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Flexibility-Constrained Energy Management of Smart Energy Hubs Considering Peer to Peer Transactive Energy and Demand Response program

Ali Riki | Mahmoud Oukati Sadegh | Omid Narouei

Faculty of Engineering, University of Sistan and Baluchestan, Zahedan, Iran.[1,2,3]
Corresponding author's email: oukati@ece.usb.ac.ir

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ABSTRACT

The concept of an energy hub (EH) has been utilized to address the issue of performing concurrent operations of various energy generation and transmission infrastructures. This subject is exceedingly respected within the field of microgrids (MG). One of the primary concerns for investors is the efficient utilization of EH to effectively manage energy carriers, particularly in transactions with the upstream grid. In this paper the proposed smart energy hubs (SEH) manage dispatchable generation, i.e. Combined Cooling, Heat, and power (CCHP), and non-dispatchable generation, i.e. Photovoltaic (PV). SEHs consider Ice Storage Conditioner (ISC) as well as Thermal Energy Storage System (TESS) as the Energy Storage System (ESS). To mitigate dependence on gas and electricity utility companies, a peer-to-peer (P2P) energy sharing strategy has been executed. The implementation of demand response (DR) is directed toward shiftable electrical loads. The thermodynamic model of heating and cooling loads is developed with flexibility as integrated demand response (IDR) based on the desired temperature. The objective of optimization is to minimize operation and environmental costs subjected to numerous technical constraints. The flexibility constraint serves in particular to enhance the flexibility of the interrelationships between MG and the upstream network. The suggested model incorporates the probabilistic nature of PV generation as well as the electrical, thermal, and cooling demands in various scenarios. The proposed model is a Mix Integer Non-Linear Problem (MINLP), which was solved using SCIP solver in GAMS software. Implementation of the proposed framework on the typical EHs shows the impact of P2P transactive energy and flexibility constraint performance on elements such as operation costs, emissions and flexibility of the system.

Sets		$P^{ch}_{EES}(h,t,s)$	Real power charged by EES (kW).
H	Set of hubs.	$P^{EC}(h,t,s)$	Electrical power consumed by EC unit (kW).
T	Set of hours in the operation period.	$H^{HRU}(h,t,s)$	Thermal power generated by HRU (kW).
S	Set of scenarios.	$P^{dis}_{TESS}(h,t,s)$	Thermal power discharged by TESS (kW).
$j \in H$	Subset of hubs.	$H^{AC}(h,t,s)$	heating power consumed by AC unit (kW).
Variables		$P^{ch}_{TESS}(h,t,s)$	Thermal power charged by TESS (kW).
$P^{PGU}_{gas}(h,t,s)$	Gas purchased from gas grid fired by PGU (kW).	$P^{L}(h,t,s)$	Electric loads before DR (kW).
$P^{AB}_{gas}(h,t,s)$	Gas purchased from gas grid fired by AB (kW).	$\overline{H}^{air},\underline{H}^{air}$	upper/lower bound of indoor heat (kW).
$P^{PGU}_{e}(h,t,s)$	Real power generated by PGU (kW).	$\overline{H}^{ws},\underline{H}^{ws}$	upper/lower bound of hot water (kW).
$H^{AB}(h,t,s)$	Thermal power generated by AB	$\overline{C}^{air},\underline{C}^{air}$	upper/lower bound of injected cooling power

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	(kW).		(kW).
Parameters		α_s	Parameter of the Beta PDF.
$\rho(s)$	Probability of occurrence of the scenario s.	μ_s	Mean of forecasted solar irradiance (kW/m2).
$\rho_e(h,t)$	Electricity price "sell and purchase" ($/kWh).	σ_s	Standard deviation of forecasted solar irradiance (kW/m2).
$\rho_g(h,t)$	Gas price ($/kWh).	η^{pv}	Efficiency of PV module.
$\eta_e^{PGU}(h)$	Efficiency for electricity generation for co-product heat of PGU.	S^{pv}	Area of PV module (m2).
$\eta_h^{AB}(h)$	Efficiency for heat generation of AB.	η^{sol}	Efficiency of PV module.
$\varphi_{in}(h)$	Equivalent emission coefficients for electricity (kg/kWh).	μ_d	Standard deviation of forecasted demands (kW).
$\varphi_g(h)$	Equivalent emission coefficients for natural gas (kg/kWh).	$\eta^{TRA}(h)$	Efficiency of transformer.
ρ^{EDR}	compensation price of Electrical DR.	$K^{ISC}(h)$	Performance coefficient of ISC.
ρ^{HairDR}	compensation price of indoor heating DR.	$K^{AC}(h)$	Performance coefficient of AC.
ρ^{CDR}	compensation price of cooling DR.	**Abbreviations**	
$\overline{P}_{ESS}^{ch}, \overline{P}_{ESS}^{dis}$	Maximum real power charged /discharged by ESS (kW).	DR	Demand response
$\eta_{ESS}^{ch}(h)$	Charging efficiency of ESS.	SEH	Smart energy hub
$\eta_{ESS}^{dis}(h)$	Discharging efficiency of ESS.	CCHP	Combined Cooling, Heat, and power
$\overline{E}^{EES}(h)$	Maximum energy in ESS (kWh).	ISC	Ice Storage Conditioner
$\underline{P}_{PGU}, \overline{P}_{PGU}$	Minimum/Maximum allowable real power generated by PGU unit (kW).	TESS	Thermal energy storage system
$\underline{H}_{HRU}, \overline{H}_{HRU}$	Minimum/Maximum allowable thermal power generated by HRU unit (kW).	ESS	Energy Storage System
$\overline{H}_{AB}(h)$	Maximum allowable thermal power generated by AB (kW).	IDR	Integrated Demand Response
$\overline{H}_{AC}(h)$	Maximum allowable cooling power generated by AC (kW).	MINLP	Mixed Integer Non-linear Program
$\overline{P}^{ELE}(h)$	Maximum real power imported from the upstream grid after transformer (kW).	P2P	Peer-To-Peer
$f_b(si)$	Beta PDF of si.	MES	Multi-energy systems
si	Solar irradiance (kW/m2).	DG	Dispatchable generation
MGO	Micro grid operator	EV	Electrical Vehicle
RES	Renewable energy sources	QPSO	Quantum Particle Swarm Optimization
MCE	Multi-carrier energy	SPCAES	Solar-Powered Compressed Air Energy Storage
HSS	Hydrogen storage system	DRC	downside risk constraint
RO	Robust optimization	P2G	power-to-gas
TDR	Thermal demand response	ADMM	Alternating Direction Method of Multipliers
EDR	Electrical demand response	AB	Auxiliary Boiler
EMS	energy management system	PGU	Power Generation Unit
IGDT	information gap decision theory	AC	Absorption chiller
CHP	combined heat and power	EC	Electrical Chiller
WT	wind turbine	HRU	Heat Recovery Unit
PDF	Probability Density Function		

I. Introduction

A. Motivation and incitement

Traditional energy systems such as power, natural gas, heat and cooling systems are mostly planned and operated separately. Lack of coordination among traditional energy systems hinders the economical and efficient operation of the entire system. by development of the energy Internet [1], the coupling of various energy sources (electricity, gas, heat and cooling) has become much tighter, and the interaction between energy sources, power grid, and consumers is constantly intensified. This makes the coordinated operation of multiple energy sources an increasingly urgent task. For MESs, supplying and converting different energy sources can improve the flexibility and stability of the overall system. In addition, MESs can increase the efficiency of energy consumption by coupling multiple energy sources [2]. For the supply, conversion and storage of different types of energy and load demand and their relationship in a MES, a system called EH is used and applied to all carriers [3]. Considering the use of different technologies, DGs and ESSs in MG Based on EH, energy management may create many challenges for MGO in the future.

On the other hands Finding improved ways to use environmentally friendly RES is of great interest, especially in developed countries. Because these solutions can curb the harmful effects of CO_2 emissions, which pose a challenge to an environment that is already experiencing alarming scales of global warming. Photovoltaics accounted for 48% of the total new power capacity added in 2019, as the share of RESs to meet power demand increases [4]. Although their presence provides some benefits to the power system, variable power generation in PV systems increases the net load ramp rate of the power system. For example, on July 16, 2020, in California, increased demand combined with a drop in PV production toward evening led to an 11 MW increase in ramp rate over three hours [5]. In such systems, the MGO must make new decisions to reduce the ramp rate of the system. Due to the increasing installation of PV systems, one of the main solutions to reduce system ramp rates is collaboration between MGO and individual customers. To this end, MGO may limit the ramp rate of power exchanged by EH with the upstream grid by setting flexibility constraints [6]. The flexibility constraint is the absolute value of the ramp rate for power purchased from the grid minus the ramp rate for power sold to the grid as less than or equal to the maximum ramp rate limit. With this constraint, the ramp rate is defined as the capacity to buy/sell from/to the grid at time step t minus these values at time step t-1. Therefore, this paper aims to model the flexibility-constrained energy management problem of SEHs equipped with RESs, considering DR and P2P energy to reduce emission costs and increase system flexibility.

