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Transactive Energy Framework for Optimal Energy Management of Multi-Carrier Energy Hubs Under Local Electrical, Thermal, and Cooling Market Constraints

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Abstract

The interactions among the multi-carrier energy system provide the opportunity to achieve affordable and clean energy by using energy resources in a more efficient way. In this paper, a transactive energy (TE) framework for optimal energy management of multiple energy hubs (EHs) is proposed. Each EH is a multi-carrier energy system performing day-ahead energy management to schedule its electrical, thermal, and cooling demand profiles and manages its internal energy resources to reduce total energy expenses and the emission level of CO_2. In the first step, each EH indicates the expected surplus/deficit electrical, thermal, and cooling energies, which need to be traded with either district or local markets. Then, in the next step, EHs participate in different markets to trade various forms of energy with each other and to improve their energy efficiency. In the local markets, EHs participate in the peer-to-peer (P2P) energy trading by offering their energy surplus/deficit to other EHs. Case studies demonstrate that the proposed framework reduces the reliance of EHs on the district markets, which in turn reduces EHs energy cost by 22%, and decreases emitted CO_2 by 13%.

Keywords: Energy hub, optimal scheduling, transactive energy, local markets, peer-to-peer (P2P) trading.

Nomenclature

Abbreviations

AC	Absorption chiller
CCHP	Combined cooling, heating, and power
CS	Cooling storage
EC	Electric chiller
EH	Energy hub
ES	Electrical storage
EX	Exchanger
GB	Gas boiler
GT	Gas turbine
ICS	Ice storage conditioner
LMO	Local market operator
P2P	Peer-to-peer
PV	Photovoltaic
ST	Solar thermal
TE	Transactive energy
TS	Thermal storage
WT	Wind turbine

Indices and sets

$\mathcal{H}$	Set of time slots, $h \in \mathcal{H}$
$\mathcal{M}$	Set of EH offer's steps, $m \in \mathcal{M}$
$\mathcal{N}$	Set of EHs, $i, j \in \mathcal{N}$
$\mathcal{S}$	Set of scenarios, $s \in \mathcal{S}$

Parameters

β_e/β_G	Generated CO_2 due to consuming electricity/gas (kg/kWh)
Δh	Time interval (h)
$\kappa_{pv,i}/\kappa_{st,i}/\kappa_{wt,i}$	Number of PV/solar thermal/wind turbine units

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$\mathcal{I}$	Solar irradiation (kW/m^2)
ν_{ws}	Wind speed (m/s)
$\nu^{in}_{wt,i}/\nu^{r}_{wt,i}/\nu^{out}_{wt,i}$	Cut-in/rated/cut-out speed of wind turbine (m/s)
ρ	Cost equivalent of emitted CO$_2$ per kilogram (¢/kg)
ς_i, ϱ_i	Bidding factors of EH i (¢/kWh)
$\zeta_{es,i}/\zeta_{ts,i}/\zeta_{cs,i}$	Degradation cost of electrical/thermal/cooling storage (¢/kWh)
$A_{pv,i}/A_{st,i}$	Surface area of photovoltaic/solar thermal panel (m^2)
$\delta_{es,i}/\delta_{ts,i}/\delta_{cs,i}$	Energy loss ration of electrical/thermal/cooling storage
$\eta_{ac,i}/\eta_{ec,i}$	Efficiency of absorption/electric chiller
$\eta^c_{es,i}/\eta^c_{ts,i}/\eta^c_{cs,i}$	Charge efficiency of electrical/thermal/cooling storage
$\eta^d_{es,i}/\eta^d_{ts,i}/\eta^d_{cs,i}$	Discharge efficiency of electrical/thermal/cooling storage
$\eta_{gb,i}/\eta_{ex,i}/\eta_e$	Efficiency of gas boiler/heat exchanger/electrical transformer
$\eta_{gt,e,i}/\eta_{gt,t,i}$	Efficiency of generated electricity/heat by gas turbine
$\eta_{pv,i}/\eta_{st,i}$	Efficiency of photovoltaic/solar thermal panel
λ_G	Purchased gas price (¢/kWh)
$\lambda^+_{U,e}/\lambda^+_{U,t}/\lambda^+_{U,c}$	Buying price of district electricity/thermal/cooling market (¢/kWh)
$\lambda^-_{U,e}/\lambda^-_{U,t}/\lambda^-_{U,c}$	Selling price of district electricity/thermal/cooling market (¢/kWh)
$\overline{C}_{ac,i}/\overline{P}_{ec,i}$	Maximum capacity of absorption chiller/electric chiller (kW)
$\overline{H}_{gb,i}/\overline{P}_{gt,i}/\overline{P}_{wt,i}$	Maximum capacity of gas boiler/gas turbine/wind turbine (kW)
$\overline{P}^c_{es,i}/\overline{P}^d_{es,i}$	Maximum charge/discharge rate of electrical storage (kW)
$\overline{P}^{+/-}_{U,i}/\overline{H}^{+/-}_{U,i}/\overline{C}^{+/-}_{U,i}$	Maximum limit of exchanging power with district markets (kW)
$\underline{E}_{es,i}/\overline{E}_{es,i}$	Minimum/maximum stored energy in the electrical storage (kWh)
$D_{e,i}/D_{t,i}/D_{c,i}$	Electricity/thermal/cooling demand of EH i (kW)

Variables

$\chi^{+/-}_{e,i}/\chi^{+/-}_{t,i}/\chi^{+/-}_{c,i}$	Binary variables indicating importing/exporting energy from/to electrical/thermal/cooling market
$\chi^c_{es,i}/\chi^d_{es,i}$	Binary variables indicating charge/discharge operation mode of electrical storage
$C_{ec,i}/C_{ac,i}$	Generated cold power by electric/absorption chiller (kW)
$H_{ac,i}$	Consumed heat by absorption chiller of EH i (kW)
$H_{gb,i}/H_{st,i}/H_{ex,i}$	Generated heat by gas boiler/solar thermal/heat exchanger (kW)
$P_{ec,i}$	Consumed electricity by electricity chiller of EH i (kW)
$P_{pv,i}/P_{gt,i}/P_{wt,i}$	Generated power by PV/gas turbine/wind turbine/ (kW)
$TC_{e,i}/TC_{t,i}/TC_{c,i}$	Total electricity/thermal/cooling power consumption by EH i (kW)
$E_{es,i}/E_{ts,i}/E_{cs,i}$	Stored energy in electrical/thermal/cooling storage of EH i (kWh)
$P^c_{es,i}/P^c_{ts,i}/P^c_{cs,i}$	Charged power by electrical/thermal/cooling storage (kW)
$P^d_{es,i}/P^d_{ts,i}/P^d_{cs,i}$	Discharged power by electrical/thermal/cooling storage (kW)
$P^{+/-}_{L,i}/H^{+/-}_{L,i}/C^{+/-}_{L,i}$	Imported/exported power by EH i from/to local electricity/thermal/cooling market (kW)
$P^{+/-}_{U,i}/H^{+/-}_{U,i}/C^{+/-}_{U,i}$	Imported/exported power by EH i from/to district electricity/thermal/cooling market (kW)
$\gamma^*_{e,i\to j}/\gamma^*_{t,i\to j}/\gamma^*_{c,i\to j}$	Energy price in transaction between EH i and j (¢/kWh)
$\gamma^{-/+}_{e,i}/\gamma^{-/+}_{t,i}/\gamma^{-/+}_{e,i}$	Offer/bid price by EH i for selling/buying energy in local electricity/thermal/cooling market (¢/kWh)
$\hat{P}^{+/-}_{E,i}/\hat{H}^{+/-}_{E,i}/\hat{C}^{+/-}_{E,i}$	Scheduled electrical/thermal/cooling power to be imported/exported by EH i from external resources (kW)
$\Theta^{-/+}_{e,i}/\Theta^{-/+}_{t,i}/\Theta^{-/+}_{e,i}$	Offer/bid of EH i in local electricity/thermal/cooling market
$P^*_{L,i\to j}/H^*_{L,i\to j}/C^*_{L,i\to j}$	Allocated electrical/thermal/cooling power from EH i to EH j (kW)

1. Introduction

1.1. Motivations and prior art

Recently, due to global concerns about climate change, deployment of distributed energy resources (DERs) and electrical and thermal energy storage has been accelerated to minimize CO$_2$ emissions. Besides, the optimal energy management of these energy resources has been accentuated to decrease the need for new energy resources. A promising way for efficient energy management is combining the use of electricity, heat, cooling, and natural gas. Hence, energy hubs (EHs) are proposed as an interface between different energy infrastructures, which help to model and manage multi-carrier energy systems [1, 2]. In an EH, different forms of energy are generated, and by having appropriate energy couplings and conversions, they will be used for various types of energy demands [3].

