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A Configurable µVPP with Managed Energy Services: A Malmo Western Harbour Case

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***Abstract* —This paper describes an exemplar pre-commercial micro Virtual Power Plant (µVPP) that has been successfully commissioned and operated since July 2014 in Malmo, Sweden. The embedded Home Energy Management System concurrently manages downstream assets within a typical residential community of multiple apartments and delivers different energy services that benefit both end-users and system operators. A Fuzzy Logic based generic algorithm is developed to accommodate different types of services with the appreciation of system constraints. Each managed energy service is demonstrated in terms of its function, the level of utilization for asset capacity and the economic benefit to participants. It addresses the viability of mass market promotion for this µVPP by establishing detailed business model for all participants in the energy portfolio.**

***Index Terms*— Home Energy Management System (HEMS), micro Virtual Power Plant (µVPP), Fuzzy Logic Controller (FLC), Domestic Energy Management**

I. INTRODUCTION

EU member countries have taken on a key target for raising the share of renewables in their energy consumption to an average of 20% and achieving 20% cut in consumption by 2020 [1], according to the 2020 climate & energy package enacted in legislation by European Commission in 2009. Households, being the second largest sector in dominant energy use [2], is faced with a continuous energy price rise that creates barriers towards an affordable electricity future and addresses the importance to keep domestic energy cost in check. A prominent method to exploit the households' contribution to the EU 2020 target is to introduce Energy Management System (EMS) and other novel energy technologies to save both energy and money.

Many Home Energy Management System (HEMS) designs have been proposed. An intelligent HEMS architecture presented in [3] established the information route between household micro-generation and consumption. A smart home server was developed to gather estimated renewable generation data and use this information to control the home energy use schedule. Stationary battery based Energy Storage System (ESS) was introduced in [4] to the household assets and its charging/discharging actions were determined according to appliance priority to further reduce the overall energy consumption. The deployment of such energy storage system in typical household also raises concerns for the high initial costs and wasted system resources such as oversized battery capacity. Among the proposed HEMS architectures, most of them have the sole purpose of reducing electricity expense with only a few actually take the stability of electricity system into consideration. An exemplar solution was the combined Real-Time Pricing (RTP) model with regards to alleviate the power Peak-to-Average Ratio (PAR) facilitated in [5]. Under the prerequisite to allocate appliances to low-price period, the proposed algorithm can mitigate the risk of creating harmful peak load to the electricity system by decreasing the PAR. In recent years, the landscape in which ESS is dedicated to one household or building is changed and a shared ESS structure becomes the trend. In [6, 7], an ESS was shared by multiple consumers as the means to compensate peak demands and provide electricity backup during outages. However, both of the shared ESS designs lack the evidence of an optimized local power flow where the surplus power of micro-generation can be immediately redistributed to supply local demand.

Only a few of the HEMS designs above were demonstrated on hardware platform [8-10] and the test beds were developed only for demonstration purpose. The data communication and control electronics were fully established but consumer loads were often simulated simply using high-wattage light bulbs or hair dryers, not to mention the absence of renewable generation, ESS or their equivalent simulators in the test bed setup. With the emerging incentive policies for smart household energy renovations and funding filtering down to support the establishment of pilot projects, there is a pressing need to move on from laboratory display towards pre-commercial implementation, to include the full asset portfolio of a smart energy neighborhood and to explore the viability of business models that creates profitable money stream for both end-users and system operators.

As smart switches are gradually replacing the twiddly timer switches for domestic appliances such as Electric Heat Pumps (eHeat Pumps) and boilers [11], the device operation in HEMS can be treated as binary variables, representing ON or OFF status with their average power consumption in each working interval. Therefore in the context of algorithmic implementation, the optimization problem with both binary and continuous variables in residential energy management was addressed as a mixed integer linear programming (MILP) by many previous works. In [12], the author proposed a MILP framework-based demand response strategy to realize bi-directional utilization of Electric Vehicles (EV) in smart households. The investigation was conducted under the assumptions that the complete real-time pricing signal was known perfectly before the optimization horizon, so was the EV user preferences and

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consumption behavior. And the reliability of the optimal decision sets was highly dependent on the forecast of user behavior. Efforts were made in [13] to control the financial risks associated with real-time electricity price forecast uncertainties in a HEMS solution for residential appliances, Monte Carlo simulations and scenario reduction technique were applied under MILP framework in order to minimize the risk while guaranteeing real-time decisions can be delivered for every 5 minutes. But the financial risk brought by forecast error in appliance consumption was not discussed in the paper. In [14], a MILP based EMS introduced rolling horizon strategy to reduce the impact of the uncertainties oriented from all input variable forecasting. However, as [15] pointed out, the forecast capability may reside within the EMS or it may take the form of external forecasting services. Either way the forecast cost is not negligible. It can take up to a considerable percentage of operation cost if the forecast horizon is required to be distant and the resolution should be high. Apart from the difficulty in obtaining cheap and accurate forecast data, MILP formulation becomes complex when scaling up the EMS and more appliances are involved with their binary ON/OFF decisions waiting to be made. Due to the NP-hardness (non-deterministic polynomial-time hardness) of MILP approach in the number of binary variables used in problem formulation, computational requirements grow significantly as the number of binary variables increases [16]. Therefore the MILP approach becomes computationally time-consuming and may not be competent to deliver real-time control signals within operation window less than 3-5 minutes, which smart switch electronics can already accommodate at the moment.

Compared with classical MILP optimization approach, Fuzzy Logic Control (FLC) is often applied and has a good reputation in dealing with automated systems with model uncertainty and complex decisions [17-19]. [17] proposed a multi-agent FLC based energy management of hybrid system, in which the hybrid system was not treated as a global system to control but rather as a cluster of independent entities that nevertheless collaborate. Such system architecture matched FLC’s quick response to the real-time changes in input data and the proposed system demonstrated its capability to work continuously without perturbation. In [18], a FLC based battery auxiliary power unit was designed and the proposed fuzzy system can be easily retrofitted for other devices or ranges of operation by identifying specific input variables and determining the corresponding human expertise rules. The adoption of FLC in future microgrid development was further addressed in [19], where conclusions were drawn that FLC can not only encompass subjective decision-making process without forecast information but also fit the plug and play concept to deliver low cost expansion for residential EMS. In [20], the author studied a half-hour rolling optimization problem for HEMS and three control approaches namely MILP, continuous relaxation (CR) and FLC were evaluated against cost optimization, computational resource and practical implementation. The comparative results pointed out that MILP and CR approaches consume much more computation time with insignificant increase to the accuracy of the optimization solution. To sum up, FLC approach surpasses classical optimization counterparts from a practical point of view: it does not need forecast information and in the meantime it does not consume large computational resource and hence can be accommodated on low cost central processing units. Furthermore it is compatible for EMS appliance clusters of any scale without bringing in computation burden. Last but not least, the credit should be given to FLC decision-making. The FLC decision sets are, if not the most optimal at all times, at a very satisfactory level towards the optimization goal and obtained via the most economic pathway.

This paper presents a micro Virtual Power Plant (µVPP) – a unit of Virtual Power Plant (VPP) that has all the necessary interfaces ready for vertical aggregation into one VPP, established in Malmo, Sweden. It is an exemplar pre-commercial system designed, manufactured and deployed by the joint research endeavors of University of Birmingham, E.ON UK and E.ON Sweden. Since July 2014 when the µVPP was fully commissioned, it has been an unprecedented showcase which fulfilled an ambitious initiative: make smart home technologies part of everyday lives in actual homes [21]. The µVPP is equipped with Solar PV micro-generation, Controllable Loads (CLs) such as Electric Vehicles (EV) and Electric Heat Pumps (eHeat Pump), a scalable ESS, generic HEMS and other critical household appliances, representing a typical residential community of multiple apartments. The HEMS hosted on an Embedded PC (EPC) connects to all managed devices via ZigBee to retrieve monitoring data of micro-generation and consumption as well as sending control commands to the devices.

