimising the forecast uncertainties are among the main control design challenges. Usually, optimal battery dispatch formulations are related to designing the charging-discharging signal of the battery and considering the load demand and PV generation forecast [15]. However, the output of the optimisation algorithms may not be directly applied in practice due to the stochastic nature of the load and generation [16], [17]. Moreover, optimisation algorithms may use modelling assumptions to identify the system's parameters. In order to address the above shortcoming, real-time/robust control approaches have been proposed in the literature using Heuristic/rule-based [18], meta-heuristic [13], [19], deterministic techniques [8], [9].

The modality of the control solution also presents many design challenges. To achieve an optimal/near-optimal operation control system engineers have to deal with multiple objectives that are sometimes conflicting and not on the same time scale. The authors in [20], review different control strategies and give an insight into the hierarchical control approach. The latter control structure is getting increasing interest in residential level thanks to its design flexibility and ability to combine multi-objectives and time scale constraints in a unique control framework [21]. Practicability and stable operation of such a control structure have been assessed in [22] using a real-time testbed.

A very important practical point to consider while designing the implementation framework for residential ESS is the implementation of control solution; centralised/remote, end-user localised/decentralised, or distributed. In a centralised solution, the aggregator hosts the entire controller. This may achieve optimal efficiency, but the full control of the ESS at the end-user premises would be hardly accepted [23]. Moreover, the real-time management of the local resources is very challenging, requiring a fast, reliable, and robust communication network, and specially when the aggregator is geographically located in a different place and operate the overall controller from a cloud control platform. A control/communication failure will have a dramatic impact on the system. In decentralised solutions, adequate forecasting tools, sophisticated hardware/software, and high-performance controllers should be installed at the residential level, which may raise techno-economic concerns about the solution, considering the low energy consumption level of residential houses. Distributed implementation solutions are gaining potential interest. While enabling to overcome the shortcoming of centralised and decentralised solutions, it offers a high level of flexibility for designing the control solution and path the way toward better integrating residential prosumers into the transactive energy market [23]. The concept is recently addressed, and the distributed implementation of a control solution for optimally managing residential prosumers' resources using sophisticated forecasting tools in the cloud is still an open topic.

### A. Related Work

Despite the surge of interest and ongoing industrial effort, there are only a few works found with the objective that can closely match the implementation of a complete, efficient, and practical solution for residential prosumers considered in this paper. For instance, the author in [9] proposed an online control algorithm based on Lyapunov optimisation to manage ESS sharing for residential consumers. Distributed implementation is suggested while the online controller is implemented locally; however, an offline parameters design is managed by a third party/aggregator. However, the proposed solution do not target to minimise the electricity expenses in a TOU electricity supply market as this paper aims.

A real-time control algorithm based on MPC in distributed implementation mode has been proposed in [24]. It ensures that optimal control decisions are taken locally and maximise local self-consumption. The proposed approach suggests coordinating real-time operating conditions and day-ahead/intra-day energy dispatch through the MPC optimisation framework. Noting that the MPC deployment in real-time controller is computationally intensive, require extensive processing capabilities. Thus, the solution has limited applicability to be implemented in residential environments.

A distributed implementation of two-layer control strategy of residential ESS for substation constraint management is proposed in [23]. The upper layer is designed to manage the aggregated power output. The second layer, based on MPC approach and control at 5min interval, is locally implemented for each residential house to deal with home energy management. The proposed solution did not assess the real-time controller implementation with load demand and local generation uncertainties.

Another distributed control approach for automatically managing power requirements according to the end-user priorities and utility constraints is proposed in [14]. A heuristic method is proposed (both for online and real-time controllers) to deal with the instantaneous load and grid conditions. Noting that for bill minimisation, the heuristic scheduling approach may not guarantee an optimal solution. Moreover, an adequate real-time control should be proposed to consider forecasting uncertainties and ESS operating conditions. A dynamic programming-based scheduling control scheme for residential ESS is proposed in [25]. It determines the optimal charging/discharging of the ESS to minimise the energy cost for the residential customers based on the real use case of Australian network tariffs. The authors conduct a comprehensive analysis of cost-saving and load re-shaping effect on the ESS, however, the implementation of the solution did not assess the uncertainties and the real-time operation was also not discussed.

A two-layers control framework for using clusters of residential ESS, HVACs, and electric water heaters for energy arbitrage, frequency regulation and peak shaving is also proposed in [26]. It is based on stochastic optimisation scheduling approach and two real-time dispatch methods; an MPC-based and a droop-based real-time dispatch algorithms. The proposed solution suggests 1h interval for offline solution, and the real-time control intervals are 4s and 0.1s, respectively, for the MPC and droop-based real-time dispatch algorithms. This can limit the implementation of such a solution to deal with real-time control approach. Moreover, the implementation aspect is not assessed in this paper. Furthermore, the solution did not consider the local PV generation in the proposed model.

Meta-heuristic approaches had been developed in [13], [27] where a fuzzy logic-based real-time controllers is proposed for residential microgrid for power profile smoothing and reducing renewable generation intermittency impact on the grid. However, the solution did not consider the economic impact of the TOU scheme on the system. Moreover, the shortcoming of such a meta-heuristic approach raise when dealing with the replicability of the control solution for other end-users (as they exhibit different load and generation patterns).

