A novel energy management system for optimal energy and flexibility scheduling of residential buildings: a case study in HSB Living Lab

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***Abstract*—The future distribution system needs more flexibility to handle the peak power demand arising from the electrification of heating and transportation. This paper proposes a novel energy management system (EMS) for residential buildings to optimize their electric and heat consumptions while offering flexibility in response to the requirements of the Distribution System Operator (DSO). The aim of the proposed EMS is to minimize the energy and peak power costs while simultaneously maximizing the revenue from offering flexibility. This is achieved through the optimal scheduling of battery energy storage charging and discharging as well as the efficient utilization of the heat pump. To cope with forecasting uncertainties, a rolling horizon-based algorithm with uncertainty modelling based on the chance constraint method is incorporated. The performance of the proposed EMS is investigated by simulating the daily operation of a real residential building. The case studies indicate that the scheduled flexibility can be successfully dispatched even in the presence of forecasting uncertainties, causing 6% reduction in the payment cost of the building.**

Keywords— Energy management system, flexibility, rolling horizon, optimization, uncertainty modelling.

I. INTRODUCTION

The electrification of heating and transportation has the potential to lead to an undesirable increase in peak power demand in distribution grids. As a result, distribution system operator (DSO) faces congestion issues and needs to invest in the grid reinforcement to meet the peak power demand [1]. Thanks to smart grids, it is possible to leverage demand-side flexibility for congestion management as a viable and cost-effective solution. In this regards, new business models have been proposed for DSOs to maximize the flexibility deployment of demand-side [2]. However, the successful implementation of these models relies on the development of advanced energy management systems (EMSs) to enable optimal engagement of the demand-side in offering flexibility to the DSO.

The building sector is a major demand-side in distribution grids, holding the highest share of energy consumption among other sectors. It contributes to 33% of the global and 40% of the European Union's total energy consumption [3]. Hence, researchers have demonstrated considerable interest in the energy management of buildings (BEMS) focusing on: (i) minimizing the energy expenses, maximizing the energy revenues, decreasing carbon emissions, or attaining a specific target load profile [4] (ii) developing strategies to accomplish these objectives [5] (iii) controlling household appliances [6] (iv) modelling and architecture [7]. Recently, the idea of flexibility provision from buildings is evident in numerous studies. For example, in [8] a two-stage energy management model has been proposed for a building. In the first stage, the aim is to minimize energy expenses, while in the second stage, the focus is to maximizing revenue by flexibility provision for the DSO. In [9], novel indexes have been proposed to evaluate the building flexibility that can be provided for the DSO. Also, a trading market has been established to incentivize buildings that effectively utilize their flexibility in response to DSO needs. Authors of [10] have developed a scenario-based stochastic optimization model for dispatching the energy and flexibility of a building microgrid. The model is solved in rolling horizon to consider the most recent forecast profiles for solar power and electricity demand. A model predictive control framework has been introduced in [11] to determine flexibility ranges of buildings and control device based on the receiving flexibility requests from the DSO. In [12], flexibility of thermostatically controlled appliances are investigated. Authors of [13] have developed an EMS for buildings to enable flexibility from electric vehicles and battery energy storages (BESs). In [14], by using the EMS's capability to shift specific appliances, ensuring the match between demand and supply of flexibility. In [15], a two-stage optimization model has been introduced in which EMSs of buildings optimize their respective energy consumption together, and determines their flexibility provision.

This paper proposes an EMS for residential buildings to optimize their electric and heat consumptions while offering flexibility in response to the requirements of the DSO. To this end, the scheduling horizon is partitioned into three distinct phases: energy scheduling, energy and flexibility scheduling, and energy scheduling with flexibility provision. In the first phase, the EMS aims to minimize the energy and peak power costs through the optimal scheduling of BES charging and discharging as well as the efficient utilization of the heat pump (HP). In the second phase, the EMS tries to maximize the revenue from offering flexibility. In the last phase, the EMS aims to provide the accepted flexibility. Then, to address forecasting uncertainties, an algorithm based on a rolling horizon approach is introduced, utilizing uncertainty modeling through the chance constraint method.

