BUILDING ENERGY MANAGEMENT SYSTEM

Deliverable 6.2

SUMMARY

Developing an advanced EMS to minimize both energy and peak power costs within a residential building, concurrently maximizing revenue by meeting flexibility requirements set forth by the DSO.

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List of Acronyms and Symbols

EMS – Energy Management System

DSO – Distribution System Operator

BES – Battery Energy Storage

HP – Heat Pump

PV – Photovoltaic system

EC – Energy purchasing cost

HC – Heat purchasing cost

PC – Peak power cost

EI – Energy selling income

FI – Flexibility selling income

π^{trans} – Energy transmission price

π^{tax} – Tax price

π^{taxred} – Tax reduction price

π_t^{spot} – Spot market price

$\pi^{elec,peak}$ – Peak load price

π_t^{heat} – Heat energy price

$\pi^{penalty}$ – Penalty price due to the violation from the scheduled flexibility

π^{incen} – Incentive price due to reducing loss

π_t^{flex} – Flexibility provision price

P_t^{imp}- Imported power from the grid

P_t^{exp} – Exported power to the grid

P^{peak} – Peak load during scheduling horizon

P_t^{dev} – Violation from the scheduled flexibility

P_t^{flex} – Scheduled flexibility

P_t^{PV} – Power production of photovoltaic system

$P_t^{BES,dis}$ – Discharging power of the battery

$P_t^{BES,cha}$ – Charging power of the battery

P_t^{HP} – Power consumption of the heat pump

P_t^{EL} – Electric load demand

H_t^{HP} – Heat power production of the heat pump

H_t^{DH} – Imported heat from the district heating system

H_t^{HL} – Heat load demand

$P^{grid,max}$ – Maximum electric power exchanged with the grid

$H^{DH,max}$ – Maximum heat power exchanged with the district heating

$u_t^{BES,dis}$ – Binary variable to indicate charging/discharging state of the battery

SOC_t – State of charge of the battery

η^{cha}/η^{dis} – Charging/discharging efficiency of the battery

E^{BES} – Capacity of the battery

COP_t – Coefficient of the performance of the heat pump

$k_0/k_1/k_2$ – Coefficients that are used in the COP equation

$\theta_t^{supply}/\theta_t^{source}$ – Temperature of the supply/ source side of the heat pump

$P^{HP,max}$ – Maximum power consumption of the heat pump

1 Introduction[1]

1.1 Purpose and structure of the report

The future distribution system needs more flexibility to handle the congestion arising from the electrification of heating and transportation. Thanks to smart grids, it is possible to leverage residential buildings' flexibility for congestion management as a viable and cost-effective solution. However, residential buildings need an advanced energy management system (EMS) to optimize their electric and heat consumptions while providing flexibility to satisfy the requirements of the distribution system operator (DSO). In response to this need, an advanced EMS is developed as part of the GENTE project. The primary objective of developed EMS is to minimize both energy and peak power costs within a residential building, concurrently maximizing revenue by meeting flexibility requirements set forth by the DSO. The developed EMS achieves this through the optimization of charging and discharging cycles of the Battery Energy Storage (BES) system, as well as optimal control of the Heat Pump (HP) and district heating dispatches.

In the next section of the report, the model formulation and solution algorithm are given. Then, the performance of the developed EMS is investigated by simulating the daily and monthly operation of HSB living lab as a real residential building located within the campus of Chalmers. Finaly, the results are summarized.

1.2 Literature Review

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 [1]. Therefore, researchers have demonstrated considerable interest in the energy management of buildings focusing on: (i) minimizing the energy expenses, maximizing the energy revenues, decreasing carbon emissions, and attaining a specific target load profile [2] (ii) developing strategies to accomplish these objectives [3] (iii) controlling household appliances [4] (iv) modelling and architecture [5]. Recently, the idea of flexibility provision from residential buildings is evident in numerous studies. For example, in [6] a two-stage energy management model has been proposed for a building. In the first stage, the aim is to minimize energy costs, while in the second stage, the focus is maximizing revenue by flexibility provision for the DSO. In [7], 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 requirements of the DSO. Authors of [8] have developed a scenario-based stochastic optimization

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[1] This deliverable has been presented at the EEE-AM 2023. M. Mazidi, D. Steen and L. A. Tuan, "A Novel Energy Management System for Optimal Energy and Flexibility Scheduling of Residential Buildings: A Case Study in HSB Living Lab," 2023 Asia Meeting on Environment and Electrical Engineering (EEE-AM), Hanoi, Vietnam, 2023, pp. 01-06.