Last but not least, interesting work to mention, which is related to our proposed scheme, is [18]. It develops a two-stage energy management system for residential ESS while considering a cost reduction objective. A combination of offline MPC and real-time rule-based technique has been applied. The offline decentralised controller is designed using demand and generation forecast while solving MILP formulation. Moreover, the authors have considered a reduced 15min resolution for solving the MILP to minimise the forecast uncertainties. However, this will require an increasing forecasting capability as well as an increased computational burden of the offline controller.

### *B. Gaps and Paper Contribution*

Despite the large development of control solutions for residential ESS applications, the validation of most works is assessed by computer simulation [8], [9], and a small number on the lab-scale [13], [18]. However, to the best of the author's knowledge, no clear and detailed proposed work has been developed and validated in real-life applications. This is mainly due to the limited number of pilot projects and the difficulties of directly integrating the control approach in a real-time industrial control platform to demonstrate in real-life application.

From the analysis and discussion above, it can be concluded that there is a knowledge gap in many aspects concerning residential ESS control, and further works should assess: 1) what would be the adequate control structure in real-life to demonstrate a complete control solution? 2) How can a real-time controller coordinate with upper control layers and meanwhile consider real-time operating conditions and constraints? 3) How to efficiently implement the control solution in residential premises? 4) How to leverage academic results to a high TRL (technology readiness level) application?

As a continuous effort to ease the market uptake of novel technologies and assess the smart integration approaches of residential prosumers to the grid, some pilot projects have been developed all over the world [28]. For instance, Con Edison is one of the residential virtual power plant (VPP) pilot projects which has been implemented in U.S. to manage efficiently the installed PV and ESS in residential houses. The Australian SA project presents good learning for the residential prosumer paradigm. It is an ongoing effort, and there is still a lot to learn and demonstrate the potential role of the residential prosumers in decarbonising the future smart grid network. Ireland is taking part in this ongoing effort. The island has been promoting grid edge technologies through the development of the National Energy and Climate Plan [29]. StoreNet pilot project [30], [31] is part of the Irish contribution to the state of the art of understanding and assessing the future role of residential prosumers in promoting smart grid application. StoreNet is an industry-led, collaborative and real-life demonstration project with SOLO Energy (aggregator), Electric Ireland (utility supplier), and ESB Networks (distribution network operator). The demonstration site is located in the Dingle peninsula in the south-west of Ireland. It is formed of twenty houses hosting 10kWhr/3.3kW peak Sonnen lithium-ion battery each. Nine of those houses have installed rooftop 2.4kW PV panels. All of the houses are equipped with smart meters with day/night time of use (TOU) tariff system. The project is demonstrating a business model for the distributed energy storage based virtual power plant which is centrally cloud controlled by SOLO Energy located in Cork, Ireland.

This work can be seen as continuity and building on previous literature works on designing control solutions for residential ESS. It will reduce the aforementioned knowledge gaps in this field while proposing a validation process in high TRL application. Indeed, this paper proposes and demonstrates in real life a novel distributed control solution for the residential prosumers with ESS using a hierarchical design approach. This proposed solution is dealing with a consumer bill minimisation strategy under the TOU tariff scheme. It provides a framework to manage the real-time power flow between the residential load, the battery, the PV generator, and the grid to deal with the main objective of the end-user. The overall control system consists of two control levels; an offline optimisation level which is placed in the cloud and a real-time local control level. At the offline level, a day ahead mixed integer linear programming (MILP) based dispatch optimisation is performed using the day ahead forecasting of load demand and PV generation. However, at the local level, the implementation of the designed offline strategy is assessed considering the real-time demand, PV generation, and system data. The offline formulation is structured to align with the considered bill minimisation objective for the consumer, considering the implementation and replicability of the whole proposed solution in the operational environment. The contribution of this paper to current knowledge and practices are:

- A real-life control structure of residential ESS and its easy integration into a virtual power plant is assessed. A complete and replicable industry-based hierarchical control solution is proposed considering onsite hardware/software resources in a real-life demonstration project.
- An adaptive real-time local controller is proposed in order to improve the synergy between proposed control levels and get better flexibility and robustness. It considers both real-time operating conditions and constraints.
- A distributed implementation of the proposed approach is performed within a residential house in a real-life environment. Efficient implementation, in term of computational and ESS deployment, is considered. The solution has been designed to integrate the available computational resources in StoreNet Project efficiently. Moreover, the algorithm itself enables efficiently managing the battery state of charge within general SOC limits for maintaining battery health and life.
- To validate the performance of the proposed solutions high TRL (7-8), the implementation of offline-online control strategy is done in real-life demonstration project, where the offline controller is placed in the cloud. This will ease the integration of consumers/prosumers with the VPP/Community based local electricity network/market controller in future.

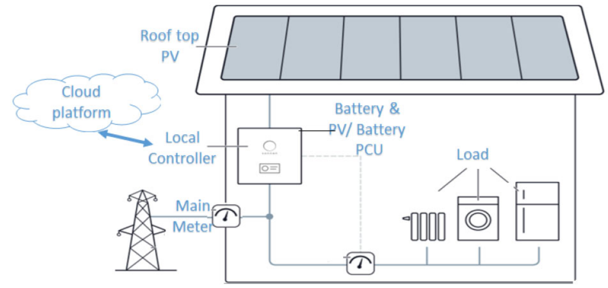


Fig. 1. House with PV/ESS and smart metering system.

