# Aggregator Service for PV and Battery Energy Storage Systems of Residential Building

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***Abstract*—Distributed energy resources (DERs), including photovoltaic (PV) systems, small wind turbines, and energy storage systems (ESSs) are being increasingly installed in many residential units and the industry sector at large. DER installations in apartment buildings, however, pose a more complex issue particularly in the context of property ownership and the distribution of DR benefits. In this paper, a novel aggregator service is proposed to provide centralized management services for residents and DER asset owners in apartment buildings. The proposed service consists of a business model for billing and benefits distribution, and a model predictive control (MPC) control algorithm for managing and optimizing DER operations. Both physical and communication structures are proposed to ensure the implementation of such aggregator services for buildings. Three billing tariffs, i.e., flat rate, time-of-use (TOU), and real time pricing (RTP) are compared by way of case studies. The results indicate that the proposed aggregator service is compatible with the business model. It is shown to offer good performance in load shifting, bill savings, and energy trading of DERs. Overall, the aggregator service is expected to provide benefits in reducing the pay back periods of the investment.**

***Index Terms*—Aggregator, battery energy storage system (BESS), distributed energy resource (DER), model predictive control (MPC).**

## I. INTRODUCTION

IN recent years, a large number of distributed energy resources (DERs) including roof-mounted PV systems and battery energy storage systems (BESS) have been installed in residential units. However, installation of DERs in apartment buildings is lagging behind primarily due to the complexity of home ownership in these multi-dwelling units.

The importance of taking residential buildings into account in optimizing DERs has received attention particularly since domestic energy consumption including use of electric vehicles (EVs) and hybrid electric vehicles has been on the rise over the past decade. In the U.S., residential energy consumption increased 13% between 2010 and 2012 [1].

There is considerable evidence to show that building integrated PV (BIPV) can reduce energy bills effectively [2]. In a study of a German PV system, it was shown how the electrical vehicle (EV) charging system alone could improve profitability of a stand-alone PV system [3]. In yet another study, a PV energy management system of a wind turbine and battery hybrid system were introduced in five houses where surplus energy from renewable generation was stored in a battery bank [4]. The use of microgrids discussed in [5] demonstrates the effectiveness of distributed generation (DG) and DERs in load shifting and $CO_2$ emission reduction. Time-based pricing such as real-time pricing (RTP) and time of use (TOU) as options to minimize utility bills and balance the demand and supply of distribution network are detailed in [6]–[9]. Demand side management especially participating demand response (DR) through direct load control (DLC) in residential houses, buildings and industry sectors are reviewed in [10]–[12].

The aforementioned studies illustrate the effectiveness and performance of combining PV, BESS and other DERs in energy bill savings, as well as load shifting and $CO_2$ emission reduction. However, from a business perspective, the motivation for building residents to participate in energy management services or for stakeholders to actively install DERs is an issue that is rarely taken into consideration.

This paper attempts to address this issue by proposing a novel aggregator as follows: a billing system based on "internal trading" theory is integrated with a central management platform for managing the EV, PV, and BESS with a goal to increase profitability of the service. In order to encourage residents to take part in the aggregator service, a low-price guarantee (LPG) strategy and rewards for participation are used. Additionally, the aggregators give residents the option to choose from three tariffs: flat rate tariff, TOU, and RTP. A five-story apartment building located in West Midlands, U.K., is used to validate the performance of the aggregator in a case study with all three billing tariffs.

## II. GENERAL OVERVIEW OF AGGREGATOR SERVICE

The aggregator service for residential apartment buildings considers not only the benefits of the DER owners, but also the residents in the building. In order to minimize both the investment and operation cost of the aggregator service while maximizing the benefits to the stakeholders, a comprehensive solution, including physical structure, communication infrastructure, billing mechanism, and optimization algorithm of the aggregator service, is presented in this section.

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There is considerable evidence to show that aggregator services could effectively increase bill savings [13], [14]. In general, the aggregator service has two main features: managing DER assets, including PV, EV, and BESS, and selling electricity to the connected residents. The aggregator buys electricity from the energy market at wholesale prices and sells it to the residents with a relatively lower retail price. The aggregator service then settles with the consumers as a whole, so that it can internally trade electricity produced from PV or stored in BESS with the residents.

### A. Physical Structure of the Building

To implement the proposed aggregator service with minimum cost, most of the physical electrical wiring and connections of the buildings will remain the same. Only a few upgrades need to be made, such as on smart remote monitoring and control devices.

As shown in Fig. 1, the residential building is assumed to have a roof-mounted PV system, a BESS and a car park with EV chargers. The BESS is located in a basement or storage rooms and EV chargers are installed in the basement car park.