This paper is organized as follows: Section 2 gives an overview of energy and flexibility scheduling. The model formulation and solution algorithm are explained in Section 3. Section 4 represents the test system, case studies and results. The paper ends with Section 5, which presents the main findings.

The work presented in this paper is financially supported by the following projects: i) FLEXI-GRID - received funding from the EU's Horizon 2020 Framework Programme under Grant Agreement No. 864048; ii) I-GRETA - received funding from Swedish Energy Agency through ERA-Net Smart Energy Systems program (with support from the EU's Horizon 2020 Framework Program under grant agreements No. 646039 and 775970); iii) GENTE – received funding from Swedish Energy Agency through ERA-Net Smart Energy Systems program (with support from EU's Horizon 2020 Framework Program under grant agreement No. 883973).

II. ENERGY AND FLEXIBILITY SCHEDULING

A. System description

In this study, we consider HSBLL which represents a residential building [16]. The schematic of HSBLL along with its components, is depicted in Fig. 1. As shown, the HSBLL owns solar panels enabling it to generate electricity on-site during daylight hours. Additionally, within HSBLL, there exists a BES that is connected to both the solar panels and the grid through an inverter. Electrical energy can be imported from the grid, and HSBLL, as a customer, also has the option to sell excess energy back to the grid. Likewise, the heat energy requirement of HSBLL can be met through HPs, procured from the district heating system, or a combination of both options. The HSBLL is a price-taker costumer; therefore, it needs to submit only the hourly flexibility bid quantities to the DSO after her/his request, and if accepted, the revenue obtained from selling flexibility in the market is settled at the flexibility price.

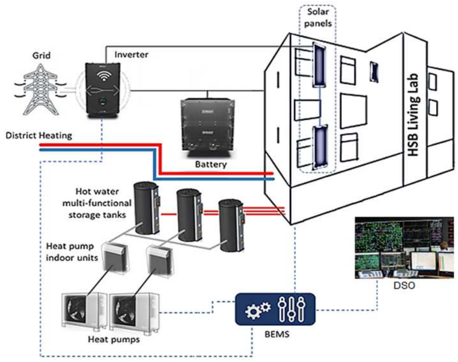

Fig. 1. Schematic of HSB LL with its components

B. Flexibility modelling approaches

In the context of congestion management, flexibility is defined as the ability of the consumer to decrease the imported power in response to a request made by the DSO. According to this definition, two approaches can be used to model flexibility which are depicted in Fig. 2 [17]. In the first approach, flexibility is offered as a capacity limitation product to the DSO. The parameter P^{Cap} represents the upper capacity limit, and it should be determined based on a value that can be readily agreed upon by both the DSO and the consumer. One feasible option is to use the capacity at the connection point as the reference value for P^{Cap}. The second approach involves offering flexibility as a baseline product to the DSO. In this approach, the flexibility is the amount of reduction from the baseline power exchange profile. Indeed, the first approach can be considered a special case of the second approach, wherein the baseline is the power exchange profile instead of P^{Cap}. In this paper, the second approach is used to model the flexibility. To this end, the baseline is considered as the power exchange profile of the building which is obtained by optimizing the energy scheduling problem without including the flexibility.