The rest of this paper is organised as follows: a detailed description of the considered system is presented in Section II. Section III deals with the design of the proposed control solution. Real life field implementation case study is presented in Section IV, and an offline analysis in the simulation environment is assessed in Section V. Finally, Section VI concludes this paper and gives insight into the obtained results and recommendations for future work.

## II. System Description and Problem Formulation

The main purpose of this paper is to design an efficient and simple control solution for the residential consumers/prosumers with ESS to minimise their electricity bills. Fig. 1 describes the main components of a house. Depending on the control objectives, the battery can charge directly from the grid and/or from the PV, the load can be powered either by the PV, the battery or directly from the grid. A power conversion unit ensures the PV and battery power conditioning. A real-time local controller is managing the battery charging/discharging. The second level controller is on the cloud and interfaces the communication framework with the local controller, ensuring the data acquisition, management, and implementation of certain predefined control sequences.

This house model is a part of the StoreNet project. The control platform is managed by an independent aggregator – a third party entity (in this project, it was SOLO Energy). The company is located in Cork, Ireland; however, the houses are in the Dingle peninsula, Ireland (almost 130 km from the company location). This company has developed the software, hardware, and IoT for this project.

## III. Design of Hierarchical Controller

The main functionalities of the proposed hierarchical controller are shown in Fig. 2. It consists of upper and lower layers. Both the Sonnen and SOLO interface and control platform are used. The upper control layer uses the forecasted data to perform the day-ahead offline optimisation in the cloud. However, the lower layer uses mainly SOLO interface and control platform for monitoring and performing real-time control of the whole system.

The solution is designed considering one day operational time period. Each day is divided into $k_T$ time slots having T duration. The time slot duration usually depends on the forecasted PV generation and load signals time resolution. In the first step, a day ahead optimisation algorithm is solved to

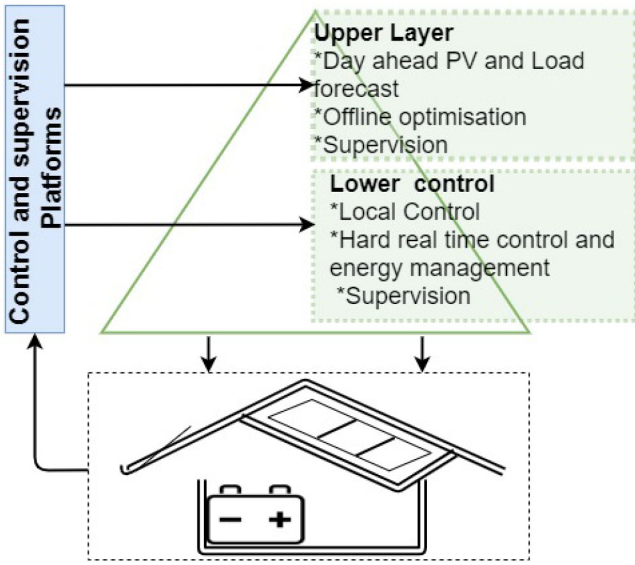


Fig. 2. Functionalities of the hierarchical control solution.

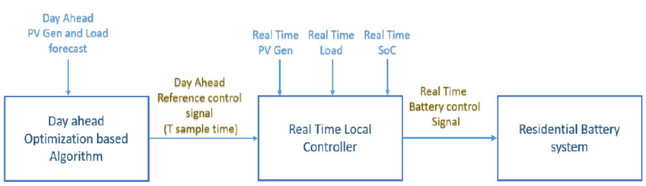


Fig. 3. Control structure.

design the optimal SoC battery reference. This is done offline at the cloud level using data from different forecasting engines. The output signal is then sent to the local controller to implement in the real-time process. The real-time controller will allow implementing the designed charging-discharging strategy in the best suitable way while dealing with the system constraints, intermittency of the load demand and PV generation, system modelling and identification of uncertainties. The inputs and outputs of the control structure are shown in Fig. 3. Details of the controller are discussed in the following sections.

### A. Day Ahead MILP Offline Optimisation (OffCtr)

A self-optimisation under TOU scheme algorithm is considered in this work while considering zero Feed-in Tariff (FIT). In other words, this algorithm is dealing with the bill minimisation objective. The main focus is to reduce the electricity purchase, especially in the on peak TOU scheme time. This objective can be presented as

$$J = min \sum_{k=1}^{k_T} \Psi_k P^{\sim}_{H,k} \tag{1}$$

where $k_T$ is the decision horizon, $\Psi_k$ denotes TOU tariff at the time interval k. $P^{\sim}_{H,k}$ is total household consumption and can be computed using equation (2). For the rest of this paper, the upper cases $^{\sim}$ and $^{-}$ refer respectively the AC and DC parameters.

$$P^{\sim}_{H,k} = P^{\sim}_{L,k} + P^{\sim}_{G/B,k} - P^{\sim}_{B/H,k} - P^{\sim}_{PV/H,k} \tag{2}$$

$P^{\sim}_{L,k}$ is the total load and $P^{\sim}_{G/B,k}$, $P^{\sim}_{B/H,k}$ , and $P^{\sim}_{PV/H,k}$ denote respectively the grid to battery, the battery to the house, and the PV to house power exchange at the interval $k$.