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 [9] to determine flexibility ranges of buildings and control device based on the receiving flexibility requests from the DSO. In [10], flexibility of thermostatically controlled appliances are investigated. Authors of [11] have developed an EMS for buildings to enable flexibility from electric vehicles and BESs. In [12], by using the EMS's capability to shift specific appliances, ensuring the match between demand and supply of flexibility. In [13], a two-stage optimization model has been introduced in which EMSs of buildings optimize their respective energy consumption together, and determines their flexibility provision.

The successful implementation of BEMS relies on co-optimization of energy and flexibility in the presence of forecasting uncertainties. However, this model has not been fully developed in the reviewed literatures with all the details. Therefore, an advanced EMS is formulated and implemented as part of GENTE project for optimal energy and flexibility scheduling of residential buildings with focusing on HPs.

1.3 Approach

The aim of the developed EMS is to optimize short-term energy and flexibility scheduling of buildings. To this end, the scheduling horizon of the EMS is divided into three distinct parts: energy scheduling, energy and flexibility scheduling, and energy scheduling with flexibility provision. In the first part, the EMS aims to minimize the energy and peak power costs through the optimization of charging and discharging cycles of the BES, as well as optimal control of the HP and district heating dispatches. In the second part, the EMS tries to maximize the revenue from offering flexibility. In the last part, the EMS aims to provide the accepted flexibility. To cope with forecasting uncertainties, a rolling horizon-based algorithm and the chance constraint method are incorporated. Finally, the model is formulated as a MILP optimization problem which can be effectively solved via commercial software packages.

2 Model Formulation and Solution Algorithm

2.1 Description of the model

The developed EMS is practically tested on HSB living lab (HSBLL) which is a residential building in the campus of Chalmers [14]. The schematic of HSBLL along with its components, is depicted in Fig. 1. As shown, the HSB 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 HSB, 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 customer; therefore, it needs to submit only the hourly flexibility bid quantities to the DSO after the request, and if accepted, the revenue obtained from selling flexibility in the market is settled at the flexibility price. Since the flexibility market is not considered in this work, the flexibility price is considered as the average spot market price at each hour of the activation period [8].

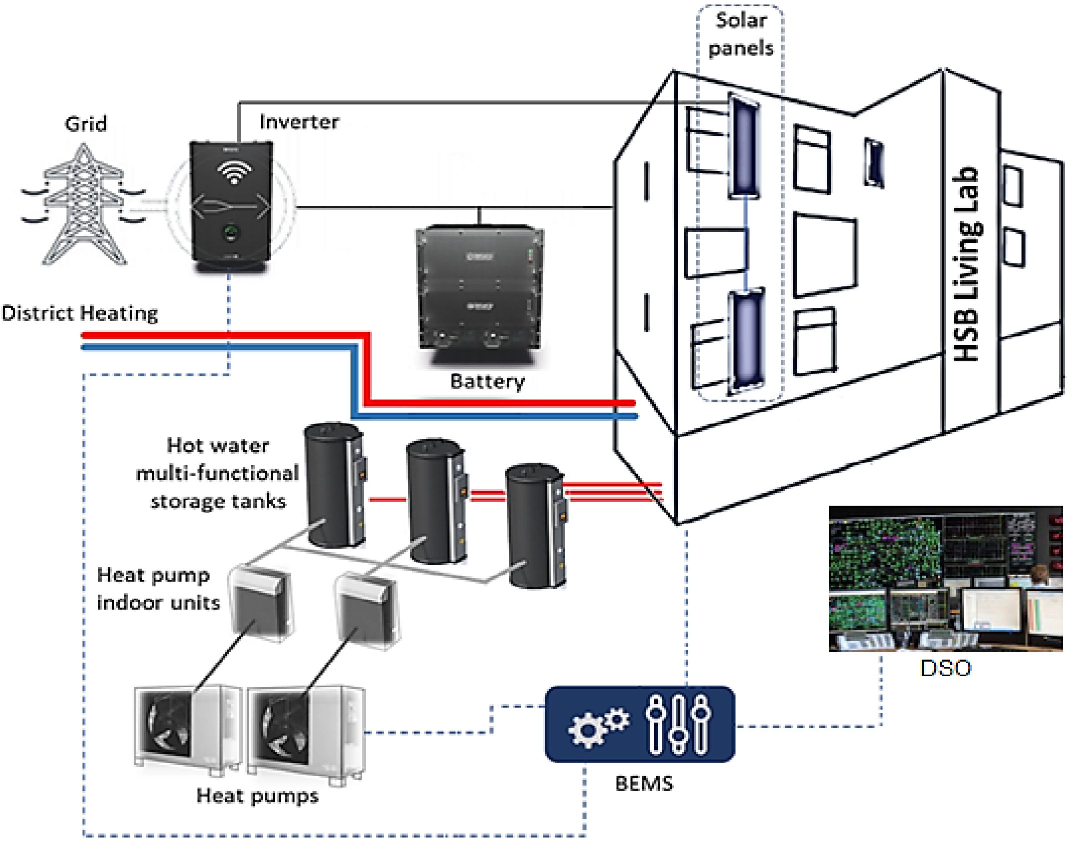

Figure 1 Schematic of HSBLL with its components

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 [15]. 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.