B. *Literature review*

The mounting prevalence of distributed generation and the emergence of MCE systems have engendered an augmented demand for EH systems within the power grid. An EH is a new idea implemented in a MCE system to transmit, receive and store different types of energy. In addition, load distribution is a pivotal optimization issue in the energy systems, whereby it plays a significant role in mitigating the consumption of non-renewable energy sources, environmental pollution, and system operating costs. Numerous investigations have been undertaken in the realm of EH management with relation to this matter. At first, the issue of energy management was explored in the absence of any contemplation environmental pollution. The article by [7] centers on examining the notion of a hydrogen-based smart micro EH while taking into account the inclusion of IDR and a fuel cell-based HSS. The purpose of the model being proposed is to achieve the minimization of the overall EH cost through the implementation of a RO strategy, taking into account the uncertainty of electricity prices.in another development, a hybrid interval-stochastic framework was proposed by [8] to create robust programming of EH which thermal energy market, TDR program and EDR program are considered to manage flexible energy management in order to reduce operation cost. Authors proposed a cooperative framework in which a network of EHs collaborate together and share their resources in order to reduce their costs. In contrast to techniques predicated upon Nash-equilibrium points, which merely identify equilibrium points without ensuring the optimality of the solution, the cooperative strategy employed in [9] herein provides a means of obtaining the optimal solution for the given problem. The study documented in reference [10], was examined the efficacy of ice storage as a nascent and evolving mechanism for energy storage with the aim of enhancing performance and diminishing the operation cost of EHs. Moreover, the stochastic behavior of ice storage was compared with deterministic conditions. A rule-based EMS based on the modifications of the traditional load following and circuit charging was developed in [11] to effectively coordinate the operation of an integrated multi-carrier hybrid energy system. A novel optimization framework based on a hybrid IGDT and RO was developed in [12] to handle the optimal self-scheduling of the EH within a medium-term horizon for large consumers. The purpose of this framework was to efficiently address the intricate binary variables and cope with the worst-case scenarios associated with the generation of wind turbines and the uncertainties in the day-ahead electricity market. Furthermore, authors in [13] were offered a linear max–min–max robust optimization-based decision-making tool that incorporates both uncertainties of the electricity market price and the wind generation. As indicated in the present discourse, the optimal load distribution in energy systems not only engenders a reduction in operational costs, but also facilitates a diminution in the consumption of non-renewable energy sources, thereby mitigating the production of deleterious substances in the environment. In this regard, the article [14] has proposed an optimal load distribution model for the EH, which aims to reduce the total cost of the EH, including operating costs and CO_2 emission costs of the system. The investigated energy hub includes the unit of CHP, gas boiler, PV systems and WT, and EV and the issue of uncertainty related to EVs was dealt with through the application of RO from a methodological viewpoint. authors in [15] were examined the design and performance of an EH to meet the heating, cooling, electricity, and freshwater demands of a coastal city. A thorough thermodynamic examination of the EH was being undertaken to consider the economic and emissions perspective in conjunction with the availability of RESs. In a recent study, a robust approach based on QPSO was employed to minimize the total cost of the EH system [16]. The investigation focused on evaluating the reduction of fuel consumption and pollutant emissions through the implementation of a TESS within the residential EH. In another development, a model for EH was considered for the purpose of the optimal operation of the MG with multiple energy carrier infrastructures for day-ahead [17]. The objective of optimization was to reduce operation and environmental expenses while taking into account various technical constraints. More specifically, the influence of SPCAES as a new ESS on the effectiveness and productivity of the EH, as well as on environmental expenses, was examined. Article [18] demonstrated the implementation of an emission cost model, which incorporates penalty factors, in regulating the usage of RESs by residential EH towards mitigating pollution emissions. As a measure to mitigate the risks arising from potential uncertainties faced by the decision-maker, a risk-aversion strategy, specifically the DRC, was adopted. Furthermore, the researchers of [19] posited an energy hub equipped with P2G technology, wherein patrons partake in an IDR program. The findings demonstrated that the P2G technology effectively mitigates CO_2 emissions via the consumption of CO_2 emanating from the CHP system and boiler. It appears that the interchanging of energy between EHs will augment the flexibility of the system while concurrently mitigating its operational costs. On the other hand, P2P energy transaction, allowing EHs to trade energy with each other in a direct manner, plays a pivotal role in mitigating the utilization of non-renewable energy sources and, consequently, in reducing carbon emissions. Despite the fact that the involvement of numerous EHs enhances flexibility and mitigates system costs, the equitable and compelling allocation of benefits remains a considerable challenge. Hereupon, the article [20] presents a market mechanism designed for the operation of multiple EHs, which relies on a P2P transaction system. The application of cooperative game theory led to the development of a just and persuasive method of distributing payoffs. The problem concerning the allocation of payoffs was structured as a two-stage problem. In the first stage, the allocation of payoffs was ascertained with the objective of minimizing the worst-case excess. Subsequently, the coalition with the highest excess was found and reintroduced into the first-phase problem. Moreover, a potential solution was presented in [21] for energy transaction through a P2P model among interconnected SEHs. EHs had the capacity to exchange both electrical and thermal energy with one another, thereby resulting in a reduction in expenditure and a decrease in reliance on gas and electricity service providers. The research conducted by Article [22] sought to investigate a completely decentralized approach to electricity trading in the framework of transactive energy markets. The proposed model presents a theoretical framework for P2P trading, which facilitates services among clients in a decentralized manner. the decentralized power flow issue was approached through the utilization of the ADMM. in article [23] the authors were focused to evaluate the significance of P2P energy transactions in conjunction with on-site flexibility resources for industrial sites. This study seeks to examine the potential impact of P2P energy transactions on uncertain parameters in light of the substantial peak power charges associated with grid power usage. Studies conducted to energy management of the EH can be categorized through multifaceted approaches. TABLE 1 presents a compilation of recent scholarly investigations pertaining to the perspectives outlined above. The presented table also outlines the unique aspects of the current work in relation to prior research.

TABLE 1 COMPREHENSIVE COMPARISON OF THIS PAPER TO LITERATURE REVIEW.

Reference	Flexibility-constrained	P2P transaction	Emission costs	Multi-carrier energy	Demand response	Uncertainty
[7]	✗	✗	✗	✓	✓	✓
[8]	✗	✗	✗	✗	✓	✓
[9]	✗	✗	✗	✓	✓	✗
[10]	✗	✗	✗	✓	✓	✗
[11]	✗	✗	✓	✓	✗	✗
[12]	✗	✗	✗	✗	✓	✓
[13]	✗	✗	✗	✓	✗	✓
[14]	✗	✗	✓	✗	✓	✓
[15]	✗	✗	✓	✓	✗	✗
[16]	✗	✗	✓	✓	✗	✓
[17]	✗	✗	✓	✓	✗	✓
[18]	✗	✗	✗	✓	✓	✓
[19]	✗	✗	✓	✗	✓	✗
[20]	✗	✓	✗	✓	✗	✓
[21]	✗	✓	✗	✗	✗	✓
[22]	✗	✓	✗	✓	✗	✓
[23]	✗	✓	✓	✓	✓	✗
Current paper	✓	✓	✓	✓	✓	✓

C. Contributions and organization

The aforementioned research has demonstrated the impact of MCE systems on the flexibility and stability of the system. Additionally, it was determined that the implementation of P2P energy and DR concepts resulted in a decrease of both operational and environmental costs for the system. Nevertheless, the stochastic nature of PV systems, which contributes to the heightened ramp rate of the system's net load, implies a void in our current research. The current investigation endeavors to explore the utilization of flexibility-constrained concepts within SEHs, with a focus on P2P energy trading and DR. This is pursued with the ultimate objective of augmenting system flexibility and diminishing both environmental and operational costs. Particularly, the study aimed at the following objectives:

- Modeling 3 CCHP-based EHs optimal operation involving DR programs and P2P energy transaction,
- In order to enhance the overall flexibility of a system, the application of the flexibility-constrained concept is recommended and
- This approach involves taking into account the scenario-based performance of various elements, such as PV systems and loads.

The following organization is considered for the rest of the paper. In Section 2, the SEHs architecture is described and problem is formulated. The mathematical model and solution algorithm are presented in Section 3. Section 4 presents and discusses the simulation results and finally, Section 5 addresses the conclusion of the study.