A MILP approach is used to reformulate the day-ahead optimal scheduling problem. This can be achieved while considering the following linear inequality and equality constraints described in (3) to (10).

$$P^{\sim}_{H,k} \geq 0, \ \forall k \tag{3}$$

$$P^{\sim}_{PV/H,k} + P^{\sim}_{B/H,k} \leq P^{\sim}_{L,k}, \ \forall k \tag{4}$$

$$1/\eta^{\sim}_{PV} P^{\sim}_{PV/H,k} + 1/\eta^{-}_{PV} P^{-}_{PV/B,k} \leq P^{-}_{PVGen,k}, \ \forall k \tag{5}$$

$$\chi_{C,k}\underline{P^{-}_{B}} < P^{Ref-}_{C,k} < \chi_{C,k}\overline{P^{-}_{B}}, \ \forall k \tag{6}$$

$$\chi_{D,k}\underline{P^{-}_{B}} < P^{Ref-}_{D,k} < \chi_{D,k}\overline{P^{-}_{B}}, \ \forall k \tag{7}$$

$$\chi_{C,k} + \chi_{C,k} \leq 1, \ \forall k \tag{8}$$

$$\underline{SoC} < SoC^{Ref}_{k} < \overline{SoC}, \ \forall k \tag{9}$$

$$SoC^{Ref}_{k_T} = \overline{SoC_h} \tag{10}$$

where $P^{\sim}_{PV/B,k}$, $P^{-}_{PVGen,k}$ are respectively the PV power used to charge the battery and the total PV power generation at the time interval $k$. $\eta^{\sim}_{PV}$, and $\eta^{-}_{PV}$ are the DC/AC and DC/DC conversion efficiency coefficients of the PV power conversion unit. The reference charging and discharging battery power signals at the time interval $k$ ($P^{Ref-}_{C,k}$ and $P^{Ref-}_{D,k}$) are described respectively in (11) and(12). $\overline{P^{-}_{B}}$ and $\underline{P^{-}_{B}}$ denote respectively the maximum, and the minimum battery charging and discharging. $\chi_{C,k}$ and $\chi_{D,k}$ refer to the charging and discharging battery states. In (9) the battery state of charge (SoC) operation boundaries are presented respectively by $\underline{SoC}$ and $\overline{SoC}$. The time interval $k$ battery reference state of charge ($SoC^{Ref}_{k}$) is computed using (13), and it's value at the end of decision horizon ($SoC^{Ref}_{k_T}$) is chosen to be equal to a predefined value ($\overline{SoC_h}$) as described by the equality constraint (10).

$$P^{Ref-}_{C,k} = \eta^{C\sim}_{B} P^{\sim}_{G/B,k} + P^{-}_{PV/B,k}, \ \forall k \tag{11}$$

$$P^{Ref-}_{D,k} = \frac{1}{\eta^{D\sim}_{B}} P^{\sim}_{B/G,k} + \frac{1}{\eta^{D\sim}_{B}} P^{\sim}_{B/H,k}, \ \forall i,k \tag{12}$$

$$SoC^{Ref}_{k} = SoC_0 + \sum_{k=1}^{k_T} \left( P^{Ref-}_{C,k} - P^{Ref-}_{D,k} - P^{SD}_{B,k} \right) \Delta k \tag{13}$$

$\eta^{C\sim}_{B}$, and $\eta^{D\sim}_{B}$ are the battery charging and discharging efficiency coefficients, $SoC_0$ is the initial battery SoC, and $P^{SD}_{B,k}$ denotes the battery self discharge for a time interval $k$.

### B. Real-Time Local Controller (RtCtr)

The lower or the primary level of the proposed solution is the real-time control layer. Both proposed control levels have to work in synergy in order to efficiently manage the power flow behind the meter at the household level. The main aim of the local controller design is to ensure the offline control strategy implementation while taking into account forecasting bias and the uncertainties of the parameters. As mentioned in the previous section, the proposed solution uses the time interval $k$ $SoC^{Ref}_{k}$ signal issued from the offline optimisation as a reference signal. Compared to the battery charging/discharging

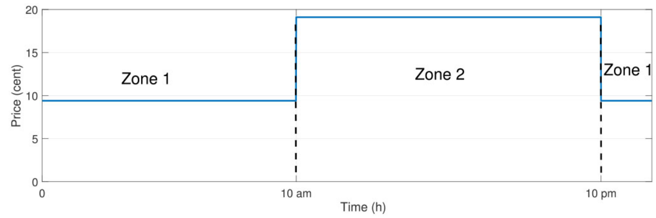


Fig. 4. Zone based Irish day night TOU electricity scheme.

reference signals tracking approach, the SoC reference tracking strategy will improve the implementation flexibility of the offline control strategy in the local level.

Noting that the offline controller is based on decision horizon discretisation into steps within a time slot T. Thus, the use of the time interval $k$ battery SoC as a reference value for the real-time controller is not adequate. Indeed, this will lead to a high peak in battery charging/discharging condition. While keeping in mind that the offline optimisation of charging/discharging output signals have a fixed value for the period $[(k-1)T \; kT]$ of the time interval k, it is proposed in this work to use a linear regression approach to transform a step based SoC reference into linear shape using the following equation:

$$SoC^{Ref}_{k,t} = \frac{\left(SoC^{Ref}_{k} - SoC^{Ref}_{k-1}\right)}{T} mod(t, T) + SoC^{Ref}_{k-1} \quad (14)$$

where $mod$ refers to the modulo operational function, and $SoC^{Ref}_0 = SoC_0$.

