Simultaneous energy hub operation and construction for investigating quantitative flexibility considering uncertain supply and demand side resources

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Abstract

In this paper, the quantitative flexibility of EH is evaluated considering a flexibility index which is based upon available maximum capacity as well as the response time of generating units. Here, the impact of simultaneous EH operation and construction are investigated on quantitative flexibility considering both uncertain supply and demand side resources. Hence, a new structure so-called multi-objective simultaneous operation/construction optimization of multi-carrier EH is presented ($\text{MOF-EH}_{\text{MC}}^{\text{soco}}$) which consists of a decrease in operation and construction costs as well increase in power system flexibility. The demand side uncertainties, including thermal/electrical demand, are implemented by the Gaussian distribution function, and uncertainty on the supply side, including gas pressure uncertainty (GPU), is modeled by the probabilistic–possibilistic Z-number method. Also, in multifarious cases, the performance of the proposed index is evaluated. It is shown how flexible resources like electrical storage systems (ESS), thermal storage systems (TSS), electrical demand response programs (EDRP), and thermal demand response programs (TDRP) can increase the flexibility of the EH. It is also conducted that how the flexibility enhancement can increase construction costs.

Keywords: Energy Hub Construction; Flexibility Index; Uncertain Supply and Demand Side Resources; Z-number; Gas Pressure Uncertainty.

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1. Introduction

Nowadays, the enlargement of the power system from generation to consumption, the occurrence of environmental factors, load growth, and efforts to become independent of fossil fuels, have increased the importance of energy in the power system. Energy, economy, and environmental factors have led to a synergistic increase in the power system, which has resulted in the formation of new energy-sharing economy frameworks, that interconnect multi-carrier energy resources to the smart grid and work as a poly-generation which are called Energy Hub (EH) systems. An EH is an abstract environment in a power grid where only energy is exchanged, regardless of transmission and grid losses. The main characteristic of an EH is the simultaneous management and operation of various energy carriers such as electricity, gas, and heating [1].

Considering renewable energy systems (RES) along with the special features of their operation has led to the presentation of different energy management strategies in the field of EH. Despite the numerous benefits of RES such as reducing environmental pollution, reducing operation costs, installation, and rapid utilization, these resources can create technical problems for the network. The main problem caused by RES such as wind turbines or solar panels is due to the uncertainty of the power generated by these resources [2]. The uncertainties due to the dependence of the RES on weather conditions make the optimal operation of the EH more complicated. In other words, the highly variant output of these power plants violates the load balance conditions.

Due to the above-mentioned uncertainties, researchers have recently become more interested in studying the uncertainties surrounding the EH. In [3], researchers simulated wind power uncertainty, electricity load, and price using the Monte Carlo probabilistic method, and then, reduced the scenarios of this modeling utilizing the backward-forward method. Reference [4] is introduced an adaptive robust optimization approach for optimal operation of multi-layout EHs under uncertainty. The concept of multi-layout EHs is presented along with its energy management in a deterministic form. In order to account for the load and upstream energy market price uncertainties, polyhedral uncertainty sets are used in [4].

Reference [5] suggests a risk-constrained energy scheduling method for an EH. The scheduling problem aims to maximize expected profit while minimizing risk or maximum relative regret level while considering various uncertainties and a preferred CO_2 emission level. A new model for unit commitment in renewable EHs has been proposed in [6]. Day-ahead EH scheduling is performed using Information Gap Decision Theory from risk-neutral, risk-averse, and risk-seeking perspectives while taking into account the uncertainties of electricity, heat, and cooling demands as well as Wind Turbine (WT), photovoltaic and electricity prices. Researchers in [7] have tried to study the operation of the EH, using the C-var scenario-based uncertainty modeling method for this purpose. One of the proposed solutions to deal with uncertainties and maximum utilization of renewable resources is the application of energy storage. This equipment reduces the operation cost, financial risk, emission, and output power fluctuations of the RES [8]. Reference [9] has presented a bi-level probabilistic optimization framework that enables an EH to optimize its daily load profile and determines its flexibility provision.

The uncertainties of renewable resources, the use of storage devices, and the implementation of Demand Response Programs (DRPs) [10,11] have bolded the concept of flexibility in power systems. Flexibility in power systems refers to the ability of the system to quickly and efficiently respond to changes in demand and supply. Flexibility can be achieved through a variety of means including energy storage, DRPs and flexible generation [12]. Multifarious definitions of flexibility in the power system have been proposed, one of the initial definitions provided in [13], is "the ability of a system to rearrange its resources in response to changes in the net load, where the net load is the residual system load Which is not supplied by Variable Generations (VGs)".

The term, power system flexibility is also used in [14]. According to this paper, a system is called flexible if it can respond very quickly to large fluctuations, planned changes, or unpredictable demand. Reference [15] defines flexibility at the generation planning level and states that flexibility is the ability of the network to respond to unmet demand by VG units. In [16], flexibility in the transmission network is defined in the sense of the system's ability to maintain network reliability at a reasonable cost while facing changes in power generation scenarios. On the other hand, flexibility studies can be divided into two areas: long-term operational planning and short-term operational flexibility [17]. Reference [18] defines flexibility as the ability of a power system to cope with rapid and widespread changes in load and energy generation. In [19], flexibility refers to the extent to which a power system can adapt its electricity generation or demand in response to expected and unexpected fluctuations. It also reflects the ability of a power network to maintain a consistent supply during temporary and significant imbalances. Although reference [20] has a new definition of flexibility in smart grids: "possibility of maintaining consumption within specific ranges".

According to reference [21], the definition of flexibility varies among research groups and is often based on the primary field of study. Two classifications of flexibility in studies are short-term operational flexibility and long-term planning flexibility. Reference [22] suggests that the flexibility area index is an appropriate measure for assessing power system flexibility, particularly when dealing with renewable resources like wind and solar farms on a large scale. Like other flexibility indices, this metric is initially defined for a single generation unit and then expanded to the entire power system through a combination of unit indices. A method for evaluating power system flexibility is outlined in reference [23], which takes into account units with DRPs, fast ramps, and energy storage. In [24], real-time pricing, direct load control and emergency demand response programs are modeled as flexibility providers through the comprehensive modeling of DRPs.

Reference [25] aims to introduce a market-oriented approach to manage transmission system congestion by utilizing demand-side flexibility resources. The framework comprises two levels, with the first level being the flexibility market cleared by the TSO and participated only by DSOs. The second level involves local markets established in each distribution network and managed by DSOs, where prosumers can offer their flexible services. According to reference [26], the interaction between gas and electricity systems is viewed as a potentially adaptable solution for flexible provision.

Reference [27] introduces a method for evaluating the flexibility of EH in handling uncertainty. The method involves calculating a flexibility index through corrective actions such as purchasing additional input carriers and implementing DRPs. It is worth mentioning that the presented flexibility index has not measured the EH response speed in the face of load fluctuations. Reference [28] is regulated network flexibility through flexible pricing services. The proposed approach seeks to minimize the gap between the network's energy cost and the income generated by EH flexibility. This paper just considered the flexibility of the EH networks, and the inner flexibility of the EH system has not been investigated.

Previous research has neglected flexibility-based EH construction, which is the main motivation of this paper. Another researcher has used many renewable resources such as wind, solar and flexible resources including thermal/electrical storage and thermal/electrical demand response resources in the EH. It should be noted that in these articles, changing the flexibility of the system in the case of using renewable and flexible resources has not been quantitatively studied. In [29], the operation and planning of the EH are accomplished to reduce the investment and operation costs. In [30], the EH problem is solved in two levels, the planning part is considered the main problem, and the operation part is considered the sub-problem. Some other papers like [31] have similarly examined the EH problem.

In an effort to address a research gap, reference [32] is introduced a new optimization problem centered around the simultaneous optimal operation and capacity of ESS in renewable EHs. A key contribution of this research is the comparative analysis of HSS and ESS. However, it should be noted that this paper does not explore how storage devices impact the flexibility of EH systems. Reference [33] main focus is on the operational challenges that arise when integrating renewable energy, natural gas, and electricity into EHs. It examines these challenges from energetic, economic, and environmental perspectives. However, the reference does not examine how resource usage affects flexibility levels. Reference [34] offers a comprehensive EH design model that takes into account technical, economic, and security criteria. The proposed model addresses operation constraints and seasonal variations of loads and solar radiation. While the paper focuses on EH resiliency, it does not consider the impact of planning on EH flexibility.

In this paper, to address the above-mentioned shortcomings, the flexibility of the EH has been investigated quantitatively using a self-inclusive index that asses flexibility from two dimensions of the system's free capacity and the rate of deploying this capacity. Furthermore, the effect of wind power uncertainty, thermal/electrical storage, and thermal/electrical DRPs on the proposed flexibility index has been studied using various numerical cases. For further investigations, the effect of construction on the EH flexibility is studied as well. Moreover, the uncertainty of the inlet gas pressure is modeled and investigated as it can affect the flexibility of the system. This uncertainty is modeled by the probabilistic–possibilistic Z-number method and its effect on changing the system flexibility has been investigated in this manuscript. To carry on the analysis, different scenarios are defined as case studies including the basic case study that inspects the effect of the Z-number inlet-gas uncertainty modeling and various other cases that consider the uncertainties of the wind resource, electrical/thermal DRP, electrical/thermal storage and their effects on the system's flexibility respectively. In addition, the last case study is defined to address the effects of the construction on the proposed flexibility index.