Energy management of EHs and combined cooling, heating and power (CCHP) systems has been extensively studied in the literature. A robust scheduling algorithm for EHs is presented in [4] in which both economic and environmental constraints are considered. In [5], the information gap decision technique has been employed to manage the uncertain nature of hybrid electric vehicles' energy consumption in EH system. The scheduling problem of EHs in a dynamic pricing market is investigated in [6], where a distributed algorithm is developed to determine the profit-maximizing strategies of EHs. In [7], a hybrid framework for optimal operation of EH is proposed, in which thermal energy market, as well as thermal and electrical demand response programs, are considered to reduce operation cost of the hub by managing its flexible energy resources. Short-term scheduling of a CCHP system considering the demand response program is presented in [8]. The coordinated operation of the multi-CCHP system is presented in [9], in which the fluctuation of renewable energy sources generation is transferred to gas distribution network and cooling or heating system. Pan *et al.* [10] have proposed a planning approach for CCHP systems, where a load aggregator manages loads of end-users in an integrated demand response program. A two-stage coordinated control approach for CCHP energy management is proposed in [11], in which economic dispatch and real-time adjusting are considered to handle uncertainties.

In the renewable generation-based EH systems, modeling uncertainties in the energy scheduling problem is of the utmost importance. Stochastic models are used in [12, 13, 14] to model uncertainties in prices and demands for energy scheduling of multi-carrier energy systems. In [15], chance-constrained programming is added to address the uncertainty factors of renewable energy generation and cooling, heating, and electrical demands. A stochastic approach for evaluating the impact of storage units on the performance of EHs is proposed in [16], where the uncertainty of EHs loads is considered. In [17], the operation of multi-EHs has been optimized considering demand and generation uncertainties. The operation of multi-EHs has been scheduled under the generation and price uncertainties in [18].

The CO_2 emission minimization is taken into account in the optimization problem in several studies. Lue *et al.* [19] considered the societal cost of CO_2 as the monetary value of the damage caused by the emission of an additional ton of carbon dioxide to the environment. In [20], the optimal energy management of EHs is modeled as a multi-objective optimization problem, which maximizes social welfare and minimizes CO_2 emissions. The works in [21, 22] have considered a penalty factor for gas emission in the optimization problem to reduce greenhouse gases emission. Multi-objective optimization is employed in [23, 24, 25] for optimal energy management of EHs with the aim to reduce both cost and emitted carbon of an EH system. In [26], it is shown that by constraining the optimization model for the operational planning of CCHPs, the annual CO_2 emissions of a given area can be reduced. The information gap decision theory has been used in [27] to manage the stochastic-nature of the wind speed in the multi-EH system considering economic and environmental constraints.

Multi-carrier energy systems can participate in district markets to minimize their operation costs. The power trading of a CCHP system with electricity markets is modeled in [28], where a stochastic-robust optimization is considered to minimize both the expected operational cost and potential risk of cost increase related to market price scenarios. In [29], the ability of a CCHP system to sell electricity to the grid is taken into account. However, the energy saving or economic saving of the excess electricity is not considered, as it is assumed that producing excess electricity is not encouraged for CCHP systems. The work in [30], assumed that the excess electricity generation by CCHPs could be fed back into the power grid at a subsidized price. Mirzapour *et al.* [3] proposed a bi-level approach to model the interaction of EHs and distribution networks aiming to minimize the cost of distribution networks.

Recently, transactive energy (TE) has been introduced as a novel approach for energy management based on control and economic signals that allows the dynamic balance of supply and demand using value as a key operational parameter [31]. TE provides a market-based solution for energy management based on economic incentives and ensures that the economic signals are in line with operational goals to ensure system reliability without resorting to override control [32]. Some recent works have studied market-based solutions for optimal energy management of EHs considering energy exchange among EHs. In [33], a transactive based energy management framework for coordinating multiple EHs is presented, in which a peer-to-peer (P2P) platform is employed to improve the economic performance of EHs. Wang *et al.* [34] proposed a TE framework to minimize the operation cost of multiple connected EHs, in which a bi-level bargaining method is used to model the cooperative trading process of EHs. However, this work assumes that all EHs are managed by the same operator, which is responsible for solving the optimization problem centrally. A TE framework for the energy management of EHs in smart communities is presented in [35], where a bi-level model is developed to manage the day-ahead scheduling of the EH. However, the energy trading and coordination of multiple EHs are not investigated.

Most of the studies in the literature focused on the participation of CCHPs and EHs in the local and district electricity markets and neglected the thermal and cooling energies. A cooperative energy scheduling and trading of a community of EHs is proposed in [36], where multiple neighboring EHs cooperated to minimize their operational costs. However, this work only considered exchange of electricity without taking into account thermal and cooling energy trading. In [37], the virtual EH is introduced as a new approach for energy scheduling of EHs, in which EHs can participate in electrical and thermal energy markets to optimize their revenue, but no cooling market is considered. A local market for energy management of microgrids as EHs is proposed in [38], in which microgrids can exchange electricity, heat, and cooling energies among themselves and with the external system. However, the cost associated with CO_2 emission and uncertainties of price and energies are not considered. In summary, in the existing literature, there is a gap in designing a holistic framework for energy management of EHs with all of the following features:

- Incorporating CO_2 emission cost and electrical, thermal, cooling, and gas market prices in the uncertain-based optimization problem;
- Considering participation of EHs in local and district markets to trade different forms of energy;

Table 1 shows a comparison between the proposed method in this paper and the state-of-the-art.

1.2. Contributions

This paper designs a TE framework for energy and emission management of multiple EHs, considering energy scheduling and trading among them. Each EH is an independent entity performing a stochastic energy scheduling to minimize its operation costs and CO_2 emissions. Then, EHs participate in local markets to trade energy with each other to improve their energy efficiency by reducing energy exchanges with district markets. The market settlement in local markets is based on a double auction, in which EHs submit their offers and bids for energy trading based on their scheduled energies. The local market is managed by a non-profit entity named as local market operator (LMO) who coordinates energy trading among EHs. The contributions of this paper are summarized as follows:

- A TE framework for energy management and trading of multiple EHs is proposed, which allows EHs to schedule their resources to minimize CO_2 emission and energy costs, and enables them to participate in competitive local markets for energy trading.
- An opt-in local market is designed for trading electrical, thermal, and cooling energies among EHs, where EHs participate in a double auction by submitting their offers and bids for energy trading based on their scheduled energy profile.
- The strategy of EHs for participating in local markets is proposed, in which seller EHs generate a multi-step offer based on the source of the surplus energy.

1.3. Paper organization

The remainder of the paper is organized as follows. In Section 2, the market structure for TE energy management is described. Section 3 presents the problem formulation for EH energy scheduling, where the optimization problem for a holistic EH model is presented. In Section 4, the trading process in local markets is presented, in which the local market problem, formulation of EHs offers, and market clearing process are explained. Simulation results are discussed in Section 5, and conclusions are drawn in Section 6.

Table 1: Comparison of the proposed framework with previous studies on energy management of EHs.

