Electric Power Systems Research 205 (2022) 107767

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

Flexibility Potential of a Smart Home to Provide TSO-DSO-level Services

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ARTICLE INFO

Keywords:
smart homes
flexibility services
energy flexibility
demand response
controllable appliances

ABSTRACT

The high penetration of intermittent renewable-based power into modern power systems increases the need for more technical ancillary services from flexible energy resources. Smart homes could provide different flexibility services related to active power control services and therefore fulfill a part of the flexibility needs of system operators. In this regard, the estimation of the flexible capacities of each smart home's flexible device is of key importance. Correspondingly, this paper first estimates the flexible capacities of a smart home with controllable devices as flexible resources. The flexible capacity of each appliance is estimated considering its flexible and non-flexible operations. Besides, the local and system-wide flexibility services are introduced and the paper discusses whether a smart home can provide these types of services. In the simulations of this paper, the flexible capacity of each household appliance is estimated and compared to each other. Finally, the profitability of the smart home's battery energy storage multi-use is analyzed when it is providing three different types of flexibility services for the transmission system operator's needs. The results demonstrate that in some scenarios, the smart home's battery energy storage can increase its profits by providing transmission-system-level flexibility.

1. Introduction

1.1. Motivation

Modern power systems aim to host renewable-based energy as much as possible to minimize the environmental impacts of energy generation. However, the power produced by renewable resources is intermittent and uncertain. The high penetration of intermittent renewable-based power into the electricity networks increases the system operators' flexibility needs. Future power systems are required to be more flexible and be able to change their operating points constantly according to the real-time demand or/and generation fluctuations. In this regard, different types of technical ancillary services i.e. flexibility services are employed to manage the future power system with increasing flexibility needs.

In general, flexibility services are procured to fulfil local and system-wide flexibility needs. Local flexibility services help local distribution system operators (DSO) increase the flexibility of their electricity distribution networks. On the other hand, system-wide flexibility services assist transmission system operators (TSO) in controlling the frequency of the system and thus enhance the system-wide flexibility. TSOs and DSOs procure flexibility services from flexible energy resources (FER). Currently, conventional fuel-based generators are the main FERs utilized to provide system-wide flexibility services [1]. Besides, DSOs use conventional regulators and devices for the local flexibility provision. However, the employment of these devices as the only approach of operating distribution networks is not enough for the future power system with the high penetration of renewable generations [2].

To this end, both DSOs and TSOs need to employ new FERs to resolve the future flexibility requirements. Active and smart residential customers connected to distribution networks are very potential FERs that can provide flexibility for the TSOs and DSOs. Smart homes have some flexible appliances that can be controlled according to the system operators' needs. In this way, they sell their flexibility i.e. flexible capacities to the system operators and receive the monetary profits accordingly. In this way, the system operators are able to exploit the maximum flexibility potential of the active customers connected to distribution networks.

1.2. Literature review

In this context, there is some research proposing the participation of smart homes and residential customers in providing flexibility services. Some studies mainly focused on the provision of local flexibility services through active residential customers. For example, [3] suggested a centralized control of smart homes' appliances with the aim of providing local flexibility services. In that research, the DSO determines dynamic

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https://doi.org/10.1016/j.epsr.2021.107767
Received 18 October 2021; Received in revised form 21 December 2021; Accepted 27 December 2021

Nomenclature

Abbreviations

AC	Air Conditioner
BES	Battery Energy Storage
DSO	Distribution System Operator
EV	Electric Vehicle
EWH	Electric Water Heater
FCR	Frequency Containment Reserve
FER	Flexible Energy Resource
FFR	Fast Frequency Reserve
FRR	Frequency Restoration Reserve
HEMS	Home Energy Management System
SOC	State of Charge
TSO	Transmission System Operator

Sets

t	Time
s	Scenario

AC-related parameters

θ^h	Lower limit of the desired temperature of the household [°C]
$\overline{\theta^h}$	Upper limit of the desired temperature of the household [°C]
θ_t^{amb}	Ambient temperature at time t [°C]
α	Constant related to the thermal characteristic of the household
β	Coefficient of the AC's performance [°C /kWh][heat: $\beta > 0$, cool: $\beta < 0$]
$\overline{P^{AC}}$	Nominal power consumption of the AC [kW]

AC-related variables

θ_t^h	Household indoor temperature at time t [°C]
P_t^{AC}	Operating power of the AC at time t (in general) [kW]
P_t^{AC-C1}	Non-flexible operating power of the AC at time t [kW]
P_t^{AC-C2U}	Operating power of the AC at time t when it provides upward flexibility [kW]
P_t^{AC-C2D}	Operating power of the AC at time t when it provides downward flexibility [kW]

EWH-related parameters

θ^w	Minimum temperature of the hot water [°C]
$\overline{\theta^w}$	Maximum temperature of the hot water [°C]
$\widetilde{Q}_h^{EWH}$	Maximum energy demand of the EWH [kWh]
k	Constant of energy conversion [kWh/J]
ρ	Specific heat of water [J/kg°C]
v^{EWH}	Capacity of the EWH tank [kg]
V_t^{tank}	Volume of the stored water in the EWH tank at time t [kg]
$\theta^{w,ini}$	Initial in-tank water temperature [°C]
θ^{cold}	Temperature of inlet cold water [°C]
$\overline{P^{EWH}}$	Nominal power consumption of the EWH [kW]

EWH-related variables

θ_t^w	Temperature of EWH's water at time t [°C]
Q_t^{EWH}	Energy demand of the drained hot water of the EWH at time t [kWh]
P_t^{EWH}	Operating power of the EWH at time t (in general) [kW]
P_t^{EWH-C1}	Non-flexible operating power of the EWH at time t [kW]
$P_t^{EWH-C2U}$	Operating power of the EWH at time t when it provides upward flexibility [kW]
$P_t^{EWH-C2D}$	Operating power of the EWH at time t when it provides downward flexibility [kW]

EV-related parameters

$\underline{SOC_t^{EV}}$	Lower limit for the EV's battery SOC at time t
$\overline{SOC^{EV}}$	Upper limit for the EV's battery SOC
Cap^{EV}	Maximum capacity of EV's battery [kWh]
$\overline{P^{AC}}$	Maximum charging power of the EV's battery [kW]
η^{EV}	Charging efficiency of the EV's battery

EV-related variables

SOC_t^{EV}	SOC of the EV's battery at time t
P_t^{EV-C1}	Non-flexible charging power of the EV's battery at time t [kW]
P_t^{EV-C2U}	Charging power of the EV at time t when it provides upward flexibility [kW]
P_t^{EV-C2D}	Charging power of the EV at time t when it provides downward flexibility [kW]

BES-related parameters

$\underline{SOC_t^B}$	Lower limit for the BES SOC at time t
$\overline{SOC^B}$	Upper limit for the BES SOC at time t
$\overline{P^{B,dis}}$	Maximum discharging power of the BES [kW]
$\overline{P^{B,ch}}$	Maximum charging power of the BES [kW]
Cap^B	Maximum capacity of the BES [kWh]
$\eta^{B,ch}$	Charging efficiency of the BES
$\eta^{B,dis}$	Discharging efficiency of the BES

BES-related variables

$P_t^{B,ch-U}$	Charging power of the BES when it provides upward flexibility [kW]
$P_t^{B,ch-D}$	Charging power of the BES when it provides downward flexibility [kW]
$P_t^{B,dis-U}$	Discharging power of the BES when it provides upward flexibility [kW]
$P_t^{B,dis-D}$	Discharging power of the BES when it provides downward flexibility [kW]

tariffs as well as daily network tariffs to manage the congestion in the distribution networks. However, the provision of system-wide flexibility services was not analyzed in the paper. In another work, [4] proposed a real-time re-scheduling model for shiftable appliances to respond to the DSO's flexibility requests. Then, it utilized evolutionary algorithms to solve the scheduling problem. The paper did not consider the constraints related to the operation of different appliances. For example, it did not consider the constraints imposed by the household thermal comfort and their impacts on the operation of the appliances. Reference [5] also analyzed the provision of local services through the aggregated commercial customers. However, the main focus of the paper was on the aggregation method and the interaction between the DSO and the aggregator, and not on the appliances' scheduling and the flexible capacity potential of the customers. Also, [6] suggested the use of flexible energy resources to tackle operational challenges of DSOs. The paper did not take into consideration the details about modeling these flexible energy resources. Finally, [7] presented a market environment for the participation of households in the provision of local flexibility services. Although the paper presented a comprehensive model, it did not introduce any details and mathematical models of household appliances and their flexible operations.