The proposed $\text{MOF-EH}_{\text{MC}}^{\text{soco}}$ structure is modeled as a MILP which is solved using the CPLEX algorithm in GAMS integrated development environment. Moreover, an overview of the previous work and the present paper in terms of planning, uncertainties, and quantitative flexibility of EH (QFEH) and EH equipment is provided in Table 1.

The rest of this paper is organized as follows. Section 2 proposed the framework $\text{MOF-EH}_{\text{MC}}^{\text{soco}}$. The economic ($f_1^{\text{MOF-EH}_{\text{MC}}^{\text{soco}}}$) and the flexibility ($f_2^{\text{MOF-EH}_{\text{MC}}^{\text{soco}}}$) framework's objectives formulation based on MILP are provided in Section 3. The numerical study and simulation results are proposed in Section 4. Finally, concluding remarks are drawn in Section 5.

2. Proposed framework of $\mathbf{MOF\text{-}EH_{MC}^{soco}}$

There are many objective functions defined for the EH, but since the purpose of this paper is to investigate EH optimization with a flexibility approach, a multi-objective function is considered for the proposed $\mathrm{MOF\text{-}EH_{MC}^{soco}}$ structure. The first objective is to reduce construction/operation costs and the second one is to increase the flexibility index, which is described in detail below.

The proposed hub structure includes a CHP, a boiler, a converter, a transformer, and electrical/thermal storage that is powered by gas, electricity, and wind power. The framework of the proposed EH is shown in Figure 1.

3. $\mathbf{MOF\text{-}EH_{MC}^{soco}}$ formulation

3.1. The economic objective function of $MOF\text{-}EH_{MC}^{soco}$

The first objective of the proposed EH framework is to simultaneously reduce construction and operation costs. From the time horizon perspective, EH construction is an issue with a time interval of one year, while the operation of the EH is considered to have a short time frame of one day i.e., 24 hours. In EH construction, the capacity of the CHP and the boiler can be increased if needed, and the optimizer can decide whether or not to install thermal/electrical storage by determining the appropriate capacity with the approach of increasing flexibility. The first goal can be formulated as:

$$f_1^{MOF\text{-}EH_{MC}^{soco}} = Min\left\{W^1\left\{OC^{MOF\text{-}EH_{MC}^{soco}}\right\} + W^2\left\{CC^{MOF\text{-}EH_{MC}^{soco}}\right\}\right\} \tag{1}$$

$\mathrm{f}_1^{\mathrm{MOF-EH_{MC}^{soco}}}$ is the value of the first objective function to reduce operation and construction costs. W^1 and W^2 are considered as weight coefficients that represent the importance of either term in the formulation, and are also adjustable. Construction costs as previously described include the price of expanding the CHP and boiler capacity:

$$CC^{MOF\text{-}EH_{MC}^{soco}} = \sum_{n=1}^{N} (IC_n Cap_n) \tag{2}$$

Daily operation costs are described in different sections as follows:

$$OC^{MOF\text{-}EH_{MC}^{soco}} = \left\{ \begin{array}{c} \boxed{\text{Up Stream Network Electricity \& WT \& Gas Power}} \\ cost_{OC}^{E} + cost_{OC}^{G} \\ \boxed{\text{Electrical \& Thermal Storage Costs}} \\ + \quad cost_{OC}^{ES} + \cos t_{OC}^{HS} \\ \boxed{\text{Electrical \& Thermal Energy Not Supplied}} \\ + \quad cost_{OC\_ENS}^{E} + cost_{OC\_ENS}^{H} \end{array} \right\} \tag{3}$$

Where $\mathrm{cost}_{\mathrm{OC}}^{\mathrm{E}}$ includes power exchange with the network and imported energy from WT and also $\mathrm{cost}_{\mathrm{OC}}^{\mathrm{G}}$ is the cost of imported NG from the grid. $\mathrm{cost}_{\mathrm{OC}}^{\mathrm{ES}}$ and $\mathrm{cost}_{\mathrm{OC}}^{\mathrm{HS}}$ represent the cost of charging and discharging the electrical and thermal storage, $\mathrm{cost}_{\mathrm{OC\_ENS}}^{\mathrm{E}}$ and $\mathrm{cost}_{\mathrm{OC\_ENS}}^{\mathrm{H}}$ are the costs of electrical and thermal energy not supply, respectively. Here, Eq (3) can be described in detail as follow [33]:

$$OC^{MOF\text{-}EH_{MC}^{soco}} = \sum_{t=1}^{24} \left\{ \begin{array}{l} \overbrace{\left\{ q_e^{Net}(t)\, p_g^{Net}(t) \right\} + \left\{ q_e^W\, p_g^{W^{Scenario/reduction}}(t) \right\}}^{cost_{OC}^{E}} \\ \quad + \overbrace{\left\{ q_g^{Net} p_g^{Net}(t) \right\}}^{cost_{OC}^{G}} + \overbrace{\left\{ q_e^{ESS} \left(p_e^{ch}(t) + p_e^{dis}(t) \right) \right\}}^{cost_{OC}^{ES}} \\ \quad\quad + \overbrace{\left\{ q_h^{HSS} \left(p_h^{ch}(t) + p_h^{dis}(t) \right) \right\}}^{cost_{OC}^{HS}} + \overbrace{\left\{ q_e^{ESS}\, p_e^{ESS}(t) \right\}}^{cost_{OC\_ENS}^{E}} + \overbrace{\left\{ q_e^{ESS}\, p_e^{ESS}(t) \right\}}^{cost_{OC\_ENS}^{H}} \end{array} \right\} \quad (4)$$

3.2- Flexibility index objective function of $MOF\text{-}EH_{MC}^{soco}$

This paper considers the flexibility index that reflects the free capacity of the system and the rate of reaching this capacity. The system responsiveness, capability of achieving maximum capacity, and system acceleration affect achieving this goal as important parameters in flexibility calculations. In brief, a system is more flexible if it can deploy more capacity in less time. With these explanations in mind, the amount of flexibility can be calculated by Eqs (5)-(10):

$$f_2^{MOF-EH_{MC}^{soco}} = Max\{SFI\} \quad (5)$$

Equation (5) is introduced as the second objective function of the EH. The maximum available capacity of the system can be calculated after an unexpected event according to Eq (6) [17].

$$SMACI = \frac{1}{TN} \sum_{ut=1}^{T-1} \frac{1}{T-ut} \sum_{t=1}^{T} \sum_{i=1}^{N} \frac{C_{(i,t,ut)}^{a}}{p_{(i,t)}^{*}} \quad \forall\, i,\ \forall\, t,\ \forall\, ut \quad (6)$$

The expected response time to reach the maximum capacity can be calculated by Eq (7).

$$SRT = \frac{1}{TN} \sum_{ut=1}^{T-1} \sum_{i=1}^{N} t_{C_{(i,ut)}^{*}} - t_{(i,j,ut)} \quad \forall\, i,\ \forall\, t,\ \forall\, ut \quad (7)$$

Based on Eqs (5)-(7), the system's flexibility index is obtained by Eq (8). Equations (9)-(10) ensure that the accessible capacity for each unit does not exceed the maximum generation capacity of the unit at each time step.

$$SFI = \frac{1}{TN}\sum_{ut=1}^{T-1}\frac{1}{T-ut}\sum_{t=1}^{T}\sum_{i=1}^{N}\frac{C^{a}_{(i,t,ut)}}{p^{*}_{(i,t)}(t_{C^{*}_{(i,ut)}} - t_{(i,j,ut)})} \quad \forall\, i,\ \forall\, t,\ \forall\, ut \tag{8}$$

$$C^{a}_{(i,t,ut)} = p^{a}_{(i,t+1,ut)} - p^{*}_{(i,t)} \quad \forall\, i,\ \forall\, t,\ \forall\, ut \tag{9}$$

$$p^{a}_{(i,t+1)} \le p^{\max}_{i} \quad \forall\, i,\ \forall\, t \tag{10}$$

3.3- Constraints of the proposed $MOF\text{-}EH^{soco}_{MC}$ structure

The electrical, thermal, and gas energy power balance is used to present stable operation of the EH. Furthermore, the amount of energy generated must be equal to the consumed load and the energy not supplied. Constraints of (11)-(13) satisfy the abovementioned power equilibrium [33].

$$\begin{aligned} p_{ed}(t) = {} & \left\{u^{NET}\eta_{T}\,p^{NET}_{e}(t)\right\} + \left\{u^{CHP}\eta_{echp}\,p^{NCHP}_{g}(t)\right\} + \left\{u^{W}\eta_{C}\,p^{W^{Scenario/reduction}}_{e}(t)\right\} \\ & + \left\{p^{dis}_{e}(t) - p^{ch}_{e}(t)\right\} + \left\{p^{shdo}_{e}(t) - p^{shup}_{e}(t)\right\} + \left\{p^{ENS}_{e}(t)\right\} \qquad \forall\, t \end{aligned} \tag{11}$$

$$p_{hd}(t) = \left\{u^{CHP}\eta_{hchp}\,p^{NCHP}_{g}(t)\right\} + \left\{\eta_{B}\,p^{NB}_{g}(t)\right\} + \left\{p^{dis}_{h}(t) - p^{ch}_{h}(t)\right\} + p^{ENS}_{h}(t) \quad \forall\, t \tag{12}$$

$$p_{gd}(t) = p^{NET^{Z-number}}_{g}(t) - p^{NCHP}_{g}(t) - p^{NB}_{g}(t) \quad \forall\, t \tag{13}$$