Reference	**Components of the model**	**CO$_2$**	**Participation in district market**			**Participation in local market**			**Uncertainties**		
		emission	Electricity	Thermal	Cooling	Electricity	Thermal	Cooling	Demand	Generation	Price
[3]	CHP, WT, central air conditioning, boiler, static VAR compensator	✗	✔	✗	✗	✔	✗	✗	✗	✗	✗
[4]	WT, PV, ST, GT, GB, EX, ES, CS, EC, AC, TS	✔	✔	✗	✗	✗	✗	✗	✗	✗	✔
[5]	PV, WT, TS, fuel cell vehicles, hydrogen unit, boiler, inverter, rectifier	✗	✔	✗	✗	✗	✗	✗	✔	✗	✗
[6]	CHP, ES, microturbine, gas furnace	✗	✔	✗	✗	✗	✗	✗	✔	✗	✔
[7]	TS, ES, CHP, boiler	✗	✔	✗	✗	✗	✗	✗	✔	✔	✔
[11]	GT, WT, EC, AC, ES, GB, TS, EX, PV, heat recovery	✗	✗	✗	✗	✗	✗	✗	✔	✔	✗
[12]	PV, GB, GT, EX, AC, EC	✗	✗	✗	✗	✗	✗	✗	✔	✔	✗
[13]	GT, GB, AC, EC, WT, PV, ES, CS, TS	✗	✗	✗	✗	✗	✗	✗	✗	✔	✗
[14]	WT, PV, AC, EX, TS, CS, thermal recovery, heat pump, solar heated water unit, power generation unit	✗	✗	✗	✗	✗	✗	✗	✔	✔	✗
[15]	PV, WT, ES, EC, AC, EX, GB, GT, heat recovery, heat tank	✔	✔	✗	✗	✔	✗	✗	✔	✔	✗
[16]	WT, CHP, boiler, ES, TS, power plant	✗	✔	✗	✗	✗	✗	✗	✔	✗	✗
[17]	WT, PV, CHP, Boiler, TS, ES, Diesel Generator	✗	✔	✔	✗	✗	✗	✗	✔	✔	✗
[18]	WT, PV, CHP, TS, ES, ICS, boiler, AC, compression chiller, electric vehicle	✗	✔	✔	✔	✗	✗	✗	✗	✔	✔
[19]	ES, PV, EC, AC, ST, diesel generator, water tank	✔	✗	✗	✗	✗	✗	✗	✗	✗	✗
[20]	PV, WT, CHP, ES, TS, gas-fired generator, gas storage, boiler	✔	✔	✗	✗	✗	✗	✗	✗	✔	✗
[21]	CHP, ES, boiler	✔	✔	✗	✗	✗	✗	✗	✔	✗	✔
[22]	WT, PV, GT, GB, EX, ES, TS, CS, EC, AC	✔	✔	✗	✗	✗	✗	✗	✗	✗	✔
[23]	GT, GB, EX, TS, ES, CS, EC, AC, PV, WT	✔	✔	✗	✗	✗	✗	✗	✗	✗	✗
[24]	PV, WT, GT, GB, EC, AC, ES, TS, CS	✔	✔	✗	✗	✗	✗	✗	✗	✗	✗
[25]	ES, PV, EC, AC, TS, diesel generator, desalination, water tank	✔	✗	✗	✗	✗	✗	✗	✗	✗	✗
[26]	AC, GT,ES, EC,CS, PV, TS, boiler, ground source heat pump	✔	✔	✗	✗	✗	✗	✗	✔	✗	✗
[27]	CHP, GB, WT, ES, TS, thermal units, Power-to-heat storage	✔	✔	✗	✗	✗	✗	✗	✗	✔	✗
[28]	ES, AC, TS, WT, GB ,microturbine, heat recovery	✗	✔	✗	✗	✗	✗	✗	✗	✔	✔
[29]	GT, TS, EC, AC, EX, heat recovery, boiler	✔	✔	✗	✗	✗	✗	✗	✗	✗	✗
[30]	WT, PV, TS, EC, AC, GT, compressed air energy storage, cooling tower, boiler, Jack water exhauster	✔	✔	✗	✗	✗	✗	✗	✗	✔	✗
[34]	CHP, ES, TS, boiler	✗	✔	✗	✗	✔	✗	✗	✗	✗	✗
[36]	CHP, ES, TS	✗	✔	✗	✗	✔	✗	✗	✗	✗	✗
[37]	CHP, EX, WT, ES, boiler, electric heat pump, compressed air energy storage	✗	✔	✔	✗	✔	✔	✗	✗	✔	✗
[38]	ES, CHP, AC, electric heat pump	✗	✔	✔	✔	✔	✔	✔	✗	✗	✗
This work	PV, WT, GT, GB, ST, EX, AC, EC, ES, TS, CS	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔

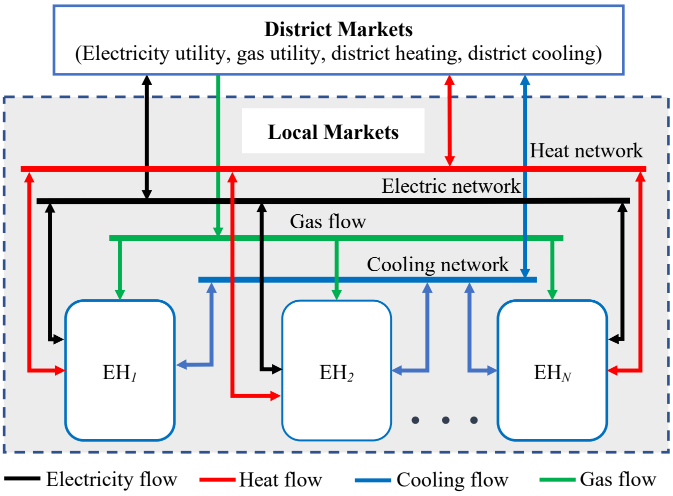

Figure 1: Transactive energy market structure with multiple EHs.

2. TE Framework

The framework considered for this study is a local TE market consisting of $\mathcal{N}$ interconnected EHs, as shown in Fig. 1. Each EH can be equipped with all or some of the following devices: wind turbine (WT), photovoltaic (PV), gas turbine (GT), gas boiler (GB), heat exchanger (EX), solar thermal (ST), electric storage (ES), electric chiller (EC), thermal storage (TS), absorption chiller (AC), and ice storage conditioner (ICS). These components generate, consume or convert different types of energy, including electrical, thermal, and cooling energies. Each EH is equipped with an energy management system, which performs a day-ahead energy scheduling to minimize the daily operation cost. The energy scheduling objective is to manage local resources such that the total daily costs related to purchasing electricity and gas, degradation cost, and cost equivalent of CO_2 are minimized.

It is assumed that EHs have access to district markets, in which they can trade various forms of energy. In addition, we define a local market, which allows EHs to trade energy among themselves in a P2P market. Participation in local markets is opt-in for EHs, which means that they can continue to obtain energy within the existing district markets. It is assumed that these EHs are connected to the same electrical network, and there are district heating and cooling networks that can be used to transfer energy between EHs in the local market. Depending on their structure, EHs have different capabilities in generating and converting energy, and their generation and demand profiles would be different. EHs may have surplus or deficit energy at different time intervals and participate in local markets as sellers or buyers (depending on their scheduled energies) by submitting their offers or bids to the LMO for each type of energy. Then, the LMO allocates energy from seller EHs to buyer EHs and indicates the price in each transaction.

3. Energy Scheduling of EH

3.1. Multi-carrier EH modeling

The structure of the proposed EH is shown in Fig. 2. The EH contains different components, which generates, consumes, and converts energy at different levels. The inputs of EH are the electricity, thermal, and cooling energy from local and district markets, while a gas utility company provides the required gas for GTs and GBs. The EH resources for electricity generation include WT, GT, and PV. The GB and ST are resources for generating thermal energy. The EC and AC convert electricity and heat to the cooling energy, respectively, and are the resources that provide EH with the cooling energy. Moreover, the EH is equipped with ES and TS to store electrical and thermal energy. ISC is considered as cooling storage (CS), which consumes electrical energy during off-peak hours and generates cooling energy when it is required. In

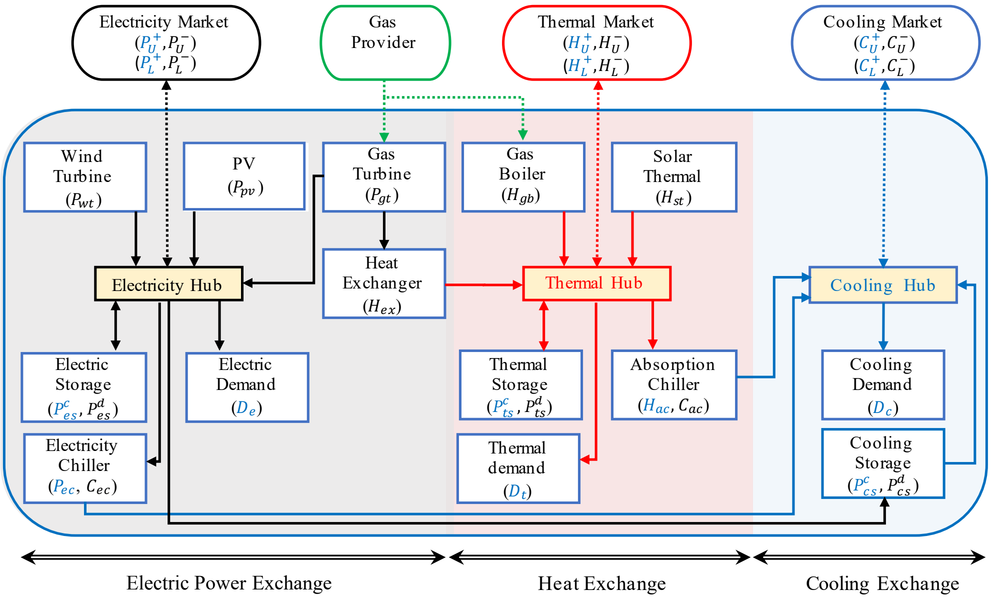

Figure 2: Energy Hub structure. The solid lines indicate energy exchange among components of EH, while the dashed line represents the energy exchange with external resources. For each component, input/output variables are given in the parentheses, in which text in blue denotes an input variable, and text in black denotes an output variable.

the EH, demands can be fulfilled by the internal resources and trading with external resources such as local markets and district markets.