The real-time controller is designed considering the Irish TOU day/night electricity tariff scheme. Figure 4 plots the tariff price relative to the time. Two time zones could be distinguished; a day time zone (Zone 2), covering the on-peak tariff period (10 am to 10 pm), and a night time (Zone 1) covering the rest of the time of the whole day. The RtCtr strategy is based on SOC reference tracking control while implementing a real-time control action, depending on the operating time zone. Indeed, during time zone 1, the RtCtr gives preference to battery charging in case of battery SoC regulation or the excess of PV generation. However, during time zone 2, discharging operating mode is given the preference while considering SoC ref tracking and battery charging is triggered only to store the excess PV generation. The detailed real-time algorithm is described in Algorithm 1.

The RtCtr inputs are the time, $SoC^{Ref}_k$, the measured state of charge of the battery ($SoC_{r,t}$), the PV generation ($P_{PVr,t}$), and load ($P_{Lr,t}$). $P_{Reg,t}$ presents the SoC regulation power signal and $P^-_{Cr,t}$ and $P^-_{Dr,t}$ are respectively the real-time charging discharging control signals.

The design of the SoC controller ($P_{Reg,t}$) is of great importance. Indeed, a fixed proportional gain controller approach will impact the controller performances. A small gain value will prevent the controller from reaching the final SoC value at the time interval $k$; however, an important value will increase the battery stress rather than distributing the tracking and regulation action all over the period T of the time interval. Hence, to balance the battery SoC regulation action, it is proposed to split the main action into two sub-actions; 1) instantaneous reference SoC regulation action and (InReg) 2) global time interval K reference SoC regulation action (GlReg). Moreover, an adaptive gain design approach is used. For instance, at the beginning of a time interval, an important weight is allocated to the instantaneous reference SoC regulation compared to the global time interval $k$ regulation action. However, while getting closer to the end of the time interval period, the weighting allocation changes, giving more ponderation weight to the global action. The mathematical formulation is given by (16).

**Algorithm 1** Real-Time Control Algorithm

**begin**
  **compute** $SoC^{Ref}_{k,t}$
  **define** *Time Zone*
  **compute** $\Delta SoC = SoC^{Ref}_{k} - SoC_{r,t}$
  **initialize** $P^-_{Cr,t} = 0,\ P^-_{Dr,t} = 0$
  **if** $Time \in Zone2$ **and** $P_{PV} \le P_L$ **and** $\Delta SoC \le 0$ **then**
    $P^-_{Dr,t} = P_{Lr,t} - P_{PVr,t}$
  **elseif** $Time \in Zone2$ **and** $P_{PV} > P_L$ **then**
    $P^-_{Cr,t} = P_{PVr,t} - P_{Lr,t}$
  **elseif** $Time \in Zone1$ **and** $P_{PV} \le P_L$ **and** $\Delta SoC > 0$ **then**
    $P^-_{Cr,t} = P_{Reg,t}$
  **elseif** $Time \in Zone1$ **and** $P_{PV} > P_L$ **and** $\Delta SoC \le 0$ **then**
    $P^-_{Cr,t} = P_{PVr,t} - P_{Lr,t}$
  **elseif** $Time \in Zone1$ **and** $P_{PV} > P_L$ **and** $\Delta SoC > 0$ **then**
    $P^-_{Cr,t} = max((P_{PVr,t} - P_{Lr,t}), P_{Reg,t}, )$
  **end**
  **if** $SoC_{r,t} \ge \overline{SoC}$ **and** $P^-_{C,t} \ge 0$ **then**
    $P^-_{Cr,t} = 0$
  **elseif** $P^-_{Cr,t} \ge \overline{P^-_B}$ **then**
    $P^-_{Cr,t} = \overline{P^-_B}$
  **end**
  **if** $SoC_{r,t} \le \underline{SoC}$ **and** $P^-_{D,t} \ge 0$ **then**
    $P^-_{Dr,t} = 0$
  **elseif** $P^-_{Dr,t} \ge \overline{P^-_B}$ **then**
    $P^-_{Dr,t} = \overline{P^-_B}$
  **end**
**end**

$$P_{Reg,t} = \frac{K_P}{2} K_A \left(SoC^{Ref}_{k} - SoC\right) + \frac{K_P}{2}\left(SoC^{Ref}_{k,t} - SoC\right) \quad (15)$$

$K_P$ is computed by a simple application of the rule of three (16). $\overline{\Delta SoC}$ is the relative battery SoC variation upon a battery full maximum power charging or discharging operation for a T period of time.

$$K_P = \frac{\overline{P^-_B}}{\overline{\Delta SoC}} \quad (16)$$

The adaptive gain $K_A$ is given by:

$$K_A = \left(1 + a\frac{mod(t, T)}{T}\right) \quad (17)$$

where $a$ is a design control parameter.