The contribution of residential customers to the system-wide flexibility, on the other hand, was more taken into consideration in the previous research. For instance, some authors proposed demand-side customers participating in peak-shaving programs. References [8, 9]–[12] are the examples that presented the optimal management of household appliances by shifting them to off-peak time slots and thus provide flexibility for the grid. The peak-shaving programs, however, cannot enhance the real-time flexibility of power systems and directly help the system operators deal with real-time flexibility issues resulted from intermittent renewable generation. On the other hand, [13] introduced a new local market for providing both system-wide and local flexibility services by residential prosumers. In that paper, the prosumers sell their flexible capacities to the TSO and the DSO, so that the system operators are able to follow their flexibility needs in real-time. However, the focus of the paper is more on the local capacity market clearing mechanism and the details of prosumers' scheduling were not included in the paper. Besides, [14] provided a tool that studies different aspects of demand response business models. It also presented a demand response business model canvas through which, a residential customer is able to analyze the demand response offers as well as the types of benefits that can be achieved by selling flexibility. The details and mathematical formulations about flexible capacities of these customers were not assessed in the paper. Authors of [15] developed a two-stage optimization problem aiming to maximize the revenues of small-scale prosumers that provide tertiary frequency services. Again, the constraints related to appliances' operation and the comfort level of household customers were not thoroughly modeled, similar to the works conducted by [16, 17] and [18]. These works tried to model household controllable appliances in a general way, by scheduling their working timetables, although each appliance may have its own operational and usage-based constraints. In other words, although a wide range of controllable appliances can be categorized into shiftable loads, their operations' limitations are different and thus they cannot be modeled together.

In comparison, some research analyzed the smart homes' flexibility provision capability using the details and the mathematical models of appliances. In this regard, [19] proposed two methods for controlling thermostatically controllable loads (TCL) and quantifying their available flexibility. Although the research utilized the mathematical models of TCL appliances, it does not calculate the flexibility potential of other flexible appliances. In another study, [20] presented a comprehensive work on how smart homes can provide demand response programs, solely or in an aggregated manner. This work did not mathematically model household appliances, individually. Besides, [21] proposed that the neighboring residential customers form a local energy community to provide frequency restoration reserves (FCR) as a system-wide service. The paper only considered EVs and a BES as a shared FER providing flexibility. In another research, [22] suggested a new method to forecast the flexibility of residential customers and schedule their electric water heaters (EWH) to provide frequency containment reserves (FCR) for the TSO. Household air conditioners (AC) were also proposed to be aggregated in [23], playing active roles in the operating reserve provision. Also, [24] introduced a general formulation to obtain the flexibility percentage of household appliances. The details and constraints of these appliances were not modeled in that work. In a similar study, [25] analyzed the response of TCLs, in general, that help to maintain the balance between the system's demand and generation. However, thermostatically controllable appliances and storage-based devices can be scheduled simultaneously for providing different types of flexibility services, which were not considered in the previous mentioned literature. Finally, [26] provided a review on flexibility potential of household appliances. The work, however, did not present any mathematical model to calculate the flexible capacities of these appliances and the residential customers.

1.3. Contribution and Structure

In this paper, smart homes aim to provide flexibility services for system operators. Table 1 compares the reviewed literature with this paper. The first four columns analyze whether they mathematically modeled the appliance as an FER. The last column assesses if the research tried to estimate, calculate, or forecast the flexible capacities adopted by the household appliances. These flexible capacities should be obtained from comparing the normal operation and flexible operation of the appliances.

Considering Table 1, the contribution of the paper can be categorized into three main points:

1- We consider two types of appliances, thermostatically controllable appliances and storage-based devices. Thermostatically controllable appliances include an AC and an EWH whose operations affect the thermal comfort of the household. Storage-based devices include an EV and a BES. The EV charging is scheduled according to its availability and the owner's charging preference while the total capacity of the BES is utilized for flexibility purposes. To the best of the authors' knowledge, the simultaneous operation of these four appliances for providing flexibility has not been considered in the existing literature.

2- We estimate the flexible capacity of a household based on the flexible and non-flexible operations of its controllable appliances. It should be noted that estimating the flexible capacity is of vital necessity for system operators, household aggregators and the household, itself. System operators should assign monetary values according to the flexible capacities of the households and the aggregators and the household need this estimation to build bidding strategies and choose the appropriate flexibility services. However, to the best of the authors' knowledge, there exists no previous research dealing with estimating the flexible capacity of households by modeling their controllable appliances.

3- Finally, we introduce different types of flexibility services based on the European terminology of TSO-level flexibility services for frequency control. Besides, in the simulation section, multi-use scenarios of a smart home's BES is analyzed and the profitability of providing three types of system-wide (TSO-level) services is assessed considering different activation scenarios.

The rest of the paper is organized as follows. Section 3 estimates the

TABLE 1
A comparison between our paper and the existing literature

Ref.	Providing mathematical models for:				
	AC as FER	EWH as FER	EV as FER	BES as FER	Flexible capacity forecast/estimation
[3]	-	-	✓	-	-
[4]	-	-	-	-	-
[5]	-	-	-	✓	-
[7]	-	-	-	-	-
[8]	-	-	-	✓	-
[9]	-	-	-	-	-
[10]	✓	✓	-	✓	-
[11]	-	-	-	✓	-
[12]	-	-	✓	-	-
[13]	-	-	-	-	-
[14]	-	-	-	-	-
[15]	✓	-	✓	-	-
[16]	-	-	-	-	-
[17]	-	-	✓	✓	-
[18]	-	-	-	-	-
[19]	✓				Quantify
[21]	-	-	✓	✓	-
[22]	-	✓	-	-	Forecast
[23]	✓	-	-	-	-
[24]	-	-	-	-	Estimation
[25]	✓	-	-	-	-
[26]	✓	-	✓	✓	-
Our paper	✓	✓	✓	✓	Estimation

flexible capacities of household appliances according to their flexible and non-flexible operations. Section 4 introduces the existing TSO-level flexibility services and discusses whether a smart home can provide these services. Section 5 provides a brief discussion about the participation of a smart home in providing DSO local services. Section 6 tries to estimate and compare the flexibility of different household appliances. Finally, section 6 concludes the paper.

2. Estimating the flexibility of a Smart Home

The flexible capacities of a smart home need to be estimated before their activation. The reasons are twofold. First, the home energy management system (HEMS) that controls the controllable appliances should evaluate the flexibility potential of the smart home before its activation to check the availability of these appliances and to conduct cost-benefit analyses. Second, system operators need to estimate the flexible capacity of a smart home that has reacted to the operators' flexibility requests. In this way, the operators are able to assign monetary compensation based on the available flexible capacity of the smart home. However, it would be difficult to distinguish between the household's actual load and its flexibility that is resulted from its reaction to the flexibility signals. It is worth mentioning that uncontrollable appliances cannot provide flexibility. It means that only controllable appliances are able to provide flexibility. However, we can estimate their flexibility by estimating the change of controllable appliances' operation according to their reaction to flexibility signals. To this end, we propose that the flexible capacity of each controllable device is estimated by comparing the device's normal operation and its flexible operation. Fig. 1 summarizes normal and flexible operations for four types of controllable appliances. It should be noted that the focus of this work is to maximize the appliances' flexible operations in near real-time. In the following section, this paper aims to estimate the flexibility of each controllable appliance based on its specific characteristics.

2.1. Estimating the flexibility of thermostatically controllable loads

Household thermostatically controllable loads (TCL) mostly come from space heating and cooling as well as the hot water consumption. In this way, this paper considers the consumption of two appliances including EWH and AC as thermostatically controllable loads. We consider two cases for the operation of these devices to estimate their flexible capacities. The first case represents the non-flexible operation of appliances whereas the second case introduces the flexible operation of the devices. It is assumed that the smart home is equipped with an intelligent HEMS that schedules the controllable appliances based on the defined objective. Fig. 2 overviews the general model of a smart home and its flexibility-related application.