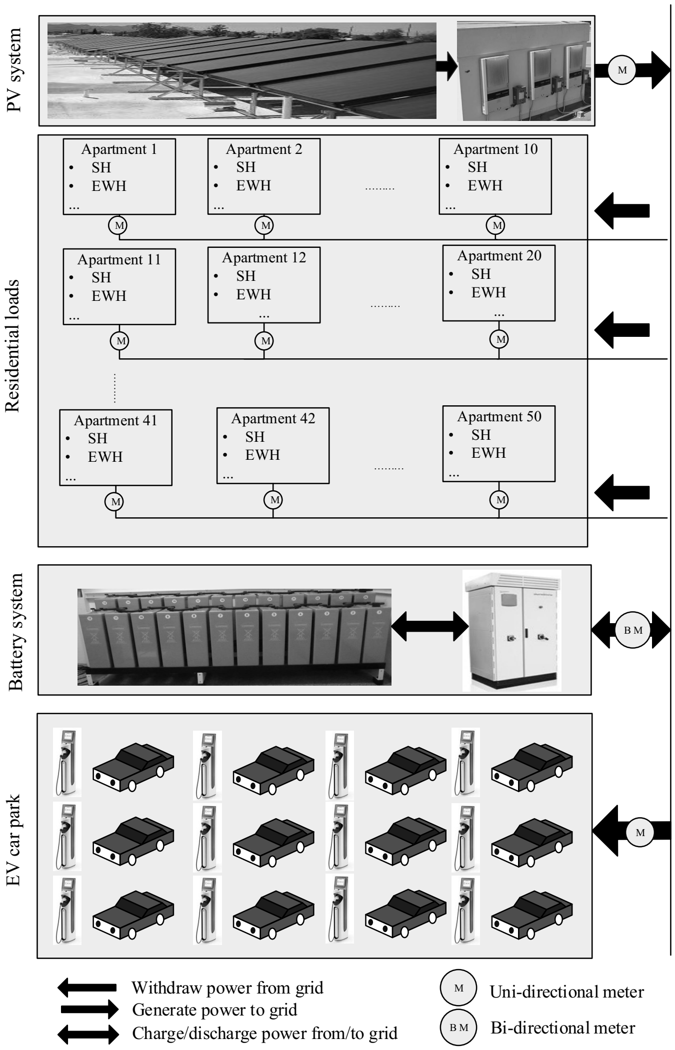

Fig. 1. Physical structure of aggregator service.

In terms of the smart remote monitoring and control devices, bi-directional smart meters are installed at the main incoming supply of the building, the PV system, and the BESS to monitor their power flows. In addition, smart control devices are installed for the BESS and EV chargers to manage the charging and discharging functions. Finally, compact monitoring and control devices are fitted into each apartment for the main incoming supply and home appliances, which are suitable for direct load control (DLC) such as electric water heater (EWH) and clothes dryer (CD). With these smart devices, the aggregator service is able to monitor power flows, including any import or export electricity from or to the grid, the consumption of each apartment, generation of the PV system, and operation of the BESS and EV. The centralized management platform helps to optimize power flows by controlling the loads from EV, BES and home appliances.

### B. Communication Infrastructure

The above monitoring and control system relies highly on information communication technology. Real-time monitoring and control data will be rapidly exchanged between the centralized aggregator service and the distributed monitoring and control nodes.

For home automation communication, choices include ZigBee, Z-Wave, WI-FI, CAN Bus, Ethernet, and PLC [15], [16]. However, the proposed aggregator service requires high security, low latency, wide area communication, and fast data exchange with an external network. Therefore, a mixture of wireless and fibre network structure is chosen. In each local area network, ZigBee communication, which is low cost, has low power consumption, and is compact, will be used to create a wireless sensor network linking local area networks to the centralized control platform using fibre optics technology.

As shown in Fig. 2, a typical five-story apartment building will have eight ZigBee sub-networks. The sub-networks are connected to a compact slave server that is coordinated by a master server through fibre optic ethernet. Each sub-network is in charge of the data transmission and processing within

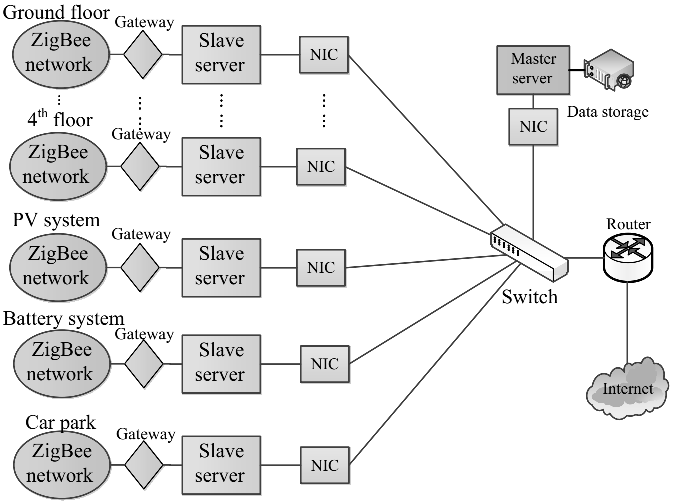

Fig. 2. Communication structure of aggregator service.

small local areas. For instance, all the smart meters of the apartments located on the ground floor will be in the same ZigBee network. The slave server will collect data from all the monitoring and control nodes within the sub-network, compress, encrypt, and then transmit the data to the master server for central data processing, which in essence reduces the communication traffic to and from the master server as well as reduces the amount of data computation and processing. Hence data transmission disturbance among various end devices will be decreased with corresponding improved communication stability.