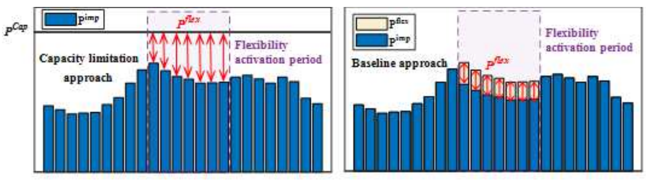

Fig. 2. Flexibility modelling approach: capacity limitation approach (left) baseline approach (right)

C. Process of energy and flexibility scheduling

The process of energy and flexibility scheduling is shown in the Fig. 3. In this depiction, the DSO send a flexibility request notification to the BEMS at $t = t_0$. Subsequently, the BEMS responses by sending the amount of flexibility it can provide to the DSO. The BEMS is informed of the accepted flexibility prior to the beginning of the subsequent time period. The accepted amount of flexibility should be dispatched during activation period, i.e., from $t = t_1$ to $t = t_2$. It means that the imported power of building should be decreased during the activation period and failure to comply will lead to the imposition of a penalty. The model formulation of BEMS is developed in the following section and then, the algorithm of energy and flexibility scheduling of HSBLL is presented.

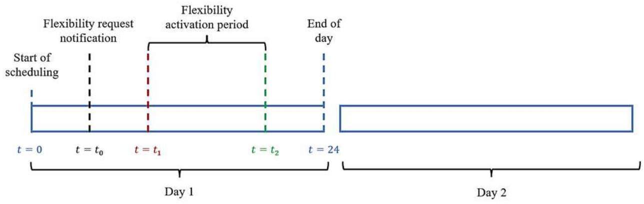

Fig. 3. Process of energy and flexibility scheduling

III. MODEL FORMULATION

In this section, the formulation of the proposed model for energy and flexibility scheduling of residential buildings are presented. Likewise, according to the flexibility modelling approach, the respective algorithm is described.

A. Objective Function

The objective of the BEMS is to minimize total payment cost of the building during scheduling horizon. The cost includes the electric and heat energy procurement cost as well as the cost due to the peak power, and the income from selling electric energy to the grid. If a flexibility request is received, the income from providing flexibility needs to be considered in the objective function. Likewise, the cost of not providing the accepted flexibility should be considered during the flexibility activation period. Accordingly, the objective function can be formulated as follows:

$$\text{Minimize} \sum_{t=1}^{N_T} (EC_t + HC_t + PC_t - EI_t - FI_t) \tag{1}$$

where

$$EC_t = \left(\pi^{trans} + \pi^{tax} + \pi_t^{spot}\right) \times P_t^{imp} + \pi^{elec,peak} \times P^{peak} \tag{2}$$

$$HC_t = \pi_t^{heat} \times H_t^{imp} \tag{3}$$

$$PC_t = \pi^{penalty} \times P_t^{dev} \tag{4}$$

$$EI_t = \left(\pi^{incen} + \pi^{taxred} + \pi_t^{spot}\right) \times P_t^{exp} \tag{5}$$

$$FI_t = \left(\pi^{trans} + \pi^{tax} + \pi_t^{flex}\right) \times P_t^{flex} \tag{6}$$

B. Constraints

1) Electric and heat balance: The electrical and heat requirements of the building must be met during each time scheduling interval through the utilization of local resources, namely PV, BES, HP, and by importing energy from grid and district heating system. Therefore,

$$P_t^{imp} + P_t^{PV} + P_t^{BES,dis} = P_t^{exp} + P_t^{BES,cha} + P_t^{HP} + P_t^{EL} \tag{7}$$

$$H_t^{HP} + H_t^{DH} = H_t^L \quad (8)$$

Note that the electric energy can be exported to the grid, however, the heat energy can only be imported from the district heating system. Note that due to the capacity limitations, the following constraints should be considered:

$$-P^{grid,max} \leq P_t^{imp} - P_t^{exp} \leq P^{grid,max} \quad (9)$$

$$H_t^{DH} \leq H^{DH,max} \quad (10)$$

2) Peak power: In order to reduce peak demand, customers are required to cover a peak power cost in conjunction with the energy cost. The daily peak power for electric and heat loads can be determined as follows:

$$P^{peak} \geq P_t^{imp} \quad (11)$$

$$H^{peak} \geq H_t^{DH} \quad (12)$$

3) BES model: The BES can be model using (13)-(18). The charging and discharging power of BES are limited by (13) and (14), respectively. The SOC dynamic of BES is given in (15). The initial SOC of BES is defined in (16). Due to the technical limitations, the SOC of BES is limited between a specified maximum and minimum values as given in (17). Likewise, (18) ensures that concurrent charging and discharging of the BES is prevented.