2.1.1. Case 1: normal operation

For the first case, the HEMS is assumed to control thermostatically controllable devices aiming to maximize the thermal comfort level. Therefore, the objective function of the HEMS is as follows:

$$\min_{\theta_t^w,\theta_t^h,P_t^{EWH-C1},\ P_t^{AC-C1}} \left|\theta_t^w - \theta^{w,des}\right| + \left|\theta_t^h - \theta^{h,des}\right| \tag{1}$$

According to (1), the HEMS aims to maximize the thermal comfort level of the household by minimizing the difference between the desired temperatures and the actual temperatures. The first term indicates the difference between the actual and desired temperature of the water whereas the second term denotes the difference between the actual and desired temperature of the household space. The introduced objective function is restricted by some operational constraints and those related to the occupants' comfort level. The HEMS should consider these constraints using the mathematical models of the appliances. For the EWH, one constraint is associated with the operation of the device which states that the temperature of the in-tank water depends on the water's temperature of the previous time step and the heat loss due to hot water demand and boiler's power rate. In fact, at each time slot, the power consumption of the boiler must be adjusted to regulate the desired temperature of outlet hot water. The related equation is indicated with (2), where the term $P_t^{EWH}\Delta t$ calculates the amount of energy needed for heating the stored water in the tank [22].

$$\theta_t^w = \theta_{t-1}^w + \frac{P_t^{EWH}\Delta t - Q_t^{EWH} - Q_t^{Loss}}{k\rho v} \tag{2}$$

There are also some settings such as maximum and minimum values for the temperature of the in-tank water that limit the operation of the EWH, as follows:

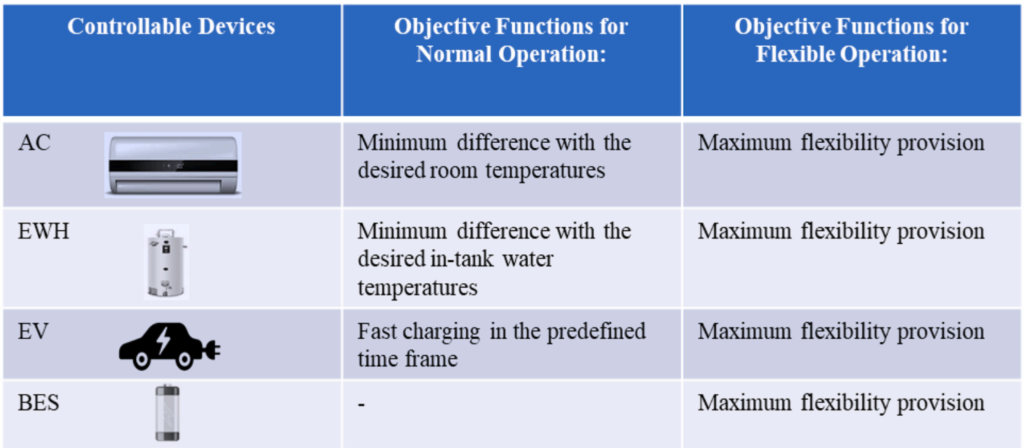
$$\underline{\theta^w} \le \theta_t^w \le \overline{\theta^w} \tag{3}$$

In addition, equation (4) refers to the required heat that increases the temperature of the specific volume of cold water to the desired level. Similarly, (5) denotes the maximum energy required to heat the full volume of the in-tank water from an initial temperature to the maximum desired temperature [27].

$$Q_t^{EWH} = k\rho v_t^{tank}\left(\theta_t^w - \theta^{cold}\right) \tag{4}$$

$$\widetilde{Q}_h^{EWH} = k\rho v^{EWH}\left(\overline{\theta^w} - \theta^{w,ini}\right) \tag{5}$$

Moreover, the EWH must fulfil the household hot water demand at each time slot, as stated in (6). Constraint (7) also guarantees that the maximum heat does not overtake the upper bound of water storage [27].



Controllable Devices	Objective Functions for Normal Operation:	Objective Functions for Flexible Operation:
AC	Minimum difference with the desired room temperatures	Maximum flexibility provision
EWH	Minimum difference with the desired in-tank water temperatures	Maximum flexibility provision
EV	Fast charging in the predefined time frame	Maximum flexibility provision
BES	-	Maximum flexibility provision

Fig. 1. Objective functions of the HEMS considering normal and flexible operations of the controllable devices

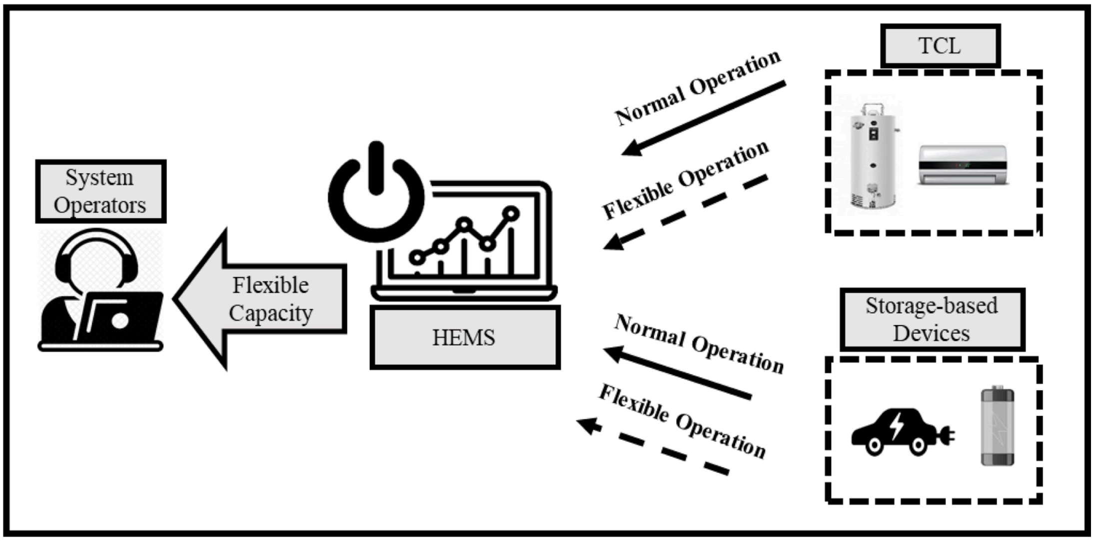


Fig. 2. The general model of the smart home and its application for providing flexibility

$$P_t^{EWH}\Delta t \geq Q_t^{EWH} \tag{6}$$

$$P_t^{EWH}\Delta t \leq \widetilde{Q^{EWH}} + Q_t^{EWH} \tag{7}$$

Finally, constraint (8) ensures that the power consumption of EWH's boiler does not exceed its maximum rated power.

$$0 \leq P_t^{EWH} \leq \overline{P^{EWH}} \tag{8}$$

Regarding an AC, this device has an internal thermostat which is in charge of adjusting the power consumption based on one or a range of desired temperatures. The range of desired temperatures could be predefined by the household customers or based on the factory settings. Eq. (9)-(12) are defined to model the operation of an AC. In this light, (9) shows the relationship between the indoor temperature with the outdoor temperature and the power consumption of the device. In this equation, the constant coefficient related to the thermal characteristics of the house along with the AC's thermal capacity are taken into consideration [28].

$$\theta_t^h = (1-\alpha)\theta_{t-1}^h + \alpha\theta_t^{amb} + \beta P_t^{AC}\Delta t \tag{9}$$

In addition, constraint (10) ensures that the indoor temperatures remain in a specific bandwidth defined by the household customer.

$$\underline{\theta^h} \leq \theta_t^h \leq \overline{\theta^h} \tag{10}$$

Finally, the power consumed by the AC should remain within its permissible range, as indicated by (11).

$$0 \leq P_t^{AC} \leq \overline{P^{AC}} \tag{11}$$

2.1.2. *Case 2: flexible operation*

The second case represents the flexible operation of thermostatically controllable appliances. In this case, the smart home is assumed to fully react to the flexibility requests. It provides upward flexibility if it receives the upward signal. In this regard, the smart home decreases the controllable appliances' consumption. In comparison, the smart home provides downward flexibility by increasing the controllable devices' consumption providing that it receives the downward signal. However, the AC's and EWH's operational constraints as well as the comfort level of the occupants need to be considered as well.