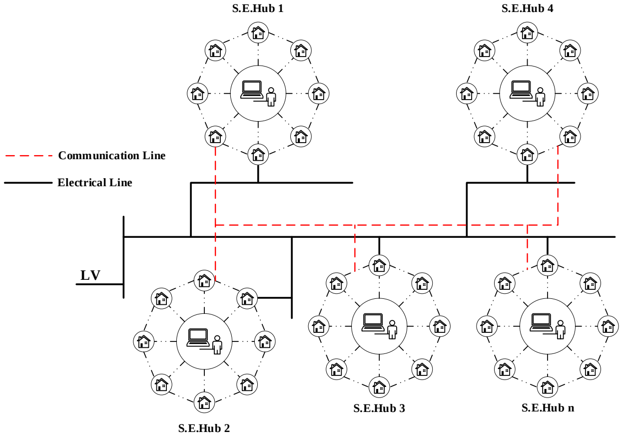

Fig. 1. Transactive framework for multiple SEHs

II. SEHs architecture and problem formulation

A. SEH architecture

An MCE framework for multiple SEHs is shown in Fig. 1. All SEHs are networked and can trade electrical energy with other hubs via the networked infrastructure. They also communicate with each other through a communication network to determine the optimal energy trading profile. Hubs are equipped with an EMS that facilitates the identification of the most effective strategy for scheduling their energy generation, consumption, and energy share. In general, Each SEH is composed of CCHP, PV, AB, ISC, ESSs and a multitude of loads pertaining to electrical, heating, and cooling functions. In an effort to enhance realism, the implementation of hubs exhibiting distinct components has been attempted. Thus, it can be posited that SEHs 1, 2, and 3 have drawn inspiration from [17], [24], and [25], correspondingly. The general schema of the proposed SEHs is depicted in Fig. 2 . The CCHP system is composed of various fundamental components, including but not limited to the PGU, HRU, and AC. The implementation of ISC has become commonplace in various cooling applications. This innovative technology has been found to be effective in reducing peak power supply tension during peak hours, as reported by previous studies [25]. In this study, the ISC consisted of a single-duty chiller (operable only in ice-making mode) and an ice storage tank that melted the stored ice only during peak hours. Additionally, the ISC could not operate in both ice-making and ice-melting modes simultaneously. Furthermore, it should be noted that the CCHP system was operated in a hybrid load mode [26]. The present inquiry pertains to a system encompassing three distinct categories of energy requisites, namely those associated with electricity, heat, and cooling. The present study posited that the MG operator possessed unfettered access to all pertinent data. according to Fig. 2, the primary portion of the natural gas streams into the PGU to generate electricity and heat. Subsequently, the second phase is initiated whereby AB triggers the generation of thermal energy. In fact, natural gas dispatch is expressed as:

$$P_{gas} = P_{gas}^{PGU} + P_{gas}^{AB} \tag{1}$$

Electricity P_e^{PGU} and heat H^{HRU} are generated through the firing of natural gas P_{gas}^{PGU} in the gas turbine as follows:

$$P_e^{PGU} = \eta_e^{PGU} \times P_{gas}^{PGU} \tag{2}$$

$$H^{HRU} = \eta_h^{PGU} \times P_{gas}^{PGU} \tag{3}$$

AB consumes natural gas for the purpose of heat generation in the subsequent manner:

$$H^{AB} = \eta_h^{AB} \times P_{gas}^{AB} \tag{4}$$

Electricity is transferred between the SEH and the upstream grid via the transformer. In the event of insufficient electricity, the SEH will procure electricity from the upstream electrical grid. Conversely, in instances of electricity surplus, the electrical hub vends the excess electricity to the upstream grid.

$$P^{ELE} = \eta^{TRA} \times P^{GRD} \tag{5}$$

The succeeding equation delineates the ice-making capacity of the chiller:

$$P_{ISC}^{dis} = K^{ISC} \times P^{ISC} \tag{6}$$

The process of injecting co-product heat H^{HRU} from PGU into the HRU results in the accumulation of heat at the heating hub. Specifically, the heating hub assembles the output heat of HRU, represented as $\eta^{HRU} \times H^{HRU}$, along with the heat emanating from AB. Subsequently, a fraction of the thermal energy, which is directed towards AC, is utilized to facilitate cooling:

$$C^{AC} = K^{AC} \times H^{AC} \tag{7}$$

Additionally, the electric chiller consumes electrical power to produce cooling energy and this process can be mathematically expressed as follows:

$$C^{EC} = K^{EC} \times P^{EC} \tag{8}$$

B. problem formulation

This subsection entails an elaboration of the problem

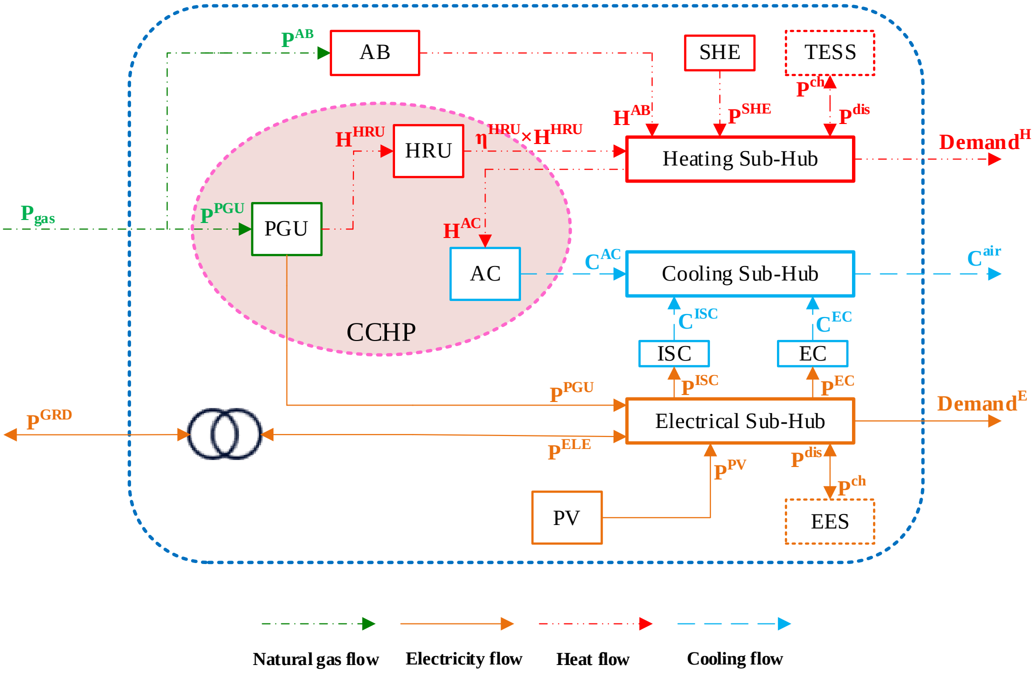

Fig. 2. General scheme of SEHs

formulation encompassing the objective function as well as the inherent constraints of the network and generation units.

2.2.1. objective functions

The following equations demonstrate the proposed objective function, which represents the operating costs of the MG (including all three SEHs) in the day-ahead market. It consists of six components: the net purchase cost of electricity and gas, the CO₂ emission cost and the compensation cost of shiftable electrical loads and flexible heating and cooling loads. This study considers operating cost minimization from the perspective of MGO seeking to economically and technically optimize the use of MG components. These components encompass CCHP, PV, TESS, ESS and ISC. In this analysis, the focus is strictly on operational costs, while disregarding investment costs associated with these MG components. The objective function can be presented in the following formulation:

$$f = \sum_{s} \rho(s) \times \sum_{h} \sum_{t} \begin{bmatrix} C_{pe}(h,t,s) + C_{pg}(h,t,s) + \\ C_{oe}(h,t,s) + C^{EDR}(h,t,s) + \\ C^{HDR}(h,t,s) + C^{CDR}(h,t,s) \end{bmatrix} \tag{9}$$

$$C_{pe}(h,t,s) = \rho_e(h,t) \times P^{GRD}(h,t,s) \tag{10}$$

$$C_{pg}(h,t,s) = \rho_g(h,t) \times \tag{11}$$

$$= \rho_g(h,t) \times \left[\frac{P_e^{PGU}(h,t,s)}{\eta_e^{PGU}(h)} + \frac{H^{AB}(h,t,s)}{\eta_h^{AB}(h)} \right]$$

$$C_{oe}(h,t,s) = \theta(h) \times \begin{bmatrix} \varphi_{in}(h) \times P^{GRD}(h,t,s) + \\ \varphi_g(h) \times \left(\frac{P_e^{PGU}(h,t,s)}{\eta_e^{PGU}(h)} + \frac{H^{AB}(h,t,s)}{\eta_h^{AB}(h)} \right) \end{bmatrix} \tag{12}$$

$$C^{EDR}(h,t,s) = \rho^{EDR} \times \Delta P^{sh,dn}(h,t,s) \tag{13}$$

$$\begin{aligned} &C^{HDR}(h,t,s) = C^{HairDR}(h,t,s) + \\ &C^{HwsDR}(h,t,s) = \rho^{HairDR} \times \\ &\left| H^{air}(h,t,s) - H^{air,forecast}(h,t,s) \right| \\ &+\rho^{HwsDR} \times \left| H^{ws}(h,t,s) - H^{ws,forecast}(h,t,s) \right| \end{aligned} \tag{14}$$

$$\begin{aligned} &C^{CDR}(h,t,s) = \rho^{CDR} \times \\ &\left| C^{air}(h,t,s) - C^{air,forecast}(h,t,s) \right| \end{aligned} \tag{15}$$

Constraints: The proposed optimization problem considers the following constraints:

Flexibility constraint: The SEH's flexibility constraint is modeled using Equation (16):

$$\begin{vmatrix} P^{buy}(h,t,s) - P^{buy}(h,t-1,s) - \\ (P^{sell}(h,t,s) - P^{sell}(h,t-1,s)) \end{vmatrix} \leq P^{Flexibility}(h,t) \tag{16}$$

whereby the power traded between the system and the upstream grid during time step t, in comparison with time step t-1, is constrained to be less than or equal to the flexibility limitation.