The amount of electrical and gas energy exchanged between the EH and the upstream grid is limited by technical constraints (14). Furthermore, the capacity limitations of the transmission lines, CHP, and the boiler are described in Eqs (15)-(18).

$$-p^{N\max}_{e} \le p^{NET}_{e}(t) \le p^{N\max}_{e} \quad \forall\, t \tag{14}$$

$$0 \leq p_g^{NET\,Z-number}(t) \leq p_g^{NET\max} \quad \forall\ t \tag{15}$$

$$\eta_{Tr}\, p_e^{NET}(t) \leq p^{Tr} \quad \forall\ t \tag{16}$$

$$\eta_{echp}\, p_g^{NCHP}(t) \leq p^{CHP} \quad \forall\ t \tag{17}$$

$$\eta_B\, p_g^{NB}(t) \leq p^B \quad \forall\ t \tag{18}$$

Electrical storages are one of the components considered in the proposed model of which the energy balancing constraint is defined by Eq (19) [35]. Equation (20) also represents the power loss of the system.

$$p_e^{ESS}(t) = p_e^{ESS}(t-1) + \eta_e^{ch}\, p_e^{ch}(t) - \left(\frac{p_e^{dis}(t)}{\eta_e^{dis}}\right) - p_e^{loss}(t) \quad \forall\ t \tag{19}$$

$$p_e^{loss}(t) = A_e^{loss}(t)\, p_e^{ESS}(t) \quad \forall\ t \tag{20}$$

The minimum and maximum capacity of the battery is specified in Eq (21). The charge/discharge capacity of the battery per hour is limited by constraints (22) and (23).

$$A_e^{\min}\, p_e^{SC} \leq p_e^{ESS}(t) \leq A_e^{\max}\, p_e^{SC} \quad \forall\ t \tag{21}$$

$$A_e^{\min}\, p_e^{SC} B_e^{ch}(t) \leq p_e^{ch}(t) \leq A_e^{\max}\, p_e^{SC} B_e^{ch}(t) \quad \forall\ t \tag{22}$$

$$A_e^{\min}\, p_e^{SC} B_e^{dis}(t) \leq p_e^{dis}(t) \leq A_e^{\max}\, p_e^{SC} B_e^{dis}(t) \quad \forall\ t \tag{23}$$

Two binary variables are used by Eq (24) to prevent concurrent charging/discharging of the storage system.

$$0 \leq B_e^{ch}(t) + B_e^{dis}(t) \leq 1 \quad \forall\ t \tag{24}$$

Thermal storage along with electrical storage can increase the efficiency of the EH. Equation (25) is the equilibrium of thermal power. The power loss of the system is represented by Eq (26). The maximum and minimum heating storage capacity is limited by the constraint (27) [36].

$$p_h^{HSS}(t) = p_h^{HSS}(t) + \eta_h^{ch} p_h^{ch}(t) - (\frac{p_h^{dis}(t)}{\eta_h^{dis}}) - p_h^{loss}(t) \quad \forall\ t \tag{25}$$

$$p_h^{loss}(t) = A_h^{loss}(t) p_h^{HSS}(t) \quad \forall\ t \tag{26}$$

$$A_h^{\min} p_h^{SC} \le p_h^{HSS}(t) \le A_h^{\max} p_h^{SC} \quad \forall\ t \tag{27}$$

The charging/discharging power of the thermal storage is defined by constraints (28) and (29). Thermal storage, like electrical storage, can only operate in either of the charging/discharging modes at each time frame, and to achieve this goal, two binary variables are used by the constraint (30).

$$A_h^{\min} p_h^{SC} \frac{1}{\eta_h^{ch}} B_h^{ch}(t) \le p_h^{ch}(t) \le A_h^{\max} p_h^{SC} \frac{1}{\eta_h^{ch}} B_h^{ch}(t) \quad \forall\ t \tag{28}$$

$$A_h^{\min} p_h^{SC} \eta_h^{dis} B_h^{dis}(t) \le p_h^{dis}(t) \le A_h^{\max} p_e^{SC} \eta_h^{dis} B_e^{dis}(t) \quad \forall\ t \tag{29}$$

$$0 \le B_h^{ch}(t) + B_h^{dis}(t) \le 1 \quad \forall\ t \tag{30}$$

3.4- Mathematical approach of $MOF\text{-}EH_{MC}^{soco}$: two-level optimization

The steps of this method to solve the proposed optimization problem are as follows [24]:

Step 1: The first objective function is solved to obtain the optimal value of $\{f_1^{\text{MOF-EH}_{\text{MC}}^{\text{soco}}} = \alpha_1^*\}$

Step 2: $\{f_1^{\text{MOF-EH}_{\text{MC}}^{\text{soco}}} = \alpha_1^*\}$ is then applied as a constraint to the second objective function to obtain the optimal value of $\{f_2^{\text{MOF–EH}_{\text{MC}}^{\text{soco}}} = \alpha_2^*\}$.

A two-level optimization problem is formulated as follows:

$$\begin{aligned} &\text{Min } \left\{ f_1^{\text{MOF-EH}_{MC}^{soco}} + eps \times s_2 / r_2 \right\} \qquad \forall s \in R^+, \forall eps \in \left\{10^{-6}, 10^{-3}\right\} \\ &s.t.: \\ &f_2^{MOF-EH_{MC}^{soco}} + s_2 = e_2 \end{aligned} \tag{31}$$

3.5- Uncertainties modeling of the proposed $MOF\text{-}EH_{MC}^{soco}$ framework

3.5.1- EH demand and wind power uncertainties

In the following, the distribution functions used are described and the Monte Carlo method is used to generate wind power scenarios and thermal/electrical demand. In this paper, the Weibull distribution function for modeling wind power is considered [37]:

$$f(v,c,k)=\left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{k-1}\exp^{-\left(\frac{v}{c}\right)^{k}} \quad \forall \quad v\geq 0 \tag{32}$$

To simulate the behavior of the thermal/electrical demand, the Gaussian distribution function is used as:

$$PDF(d)=\frac{1}{\sqrt{2\pi\sigma_d^2}}\exp\left[-\frac{(d-u_d)^2}{2\sigma_d^2}\right] \tag{33}$$

The generated wind power is calculated by Eq (34) after selecting the appropriate scenario for wind speed.

$$p_e^W=\begin{cases}0 & \forall\ \ 0\leq v\leq v_{ci}\\ P_{rated}(v-v_{ci})/(v_{rated}-v_{ci}) & \forall\ \ v_{ci}\leq v\leq v_{rated}\\ P_{rated} & \forall\ \ v_{rated}\leq v\leq v_{co}\\ 0 & \forall\ \ v_{co}\leq v\end{cases} \tag{34}$$

3.5.2- Probabilistic–possibilistic uncertainty modeling of GPU

The gas pressure (GP) entering the EH can be at its best (the highest pressure), or in some cases it may get out of this condition and the gas network may face a pressure drop. The uncertainty modeling of these states based on the Z-number [38] method is considered a fuzzy set and its probability of occurrence. To determine discrete levels of gas pressure entering the EH, the k-means algorithm and dun index are used, which are clustering tools in data mining and clustering quality evaluation index, respectively. Based on the aforementioned, the amount of network gas pressure is classified into three different levels. In addition, based on Eq (35) and Figure 2, probabilistic fuzzy sets at three different levels have been proposed for Z-number modeling. After this step, the obtained Z set can be displayed as the model presented in (37-a) -(37-i) [17].

$$\tilde{A}_G^P = \left\{ \begin{array}{ll} \tilde{A}_1 = (\alpha_1, \alpha_2, \alpha_3) & \forall \{\gamma = Low\ Gas\ Pressure,\ gp_{min} < \alpha_1 < \alpha_2 < \alpha_3 < \alpha_4\} \\ \tilde{A}_2 = (\alpha_2, \alpha_3, \alpha_4, \alpha_5) & \forall \{\gamma = Medium\ Gas\ Pressure,\ \alpha_1 < \alpha_2 < \alpha_3 < \alpha_4 < \alpha_5 < \alpha_6\} \\ \tilde{A}_3 = (\alpha_4, \alpha_5, \alpha_6) & \forall \{\gamma = High\ Gas\ Pressure,\ \alpha_1 < \alpha_2 < \alpha_3 < \alpha_4 < \alpha_5 < \alpha_6 < gp_{max}\} \end{array} \right\} \tag{35}$$

$$\tilde{R}_G^P = \left\{ \begin{array}{ll} \tilde{R}_1 = (\beta_1, \beta_2, \beta_3) & \forall \{\partial = Not\ sure,\ 0 < \beta_1 < \beta_2 < \beta_3 < \beta_4\} \\ \tilde{R}_2 = (\beta_2, \beta_3, \beta_4, \beta_5) & \forall \{\partial = Almost\ certainly,\ \beta_1 < \beta_2 < \beta_3 < \beta_4 < \beta_5 < \beta_6\} \\ \tilde{R}_3 = (\beta_4, \beta_5, \beta_6) & \forall \{\partial = Quite\ sure,\ \beta_1 < \beta_2 < \beta_3 < \beta_4 < \beta_5 < \beta_6 < 1\} \end{array} \right\} \tag{36}$$