If the household receives an upward signal, the HEMS of the responsive smart home aims to minimize the consumption of the AC and the EWH, as follows:

$$\min_{\theta_t^w,\theta_t^h,P_t^{EWH-C2U},\; P_t^{AC-C2U}} \quad P_t^{AC-C2U} + P_t^{EWH-C2U} \tag{12}$$

The objective function (12) should be limited by the operational constraints of these two devices as well as those related to the comfort level of the occupant. Thus, the optimization problem includes (12) as an objective function and (2)-(11) as constraints of the problem.

In contrast, the HEMS needs to maximize the consumption of the AC and the EWH, if it receives the downward signal. Therefore, another optimization problem should be defined for the downward case aiming to maximize the consumption of these devices, with an objective function defined in (13):

$$\max_{\theta_t^w,\theta_t^h,P_t^{EWH-C2D},\; P_t^{AC-C2D}} \quad P_t^{AC-C2D} + P_t^{EWH-C2D} \tag{13}$$

Again, constraints (2)-(11) should be taken into account in this optimization problem.

2.1.3. *Flexibility estimation*

In the first step, the HEMS needs to estimate the introduced three optimization problems. Then, it utilizes (14) and (15) to estimate the flexile capacities of the TCL.

$$Flex_t^{TCL-up} = \left(P_t^{EWH-C1} + P_t^{AC-C1}\right) - \left(P_t^{AC-C2U} + P_t^{EWH-C2U}\right) \tag{14}$$

$$Flex_t^{TCL-dn} = \left(P_t^{AC-C2D} + P_t^{EWH-C2D}\right) - \left(P_t^{EWH-C1} + P_t^{AC-C1}\right) \tag{15}$$

Eq. (14) states that the upward flexible capacities of the thermostatically controllable loads can be estimated by calculating the amount of its decreased consumption. This amount should be the result of an external flexibility signal. In other words, if a smart home does not receive flexibility signals, its decreased consumption does not mean that it provides upward flexibility. Eq. (15) estimates the available downward flexibility of the AC and the EWH, if the household receives downward flexibility signal. In this regard, the increased consumption by these appliances is considered downward flexibility providing that it receives the downward signal. To calculate the increased and decreased consumption, the TCL operation of the responsive smart home should be compared with that of the household seeking to maximize its thermal comfort. Therefore, this deviation needs to be compensated by the system operator that sent the flexibility signals before. In this way, it motivates smart homes and encourages them to play active roles in the flexibility improvement of energy systems.

2.1.4. Robust flexibility estimation

Considering constraints (2), (4), (5), (6) and (7), it can be found that the EWH's consumption power is highly related to the household hot water consumption. Hence, the water consumption needs to be forecasted to solve the related optimization problem. However, the forecasted value would not be exact and there would be uncertainties due to the household uncertain behavior regarding water consumption. To capture these uncertainties, this paper utilizes the concept of robust optimization. A robust optimization problem considers the worst-case that happens regarding the water consumption of the household. In this way, HEMS should solve another optimization problem with the following objectives to find the robust values for estimating the flexible capacities of the smart home.

$$\min_{P_{t,s}^{EWH-C1},P_{t,s}^{EWH-C2U}} \left(P_{t,s}^{EWH-C1}+P_t^{AC-C1}\right)-\left(P_t^{AC-C2U}+P_{t,s}^{EWH-C2U}\right) \tag{16}$$

$$\min_{P_{t,s}^{EWH-C1},P_{t,s}^{EWH-C2U}} \left(P_t^{AC-C2D}+P_{t,s}^{EWH-C2D}\right)-\left(P_{t,s}^{EWH-C1}+P_t^{AC-C1}\right) \tag{17}$$

The robust value of the upward flexible capacities of the TCL is equal to the objective function in an optimal point (16) while the value of the downward flexible capacities equals the solution of objective function (17). The introduced objective functions are subjected to the following constraints:

$$\theta_{t,s}^{w-C1}=\theta_{t-1}^{w}+\frac{P_{t,s}^{EWH-C1}\Delta t-Q_{t,s}^{EWH}-Q_t^{Loss}}{k\rho v} \tag{18}$$

$$\theta_{t,s}^{w-C2U}=\theta_{t-1}^{w}+\frac{P_{t,s}^{EWH-C2U}\Delta t-Q_{t,s}^{EWH}-Q_t^{Loss}}{k\rho v} \tag{19}$$

$$\theta_{t,s}^{w-C2D}=\theta_{t-1}^{w}+\frac{P_{t,s}^{EWH-C2D}\Delta t-Q_{t,s}^{EWH}-Q_t^{Loss}}{k\rho v} \tag{20}$$

Where, (18) yields the consumption power of the EWH considering different scenarios for the first-case water consumption in which the HEMS is maximizing the thermal comfort level. Equation (19) calculates the EWH's consumption power considering different scenarios for the case in which the household receives upward flexibility signal. Constraint (20) calculates the same value for the case where the household receives downward flexibility signals. As a result of solving (16) and (17), the minimum flexible capacity of the household is chosen between different scenarios of water consumption. This means that if other scenarios happen in reality, the household is still able to provide the estimated flexibility.

2.2. Estimating the flexibility of EV

The HEMS can also change the charging power and the charging timetable of an EV in order to react to the flexibility signals. However, the charging availability of the EV and the charging preference of the EV's owner are two important factors that restrict EV's flexibility provision. This paper considers two different cases to estimate the flexible capacity of an EV. The first case considers that an EV owner tries to charge the EV with the maximum rated power within a time frame specified beforehand. In the second case, the owner sets a minimum limit for the EV's SOC at each time slot within the specified time frame and it aims to react to the flexibility signal as much as possible. In this way, the EV is able to provide flexibility while still satisfying the specified minimum charging level.

2.2.1. Case 1: fast charging (normal operation)

In this case, the EV is allowed to be charged only in a specific narrow timeframe which is determined by the EV owner. In addition, the owner wants to have a fully charged EV in a short period. Hence, the EV is charged with the maximum rated power to reach the higher SOC sooner. Thus, charging the EV can be mathematically modeled as follows:

$$\begin{cases} P_t^{EV-C1}=\overline{P^{ev}}\ if\ t\varepsilon\left[\underline{t^{EV-C1}},\ \overline{t^{EV-C1}}\right]\ and\ SOC_t^{EV-C1}\le\overline{SOC^{EV}} \\ P_t^{EV-C1}=0\quad Otherwise \end{cases} \tag{21}$$

Eq. (21) states that the EV is charged at t with its maximum rated power if t is within the time range specified by the owner and if the EV's state of charge does not exceed its upper bound.

2.2.2. Case 2: flexible charging (flexible operation)

In the second case, the HEMS assigns a minimum value for the SOC of EV's battery within the time frame. EV charging can modify according to the flexibility signals. However, the battery should reach the specified SOC level at each time slot. In addition, we consider the broader charging time frame for this case in which the smart home decides to be more flexible. If the HEMS receives a downward flexibility signal, the EV is charged with the maximum rated power, similar to the first case:

$$\begin{cases} P_t^{EV-C2D}=P^{EV} ift\varepsilon\left[t^{EV-C2},t^{EV-C2}\right] and\ SOC_t^{EV-C2D}\le\overline{SOC^{EV}} \\ P_t^{EV-C2D}=0\, Otherwise \end{cases} \tag{22}$$

Where, the time frame $\left[\underline{t^{EV-C2}},\ \overline{t^{EV-C2}}\right]$ would have a broader range compared to the charging time frame of the first case. In other words, $\left[\underline{t^{EV-C1}},\ \overline{t^{EV-C1}}\right]$ can be a subset of the wider time frame $\left[\underline{t^{EV-C2}},\ \overline{t^{EV-C2}}\right]$

If the HEMS receives upward flexibility signal, the EV should decrease its charging power. However, it should reach its lower bound of the SOC. Hence, the HEMS solves an optimization problem to determine the charging power of the EV. The objective function is to decrease the charging power of the EV.

$$\min_{P_t^{EV-C2U}} P_t^{EV-C2U} \tag{23}$$

The problem is subjected to the following constraints:

$$P_t^{EV-C2U}=0 if\ t\notin\left[\underline{t^{EV-C2}},\ \overline{t^{EV-C2}}\right] \tag{24}$$

$$P_t^{EV-C2U}\le\overline{P^{EV}} \tag{25}$$

$$SOC_t^{EV}=SOC_{t-1}^{EV}+\frac{\eta^{EV}P_t^{EV-C2U}\Delta t}{Cap^{EV}} \tag{26}$$

$$\underline{SOC_t^{EV}}\le SOC_t^{EV}\le\overline{SOC^{EV}} \tag{27}$$

Eq. (24) states that the EV cannot be charged within the time frame that is not specified by the owner while (25) determines the upper limit of the charging power. In addition, (26) models the relationship between the SOC and the charging power of the EV's battery while (27) imposes a constraint on the upper and lower limits of the SOC [21]. According to (27), the lower limit is determined for each time slot to ensure that the EV's battery reaches the minimum limit of the SOC at each time slot. In this way, if all of the flexibility signals during these time frames are upward, the EV still reaches its acceptable SOC.