Three main contributions of this paper are identified: firstly, the level of implementation for the hardware and software infrastructure reaches the industrial standard and defines this µVPP as a pre-commercial product rather than a laboratory prototype. The actual micro-generation and consumption portfolio, tapping into the local electricity tariff mechanism, provide a full landscape of a pilot smart energy community. Secondly, the multiple services provided by this µVPP demonstrate the level of optimization effect in terms of energy and money savings, addressing the need to choose the right service in order to fully exploit asset values. At last, the detailed business model established in this paper seizes the opportunity of declining ESS capital price in recent years and proves the feasibility of mass market promotion in the near future.

This paper is organized into six sections. Section II introduces the system infrastructure of the µVPP. Section III illustrates the deliverable energy services and the business model of µVPP. Section IV presents the generic µVPP algorithm. Section V shows the scenario studies and the performance comparisons between different energy services. Section VI draws the conclusion and addresses the key findings.

II. µVPP System Architecture

The Western Harbour Project has deployed two µVPPs across eight residential apartments located in Malmo, Sweden. Each apartment has its own Solar PV system and each ESS is responsible to optimize the power flow of four connected apartments. A smart metering system was installed on PV

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systems and home appliances to provide real-time data. Internal information stream was formed within a local ZigBee network governing the data logging and algorithmic control over controllable loads and ESS. The external information stream was routed by interacting with cloud platform that enables remote monitoring and control of the µVPP. The µVPP system architecture is presented in Fig. 1.

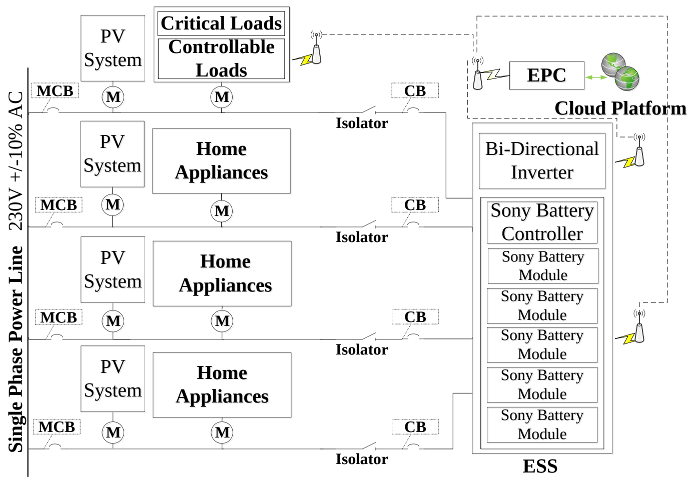

Fig. 1 µVPP system schematics

A. Home Appliances

The home appliances within the Western Harbour µVPP estate are categorized as critical appliances (e.g. lighting, TVs and refrigerators, etc) and CLs such as EVs and eHeat Pumps.

1) Electric Vehicle

The EV in the µVPP community is a typical plug-in hybrid vehicle with the battery size of 4.4kWh. Each charging point of the EV is equipped with a smart switch that receives the ON/OFF decision from the algorithm and governs the status of EV for the coming algorithmic interval.

The EV scheduling also caters for the convenience of drivers by complying with a set of physical constraints. Firstly every ON or OFF status of EV charging point should remain at least a minimum period of time before it can change to another status. This constraint prevents frequent interruptions to EV charging process and is required by the safe operation of charging point. Secondly, there is an upper limit of time for which EV is allowed to be turned off, guaranteeing a fully-charged EV daily. The EV will also be turned ON compulsorily when it has been OFF for a continuous time, which ensures the backup capacity for any unplanned use of the vehicle.

2) Electric Heat Pumps

The eHeat Pump provides domestic heating and hot water for the single apartment, a smart switch receives the ON/OFF decision from the algorithm and governs the status of eHeat Pump for the coming algorithmic interval. During winter times the wattage is often higher than warm seasons throughout the year. An unmanaged eHeat Pump would be ON constantly to maintain the domestic and water tank temperature at a certain level, while the embedded algorithm is equally capable of fulfilling the requirements in the heat sector by complying with the following constraints.

The minimum period of time for which eHeat Pump must keep its ON/OFF status before changing is a requirement of safety and operation continuity. The upper limit of time for which eHeat Pump is allowed to be turned off guarantees enough hot water and heating. At last, the continuous OFF time limit prevents sudden drops of both domestic and water tank temperature.

B. Smart Energy Storage System

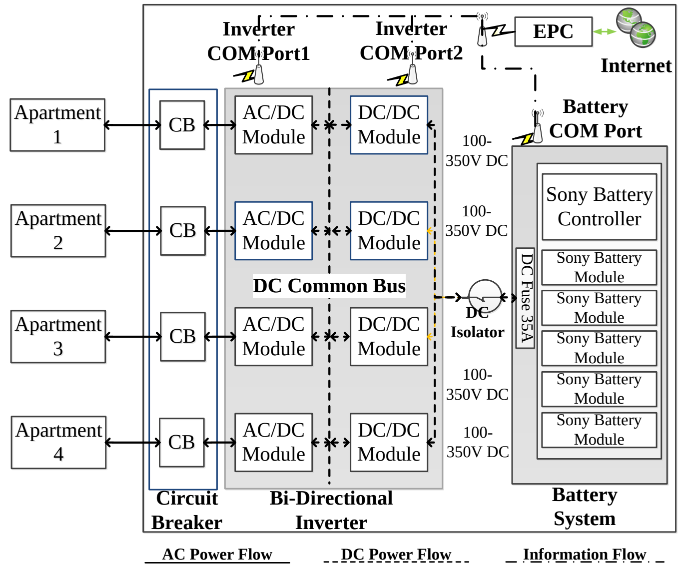

Fig. 2 Smart Energy Storage System schematics

Fig. 3 Smart Energy Storage System Installed in Western Harbour

The ESS in Western Harbour estate is an integrated system with all components housed in a 19-inch rack. Components include two 4.8kW bi-directional inverters, five 1.2kWh Sony battery modules with rated voltage of 51.2V, a system controller that integrates communication circuits and their power supply electronics. The ESS is also equipped with communication ports on both inverter and battery controller sides to facilitate two-way information logging and algorithmic control. Schematic diagram of the ESS is shown in Fig. 2 and the actual hardware installed on site is presented in Fig. 3.

The AC power lines of all four apartments are connected to the four separate AC/DC modules of the bi-directional inverter

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respectively. Those four AC/DC modules share the DC link of the inverter, which enables the internal power exchange of four apartments. Any surplus/shortage power resulting from the internal exchange will pass on the request to the other side of DC common bus and transfer the request into battery charging/discharging actions. The system controller equipped in ESS performs centralized monitoring and control over the inverter and battery system, where the collected information is broadcasted to the EPC and charging/discharging command is received from the optimization algorithm hosted on EPC. The ESS is also equipped with fuses on both AC and DC side as well as a separate DC isolator for protection purpose.

There are several physical constraints that ESS should comply with during operation. The battery SOC should not exceed the upper limit $SOC_{ESS}^{\max}$ and lower limit $SOC_{ESS}^{\min}$, meanwhile there are also upper and lower limits on the battery charging/discharging power. Another constraint requires a minimum period of time should be met before the power direction can change for inverter AC/DC modules and battery respectively. This constraint prevents frequent change of power directions for the safe operation of both inverters and battery. However, if the algorithmic interval is longer than the minimum period of direction change, this constraint is automatically satisfied.