P2P transaction constraint: The SEHs operate on a P2P basis, wherein participants are able to engage in transactions involving the purchase or sale of electrical energy based on their respective preferences. $e_h^{el} = \{e_{h,j,t}^{el},\ \forall h,j \in H,\ \forall t \in T\}$ indicates the electrical energy sharing of SEH h with j on timeslot t. If power is purchased from SEH j, $e^{el}(h,j,t)$ will be positive, and otherwise if SEH h sells to j and $e^{el}(h,j,t)$ is negative. An Energy Sharing Profile between S.E.s must satisfy the following constraints:

$$e^{el}(h,j,t,s) + e^{el}(j,h,t,s) = 0 \tag{17}$$

$\Pi_h = \{\pi_{h,j},\ \forall h,j \in H\}$ also specifies payments for energy trades between SEHs. The payment among SEH h with j, must be equal but with opposite signs, so the payment among SEHs must satisfy the bellow constraint:

$$\pi(h,j,s) + \pi(j,h,s) = 0 \tag{18}$$

The exclusion of the trading cost of energy between hubs from the optimization (1) is justified by its negligible impact on the overall social cost of the hubs. This factor solely involves the transfer of payments between the hubs and does not contribute to the calculation of the total social cost. For example, $12 is a payment hub h makes to j, so hub j receives $12 and h pay $12. Therefore, it follows that the aggregate cost incurred in relation to energy sharing remains constant.

DR programs: The DR programs facilitate the energy supply by implementing measures to regulate energy consumption among end users via various strategies and initiatives. This article examines a price-based IDR system for shiftable electric loads, and two IDR programs for flexible thermal loads.

a) Shiftable electrical loads: There are two primary programs in which the customer may participate, namely incentive-based and price-based programs. This paper presents an examination of price-based DR, a technique employed by customers who adjust their energy consumption by transferring some of their loads to alternate periods, influenced by the pricing signal. It is noteworthy that the modeling methodology employed in this study presents an IDR mechanism, wherein it is possible to transfer shiftable loads from periods of peak demand to periods of reduced activity. The mathematical formulation of the load shifting approach is demonstrated in equations (19) -(23).

$$\begin{gathered} Demand^E(h,t,s) = P^L(h,t,s) + \\ \Delta P^{sh,up}(h,t,s) - \Delta P^{sh,dn}(h,t,s) \end{gathered} \tag{19}$$

$$\begin{gathered} \sum_{t=1}^{N} \Delta P^{sh,up}(h,t,s) - \\ \sum_{t=1}^{N} \Delta P^{sh,dn}(h,t,s) = 0 \end{gathered} \tag{20}$$

$$\begin{gathered} 0 \le \Delta P^{sh,up}(h,t,s) \le \\ \overline{\Delta P}^{sh,up}(h,t) \times \psi^{sh,up}(h,t,s) \end{gathered} \tag{21}$$

$$\begin{gathered} 0 \le \Delta P^{sh,dn}(h,t,s) \le \\ \overline{\Delta P}^{sh,dn}(h,t) \times \psi^{sh,dn}(h,t,s) \end{gathered} \tag{22}$$

$$\psi^{sh,up}(h,t,s) + \psi^{sh,dn}(h,t,s) \le 1 \tag{23}$$

The terms $\Delta P^{sh,up}(h,t,s)$ and $\Delta P^{sh,dn}(h,t,s)$ a are positive variables demonstrating increased and reduced loads, respectively.

b) Flexible heating loads: The present article explicates two distinct categories of heating loads, namely indoor heating loads and hot water loads.

$$\begin{gathered} Demand^H(h,t,s) = \\ H^{air}(h,t,s) + H^{ws}(h,t,s) \end{gathered} \tag{24}$$

The mathematical representation of heating loads relies on their thermodynamic model in a manner that temperature plays a fundamental part in determining the fulfillment of heating requirements [27]. The proposed methodology broadens the range of options available to SEHs for energy transactions in meeting their heating requirements. It is worth noting that the method in question entails a comprehensive analysis of all heating loads, while simultaneously operating under the assumption that the integration form of DR is utilized. the mathematical modeling of indoor heating DR is shown in equations (25) -(28).

$$\underline{H}^{air}(h,t,s) \le H^{air}(h,t,s) \le \overline{H}^{air}(h,t,s) \tag{25}$$

$$\begin{gathered} \underline{H}^{air}(h,t,s) = H^{air,forecast}(h,t,s) - \\ \phi^H(h,t) \times H^{air,forecast}(h,t,s) \end{gathered} \tag{26}$$

$$\begin{gathered} \overline{H}^{air}(h,t,s) = H^{air,forecast}(h,t,s) + \\ \phi^H(h,t) \times H^{air,forecast}(h,t,s) \end{gathered} \tag{27}$$

$$0 \le \phi^H(h,t) \le \overline{\phi}^H \tag{28}$$

The second type of heating load is the hot water, which is one of the necessary consumptions. The aforementioned analysis is also applicable to hot water modeling:

$$\underline{H}^{ws}(h,t,s) \le H^{ws}(h,t,s) \le \overline{H}^{ws}(h,t,s) \tag{29}$$

$$\begin{gathered} \underline{H}^{ws}(h,t,s) = H^{ws,forecast}(h,t,s) - \\ \phi^{ws}(h,t) \times H^{ws,forecast}(h,t,s) \end{gathered} \tag{30}$$

$$\begin{gathered} \overline{H}^{ws}(h,t,s) = H^{ws,forecast}(h,t,s) + \\ \phi^{ws}(h,t) \times H^{ws,forecast}(h,t,s) \end{gathered} \tag{31}$$

$$0 \le \phi^{ws}(h,t) \le \overline{\phi}^{ws} \tag{32}$$

c) Flexible cooling loads: The present study considers the cooling load as defined by the air conditioning system, which is dependent on the temperature of the enclosed space. The objective of this study is to decrease the ambient temperature within the given space through the introduction of cool air into the surrounding environment. The identical thermodynamic framework is utilized in the calculation of cooling loads, with one modification in the principal equation:

$$\underline{C}^{air}(h,t,s) \le C^{air}(h,t,s) \le \overline{C}^{air}(h,t,s) \quad (33)$$

$$\underline{C}^{air}(h,t,s) = C^{air,forecast}(h,t,s) - \phi^{C}(h,t) \times C^{air,forecast}(h,t,s) \quad (34)$$

$$\overline{C}^{air}(h,t,s) = C^{air,forecast}(h,t,s) + \phi^{C}(h,t) \times C^{air,forecast}(h,t,s) \quad (35)$$

$$0 \le \phi^{C}(h,t) \le \overline{\phi}^{C} \quad (36)$$

Energy balance at SEHs: The expression for the balance of electrical power at the electrical hub is presented as follows:

$$\begin{aligned} &P^{ELE}(h,t,s) + P^{PV}(h,t,s) + P_{e}^{PGU}(h,t,s) \\ &+P_{EES}^{dis}(h,t,s) + \sum_{j} e^{el}(h,j,t,s) = \\ &Demand^{E}(h,t,s) + P^{ISC}(h,t,s) \\ &+P_{EES}^{ch}(h,t,s) + P^{EC}(h,t,s) \end{aligned} \quad (37)$$

Furthermore, the heat balance is expressed in the subsequent manner:

$$\begin{aligned} &\eta^{HRU}(h) \times H^{HRU}(h,t,s) + H^{AB}(h,t,s) \\ &+P_{TESS}^{dis}(h,t,s) = Demand^{H}(h,t,s) \\ &+H^{AC}(h,t,s) + P_{TESS}^{ch}(h,t,s) \end{aligned} \quad (38)$$

Moreover, the expression of the cooling energy balance can be stated as:

$$\begin{aligned} &C^{AC}(h,t,s) + C^{EC}(h,t,s) \\ &+ C_{ISC}^{dis}(h,t,s) \\ &= C^{air}(h,t,s) \end{aligned} \quad (39)$$

