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Title: Role of Smart Homes and Smart Communities in Flexibility Provision

Year: 2021

Version: Accepted manuscript

Please cite the original version:

Khajeh, H., Zheng, R., Firoozi, H., Laaksonen, H. & Shafie-Khah, M. (2021). Role of Smart Homes and Smart Communities in Flexibility Provision. In: Haes Alhelou, H., Heydarian-Forushani, E. & Siano, P. (eds.): *Flexibility in Electric Power Distribution Networks*, 21-40. Boca Raton: CRC Press, Taylor & Francis Group. https://doi.org/10.1201/9781003122326-2

Role of Smart Homes and Smart Communities in Flexibility Provision

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Keywords: *flexibility services, demand-side flexibility, flexibility provision, smart home energy management, smart energy communities, distribution networks*

1 OVERVIEW

The impacts of decentralization as well as the high penetration of renewable energy resources into power systems have created a necessity to change the operation and management of the power systems in recent years. Although the effects of renewables at all power system levels can be seen, it is more likely to become an issue, especially in distribution networks due to the increased integration of small-scale renewable generation units (e.g. domestic PV panels). However, the output of renewable energy sources (RES) is naturally variable and intermittent in very short-term periods due to their dependency on environmental weather related factors. Therefore, there might exist a constant imbalance between generation and demand which results in the instability of the power system. In order to prevent these instabilities, the electrical systems must become more flexible, meaning that the system must respond to the probable fluctuations rapidly, consistently, and adequately. To do so, all the potential flexibilities in the electrical systems should be deployed. Thus, the flexible capacities have to be effectively managed and controlled in a smart way by the system operators including distribution system operators (DSO) and transmission system operators (TSO) [1].

At the distribution system level, the flexible energy resources are mostly located in the demand side where the majority of consumers are generally residential households/areas. These flexible resources (which can include battery energy storage systems, electric vehicles, flexible loads, demand response, etc.) are able to contribute to enhancing the grid's flexibility by means of different operation and management methods. It is noticeable that in distribution networks, the complexity of the network and also the high amount of end-users and flexible resources worsen the process of dealing with all the end-users individually. Therefore, in order to unlock a considerable amount of flexibility in distribution networks, the system operators need to manage these flexibilities in an aggregated manner in order to be able to utilize them during critical situations. The aggregated management is possible with advanced ICT technologies such as smart management systems in homes or in energy communities with group of homes [2].

This chapter is focused on the role of smart homes and communities in providing demand-side flexibility to the grid. Several energy management methods and approaches for smart homes using home energy management systems (HEMS) for flexibility provision has been previously proposed [3]. These approaches are mostly based on demand-side management by providing dynamic prices to the rational end-users equipped with HEMS and/or taking advantage of demand response programs (DRPs). DRPs are mostly deployed to incentivize customers to react to external signals. The chapter will present the popular DRPs that can reshape the consumption pattern of smart homes and communities. In addition, the flexible resources of residential households and communities are discussed. In this way, smart homes are considered to be equipped with battery energy storages (BESs) and electric vehicles (EVs). Furthermore, the constraints related to the physics of the loads as well as storage-based resources (BES and EV) will be introduced.

Finally, the chapter will focus on the services that smart homes and communities can provide for the system operators. In this regard, DSOs can buy local flexibility services from these resources while TSOs can also utilize distribution-network-connected smart homes and communities to provide system-wide services for their needs. Our proposed case study consists of a small community with two types of flexible energy resources including batteries and plug-in electric vehicles (PEVs). The community tries to exploit upward and downward flexible capacities from these flexible energy resources. The upward and downward flexibilities as well as the optimal schedule of these resources will be discussed in the chapter.

2 DEMAND-SIDE MANAGEMENT FOR FLEXIBILITY SERVICES

Demand-side management is (DSM) the measure or implementation which can be utilized to influence the customers at the demand side with the aim to change load patterns to optimize the energy consumption and improve energy efficiency. This can be realized by using incentives, monetary benefits or administrative actions [4]. DSM can achieve energy cost reduction, energy conservation, optimizing energy consumption and help to maintain the power system more reliable. In addition, DSM postpones the investment in the reinforcement of the power system by shifting or reducing the demand. This will also assist the TSO with its balancing-related responsibilities. Previously, increased investments in generation were needed in order to fulfill the increasing demand [5]. Demand response (DR) can be applied to change the load consumption patterns in the short-term which can be implemented by load shifting or demand reduction [6]. Compared with DR, DSM includes the response of customers to change the load patterns in the short-term and long-term. Hence, DR is one potent solution of DSM that can be implemented at some specific period [5]. Based on the effect on the customer, DSM can be classified into four types as shown in Fig. 1 [7]:

- Energy Efficiency which is recognized as long-term energy conversation implementation that will be used to achieve energy-saving and demand reduction,
- Time-of-Use,
- Demand Response which can be implemented by the activities including load shifting, peak clipping or valley filling or the combination of the mentioned activities and
- Spinning Reserve (SR).