$$0 \leq P_t^{BES,dis} \leq P^{BES,max} u_t^{BES,dis} \quad (13)$$

$$0 \leq P_t^{BES,cha} \leq P^{BES,max} u_t^{BES,cha} \quad (14)$$

$$SOC_t = SOC_{t-1} + \frac{\eta^{cha} P_t^{BES,cha}}{E^{BES}} - \frac{P_t^{BES,dis}}{\eta^{dis} E^{BES}} \quad (15)$$

$$SOC_0 = SOC^{ini} \quad (16)$$

$$SOC^{min} \leq SOC_t \leq SOC^{max} \quad (17)$$

$$u_t^{BES,dis} + u_t^{BES,cha} \leq 1 \quad (18)$$

4) HP model: HPs extract heat from a low temperature location (heat source) and deliver it to a higher temperature location (heat sink). In case of air source heat pumps as in the HSBLL, the heat source is the outside temperature, and the heat sink is inside building temperature. As proposed in [18], the HP is modeled with the coefficient of performance (COP_t) as in (19) and hence, the generated heat can be calculated by (20). Likewise, the electric consumption of the HP is limited by its maximum power as represented in (21).

$$COP_t = k_0 + k_1 \times \left(\theta_t^{supply} - \theta_t^{source}\right) + k_2 \times \left(\theta_t^{supply} - \theta_t^{source}\right)^2 \quad (19)$$

$$H_t^{HP} = COP_t \times P_t^{HP} \quad (20)$$

$$P_t^{HP} \leq P^{HP,max} \quad (21)$$

5) Flexibility constraints: To provide flexibility during activation period, the BEMS should decrease the imported power from the grid. Thus, P_t^{flex} can be defined as follows:

$$P_t^{flex} \leq P_t^{imp\_base} - P_t^{imp} \quad (22)$$

where, $P_t^{imp\_base}$ is the imported power profile of the building, which is obtained by optimizing the energy scheduling problem without including the flexibility.

C. Uncertainty handling

Given the potential inaccuracies in forecasting the electric load and PV generation, there exists a risk that the scheduled flexibility may not be achieved during the activation period. This situation could result in significant penalties being imposed by the DSO. To tackle this issue, the chance constraint method is employed to optimize the scheduled flexibility under uncertain conditions. The general format of a chance constraint is formulated as:

$$Pr\{f_i(y,\xi) \geq 0, \quad i = 1,2,\dots,K\} \geq \alpha \quad (23)$$

where Pr denotes the probability measure, α is the specific confidence level, f is the constraint which involves the random variables, y is the set of decision variables, and ξ is the set of random variables. If $f_i(y,\xi)$ can be linearly presented as $\sum_j T_{i,j} y_j - \xi_i$, then, (23) can be converted into an equivalent deterministic form as following [19]:

$$\sum_i T_{j,i} y_i \geq \mu_j + \sigma_j Z_\alpha \quad (24)$$

$$Z_\alpha = \phi^{-1}\left(1 - \frac{1-\alpha}{K}\right) \quad (25)$$

In (24), μ_j and σ_j are mean value and standard deviation of the random variable and ϕ is the standard normal CDF.