## IV. Solution Implementation in Real Life Project

An implementation of the proposed control solution in the real life demonstration was performed with the support of SOLO control and software team. Due to the difficulties of modifying the local battery controller, the proposed real time controller (RtCtr) was adjusted and implemented in the cloud. The latter sends the reference charging-discharging signal as if

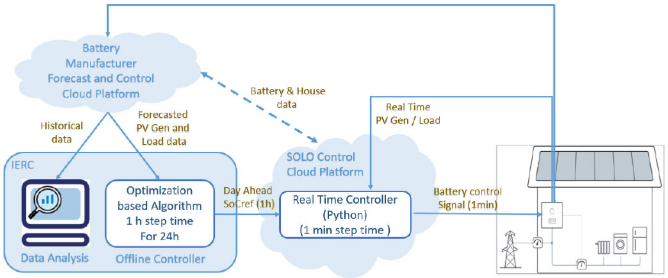


Fig. 5. Real time implementation layout.

it was implemented locally. This also confirms that even with the no/minimum accessibility of battery local controller, VPP controller can implement their control strategy to operate the local system. This will enhance the operational flexibility of the VPP and local system in future. Thus, the proposed solution demonstrates another novelty of this work. The overall implementation of the control and real life testing procedure is illustrated in Fig. 5. To emulate the real-time operation, we have tried to minimise the controller sample time. Indeed, the preliminary tests were performed using a 5 min sample time. These tests allowed us to get a better knowledge of the system and insight into the communication platform and system dynamics. Afterwards, the sample time has been reduced to 1 min interval. The final test was performed on November 3rd 2020, and due to StoreNet project closure scheduled on November 30th, we were not able to go ahead in adjusting the control parameters further.

The offline optimisation algorithm was computed using the forecasted PV generation and load demand data for a typical day, November 3rd 2020. These forecast data were available in a day ahead period. They were fed into the MATLAB program to solve the MILP problem using intlinprog solver. Afterwards, the real-time measured $SoC_{r,t}$, and $P_{PVr,t}$ data were extracted from the cloud server. Battery parameters were taken from the manufacturer data sheet. Efficiency and battery self discharge data were estimated by the authors according to a literature study and some discussion with experts in this field. All considered parameters are given in the Appendix.

For implementation purposes, the RtCtr has been rewritten using Python software. Testing and verification phases have been performed before implementation and control platform integration. The control platform disposes of 1 min mean value load, PV generation, and SoC measurement. These signals have been used to feed the RtCtr. The cloud control platform sends a 1 min sample time charging-discharging control signals to the RtCtr, which were implemented in the local battery EMS and power conversion unit for real time operation.

To start the analysis, Figs. 6 and 7 are depicted. These include a comparison between the forecasted and the real PV generation and load data. As it can be seen, the deployed prediction algorithm was able to forecast more or less the measured signal pattern; however, 1h algorithm sample time is too long period to allow a perfect signal prediction. Moreover, the measured data show high intermittency. Thus, the direct deployment of the prediction algorithm outputs for real-time

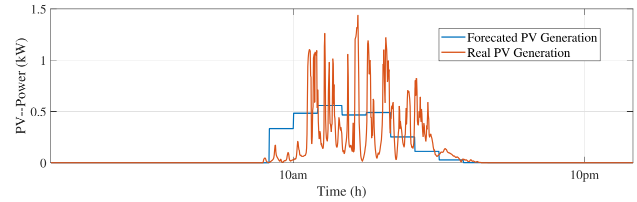


Fig. 6. Forecasted and Real PV Generation.

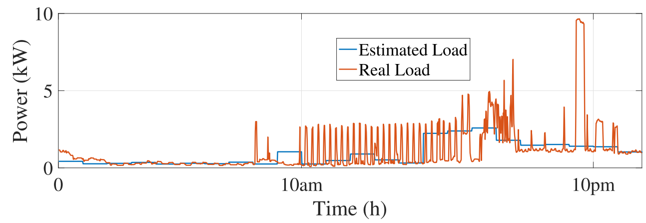


Fig. 7. Forecasted and Real load.

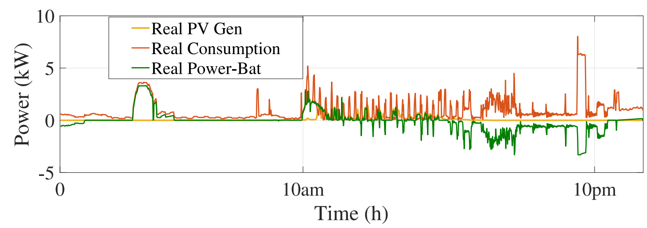


Fig. 8. Performance of proposed controller (24 hrs).

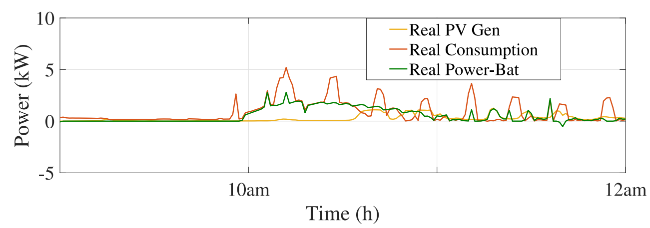


Fig. 9. Zoom on (9 am-12 am): during PV generation.

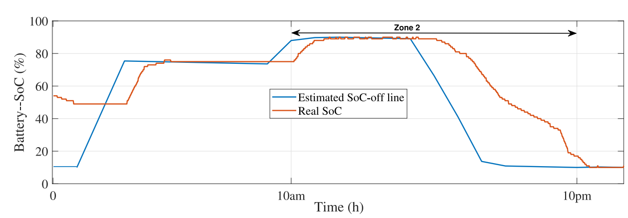


Fig. 10. Battery SoC and estimated ref signals.

implementation is inappropriate, and a real-time intermediate controller is highly recommended.