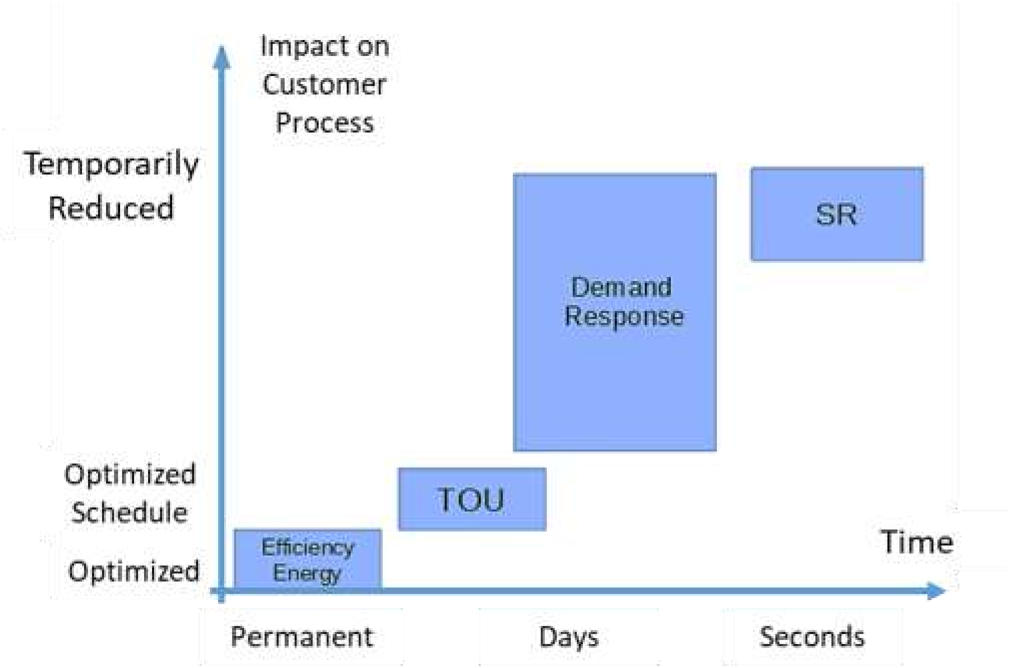

Fig. 1. Classification of DSM programs

Depending on the different impacts to the end-users, DR programs consist of two types: price-based and incentive-based. In price- or time-based DR programs the end-users will reshape the demand according to external signals like price signals. This kind of programs can motivate customers indirectly to follow system changes. In incentive-based DR programs the end-users can receive some incentives, cash benefits, payments, or preferential prices if they can shift or reduce the energy consumption according to the system needs. Market-Based Programs are based on specific electricity market places where the price structures are set up and the electricity is traded [5]. As presented in Fig. 2, price-based DR programs consist of Time-of–use Rates (TOU), Critical Peak Pricing (CPP) and Real Time Pricing programs (RTP). For the Incentive-Based programs (IBP), they can be further classified into two types namely, market-based and classical programs. Classical programs consist of Direct Load Control (DLC) programs and Interruptible/Curtailable Programs, while Market Based programs consist of Emergency Demand Response programs (EDR), Capacity Market, Demand Bidding/Buyback Programs and Ancillary market services programs [8], [9].

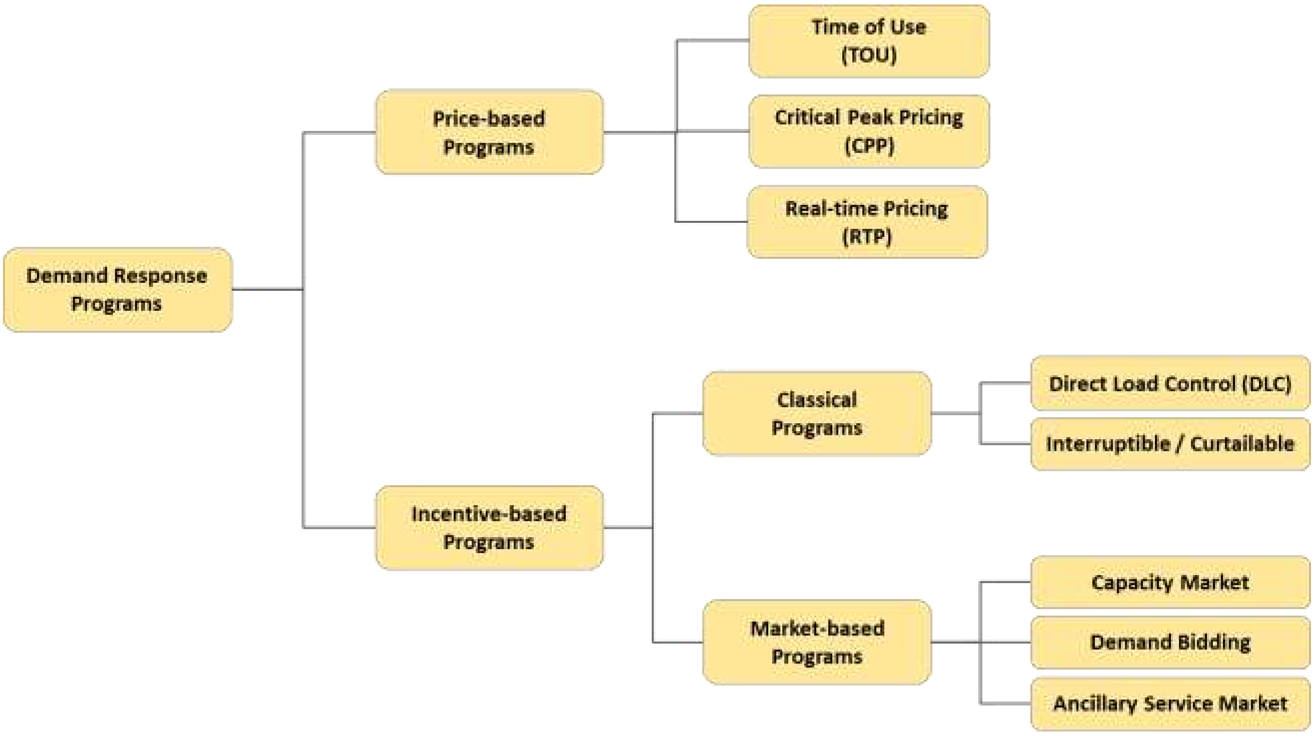

Fig. 2. Classification of DR Programs

2.1 Price- or Time-Based

Price-Based programs are depending on the dynamic pricing where the tariff of electricity is not flat and the pricing rate will change in response to the real-time energy cost. In this kind of program, the high pricing at peak demand time or low pricing at the off-demand time will be offered to flatten the curve of the consumption. Priced-based DR programs can be applied in the industrial sector where the energy costs are regarded as partial production cost. Rational customers equipped with ICT technologies can also react to these programs. Increased electricity costs will result in more production costs. Hence, the manufacturer with larger energy consumption would like to attend price-based programs with the purpose of energy cost reduction. With the fast-growing deployment of information and communication in residential sectors, the application of DR programs becomes more available for smart homes and communities as well [10].