The master server is a powerful server that acts as the "brain" of the aggregator. From a data transmission perspective, it not only collects data from the local devices, but also sends control commands to the subnetworks. In terms of data processing, the central management platform is operated in the master server, which optimizes the operation of all the controllable assets. In addition, in order to ensure the integrity and security of the network, only the master server is able to exchange data with various external platforms using a dedicated encrypted links, such as VPN. For example, it can get the real time electricity pricing data or notifications from energy suppliers or DNOs. A data storage system with high redundancy and resiliency will be attached to the master server which will store raw data as well as processed data from the master server to support services, such as the billing systems, devices operation optimization, and consumer behavior analysis.

### C. Incentive Mechanisms

Developing an incentive mechanism perhaps will be key in promoting the aggregator service in domestic buildings. The residents will not join any aggregator service unless they are rewarded with attractive benefits. As such, we provide a set of incentive mechanisms for the aggregator services, as follows.

*1) Low Price Guarantees (LPG):* This incentive mechanism applied in the aggregator service can be classified into three types: discount price for off-peak time, direct refunds of energy bills, and specific rewards for participating in a DR program or any other similar program [17], [18]. Customers can take part in the aggregator service with promises of the proposed LPG solution. It guarantees that customers can get the lowest electricity price from the aggregator compared to other mainstream conventional energy suppliers, which is the most efficient way to attract customers [19].

*2) Rewards for Participation:* The roof-mounted PV and BESS will take up considerable public space in the buildings so the residents should be rewarded for participating in the aggregator service. The reward will be divided into two parts: 1) exemption of the "daily standing charge," which is usually 10 to 30 p/day depending on the retailer and 2) dividends from profits gained by the aggregator based on the net margin.

*3) Smart EV Charging:* The aggregator service managing the controllable assets will provide smart EV charging services to all connnected customers free of charge. The EV owners will enjoy a lower charging cost since the centralized service platform will schedule and shift the charging period to a lower electricity price and also also one that guarantees to have little impact on the customers.

### D. Profit Approach of Aggregator Service

*1) Centralized Energy Management Systems for DERs and Internal Trading:* The centralized energy management systems introduced by the aggregator will control and manage the controllable assets. Therefore, electricity can be managed, balanced and traded internally within the apartment building to minimize the amount of electricity imported from the grid. Internal trading enables the aggregator to sell electricity from PV and BESS to the consumers at a much higher price than the grid export rate. The current export rate of DERs is only 4.77 p/kWh, which is only 1/3 of the average grid import rate in U.K. [20]. In addition, this trading mechanism allows customers to purchase energy from the aggregator rather than from the public retailers at a relatively lower price. At the same time, the aggregator is in a much stronger position than the individual residential customers in terms of negotiating with the grid, which is likely to get a further lower price from energy suppliers [21]. The aggregator can even bid in the electricity market if the capacity is large enough to get a more competitive wholesale energy price, which essentially reduces the margin of operation costs.

*2) EV Scheduling:* Although EV owners benefit from the smart EV charging service, they still need to pay for the electricity used, even at a slighly lower price. Since the aggregator will schedule the EV to be charged at off-peak hours, the aggregator will essentially benefit from the low grid import price. Therefore, the aggregator profits from EV scheduling as well. In addition, since the EV is a large task-oriented resource in the building, the aggregator can potentially get further profits from EVs by joining reserve markets, such as the DR program [21].

### E. Billing Mechanism

The billing systems is expected to influence the profitability and attractiveness of the aggregator service. Based on current electricity tariffs in the U.K. and EU countries, the aggregator service typically will pay three types of electricity tariffs: flat rate, TOU, and RTP tariffs. All three tariffs follow the incentive mechanisms introduced in the previous section where the residents can choose from any of these. The detailed information of the three tariffs is given as follows. It is worth mentioning that all the tariff information of the U.K. energy suppliers are collected from U.K.Power.co.uk.

*1) Flat Rate:* The flat rate applied in the U.K. market consists of the daily standing charge, which is similar to a phone line rental fee, and the constant unit price of electricity (£/kWh). Regarding the flat rate tariffs provided by three U.K. main power suppliers for West Midlands, the flat rate tariff will follow the lowest price tariff to fulfill the LPG strategy. In addition, customers are exempted from the daily standing charge as part of the reward of participating in the scheme. The price data of the flat rate tariff of the main U.K. power suppliers and aggregators are presented in Table I.