The outputs of the implemented solution are presented in Figs. 8, 9, and 10. Indeed, the battery power output is plotted in Fig. 8. To analyse the battery charging/discharging pattern, the latter figure includes also a plot of the PV generation and load signals. Moreover, the performance from 9:00 am to 12:00 am is zoomed out and displayed in Fig. 9. Finally the evolution of the real SoC of the battery and the obtained off-line controller output is presented in Fig. 10.

First, the performance of the real-time controller to deal with the PV generation and load uncertainties is well shown in Fig. 8. The battery is charging when there is excess PV generation in the daytime, and the discharging pattern is well controlled.

Second, the high impact of forecast uncertainty on battery SoC can be well observed and displayed while comparing the measured and estimated SoC waveforms in Fig. 10. It has been remarked that the implemented real-time controller considers the period 11:00 am - 11:00 pm as the daytime period instead of 10:00 am - 10:00 pm. Indeed, the battery was charging from the grid between 10:00 am and 11:00 am. The same issue has also been pointed out while analysing the SoC signals. Indeed, it seems that the offline controller output and the real-time controller reference times are not synchronized. The authors have remarked that this problem impacts only this test and did not appear previously while running previous tests performed between May and September 2020. Thus, it is understood that this issue is caused mainly by the change of the daylight saving time in Ireland which was effective from October 25th, 2020. Indeed, it is estimated that a synchronization issue is happening between different servers used to perform the prediction, store the data, and host the controller platform.

Third, it can be seen that the initial battery SoC for the test is higher than the initial predefined value. This issue was caused by some technical problems while preparing the test, and the full discharge of the battery to the initial reference SoC (10%) was not taken place. However, this was not preventing the battery from reaching the reference value before starting the zone 2 time period. In other words, this was a positive point for the test to show the performance of the real-time algorithm to deal with different types of system disturbances and uncertainties and perform a robust implementation of the offline-online control strategy.

Finally, while assuming that the reference time issue is not happening and the daytime zone is from 11:00 am to 11:00 pm, the overall proposed control solution has been performing very well. The battery used all PV generation during zone 1 time period to charge the battery and SoC regulation. However, for zone 2, only the excess of PV generation was used to charge the battery when there is enough room. During zone 2, the battery showed good dynamics in household load powering and SoC regulation. Indeed, the time synchronisation where the local controller (system) and virtual/cloud controller are located in different time-zone must be taking consideration in such type of VPP or market operation in future.

## V. Offline Results Analysis

In order to better analyse field implementation outputs, offline analysis is also carried out. We replicate the whole system in a simulation offline environment. The simulation layout consists of a battery system model block, controller block, real-time inputs, and offline inputs blocks (Fig. 11). The

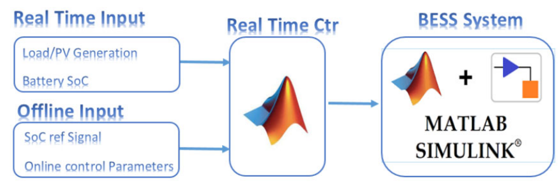


Fig. 11. Simulation layout.

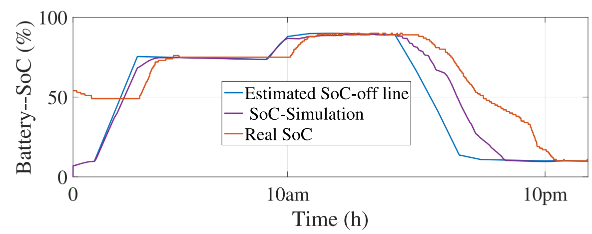


Fig. 12. $SoC_{k,t}^{Ref}$ vs Battery SoC simulation output.

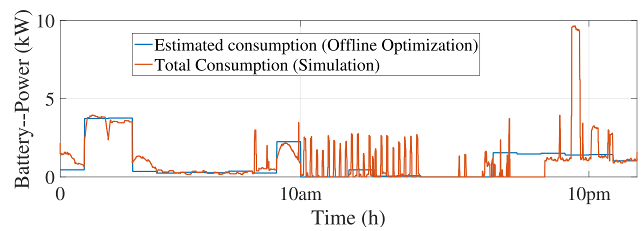


Fig. 13. Estimated consumption (Offline) vs simulated house consumption.

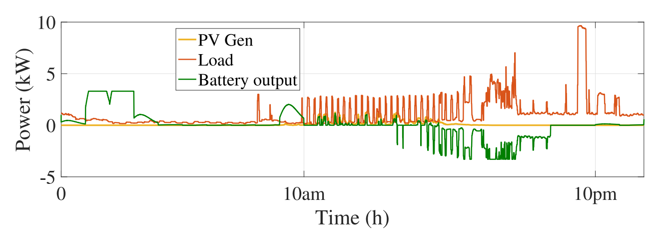


Fig. 14. Simulated battery output vs PV generation and house load.

offline inputs are computed using the offline day-ahead optimisation algorithm that includes mainly battery control ($SoC_k^{Ref}$), and some other control parameters. It is to be recalled that the real-time inputs are the time, and the measured state of charge of the battery ($SoC_{r,t}$), the PV generation ($P_{PVr,t}$), and load demand ($P_{Lr,t}$). These data were extracted from the controller dashboard the next day. It is worth noting that all mentioned measured signals were taken within 1 min resolution time, and all simulations were performed while considering 0.1 s sample time.