2.1.1 Time-of-Use Rates

TOU rates refer to the varying electricity prices designed for a different time. The prices vary over the day and are well defined in advance [8]. The time period of a day can be split up into three periods including peak, off-peak and shoulder according to different load-demand levels [11]. Generally, the prices are specified based on historical data in which the prices of high demand time are defined to be higher while the prices at off-peak periods are defined to have low rates. This is a core point for the grid utilities as it will encourage customers to decrease the load demand during peak periods and increase the consumption during off-peak periods. Thus, the end-users can gain the energy cost reduction by reducing the load demands. TOU rates are favorable for the grid operator due to the constant price for each period of the day compared with other price-based programs [11]. This is the basic DR program and can be applied in specific periods even in the whole year. The application of TOU rates can partially change the load demand patterns of the end-users, but actually, TOU rates are regarded as beyond DR programs due to their long-term application. In order to achieve favorable incomes, customers need to be equipped with advanced ICT technologies and smart controllers which can be used to control the operation of their resources [7].

2.1.2 Critical Peak Pricing

CPP refers to very high critical prices which are pre-set electricity prices added to TOU or flat prices at critical load peak times [12]. CPP based DR programs are usually applied in some specific hours or days with high wholesale market prices or the periods in system contingencies. In practice, the participants for the CPP programs will receive preferential prices at non-critical peak demand times. This helps the customer to make a more precise determination to utilize the energy more efficiently. CPP offers more precise information on the energy cost for the end-users, especially at peak load times, the more precise determination will be made by the customers on the energy consumption and then the energy cost reduction can be achieved [8]. CPP may happen in extreme situations with very high loads in the summertime and wintertime, some festival days or holidays like Christmas or Easter day.

2.1.3 Real-Time Pricing

RTP rates refer to for example the wholesale electricity prices which vary continuously according to the time during the day [13]. In RTP programs, the end users will receive the bills based on the hourly day-ahead pricing that reflects the real-time energy bill cost. Price-based DR is a key demand response that will use price-based signals to control the energy consumption of customers.

2.1.4 Comparison of Different Priced-Based DR programs

In [10], the merits and demerits of price-based DR programs have been addressed. For TOU programs, it has two advantages. First, it is easy for the participants to understand the TOU pricing portfolios and make the plan for the daily energy consumption since the same price scheme is maintained by TOU pricing. Second, compared with the other two DR programs, the levels of participants attending the programs are stable. The disadvantage is that when the peak load is reduced by TOU pricing DR programs, the new peak may be created.

Regarding the CPP program, it consists of three merits. First, it is easy to understand and follow the CPP portfolio; Second, CPP programs can help the operator to shift the peak load demand effectively. Third, the incentive payment for the participant can be estimated. However, this program is not without disadvantages. First, CPP programs cannot be applied on a daily basis, because the system does not face severe situations every day. Hence, the CPP programs will not reduce the energy bill costs, effectively.

For RTP programs, electricity prices are varying continuously with the market prices. The dynamic prices can help participants reduce or shift their loads in order to maximize their profits or reduce their costs. But the full utilization of RTP programs need the deployment of smart metering and automated control, because it is difficult to control the load manually in response to time-differentiated pricing [14].

2.2 Incentive-Based

2.2.1 Direct Load Control

DLC means the grid operators or utilities can access to the electrical equipment freely and control it remotely and directly on short notice. The remotely controlled equipment typically refers to house appliances such as thermostatically controllable ones including water heaters and air conditioners. This kind of DR program has been implemented in small commercial customers or residential customers [15]. In this regard, the operator can switch the appliances on or off in the limited periods of each year or season. Generally, this type of program will be utilized on the remotely controlled devices like water boilers and air conditioners by residential houses or some small commercial customers [9].

2.2.2 Interruptible/ Curtailable Rates

Interruptible / Curtailable Rates program means the end-users agreeing on this program in return to gain some incentives, bill discount or cash payments by reducing or shifting their loads to pre-set values during the periods in which the systems are in contingencies or need flexibility. The customers who do not follow the agreement will be penalized. Typically, there exists a minimum capacity for participants who want to contribute to this program. The load needs to be curtailed by the participants during a specified period after being notified [5].

2.2.3 Emergency Demand Response programs

EDR programs are utilized to keep the reliability of the system within certain limits, but it is voluntary for customers to curtail their load. The incentives will be provided to the customers that reduce the load. Recently many studies have been on optimization of energy management of microgrid but do not consider demand response programs on the operation. This will result in suboptimal operation and control of microgrid. The operation cost and peak load will decrease while applying EDRP in the operation of microgrid. But the running cost of EDPR will increase when the level of participation is over 50% due to incentive payment to the customers [16]. In [10], the contribution of EDPR has been investigated. EDPR can help balance market power in at the supply side and provide the benefits for the end-users due to the demand reduction. Meanwhile, the reliability of system will be fulfilled by load shedding at Peak times.

2.2.4 Capacity Market Programs

The capacity market programs are formed so that the end-users are committed to reducing the load demand to the pre-defined values in system contingencies. The customers will receive penalties if they refuse to curtail when being notified by the utilities. This kind of program can be considered as insurance. In addition, the guaranteed payments will be offered to the participants [5].

2.2.5 Demand Bidding/ Buyback Programs

Demand Bidding/ Buyback programs refer to programs in which the large end-users are encouraged to provide some specific load curtailment at bidding prices in the wholesale electricity market. When the bidding price is less than the wholesale electricity price, this bid would be accepted. The agreed specific load curtailment should be made when the customers offer the bid or they will be subjected to penalties. This kind of program is based on the day-ahead prediction of demand. The program is applied when the end-users are willing to reduce energy consumption at a specific preset price. One example of demand bidding programs is the application of programmable thermostat that can be used to control heating and air-conditioning systems. The setting of the thermostat can be changed based on the electricity pricing levels. This setting can also need to be modified with seasons [17].

2.2.6 Ancillary services market

Ancillary services market programs refer to programs in which the end-users are allowed to offer their flexible capacities in upward and downward directions using their available flexible energy resources [18].

2.3 Benefits of the DR programs

As presented in Fig.3, the potential benefits from DR programs are summarized under three categories: 1) end-users, 2) system costs and 3) system reliability [9].