3.2. *Objective function*

In the first step, each EH optimizes the scheduling of all of its components to minimize daily operation costs. The objective function of energy scheduling is given by

$$\begin{aligned}
\min_{\Gamma_i^P} \quad \sum_{h\in\mathcal{H}}\sum_{s\in\mathcal{S}}[(\lambda_{U,e}^{+,h,s}\frac{\hat{P}_{E,i}^{+,h,s}}{\eta_{e,i}} &+ \lambda_{U,t}^{+,h,s}\hat{H}_{E,i}^{+,h,s} + \lambda_{U,c}^{+,h,s}\hat{C}_{E,i}^{+,h,s}) \\
&- (\lambda_{U,e}^{-,h}\hat{P}_{E,i}^{-,h,s} + \lambda_{U,t}^{-,h}\hat{H}_{E,i}^{-,h,s} + \lambda_{U,c}^{-,h}\hat{C}_{E,i}^{-,h,s}) \\
&+ \zeta_{es,i}P_{es,i}^{d,h,s} + \zeta_{ts,i}P_{ts,i}^{d,h,s} + \zeta_{cs,i}P_{cs,i}^{d,h,s} \\
&+ \zeta_{es,i}P_{es,i}^{c,h,s} + \zeta_{ts,i}P_{ts,i}^{c,h,s} + \zeta_{cs,i}P_{cs,i}^{c,h,s} \\
&+ \rho(\beta_e\frac{\hat{P}_{E,i}^{+,h,s}}{\eta_{e,i}} + \beta_G(\frac{P_{gt,i}^{h,s}}{\eta_{gt,e,i}} + \frac{H_{gb,i}^{h,s}}{\eta_{gb,i}})) \\
&+ \lambda_G(\frac{P_{gt,i}^{h,s}}{\eta_{gt,e,i}} + \frac{H_{gb,i}^{h,s}}{\eta_{gb,i}})]\pi_s\Delta h \\
&\text{s.t.} \quad (2)-(19)
\end{aligned} \tag{1}$$

where $\Gamma_i^P = \{\hat{P}_{E,i}^{+/-,h,s}, \hat{H}_{E,i}^{+/-,h,s}, \hat{C}_{E,i}^{+/-,h,s}, P_{es,i}^{d,h,s}, P_{ts,i}^{d,h,s}, P_{cs,i}^{d,h,s}, P_{es,i}^{c,h,s}, P_{ts,i}^{c,h,s}, P_{cs,i}^{c,h,s}, P_{gt,i}^{h,s}, H_{gb,i}^{h,s}\}$ are the set of decision variables of EH i in the energy scheduling problem. The first line of (1) is the total cost of buying energy from external resources. The second line indicates the profit of selling energy, while the third and forth lines indicate the degradation cost of discharging and charging storage units, respectively. The equivalent cost of CO$_2$ emission is calculated in the fifth line, which is composed of the equivalent emission costs for electricity purchased from the utility grid and gas purchased from gas grid [39]. Finally, the sixth line denotes the cost of buying gas from the utility gas company.

3.3. Constraints

The optimization problem in (1) is subject to the constraints associated with EH's components, as well as energy balance constraints. The generated power by PVs and STs depends on the surface area of the panel, the forecasted solar irradiation, and the efficiency of the PV and ST. The output power of a PV and ST system is given by (2), and (3), respectively

$$P^{h,s}_{pv,i} = A_{pv,i}\mathcal{I}^{h,s}\eta_{pv,i} \tag{2}$$

$$P^{h,s}_{st,i} = A_{st,i}\mathcal{I}^{h,s}\eta_{st,i}. \tag{3}$$

The WT generates power if the wind speed is higher than its cut-in speed and lower than the cut-out speed. In this case, the generated power is a function of wind speed and the rated speed of WT. The generated power by a WT at different wind speeds is given by the following equation.

$$P^{h,s}_{wt,i} = \begin{cases} 0 & \nu^{h,s}_{ws} < \nu^{in}_{wt,i} \text{ or } \nu^{h,s}_{ws} > \nu^{out}_{wt,i} \\ \overline{P}_{wt,i}(\frac{\nu^{h,s}_{ws} - \nu^{in}_{wt,i}}{\nu^{r}_{wt,i} - \nu^{in}_{wt,i}})^3 & \nu^{in}_{wt,i} \leq \nu^{h,s}_{ws} \leq \nu^{r}_{wt,i} \\ \overline{P}_{wt,i} & \nu^{r}_{wt,i} \leq \nu^{h,s}_{ws} \leq \nu^{out}_{wt,i} \end{cases} \tag{4}$$

The electrical energy storage is modeled using (5). The stored energy in the storage in each time slot depends on the amount of stored energy in the previous time slot, charged and discharged energy to/from storage as in (5a). Equations (5b) and (5c) bound the charged and discharged energy at each time slot. Equation (5d) avoids battery from being charged and discharged simultaneously. The stored energy in the storage is bounded by (5e) to reduce the degradation cost.

$$E^{h,s}_{es,i} = E^{h-1,s}_{es,i}(1 - \delta_{es,i}) + (P^{c,h,s}_{es,i}\eta^{c}_{es,i}) - (\frac{P^{d,h,s}_{es,i}}{\eta^{d}_{es,i}}) \tag{5a}$$

$$0 \leq P^{c,h,s}_{es,i} \leq \overline{P}^{c}_{es,i}\chi^{c,h}_{es,i} \tag{5b}$$

$$0 \leq P^{d,h,s}_{es,i} \leq \overline{P}^{d}_{es,i}\chi^{d,h}_{es,i} \tag{5c}$$

$$\chi^{c,h,s}_{es,i} + \chi^{d,h,s}_{es,i} \leq 1 \tag{5d}$$

$$\underline{E}_{es,i} \leq E^{h,s}_{es,i} \leq \overline{E}_{es,i}. \tag{5e}$$

In a similar way, the modeling of thermal and cooling storage systems are formulated. The EC absorbs electrical energy and converts it to cooling energy as in (6a). The absorbed electric energy by the EC is bounded by (6b).

$$C^{h,s}_{ec,i} = P^{h,s}_{ec,i}\eta_{ec,i} \tag{6a}$$

$$0 \leq P^{h,s}_{ec,i} \leq \overline{P}_{ec,i}. \tag{6b}$$

The AC absorbs heating energy from the thermal hub and converts it to cooling energy as in (7a), and this generated cooling energy is limited by (7b).

$$C^{h,s}_{ac,i} = H^{h,s}_{ac,i}\eta_{ac,i} \tag{7a}$$

$$0 \leq C^{h,s}_{ac,i} \leq \overline{C}_{ac,i}. \tag{7b}$$

The generated heat power by a GB is bounded by (8). Similarly, the generated electricity by a GT is limited by (9). The heat exchanger converts the generated power by the GT to heating energy as in (10), where the generated heating energy depends on the efficiency of the exchanger and the GT.

$$0 \leq H^{h,s}_{gb,i} \leq \overline{H}_{gb,i} \tag{8}$$

$$0 \leq P_{gt,i}^{h,s} \leq \overline{P}_{gt,i} \tag{9}$$

$$H_{ex,i}^{h,s} = \eta_{ex,i}\eta_{gt,t,i}\frac{P_{gt,i}^{h,s}}{\eta_{gt,e,i}}. \tag{10}$$

The imported/exported energy by each EH from/to electricity, thermal and cooling market is limited by a maximum limit as in (11)-(13). These constraints represents the maximum capacity of the tie-line between EH and district markets. Also, (14)-(16) are considered to avoid the EH from importing and exporting energy simultaneously.