TABLE I
FLAT RATE TARIFF

| Supplier | Unit Price (£/kWh) | Standing Charge (£/day) |
|---|---|---|
| EDF | 13.03 p | 18.00 p |
| E.ON | 13.06 p | 15.64 p |
| SSE | 12.43 p | 14.09 p |
| Aggregator | 12.43 p | 0 p |

*2) Time-of-Use (TOU) Tariff (Economy 7 Tariff):* Since the installation of an increasing number of smart meters in the U.K., the TOU tariff has become more popular. Also referred to as the economy 7/10 tariff, it provides peak-time and off-peak time prices to the customers, for 7 or 10 hours during the night time hours. The off-peak time defined by Economy 7 tariff in the U.K. usually takes 7 hours between 10 pm and 8:30 am. The formulation of the aggregator TOU tariff is the same as the aggregator flat rate tariff. Table II shows three the TOU tariffs for the West Midlands area as provided by three different U.K. power suppliers as well as the aggregators.

TABLE II
TOU TARIFF

| Electricity Supplier | Day Time Unit Price (£/kWh) | Night Time Unit Price (£/kWh) | Standing Charge (£/day) |
|---|---|---|---|
| EDF | 14.57 p | 5.26 p | 18.00 p |
| E.ON | 16.11 p | 6.56 p | 15.64 p |
| SSE | 14.89 p | 6.83 p | 14.09 p |
| Aggregator | 14.57 p | 5.26 p | 0 p |

*3) Real Time Pricing (RTP):* The RTP tariff has a dynamic electricity price that changes on an hourly or half-hourly basis. Currently, few RTP tariffs exist in the U.K. market for residential customers. Therefore, the RTP tariff data is acquired from GDF Suez in the U.S. It should be noted that the price data has been slightly modified based on the U.K. average domestic electricity price given in [22].

## III. CONTROL METHODLOGY

The mathematical model and optimization approach for the central management platform provided by the aggregator is introduced in the following paragraphs.

### A. *Optimization Objective Function*

The aggregator aims to minimize the costs of the import electricity from the grid. The objective can be expressed as follows:

$$\begin{aligned} \text{Min}\sum_{k=1}^{T} B_t &= \sum_{t=1}^{T}(S_t + O_t). \\ S_t &= p_t^{\text{ag}} \cdot C_t^{\text{s}} \cdot \Delta t \quad (\text{if } p_t^{\text{ag}} < 0) \\ O_t &= p_t^{\text{ag}} \cdot C_t^{0} \cdot \Delta t \quad (\text{if } p_t^{\text{ag}} > 0) \end{aligned} \tag{1}$$

where $t$ is the index of the time interval, and $T$ is the total number of time steps. $\Delta t$ is the length of each time step. $B_t$ is the costs of aggregator at time $t$. $S_t$ is the benefits the aggregator should get from selling energy to the grid at time $t$. $O_t$ is the cost the aggregator should pay for the energy at time $t$. $p_t^{\text{ag}}$ is the power the aggregator is importing from or exporting to the grid at the time $t$. $C_t^{\text{s}}$ is the price at which the aggregator exports energy to the grid at time $t$. $C_t^{\text{o}}$ is the price at which the aggregator imports energy from the grid at time $t$.

### B. *Constraints of BESS and EV*

The power from the BESS, PV, and grid should be equal to the power consumption, including residential consumptions and EV charging. The power balance can be expressed as (2). It should be mentioned that BESS is charging when $p_t^{\text{bt}}$ is in positive and discharging when $p_t^{\text{bt}}$ is in negative.

$$\sum_{m=1}^{N_{\text{h}}} p_t^m + \sum_{n=1}^{N_{\text{EV}}} p_t^{\text{EV},n} + p_t^{\text{bt}} - p_t^{\text{ag}} - p_t^{\text{PV}} = 0 \tag{2}$$

where $p_t^m$ is the power of the $m^{\text{th}}$ apartment at time $t$. $p_t^{\text{EV},n}$ is the charge rate of $n^{\text{th}}$ EV at time $t$. $p_t^{\text{bt}}$ is the charging/discharging power of BESS at time $t$. $p_t^{\text{ag}}$ is the power the aggregator buys from or sells to the grid at time $t$; $p_t^{\text{PV}}$ is the PV generation at time $t$.