End-users or customers involved in DR programs can reduce their energy bill costs when they lower the electricity consumption at peak times or offer flexibility services [19]. The end-users can also increase their energy-saving by load shifting from peak times to off-peak times. In addition, the customers participating in incentive-based DR programs will get incentives. The incentive payments for the participants in DR programs, capacity market programs, demand bidding programs and ancillary services market programs will be dependent on their performance and the system need.

Regarding the system costs related benefits, the wholesale electricity prices may be reduced due to the reaction of demand-side resources during peak hours. In addition, the grid capacity can increase using price-based DR programs and thus the capacity costs will reduce or postpone. In other words, these programs will defer the investment for grid upgrade or enforcement. The participants in market-based DR and price-based programs can affect the electricity market by rescheduling the operation of their flexible energy resources. DR programs can also offer another benefit through price volatility reduction [20].

Participants can enhance the reliability of the power system as well. If DR programs are well defined, the customers will mitigate the outage risks and at the same time, the customers can reduce the risk for the blackout. As a result, the system operators can have more resource to maintain the system in a reliable state [4].

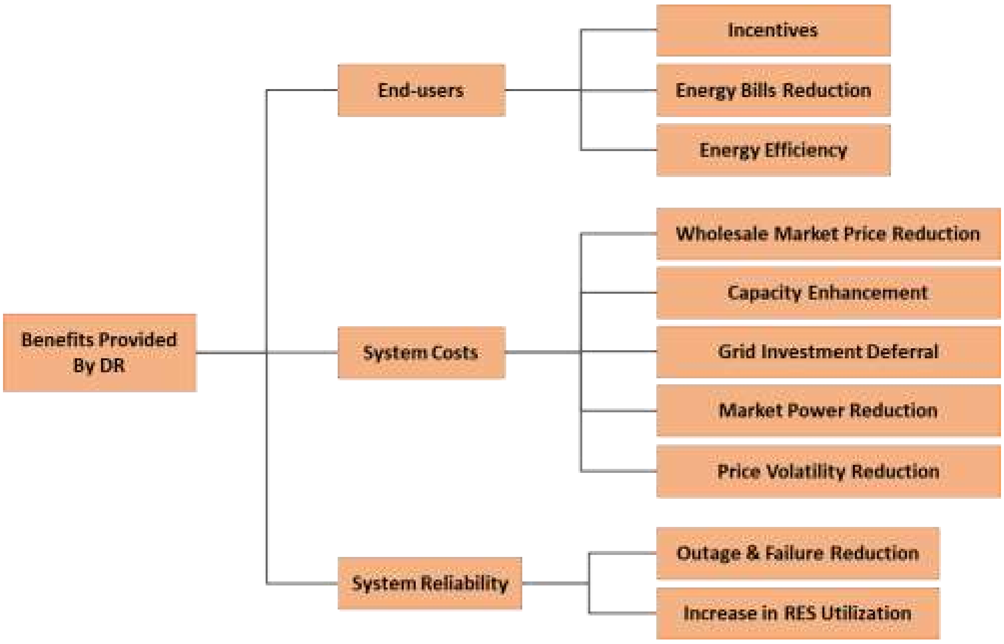

Fig. 3. Benefits Provided by Demand Response Programs

3 DEMAND-SIDE FLEXIBLE ENERGY RESOURCES

The conventional types of electrical power and energy systems were based on the one-directional energy supply starting from bulk generation units to the final consumers at the end. This type of energy systems are increasingly being replaced by decentralized structures in all levels such as generation, transmission, distribution, and demand in recent years. With this regard, the balancing and ancillary services are experiencing a transition as well. The system-wide services, like balancing and frequency control, which were previously provided by bulk generation units, are in the future increasingly provided by the flexible energy resources (FERs).

Demand-side FERs refer to storage-based resources as well as load-based resources which are capable of changing their power in order to contribute to different kinds of local and system-wide flexibility services. There exist various types of appliances which could participate in smart homes'/communities' energy management or demand response programs by curtailing or shifting their consumption over time [21]. However, the focus of this section is on the FERs that could provide power-based flexibility services to local and system-wide networks. The output power of these resources can be controlled and these resources mostly can have a rapid response to the changes when it is required.

There are different types of FERs introduced so far. However, the FERs which are more commonly utilized in smart homes/communities are battery energy storage system (BESS), plug-in electric vehicle (PEV) and thermostatically controlled load (TCL). A general categorization of the most common FERs in smart homes/communities is presented in Fig. 4. These resources will be explained in the following subsections.

Fig. 4. Overview of the most common FERs in smart homes / communities

3.1 Battery Energy Storage System

Battery energy storage systems (BESS) as one of the most prevailing FERs in electrical systems have become quite popular in smart homes/communities, especially, for those households that are equipped with small-scale generation units such as solar panels. BESS could be utilized efficiently in smart homes or communities for energy management purposes as well as flexibility enhancement of the whole community in an aggregated manner. Accordingly, the small-scale BESS in smart homes could contribute to the cost reduction of the house by discharging its stored energy to the house when it is required. Moreover, the BESSs in a community could be aggregated and controlled to provide flexibility services to the upstream grids (i.e. transmission system-level or distribution system-level networks) for fulfilling networks' flexibility needs. In return, the households or community members can take the advantage of selling energy/flexibility to different entities. Eq. (1)-(2) indicate the relation between the stored energy in the BESS and its power rate when it is in charging and discharging mode, respectively.

$$E(t) = E(t-1) + \gamma P^{ch}.T \qquad (1)$$

$$E(t) = E(t-1) - \frac{P^{dch}}{\gamma}.T \qquad (2)$$

Eq. 1() states that the stored energy in the BESS at each time step is directly related to the stored energy at the previous time step in addition to the multiplied values of power rate, efficiency, and the duration of charging considering the efficiency of BESS. In contrast, the stored energy after a period of discharging would be equal to the stored energy in the previous time step minus the discharged energy in the discharging period considering the efficiency of BESS, as in (2). It has to be mentioned that the power rate of BESS could be either constant or adjustable. It is obvious that the adjustable power rate of BESS could be more beneficial than the constant power rate when it comes to flexibility provision. Thus, the power output and its direction (charging or discharging) should be determined by the energy management system. However, the stored energy in the BESS should remain within its limit. This limitation can be denoted by a simple constraint denoted by (3).

$$E^{min} \leq E(t) \leq E^{max} \qquad (3)$$

3.2 Plug-in Electric Vehicle

Plug-in electric vehicles (PEVs) have been the most prevailing FER among the smart homes' dwellers in recent years. The presence of PEVs could affect the operation of the electrical network adversely. However, the optimized operation and charging strategy of these resources could help the networks in terms of flexibility provision. In this manner, a smart home can schedule charging of the PEVs through its home energy management system (HEMS). A community manager can also control the charging behavior of its EVs through its energy management system. PEVs are potent resources which can provide the operators with flexibility services. In this way, their charging pattern can be modified according to the system flexibility needs [22].