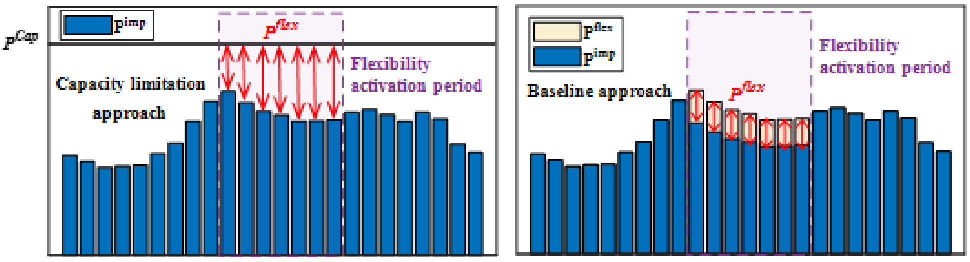

Figure 2 Flexibility modelling approach: 1- capacity limitation approach (left) 2- baseline approach (right)

The process of energy and flexibility scheduling is shown in the Fig. 3. In this depiction, the DSO sends a flexibility request notification to the EMS at $t = t_0$. Subsequently, the EMS responses by sending the amount of flexibility it can provide to the DSO. The EMS 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 penalty is due to the exceeding of DSO from the subscription level that should be paid to the Transmission System Operator (TSO) [16]. The model formulation of EMS is developed in the following section and then, the algorithm of energy and flexibility scheduling of HSBLL is presented.

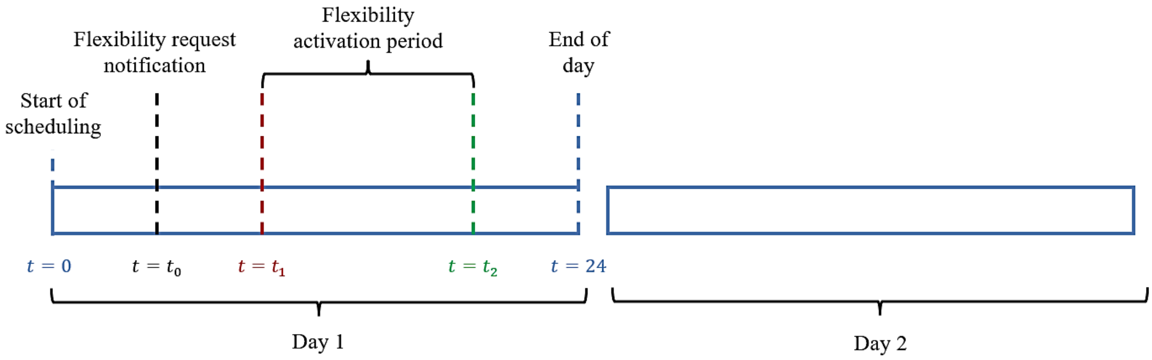

Figure 3 Process of energy and flexibility scheduling

2.2 Formulation of the model

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.

2.2.1 Objective function

The objective of the EMS is to minimize total payment cost of the building during scheduling horizon which is 24 hours. 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,

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

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

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

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

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

2.2.2 Constraints

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,

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

$$H_t^{HP} + H_t^{DH} = H_t^{HL} \tag{8}$$

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

$$-P^{grid,max} \le P_t^{imp} - P_t^{exp} \le P^{grid,max} \tag{9}$$

$$H_t^{DH} \leq H^{DH,max} \tag{10}$$

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:

$$P^{peak} \geq P_t^{imp} \tag{11}$$

$$H^{peak} \geq H_t^{DH} \tag{12}$$

BES model: The BES can be modelled 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.

$$0 \leq P_t^{BES,dis} \leq P^{BES,max} u_t^{BES,dis} \tag{13}$$

$$0 \leq P_t^{BES,cha} \leq P^{BES,max} u_t^{BES,cha} \tag{14}$$

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

$$SOC_0 = SOC^{ini} \tag{16}$$

$$SOC^{min} \leq SOC_t \leq SOC^{max} \tag{17}$$

$$u_t^{BES,dis} + u_t^{BES,cha} \leq 1 \tag{18}$$

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 [17], the HP is modelled 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).