ESS operation constraints: In the context of the operation of ESSs in an SEH environment, emphasis has been placed on several limitations, which take the form of generic models, as documented in academic sources such as [26] and [28]. It should be highlighted that within the framework under consideration, ESS pertains to the composite entities of EES, TESS, and ISC.

$$0 \le P_{ESS}^{ch}(h,t,s) \le \overline{P}_{ESS}^{ch}(h) \times U_{ESS}^{ch}(h,t,s) \quad (40)$$

$$0 \le P_{ESS}^{dis}(h,t,s) \le \overline{P}_{ESS}^{dis}(h) \times U_{ESS}^{dis}(h,t,s) \quad (41)$$

$$U_{ESS}^{ch}(h,t,s) + U_{ESS}^{dis}(h,t,s) \le 1 \quad (42)$$

$$E_{ESS}(h,t,s) = E_{ESS}(h,t-1,s) - P_{ESS}^{dis}(h,t,s) \times \eta_{ESS}^{dis}(h) + \left(\frac{P_{ESS}^{ch}(h,t,s)}{\eta_{ESS}^{ch}(h)}\right) \quad (43)$$

$$0 \le E_{ESS}(h,t,s) \le \overline{E}^{EES}(h) \quad (44)$$

$$E_{ESS}(h,0,s) = E_{ESS}(h,24,s) \quad (45)$$

Generation limits for PGU and HRU: The electrical and heating power generated by CCHP in SEHs must adhere to a set of predetermined limits [26], [29]:

$$\underline{P}_{PGU}(h) \le P_{e}^{PGU}(h,t,s) \le \overline{P}_{PGU}(h) \quad (46)$$

$$\underline{H}_{HRU}(h) \le H^{HRU}(h,t,s) \le \overline{H}_{HRU}(h) \quad (47)$$

AB and AC operation limits: The heating and cooling power produced by AB and AC are required to fall within predetermined minimum and maximum thresholds, as shown below [26]:

$$0 \le H^{AB}(h,t,s) \le \overline{H}_{AB}(h) \quad (48)$$

$$0 \le H^{AC}(h,t,s) \le \overline{H}_{AC}(h) \quad (49)$$

Power limits for the transformer: The output real power of transformers should meet the following conditions:

$$0 \le P^{ELE}(h,t,s) \le \overline{P}^{ELE}(h) \quad (50)$$

Uncertainty modeling: This section expounds on the uncertainty models used for the output power of PVs, and electrical, heating, and cooling demands.

Solar irradiance modeling: A common approach in analyzing the distribution of solar irradiance at any given hour is to employ a bimodal distribution model, which is characterized by the linear combination of two unimodal distributions. The Beta PDF serves as a suitable choice for each of these unimodal distributions. The sources cited as [30] and [31], present the following information:

$$f_b(si) = \begin{cases} \dfrac{\Gamma(\alpha_s+\beta_s)}{\Gamma(\alpha_s)\Gamma(\beta_s)} \times si^{(\alpha_s-1)} \times (1-si)^{(\beta_s-1)} & 0 \le si \le 1,\ \alpha_s \ge 0,\ \beta_s \ge 0 \\ 0 & otherwise \end{cases} \quad (51)$$

$$\beta_s = (1-\mu_s) \times \left(\frac{\mu_s \times (1+\mu_s)}{\sigma_s^2} - 1\right) \quad (52)$$

$$\alpha_s = \frac{\mu_s \times \beta_s}{(1-\mu_s)} \quad (53)$$

In order to forecast the average and variance of solar irradiance at hourly intervals, researchers refer to historical data sourced from the neighboring meteorology station [31], [32]. The Beta PDF is defined as a range spanning from (51) to (53) for each hour, with respect to its respective mean and standard deviation. Various factors, namely solar irradiance, surface area, efficacy of PV modules, and solar collectors, are pivotal in determining the generated power of PV and solar collector units. The computation of the output power for both PV and solar collector units is carried out utilizing the Beta PDF across various conditions [30], [31], [33]:

$$\begin{aligned} &P_{pv}(si) = \eta^{pv} \times S^{pv} \times si \\ &P_{SHE}(si) = \eta^{sol} \times S^{sol} \times si \end{aligned} \quad (54)$$

Modelling the electrical, heating, and cooling demands: The modelling of uncertainty in the forecast of electrical, heating, and cooling demands is carried out using a Normal PDF, as follows [31], [34]:

$$f_d(\ell) = \frac{1}{\sigma_d \times \sqrt{2\pi}} \times e^{\frac{-(\ell-\mu_d)^2}{2\sigma_d^2}} \qquad (55)$$
$$\ell = z \times \sigma_d + \mu_d$$

The PDF for the normal distribution of each hour is determined by utilizing the calculated mean and standard deviation derived from the forecasted electrical, heating, and cooling demands.

Techniques for scenario reduction: For a majority of practical issues, the optimization problem that encompasses all conceivable scenarios (known as the deterministic equivalent program) is excessively extensive. In order to address the challenges posed by computational complexity and temporal limitations, algorithms are employed to mitigate the scenarios. The present study employs the SENRED tool, comprising three distinct algorithms (The Fast-Backward method, a mix of Fast-Backward/Forward methods and a mix of Fast Backward/Backward methods), to address the research objective.

III. The mathematical model and solution algorithm

The mathematical model for optimal operation proposed in this study is formulated as a MINLP model. MINLP is a mathematical optimization which encompasses problems that entail both continuous and integer variables, but are nonlinear in nature. The present optimal operation mathematical model is characterized by a combination of binary and continuous variables. The introduction of binary variables serves to prevent the concurrent operation of charging and discharging processes in ESSs. The variables of interest in this study are continuous and include electrical power from CCHP, heating power from ABs, electrical power exchanged between the system and the upstream grid, electrical power exchanged with EES, heating power exchanged with TESS, and cooling power supplied by ISC and EC in each hour of operation. Non-linear terms with the problem include compensation costs resulting from DR programs. The application of the absolute value function results in non-linearity of said variables [35]. The utilization of the SCIP solver has been employed for the resolution of the optimal dispatch model, owing to its exceptional competence in addressing MINLP problems. The Solver is the SCIP (implemented as C callable library and provides C++ wrapper classes for user plugins) as a tool of the GAMS software. The computational procedure was conducted utilizing a PC featuring an Intel Core i7,3.9GHz CPU with 16 GB of RAM. Fig. 3 depicts the implementation flowchart of the proposed model.

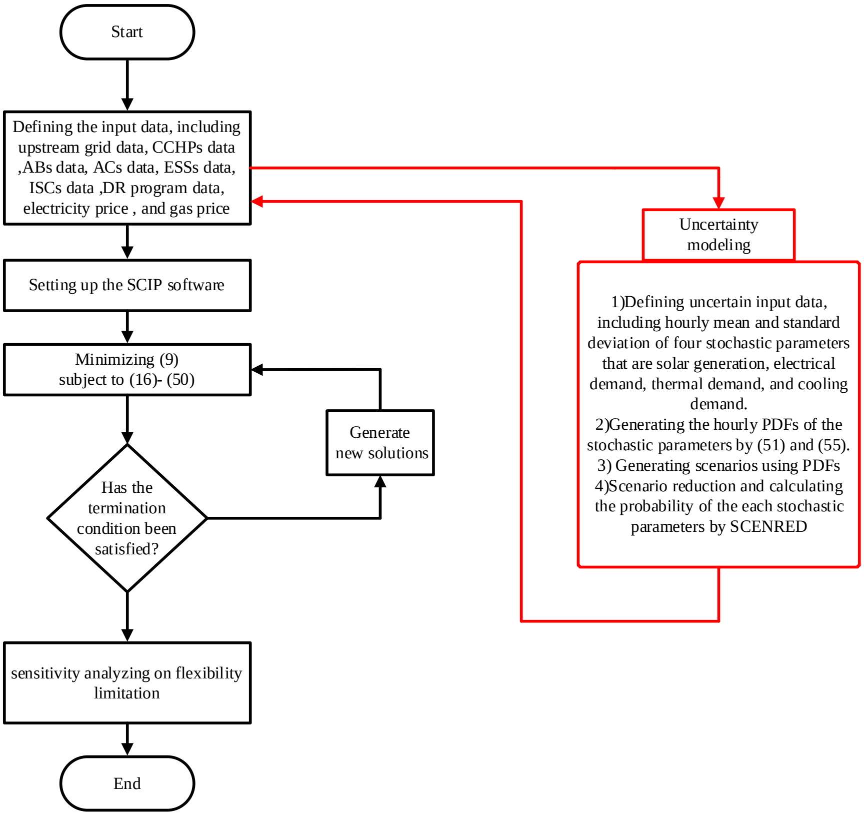

Fig. 3. Flowchart of the proposed model.