The equation that represents the operation of the PEV's battery is the same as BESS. Regarding the operation of PEVs in smart homes/communities, the constraints related to the stored energy in the PEVs' battery must be taken into account in the problem formulation as in (4):

$$E^{PEV,min} \leq E^{PEV}(t) \leq E^{PEV,max} \qquad (4)$$

Eq. (4) limits the upper and lower bounds of stored energy in the PEVs' battery in order to prevent rapid depreciation of the battery since limiting the cycles of charging/discharging prevent shortening the life of PEV's battery. In (4), $E^{PEV}(t)$ is the stored energy in the PEV's battery at time slot t whilst $E^{PEV,min}$ and $E^{PEV,max}$ are the minimum and maximum desired level of stored energy in the PEV's battery, respectively.

In contrast, models of PEVs have been introduced in recent years that have the capability of vehicle-to-grid (V2G) energy flow as well. This means that PEVs could contribute to upward flexibility provision to the network by injecting the stored energy in their batteries back to the grid in the critical moments. It is noticeable that the V2G operation mode of the PEVs could is along with a depreciation in their batteries, which should be considered in the V2G operation mode [23], [24].

Moreover, the charging infrastructure of PEVs might be various in terms of power rate and technology. The power of charging in these charging infrastructures could be either constant or dynamic [22]. There have been introduced some domestic PEVs' charging piles recently that have the ability of changing the charging/discharging power rates. These charging/discharging method are known as dynamic charging/discharging. The benefit of dynamic power rates for PEVs is in their capability of flexibility provision in a shorter period of time. With this regard, the constraints related to dynamic charging/discharging of PEVs also must be considered in flexibility provision problems as in (5)-(6):

$$0 \leq P^{ch,PEV}(t) \leq P^{ch,max} \qquad (5)$$

$$0 \leq P^{dch,PEV} \leq P^{dch,max} \qquad (6)$$

3.3 Thermostatically controlled Load

Another type of FERs that could be found almost in every smart home is thermostatically controlled load (TCL). These kind of FERs are, in fact, demand-based FERs which are capable of changing their power consumption through a thermostat and a command signal. In other words, TCL is following the variation of temperature on the one hand, and are responsive to the receiving command signals on the other hand. The input command signal to the TCLs could be based on different purposes such as demand response programs, flexibility provision, or even energy management inside the smart homes/communities.

There are different types of TCLs inside smart homes such as electric water heater (EWH) and heating, ventilation, and air conditioning (HVAC) systems. These TCLs could effectively contribute to the issue of flexibility provision from the demand side. It has to be mentioned that these resources are not as fast as storage-based flexible resources when it comes to responsiveness. Therefore, they might not be capable of participating in all kinds of flexibility services. However, since the TCLs are responsible for a great portion of demand-side energy consumption, utilization of their flexibility could be quite beneficial in electricity network service provision [25].

One of the most popular flexible resources amongst TCLs is EWH. This resource is a load that its power consumption could be changed over time by changing the status of the device between ON and OFF in order to provide flexibility services. Accordingly, when the device changes its status from ON to OFF, its power consumption is curtailed and changes to zero, which could be realized as upward flexibility service to the grid. In contrast, when the device changes its status from OFF to ON, its power consumption will increase to the nominal rate, which could be realized as downward flexibility service to the grid. However, there have been introduced some kinds of EWH with cutting-edge technologies in recent years, which their power consumption is adjustable as well.

Another type of TCL which could be found in smart homes is HVAC. This resource is also a load that its power consumption could be changed for flexibility services. In recent decades, the brand new models of HVAC are introduced that are more flexible. These HVACs could adjust their power consumption to an exact value by using power electronic devices (i.e. inverter). This ability could be quite advantageous when a specific amount of flexibility is required from the smart homes or communities.

4 FLEXIBILITY PROVISION BY SMART HOMES AND COMMUNITIES

As previously mentioned, smart homes have some controllable appliances and storage-based resources as FERs, enabling them to provide flexibility services for the system operators, including DSOs and TSOs. DSOs can procure local services from smart homes. These services can be related to voltage control and congestion management of the distribution network. However, for providing TSO-level services, smart homes need to be aggregated in order to be able to provide system-wide services. System-wide services are mainly referred to those utilized to control the frequency of the system. Fig. 5 illustrates the potent flexibility services that can be procured from smart homes and communities.