A BESS is assumed to be installed in the residential building with second-life automotive batteries. The operation of the BESS should follow the constraints as below.

$$P_{\text{BT\_ch}}^{\min} \le p_t^{\text{bt}} \le P_{\text{BT\_ch}}^{\max} \text{ when } p_t^{\text{bt}} > 0 \tag{3}$$

$$P_{\text{BT\_disch}}^{\min} \le p_t^{\text{bt}} \le P_{\text{BT\_disch}}^{\max} \text{ when } p_t^{\text{bt}} > 0 \tag{4}$$

$$E_{\text{BT}}^{t+\Delta t} = \begin{cases} E_{\text{BT}}^t + p_t^{\text{bt}} \cdot \eta_{\text{BT}}^{\text{ch}} \cdot \Delta t & \text{when } p_t^{\text{bt}} \ge 0 \\ E_{\text{BT}}^t + p_t^{\text{bt}} / \eta_{\text{BT}}^{\text{disch}} \cdot \Delta t & \text{when } p_t^{\text{bt}} < 0 \end{cases} \tag{5}$$

where $P_{\text{BT\_ch}}^{\min}$ and $P_{\text{BT\_ch}}^{\max}$ are the minimum and maximum charging power (kW) of the battery system. $P_{\text{BT\_disch}}^{\max}$ and $P_{\text{BT\_disch}}^{\min}$ represent the maximum and minimum discharging power (kW) of the battery system. $p_{\text{BT}}^t$ denotes the charging/discharging power (kW) of the inverter at time $t$. $E_{\text{BT}}^t$ denotes the capacity of the battery at time $t$.

For the second-life automotive batteries in the BESS, we assume all the batteries have the same state of health (SOH) and their initial capacity $E_{\text{BT}}^{\text{Ori}}$ are the same. The battery modules in the BESS should fulfill (6) and (7).

$$E_{\text{BT}}^{\text{cap}} = N \cdot E_{\text{BT}}^{\text{Ori}} \cdot SOH \tag{6}$$

$$0 < SOC^t = \frac{E_{\text{BT}}^t}{E_{\text{BT}}^{\text{cap}}} \le 100 \tag{7}$$

where $N$ is the number of the automotive batteries, $SOC^t$ denotes the state of charge ($SOC$) of the battery modules at time $t$.

In terms of the EV chargers, current models are compatible with multiple EV charging standards, and they provide a number of customized functions on the interface. For instance, the EV owners can set the preferred charging period and expected mile ranges once they connect the EV with the charging points. In addition, some EV charging points can even acquire battery information such as SOC level from the EV via CAN bus communication.

It is assumed that EV chargers in the proposed residential building car park charge at a constant rate and the EV owners can set the departure time and expected miles. The EV charging operation should satisfy the constraints below.

$$\sum_{t=T_{\text{EV}}^{\text{start},n}}^{t=T_{\text{EV}}^{\text{end},n}} S_t^{\text{EV},n} \cdot p^{\text{EV}} \cdot \Delta t = E_{\text{EV}}^n \tag{8}$$

$$T_{\text{EV}}^{\text{start},n} \le t \le T_{\text{EV}}^{\text{end},n} \tag{9}$$

$$S_t^{\text{EV},n} = 0 \text{ or } 1 \tag{10}$$

where $p^{\text{EV}}$ refers to the constant charging power of EV charger. $S_t^{\text{EV},n}$ is a binary variable which denotes the status of the $n^{\text{th}}$ EV charger at time $t$, where 0 refers to "off" and 1 refers to "on." $T_{\text{EV}}^{\text{start},n}$ and $T_{\text{EV}}^{\text{end},n}$ refers to the EV arrival and departure times, respectively. $E_{\text{EV}}^n$ refers to the total charging demand of the $n^{\text{th}}$ EV.

### *C. Optimization Approach*

From the above mathematical models, we see that the variables for the EV are integer values, and the rest are continuous variables. Thus, this model is a mixed-integer linear programming (MILP) problem. However, the larger the number of EVs is, the more computationally challenging the problem becomes. Moreover, the optimization of the problem will take a considerably longer time—just to schedule the charging of EVs. The aggregator, thus, is more unlikely to manage the EVs efficiently. A comparison among the continuous relaxation methods, fuzzy logic control, and the MILP method for optimizing the energy management problem has been given in [23]. The results show that the continuous relaxation method shows promising performance in energy management and is much faster than the MILP. Thus, to tackle this problem, an optimization approach based on continuous relaxation is applied. The optimization approach is divided into two stages as follows.

In the first stage, the integer variable is taken as a continuous variable, varying between [0, 1]. And the problem is solved as purely a linear problem. The values for the integral variables (varying between [0, 1]) can be determined, and they are compared with a specified threshold to determine the final result (0 or 1). So the integral values are determined by a continuous relaxation method.

Since values for the integral variables have been determined in the first stage, the other values need to be determined in the second stage, which is to solve the linear problem. The process of the proposed optimization approach is shown in Fig. 3.

In addition, since the forecast information will introduce error to the electric price, PV generation, and EV scheduling, a model predictive control (MPC) based optimization approach shown in Fig. 4 is adopted for managing the controllable loads based on the results in [6]. The optimization will operate every half hour with real-time and predictive data and optimize the operation of EV and BESS for 24 hours. Due to the prediction error, the control horizon is set as 0.5 hour, which means the EV and BESS will only execute the optimized commands for 0.5 hours rather than 24 hours to minimize the error.