In (22), P_t^{imp} is a random variable which can be represented as follows:

$$P_t^{imp} = P_t^{BES,cha} - P_t^{BES,dis} + P_t^{HP} + P_t^{EL} - P_t^{PV} + \Delta e_t \quad (26)$$

where Δe_t is the forecast error, which combines uncorrelated forecast errors of electric load and PV generation. Hence, the standard deviation of Δe_t can be calculated as:

$$\sigma_t = \sqrt{(\sigma_t^{EL})^2 + (\sigma_t^{PV})^2} \quad (27)$$

where σ_t^{EL} and σ_t^{PV} are standard deviations of electric load and PV generation, respectively, approximated as follows [20]:

$$\sigma_t^{EL} = \frac{d}{100} P_t^{EL} \quad (28)$$

$$\sigma_t^{PV} = \frac{1}{5} P_t^{PV} + \frac{1}{50} P^{PV,peak} \quad (29)$$

Based on the above description, the forecast error of imported power can be represented by a Gaussian distribution. Hence, in order to guarantee the provision of scheduled flexibility during the activation period, the subsequent chance constraint is formulated:

$$Pr\left\{P_t^{imp\_base} - P_t^{flex} - P_t^{imp} \geq 0\right\} \geq \alpha \quad (30)$$

As explained, (30) can be converted into an equivalent deterministic form as follows:

$$P_t^{imp\_base} - P_t^{flex} \geq P_t^{imp} + \sigma_t Z_\alpha \quad (31)$$

D. Algorithm description

As depicted in Fig. 3, the BEMS engages in energy optimization for the building until it receives a flexibility request notification from the DSO. Upon receiving the notification, the BEMS enters a co-optimization phase where it optimizes energy and flexibility for the duration of the flexibility activation period. During the activation period, the BEMS ensures flexibility provision by effectively dispatching the BES and HP. Then, it reverts to energy optimizing of the building. The BEMS can govern this process by a closed loop, i.e., rolling horizon, based algorithm which is shown in Fig. 4 and described in the following steps:

Step 1: The length of scheduling horizon, i.e., N_T, is selected to span all hours for which the spot market price is available, extending up to a maximum of 24 hours. This approach eliminates the need to forecast the spot market price and only PV generation, electric and heat load are forecasted for the scheduling horizon of $t = \tau, \dots, \tau - 1 + N_T$.

Step 2: As outlined in the flowchart, three problems can be solved to schedule energy, schedule energy and flexibility, and schedule energy and provide flexibility. As shown, by comparing τ with the predefined times t_0, t_1, and t_2, one problem is selected and optimized to obtain results of energy and flexibility scheduling. To schedule flexibility, first, the energy and flexibility scheduling problem without considering flexibility, i.e., the energy scheduling problem, is solved and the imported power during the activation period is considered as a baseline. Next, the energy and flexibility scheduling problem is solved to determine the flexibility bids during activation period.

Step 3: The set points of the first scheduling horizon are sent to the BES and the HP if $t < t_1$ *or* $t \geq t_2$ and $t \neq t_0$. If $t = t_0$, the flexibility bids sent to the DSO. Then, prior to starting the subsequent interval, i.e., $t_0 + 1$, the DSO responses with the accepted flexibility bids for the BEMS. During the flexibility activation period, i.e., $t_1 \leq t < t_2$, the BEMS optimizes the energy scheduling of the building and sends the set points of the first scheduling horizon to the BES and the HP. Likewise, the BEMS ensures that the imported power from the grid is decreased to the level that the accepted flexibility is provided, otherwise a penalty should be paid to the DSO. The variation in imported power arises from inaccuracies in forecasting electric load and PV generation can be calculated as follows:

$$P_t^{dev} = P_t^{imp}\Big|_{output\ of\ optimization\ model\ at\ t\in[t_1 t_2)} - P_t^{imp}\Big|_{output\ of\ Optimization\ model\ at\ t=t_0} \quad (32)$$

Step 4: The initial SOC of the BES is updated and the scheduling horizon is shifted to the next time. Then, the process is repeated from the first step.