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

$$H_t^{HP} = COP_t \times P_t^{HP} \tag{20}$$

$$P_t^{HP} \leq P^{HP,max} \tag{21}$$

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:

$$P_t^{flex} \leq P_t^{imp\_base} - P_t^{imp} \tag{22}$$

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.

2.3 Uncertainty handling by chance constraint method

Given the potential error 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:

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

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 [18]:

$$\sum_j T_{i,\mathrm{j}} y_j \geq \mu_i + \sigma_i Z_\alpha \tag{24}$$

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

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:

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

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:

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

where $\sigma_t^{EL}$and σ_t^{PV} are standard deviations of electric load and PV generation, respectively, approximated as follows [19]:

$$\sigma_t^{EL} = \frac{d}{100} P_t^{EL} \tag{28}$$

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

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:

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

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

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

This section includes a description of the overall goals and objectives of the research. It includes a description of the measures that will be put in place such as checks on the accuracy and completeness of the work to ensure the quality of the research and to ensure project activities fulfil project's objectives and expected impacts. This includes the criteria for evaluating the success of the project.

2.4 Solution algorithm

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 hour 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:

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

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.

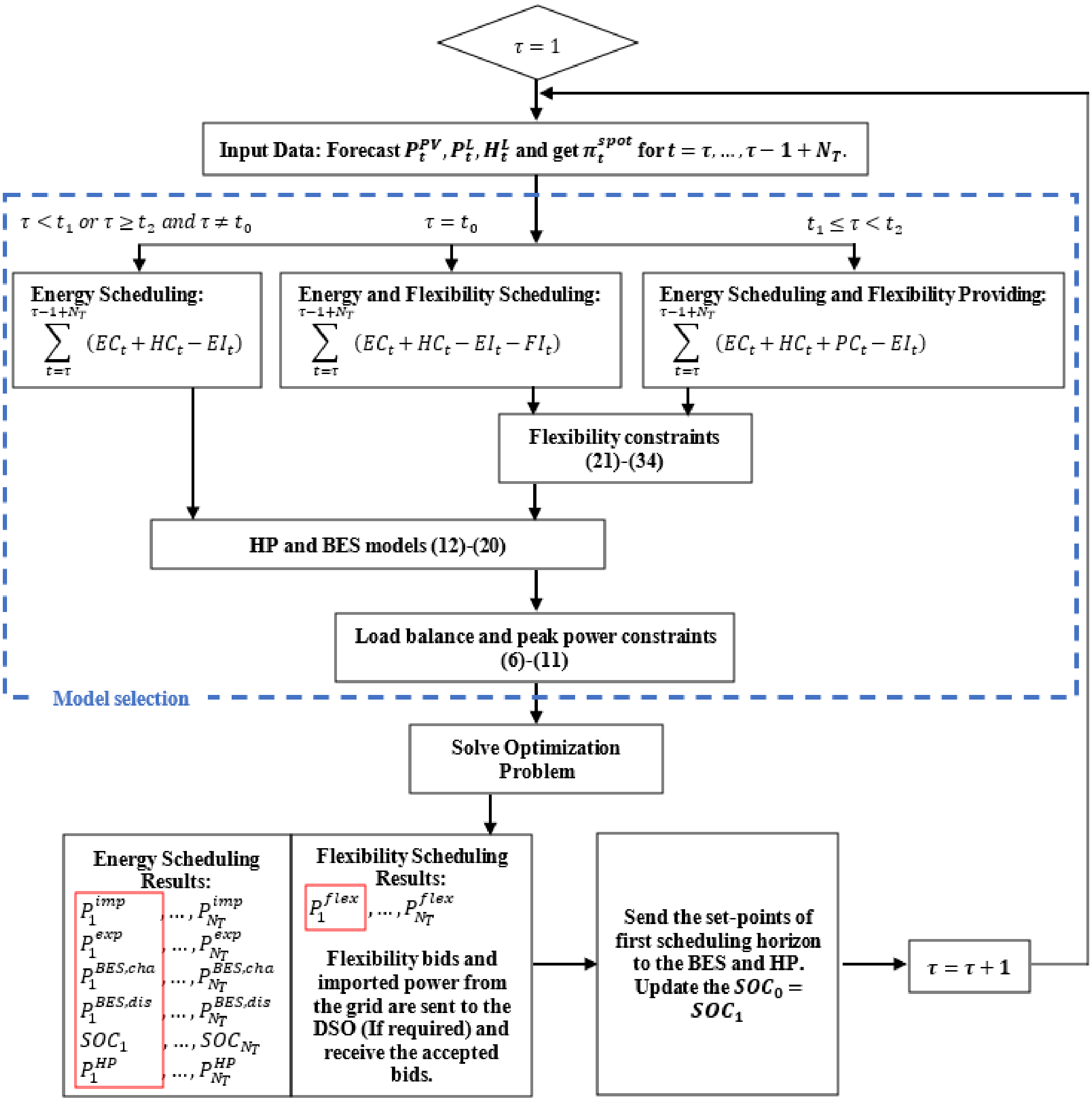

Figure 4 Flowchart of energy and flexibility scheduling

3 Simulation Results

The optimal energy and flexibility scheduling are 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 2. The code can be found in the GitHub repository with following address: https://github.com/mrezamazidi/EMSFLEX_GENTE.git. Simulations are performed according to the test cases described in Table 2 on a PC with 2.9 GHz Intel Core i7-10700 CPU and 32 GB of RAM.

Table 1 – 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	✓

3.1 Data and assumptions

The technical characteristics of HSBLL's components are given in Table 3. 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 [20]. 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 4 [21]. It is assumed that the revenue from selling 1 kW of flexibility at each hour of activation period equals to selling 1 kWh/h of energy at average daily spot market prices [8]. The penalty for not providing flexibility is $\pi^{penalty} = 2.8\, SEK/kWh$ which is based on the 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 are forecasted using a LSTM neural network which have been described in [22].

Table 2 – 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	$\mathbf{3.8209 + 0.12110\theta_t^{source} + 0.00098740\theta_t^{source^2}}$
PV	$\boldsymbol{Capacity\ (kWp)}$	13