III. μVPP Business Model and Managed Energy Services

A. μVPP Business Model

In order to determine the context and beneficiaries of the managed energy services and therefore design the corresponding generic algorithm, the μVPP business model should be developed addressing the roles and value transactions between participants including Distribution Network Operator (DNO), utility company, μVPP and end-users as presented in Fig. 4.

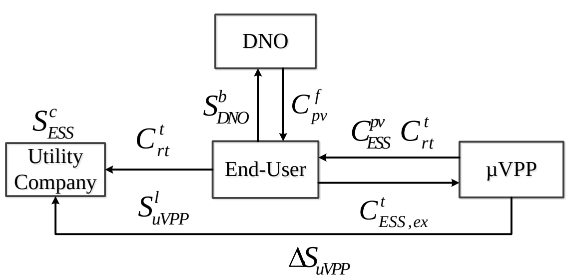

Fig. 4 Value stream transactions between μVPP participants

1) Utility company

Utility Companies such as E.ON is the legal representative for the μVPP, providing a leasing service of μVPP to the end-users. It invests initial capitals, mainly the ESS capital at price S_{ESS}^{c} (\$/kWh), for the hardware and software infrastructure of the μVPP. By signing a binding contract with the end-user, utility company receives annual revenue of S_{uVPP}^{l} (\$) for the leasing service. Also it is obligated for the profit of μVPP ΔS_{uVPP} (\$) from the transaction with end-users. For utility company, the retail income from selling electricity to end-users at price C_{rt}^{t} (\$/kWh) does not belong to the μVPP service therefore only S_{uVPP}^{l} and ΔS_{uVPP} constitute the return on the investment. The return period is calculated as:

$$t_{re} = \frac{S_{ESS}^{c} \times E_{ESS}^{c}}{S_{uVPP}^{l} + \Delta S_{uVPP}} \tag{1}$$

where the term $S_{ESS}^{c} \times E_{ESS}^{c}$ represents the total capital cost of an ESS of size E_{ESS}^{c} (kWh) at price S_{ESS}^{c} (\$/kWh); the term $S_{uVPP}^{l} + \Delta S_{uVPP}$ is the annual revenue of the utility company from operating the μVPP service and then the payback period t_{re} in terms of years can be derived from (1).

2) DNO

The DNO manages local distribution network where the μVPP taps into, it charges end-users S_{DNO}^{b} (\$) for the usage of the network based on each customer's highest monthly consumption power rate (kW). Also the DNO pays the end-users for the renewable generation that feeds into the local grid at feed-in tariff C_{pv}^{f} (\$/kWh). Although DNO's economic benefit is not included directly in the optimization goal, its presence in the business model provides opportunity for μVPP and its end-users to take advantage of grid usage fee S_{DNO}^{b} (\$) and renewable feed-in tariff. In return, the consumption profile smoothed by μVPP algorithm creates flexibility in grid connection point for DNO operation.

3) End-user

As the consumer of grid import electricity, the electricity bill of end-users consists of two parts in Sweden: the retail electricity fee paid at the real-time price C_{rt}^{t} (\$/kWh) to utility company according to the actual consumption E_{rt}^{g} (kWh) and the grid usage fee S_{DNO}^{b} (\$) paid to the DNO. As renewable energy generators, the end-user receives payment for energy E_{pv}^{f} (kWh) generated from their solar PV systems at feed-in tariff C_{pv}^{f} (\$/kWh). As the customer that enjoys the service of μVPP, end-users pay utility company a leasing fee of S_{uVPP}^{l} annually. Finally as the party that trades energy with ESS bi-directionally, there are two types of income and one type of expense on end-user side:

1. The apartment contributes its surplus energy E_{ESS}^{pv} (kWh) (remaining energy produced by PV generation after satisfying load demand) to be stored in ESS or used immediately by another apartment, thus receiving an income at a price C_{ESS}^{pv} (\$/kWh) higher than feed-in tariff. The higher price of C_{ESS}^{pv} provides incentive for end-users to export their surplus to ESS rather than back to the grid;
2. The apartment has imported more than its consumption demand during low retail price period to charge ESS for later use, thus receiving an income for the extra imported E_{ESS}^{g} (kWh) at the current retail price C_{rt}^{t};
3. The apartment purchases electricity E_{ESS}^{ex} (kWh) from ESS at a price $C_{ESS,ex}^{t}$ (\$/kWh) that is cheaper than the real-time retail price. The cheaper electricity sold by ESS provides incentive for end-users to involve in trading with ESS.

Thus the annual electricity bill of end-users in μVPP environment is calculated as:

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$$S^b = \sum C_{rt}^t \times E_{rt}^g + S_{DNO}^b + \sum C_{ESS,ex}^t \times E_{ESS}^{ex} + S_{uVPP}^l - C_{pv}^f \times E_{pv}^f - C_{ESS}^{pv} \times E_{ESS}^{pv} - \sum C_{rt}^t \times E_{ESS}^g \quad (2)$$

where the term $\sum C_{rt}^t \times E_{rt}^g$ represents the expense end-users pay for retail electricity; the term $\sum C_{ESS,ex}^t \times E_{ESS}^{ex}$ is the payment to ESS for the cheaper imported electricity. The other two terms of end-user expense are grid usage fee S_{DNO}^b paid to DNO and the leasing fee paid to utility company for μVPP service. As for income terms, $C_{pv}^f \times E_{pv}^f$ stands for the income of end-users received from DNO for the PV generation exported back to the grid; the term $C_{ESS}^{pv} \times E_{ESS}^{pv}$ represents the income received from ESS for the surplus electricity of end-users being stored into ESS or being rerouted in the DC bus of ESS; the final term $\sum C_{rt}^t \times E_{ESS}^g$ is the compensation income received from ESS for importing extra electricity to charge ESS.

4) *μVPP*

Although in concept μVPP is an upper level aggregation that includes micro-generation, ESS and end-users, the μVPP entity in business model is the agent that represents the interest of ESS in the internal energy transaction with each apartment. Its profit ΔS_{uVPP} in the internal trading will pass on to the utility company and is calculated as:

$$\Delta S_{uVPP} = \sum C_{ESS,ex}^t \times E_{ESS}^{ex} - C_{ESS}^{pv} \times E_{ESS}^{pv} - \sum C_{rt}^t \times E_{ESS}^g \quad (3)$$

Corresponding to the monetary terms in (2) that originated from end-users' transaction with ESS, the μVPP agent receives $\sum C_{ESS,ex}^t \times E_{ESS}^{ex}$ for selling electricity and pays $C_{ESS}^{pv} \times E_{ESS}^{pv}$ and $\sum C_{rt}^t \times E_{ESS}^g$ for purchasing surplus PV generation and extra grid import electricity, respectively.

B. μVPP Managed Energy Services

Based on the business model and the decomposition of end-user electricity bill shown in (2), the embedded algorithm takes different approaches to decrease the bill and create value stream for other participants by providing the following energy services:

1) *Service 1 – maxSelf service*

Considering the low feed-in tariff, this service aims at utilizing local micro-generation of the estate as much as possible thus reducing the energy imported from the main grid. CLs are not activated in this service.

2) *Service 2 – dynamic tariff service*

This service fully utilizes the dynamics in the grid tariff for electricity bill savings by using grid supplied energy when it is at its cheapest. This service will charge ESS from grid import energy when it is cheap and release the stored energy to apartments during high price period. CLs are not activated in this service.