2.2.3. Flexibility estimation

Similar to the flexibility that comes from TCLs, the flexibility of the EV can be estimated by calculating the difference between the charging power considering the first and the second case. If the HEMS receives the upward signal, it calculates the reduced charging power in the second case, as denoted by (28):

$$Flex_t^{EV-up}=P_t^{EV-C1}-P_t^{EV-C2U} \tag{28}$$

The downward flexible capacity of the EV is estimated through calculating the increased charging power of the EV, as follows:

$$Flex_t^{EV-dn} = P_t^{EV-C2D} - P_t^{EV-C1} \tag{29}$$

2.3. *Estimating the flexibility of BES*

Unlike thermostatically controllable appliances and EVs which are must-run appliances, BESs are not must-run devices. It means that they are specifically employed for flexibility purposes. Thus, BESs are an important source of flexibility. They can inject power as well as consuming it when needed. As a result, they can create bidirectional flexibility through charging and discharging. However, unlike other introduced controllable appliances, the battery charging and discharging power can be fully used as flexibility. In this way, the HEMS discharges the battery when it receives an upward flexibility signal while the battery is charged during time slots that the HEMS receives a downward signal. In the case of the upward signal, an optimization problem with the following objective function should be solved by the HEMS:

$$\max_{P_t^{B,dis-U}} P_t^{B,dis-U} \tag{30}$$

Where, (30) states that the HEMS tries to maximize the discharging power of the BES as soon as it receives the upward signal. The objective function is subjected to (31)-(34) [21].

$$0 \le P_t^{B,dis-U} \le u_t \overline{P^{B,dis}} \tag{31}$$

$$0 \le P_t^{B,ch-U} \le (1-u_t)\overline{P^{B,ch}} \tag{32}$$

$$SOC_t^B = SOC_{t-1}^B + \frac{\eta^{B,ch} P_t^{B,ch-U} \Delta t - \eta^{B,dis} P_t^{B,dis-U} \Delta t}{Cap^B} \tag{33}$$

$$\underline{SOC^B} \le SOC_t^B \le \overline{SOC^B} \tag{34}$$

Where, (31) and (32) define the upper limit for discharging and charging power of the BES, respectively. Additionally, the binary variable u_t prevents the BES from charging and discharging simultaneously. Eq. (33) models the relationship between BES charging /discharging power and the SOC of the BES. In this regard, the SOC of the BES increases when it is charging whereas discharging the BES results in an SOC decrease. Finally, (34) restricts the upper and lower limits of the battery's SOC. As a result of solving the optimization problem (30)-(34), the upward flexibility of the battery can be estimated by determining the discharging power of the battery.

$$Flex_t^{B-up} = P_t^{B,dis-U} \tag{35}$$

On the other hand, if the HEMS receives the downward signal, it tries to charge the BES as much as possible. In this way, the objective function can be defined to maximize the charging power with some constraints related to the operation of the BES as stated in (36)-(41).

$$\max_{P_t^{B,ch-D}} P_t^{B,ch-D} \tag{36}$$

$$0 \le P_t^{B,dis-D} \le u_t \overline{P^{B,dis}} \tag{37}$$

$$0 \le P_t^{B,ch-D} \le (1-u_t)\overline{P^{B,ch}} \tag{38}$$

$$SOC_t^B = SOC_{t-1}^B + \frac{\eta^{B,ch} P_t^{B,ch-D} \Delta t - \eta^{B,dis} P_t^{B,dis-D} \Delta t}{Cap^B} \tag{39}$$

$$\underline{SOC^B} \le SOC_t^B \le \overline{SOC^B} \tag{40}$$

Finally, the downward flexibility of the BES can be estimated by determining the charging power of the BES.

$$Flex_t^{B-dn} = P_t^{B,ch-D} \tag{41}$$

3. TSO-level Flexibility Services

A TSO requires to maintain the balance between the system's generation and demand closely to fix the system's frequency at the predefined value. The imbalance between the generation and the demand causes a frequency deviation which can risk the frequency stability of the system. Hence, the TSO procures various types of TSO-level or system-wide flexibility services to maintain the frequency within its permissible range. In this regard, there exist different flexibility services for different frequency deviation levels. Table 2 indicates the flexibility service utilized for each frequency deviation range. If smart homes are willing to contribute to the provision of system-wide flexibility services, they need to be aggregated through an aggregator to reach the minimum capacity needed for the service provision. The last column of Table 2 indicates the required minimum capacity for each service. The aggregator aggregates the flexible capacities of smart homes and activates the flexibility by measuring the frequency deviation in real-time. Without the aggregator, smart homes cannot participate in providing TSO-level flexibility services because there exists a lower limit of capacity for participation in most TSO-level markets, as illustrated in Table 2 [13]. Besides, the table summarizes the activation time required for each service. For example, according to Table 2, the FER providing FCR-N service needs to activate its full capacity (100%) in less than 180 s.

FCR services comprise FCR-N deployed for normal operations of the power system and FCR-D for disturbance situations. FCR-D service consists of two individual services for upward and downward directions whereas FCR-N is a symmetric service [29, 30, 31].It means that the FER providing FCR-N should be able to provide both upward and downward flexibility, simultaneously.

The main purpose of the FFR is to compensate for the loss of an individual producer or the loss of a high voltage direct current (HVDC) line that causes the frequency drop. The FFR service is mainly procured for the better management of the system in low-inertia situations. At the moment, this service is activated as the upward flexibility service meaning that the FERs should inject more power to the grid or reduce their consumption [32]. In Finland, the FFR service gives the FER three options including the combinations of different activation frequencies and activation time as indicated in Table 2 [32].

FRR services are categorized into automatic FRR (aFRR) and manual FRR (mFRR). In general, the main responsibility of FRR services is to restore the frequency to its nominal value and to help release the FCR that has been activated earlier. Unlike FCR and FFR services that require measuring devices to respond to the flexibility needs, the FERs providing FRR services need to continuously be in touch with the TSO and receive flexibility signals constantly.

Automatic FRR is a service associated with the Nordic power system and is an automatically activated reserve in a centralized manner [33]. It means that its activation is based on the frequency deviation of the whole Nordic synchronized area and is only utilized for certain hours in mornings and evenings [33]. Since this service is related to all Nordic areas, there should be an entity coordinating the TSOs of these areas so that they agree on the flexibility activated for restoring the frequency. In this regard, Statnett's operation control system was assigned to be in

TABLE 2
The technical requirements needed for each TSO-level service

Service	Frequency deviation [Hz]	Activation time [s]- activation percentage[%]	Minimum size [MW]
FCR-N	±0.1	180-100%	0.1
FCR-D	±(0.1, 0.5)	5-50% 30-100%	1
FFR	− 0.3, − 0.4, − 0.5	1.3, 1, 0.7-100%	1
aFRR	-	350-100%	5
mFRR	-	900-100%	5

charge of determining the activation power of aFRR. The activation requests are sent to the TSO in each area and are then forwarded to the flexibility aggregators. For example, Fingrid, the Finnish TSO, sends the activation signal of aFRR to the balancing service providers playing the role of flexibility aggregators, every 10 seconds [33] [34] [35] [36].

Manual FRRs are procured through balancing markets. This service is used to manage the flow of the grid and used in the case of expected frequency deviations such as outages [33]. Manual FRR is localized so that the synchronous Nordic system can be balanced moment by moment. The TSO procures mFRR according to its local TSO flexibility requirements. In this way, the TSO takes into consideration the bottlenecks as well as the dimensioning faults happening in its networks and procures the mFRR accordingly [33].