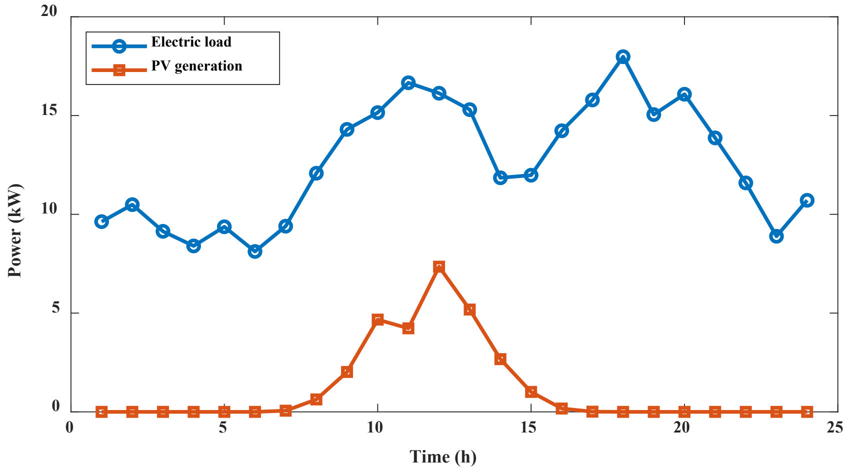

Figure 5 Hourly electric load and PV generation profiles

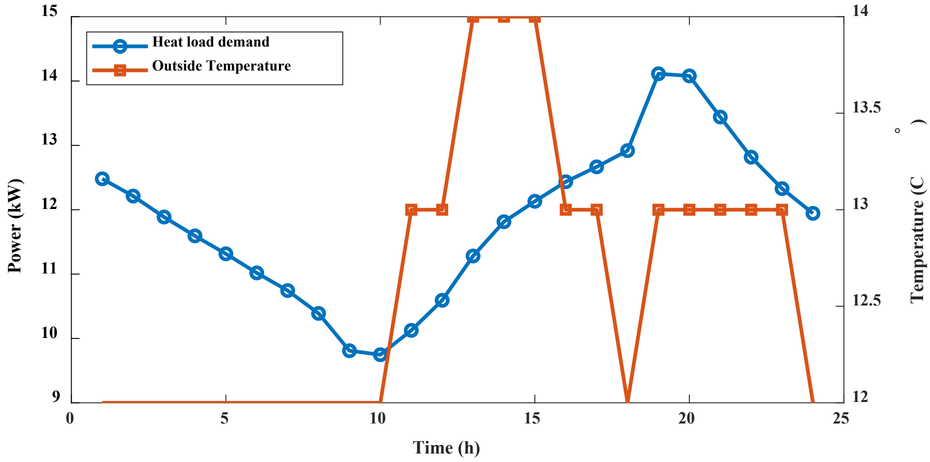

Figure 6 Hourly heat load profile and outside temperature

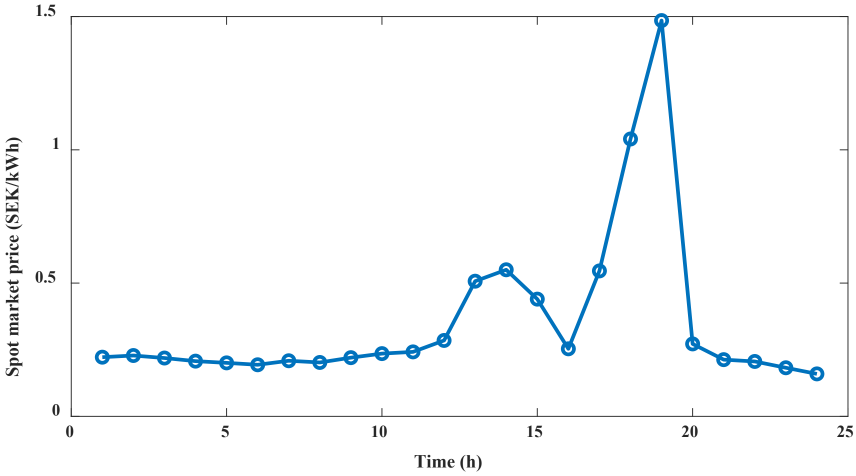

Figure 7 Hourly spot market price

Table 3 – The energy and power tariff fee of electricity and heat

Parameters	Value
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

3.2 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.