$$0 \leq P_{U,i}^{+/-,h,s} \leq \overline{P}_{U,i}^{+/-} \chi_{e,i}^{+/-,h,s} \tag{11}$$

$$0 \leq H_{U,i}^{+/-,h,s} \leq \overline{H}_{U,i}^{+/-} \chi_{t,i}^{+/-,h,s} \tag{12}$$

$$0 \leq C_{U,i}^{+/-,h,s} \leq \overline{C}_{U,i}^{+/-} \chi_{c,i}^{+/-,h,s} \tag{13}$$

$$\chi_{e,i}^{+,h,s} + \chi_{e,i}^{-,h,s} \leq 1 \tag{14}$$

$$\chi_{t,i}^{+,h,s} + \chi_{t,i}^{-,h,s} \leq 1 \tag{15}$$

$$\chi_{c,i}^{+,h,s} + \chi_{c,i}^{-,h,s} \leq 1. \tag{16}$$

In each hub, the total produced energy has to be equal to the demand at each period. Therefore, the energy balance constraints for electricity, heating and cooling energy can be written as (17), (18) and (19) respectively

$$\overbrace{D_{e,i}^{h,s} + P_{es,i}^{c,h,s} + P_{cs,i}^{c,h,s} + P_{ec,i}^{h,s} + \hat{P}_{E,i}^{+,h,s}}^{TC_{e,i}^{h,s}} = P_{es,i}^{d,h,s} + \kappa_{wt,i}P_{wt,i}^{h,s} + P_{gt,i}^{h,s} + \kappa_{pv,i}P_{pv,i}^{h,s} + \hat{P}_{E,i}^{-,h,s} \tag{17}$$

$$\overbrace{D_{t,i}^{h,s} + H_{ac,i}^{h,s} + P_{ts,i}^{c,h,s} + \hat{H}_{E,i}^{+,h,s}}^{TC_{t,i}^{h,s}} = H_{gb,i}^{h,s} + \kappa_{st,i}H_{st,i}^{h,s} + H_{ex,i}^{h,s} + P_{ts,i}^{d,h,s} + \hat{H}_{U,i}^{-,h,s} \tag{18}$$

$$\overbrace{D_{c,i}^{h,s} + \hat{C}_{E,i}^{+,h,s}}^{TC_{c,i}^{h,s}} = C_{ec,i}^{h,s} + C_{ac,i}^{h,s} + P_{cs,i}^{d,h,s} + \hat{C}_{E,i}^{-,h}. \tag{19}$$

Since the energy scheduling of the EH is performed ahead of time, the uncertainties in price, generation and demand need to be considered. In this paper, the Monte-Carlo method has been employed to generate a set of $\mathcal{S}$ scenarios for each parameter. Then, the SCENRED2 tool of the GAMS software is used to reduce the number of scenarios and consequently to decrease the computation burden of solving the optimization problem.

4. Trading in Local Markets

4.1. Market clearing process

After the energy scheduling step and indicating the energy surplus/deficit for each hour, EHs participate in local markets to trade their surplus/deficit energy with each other instead of trading with district markets. The role of each EH in the local market depends on the value of its scheduled energy in the scheduling step. For instance, in time interval h, EH i participates in the local electricity market as a seller if $\hat{P}_{E,i}^{-,h} > 0$, and as a buyer if $\hat{P}_{E,i}^{+,h} > 0$. The market mechanism for energy trading in the local market is implemented using a double auction-based approach. Double auction has been used in the local energy market as it involves both buyers and sellers in the market settlement process [40].

In the considered double auction, EHs independently decide on the amount and price of energy to be traded in the local markets and express their interest in local trading through submitting their offers/bids

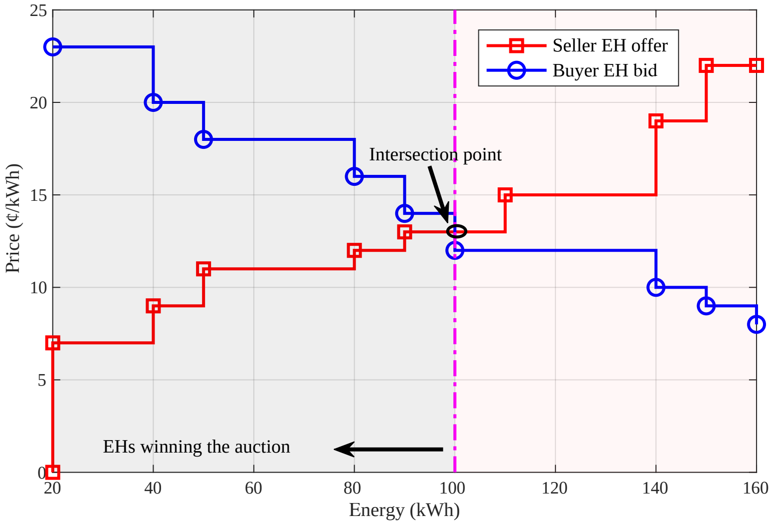

Figure 3: Market clearing in the local electricity market using double auction mechanism.

to the LMO. Then, the LMO *(i)* determines the number of EHs who can trade energy in the local market, *(ii)* allocates energy from seller EHs to buyer EHs, and *(iii)* indicates the price in each transaction. The offer of each EH includes the amount of energy that EH offers to the market and its corresponding price and is represented by $\Theta^-_{e,i} = \{P^-_{L,i}, \gamma^-_{e,i}\}$, $\Theta^-_{t,i} = \{H^-_{L,i}, \gamma^-_{t,i}\}$, $\Theta^-_{c,i} = \{C^-_{L,i}, \gamma^-_{c,i}\}$ for selling electrical, thermal, and cooling energy, respectively. Similarly, the bid for buying energy includes the amount of energy and the price that EH offers to buy the energy, and is represented by $\Theta^+_{e,i} = \{P^+_{L,i}, \gamma^+_{e,i}\}$, $\Theta^+_{t,i} = \{H^+_{L,i}, \gamma^+_{t,i}\}$, $\Theta^+_{c,i} = \{C^+_{L,i}, \gamma^+_{c,i}\}$ for selling electrical, thermal, and cooling energy, respectively. After receiving these offers and bids, the LMO clears the market by allocating energy from seller EHs to buyer EHs. The clearing process of local markets for all types of energy is the same. Hence, for the sake of brevity, in this section, we only explain the clearing process in the electricity market. Also, for notational simplicity, we use notations i and j to distinguish between the seller and buyer EHs.

At each time slot, each EH submits its offer as $\Theta^-_{e,i}$ for selling energy, or its bid as $\Theta^+_{e,j}$ for buying energy. These offers and bids are calculated using the approach explained in Section 4.2. Once all the offers/bids are received by the LMO, they will be arranged in ascending order for offers from seller EHs, and descending order for bids from buyer EHs. Then, the LMO generates the aggregated demand-supply curve using ordered offers and bids of EHs, as shown in Fig. 3 to determine the number of EHs who can participate in the local markets. The price at the intersection point indicates the EHs who win the auction, and the seller/buyer EHs with offered prices lower/higher than this price will trade energy.

In the next step, starting from the seller with the lowest offer, energy is allocated to the buyer with the highest bid, till the total energy of winning sellers is allocated to the buyers. The allocated energy and its price in each transaction between EH i and j are calculated by (20) and (21) respectively

$$P^*_{L,i\to j} = \min(P^-_{L,i}, P^+_{L,j}) \tag{20}$$

$$\gamma^*_{e,i\to j} = \frac{\gamma^-_{e,i} + \gamma^+_{e,j}}{2}. \tag{21}$$

The reason for choosing the pricing rule as in (21) is to achieve market fairness and balance the performance of auction for both sellers and buyers (See [40] for the proof). Once the local market is cleared, EHs update their exchanged energy with the district market. In the similar way, the market for thermal and cooling energies are cleared, and $H^*_{i\to j}, C^*_{i\to j}, \gamma^*_{t,i\to j}$, $\gamma^*_{c,i\to j}$ are calculated for all transactions.

The information exchange between EHs, LMO, and district markets is illustrated in Fig 4. In the first step, after receiving energy prices from district markets and solving the optimization problem in (1), each

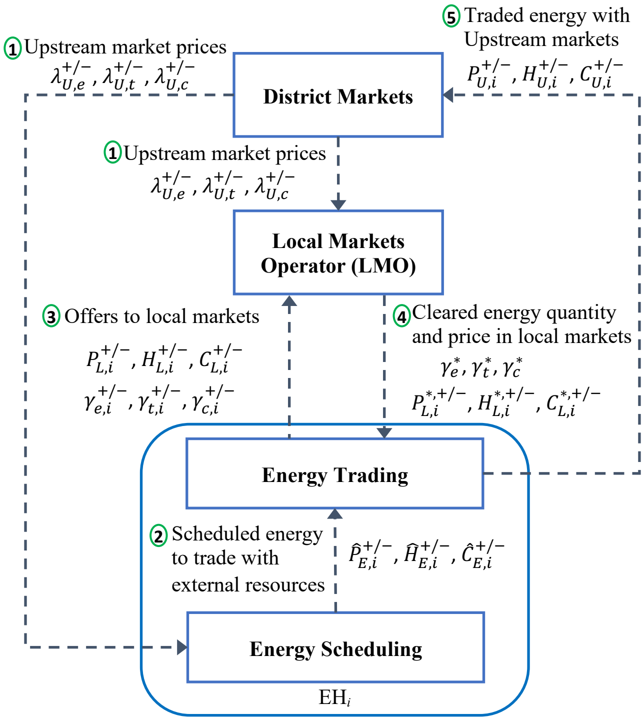

Figure 4: Information exchange between EH, local markets, and district markets.