3) *Service 3 – dynamic tariff with controllable loads*

Based on Service 2, Service 3 adds an extra feature of scheduling the CLs according to the grid tariff dynamics which leads to further bill reductions.

4) *Service 4 – dynamic tariff with load shedding*

Based on Service 3, Service 4 adds an extra feature of shedding the CLs during high domestic consumption period. This service minimizes the monthly grid usage fee S_{DNO}^b by restraining the peak hourly usage for each apartment.

Different managed energy services can be easily switched from one to another by adjusting parameters of the system configuration file without any system re-engineering. This is also the prerequisite of the μVPP generic algorithm architecture. One of the novelties of this paper lies in the fact that not only a generic μVPP is set up to support all HEMS propositions such as maximizing self-consumption, responding to price dynamics and applying load control, but also these propositions are summarized and classified as different energy services for the first time. By switching between services, a quantifiable way is presented to measure how far the assets can be stretched to create value for investors and customers.

IV. μVPP Generic Algorithmic Flow

A. Overview of the μVPP Algorithm

The actual μVPP system adopts 3 minutes as algorithmic interval length for an accurate operation. At the beginning of each interval, meter readings of PV generation, critical load consumption, CLs ON/OFF status and their power are inputted to the algorithm. As the algorithmic results, the charging/discharging command of ESS is obtained and its fractions of the target power will be assigned to each individual apartment. Meanwhile the decisions to turn CLs ON or OFF are derived. Also the time variables of CLs such as the total OFF time will be updated according to the decisions made.

The standardized workflow within the μVPP generic algorithm architecture is structured into three workflow stages as presented in Fig. 5.

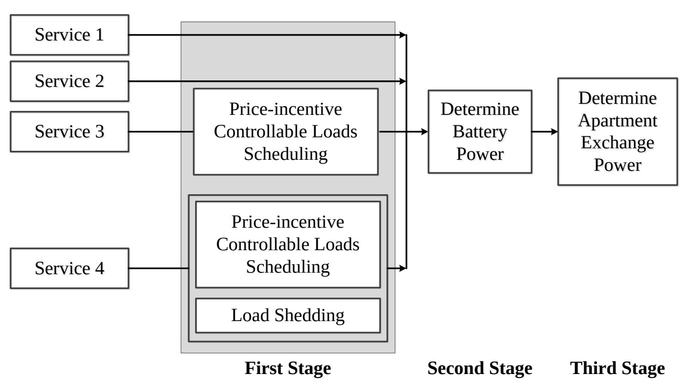

Fig. 5 μVPP algorithm execution in different services

A detailed flow chart of the algorithm is presented in Fig. 6, which consists of three stages. A brief description of these stages is as follows:

1) The first stage applies FLC to determine the ON/OFF decisions for controllable loads. Load shedding will be activated if necessary thus the consumption status for all the apartments could be settled at the end of this stage.
2) The second stage applies FLC first to determine charge/discharge power for ESS and this decision is denoted as "Preliminary Decision". After that the total surplus/shortage power for all the apartments is taken into consideration and the ESS charge/discharge power decision will be finalized. This finalized decision is the DC bus power that will be charged into or discharged from ESS.

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3) In the third stage, according to the actual physical system depicted in Fig. 2, four apartments are connected to ESS via four separate AC/DC power converters thus the ESS power derived from the second stage should be distributed among these four apartments, and hence the exchange power between each apartment and ESS can be obtained.

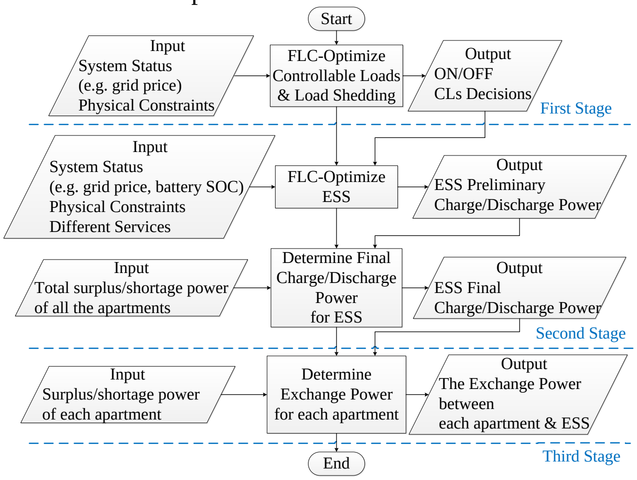

Fig. 6 µVPP generic algorithm workflow

B. *First Stage – Optimize Controllable Loads*

This stage exists in Service 3 and 4 while Service 1 and 2 proceed straight to Second Stage. The first stage of the algorithm optimizes all CLs (i.e. EVs and eHeat Pumps in Western Harbour µVPP) and decides whether each one of them should be turned ON or OFF for the next interval.

Firstly a fuzzy logic engine is used and takes three steps of fuzzification of inputs, rule-based inference and defuzzification of outputs to perform FLC of the CLs scheduling.

The principles of optimizing CLs are to turn on loads when grid price is comparatively low and to satisfy physical constraints of the CLs. The two fuzzy inputs into the Fuzzy Logic Engine include the real-time retail electricity price C_{rt}^{t}, available charging ratio η_{EV}^{fuzzy} for EV and C_{rt}^{t}, available off time ratio η_{ePump}^{fuzzy} for eHeat Pump respectively. The ratio η_{EV}^{fuzzy} indicates how much time the EV has left to perform charging while it is parked in the garage and can therefore access to the charging point:

$$\eta_{EV}^{fuzzy} = 1 - \frac{t - t_{EV}^{plug}}{T_{EV}^{daily}} \quad (4)$$

where the term $t - t_{EV}^{plug}$ represents the time that has passed by since EV was plugged in for the first time on the optimization day; divided by the total available hours T_{EV}^{daily} that EV can access to the charging point, the term $\frac{t - t_{EV}^{plug}}{T_{EV}^{daily}}$ accounts for the percentage of available charging time that EV has already consumed which makes η_{EV}^{fuzzy} the remaining available time left for EV to carry on charging activity. The smaller η_{EV}^{fuzzy} is, the more urgent it becomes to charge EV. With the value of η_{EV}^{fuzzy} ranging from 0 to 1, the EV charging status is fuzzified as "Very Urgent (VU)", "Urgent (U)", "Medium (M)", "Flexible (F)" and "Very Flexible (VF)". The real-time electricity price is fuzzified as "Very Low (VL)", "Low (L)", "Medium (M)", "High (H)" and "Very High (VH)". The FLC output describes "turn on" or "turn off" commands and it is fuzzified as two linguistic variables "ON" and "OFF". Each rank of the variables is depicted by its own membership functions shown in Fig. 7.

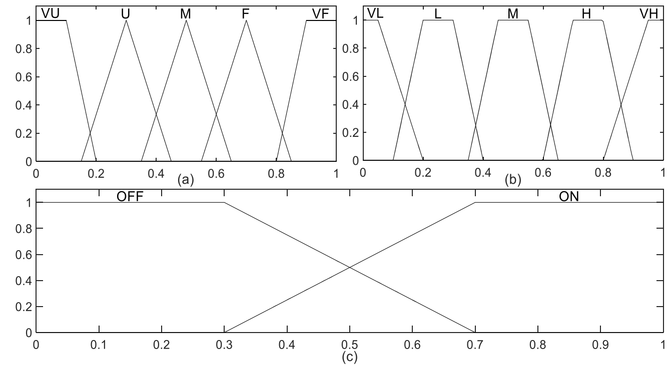

Fig. 7 Membership function of inputs and output for EV (a) Available Charging Ratio; (b) Electricity Price; (C) EV FLC Decision

The fuzzy inference rules are designed to deliver an empirical control command based on the joint assessment of charging point availability and the real-time electricity price: EV charging point has the tendency to be turned on if it is soon to be unavailable or if the electricity price is low. 25 rules are set for more sensitive response to input variations and the rules take the following form:

IF available charging ratio η_{EV}^{fuzzy} indicates flexible status (i.e. there is no rush to charge EV right now),

AND real-time electricity price C_{rt}^{t} is low,

THEN FLC decides to turn on EV charging point.