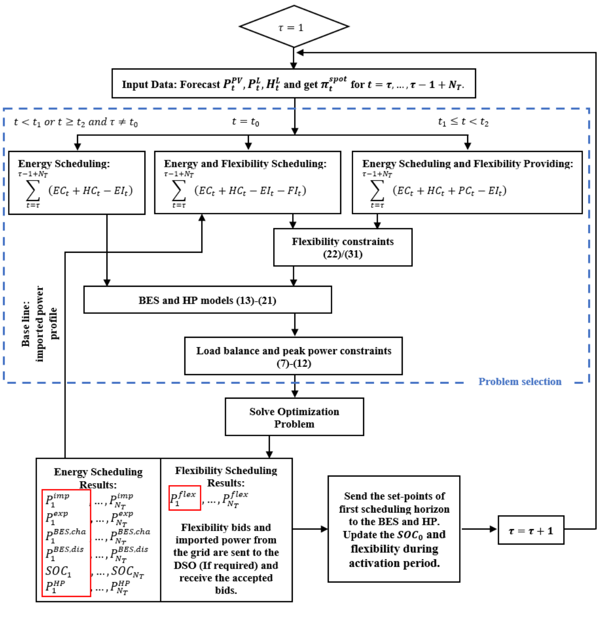

Fig. 4. Flowchart of energy and flexibility scheduling

IV. SIMULATION RESULTS

The optimal energy and flexibility scheduling were simulated for a day considering HSBLL as a residential building. The proposed model was implemented in the Python programming language with Gurobi to solve the MILP problem formulated in the Section II. Simulations were performed according to the test cases described in Table I on a PC with 2.9 GHz Intel Core i7-10700 CPU and 32 GB of RAM.

A. Data

The technical characteristics of HSBLL's components are shown in Table II. The electric load and PV generation profiles as well as heat load and outside temperature profiles during the scheduling day are shown in Figs. 5 and 6, respectively. The spot market price is extracted for day of study is extracted from the Nord Pool market and shown in Fig. 7 [21]. The energy and power tariff as well as tax fee, transmission fee, and incentive fee are taken from the website of the local DSO and presented in Table III [22]. It is assumed that the revenue from selling 1 kW of flexibility at each hour of activation period equals to selling 1 kW of energy at average daily spot market prices [10]. The penalty for not providing flexibility is $\pi^{penalty} = 2.8\ SEK/kWh$ which is based on charging for the exceeding the subscription level. Without loss of generality, it is assumed that all flexibility bids are accepted by the DSO. The capacity of the connection point for electricity grid and district heat system are 50 kW and 30 kW, respectively. The simulations are performed in hourly time steps as shown in Fig. 4. For each simulation, the hourly values of electric and heat loads as well as PV generation can be forecasted using a LSTM neural network.

TABLE I. DETAILS OF CASE STUDIES

	Time of notification	Flexibility activation period	Uncertainty modelling
Case I	8:00	12:00-20:00	✗
Case II	8:00	12:00-20:00	✓

TABLE II. THE TECHNICAL CHARACTERISTICS OF HSBLL'S COMPONENTS

Component	Parameters	Value
BES	$P^{BES,max}$ (kW)	3
	E^{BES} (kWh)	7.2
	η^{cha}/η^{dis} (%)	92.3
	$SOC^{ini}/SOC^{min}/SOC^{max}$ (%)	90, 10, 90
HP	$P^{HP,max}$ (kW)	5
	θ_t^{supply} (C°)	35
	COP_t	$3.8209 + 0.1211\theta_t^{source} + 0.0009874\theta_t^{source\,2}$
PV	Capacity (kWp)	13