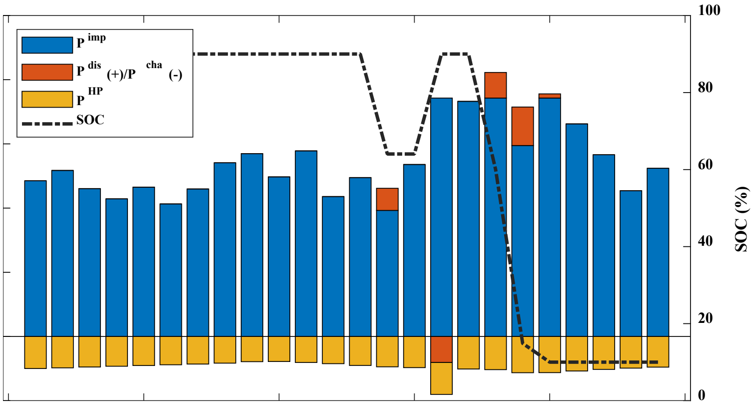

Figure 8 Hourly energy scheduling result

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 cancelling 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.

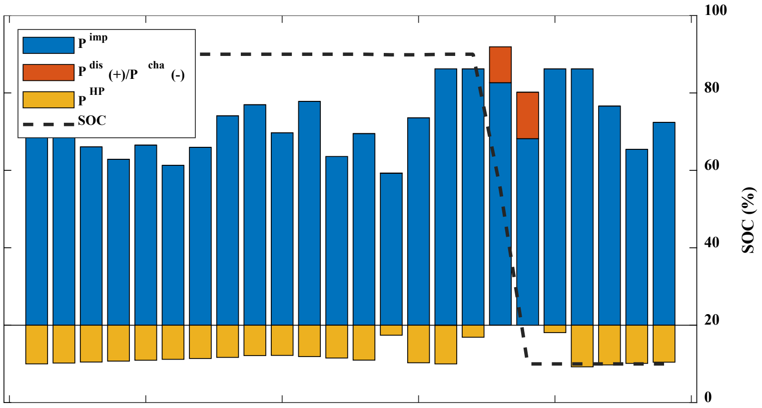

Figure 9 Hourly energy scheduling result in Case I

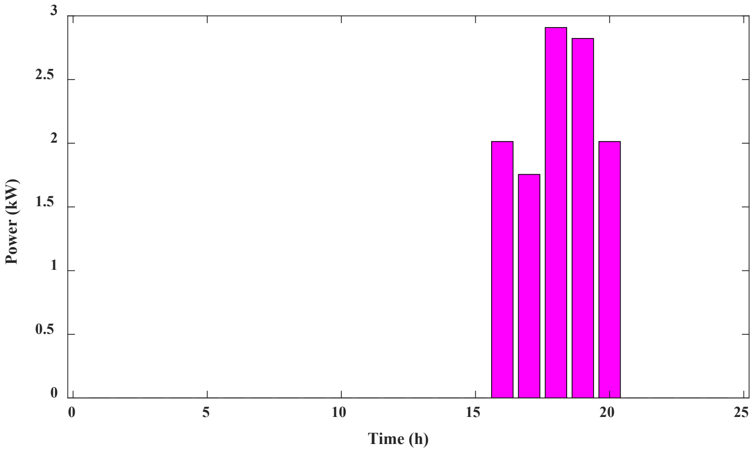

Figure 10 Hourly flexibility scheduling result with increasing the flexibility price in Case I