Also two extreme conditions are considered in rule setting:

IF available charging ratio η_{EV}^{fuzzy} indicates very urgent status (i.e. the charging point will soon be unavailable for today's optimization window),

THEN FLC decides to turn on EV charging point no matter how expensive electricity price is;

IF the electricity price is very low;

THEN FLC decides to turn on EV charging point even if there is no rush to charge EV right now.

The fuzzy inference rules for EV are presented in Table I.

TABLE I FUZZY INFERENCE RULES FOR EV OPTIMIZATION

η_{EV}^{fuzzy} \ C_{rt}^{t}	VL	L	M	H	VH
VU	ON	ON	ON	ON	ON
U	ON	ON	ON	ON	OFF
M	ON	ON	ON	OFF	OFF
F	ON	ON	OFF	OFF	OFF
VF	ON	OFF	OFF	OFF	OFF

Fuzzy logic control of eHeat Pumps is carried out in the same fashion as EV. The decisions obtained from FLC are the final commands sent to the smart switches under Service 3. However, in Service 4 configuration where the CLs optimization taps into the local DNO grid usage tariff, the system threshold of maximum load limit should be considered to refine FLC

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decisions. To shed CLs during high domestic consumption period can effectively level the peak monthly consumption power rate thus slashing the grid usage fee of the electricity bill. This load shedding process is described as follows:

Step 1) Calculate the net load of each apartment by deducting the PV generation from total demand;

Step 2) Compare the net load with preset maximum load limit, activate ESS compensation (i.e. 5% of ESS capacity is reserved for this purpose);

Step 3) If ESS fail to compensate for the exceeding net load, activate load shedding;

Step 4) Identify CLs that are scheduled to be ON by FLC, treat them as potential shedding targets and check if the FLC decisions can be inverted that CLs can be turned OFF for next interval;

Step 5) If the potential CLs can be turned OFF, shed eHeat Pump first and EV later until the net load falls under maximum limit.

According to the steps above, load shedding will not be activated if the net load can be compensated by ESS reserve power alone or the inverted FLC decision will risk violating physical constraints of CLs. The shedding priority given to eHeat Pump rather than EV in Step 4) has considered the lower power rate of eHeat Pump thus shedding eHeat Pump alone may fulfill the task without involving EV. To sum up, the process is engineered to deliver reduced peak load consumption with a minimal impact on CL operations.

C. Second Stage - Determine ESS Power

This stage determines the power level with which the ESS is charged or discharged. ESS produces profit in the internal energy transactions with each apartment which is a vital source for the return of its own capital investment. Since the control strategy of the physical system is to control the AC/DC power flow between each apartment and the DC/DC link will follow to produce the suitable DC power to charge/discharge the battery, the algorithm uses a reverse-engineering process to determine the final DC power level for ESS first. Then the DC power command will be processed by bi-directional inverter and the corresponding AC power will be fed in or withdrawn from each connected apartment.

1) Preliminary ESS power decision

A preliminary ESS charge/discharge decision P_{ESS}^{pre} stands at the ESS point of view and it considers ESS' own interest and safety (i.e. Upper limits of SOC and ESS power) as priority. This preliminary process is also tied to the specific service type and the preliminary decision varies under Service 1 and the other services. The reason behind different charge/discharge schemes is to determine at which position the ESS can deliver more benefits. Under Service 1, ESS serves only as a complementary device to the PV micro-generation system, the charge/discharge is a passive action based on PV productions and user demand. However, under Service 2, 3 and 4, ESS becomes a responsive device to the electricity price dynamics and takes a much more active role in charge/discharge.

When the energy service is configured to perform Service 1, the preliminary ESS decision is derived from the perspective of charging process and discharging process separately. In essence of maximizing the utilization of micro-generation, ESS will store as much surplus energy as possible if there is extra micro-generation remaining after satisfying the consumption. The discharging of ESS adopts the same fuzzy execution engine used in First Stage and there are two fuzzified inputs: the current SOC_{ESS} and the ratio of total net load power from all the apartments divided by the maximum ESS power rate.

$$\eta_{ESS}^{fuzzy} = \frac{\sum P_{apt}^{ideal}}{P_{ESS}^{\max}} \tag{5}$$

where the term $\sum P_{apt}^{ideal}$ represents the total net load from all the apartments and can be interpreted as the amount requested by all the apartments to discharge ESS. Therefore the discharging demand ratio η_{ESS}^{fuzzy} is fuzzified as linguistic variables of "Low (L)", "Medium (M)" and "High (H)" which correspond to the scenarios that "requested power level from discharging ESS is low", "requested power level from discharging ESS is medium" and "requested power level from discharging ESS is high". The second input SOC_{ESS} also takes the form of "Low (L)", "Medium (M)" and "High (H)".

The fuzzy output Discharge Demand Satisfaction Ratio $\varepsilon_{ESS}^{fuzzy}$ has three values of "Low (L)", "Medium (M)" and "High (H)" which correspond to the scenarios that "the discharge demand of apartments from ESS is poorly met", "the discharge demand of apartments from ESS is met at medium level" and "the discharge demand of apartments from ESS is well satisfied". $\varepsilon_{ESS}^{fuzzy}$ will then be defuzzified to obtain the preliminary ESS discharging decision.

$$P_{ESS}^{pre} = -\varepsilon_{ESS}^{fuzzy} \times P_{ESS}^{\max} \tag{6}$$

where the preliminary decision P_{ESS}^{pre} is always a negative value since the ESS FLC here only dedicates to the discharging process.

The fuzzy inference rules for preliminary ESS decision under Service 1 are presented in Table II. They are set based on the empirical knowledge of how ESS will respond to the apartment request and its own SOC: If SOC_{ESS} is low then only the low level discharging request will be well satisfied while the high level request will be poorly met; If SOC_{ESS} is medium then both low and medium level discharging request will be well satisfied, leaving the high discharging request be halfway met; If SOC_{ESS} is high then there is enough ESS capacity to make all discharging request well satisfied.

Table II Fuzzy Inference Rules for ESS Preliminary Decision Under Service 1

η_{ESS}^{fuzzy} \ SOC_{ESS}	L	M	H
L	H	H	H
M	M	H	H
H	L	M	H

However, under Service 2, 3 and 4, the FLC is utilized in both charging and discharging ESS process. The fuzzy output has six values of "Charge Low (CL)", "Charge Medium (CM)", "Charge High (CH)", "Discharge Low (DL)", "Discharge Medium (DM)" and "Discharge High (DH)" indicating the

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charge/discharge decision and the level of power. Two fuzzy inputs including the current SOC_{ESS} and the real-time electricity price are considered. Both inputs are fuzzified as linguistic variables of "Very Low (VL)", "Low (L)", "Medium (M)", "High (H)" and "Very High (VH)" and each rank of the input/output variables is depicted by its own membership function shown in Fig. 8.