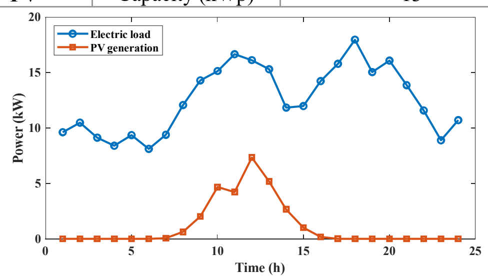

Fig. 5. Hourly electric load and PV generation profiles

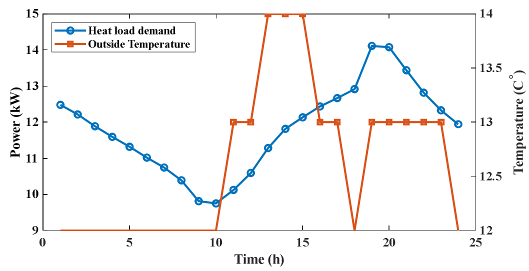

Fig. 6. Hourly heat load profile and outside temperature

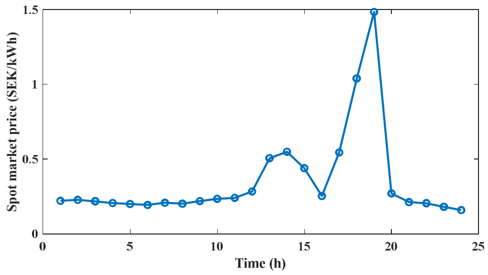

Fig. 7. Hourly spot market price

TABLE III. THE ENERGY AND POWER TARIFF FEES OF ELECTRIC AND HEAT DEMAND

Time of notification	Flexibility activation period
π^{trans}/π^{tax} (SEK/kWh)	0.255/0.49
$\pi^{elec,peak}$ (SEK/kWh)	1.21
π_t^{heat} (SEK/kWh)	0.521
$\pi^{heat,peak}$ (SEK/kWh)	0.104
π^{incen}/π^{taxred} (SEK/kWh)	0.08/0.60

B. Case *studies*

The energy scheduling of the HSBLL is illustrated in Fig. 8. As can be seen, the BES is discharged during the 14th, 18th, 19th, and 20th hours, which correspond to periods when the spot market prices are relatively higher. Likewise, to keep the SOC within the predefined range, the BES is charged during the 16:00 hour. The HP is mainly used to supply the heat demand of HSBLL. The reason is that the high value of COP makes the HP a more viable option to meet the heat demand compared to importing from the district heating system.

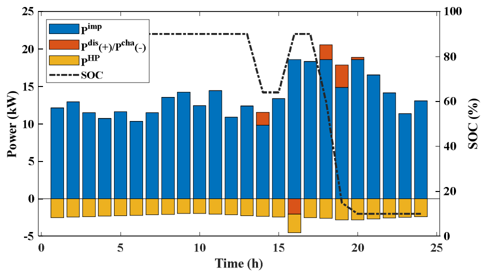

Fig. 8. Energy scheduling of the HSBLL

The energy and flexibility scheduling of the HSBLL in Case I are illustrated in Figs. 9 and 10, respectively. As can be seen, to provide flexibility, adjustments are made to the charging/discharging of the BES, as well as the power consumption of the HP, in comparison to the base case. More in details, it is beneficial to reduce the power consumption of the HP during the 14th hour and from 17th to 20th hours and, instead, supply the heat demand using the district heating system. The scheduled discharging of the BES at 14:00 is revoked in order to reduce the imported power from the grid at 16:00 which is achieved by canceling the scheduled discharging of the BES. This strategy results in a decrease in energy costs and an increase in flexibility income. Consequently, the daily total cost experiences a reduction.

The flexibility activation period spans from 12:00 to 20:00, however, as shown in Fig. 10, the flexibility scheduling occurs from 16:00 to 20:00. The reason is that the flexibility price is not high enough to cover total cost increment associated with providing flexibility throughout the entire activation period. As can be seen in Fig. 11, the scheduled flexibility remains the same when the flexibility price is assumed to be equal to the spot market price. However, it increases when the flexibility price is assumed to be equal to the highest spot market price within the scheduling horizon. Therefore, to use all flexibility potential of buildings, the DSO should consider a fair price for flexibility.