The simulation results are described in Figs. 12, 14, and 13. It can be remarked that the SoC follows almost the reference in case of charging or idle operation. However, for discharging, there are some delays between the two presented SoC signals. This can be explained by the fact that the PV generation was not very significant for that day. Then, the battery charging is almost planned to be powered from the grid. However, the forecasted load during the planned discharging period was less than the real one. Then, the battery has to spend more time

TABLE I
COMPARATIVE STUDY-ECONOMIC ASPECT

| | Initial bill (Load expenditure) (€) | New bill (Consumption expenditure) (€) | Saving (%) |
|---|---|---|---|
| OffCtr | 3.607 | 2.603 | 27.835 |
| OffCtr+RtCtr (Simulation) | 4.255 | 3.157 | 25.812 |
| OffCtr+RtCtr (Measured) | 4.255 | 3.168 | 25.557 |

to discharge and to reach the final value at the end of zone 2. Compared to the real life implementation outputs, the pattern of the battery SoC signal follows better the reference signal generated from the offline optimisation. This can be justified by the initial battery SoC mismatch as well as the operational field conditions.

The estimated consumption from running the offline optimisation and the computed total consumption is displayed in Fig. 13. The high impact of hourly forecast and the uncertainties can be well observed here. Similarly, for the real time implementation case, the real time controller has shown a good dynamic and the battery charging/discharging control signal satisfies the design objective (as shown in Fig. 14).

In Table I, a comparative study between the economic output aspect of the day-ahead optimisation and the real-time performance of the system (considering an implementation of the real-time controller) is presented. This table also describes the original bill (considering only the load), the new electricity bill considering the PV and battery contribution, the simulation's saving ratio, and the real-time implementation of the proposed control solution considering the November 3rd 2020 operation condition. The obtained results show that the estimated bill is 15% less than the real one. Thus, the estimated bill (after using PV resources) was less than the simulation or real bill value. It was estimated that using the forecast values and the day-ahead offline optimisation, the system can achieve 27.835% bill saving; however, the real-time implementation outputs were less, respectively by 2.023% and 2.278%, compared to simulation outputs and field implementation results. This is mainly due to the real-time system operation and forecast uncertainties. An important point in this comparative study is the difference in bills between the real-time simulation and field implementation case studies. This difference is mainly caused by the simulation and the field implementation conditions (mentioned above in this section) and the time zone mismatch operation that could impact the control solution performances outputs.

## VI. CONCLUSION

This paper proposes a hierarchical control solution for a residential ESS in the presence of PV micro-generation aiming to minimise the household electricity bill taking into consideration a TOU tariff scheme. The overall solution is designed to optimally control the power flow between the load, battery, PV generator, and the grid to deal with the main objective of the end-user. The day/night time of use (TOU) electricity tariff scheme was considered, and the analysis was performed according to the Irish network regulation imposing a zero Feed-in Tariff (FIT). The proposed solution consists of a distributed implementation of a two control layers: an offline optimisation and a real-time local controller. The VPP cloud control framework was utilised to carry out a partial implementation of the control solution for a residential battery system for the future integration with a VPP controller. The analysis of the different results concluded that the combination of the online controller and the offline optimisation presents a promising solution for a holistic design of a ESS control system. Indeed, the synergy is well tested, and the controller was stable and showed good dynamics. On the other hand, it was pointed out that the deployed forecasting algorithm for hourly load and PV generation prediction affects the performances of the control and the accuracy of the total consumption estimation in this project.

Due to the scarcity of information on battery control system design and the confidentiality of this kind of information from the battery manufacturers, the presented approach and results could be of great importance for future academic researchers and engineers in the industry. Indeed, it can provide a framework for a holistic control approach development for a residential virtual power plant to operate in the future in the local electricity market mechanism. Moreover, it is also showing the way to develop and integrate other control levels to deal with voltage support in the LV network or to provide other grid services.

The proposed control solution in this paper has been designed to fit with the available on-site hardware/software resources. The implementation was performed in real conservative conditions. The online-offline structure of this type of solution showed great potential and can play a significant role in performing a smart integration of residential consumers/prosumers with/without ESS into the local electricity market. The coordination between residential ESS provider and aggregator/battery/market operator has a pivotal role in this case. They should communicate critical information about different hardware and control pieces. Thus the effective implementation of an online/real-time controller requires close technical support from the ESS manufacturer. In the counterpart, the ESS operator/aggregator needs to get a good understanding of real-time ESS operation and control structure while designing the global control architecture for aggregation to perform any grid service operation or participate in other electricity market mechanisms.

## APPENDIX

**Real Data** $\underline{P_B^-} = 0kW$, $\overline{P_B^-}, = 3.3kW$.

**Estimated System data** $\widetilde{\eta}_{PV} = 0.95$, $\overline{\eta}_{PV} = 0.95$, $\eta_B^{C\sim} = 0.95$, $\eta_B^{D\sim} = 0.95$, $SoC_0 = 10\%$, $\underline{SoC} = 10\%$, $\overline{SoC} = 90\%$, $\bar{P}_{bS,k}^h = 7\%/day$.

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