$$gp_1^Z(t) = (Low\ Gas\ Pressure,\ Not\ sure) = (\tilde{A}_1,\ \tilde{R}_1) \tag{37-a}$$

$$gp_2^Z(t) = (Low\ Pressure,\ Almost\ certainly) = (\tilde{A}_1,\ \tilde{R}_2) \tag{37-b}$$

$$gp_3^Z(t) = (Low\ Gas\ Pressure,\ Quite\ sure) = (\tilde{A}_1,\ \tilde{R}_3) \tag{37-c}$$

$$gp_4^Z(t) = (Medium\ Gas\ Pressure,\ Not\ sure) = (\tilde{A}_2,\ \tilde{R}_1) \tag{37-d}$$

$$gp_5^Z(t) = (Medium\ Gas\ Pressure,\ Almost\ certainly) = (\tilde{A}_2,\ \tilde{R}_2) \tag{37-e}$$

$$gp_6^Z(t) = (Medium\ Gas\ Pressure,\ Quite\ sure) = (\tilde{A}_2,\ \tilde{R}_3) \tag{37-f}$$

$$gp_7^Z(t) = (High\ Gas\ Pressure,\ Not\ sure) = (\tilde{A}_3,\ \tilde{R}_1) \tag{37-g}$$

$$gp_8^Z(t) = \left(High\ Gas\ Pressure,\ Almost\ certainly\right) = (\tilde{A}_3,\ \tilde{R}_2) \tag{37-h}$$

$$gp_9^Z(t) = \left(High\ Gas\ Pressure,\ Quite\ sure\right) = (\tilde{A}_3,\ \tilde{R}_3) \tag{37-i}$$

By Eq (38), the probabilistic part of the Z-number is converted to a deterministic number and then this value is combined with the fuzzy part. The final result is converted from non-standard to standard mode using equation (39) as shown in Figure 3. Finally, the centroid method is considered to fuzzified and obtain the final gas pressure.

$$\gamma = \frac{\int_{-\infty}^{+\infty} gp\,\mu_{\tilde{R}}(gp)dgp}{\int_{-\infty}^{+\infty} \mu_{\tilde{R}}(gp)dgp} \tag{38}$$

$$\mu(gp) = \gamma\mu_{\tilde{R}}(gp) \tag{39}$$

Figure 4 shows the steps of using Z-number to model GPU and the relationship between gas pressure and uncertainty can be modeled as follows:

$$p_g^{NET\,Z-number}(t) = gp^Z(\mathrm{t})g(t)' \tag{40}$$

4. Simulation results

In this section, the proposed flexibility index has been implemented in a plenary case study to prove the proficiency and effectiveness of the presented model. The proposed EH includes a CHP, a boiler, converters, and transformers to convert different types of energy. The EH is powered by gas and electricity from the upstream network to supply the electricity, gas, and heating demand. To investigate the fluctuations in the EH flexibility due to uncertain resources, the presence of DRPs, and energy storage and construction, four case studies are defined. The results of these case studies are compared and analyzed based on operation costs, construction and flexibility. The differences between all studied cases and their purposes are listed in Table 2. According to this table, in the last case, the EH optimization has been implemented by two objectives. Furthermore, reducing EH operation/construction costs and enhancement of EH flexibility have been considered distinct goals.

Thermal, electric, and gas demand, electricity price, and other EH information are given in Figure 5 and Figure 6. Wind speed, wind turbine and the information of the EH parameters specifications are taken from [33].

4.1. Plenary case study

As mentioned in Table 2, the plenary case study includes a CHP and a boiler. The operation cost and the flexibility value are calculated equal to 181238.1 cents and 0.717, respectively. The operation cost in [33] is 190734.8 cents, which is nearby to the operation cost of the plenary case study of this paper. Table 3 shows the results of the plenary case study. It is inferred from the results that at time steps, the CHP is generating at its maximum capacity and is being used as the main source of electricity and heat generation because imported gas from the upstream network has a lower price than the price of electricity. Electrical exchange via the upstream network has negative values from $t=1$ to $t=7$, which is due to the sale of the electricity generated by the CHP to the upstream network. From $t=19$ to $t=21$, the electrical demand and from $t=10$ to $t=19$, the heat demand is not supplied by the EH, which indicates the low reliability of this case. During these time steps, the operation costs increase due to the imposed penalties.

4.2. Case study 1

In this section, the wind turbine is added to the plenary case. As a result, electrical demand is supplied by the CHP, upstream network, and wind power. Results compared to the base model demonstrate that the system reliability has increased and electrical ENS has improved slightly. The amount of thermal ENS has ameliorated by a small amount as much as 10 KW. In this case, the operation costs are 151353.7 cents, which is less than the previous case. It is noteworthy that adding wind power to the EH with uncertainties has a great impact on reducing operation costs. Furthermore, it has a significant effect on EH flexibility. In this case, the flexibility value has been reduced to 0.602. The Optimal results of case study 1 are presented in Table 4.

4.3. Case study 2

Thermal/electrical DR programs' [33] effects on the EH flexibility have been investigated in this part. Also, the effects of these resources on operation costs and reliability are analyzed. According to the results from *t=13* to *t=21*, when the electricity demand is higher than other hours, the DRP has mostly shifted the electrical load to *t=1-12* period. The results obtained from the EH show that at *t= 4*, *9*, and *19*, there was a thermal load shift towards *t=21*, which reduced the operation costs. It should be noted that the electrical/thermal ENS has been reduced to zero, so in this case, the EH reliability is improved. The total operation costs are 138392.7 cents, which is lower than the previous cases. The EH flexibility has increased to 0.630 compared to the previous case, but the presence of DRPs has not been able to compensate for flexibility decrement due to wind power uncertainty.

4.4- Case study 3

In this case, electrical/thermal storage units have been added to the EH to study the operation costs and flexibility. Electrical/thermal ENS is equal to zero which indicates that the reliability of the system is maintained at a high level. According to Table 5 and Table 6 from *t=3* to *t=4*, when the electricity price is low, the electrical storage is charged at the rate of 277 kW. At t=18, when the price of electricity is high, the storage begins discharging. On the other hand, the thermal storage is charged at *t=1*, *t=18*, and discharged at *t=19*. The presence of thermal and electrical storage has reduced operation costs to 131887.2 cents. Although flexibility has increased to 0.694, storage and DRPs are incapable of covering the flexibility decrement caused by wind power uncertainties.

4.5- Case study 4

In this case, the simultaneous operation/construction of the EH to increase flexibility has been examined. Since improving the flexibility index is in conflict with reducing operation/construction costs, it is considered a separate goal. Finally, concerning Figure 7 and Figure 8 Pareto fronts, the proposed EH flexibility is analyzed.

The proposed hub structure in case 4 can increase the CHP and the boiler capacity to 500 kWh and 2500 kWh, respectively. The purpose of this framework is to examine the effect of construction on EH flexibility. According to Figure 7 and Figure 8, it is observed that when the $MOF\text{-}EH_{MC}^{soco}$ framework has increased the CHP or the boiler capacity, the system flexibility has increased, but on the other hand, the construction costs are increased. It can be interpreted from the performed analysis that flexibility enhancement is directly related to construction cost increment.

According to Figure 7 Pareto front, at a point where the total operation and construction cost is at the minimum and equal to 152000 cents, the EH flexibility value is 0.7016. Moreover, at a point where the total operation and construction cost is at the maximum level, i.e. equal to 62615069 cents, the flexibility value is 0.8009. The results clearly show an increase in the EH flexibility with respect to the construction cost. According to the Figure 8 Pareto front, when GPU is modeled, CHP and boiler cannot operate at their maximum capacity due to the reduced gas capacity of the EH. Furthermore, the flexibility of the EH has reached 0.785, which has decreased by 2% compared to Figure 7.

The impact of flexible resources on the system flexibility index is shown in Figure 9, which shows that the CHP has the lowest effect on flexibility. CHP is generating at its maximum capacity from the first to the third case, as a result, the share of the CHP in the system flexibility is zero, and the majority of the EH flexibility is provided by the boiler. Due to the employment of storage devices and DRPs, the dependence of EH flexibility on the boiler has gone down to 18% in the third case. Although the presence of these resources has improved the flexibility of the EH, the share of CHP is still zero. In the last case, it is shown that when the construction increases the capacity of the CHP, its participants in the EH flexibility go up to 14%, and a greater balance is created in the flexibility contribution of resources. Finally, it should be noted that the two parts of the set of Z-numbers for gas pressure are presented in Figures 10 and 11. The results of all cases are summarized in Table 7. The result of the base case of [33] is also presented in Table 7 to emphasize the validity of the result.

5. Conclusion

In this paper, an integrated framework including the simultaneous construction and operation of the energy hub with the approach of improving flexibility is presented. The flexibility index considered in this manuscript evaluates the system flexibility quantitatively according to the EH available free capacity and the rate of deploying this capacity. To make the proposed model more realistic a possibilistic/probabilistic Z-number method has been utilized to model the EH's GPU. In various scenarios, the shares of the factors affecting the EH flexibility such as CHP, boiler, EDRP, TDRP, ESS, and TSS are demonstrated in percentage. Moreover, simultaneous construction and operation scheduling proved to be the most effective solution for flexibility improvement in this framework. The results show that simultaneous construction/operation can improve the EH flexibility and compensate the flexibility deficiency caused by the presence of uncertain wind resources. In this paper, it is demonstrated that wind resource reduces the flexibility level in such a way that even utilization of the demand response programs and energy storage cannot fill this gap. This method proved to enhance the decreased flexibility -due to the wind power uncertainty- by 32%. It's worth mentioning that DRPs and ESS/TSS have increased system flexibility and reduced operation costs. The results of the carried-out analysis show that increasing flexibility leads to increased construction costs and reduced operation costs. Employing storage devices and demand response programs have a total share of 14% in flexibility provision. Although the CHP generates at its maximum capacity at all time steps, and its participation in flexibility has been zero, the simultaneous construction and operation method with a flexibility approach has made the role of the CHP in flexibility go up 14%. Furthermore, the boiler has the biggest share in the EH flexibility value. Furthermore, future work can consider the impact of other resources with high ramp capabilities, on the EH flexibility level.