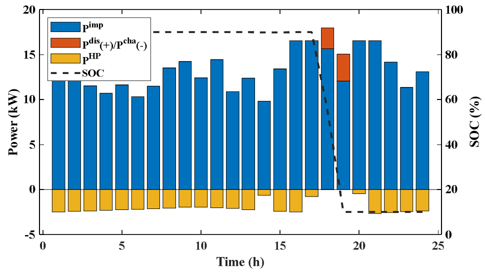

Fig. 9. Energy scheduling of the HSBLL in Case I

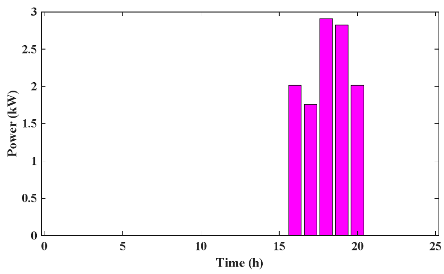

Fig. 10. Flexibility scheduling of the HSBLL with increasing the flexibility price in Case I

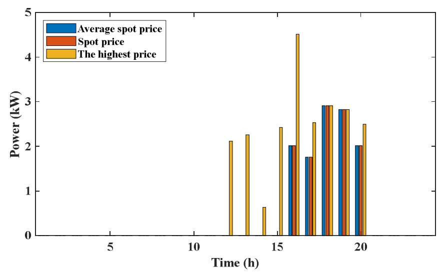

Fig. 11. Flexibility scheduling of the HSBLL with increasing the flexibility price in Case I

The total cost and income of the building obtained from energy scheduling and energy and flexibility scheduling are compared in Table IV. As can be seen, the total cost in the energy and flexibility scheduling increases due to flexibility provision, yet this increase is outweighed by the income obtained from providing flexibility, resulting in a payment reduction.

TABLE IV. COMPARISON OF TOTAL COST/INCOME IN THE ENERGY SCHEDULING AND ENERGY AND FLEXIBILITY SCHEDULING

	Energy scheduling	Energy and flexibility scheduling		
		Average spot price	*Spot price*	*The highest spot price*
Cost [SEK]	**387.1**	**397.54**	**397.54**	**414**
Income [SEK]	**0**	**12.66**	**17.81**	**50.63**
Payment [SEK]	**387.1**	**384.88**	**379.73**	**363.37**

Fig. 12 illustrates the robust scheduled flexibility for varying confidence levels. As can be seen, the robust scheduled flexibility is comparatively lower when compared to the Case I where uncertainty is disregarded. Since during flexibility activation period, the unforeseen increase in net load necessitates compensation through the reduction of HP consumption or the discharging of the BES, both of which in turn decrease the schedulable flexibility and therefore the revenue. It should be mentioned that this revenue reduction is the cost of robustness, however, the scheduled flexibility is assured.

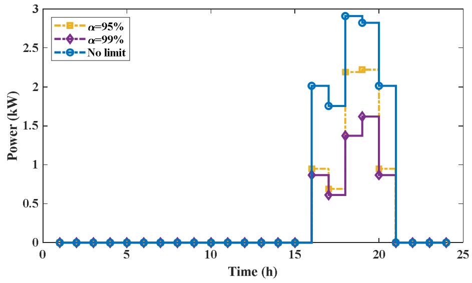

Fig. 12. Flexibility scheduling of the HSBLL in Case II

V. CONCOLUSION

In this paper, we introduced a novel EMS for residential buildings. The EMS is designed to optimize electric and heat consumption while simultaneously providing flexibility aligned with DSO requirements. By simulating the daily operations of a real residential building, we assessed the performance of the proposed EMS. Our findings demonstrated the successful dispatch of scheduled flexibility even in the presence of forecasting uncertainties. This achievement led to a notable 6% reduction in the building's payment cost. Through sensitivity analysis, we highlighted the significance of setting a fair flexibility price, which encourages residential buildings to contribute more flexibility to the DSO. Therefore, future endeavors will involve devising a pricing mechanism for the DSO that maximizes the utilization of buildings' flexibility potential.

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