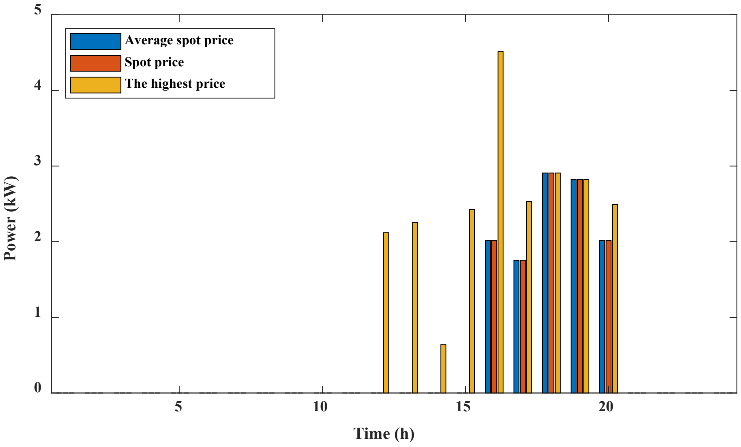

Figure 11 Hourly flexibility scheduling result with increasing the flexibility price in Case I

The daily cost and income of the HSBLL obtained from energy scheduling and energy and flexibility scheduling are compared in Table 5. 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 4 – Comparison of daily 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. It should be mentioned that d in (28) is assumed 5%. 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.

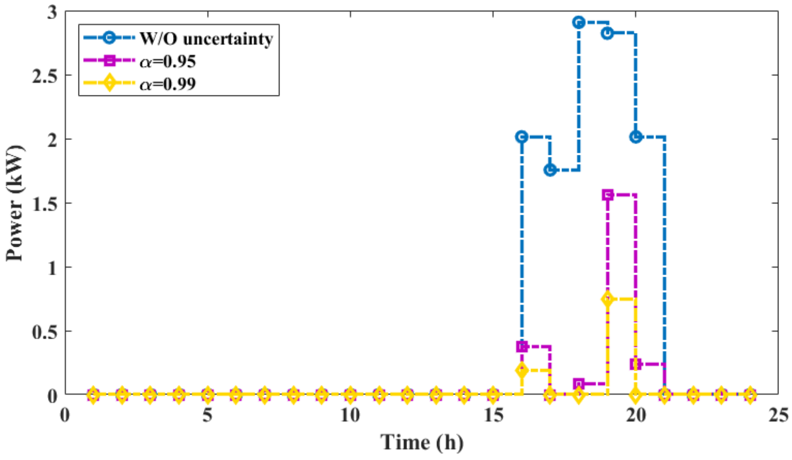

Figure 12 Hourly flexibility scheduling result in Case II

The outcomes of the rolling horizon chance constraint algorithm are illustrated in Figure 13. It is evident that the power imported from the main grid experiences a reduction between 12:00 and 20:00, contributing to enhanced flexibility. Nevertheless, when accounting for uncertainties in load demand and PV generation, the imported power cannot consistently meet the scheduled flexibility. Consequently, power deviations occur in certain hours, incurring penalties to be paid to the DSO. To account for the impact of uncertainty in flexibility scheduling, the chance constraint method is employed, and the corresponding results are depicted in Figure 14. As evident in the results, the imported power increases when compared to the scenario where uncertainty is not taken into account. This is due to the fact that, with the incorporation of uncertainty, as illustrated in Figure 15, the scheduled flexibility is curtailed to ensure its reliable provision.

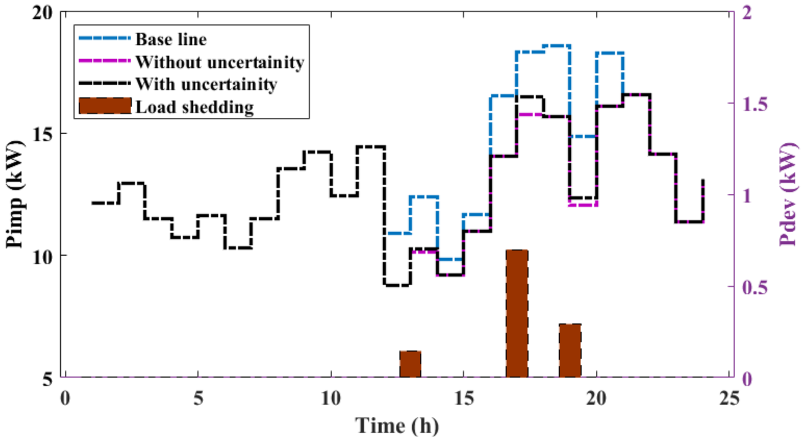

Figure 13 Hourly flexibility provision with/without considering uncertainty and without chance constraint