IV. Simulation result

The present study utilizes a smart grid system based on EH as a testbed to assess the effectiveness of the proposed mathematical model and it does not belong to any special geographical area. However, it is noteworthy that all three SEHs are frequently used by other researchers. The smart grid under consideration comprises three central hubs, with each hub featuring three sub-hubs, namely the electrical sub-hub, the heating sub-hub, and the cooling sub-hub. The electrical sub-hub imports electrical power from PGU and PV while it exports to ISC, EC, and electrical demand. Besides, it exchanges the electrical power with upstream grid and EES. The heating sub-hub imports heating power from AB, SHE, and HRU while it exports to AC and heating demand. Also, it exchanges the heating power with TESS. The cooling sub-hub imports cooling power from AC, EC, and ISC while it exports to cooling demand.

TABLE 2 PARAMETERS OF THE SEHS.

		Value				Value				Value	
Parameter	SEH 1	SEH 2	SEH 3	Parameter	SEH 1	SEH 2	SEH 3	Parameter	SEH 1	SEH 2	SEH 3
η_e^{PGU}	0.42	0.4	0.3	$\underline{P}_{PGU}$	140	0	0	$\overline{H}_{AC}$	300	2000	1000
η_h^{AB}	0.88	0.88	0.9	$\overline{P}_{PGU}$	1050	1200	1000	$\overline{H}_{AB}$	2300	2640	800
η_h^{PGU}	0.48	0.5	0.4	$\underline{H}_{HRU}$	155	0	0	$\overline{H}_{HRU}$	1640	1500	1000
η^{HRU}	0.82	1	0.82	K^{EC}	0	0	4	η^{TRA}	0.99	0.95	0.98
K^{AC}	0.9	0.9	1.2	K^{ISC}	0.9	0.85	0.95	$\overline{E}^{EES}$	1000	4200	1800
$\overline{P}_{ESS}^{ch}$	470	450	500	$\overline{P}_{ESS}^{dis}$	180	450	700	η_{ESS}^{ch}	0.9	0.9	0.96
η_{ESS}^{dis}	0.95	0.9	0.96	$\overline{P}^{ELE}$	3500	2850	1470				
S^{pv}	1300	η^{sol}	66.6	S^{sol}	1300	η^{pv}	18.6	$\overline{\Delta P}^{sh,up}$	150	$\overline{\Delta P}^{sh,dn}$	250
θ	0.45	φ_{in}	0.972	φ_g	0.23	ρ^{EDR}	2	ρ^{HairDR}	2	ρ^{HwsDR}	2
ρ^{CDR}	2	$\overline{\phi}^{H}$	0.2	$\overline{\phi}^{ws}$	0.2	$\overline{\phi}^{C}$	0.2				

A. Basic data

As specified, the proposed model analyzes three type of loads Fig. 4 illustrates the electrical demand of SEHs collectively. The combined forecast for indoor heating and hot water consumption is illustrated in Fig. 5. 70% of the aforementioned quantity is designated for the purpose of heating water, whilst the remaining portion is allocated towards indoor heating needs. the forecast cooling demand is demonstrated in Fig. 6, Fig. 7 shows the day-ahead forecasted electricity price for the smart grid. Each SEH has a set price for natural gas, with SEH 1 being priced at 3.5 cents, SEH 2 at 5.5 cents, and SEH 3 also at 5 cents. The mean of the forecasted solar generations during day-ahead are shown in Fig. 8 standard deviation of stochastic generations is considered 5%. The characteristics of SEHs and grid are represented in TABLE 2

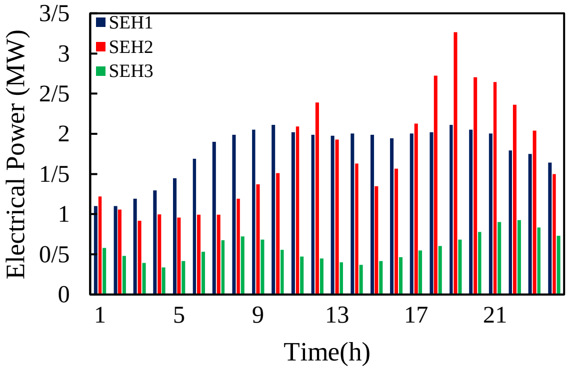

Fig. 4. Electrical demand of SEHs.

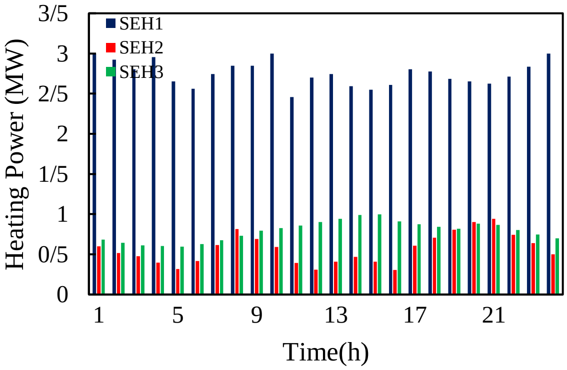

Fig. 5. Forecasted heating demand of SEHs.

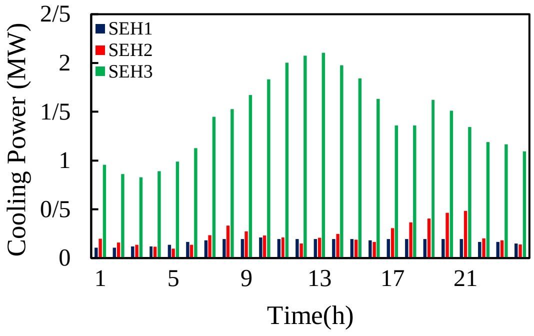

Fig. 6. Forecasted cooling demand.

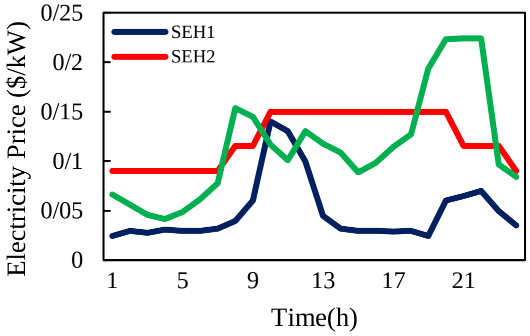

Fig. 7. Electricity price of smart grid.

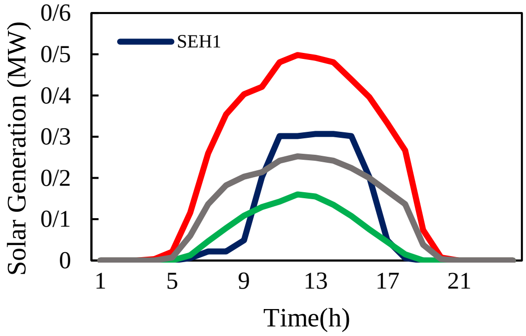

Fig. 8. Solar generations.

B. *Results and discussion*

The present study endeavors to analyze the effects of P2P transaction and DR programs on costs reduction, as well as the influence of flexibility constraint on enhancing system flexibility. To achieve this objective, three distinct cases have been considered as follows:

Case 1: energy management of SEHs without considering P2P transactions, DR programs, and flexibility constraint

Case 2: energy management of SEHs with considering P2P transactions and DR programs and without considering flexibility constraint

Case 3: energy management of SEHs with considering P2P transactions, DR programs, and flexibility constraint equal to 300KW

The sub-hubs play a crucial role in the collection and allocation of multi-energy. It is necessary for each sub-hub to maintain a balance in energy flow at any given moment. Figures 9-11 show the optimal distribution of energy flows at power, heating and cooling sub-Hubs for different cases. In figures 9-11, the upper and lower sides of the horizontal axis represent the energy flowing into the sub-hub and the energy flowing out of the sub-hub, respectively.