The control algorithm is coded with YALMILP and solved using CPLEX.

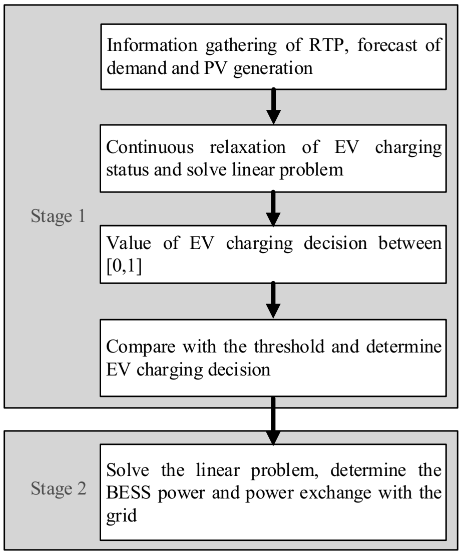

Fig. 3. Control approach process.

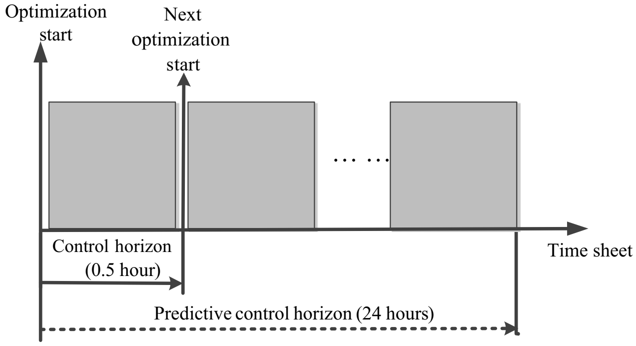

Fig. 4. MPC based optimization approach.

## IV. Case Studies

The mechanism and model of the residential apartment building aggregator service have been given in previous sections. In order to validate the performance of the proposed aggregator service, the parameters applied in the aggregator are first introduced. Then the test of the aggregator using the proposed parameters in MATLAB is given. Finally, the profitability of the aggregator with the provided tariffs is discussed.

### *A. Input Parameters of Aggregator Service*

A five-story residential building with 50 apartments (30 2-bedroom apartments and 20 1-bedroom apartments) located in the U.K. West Midland is used for the simulation. The roof area is 900–1200 $\text{m}^2$ and basement area is around 1200 $\text{m}^2$. Fifty parking spaces are available in the building.

In the U.K. electricity market, the Department of Energy & Climate Change (DECC) has reported that the energy tariffs for large, medium, and small energy consumers are 46.2%, 38.8%, and 32.6% cheaper, respectively, when compared to domestic consumers during 2012–2014 [22]. In this case study, it is assumed the aggregator is a small/medium size energy

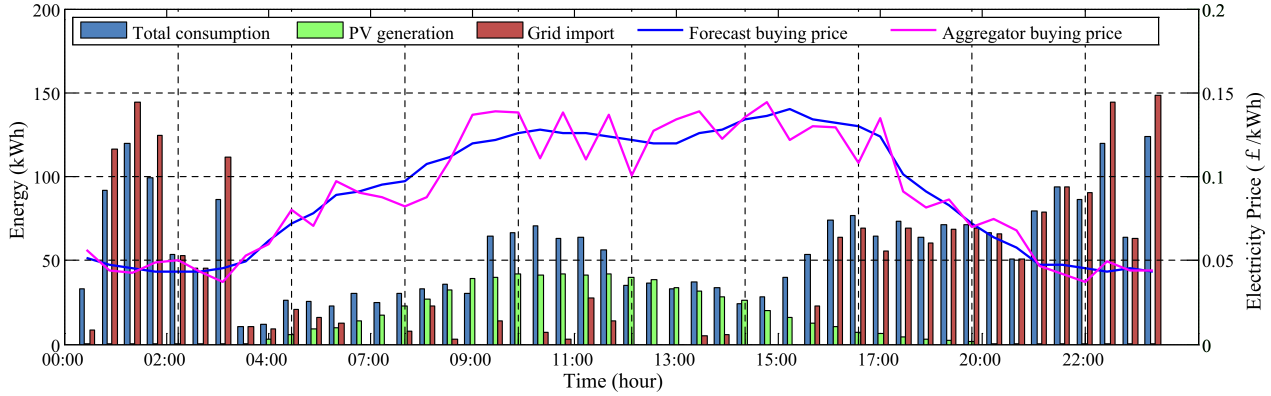

Fig. 5. Performance of aggregator service in 50-apartment residential building.

consumer, entitled to 35% reduction in the domestic RTP tariff proposed in the previous section.

The PV generation capacity is assumed to be 100 kWp, which is estimated based on the roof area. One-day generation data of the solar system is given in Fig. 5 based on the real-time data from Newquay Weather Station [24].