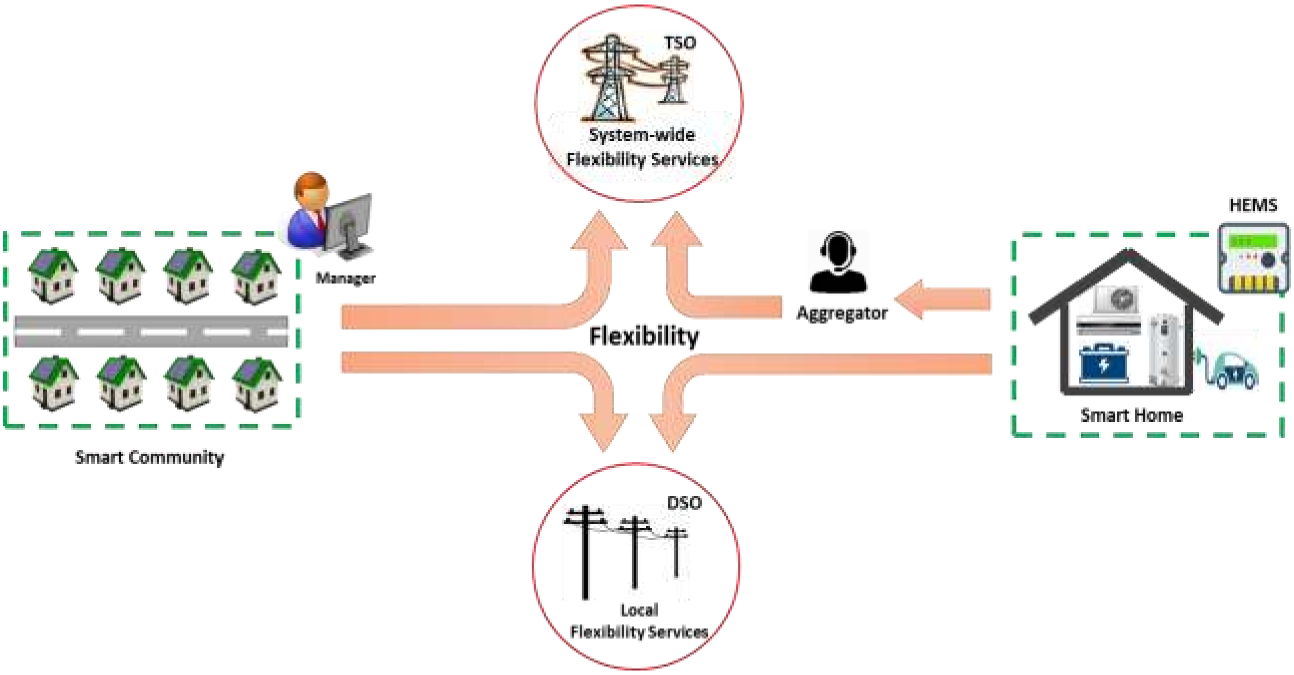

Fig. 5. The potent services that can be provided by smart homes and a community

4.1 Local Flexibility Provision

Distribution feeders in rural areas, especially those within weak electrical systems and the high number of customers, are often operated close to their voltage and thermal limits. The excessive number of distributed generation units connected to distribution networks may cause violation of the physical capacity constraints. These capacity constraints can be defined as $P^{generation} - P^{load} < P^{max}$ and $P^{load} - P^{generation} < P^{max}$. Where, $P^{generation}$ is the power produced and P^{load} is the amount consumed. Accordingly, with the high number of DGs constraint $P^{generation} - P^{load} < P^{max}$ may be violated which in turn jeopardize the security of the distribution network. Another situation can happen for the network with a huge number of electric vehicles which are charging simultaneously. In this situation, constraint $P^{load} - P^{generation} < P^{max}$ regarding the feeder thermal capacity may be exceeded. In addition to capacity constraints, the future DSOs should deal with serious challenges related to voltage control since DGs which are located close to the loads may increase voltage at these nodes if simultaneously generation is very high and load is very low [26].

Currently, DSOs perform some costly actions in order to alleviate the congestion of feeders and control voltages in the distribution network. Changing the set points of on-load tap changer (OLTC) transformers, re-dispatching the generation units, utilizing voltage regulators, capacitor banks, and static voltage compensators are the actions taken by the current DSOs in order to operate the network. However, these methods can be costly and may fail to effectively operate the distribution networks with high injection of intermittent power [27].

Demand side flexible energy resources such as smart homes are able to provide an alternative solution instead or in addition to the current DSO actions. In fact, smart homes have the capability to reshape their consumption and curtail their production according to the requests sent by the DSO. In return, they will receive monetary benefits.

In order to find the optimal amount of flexibility, DSO needs to solve an optimization problem taking into account the power flow equations in the distribution network. Afterward, the DSO finds the amount of downward and upward flexibility which is required for each node. These upward and downward flexibility need can be provided by the flexible energy resources located at those specific nodes. Smart homes and residential energy communities are thus the potential flexible resources capable of providing flexibility services. They can provide the required flexibility through controlling their appliances or utilizing their storage-based resources. If the DSO needs downward flexibility, the smart homes can charge their EVs and batteries or switch off their appliances such as washing machine. If the DSO requests for upward flexibility, they can discharge their batteries or curtail their curtailable loads.

An energy community can consist of a group of smart homes who voluntarily join the community [22]. The members of a community can be smart consumers or smart pro-active consumers which are called prosumers. Energy communities might have some shared resources in order to increase flexibility and self-sufficiency of the community such as a bulk energy storage system, a PV system as well as a wind turbine. The energy community can be also a potent resource for providing local flexibility services. In this way, the manager of the community can control the resources within the community aiming to maximize the total profits of the members.

4.2 System-wide Flexibility Provision

The volatility and uncertainty resulted from intermittent renewable-based power injected in power systems has decreased the stability and flexibility of the systems. However, the TSO needs to increase the flexibility of the system through adjusting the operating point of the system and accommodate the variations and fluctuations resulted from uncertainties and variability of loads and renewable-based generation resources. The flexibility of the system will be enhanced by using flexible energy resources [18]. Flexible energy resources can be located at different levels of the power system including DSO-level (those located at distribution networks) as well as TSO-level (those connected to transmission networks). Currently, conventional generators are the only flexible energy resources utilized to provide system-wide flexibility services. System-wide flexibility services are mainly referred to the services related to controlling the frequency of the whole system.

In order to increase the flexibility of power system, flexible energy resources connected to distribution networks should be also able to provide system-wide flexibility services. In this regards, the aggregated smart homes and distribution-network-located energy communities are potent resources which can provide the TSO with frequency services.

Frequency services mostly include reserves that help TSOs to maintain the frequency of the whole system at a predefined threshold. The reserve services can be different based on the characteristic of the system and the current state of the system.

In Finland, as an example of Nordic countries, frequency reserve services are divided into primary reserves which is called "frequency containment reserve" (FCR), the secondary reserves which is called "automatic frequency restoration reserve" (aFRR) as well as tertiary reserves which is named "manual frequency restoration reserve" (mFRR). These reserve services are requested based on the need of the system. However, the primary reserve, FCR, should be procured all the time. This reserve is required to automatically respond to spontaneous frequency deviations. FCR may be adopted only for normal operation of the system which is called (FCR-N) or be deployed in disturbance condition which is called (FCR-D). Moreover, the aFRR is used to restore the frequency automatically. However, the manual FRR is just applied in case of outages, or some situations associated with unexpected sustained activation of aFRR [28]. In addition to the mentioned services, a new kind of flexibility service was introduced in Finland which is called "fast frequency reserve" (FFR). This kind of service is deployed to handle rapid frequency fluctuations in low inertia situations [22].