The graphical representation of the optimal dispatch of power flow at the electrical sub-hubs in Case 1 can be observed in the 1st row of Fig. 9 where upstream grid and PV systems supply the electrical demand at the majority of hours. The balance between electrical power generation and electrical consumption is achieved at each hour in electrical sub-hubs. For example, at hour 13, the generation outputs of PV, PGU, and importing from upstream grid in SEH 1 are 306.8 (kW), 140 (kW), and 1528.02 (kW), respectively, while the electrical demand is 1974.8 (kW) at the same hour. On the other hand, in SEH 2, during hours 21-23, when PV generation is zero and the electricity price is low, most of the electrical demand is met by purchases from the upstream grid and less electricity is generated by PGU. In addition, PV generation plays an important role in supplying electrical demand in hours 8-10 and 12-14 in SEH 3. Also, due to the reduction of PV generation at hour 19 in SEH 1, most of the electrical demand is supplied by PGU and upstream grid. the results of power flow in Case 2 are shown in the 2nd row of Fig. 9 While these results are similar to those in Case 1 Since the generation of PGU unit is specifically related to the purchase price of electricity from the upstream grid, during hours 9-13, the role of PGU in providing power demand is more than power traded

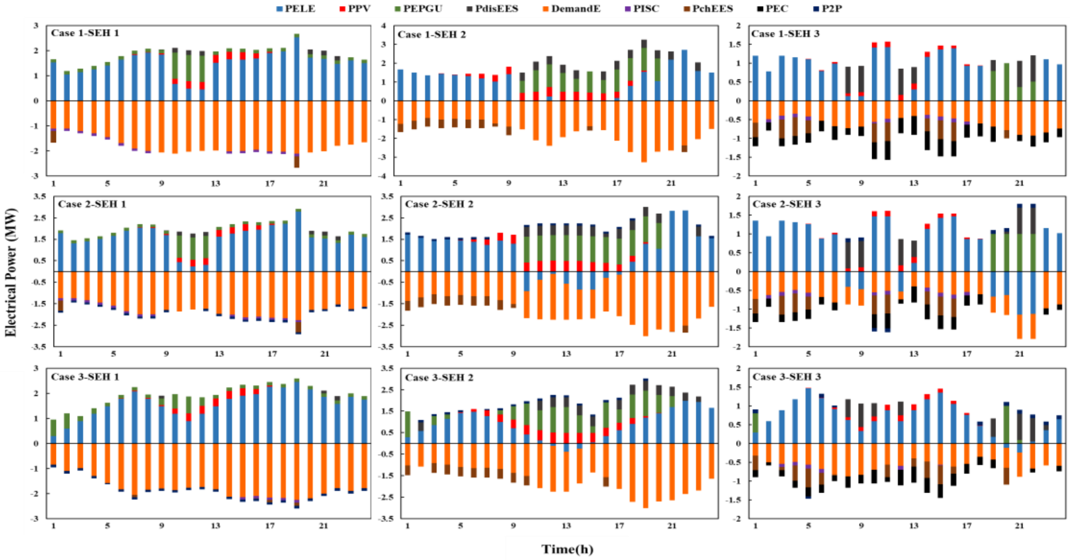

Fig. 9. Electrical power flow at SEHs.

with grid in SEH 1. In SEH 2, there exists evidence showcasing the efficacy of EES. Specifically, EES is charged during the first nine hours of the day that the price of electricity is comparatively lower than the subsequent hours. Consequently, EES unit is discharged during the period of 10 AM - 8 PM when there is a substantial surge observed in the price of electricity. The DR program incorporated in the proposed model operates by curbing the electrical demand in SEH 3 during specified hours of 8, 9, 11, and 12-22, resulting in a drop to 1750 kW, while augmenting the demand during other times of the day to capitalize on the more cost-efficient electricity prices. The implementation of DR strategies has been found to result in a reduction of operational cost through the shiftable electrical loads. Fig. 10 illustrates the energy transfer between interconnected hubs. The utilization of peer-to-peer transaction energy has been found to result in a notable reduction in the production of PGU, as well as a decrease in the need to purchase electricity from the upstream network. This approach also leads to the improvement of energy management within the network. As has been previously indicated, the cost of energy exchange between hubs is not anticipated to have an impact on the total cost.

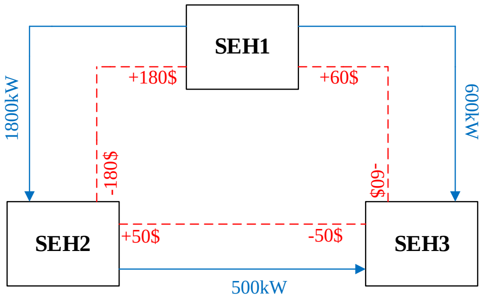

Fig. 10. Energy transfer between SEHs

the results of case 3 shown in the 3rd row of Fig. 9 indicate that the presence of flexibility constraints increases the flexibility of the system and thus the total cost. In the current scenario, the ramp rate at energy is traded with the upstream grid is limited to a maximum of 300. This limitation has resulted in a smoother PELE diagram while increasing the flexibility of the system. As illustrated in the figures, the growth of PELE is limited in the first hours of the day in SEH 1, so PGU production must be increased to meet demand. This increase in production leads to amplified operational costs and carbon emissions. In addition, SEH 2 experiences a significant increase in energy procurement costs during midday hours. This escalation is due to the rigidity constraint that the EH faces, which prevents it from immediately minimizing energy procurement from the upstream grid. Instead, the EH resorts to incremental reductions in energy procurement, resulting in an incremental gradient that inevitably increases system costs.

The 1st row of Fig. 11 shows the optimal dispatch of heat flow at the heating sub-hubs in Case 1. It can be seen that the heating power is balanced in thermal sub-hubs at each hour. For example, at hour 20, the discharge power of TESS and the heat generation of HRU and AB in SEH 1 are 180 (KW), 1640 (kW), and 1346.2 (kW), respectively, while the heat demand and AC consumption are 2653.27 (kW) and 217.75 (kW), respectively at the same hour. It can be seen that the heat demand is mostly covered by HRU. However, during the hours when the electricity price is low and PGU works less to provide the electrical demand, the role of HRU is reduced and AB should supply the heat demand. In addition, for SEH1 and SEH 3, the charging/discharging TESS during favorable hours reduces operating costs at the thermal sub-hub.in SEH 2, the HRU is less active due to the presence of SHE.in Case 2, the 2nd row of Fig. 11 depicts the optimal dispatch of heat flow at the sub-hubs. Although P2P energy transactions have not yielded so much significant impact on the thermal balance of the system, the DR program has successfully facilitated effective energy management in smart hubs. As an illustration, the implementation of the DR program within SEH 1 has resulted in a decrease in the production of AB, thereby contributing to a corresponding reduction in associated carbon emission costs. the flexibility constraint has resulted in marginal modifications in the heat flow, as illustrated in Fig. 11

The 1st row of Fig. 12 shows the optimal dispatch of cooling flow at cooling sub-hubs in Case 1. It is observed that the AC supplies the cooling demand during all hours. In SEH 3, the assistance of AC alongside EC serves as a substantial contribution to meeting the high demand for cooling and energy supply. The implementation of the discharging process of the ISC during 9-14 within SEH 1 is aimed at mitigating operational costs. In the context of Case 2, the 2nd row of Fig. 12 illustrates the optimized distribution of cooling flow within cooling sub-hubs. Similar to the phenomenon of thermal flow, the utilization of a demand response program within the cooling flow enhances the efficacy of energy management strategies within the system.

TABLE 3 COMPARISON OF TOTAL COST IN THREE CASES

Case Study	**Total Cost ($)**	**Cost of purchasing electricity ($)**	**Cost of purchasing natural gas ($)**	**Cost of Emission ($)**	**compensation cost of EDR ($)**	**compensation cost of TDR ($)**	**compensation cost of CDR ($)**
Case 1	10400.67	5929.00	4019.8	451.86	0	0	0
Case 2	9231.81	4285.49	3947.08	418.54	109.00	302.42	131.65
Case 3	10142.25	5587.38	3555.16	421.55	87.81	302.42	150.30

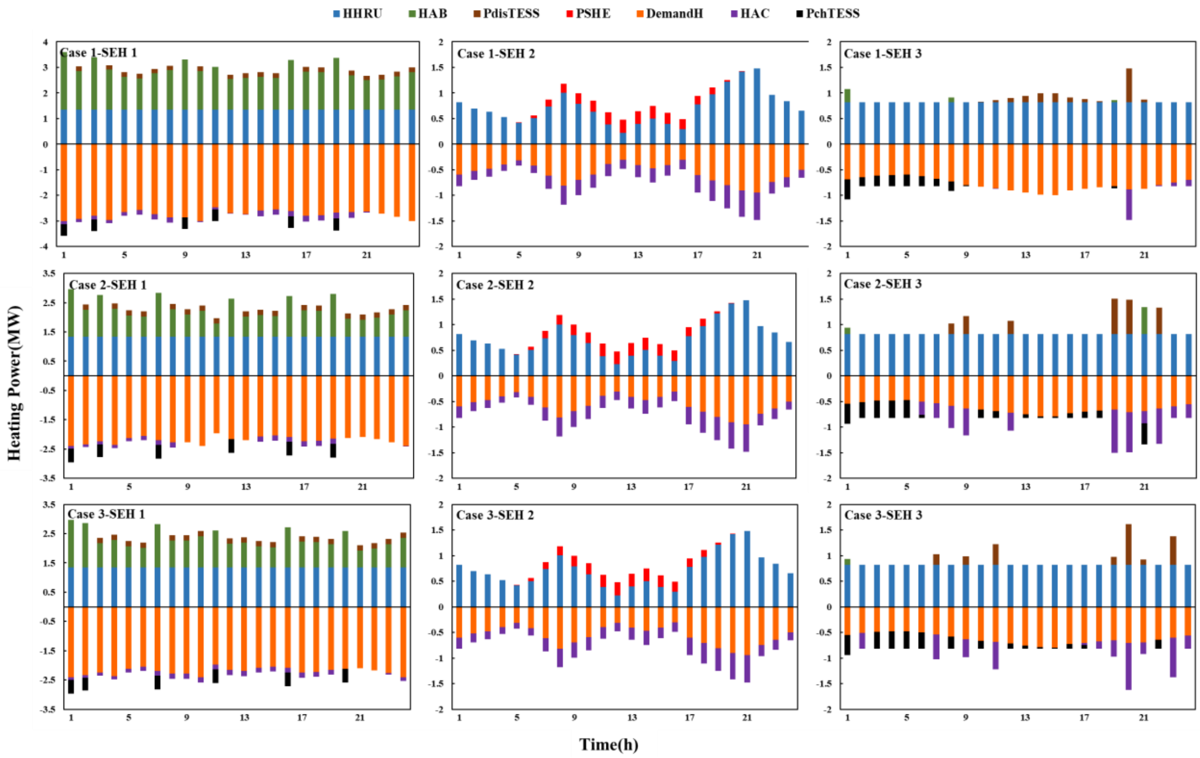

Fig. 11. Heating power flow at SEHs.