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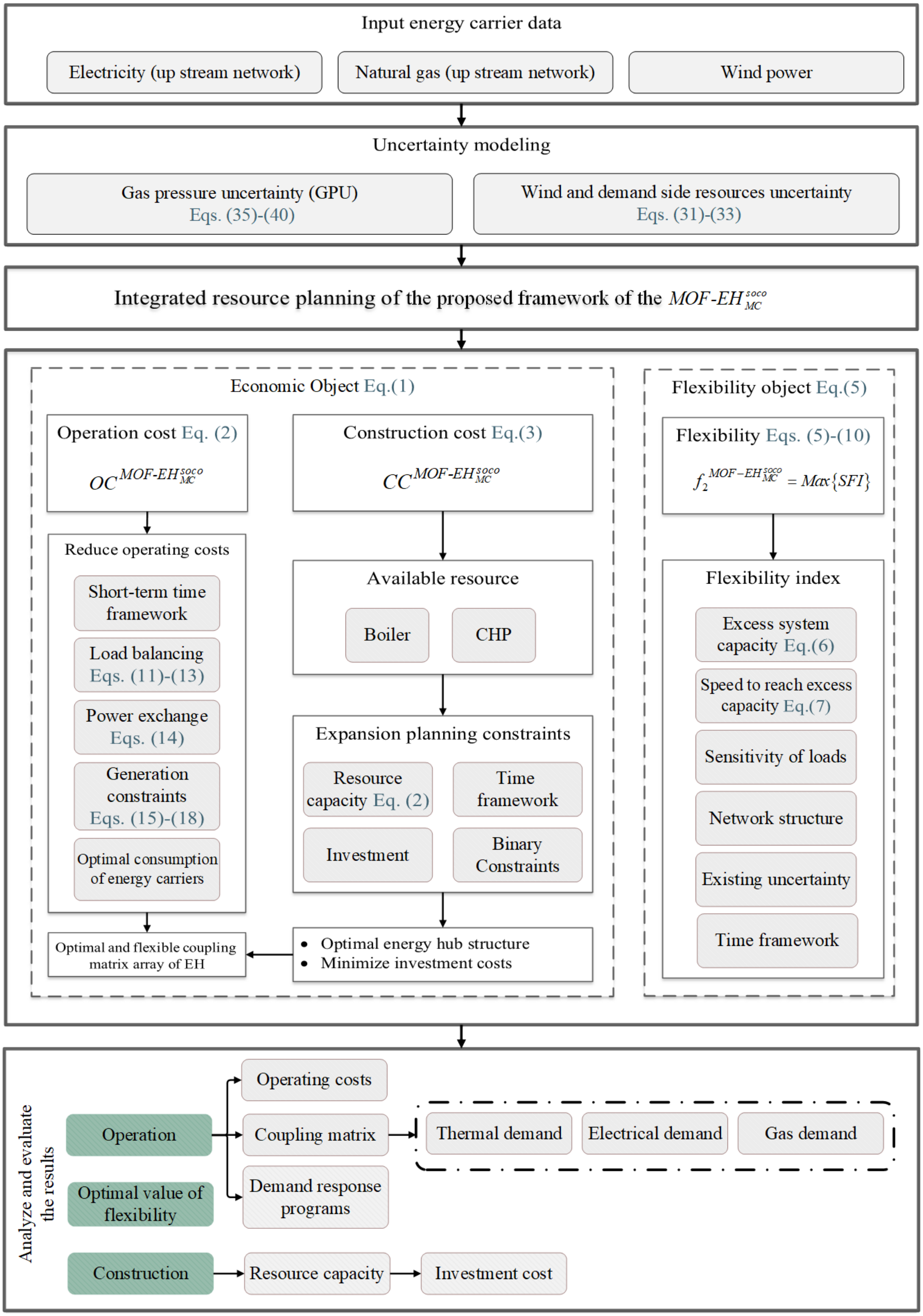
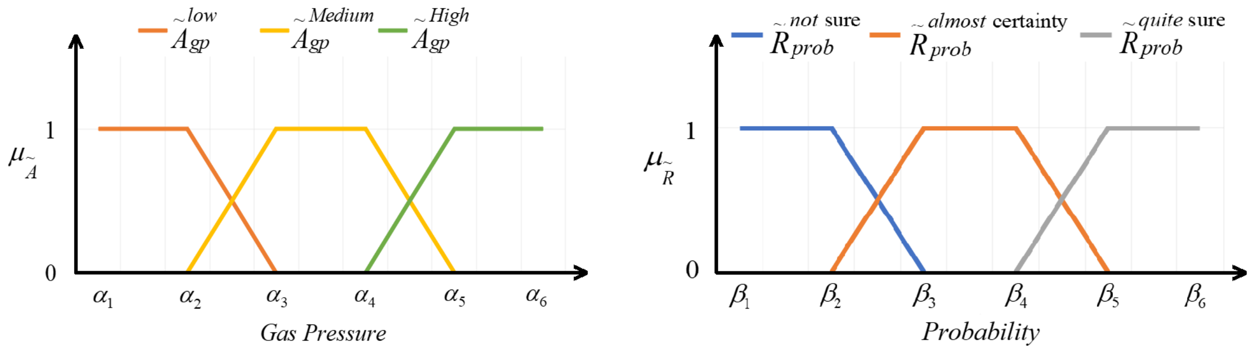
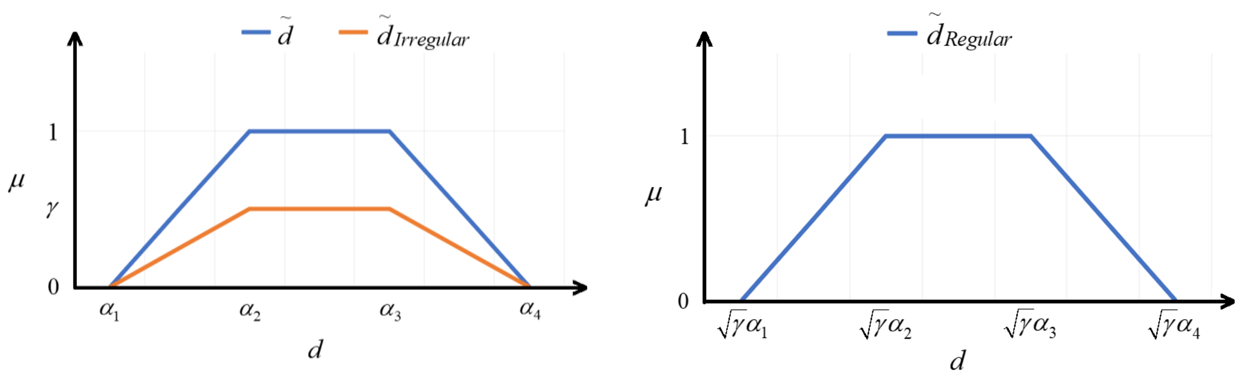


Figure 1. Framework of implementing proposed $\text{MOF-EH}_{\text{MC}}^{\text{soco}}$



(a) (b)

Figure 2. Gas pressure level (a) and probability modeling of gas pressure level (b) in the Z-number method



(a) (b)