As previously mentioned, currently, fuel-based generators are the main resources providing reserves for the TSO. However, distribution-network-connected resources such as aggregated smart homes and communities are also capable to provide different types of reserves and frequency services. With the growing injection of renewable-based resources in the future, the participation of distribution-network-connected resources as well as transmission-network-resources is of vital necessity in order to increase the flexibility of the system.

The flexibility of smart homes can be aggregated and be utilized to provide different types of reserve services. Each reserve service has its own reserve market with its specific technical consideration. Accordingly, a smart home selected as a FCR provider should have a resource or a combination of resources that can provide upward and downward flexibility. The direction of the flexibility is mainly determined in real-time based on the instant need of the TSO. In other words, the TSO chooses the type of flexibility service that will be activated in real-time. This request can be sent to the resources through its control system. The resource (e.g. the smart home) should be able to automatically react to the request of the TSO.

The HEMS of a smart home can choose the most beneficial services that the home can provide for the grid. In this regard, there exist a variety of system-wide and local services that the smart home is able to provide for the TSO and DSO. The HEMS can run an optimization problem to select the services that help the household maximize its profits (or minimize its costs). However, the technical constraints of each service should be taken into consideration as well. It is worth mentioning that a household, itself, cannot separately participate in reserve markets since it does not have enough capacity to take part solely in the market. Thus, the smart homes are required to be aggregated by an aggregator so as to be able to contribute to the provision of system-wide services.

When it comes to an energy community, a community manager via a centralized energy management system controls the flexible resources of the community. These flexible resources can be the shared resources which are centrally controlled or those which are belong to the household as members of the community. In this way, the community manager aims to maximize the profits of all member by choosing the most appropriate flexibility services that can be provided for the DSO and TSO.

5 CASE STUDY

In the case study, we consider an energy community which consists of two 200kWh/50kW batteries as well as five similar electric vehicles with a capacity of 40 kWh as flexible energy resources. PEVs are considered to be charged with the constant power which is equal to 5 kW. It should be noted that it is assumed that PEVs should be charged just early in the morning i.e. from 1:00 to 8:00.

The community aims to provide upward and downward services for the grid operators. Thus, the community is assumed to find the capacity that can be offered for grid services. In this regard, the objective function can be maximizing the profits achieved from the provision of upward and downward flexibility.

$$\max_{Flex_t^{up},Flex_t^{dn}} \pi_t^{flex,up} Flex_t^{up} + \pi_t^{flex,dn} Flex_t^{dn} \qquad (7)$$

Where, $Flex_t^{up}$ is the upward capacity of the community devoted to upward flexibility services at timeslot t and $Flex_t^{dn}$ denoted the downward flexible capacity of the community devoted to downward flexibility services at time slot t. In addition, $\pi_t^{flex,up}$ and $\pi_t^{flex,dn}$ are the prices of upward and downward flexibility, respectively.

Charging capacities of batteries and PEVs are considered as downward capacities of the community while discharging batteries are regarded as the upward flexible capacity of the community. The related balancing constraints are denoted with (8) and (9):

$$\sum_b P_{b,t}^{ch} + N_t^{ev} P^{ev} = Flex_t^{dn} \qquad (8)$$

$$\sum_b P_{b,t}^{dis} = Flex_t^{up} \qquad (9)$$

In (8), N_t^{ev} denoted the number of PEVs which are being charged at time slot t. P^{ev} is the constant power used for charging EVs. In addition, $P_{b,t}^{ch}$ is the charging power of battery b at timeslot t. Accordingly, (8) states that the downward flexibility ($Flex_t^{dn}$) should be provided by charging power of batteries and PEVs of the community. However, according to (9), only discharging power of batteries is taken into account as upward flexible capacity of the community which is denoted by $Flex_t^{up}$.

Moreover, the constraints related to the charging/discharging power and energy of batteries and PEVs were introduced in the previous section.

According to the above-mentioned equations, the upward flexible and downward flexible capacities of the community for 24 hours are estimated based on its flexible energy resources including its PEVs and batteries. The obtained upward and downward flexibility that the community will provide is depicted in Fig.6. As can be seen in the figure, the community can provide both upward and downward flexibility in time slots 2:00-6:00, 8:00-16:00 and 19:00 using its batteries and PEVs. However, in the other timeslots, the community is just able to provide either upward or downward flexibility.

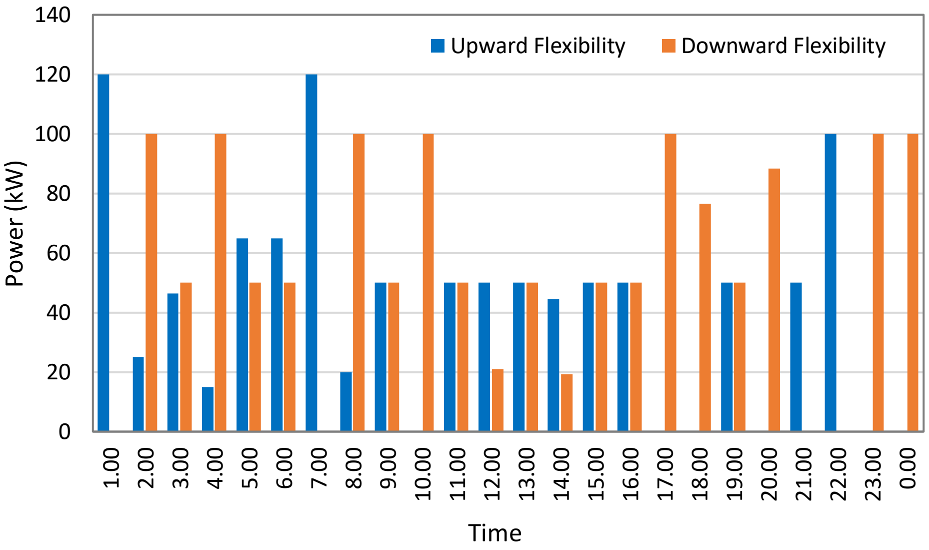

Fig. 6. The amount of upward and downward flexible capacities provided by the considered community

The variation of the state-of-charge (SOC) of batteries and PEVs of the community are illustrated in Fig. 7 and Fig.8, respectively.