EH indicates its scheduled energy for trading with external resources. Then, before trading with district markets, EHs try to trade their surplus/deficit energy in local markets by submitting their offers/bids to the LMO, who clears the market and indicates the cleared quantity and price for different types of energy. Finally, EHs update their traded energy with district markets considering the accepted offers/bids in the local markets. It should be noted that participation in local markets is opt-in for EHs, which means that EHs can continue to obtain energy within the existing district markets if they are not willing to participate in the local markets, or they cannot find a suitable trade in the local market.

4.2. Formulation of EH offers and bids

In this section, we outline the strategy that EHs use to indicate their offers/bids in the local markets. The scheduled imported/exported energy in the scheduling step can be traded with local and district markets, i.e.

$$P_{L,i}^{+/-} + P_{U,i}^{+/-} = \hat{P}_{E,i}^{+/-} \tag{22}$$

$$H_{L,i}^{+/-} + H_{U,i}^{+/-} = \hat{H}_{E,i}^{+/-} \tag{23}$$

$$C_{L,i}^{+/-} + C_{U,i}^{+/-} = \hat{C}_{E,i}^{+/-}. \tag{24}$$

To incentivize EHs to participate in local markets, market clearing prices in local markets should be beneficial for both seller and buyer EHs. Hence, each EH first tries to exchange the maximum energy in the local markets. To do so, the exchanged energies with district markets are set to zero and EHs try to trade their scheduled energy in the local markets. From (22)-(24) the offered/requested energy by each EH is calculated by

$$P_{L,i}^{+/-} = \hat{P}_{E,i}^{+/-}, \quad P_{U,i}^{+/-} = 0 \tag{25}$$

$$H_{L,i}^{+/-} = \hat{H}_{E,i}^{+/-}, \quad H_{U,i}^{+/-} = 0 \tag{26}$$

$$C_{L,i}^{+/-} = \hat{C}_{E,i}^{+/-}, \quad C_{U,i}^{+/-} = 0. \tag{27}$$

In the next step, the offered price for each type of energy should be indicated. First, we explain how EHs calculate their offers for selling and buying energy in the local electricity market. Let assume that after energy scheduling, EH i has surplus power to exchange with external resources (i.e. $\hat{P}_{E,i}^{-} \neq 0$). Seller EH can submit an m-step offer ($m \in \mathcal{M}$) for each time slot. Each step indicates the amount of energy that EH is willing to sell and the offered price for this energy. The offered price depends on the source of the generation. If this energy is generated by PV or WT, since the energy from these resources is free, EH offers a low price close to the buying price of the district electricity market. If the surplus energy is generated by GT, EH considers the purchased gas price in the pricing. Also, if EH needs to discharge its ES to provide the energy, the degradation cost of the battery should be added to the offered price. Therefore, the offer of EH i for selling energy in the local electricity market can be defined as

$$P_{L,i,m}^{-} = \begin{cases} \max(0, P_{pv,i} + P_{wt,i} - TC_{e,i}), & m = 1 \\ \max(0, P_{pv,i} + P_{wt,i} + P_{gt,i} - TC_{e,i}), & m = 2 \\ \hat{P}_{E,i}^{-}, & m = 3 \end{cases} \tag{28a}$$

$$\gamma_{e,i,m}^{-} = \begin{cases} \lambda_{U,e}^{+} + \varsigma_{e,i,m}, & m = 1 \\ \max(\lambda_{U,e}^{+}, \lambda_G) + \varsigma_{e,i,m}, & m = 2 \\ \max(\lambda_{U,e}^{+}, \lambda_G) + \zeta_{es,i} + \varsigma_{e,i,m}, & m = 3 \end{cases} \tag{28b}$$

where, $\varsigma_{e,i,m}$ is the bidding factor of EH i for the step m and is chosen such that $\varsigma_{e,i,1} < \varsigma_{e,i,2} < \varsigma_{e,i,3}$. If the EH needs to buy energy from the local electricity market (i.e. $\hat{P}_{E,i}^{+} \neq 0$), any price lower than the district selling price would be acceptable for the EH. Hence, the bid of EH i for buying energy in the local electricity market can be defined as:

$$\begin{cases} P_{L,i}^{+} = \hat{P}_{E,i}^{+} \\ \gamma_{e,i}^{+} = \lambda_{U,e}^{-} - \varrho_{e,i}. \end{cases} \tag{29}$$

The offers of EHs for selling energy in the local thermal market can be calculated in the similar way. If the heat energy is generated by the ST, the EH offers a price close to the buying price of the district thermal market. For the energy generated by the GB and GT, the price of purchased gas need to be considered, and for the energy discharged from the TS, the degradation cost of storage is added to the offered price. Therefore, the offer of EH i for selling energy in the local thermal market can be expressed as:

$$H_{L,i,m}^{-} = \begin{cases} \max(0, H_{st,i} - TC_{t,i}), & m = 1 \\ \max(0, H_{st,i} + H_{gb,i} + H_{ex,i} - TC_{t,i}), & m = 2 \\ \hat{H}_{U,i}^{-}, & m = 3 \end{cases} \tag{30a}$$

$$\gamma_{t,i,m}^{-} = \begin{cases} \lambda_{U,t}^{+} + \varsigma_{t,i,m}, & m = 1 \\ \max(\lambda_{U,t}^{+}, \lambda_G) + \varsigma_{t,i,m}, & m = 2 \\ \max(\lambda_{U,t}^{+}, \lambda_G) + \zeta_{ts,i} + \varsigma_{t,i,m}, & m = 3 \end{cases} \tag{30b}$$

and the bid for buying energy in the local thermal market is defined as follows.

$$\begin{cases} H_{L,i}^{+} = \hat{H}_{E,i}^{+} \\ \gamma_{t,i}^{+} = \lambda_{U,t}^{-} - \varrho_{t,i}. \end{cases} \tag{31}$$

Similarly, the offers for selling and bids for buying energy in the local cooling market are expressed using (32) and (33) respectively.

$$C_{L,i,m}^{-} = \begin{cases} \max(0, C_{ec,i} + C_{ac,i} - TC_{c,i}), & m = 1 \\ \hat{C}_{E,i}^{-}, & m = 2 \end{cases} \tag{32a}$$

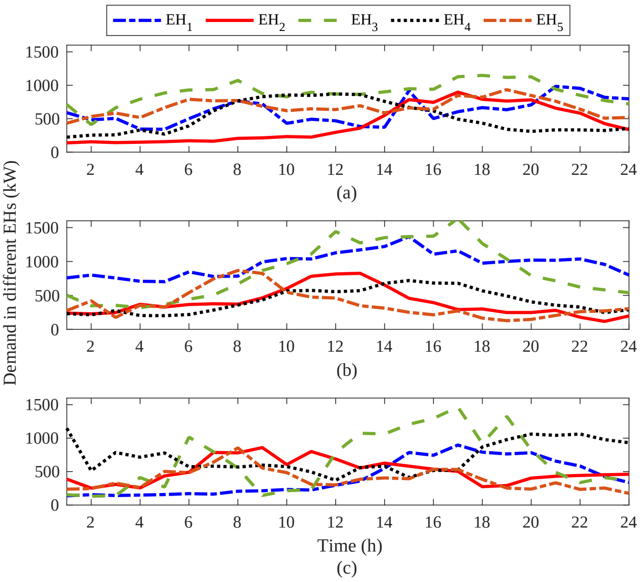

Figure 5: Average daily demand profile of EHs: a) electrical, b) thermal c) cooling.

$$\gamma^{-}_{c,i,m} = \begin{cases} \max(\lambda^{+}_{U,c}, \lambda_G) + \varsigma_{c,i,m}, & m = 1 \\ \max(\lambda^{+}_{U,c}, \lambda_G) + \zeta_{cs,i} + \varsigma_{c,i,m}, & m = 2 \end{cases} \tag{32b}$$

$$\begin{cases} C^{+}_{L,i} = \hat{C}^{+}_{E,i} \\ \gamma^{+}_{c,i} = \lambda^{-}_{U,c} - \varrho_{c,i}. \end{cases} \tag{33}$$

It is worth mentioning that the prices in the local market should be bounded by buying and selling prices of district markets to incite EHs to participate in the local markets. Hence the LMO does not accept any offer/bid that is higher/lower than the district market selling/buying price. Therefore, EHs should select their bidding factors for different markets such that the offered prices meet the requirements in (34)-(36).

$$\lambda^{+}_{U,e} \leq \gamma^{+/-}_{e,i} \leq \lambda^{-}_{U,e} \tag{34}$$

$$\lambda^{+}_{U,t} \leq \gamma^{+/-}_{t,i} \leq \lambda^{-}_{U,t} \tag{35}$$

$$\lambda^{+}_{U,c} \leq \gamma^{+/-}_{c,i} \leq \lambda^{-}_{U,c}. \tag{36}$$

5. Case Studies

This section evaluates the performance of the proposed framework. First, the test system is described. Then, the simulation results are presented to demonstrate how the proposed framework improves the overall energy efficiency of EHs.