Figure 3. Regulation of fuzzy number process

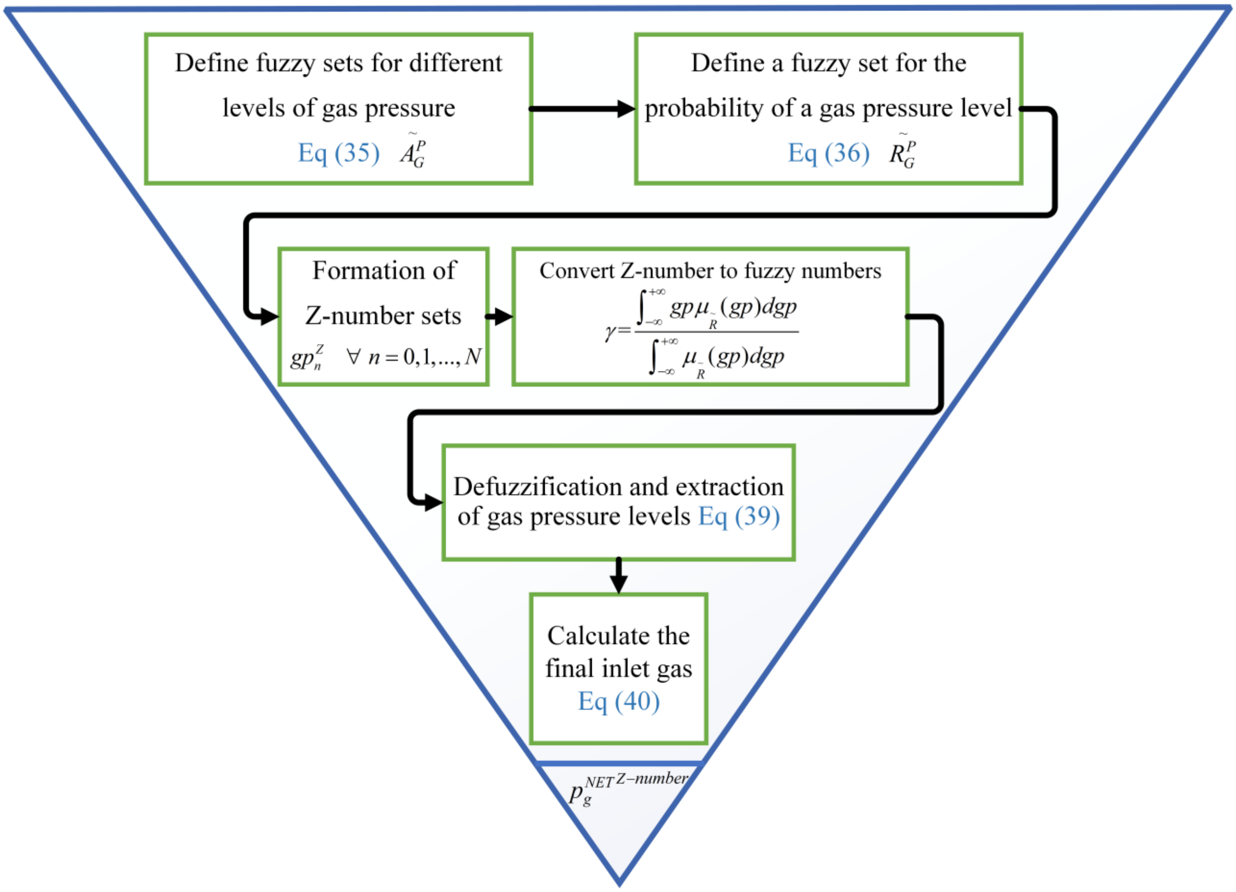


Figure 4. GPU modeling process using Z-number

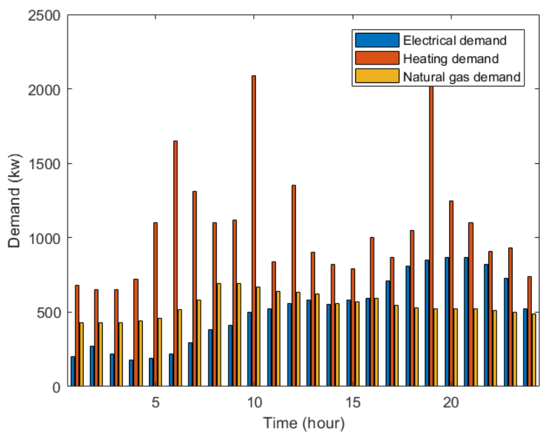


Figure 5. Thermal, electrical, and gas demand [33]

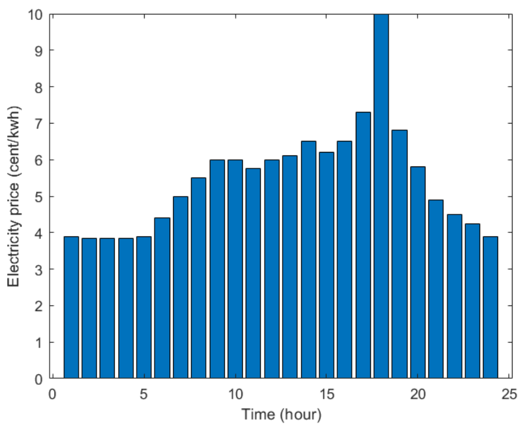


Figure 6. Electricity price [33]

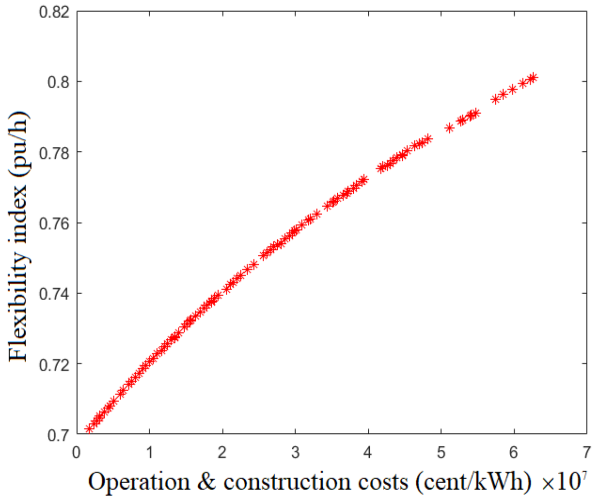


Figure 7. Pareto front of $MOF\text{-}EH_{MC}^{soco}$ problem without GPU

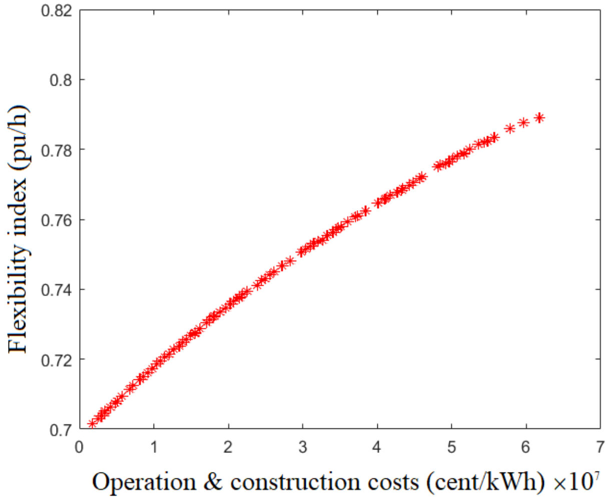
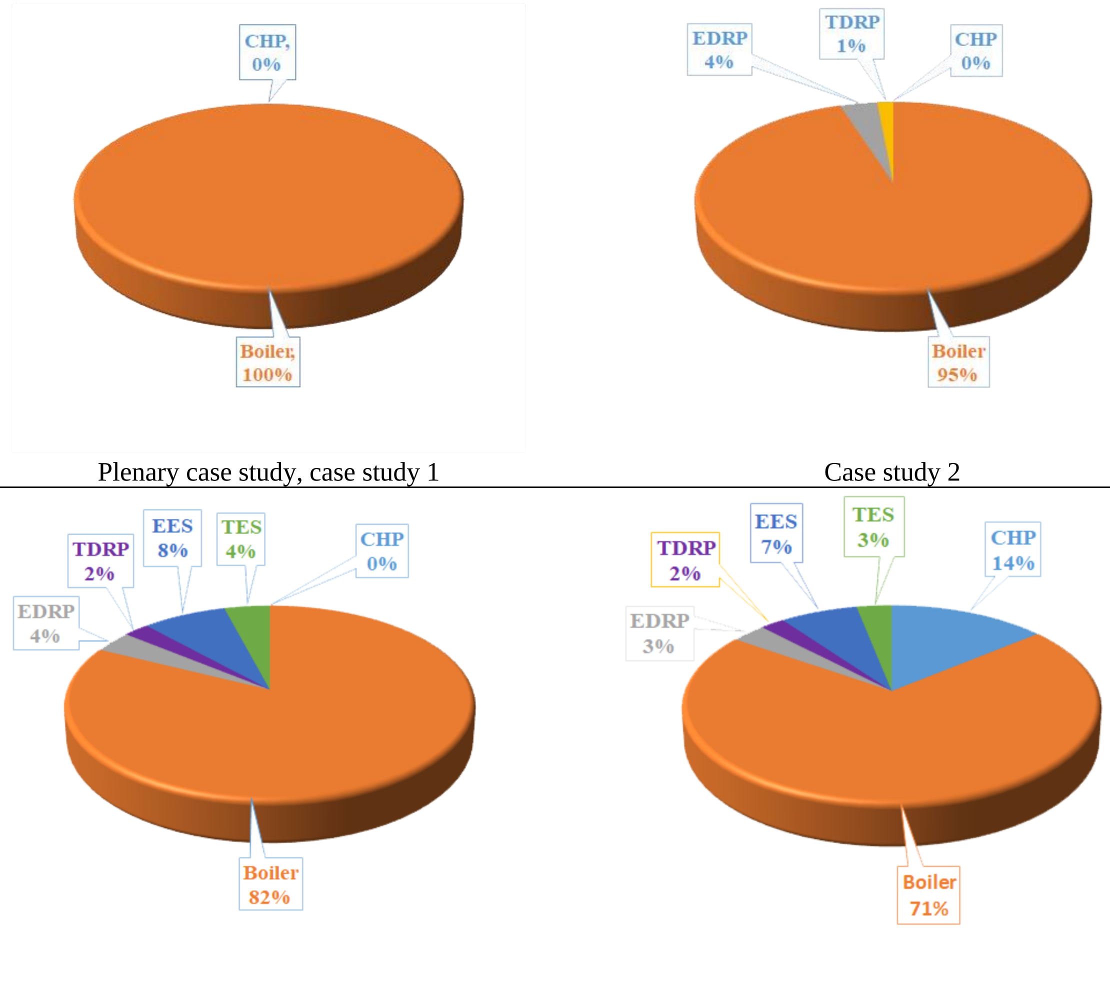