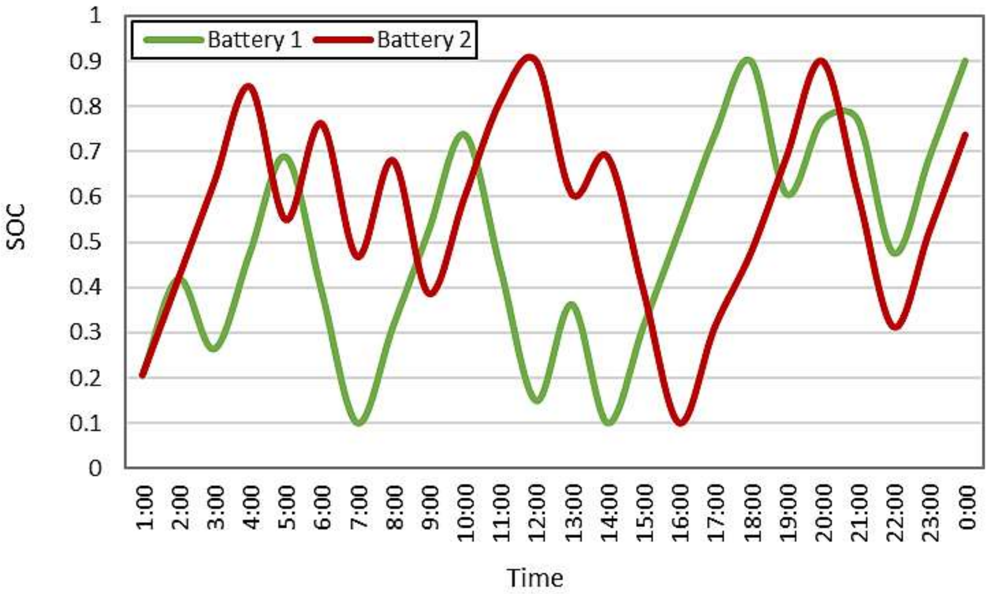

Fig. 7. The SOC of batteries in the community

Fig. 7 states that the variation of SOC for two batteries is in opposite directions in the most of time slots. It means that, during time slots that battery 1 is charging, battery 2 is discharging. In this way, the community would be able to provide both upward and downward flexibility simultaneously.

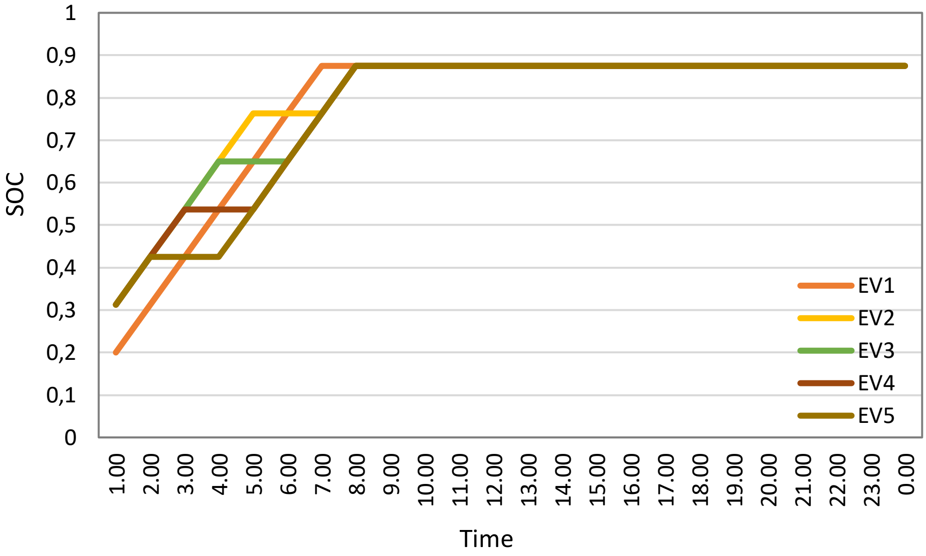

Fig. 8. The SOC of PEVs' batteries in the community

Fig. 8 shows the SOC variation of the batteries of PEVs. The downward flexible capacities of PEVs are mainly deployed in early morning to satisfy the constraint applied by the PEV owners since after these hours the PEV owners do not want their vehicles to be charged. Thus, their flexibility capabilities are highly exploited in our model.

6 SUMMARY

The impacts of decentralization as well as the high penetration of renewable energy resources into power systems have created the necessity of changing the way of network management for power system operators in recent years. Although the effects of renewables in all levels of the system can be seen, it is more likely to become an issue, especially in distribution networks due to the ever-increasing utilization of small-scale renewable generation units (e.g. domestic PV panels).

Distribution-network-located flexible energy resources such as mart homes and energy communities can increase flexibility of power system. Smart homes and communities can reshape their consumption and production through their flexible energy resources including battery energy storage systems, electric vehicles, or their other controllable appliances. By utilizing these resources, they are able to contribute to enhancing the grid's flexibility. In this way, for example, PEVs and batteries should be charged if the system needs downward flexibility while the batteries should be discharged during time slots that the system operator requests for upward flexibility.

Different kinds of DR programs can incentivize customers to actively respond to the system requests. These programs can indirectly control the flexible energy resources such as direct load programs or can indirectly affect the load of the customers. However, in order to receive an acceptable response, customers need to be equipped with decent ICT technologies and energy management systems.

Both customers and system operators can benefit from DR programs and flexibility services procured from demand-side resources. DSOs can procure local services from smart homes and energy communities connected to distribution networks. These services can be related to voltage control and congestion management of the distribution network. However, for providing TSO-level services, smart homes need to be aggregated in order to be able to provide system-wide services. System-wide services are mainly referred to those utilized to control the frequency of the system. In this way, the resources need to be automatically control.

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