3.1. *The participation of smart homes*

Firstly, it should be mentioned that the TSO does not reach every single household to provide flexibility services. The TSO and smart homes indirectly communicate through local frequency measurements. For example, as stated in table 2, if the household is going to provide FCR-N services, it should activate its upward flexibility when the frequency falls to (49.9-50) Hz and activate its downward flexibility when the frequency goes up to (50-50.1) Hz. Smart homes with flexible appliances have a considerable potential to provide the TSO with different flexibility services. However, each FER should pass the prequalification process to be qualified for the provision of that specific service. In addition, smart homes and flexible capacities of other small-scale resources need to be aggregated to be able to take part in the provision of these services. The aggregator can decide on the bidding strategy based on the estimated flexible capacities and the types of services that can be provided by its FERs including smart homes.

Regarding FCR-N services, an aggregated of smart homes with BESs (or a large-scale BES system) is able to provide this service. In this way, they are able to provide flexibility in both directions. However, for example, a BES system that is nearly full cannot provide FCR-N because it cannot simultaneously provide upward and downward flexibility. The following constraint should be taken into account for an FER contributing to the provision of FCR-N.

$$Flex_t^{up} = Flex_t^{dn} \tag{42}$$

Equation (42) states that at each time slot, the FER needs to have both upward and downward flexible capacities. Storage-based devices that have the capability of charging and discharging are potent resources. However, when the energy storage device reaches its maximum or minimum SOC level, it should interrupt the activation of the flexibility service until the direction of the frequency deviation changes or until it reaches its capability to provide the symmetric services. In this regard, designing the BES's recharging timetables is an important concern. The aggregator can be in charge of designing timetables and coordinating BESs of different households so that it leads to the maximum profits and minimum operational costs for their owners. Moreover, it is worth mentioning that the BES should have the capability to activate FCR-N reserves for 30 minutes. Hence, it requires to have a sufficient level of the SOC to be able to provide the 30-min service. Besides, the resource should be able to respond in less than 3 minutes.

Regarding FCR-D, all of the household appliances can provide these services. However, they need 30-second response time as well as the ability to activate the reserve for 30 minutes. Thus, it can be concluded that the participation of some appliances such as EWHs that their operations are restricted by the occupants' uncertain behavior should be more analyzed in future works. Other appliances such as ACs can provide FCR-D providing that they have scheduled beforehand for all of the possible activations. Besides, the HEMS should ensure that the constraints related to the thermal comfort level of the owner are satisfied during the activation period.

The household's participation in the provision of FFR is highly restricted since it requires an extremely fast response in less than a second. It means that not only the communication latency should be very low, but also the households should use the appliances whose operations are not strictly limited. In this regard, BESs are better options compared to thermostatically controllable appliances whose operations seriously affect the occupants' comfort. In comparison, the participation of smart homes in providing FRR services is more possible since they require more than 350-second activation time. However, the smart homes and the corresponding aggregator need to be constantly in touch with each other and with the TSO to receive the flexibility signals.

4. DSO-level Flexibility Services and Smart Home Participation

DSO-level flexibility services help DSOs to operate their networks. The main responsibilities of DSOs include congestion management and voltage control of the distribution networks [37]. In the long term, DSOs reinforce the network according to their forecasted needs in the future [38]. In this way, the DSO tries to invest in the grid's infrastructure and increases its hosting capacity for more renewable resources and be prepared for customers' increasing demand. In the short term, DSOs currently use conventional approaches to reconfigure the set points of regulators and assets of the network. DSOs may also utilize re-dispatching generation resources and request curtailment if needed. Traditionally, DSOs employ some devices such as on-load tap changer transformers, switched capacitors, and step voltage regulators to control the node voltages of their networks [39]. These mentioned devices estimate the voltage drops along the feeder and accordingly adjust the voltage. However, the high penetration of renewable-based DGs in distribution networks has restricted the operational effectiveness of these conventional methods. For example, the voltage regulator devices fail to track the variation of highly volatile voltage that results from the intermittent power of renewable-based DGs [2]. Besides, these devices incur extra costs in terms of their lifetime and maintenance if they rapidly react to the voltage variations [2]. As a result, the DSO requires new active network management schemes to operate its network. In this way, the potential of FERs connected to the distribution networks such as smart homes are less considered. Hence, the DSO needs to coordinate between traditional functionalities, distributed FERs control settings as well as possible new market structures [40–43]. Smart homes that have flexible appliances can help DSOs to operate their network more effectively. In this regard, the DSO needs to provide an appropriate incentive such as a flexibility trading marketplaces as well as a suitable clearing mechanism to coordinate the flexible capacities of smart homes according to its flexibility needs. In such a market, households play the role of sellers and the DSO is a flexibility buyer. The households benefit from the economic revenues obtained from selling flexibility while the DSO accesses several additional FERs at different locations which in turn facilitates the secure operation of the distribution network.

Regarding communication between the DSO and the smart homes, there may be a situation in which each household is located at a specific node. Hence, if the DSO needs flexibility (power injection or consumption) at that specific node, the DSO should directly communicate with the corresponding household energy management system by sending the flexibility signals.

5. Case Study and Simulation Results

5.1. *Case study*

In this paper, we consider a smart home with some controllable appliances, including an AC, an EWH, an EV, and a BES. The details of each appliance can be found in Table 3. It is assumed that the flexible capacity of the household is estimated for a time horizon of one hour. Thus, in a short-term time horizon, the HEMS can predict hot water consumption with acceptable accuracy. Moreover, the predicted

TABLE 3
The parameters related to the household controllable appliances

AC-related Parameters					
$\overline{P^{AC}}$ [kW]	α	β[°C /kWh]	$\theta^{h,des}$[°C]	$\underline{\theta^{h}}$[°C]	$\overline{\theta^{h}}$[°C]
2	0.9	11	24	21	26
EWH-related Parameters					
$\overline{P^{EWH}}$[kW]	$\widetilde{Q^{EWH}}$[kWh]	$\theta^{w,des}$[°C]	$\underline{\theta^{w}}$[°C]	$\overline{\theta^{w}}$[°C]	$k\rho v$[kWh/°C]
2.4	2.6	45	40	60	0.17
EV-related Parameters					
$\overline{P^{EV}}$[kW]	Cap^{EV}[kWh]	Charging availability [hour]	η^{EV}		
7.6	62	2-7, 16-24	0.9		
BES-related Parameters					
$\overline{P^{B,ch}}$[kW]	$\overline{P^{B,dis}}$[kW]	Cap^{B}[kWh]			
5	5	13.5			

ambient temperature is also needed to estimate the flexibility of thermostatically controllable appliances. The hourly water consumption and ambient temperatures considered in the simulation are illustrated in Fig. 3. Manual FRR is chosen as a flexibility service that the smart home provides for the TSO. The smart home is assumed to provide the TSO's flexibility needs, based on the hourly signal. The signal is assumed to be "1" when the TSO needs upward flexible capacity, "-1" in case of downward flexibility request, and "0" when the TSO does not need flexibilities. The flexibility signals are extracted from the mFRR needs regarding the Finnish TSO, Fingrid, on 1.9.2020, and are shown in Fig. 4. We assume that the flexible capacities of the smart home are fully activated for each hour according to these flexibility signals. The proposed optimization problems were all developed as linear programming (LP) problems since they have linear and convex constraints and objective functions with continuous variables. We utilized GAMS software and the CPLEX solver to solve the proposed LP problems. It should be noted that the CPLEX solver applies dual simplex algorithm for solving LP problems [44].

5.2. *Flexible capacities of different devices*

The upward and downward capacities of each appliance are maximized based on the mFRR flexibility needs. Accordingly, we obtain the optimal operation of each device for providing the TSO with the required mFRR services. As proposed in the above sections, we estimate the operating power of each flexible appliance considering its flexible and non-flexible operation. The results associated with the flexible charging and non-flexible charging of the EV for one day are depicted in Fig. 5. The BES charging and discharging patterns for the flexibility provision are illustrated in Fig. 6. In addition, the flexible and non-flexible operations of TCLs including the AC and the EWH can be found in Fig. 7 and Fig. 8. By comparing the general patterns and behavior of these appliances in Fig. 5-8 with the pattern of flexibility signals in Fig. 4, it can be concluded that flexible appliances were able to follow the flexibility signals in most of the time slots.