Figure 8. Pareto front of $MOF\text{-}EH_{MC}^{soco}$ problem under GPU



Plenary case study, case study 1 | Case study 2

Case study 3 | Case study 4

Figure 9. Share of flexible resources on EH flexibility provision

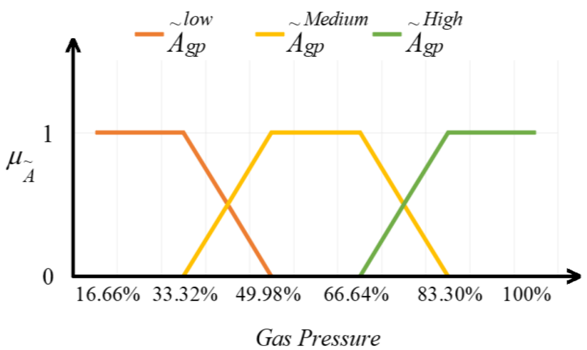


Figure 10. Defined Z-number fuzzy sets for gas pressure

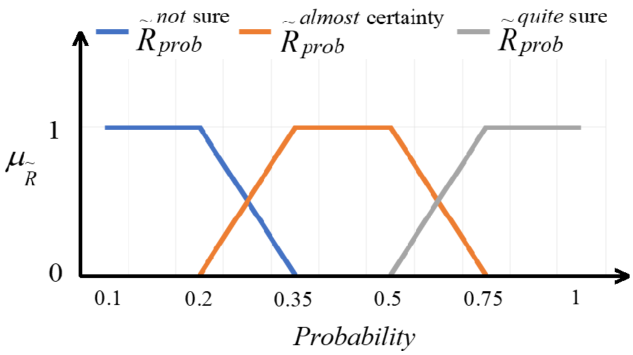


Figure 11. Defined Z-number probabilistic sets for gas pressure

Nomenclature		p^{Tr}	Transformer capacity [KW]
		p^{B}	Boiler capacity [KW]
Indexes:		q_e^{DR}	Demand response operation cost
i	Index of the generation unit	q_h^{ENS}	Cost of heating energy not supplied [¢/KWh]
T	Time [Hour]	$q_e^{N}(t)$	Electricity price [hour]
t	Index of time [Hour]	q_e^{S}	Electrical storage operation cost [¢/KWh]
Acronyms:		q_e^{W}	Produced wind power cost [¢/KWh]
B	Boiler	q_g^{N}	Gas price [¢/KWh]
C	Converter	q_h^{S}	Thermal storage operation cost [¢/KWh]
ch/dis	Charge/Discharge	$\tilde{R}_G^{P}$	Fuzzy set for the probability of a gas pressure level
DRP	Demand response program	u_e^{N}	Availability of electricity network
e	Electricity	u^{CHP}	Availability of CHP
ed	Electrical demand response program	η_e^{ch}/η_e^{dis}	Electrical storage charge/discharge efficiency
$EDRP$	Electrical	η_h^{ch}/η_h^{dis}	Thermal storage charge/discharge efficiency
ESS	Electrical storage system	η_C	Converter electrical efficiency
es	Electrical storage	η_{Tr}	Transformer electrical efficiency
g	Gas	η_{eCHP}	CHP gas to electricity efficiency
gd	Gas demand	η_{hCHP}	CHP heat to electricity efficiency
GPU	Gas pressure uncertainty	η_B	Boiler gas to heat efficiency
h	Heat	***Variables:***	
hd	Heating demand	gp^{Z}(t)	Uncertain gas pressure for each time
hs	Heating storage	$OC^{MOF\text{-}EH_{MC}^{soco}}$	The operation cost of a problem
NG	Natural gas	$p_e^{ch}(t)/p_e^{dis}(t)$	Charged/Discharged power of electrical storage [KWh]
$QFEH$	Quantitative flexibility of energy hub	$p_e^{ENS}(t)$	Electrical energy not supplied [KWh]
RES	Renewable energy system	$p_e^{W^{Scenario/reduction}}$	Wind power after scenario reduction [KWh]
$SOCO$	Simultaneous operation and construction optimization	q_e^{ENS}	Cost of electricity energy not supplied [¢/KWh]
$TDRP$	Thermal demand response program	$q_e^{N}(t)$	Network power exchange [KWh]
Tr	Transformer	$p_e^{loss}(t)$	The power loss of electrical storage [KWh]
TSS	Thermal storage system	$p_e^{S}(t)$	The electrical storage power level [KWh]

ut	Unexpected event occurrence	$p_e^{shup}(t)/p_e^{shdo}(t)$	Shifted up/down power by demand response [KWh]
WT	Wind turbine	$p_g^{NCHP}(t)$	CHP purchased gas from the network [KWh]
A_e^{loss}	Electrical storage loss efficiency	$p_g^{NB}(t)$	Boiler purchased gas from the network [KWh]
A_h^{loss}	Thermal storage loss efficiency	$p_g^{NET^{Z\text{-}number}}(t)$	Uncertain inlet gas pressure to the energy hub [KWh]
A_e^{min}/A_e^{max}	Electrical storage min/max factor	$p_h^{ch}(t)/p_h^{dis}(t)$	Thermal storage charged/discharged power[KWh]
A_h^{min}/A_h^{max}	Thermal storage min/max factor	$p_h^{loss}(t)$	The power loss power of thermal storage [KWh]
$\tilde{A}_G^P$	Fuzzy sets for different levels of gas pressure	$p_h^S(t)$	The thermal storage power level [KWh]
Cap_n	The capacity of each unit	$p_e^{CHP}(t)$	CHP electricity generated [KWh]
CC	The construction cost of the problem	$p_h^{CHP}(t)$	CHP heat generated [KWh]
$C_{(i,t,ut)}^a$	Accessible capacity for each unit	$p_h^B(t)$	Boiler Heat generated [KWh]
IC_n	Investment cost of unit n	$p_{(i,t)}^*$	Generators' initial set point [KWh]
p^{CHP}	CHP capacity [KW]	p_i^{max}	maximum generation level [KWh]
$p_{ed}(t)$	Electricity demand [KWh]	SFI	System flexibility index [pu/h]
$p_{gd}(t)$	Gas demand [KWh]	$SMACI$	System maximum accessible capacity index [KWh]
$p_{hd}(t)$	Heat demand [KWh]	SRT	System response time [hour]
p_e^{Nmax}	Electricity network maximum capacity [KW]	***Binary Variables:***	
p_g^{Nmax}	Gas network maximum capacity [KW]	$B_e^{ch}(t)/B_e^{dis}(t)$	Electrical storage charge/discharge state binary variable
p_e^{sc}	Electrical storage capacity [KW]	$B_h^{ch}(t)/B_h^{dis}(t)$	Thermal storage charge/discharge state binary variable
p_e^{sc}	Thermal storage capacity [KW]	$B_e^{shup}(t)/B_e^{shdo}(t)$	Electricity demand shift up/down binary variable

Table 1. An overview of previous work and the present paper

References	EH technologies					DRP		Optimization		Uncertainty	Flexibility
	CHP	Boiler	WT	ESS	TSS	EDRP	TDRP	Construction	Operation	GPU	QFEH
[1]	√	–	–	–	–	–	–	–	√	–	–
[2]	√	√	–	√	–	–	–	√	√	–	–
[3]	√	√	√	√	√	√	–	√	√	–	–
[4]	√	–	–	√	–	–	–	–	√	–	–
[6]	√	√	√	√	√	–	–	–	√	–	–
[7]	√	–	√	√	–	–	–	–	√	–	–
[8]	√	√	–	√	–	–	–	–	√	–	–
[9]	√	–	–	√	√	√	–	–	√	–	–
[10]	√	√	√	√	√	√	–	–	√	–	–
[27]	–	√	√	√	√	√	–	–	√	–	–
[28]	√	–	–	√	–	–	–	–	√	–	–
[29]	√	–	–	√	–	–	–	√	√	–	–
[30]	√	√	–	√	√	√	–	√	√	–	–
[31]	√	√	√	√	√	–	–	–	√	–	–
[32]	√	√	–	√	√	–	–	√	√	–	–
[33]	√	√	√	√	√	√	√	√	√	–	–
[34]	√	√	–	√	√	√	–	–	√	–	–
Proposed Structure $MOF\text{-}EH_{MC}^{soco}$	√	√	√	√	√	√	√	√	√	√	√

Table 2. Structure & results of the studied cases

Case studies	Flexibility resources				DRP		Optimization		Uncertainty		Flexibility
	CHP	Boiler	ESS	TSS	EDRP	TDRP	Operation	Construction	GPU	WT	QFEH
Plenary case study	√	√	–	–	–	–	√	–	–	–	√
Case study 1	√	√	–	–	–	–	√	–	–	√	√
Case study 2	√	√	–	–	√	√	√	–	–	√	√
Case study 3	√	√	√	√	√	√	√	–	–	√	√
Case study 4	√	√	√	√	√	√	√	√	√	√	√