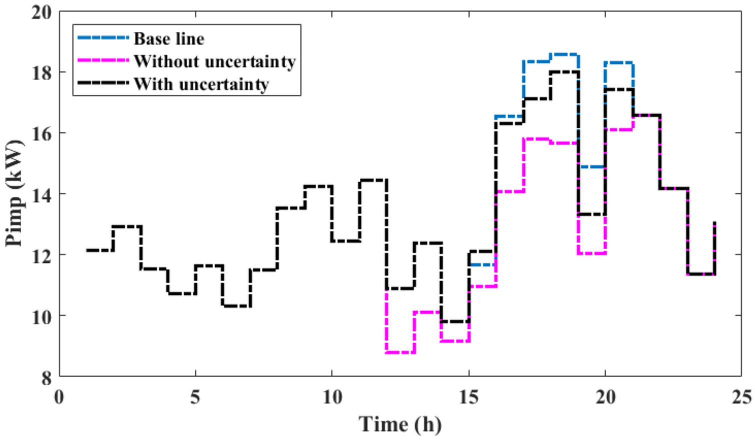

Figure 14 Hourly flexibility provision with/ without considering uncertainty and with chance constraint ($\alpha = 0.95$)

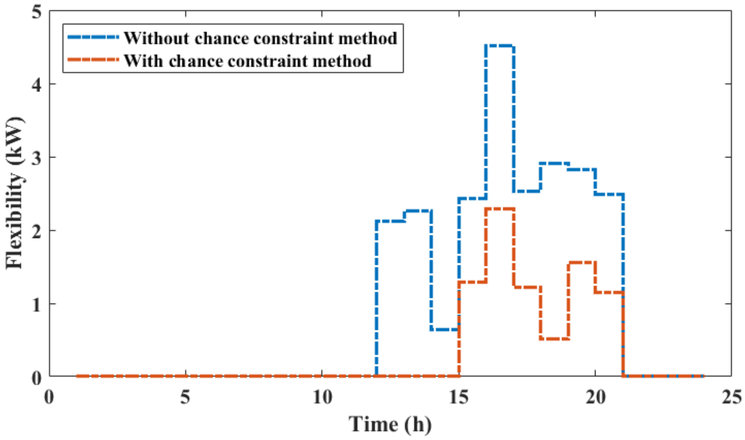

Figure 15 Hourly scheduled flexibility with/without using chance constraint method

Table 5 represents the payment of the HSB Living Lab in March with the energy scheduling and energy and flexibility scheduling. The flexibility price is considered as the average spot market price at each hour of the activation period. Likewise, the robustness level is assumed 0.99. As can be seen, the payment in the energy and flexibility scheduling reduces by 619 SEK.

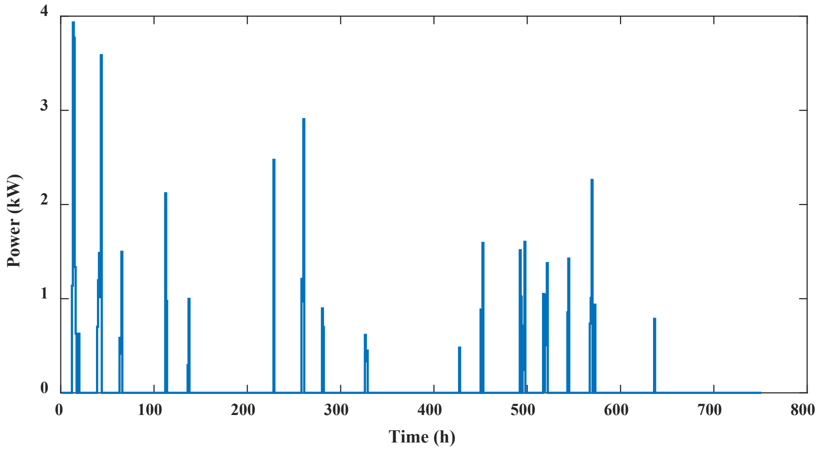

Figure 16 Hourly flexibility scheduling result in month of March

Table 5 – Comparison of monthly payment in the energy scheduling and energy and flexibility scheduling

	Energy scheduling	Energy and flexibility scheduling
Payment [SEK]	18665	18046

4 Conclusion

In this report, 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 endeavours will involve devising a pricing mechanism for the DSO that maximizes the utilization of buildings' flexibility potential.

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