To compare the flexible capacities of different appliances and to estimate the flexible capacities in more detail, we introduce an indicator that calculates the ratio of appliance's flexibility, as stated in (43).

$$Flex_t\% = \frac{Flex_t}{\overline{P_t}} \times 100 \tag{43}$$

Where $Flex_t$ is the estimated flexible capacity of each appliance and $\overline{P_t}$ denotes its maximum operating power. If $Flex_t$ of an appliance equals 100%, it means that the appliance fully decreased or increased its consumption according to the flexibility signal. If the $Flex_t$is equal to zero, the appliance did not change its consumption due to its operational limits or those imposed by the owner.

This indicator is calculated for 24 hours considering the operation of the household's appliances, AC, EWH, EV, and the BES. The results are depicted in Fig. 9. The following results can be obtained from the Fig. 9.

- By comparing the general pattern of Fig. 9 and that of Fig. 4, it can be comprehended that the controllable appliances have followed the flexibility signals in an acceptable way.
- In this regard, storage-based devices including the EV and the BES were the most flexible devices whereas the flexibility percentage of the EWH was less than 40%. The BES was able to react to the flexibility signals with its maximum capacity at hours 1:00, 3:00, 11:00-13:00, 21:00, 22:00, and 24:00. It also responded with its 70% capacity at hour 23:00. The only constraints restricting the operation of the BES are its SOC limit as well as its working power's upper bound. Accordingly, it can be more flexible compared to other appliances since the owner does not impose any constraints on its working power and it is availability during the whole day.
- It is worth mentioning that the EV is assumed to be unavailable between 8:00-18:00. Hence, it could not provide flexibility at these hours. However, it was able to follow flexibility signals in the time span between 1:00-4:00 and at 24:00. At these hours, the EV devoted 100% percent of its capacity for the flexibility provision, except for hour 4:00, at which its flexible capacity is estimated to be 28%.
- Although the flexible capacity of the AC is not as high as that of the storage-based appliance, it was able to follow the flexibility signals at all of the hours. It means that the AC provided flexibility continuously but not much. The low flexibility percentage of the AC is due to the fact that the operation of the AC highly affects the temperature of the smart home. Hence, the temperature constraints prevent the AC from providing higher flexibility.
- In comparison, the EWH participation in providing flexibility is low because the operation of the EWH is affected by the water consumption of the household and the desired temperature of the water. These constraints are restricted the working power and thus the flexibility provision of the EWH.

5.3. *Revenue comparison and discussion*

Smart homes can be more motivated to provide flexibility, if they

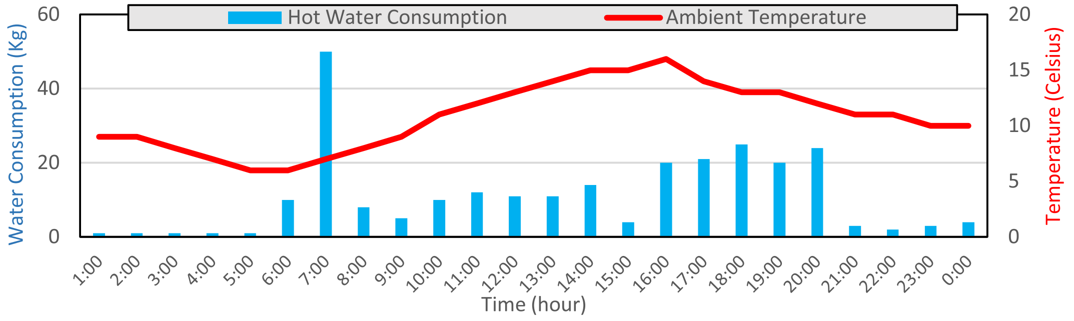


Fig. 3. The hourly hot water consumption and the ambient temperatures of the house

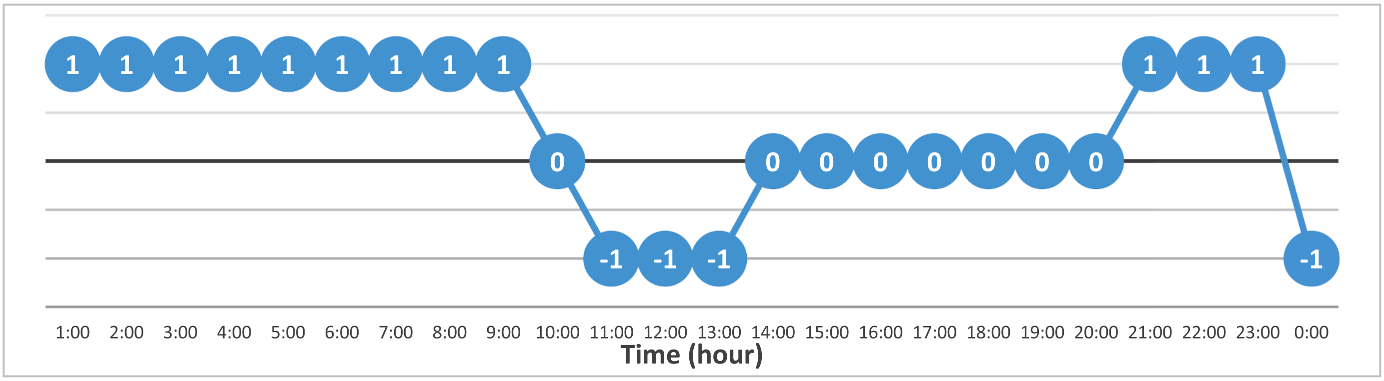


Fig. 4. Flexibility signals associated with mFRR services

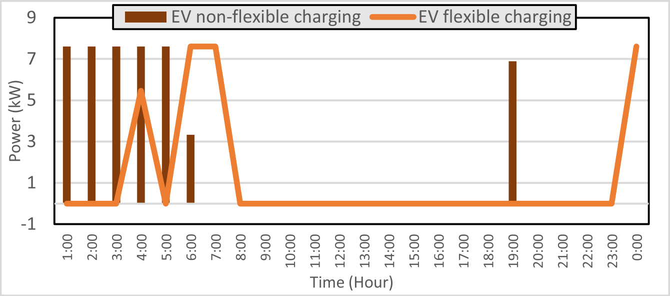


Fig. 5. The flexible and non-flexible charging behavior of the EV

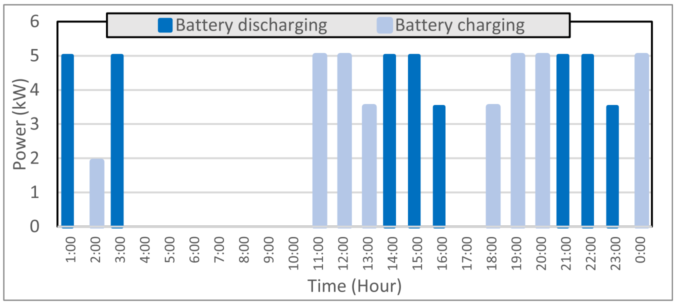


Fig. 6. BES's charging and discharging patterns for providing flexibility

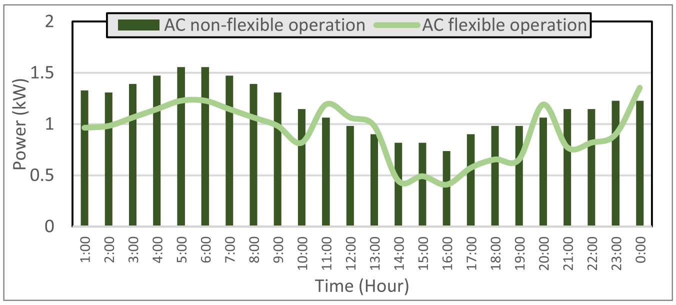


Fig. 7. The flexible and non-flexible operation of the AC

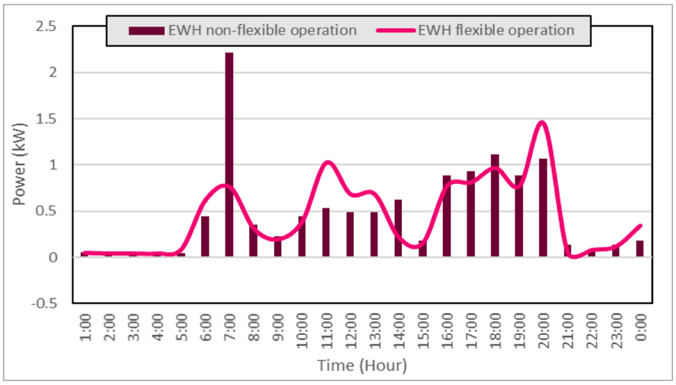


Fig. 8. The flexible and non-flexible operation of the EWH

achieve revenues from the flexibility provision. Regarding upward TSO-level flexibility services, the FER providing flexibility services receives a fixed amount for its flexible capacity and a variable amount based on the flexibility activation. Regarding downward TSO-level flexibility, the FER is paid a fixed amount for providing the flexible capacity and pays a variable amount based on the activation of the downward flexibility. It should be highlighted that considering balancing markets, the prices of upward flexibility are equal or higher than those of the energy markets and the prices of downward flexibility are equal or lower than those of the energy markets [35]. Accordingly, it can be concluded that the participation of must-run appliances is always beneficial since they can consume energy at lower prices and achieve extra revenues if they curtail their consumption to provide upward flexibility. However, this participation should consider the desired comfort level of the household customers as introduced in the formulation section.