Table 3. Optimal results of the plenary case study

t	P_e^N (KWh)	P_e^{CHP} (KWh)	P_e^{ENS} (KWh)	P_g^N (KWh)	P_g^{NB} (KWh)	P_g^{NCHP} (KWh)	P_h^B (KWh)	P_h^{CHP} (KWh)	P_h^{ENS} (KWh)
1	-111.111	300	0	1671.177	491.1765	750	417.5	262.5	0
2	-33.3333	300	0	1635.882	455.8824	750	387.5	262.5	0
3	-88.8889	300	0	1635.882	455.8824	750	387.5	262.5	0
4	-133.333	300	0	1730.235	538.2353	750	457.5	262.5	0
5	-122.222	300	0	2195.294	985.2941	750	837.5	262.5	0
6	-88.8889	300	0	2897.353	1632.353	750	1387.5	262.5	0
7	-5.55556	300	0	2562.353	1232.353	750	1047.5	262.5	0
8	88.88889	300	0	2425.294	985.2941	750	837.5	262.5	0
9	122.2222	300	0	2448.824	1008.824	750	857.5	262.5	0
10	222.2222	300	0	3537.647	2117.647	750	1800	262.5	27.5
11	244.4444	300	0	2069.412	679.4118	750	577.5	262.5	0
12	288.8889	300	0	2664.412	1279.412	750	1087.5	262.5	0
13	311.1111	300	0	2130.882	755.8824	750	642.5	262.5	0
14	277.7778	300	0	1965.882	655.8824	750	557.5	262.5	0
15	311.1111	300	0	1940.588	620.5882	750	527.5	262.5	0
16	327.7778	300	0	2207.647	867.6471	750	737.5	262.5	0
17	455.5556	300	0	2009.706	714.7059	750	607.5	262.5	0
18	566.6667	300	0	2206.471	926.4706	750	787.5	262.5	0
19	600	300	10	3392.647	2117.647	750	1800	262.5	137.5
20	600	300	30	2431.765	1161.765	750	987.5	262.5	0
21	600	300	25	2255.294	985.2941	750	837.5	262.5	0
22	577.7778	300	0	2021.765	761.7647	750	647.5	262.5	0
23	477.7778	300	0	2035.294	785.2941	750	667.5	262.5	0
24	244.4444	300	0	1801.765	561.7647	750	477.5	262.5	0

Table 4. Optimal results of the case study 1

t	P_e^{N} (KWh)	P_e^{CHP} (KWh)	P_e^{ENS} (KWh)	P_g^{N} (KWh)	P_g^{NB} (KWh)	P_g^{NCHP} (KWh)	P_h^{B} (KWh)	P_h^{CHP} (KWh)	P_h^{ENS} (KWh)
1	-100	289	0	1656.2	501.6	724	426.4	253	0
2	-33.3	300	0	1635.8	455.8	750	387.5	262.5	0
3	-89.8	300	0	1635.8	455.8	750	387.5	262.5	0
4	-100	270	0	1686.1	569.1	675	483.7	236.2	0
5	-100	280	0	2165.8	1005.8	700	855	245	0
6	-88.8	300	0	2897.3	1632.3	750	1387.5	262.5	0
7	-5.5	300	0	2562.3	1232.3	750	1047.5	262.5	0
8	88.8	300	0	2425.2	985.2	750	837.5	262.5	0
9	118.2	300	0	2448.8	1008.8	750	857.5	262.5	0
10	214.5	300	0	3537.6	2117.6	750	1800	262.5	27.5
11	238.6	300	0	2069.4	679.4	750	577.5	262.5	0
12	276.2	300	0	2664.4	1279.4	750	1087.5	262.5	0
13	291.9	300	0	2130.8	755.8	750	642.5	262.5	0
14	258.5	300	0	1965.8	655.8	750	557.5	262.5	0
15	291.9	300	0	1940.5	620.5	750	527.5	262.5	0
16	311.4	300	0	2207.6	867.6	750	737.5	262.5	0
17	446.1	300	0	2009.7	714.7	750	607.5	262.5	0
18	549	300	3	2206.4	926.4	750	787.5	262.5	127.5
19	600	300	22.7	3392.6	2117.6	750	1800	262.5	0
20	600	300	8	2431.7	1161.7	750	987.5	262.5	0
21	600	300	0	2255.2	985.2	750	837.5	262.5	0
22	566.8	300	0	2021.7	761.7	750	647.5	262.5	0
23	473.9	300	0	2035.2	785.2	750	667.5	262.5	0
24	244.4	300	0	1801.7	561.7	750	477.5	262.5	0

Table 5. Optimal results of the case study 3

t	P_e^N (KWh)	P_e^{CHP} (KWh)	P_e^{shdo} (KWh)	P_g^N (KWh)	P_e^{shup} (KWh)	P_h^{shdo} (KWh)	P_h^B (KWh)	P_h^{CHP} (KWh)	P_h^{shup} (KWh)
1	-66.9	300.0	0.0	1700.9	40.0	0.0	442.8	262.5	0.0
2	26.7	300.0	0.0	1791.9	54.0	0.0	520.1	262.5	0.0
3	-11.0	300.0	0.0	1635.9	44.0	0.0	387.5	262.5	0.0
4	184.4	300.0	0.0	1730.2	36.0	0.0	457.5	262.5	0.0
5	-80.0	300.0	0.0	2195.3	38.0	0.0	837.5	262.5	0.0
6	-40.0	300.0	0.0	2897.4	44.0	0.0	1387.5	262.5	262.0
7	60.0	300.0	0.0	2870.6	59.0	0.0	1309.5	262.5	0.0
8	173.3	300.0	0.0	2425.3	76.0	0.0	837.5	262.5	0.0
9	131.2	300.0	0.0	2448.8	11.5	0.0	857.5	262.5	0.0
10	325.7	300.0	0.0	3537.6	100.0	27.5	1800.0	262.5	0.0
11	354.2	300.0	0.0	2069.4	104.0	0.0	577.5	262.5	150.0
12	400.7	300.0	0.0	2841.5	112.0	0.0	1238.0	262.5	0.0
13	163.0	300.0	116.0	1917.9	0.0	181.0	461.5	262.5	0.0
14	136.4	300.0	110.0	1772.9	0.0	164.0	393.5	262.5	0.0
15	163.0	300.0	116.0	1940.6	0.0	0.0	527.5	262.5	0.0
16	179.2	300.0	119.0	2207.6	0.0	0.0	737.5	262.5	0.0
17	288.4	300.0	142.0	2009.7	0.0	0.0	607.5	262.5	210.0
18	91.2	300.0	162.0	2453.5	0.0	0.0	997.5	262.5	0.0
19	414.5	300.0	170.0	3386.8	0.0	0.0	1795.0	262.5	0.0
20	600.0	300.0	22.7	2137.6	0.0	250.0	737.5	262.5	0.0
21	600.0	300.0	8.1	2255.3	0.0	0.0	837.5	262.5	0.0
22	600.0	300.0	0.0	2021.8	29.8	0.0	647.5	262.5	0.0
23	600.0	300.0	0.0	2035.3	113.5	0.0	667.5	262.5	0.0
24	360.0	300.0	0.0	1801.8	104.0	0.0	477.5	262.5	0.0

Table 6. Optimal results of the case study 3

t	P_e^{ch} (KWh)	P_e^{dis} (KWh)	P_e^{S} (KWh)	P_h^{ch} (KWh)	P_h^{dis} (KWh)	P_h^{S} (KWh)	P_g^{NB} (KWh)	P_g^{NCHP} (KWh)
1	0.0	0.0	0.0	25.2	0.0	24.0	520.9	750
2	0.0	0.0	0.0	0.0	0.0	24.0	611.9	750
3	27.0	0.0	25.7	0.0	0.0	24.0	455.9	750
4	250.0	0.0	263.2	0.0	0.0	24.0	538.2	750
5	0.0	0.0	263.2	0.0	0.0	24.0	985.3	750
6	0.0	0.0	263.2	0.0	0.0	24.0	1632.4	750
7	0.0	0.0	263.2	0.0	0.0	24.0	1540.6	750
8	0.0	0.0	263.2	0.0	0.0	24.0	985.3	750
9	0.0	0.0	263.2	0.0	0.0	24.0	1008.8	750
10	0.0	0.0	263.2	0.0	0.0	24.0	2117.6	750
11	0.0	0.0	263.2	0.0	0.0	24.0	679.4	750
12	0.0	0.0	263.2	0.0	0.0	24.0	1456.5	750
13	0.0	0.0	263.2	0.0	0.0	24.0	542.9	750
14	0.0	0.0	263.2	0.0	0.0	24.0	462.9	750
15	0.0	0.0	263.2	0.0	0.0	24.0	620.6	750
16	0.0	0.0	263.2	0.0	0.0	24.0	867.6	750
17	0.0	0.0	263.2	0.0	0.0	24.0	714.7	750
18	0.0	250.0	0.0	132.6	0.0	150.0	1173.5	750
19	0.0	0.0	0.0	0.0	142.5	0.0	2111.8	750
20	0.0	0.0	0.0	0.0	0.0	0.0	867.6	750
21	0.0	0.0	0.0	0.0	0.0	0.0	985.3	750
22	0.0	0.0	0.0	0.0	0.0	0.0	761.8	750
23	0.0	0.0	0.0	0.0	0.0	0.0	785.3	750
24	0.0	0.0	0.0	0.0	0.0	0.0	561.8	750

Table 7. Different Case study SFI, operation, and construction costs

	SFI (pu/h)	Operation (¢)	Construction (¢)
Base case: [33]	–	190734.8	–
Plenary case study	0.717	181238.1	–
Case study 1	0.602	151353.7	–
Case study 2	0.630	138392.7	–
Case study 3	0.694	131887	–
Case study 4	0.8009	131854	62483215