The assumption is that a 150 kWh BESS is installed in the building based on the renewable generation capacity and the demand from consumers. The maximum charging/discharging power limit of the BESS is taken as 50 kW. Both charging and discharging efficiency are defined as 95% as in [9]. It should be mentioned that the final SOC level of the BESS will remain the same as the initial SOC level by the end of the optimization.

The EV car park in the building is assumed to have 50 chargers rated at 3.3 kW each. The capacity of each EV is 24 kWh, which is the same as regular mainstream EV, e.g., Nissan Leaf. The arrival, departure, and battery charging times are estimated based on EV user pattern data from [25].

The residential energy usage of 50 apartments for one day is estimated from [1]. It should be noted that the optimization of EV and BESS requires forecast information. It is assumed the predicted data are provided by energy suppliers, the meteorological department, and other related organizations. In the simulation, a ±15% random error rate is added on the acquired data to mimic the forecast information.

### *B. Operation Results of Aggregator Service*

*1) General Performance:* One whole day operation results of the residential building using the aggregator service is given in Fig. 5. The purple curve represents the grid electricity price, and the blue curve represents the forecasted electricity price. The green bars are the PV generation, and the blue bars refer to total consumption including home energy consumption and EV charging power. The red bars represent the grid import power.

The grid import price is higher during daytime between 9:00 am and 6 pm and cheaper during 6:00 pm to 10:00 pm and 3:00 am to 8:00 am. The grid import price is extremely cheap during 10:00 pm to 3:00 am. Therefore, the electricity from the grid is significantly higher than the total residential consumption power, which indicates that the aggregator stores cheaper electricity in the BESS for later peak demand uses. The PV system exports considerable power to cover the residential energy consumption when the import electricity price is high between 9:00 am and 4:00 pm. The PV generation contributes profits to the aggregator. In addition, with the assistance of BESS, the stored electricity is discharged to meet the energy consumption during peak hours so that it can be sold for a relatively high retail price. Due to contributions from PV and BESS, the energy imported from the grid during the peak price period has been effectively maintained at a relatively low level. In addition, it is worth mentioning that the forecasted prices, shown as the blue curve, have certain errors during the daytime hours. Nevertheless, the import energy is still controlled at a relatively low level, which indicates that the optimization approach of the centralized control platform provided by the aggregator effectively reduces the influence of the forecast error.

Fig. 6 compares the EV scheduling results before and after applying the aggregator service. The blue bars refer to the original charging status of the EVs. It can be seen that around 30% of the unmanaged charging happens between 4:00 pm and 8:00 pm at which point the electricity price is still very high. On the contrary, the optimized charging schedule shifts most of the charging activity from 4:00 pm to 8:00 pm, to 9:00 pm to 3:00 am, which has a much lower grid price.

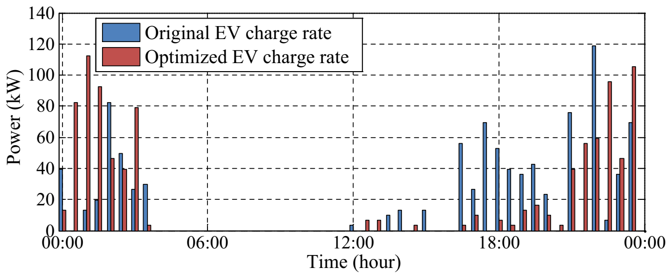

Fig. 6. EV scheduling results.

Fig. 7 presents the charging/discharging status of the BESS within one day. The BESS discharges power to the apartments during the peak price period to meet the residential energy consumption. The total discharged energy during this period is 120.5 kWh, which means 80.3% of the stored energy in the battery system has been used. With the comparison of the discharging power during the peak price period and charging power during low price period, it can be concluded that the aggregator will get profits from the price differences of shifting loads.

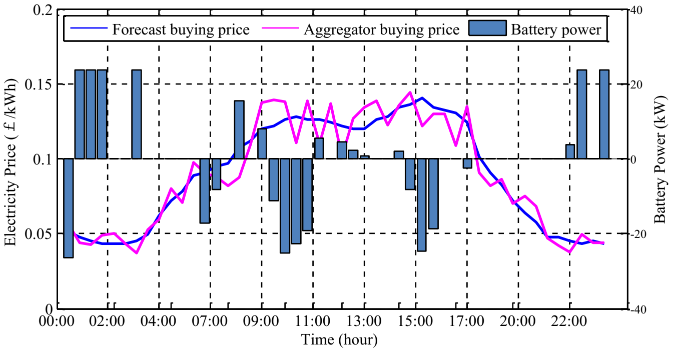

Fig. 7. Operation states of BESS.