5.1. Test system and input data

The proposed framework is implemented for a local market with 5 EHs to validate its performance. The operation period is 24 hours that is divided into one-hour time slots. The energy scheduling takes place at the beginning of each day for 24 hours, and the trading step takes place at the beginning of each one hour time slot. The number of scenarios considered for uncertainty modeling is $\mathcal{S} = 100$, which are reduced to 5 scenarios using the mix of fast backward/forward methods in the SCENRED2 tool of the GAMS

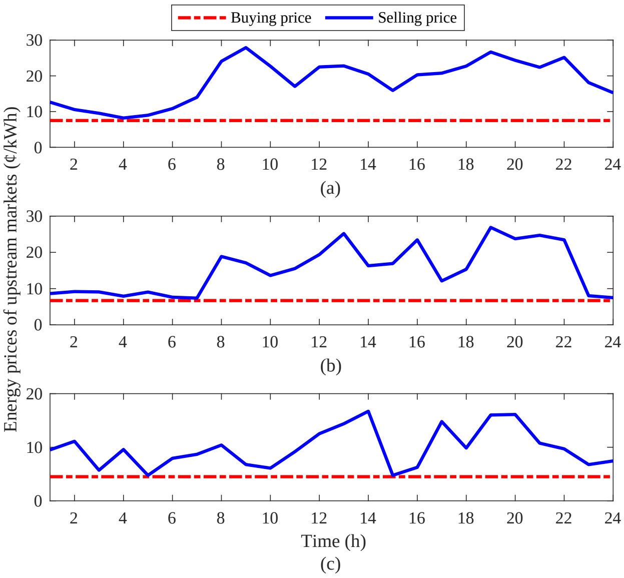

Figure 6: Average district market prices: a) electrical, b) thermal c) cooling.

Table 2: Energy hubs structure and operation parameters.

Device {parameters}	**EH$_1$**	**EH$_2$**	**EH$_3$**	**EH$_4$**	**EH$_5$**
WT	✔	✔		✔	✔
$\{\overline{P}_{wt,i}$ (kW), $\kappa_{wt,i})\}$	{16.5, 10}	{16.5, 15}		{16.5, 25}	{16.5, 2}
PV	✔	✔	✔		
$\{A_{pv,i}$ (m^2), $\eta_{pv,i}$, $\kappa_{pv,i}\}$	{400, 0.14, 10}	{400, 0.14, 20}	{400, 0.14, 25}		
ST	✔	✔	✔		
$\{A_{st,i}$ (m^2), $\eta_{st,i}$, $\kappa_{st,i}\}$	{100, 0.6, 5}	{100, 0.6, 15}	{100, 0.6, 20}		
GT/EX	✔				✔
$\{\overline{P}_{gt,i}$ (kW), $\eta_{gt,e,i}$, $\eta_{gt,t,i}$, $\eta_{ex,i}\}$	{900, 0.3, 0.4, 0.95}				{1200, 0.3, 0.4, 0.95}
GB	✔		✔	✔	
$\{\overline{H}_{gb,i}$ (kW), $\eta_{gb,i}\}$	{800, 0.9}		{700, 0.9}	{750, 0.9}	
ES	✔		✔	✔	
$\{\overline{E}^{c}_{es,i}$ (kW), $\overline{E}^{d}_{es,i}$ (kW), $\underline{E}_{es,i}$ (kW), $\overline{E}_{es,i}$ (kW) $\}$	{500, 700, 400, 1800}		{550, 780, 450, 2000}	{410, 580, 330, 1500}	
TS	✔			✔	✔
$\{\overline{E}^{c}_{ts,i}$ (kW), $\overline{E}^{d}_{ts,i}$ (kW), $\underline{E}_{ts,i}$ (kW), $\overline{E}_{ts,i}$ (kW) $\}$	{800, 800, 400, 1800}			{980, 980, 490, 2200}	{660, 660, 330, 1500}
CS	✔	✔			
$\{\overline{E}^{c}_{cs,i}$ (kW), $\overline{E}^{d}_{cs,i}$ (kW), $\underline{E}_{cs,i}$ (kW), $\overline{E}_{cs,i}$ (kW) $\}$	{700, 800, 400, 1800}	{850, 980, 490, 2200}			
AC	✔			✔	✔
$\{\overline{C}_{ac,i}$ (kW), $\eta_{ac,i}\}$	{550, 1.2}			{510, 1.2}	{480, 1.2}
EC	✔	✔	✔		
$\{\overline{P}_{ec,i}$ (kW), $\eta_{ec,i}\}$	{320, 4}	{350, 4}	{280, 4}		

software. The probabilities of reduced scenarios are 0.1196, 0.272, 0.128, 0.184, and 0.2964, respectively. The scheduling problem, which is a mixed-integer programming problem is solved in GAMS software utilizing the CPLEX solver, and the trading problem is modeled in MATLAB simulation environment.

The average daily demand profiles of EHs for electrical demand, equivalent thermal, and cooling loads are presented in Fig. 5. Fig. 6 illustrates the average trading prices of district markets for selling and buying energy to/from EHs. The price for purchasing gas from the gas utility company is set to $\lambda_G = 3.5$ ¢/kWh. The maximum limit of exchanging energy with district electricity, cooling, and thermal markets for all EHs is set to 1000 kW.

List of devices of different EHs and their operation parameters is given in Table 2. The WT unit operational parameters are $\nu^{r}_{wt,i} = 8$, $\nu^{in}_{wt,i} = 3.5$, and $\nu^{out}_{wt,i} = 25$ m/s. The charging and discharging

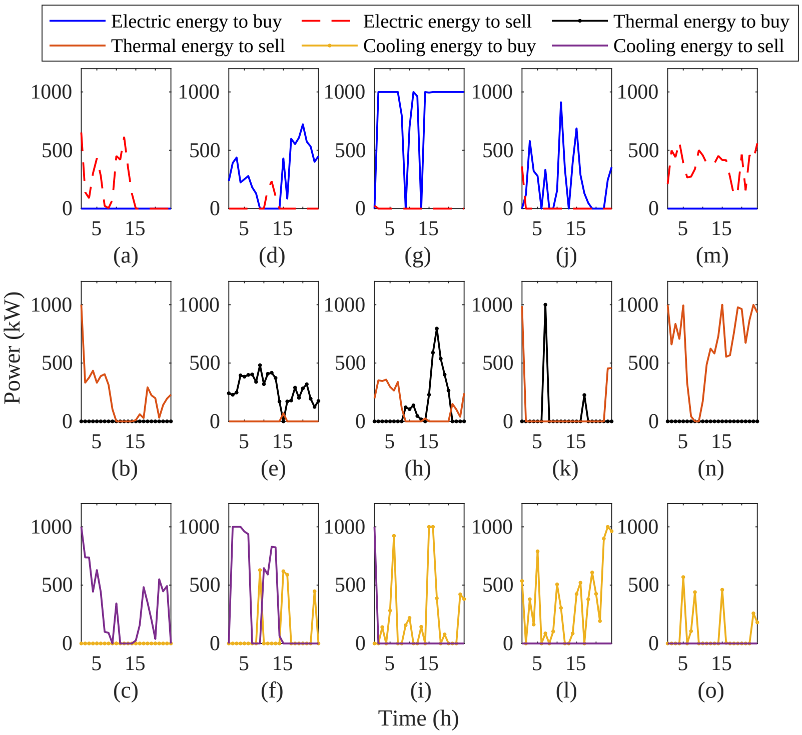

Figure 7: Scheduled energy to trade with external resources: EH_1 (a-c), EH_2 (d-f), EH_3 (g-i), EH_4 (j-l), EH_5 (m-o).

efficiency for ES, TS, and CS are 0.96, 0.98, and 0.97, respectively, while the energy loss ration for these devices are 0.01, 0.02, and 0.02, respectively [39]. The storage degradation cost parameters are set to $\zeta_{es,i} = 1.6$, $\zeta_{ts,i} = 0.5$, and $\zeta_{cs,i} = 0.1$ ¢/kWh for all EHs. The efficiency of electrical transformer is set to $\eta_e = 0.98$, the cost equivalent of emitted CO_2 is $\rho = 0.05$ ¢/kg, and generated CO_2 due to consuming electricity and gas are set to $\beta_e = 0.97$, and $\beta_G = 0.23$ kg/kWh, respectively.