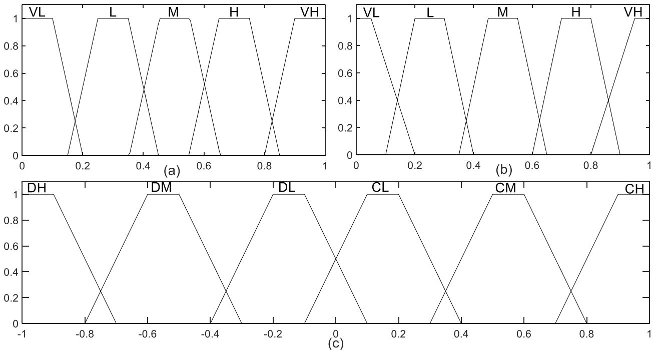

Fig. 8 Membership function of inputs and outputs for ESS (a) SOC; (b) Electricity Price; (c) ESS Preliminary Decision

25 rules are created for sensitive response to variations in SOC and electricity price. The design is based on the logical reaction of an ESS: charging action tends to happen during low price period and when SOC is low; otherwise discharging action may take place. Then depth of charging/discharging depends on the level of both inputs. The fuzzy inference rules are presented in Table III.

TABLE III FUZZY INFERENCE RULES FOR ESS PRELIMINARY DECISION UNDER SERVICES 2, 3 AND 4

SOC_{ESS} \ C_{rt}^{t}	VL	L	M	H	VH
VL	CH	CH	CM	DL	DH
L	CH	CM	CL	DM	DH
M	CH	CL	DM	DM	DH
H	CH	CL	DM	DH	DH
VH	CH	CL	DH	DH	DH

2) Final ESS power decision

The preliminary ESS decision P_{ESS}^{pre} will then be adjusted according to the total surplus/shortage power $\sum P_{apt}^{ideal}$ that stands for the collective of four connected apartments. Thus the final decision of ESS power can represent the mutual interest of both end-users and ESS. A positive value of P_{ESS}^{pre} represents that ESS needs to be charged, a negative value of P_{ESS}^{pre} represents that ESS needs to be discharged and zero represents idle status for next interval. A positive value of $\sum P_{apt}^{ideal}$ indicates that the apartments have net load thus they require the ESS to discharge, a negative value of $\sum P_{apt}^{ideal}$ indicates that the apartments have surplus power from micro-generation to be charged into the ESS. The final ESS decision P_{ESS}^{final} in kW is obtained according to the adjustment rules presented in Table IV.

TABLE IV ADJUSTMENT RULES FOR ESS FINAL DECISION

ESS \ Apt	$\sum P_{apt}^{ideal} < 0$	$\sum P_{apt}^{ideal} = 0$	$\sum P_{apt}^{ideal} > 0$
$P_{ESS}^{pre} < 0$	$-\sum P_{apt}^{ideal}$	0	$-\min(\lvert\sum P_{apt}^{ideal}\rvert, \lvert P_{ESS}^{pre}\rvert)$
$P_{ESS}^{pre} = 0$	$-\sum P_{apt}^{ideal}$	0	0
$P_{ESS}^{pre} > 0$	$-\sum P_{apt}^{ideal} + P_{ESS}^{pre}$	P_{ESS}^{pre}	P_{ESS}^{pre}

The adjustment rules above are determined after examining all the possible combinations of apartment requests and ESS intention regarding charging/discharging. The possible scenarios are summarized as follows:

1. If the collective of all the apartments has excess power then the final decision is to charge this surplus amount into ESS. If ESS itself decides to charge as well due to low price or low SOC, the additional amount of P_{ESS}^{pre} should be added. This scenario represents the first column of results;
2. If the PV generation balances load consumption for all the apartments then ESS will only perform the preliminary charging decision P_{ESS}^{pre} since the discharging is unnecessary. This scenario represents the second column of results;
3. If the collective of all the apartments has net load, the ESS final action depends on its preliminary decision: (This scenario represents the third column of results)
   - 3.1. ESS will carry on its preliminary discharge decision to satisfy the smaller value out of the apartment needs and its own needs. It is unnecessary to discharge more than the apartment demand and inflict waste, also ESS can't stretch to satisfy a demand beyond its capability;
   - 3.2. ESS will carry on its preliminary idle or charge decision and this will allow the apartments to be supplied by the grid. The reason behind the situation described here is either the cheap electricity price or physical constraint that forbids ESS to discharge.

D. Third Stage - Determine Apartment Exchange Power

Given the fact that the final decision of ESS power is different from the total ideal power $\sum P_{apt}^{ideal}$ from all connected apartments in some scenarios, it is necessary to adjust each individual ideal power P_{apt}^{ideal} to fulfill the target ESS power P_{ESS}^{final}. In other words, this stage converts the target ESS power P_{ESS}^{final} on the DC bus into required AC power and allocates the fraction of target power to each connected apartment. The allocation has fully appreciated the difference of each apartment in consumption and the physical constraints they should comply with. The principles of this stage are to guarantee the fairness and equality of each apartment, the safety of operation and the reasonability in both economic and power flow point of view.

1) Priority queuing of apartments

The priority queuing determines the sequence of apartments to take on the fraction of allocated power in order to achieve target ESS power P_{ESS}^{final}. For instance, apartment 1 and apartment 2 are assumed to have surplus power 0.5kW and 0.75kW respectively from PV generation while apartment 3 and apartment 4 have net load of 0.45kW and 0.5kW respectively. Thus the collection of four apartments has surplus power of 0.3kW. Meanwhile the target ESS power P_{ESS}^{final} is zero and the surplus power 0.3kW becomes redundant that needs adjustment (the target zero ESS power results from physical constraints, ESS is designed to prevent frequent change of power direction). For apartment 1 and 2 with excess power, they need to store less power into ESS; however for apartment 3 and apartment 4 with net load, it will be unfair to require them increase their net load in order to digest the surplus power. Thus only apartment 1 and

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2 will be presented in the priority queue. Considering apartment 1 has a smaller room to reduce surplus power due to its smaller amount of excess power, the final queue is to adjust apartment 1 first and apartment 2 later. The proposed queuing strategy is summarized in the following steps:

Step 1) Derive the priority factor δ_1^n of apartment n=1,2,3,4 and δ_2^n according to (7);

$$\delta_1^n = P_{apt}^{ideal} \times (\sum_{n=1}^{4} P_{apt}^{ideal} + P_{ESS}^{final})$$
$$\delta_2^n = P_{ESS}^{final} \times (\sum_{n=1}^{4} P_{apt}^{ideal} + P_{ESS}^{final}) \quad (7)$$

Step 2) Sort apartments in a queue according to the ascending order of δ_1^n, set the queue empty if $\sum_{n=1}^{4} \delta_1^n = 0$;

Step 3) For those queues with $\delta_2^n \le 0$, remove the apartments of which $\delta_1^n < 0$ from the queue obtained in step 1 and denote the final queue as the priority queue.

Following the steps the priority factor can be derived as $\delta_1^1 = 0.15$, $\delta_1^2 = 0.225$, $\delta_1^3 = -0.135$, $\delta_1^4 = -0.15$ and $\delta_2^n = 0$ for all the apartments. Step2) sorts apartments as [4, 3, 1, 2] and Step 3) removes apartment 3 and 4 from the queue thus deriving the final queue as [1, 2]. The queuing strategy above is summarized in an empirical approach after examining every possible scenario of ESS final decision P_{ESS}^{final} and the total surplus/shortage power $\sum P_{apt}^{ideal}$ for all the apartments. The adoption of priority factors provides a general solution that can handle large number of apartments efficiently than the exhaustive method. The determination of priority factors in this step is not in the key scope of this paper thus will not be presented here.