Nevertheless, thorough cost-benefit analyses should be conducted for the participation of those appliances which are specially used for flexibility purposes such as BESs. These devices are not must-run and they are used to support the flexibility of the system. Thus, they need more accurate analysis to realize whether their contribution to the provision of flexibility is beneficial for the owner or not. As an example of this analysis, we calculate the income of the smart home's BES obtained from selling upward flexibility and energy at one time slot with the prices of energy and flexibility at 9:00 on 1.9.2020. In this way, the BES is considered to be discharged at this time slot. The income is calculated as the difference between the revenues and the operational costs of the BES. We use the same method applied in [21], to calculate the operational cost of the BES. The BES is considered to receive revenues for selling its flexible capacities. In addition, it receives compensation based on the flexibility activated at that time slot based on the price of the balancing energy market at that specific hour. Three types of TSO-level flexibility are considered for this case and the results are shown in Fig. 10.

As the figure explains, the black line is the income of the BES from selling its discharging power to the energy market. In comparison, the bar charts denote the revenues obtained from selling TSO-level flexibilities, considering different activation percentages. It means that in 100% case, all of the 5-kW discharging capacity of the BES is activated

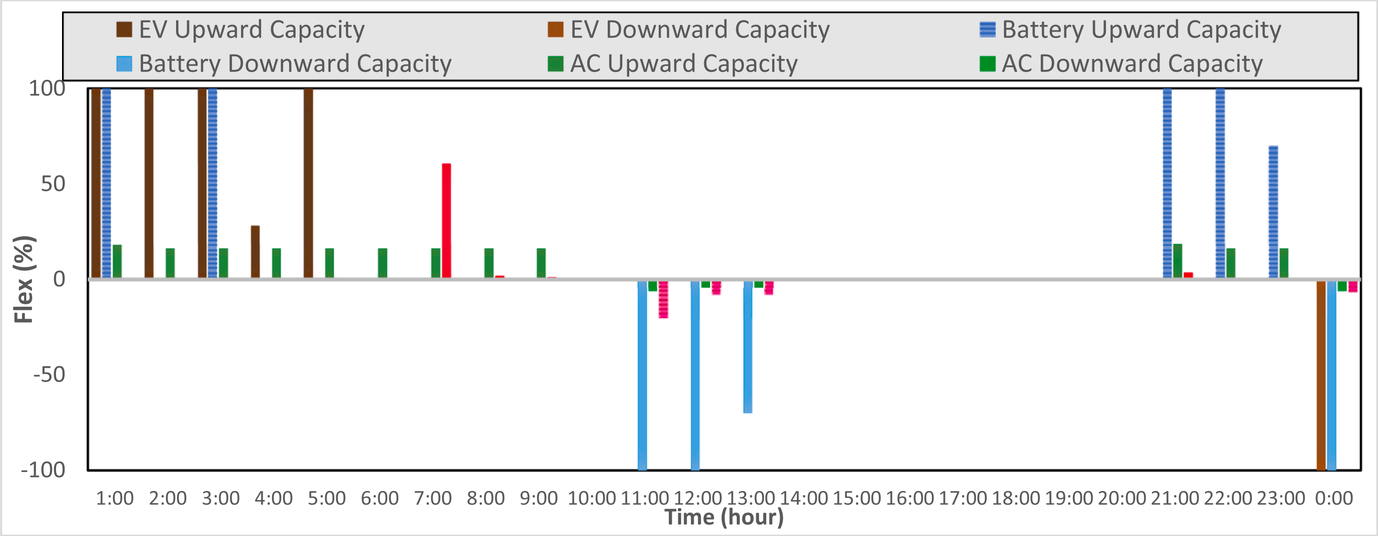


Fig. 9. The flexibility indicator calculated for each controllable appliance

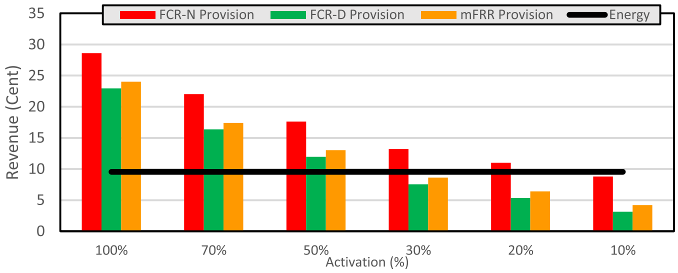


Fig. 10. Hourly revenues obtained from the participation of the BES in providing TSO-level services considering different activation scenarios

while in the 50% case, the BES is discharged with 2.5 kW. The results demonstrate that the provision of flexibility is highly dependent on the activation of the flexibility. However, the BES can achieve more than double income if it participates in the provision of flexibility and its whole amount of capacity is activated. In this case, if more than 50% of the capacity is activated, the provision of flexibility is still more profitable for the BES owner than selling its capacity to the energy market. However, the 10% activation was not a more profitable option in comparison with the energy case. Moreover, Fig. 10 states that providing FCR-N service is the most profitable option for the BES. Providing the mFRR service stands in the second rank and FCR-D is the least profitable service. This is due to the fact that at the moment, the capacity prices of providing FCR-N services are higher than those of the mFRR and FCR-D. The capacity price of mFRR for the considered time slot was also higher than that of the FCR-D [45].

6. Conclusion

This paper studied the participation of smart homes in providing flexibility services for DSO and TSO. In this way, the estimation of smart home's flexible capacities is of vital necessity because the home energy management system can schedule its controllable appliances more effectively and the system operators can assign the monetary compensation based on the available flexible capacity of the smart homes. To estimate the flexible capacity of a smart home, the flexible capacity of its controllable appliances should be estimated. Thus, this paper separately estimates the flexible capacities of four controllable appliances based on their characteristics. These appliances include an air conditioner, an electric water heater, an electric vehicle, and a battery energy storage. In addition, the constraints related to the comfort level and household customer's settings are taken into account in the flexible operations of the devices. In the next step, system-wide and local flexibility services are introduced and the paper discusses whether the smart home can provide these flexibility services.

In the simulation section, a smart home with some controllable devices was considered. The flexible capacities of the appliances were estimated assuming that the smart home provides a TSO-level service. The results indicated that storage-based devices have higher flexible capacities compared to thermostatically controllable appliances. This is due to the fact that the flexible operations of thermostatically controllable appliances are highly dependent on the thermal comfort level of the household customers. Finally, the paper analyzed whether the participation of the battery energy storage in providing system-wide flexibility services is profitable for its owner. The results demonstrated that the hourly profits of this participation are highly dependent on the activation of the flexibility. Finally, future works can be conducted in the following directions:

1- The 24-hour scheduling of a smart home or an aggregator of the smart home that participate in day-ahead flexible capacity markets, considering the flexibility prices
2- Comprehensive analysis and study on flexibility aggregators that participate in different flexibility markets, as well as their mutual interactions with households and system operators

CRediT author statement

H.K., H.F.: Conceptualiazation, Methodology, Investigation, Simulation. **H.K., H.L.**: Writing- Original draft preparation. **H.K., H.L.**: Writing- Reviewing and Editing, **H.L.**: Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

This work was supported in part by the FLEXIMAR Project (novel marketplace for energy flexibility) through Business Finland under Grant 6988/31/2018, and in part by the Finnish companies.

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