*2) Performance of Aggregator with Different Tariffs:* The billing information is calculated based on data from the simulation results, and are given in Table III. It shows that the bills of three different tariffs are similar for a whole day, indicating that the proposed billing mechanism is fair to all the customers. The flat rate tariff is slightly higher than the bills of other two tariffs. This is because the EV owners cannot get benefits from the EV charging scheduling since they have a constant retail price. The way to minimize this problem will be to allow certain subsidies to the EV owners who choose flat rate tariffs. In addition, the PV system contributes more than 300 kWh electricity in order to meet the energy consumption. For this reason, the grid import power is also much less than the total energy usage.

TABLE III
BILLING DETAILS

| Cost (£) | Flat Tariff | TOU Tariff | RTP Tariff |
|---|---|---|---|
| Grid import | 65.40 | 65.40 | 65.40 |
| PV | 44.57 | 47.11 | 58.90 |
| Battery system | 11.90 | 11.10 | 18.00 |
| Internal trading | 45.68 | 32.30 | 12.55 |
| Total | 167.55 | 155.91 | 154.85 |

The contribution of the PV and battery systems using RTP tariff is significantly higher than the flat rate and TOU tariffs. This is because the higher electricity price during peak times brings larger price differences to the aggregator. In the meantime, the PV and BESS energy can be sold to customers at a relatively higher price. The relatively high internal trading contribution in flat tariff is because the aggregator can shift the EV charging to a low price period so that the EV owners using TOU and RTP tariffs will pay less than the owners using flat tariff.

### *C. Payback Period Comparison*

It is assumed that the residential apartment building in this case study has already installed 100 kWp PV system and 150 kWh BESS using second-life automotive battery packs. The estimation of PV and battery system cost is calculated based on [26] and [27]. The input data for the payback period calculation includes the PV generation, electricity price, and the EV charging information. The PV generation data is obtained from [24] with the whole year data of 2013. The electricity price and the EV charging information are assumed as being the same as the data used in the case study and applied in a whole year optimization, which repeatedly calculates the payback period results. The equations of payback period calculation are given as below.

$$\text{Payback period (year)} = \frac{C_{\text{BESS}} + C_{\text{PV}}}{C^{\text{annual}}_{\text{aggregator}}} \tag{11}$$

$$C^{\text{annual}}_{\text{aggregator}} = \sum\nolimits_{k=1}^{n} C_k \tag{12}$$

where $C_{\text{BESS}}$ and $C_{\text{PV}}$ are the investment on BESS and PV respectively. $n = 365$ represents the day number of one year and $C_k$ represents the profit of aggregator in day $k$ while $C^{\text{annual}}_{\text{aggregator}}$ represents the annual profit of the aggregator. It is worth mentioning that the maintenance cost and the efficiency reduction caused by depreciation of PV and BESS are not included in the calculation.

The investment, payback period, and optimized payback period is shown in Table IV. It should be mentioned that the battery modules used in the BESS are considered as the second-life automotive batteries, so that the BESS cost only includes the investment on the inverters.

The general payback period for the PV and BESS is estimated based on the investigation of the U.K. PV payback period developed by O'Flaherty [28]. The payback period of the PV and BESS used by the aggregator is calculated from the PV and battery contribution data shown in Table IV and the U.K. solar PV feed-in tariff [20]. Compared to the general payback period, all three tariffs can significantly reduce the time; in other words, the property management companies or investors will have much more interest in installing DERs in the residential building apartments.

TABLE IV
PAYBACK PERIOD OF PV AND BATTERY SYSTEMS

| | Flat Tariff | TOU Tariff | RTP Tariff |
|---|---|---|---|
| PV system cost (£) | 195,000 | | |
| Battery system cost (£) | 18,000 | | |
| General payback period (year) | 12–20 | | |
| Payback period after using aggregator (year) | 7.08 | 6.94 | 5.72 |

## V. CONCLUSION

In this paper, a novel aggregator service for residential apartment building with PV and BESS based on MPC, RTP, internal trading, and LPG is proposed. Both physical and communication structures of the aggregator are developed to support the implementation of the aggregator in the building. The business model, including billing system and incentive mechanisms introduced by the aggregator, is discussed as well. The LPG and reward of participation promised by the aggregator can effectively attract consumers to take part in the proposed service.

To validate the effectiveness of the aggregator, three billing tariffs: flat rate tariff, TOU, and RTP are compared in the case studies. The results show that the proposed aggregator can derive considerable profits while at the same time provide low price energy to residents. The PV system and BESS play a critical role in the aggregator service which contributes up to 78.7% margin profits when residents choose RTP tariff. Compared to the general payback periods of DERs, the aggregator can reduce the pay back periods down to 5.72 years, which is 64.3% shorter than the general payback period.

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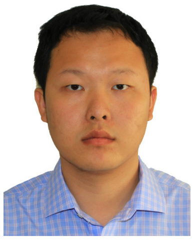

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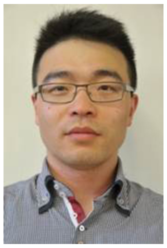

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