2) Allocation to each apartment

After obtaining a priority queue with $M(M \le 4)$ apartments in it, the allocation strategy is summarized in following steps:

Step 1) Calculate the total distribution power ΔP_{dis};

$$\Delta P_{dis} = \sum_{n=1}^{4} P_{apt}^{ideal} + P_{ESS}^{final} \quad (8)$$

Step 2) For apartment $m = 1,2,...,M$, repeat the following steps:

2.1. Derive the final exchange power P_{apt}^{final} of apartment m;

$$P_{apt}^{final} = P_{apt}^{ideal} - \frac{\Delta P_{dis}}{M-(m-1)} \quad (9)$$

2.2. Update the total distribution power ΔP_{dis};

$$\Delta P_{dis} = \Delta P_{dis} - P_{apt}^{final} \quad (10)$$

The term ΔP_{dis} denotes the difference between ESS final target P_{ESS}^{final} and the total surplus/shortage power for all the apartments $\sum P_{apt}^{ideal}$, which is the amount of adjustment to be distributed among the apartments in the priority queue. Step 2.1 indicates an iterative approach to distribute ΔP_{dis} evenly among the queue members while Step 2.2 updates ΔP_{dis} until it equals to zero. At the end of this stage the final exchange power command of each apartment P_{apt}^{final} is derived and it will be sent to each AC/DC link in bi-directional inverter to execute accordingly. Referring to the same example in the Priority Queuing where only apartment 1 and apartment 2 are included and ΔP_{dis} is -0.3kW, apartment 1 and 2 are adjusted to charge 0.35kW and 0.6kW into ESS respectively.

V. Comparative Performance Scenarios

For the money stream parameters in business model, the real-time retail electricity price is extracted from Nord Pool price data 2015 [22], the feed-in tariff and monthly grid usage fee are provided by E.ON Sweden. In [23], the current initial investment for ESS is high but it is predicted to decline 20-30% annually and reaches a commercial/utility level at 2020. Two payback periods are presented in this section: the payback period based on current ESS capital investment and the shortened payback period for decreased ESS upfront cost. The leasing fee of µVPP is set to be 40% of the final electricity bill savings on customer end, thus guaranteeing the larger half goes to the end-user while the utility company still receives considerable revenue to recoup the capitals. All the µVPP operation data including PV generation, consumption and CLs usage from January 2015 to December 2015 are recorded by smart metering system onsite and downloaded from µVPP cloud database. The ESS of the system has a capacity of 6kWh with an estimated life of 4500 cycles and EV battery capacity is 4.4kWh. The important business model parameters are shown in Table V.

Table V µVPP Business Model Parameters

Parameters	Value	Parameters	Value
C_{rt}^t ($/kWh)	0.18 Avg.	Current S_{ESS}^c ($/kWh)	500
C_{pv}^f ($/kWh)	0.08	Decreased S_{ESS}^c ($/kWh)	165
C_{ESS}^{pv} ($/kWh)	0.12	S_{DNO}^b ($/kW)	15
$C_{ESS,ex}^t$ ($/kWh)	$C_{rt}^t \times 90\%$		

The scenarios for comparative study are service-based, one set of daily data in quarter 3 2015 is used in the demonstration of service feature and another set of annual data of 2015 is used for µVPP economic analysis. The result terms "electricity bill" and "bill savings" are defined with regard to the collective of four apartments in the period of one year. The generic algorithm is coded in C# for the actual Western Harbour µVPP and transferred on MATLAB platform. All the code was run on an Intel Core-i5 2.5-GHz computer.

A. Case A – Service 1

When µVPP is configured to run Service 1, the ESS SOC trajectory shown in Fig. 9 follows the pattern of PV generation and the ESS is being charged frequently during daytime when the sunlight is abundant.

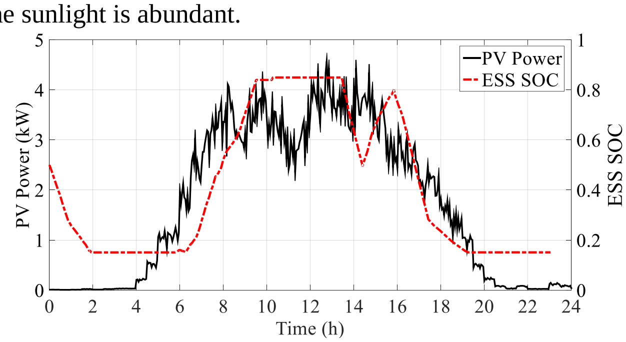

Fig. 9 ESS charging pattern under Service 1

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Under Service 1, the result shows high PV utilization rate due to reduced PV feed-in energy, which also leads to the reduction of grid import energy. For economic analysis, the total savings on electricity bill for end-users, the return period of ESS capital investment and the ESS life time are displayed. The savings are derived by setting up a reference scenario called "No service" where each apartment only owns PV generation but no ESS or other µVPP infrastructures. ESS of different dimensions is included in the analysis to determine whether it is worthwhile to resize the asset.

TABLE VI SERVICE 1 PERFORMANCE WITH 1.2KW PV

Results \ ESS	No service	3.6kWh	6kWh	8.4kWh	12kWh
Electricity bill ($)	3639.85	3593.12	3582.13	3573.6	3563.48
Bill savings ($)	N/A	46.73	57.52	66.25	76.37
ESS charge cycle	N/A	155.68	126.76	110.04	93.86
µVPP profit ($)	N/A	25.9	28.76	29.45	27.66
Payback period (yrs)	N/A	40	57	75	103
Shortened payback period (yrs) *	N/A	13	19	24	34
ESS life time (yrs)	N/A	28	35	40	47

*Shortened payback period corresponds to a reduction of 67% of ESS cost

With the current 1.2kW PV, the electricity bill savings is very insignificant and it does not increase much if adding up the ESS capacity. As for ESS utilization, it takes more than two days even in the best case scenario to complete one full charge cycle. This low ESS charge cycle throughout the year under Service 1 shows poor utilization of the battery capacity. Also, the µVPP agent receives negligible profit in this service for all ESS sizes.

Economically speaking, the insignificant bill savings and µVPP profit put utility company in a very slow lane to recoup its capital investment, even for the shortened payback period where ESS cost drops to 33% of the current price. Although the low ESS charge cycles per year prolongs the system life time, the performance of battery modules will be compromised by depreciation and aging in the later commission period. To sum up, the idea of using ESS as a pure complementary device to the micro-generation poses great challenges to the return of capital investment. With the increasing penetration of micro-generation, it is commercially prohibitive to run Service 1 for µVPP.

B. *Case B – Service 2*

When µVPP is configured to run Service 2, the ESS SOC trajectory shown in Fig. 10 follows the pattern of retail electricity price and the charging action is allocated to low price period while the discharging action is allocated to high price period.

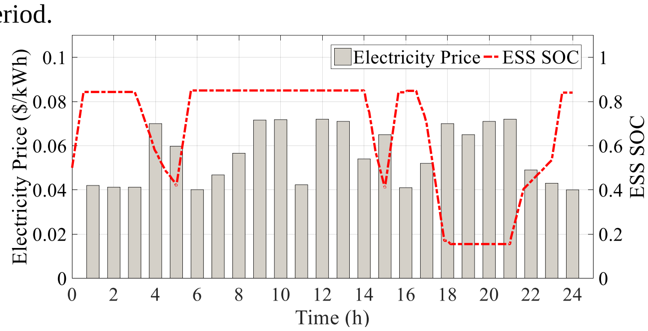

Fig. 10 ESS SOC pattern under Service 2

The price-incentive ESS under this service mitigates distribution grid pressure during times of high demand (usually the peak price period) by releasing the energy stored earlier to supply consumers while increasing distribution grid utilization during times of low demand by active charging actions. For end-users, this service aims at reducing electricity bills by enhancing the internal trading between each apartment and the ESS.