5.2. Results and discussion

Figure 7 depicts the power profile which is scheduled by EHs to exchange with external resources. As the EH_1 is equipped with several generation resources, in most of the hours, it has surplus energy to trade with external resources, and it does not need to buy energy from these resources. The EH_2 plan is to buy and sell energy in the electricity and cooling markets and buy energy in the thermal market. The EH_3, and EH_4 need to buy electricity, thermal, and cooling energies in most of the hours. The EH_5 is able to sell energy in the electricity and thermal markets, while it needs to buy cooling energy from the cooling market. In general, EHs can participate in different markets as a seller or buyer, depending on their power profile at each hour. However, as can be observed from Fig. 7 they do not buy and sell energy at the same time.

Results of energy trading in local markets are illustrated in Fig. 8. As stated in Section 4.1, each transaction between a seller and buyer EHs has a unique price based on their offers. The average price of all transactions in each hour is calculated and represented in Fig. 8, which verifies that the prices in local markets are always beneficial for both seller and buyer EHs. In the electricity market, the gap between district market buying and selling prices between hours 3 and 5 is too small. Hence, EHs are not incentivized to participate in the market, and traded energy in these hours is zero. Moreover, at hours 9 and 13, the total scheduled energy by all EHs to exchange with external resources is zero, and no energy is traded in the local market. Fig. 8b shows the results in the local thermal market, in which at hours 7, 23, and 24 there is no thermal energy to trade in the market, and hence, the exchanged thermal energy is zero. In the

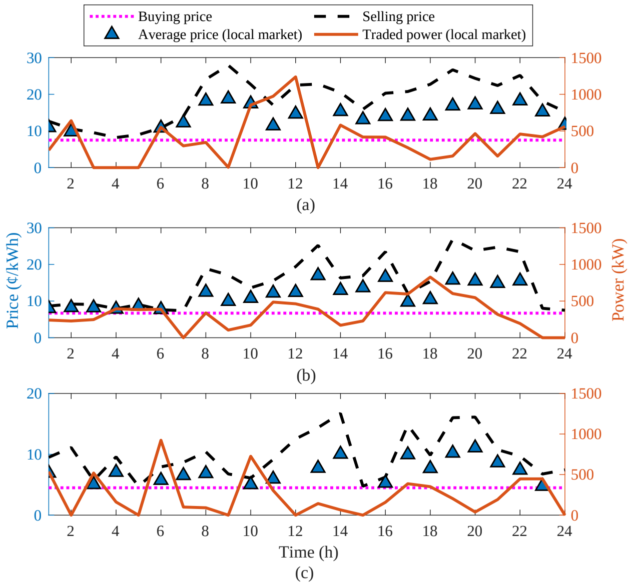

Figure 8: Results of local markets, illustrating traded energy and the average energy price in each hour: a) electrical, b) thermal c) cooling markets.

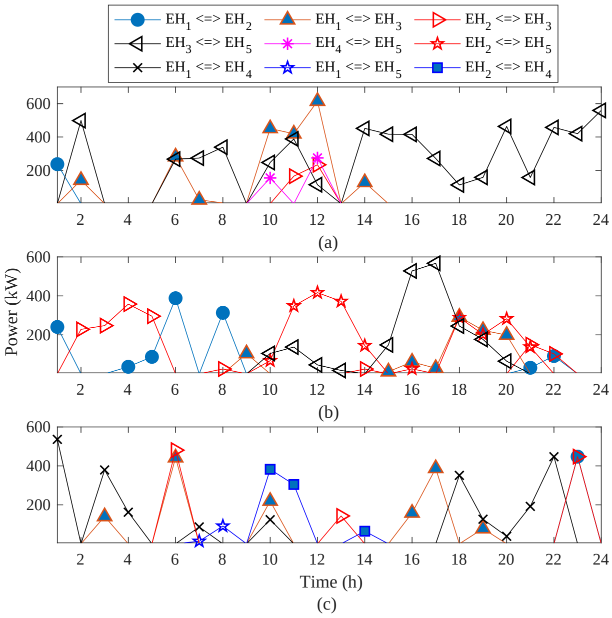

Figure 9: Exchanged energy between EHs in local markets: a) electrical, b) thermal c) cooling markets.

local cooling market, the traded energy between hours 12 to 15 is almost zero, as EH_1 has no energy to sell, and EH_2 is the only cooling energy seller.

Figure 9 illustrates exchanged energies between EHs in different markets. In the electricity market, EH_1 and EH_5 sell energy to other EHs, as they have surplus power generation in most of the hours. Similarly, in the thermal market, EHs with excess heat energy sell their energy to other EHs with an energy deficit. For instance, EH_5 sells energy to EH_2 during hours 10 to 15, and to EH_3 between hour 14 and 21 (see Fig. 7(e), (h) and (n)). In the same way, EH_1 and EH_2 with excess cooling energy, sell their energy to other EHs in

Table 3: Comparison of average daily imported energies from district markets, total operation cost and generated CO_2 with and without participating in local markets.

	Without local markets					With local markets					Total % of decrease for all EHs
	EH_1	EH_2	EH_3	EH_4	EH_5	EH_1	EH_2	EH_3	EH_4	EH_5	
Imported electrical power (MW)	0	7.08	20.45	5.19	0	0	6.85	11.97	4.76	0	27%
Imported heat power (MW)	0	6.73	3.24	1.22	0	0	3.25	0	0	0	70%
Imported cooling power (MW)	0	2.28	5.13	8.36	2.01	0	1.38	3.08	5.61	1.91	32%
Total Operation cost ($\times 10^3$ \$)	2.48	2.36	6.35	2.7	2.23	1.63	1.98	5.49	2.58	0.7	22%
Total CO_2 emission ($\times 10^3$ kg)	16.4	6.86	24.12	9.63	18.44	16.4	6.64	15.9	9.21	18.44	13%

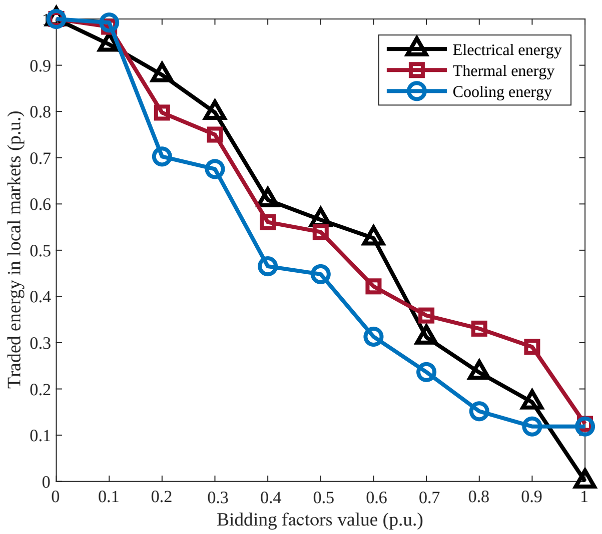

Figure 10: Impact of chosen bidding factors by EHs on the total traded energies in the local markets.

the local cooling market.

Table 3 provides a comparison of the imported energies to EHs, operation cost of EHs, and the CO_2 emission with and without having local markets. For this case study, the performance of EHs over one month is considered, and the average daily values of imported energy, operation cost, and the CO_2 emission are calculated. Through participating in local markets, the total imported energy from district markets to EHs has reduced by 27%, 70%, and 32% for electricity, heat, and cooling energies, respectively. The reduction in imported energy from district market has reduced the operation cost of EHs by 22%, and CO_2 emission of EHs is reduced by 13%. The change in the operation costs incorporates the increase in the revenue by selling energy at higher prices, or a decrease in the cost by buying energy at lower prices in the local markets. These results verify the efficacy of the proposed local market framework in reducing EHs operation cost, as well as CO_2 emission.

In order to assess the impact of EHs' bidding factors on the market-clearing results, total traded energy in local markets for different values of bidding factors are compared in Fig. 10. It can be observed that an increase in the value of bidding factors decreases the total traded energy in different markets. The higher value of bidding factors means that EH is more greedy, which decreases its chance in winning the auction, and consequently, reduces the amount of traded energy in the local markets.

6. Conclusions

In this paper, a TE framework is proposed for energy management and trading of multi-carrier EHs, which enables them to participate in local markets to trade different forms of energy. A holistic model for

EH is employed to develop the energy scheduling problem. We employed a double auction for the market clearing that allows EHs to express their interests in energy trading by submitting their offers and bids. Also, the EH offers for each type of energy is formulated, in which the offering price is determined based on the source of energy. Through participation in the local markets, EHs reduce their energy costs by reducing the exchanged energy with district markets. The obtained results show that the average daily imported power from district market to EHs has reduced by 27-70% for different forms of energy, and consequently, the daily operation cost of EHs is reduced by 22%, and the amount of CO_2 emission is decreased by 13%. A potential extension of the proposed work is the investigation of the impact of mobile storage systems in the decentralized structure of multi-carrier EHs. Also, this work can be extended by implementing the proposed framework for flexibility trading between EHs and the district markets.

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