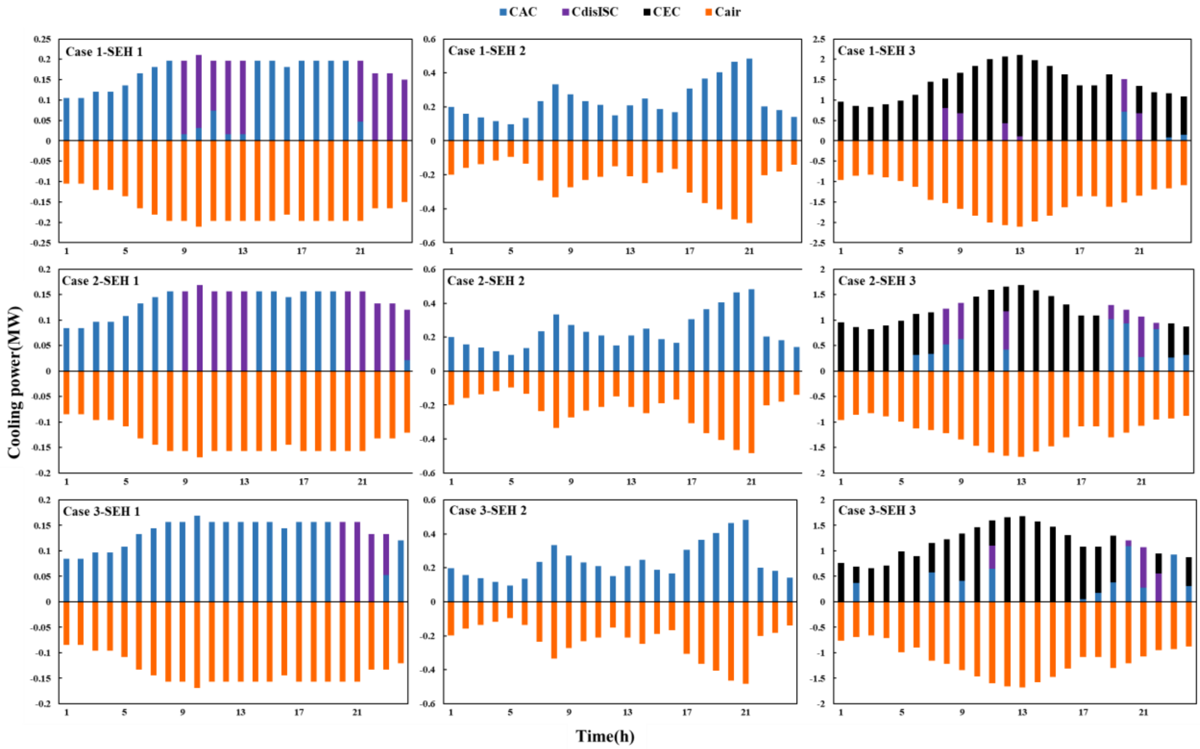

Fig. 12. Cooling power flow at SEHs.

TABLE 3 illustrates the fluctuations in total costs across cases 1 through 3. The utilization of the DR program and the P2P transactive energy has resulted in a reduction of the total cost by 11.2%. In contrast, the implementation of the flexibility constraint with the objective of enhancing the system's flexibility has resulted in a 9.5% rise in operating costs in comparison to Case 2. It is apparent that a decrease in the variable "$P^{Flexibility}$" results in an escalation of the overall system cost. This phenomenon will be thoroughly evaluated through sensitivity analysis in the subsequent section.

C. sensitivity analysis

The flexibility of the interdependence between the upstream grid and SEHs is contingent upon the smooth continuity of the energy exchange graph, which should lack sudden fluctuations. As illustrated in Fig. 13, a decrease in the $P^{Flexibility}$ value corresponds to a reduction in the ramp rate of power exchanged with the upstream grid. This subsequently constrains the ability of energy hubs to meet their energy demands, thereby necessitating a greater reliance on productions from PGUs. Consequently, the cost of system operation and carbon emission experiences an escalated trajectory. Based on the findings depicted in Fig. 13, the selection of $P^{Flexibility}$ by operators should be strategically implemented to ensure the concurrent optimization of the flexibility and total cost of system.

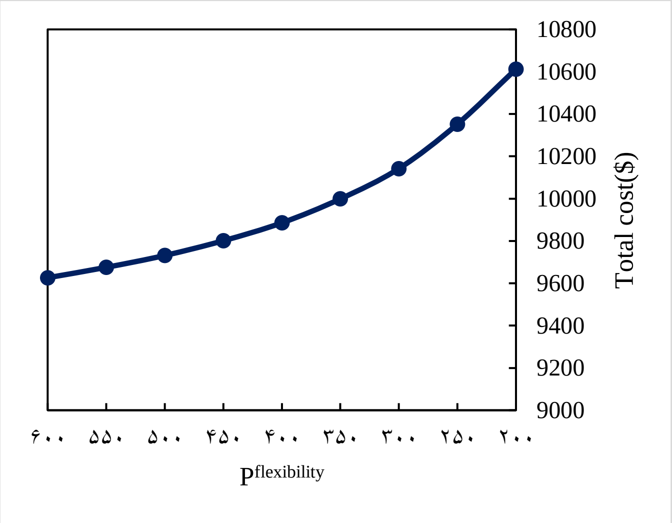

Fig. 13. Sensitivity analysis on Pflexibility

V. Conclusion

In recent years, there has been a surge in need for a variety of energy carriers and a requisite to provide high levels of reliability for fulfilling various energy requirements, with a focus on achieving optimal and economically efficient utilization of energy resources. Consequently, the concept of multi-energy systems has emerged as a solution to these challenges. The concept of energy hub has gained widespread adoption as a potential solution for the utilization of multi-carrier energy systems (MCESs) in various applications. The

SEHs architecture proposed in this study introduces a generic method for reducing the costs of transferring, conversion, and saving energies and optimal dispatch in MG. Furthermore, in this article, special attention has been paid to the flexibility of the system by flexibility constraint. It is noteworthy that the method adopted herein is limited to steady-state energy flow analysis. However, it holds potential for utility in the study of dynamic energy flow as well. In certain instances, wherein the MGO does not possess ownership of specific equipment, such as CCCHP, WT, PV, TESS, SPCAES, and ISC, it is imperative to take into account the investment cost of the said components in relation to the electricity price proffered by the equipment owners to the MGO. The examination of the equipment matter may be analyzed as a prospective area of research.

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Ali Riki earned his B.Sc. in Electrical Engineering from Ferdowsi University of Mashhad, Iran, in 2021, followed by an M.Eng. from the Department of Electrical Engineering at Sistan and Balouchistan University, Zahedan, Iran, in 2023. He is currently pursuing a joint Ph.D. at the Department of Electrical Engineering at Bahonar University of Kerman. His research interests focus on power system optimization, energy hubs, and energy management.

Mahmoud Oukati Sadegh was born in 1966 in Zabol, Iran. He received the B.Sc. and M.Sc. degree in electrical power system engineering from Tehran University, Tehran, Iran, in 1989 and 1992 respectively. the Ph.D. degree in electrical engineering from Strathclyde University in Glasgow, UK in2003. Currently, he is an Assistant Professor in the Department of lectrical and Electronic Engineering, University of Sistan and Baluchestan, Zahedan, Iran. His research interests are power system control and operation, Electrical distribution system and Smart grids.

Omid Narouie received the B.Sc. degree in electrical engineering from Shahid Rajaee Teacher Training University, Tehran, Iran, in 2017, and the M.Eng. degree from the Department of Electrical Engineering, Sistan and Balouchistan University, Zahedan, Iran, in 2021. He is currently working toward the joint Ph.D. degree with the Department of Electrical Engineering, Sistan and Balouchistan University. His research interests include power system optimization, power system resilience, restoration and energy management.