TABLE VII SERVICE 2 PERFORMANCE WITH 1.2KW PV

Results \ ESS	No service	3.6kWh	6kWh	8.4kWh	12kWh
Electricity bill ($)	3639.85	3551.67	3529.15	3512.45	3496.42
Bill savings ($)	N/A	88.18	110.7	127.4	143.43
ESS charge cycle	N/A	703.9	550.9	481.4	397.1
µVPP profit ($)	N/A	36.53	67.36	106.5	154.66
Payback period (yrs)	N/A	25	26	26	28
Shortened payback period (yrs) *	N/A	8	9	9	10
ESS life time (yrs)	N/A	6	8	9	11

*Shortened payback period corresponds to a reduction of 67% of ESS cost

Compared with Service 1, Service 2 can deliver better performance with the exact same size of PV and ESS. The electricity bill savings are nearly doubled that of Service 1 and the µVPP agent becomes more profitable. In terms of ESS charge cycle, at least one full charge cycle is accomplished daily on average throughout the year, which is the ideal utilization frequency that guarantees the full use of ESS capacity while maintaining a healthy battery life. With the ESS cost brought down in the near future, the economic rationale becomes clear as the shortened payback period falls under 10 years. Utility companies and end-users will be equally motivated in Service 2 proposition as a sustainable business model has been established. Treating ESS as an active, price-responsive asset in the µVPP environment can bring the system to the point of mass adoption potential in 2020.

C. *Case C – Service 3*

When µVPP is configured to run Service 3, the CLs including EV and eHeat Pump start to respond to retail electricity price dynamics and perform smart scheduling. The scheduling of EV charging activity is used to demonstrate the service function

As shown in Fig. 11, this service turns EV off during 19:00 to 20:00 when the electricity price is high. Under the prerequisite that each EV would be charged to maximum SOC limit on a daily basis, the charging action is allocated to low price period which yields further economic benefit.

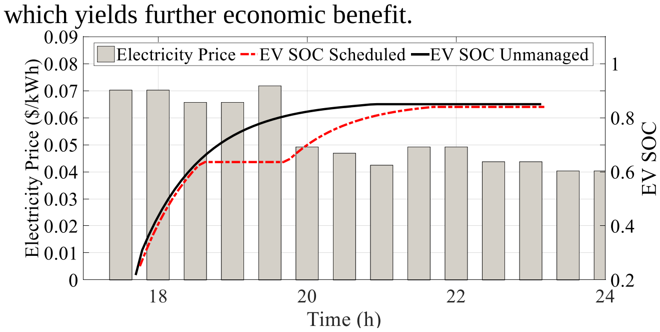

Fig. 11 EV charging responds to electricity price dynamics

TABLE VIII SERVICE 3 PERFORMANCE WITH 1.2KW PV

Results \ ESS	No service	3.6kWh	6kWh	8.4kWh	12kWh
Electricity bill ($)	3639.85	3404.33	3383.08	3367.73	3351.73
Bill savings ($)	N/A	235.52	256.77	272.12	288.12
ESS charge cycle	N/A	686.6	536.2	462.3	383.13

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µVPP profit ($)	N/A	35.7	66.47	105.23	152.63
Payback period (yrs)	N/A	13	18	19	22
Shortened payback period (yrs) *	N/A	5	6	7	8
ESS life time (yrs)	N/A	6	8	9	11

*Shortened payback period corresponds to a reduction of 67% of ESS cost

Often being the loads with the largest consumption power rate, the scheduling of both EVs and eHeat Pumps leads to a significant reduction on electricity bill – the end-users can save up to 8% of their former bill. Other key criteria including the µVPP profit and ESS life time are kept at prominent level while the payback period is slashed further. Compared with Service 2, Service 3 has shortened the payback period for another 2-3 years. Thus the value proposition for incorporating the CLs into the service is significantly more compelling.

D. Case D – Service 4

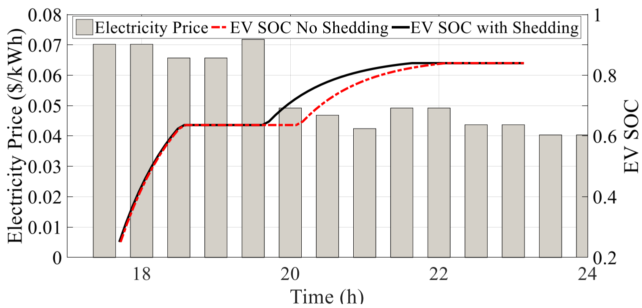

Fig. 12 EV performs load shedding during times of high consumption

When configured to run Service 4, the µVPP takes advantage of the local DSO's monthly grid fee tariff scheme in which the grid usage fee is calculated as the monthly peak hourly consumption multiplied by the real-time electricity price. After setting an initial peak hourly usage cap value, the algorithm will automatically adjust the cap to suit the consumption level of each particular apartment. In order to restrain consumption under the peak usage cap, CLs will have to perform additional load shedding during peak load period on top of the price-incentive scheduling.

As shown in Fig. 12, EVs in Service 3 and Service 4 are both turned OFF during 19:00 to 20:00, but Service 4 commands EV to stay OFF for another half an hour due to the presence of high load consumption during 20:00 to 20:30. The task of charging EV to full is accomplished in both services within time, but the peak consumption power rate is lower in Service 4 and so is the monthly grid usage fee.

TABLE IX SERVICE 4 PERFORMANCE WITH 1.2KW PV

Results \ ESS	No service	3.6kWh	6kWh	8.4kWh	12kWh
Electricity bill ($)	3639.85	3277.28	3256.17	3241.46	3225.93
Bill savings ($)	N/A	362.57	383.68	398.4	413.92
ESS charge cycle	N/A	715.06	553.56	472.33	389.17
µVPP profit ($)	N/A	24.23	55.43	92.08	137.15
Payback period (yrs)	N/A	10	14	16	20
Shortened payback period (yrs)*	N/A	4	5	6	7
ESS life time (yrs)	N/A	6	8	9	11

*Shortened payback period corresponds to a reduction of 67% of ESS cost

Being the most comprehensive service with the full exploration of asset potentials, Service 4 derives the largest savings on electricity bills even with the combination of the smallest PV and ESS sizes. End-users under Service 4 pay up to 11% less than their former bills. By tapping into the local DNO's grid usage tariff, a µVPP with 3.6kWh ESS is already commercially feasible under the current high initial investment since the payback period has been brought down to 10 years. With the upcoming cheap ESS, Service 4 can put utility company on a fast track to recoup their investment. The promising business prospect addresses the importance to source additional incentives from DNO side in the mass adoption of µVPP.

VI. CONCLUSION

This paper describes an exemplar pre-commercial micro Virtual Power Plant (µVPP) that has been established and successfully operated for one and half year in Malmo, Sweden. The embedded algorithm concurrently manages downstream assets within a residential neighborhood to provide multiple energy services to both end-users and system operators. Four case scenarios corresponding to each energy service demonstrate the µVPP's capability in fully exploiting the optimized potential of renewable micro-generation, direct load control, energy storage and dynamics in grid tariffs. The technical and economic analysis has also identified Service 4 as the optimal service type and revealed the feasibility in mass commercial adoption. Moreover, the scope of the analysis extends to explore the influence of different ESS dimensions on the created value stream and provides evidence to make economically viable decisions for asset size configuration. As a modular and scalable Virtual Power Plant unit, this µVPP could be utilized for a vertical aggregation in the context of large-scale VPP. Future work includes the setup of the corresponding VPP market for both day-ahead and intra-day biddings and the facilitation of energy transactions between multiple µVPP. With the extension of business model in terms of market and participants, it is expected to transform this pre-commercial solution to a full-scale deployment.

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