

Operational scheduling of integrated multi-carrier energy system considering transactive microgrids energy and flexibility contributions

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ABSTRACT

A three-stage optimization framework is developed in this paper for optimal operation planning of an Integrated Multi-Carrier Energy System (IMCES). The model introduces the Day-Ahead (DA) and Real-Time (RT) scheduling for energy transactions, considering both Transactive MicroGrids (TMGs) and Non-Transactive MicroGrids (NTMGs). The overall impacts of both TMGs and NTMGs on the availability of energy resources, flexibility, and resiliency of IMCES have been modeled. Further, the optimal resilient scheduling of IMCES considering both energy and ancillary service procurement of TMGs is formulated. The presented method determines the optimal energy transactions of NTMGs and TMGs, TMGs and IMCES, and the DA scheduling of IMCES in the different levels of the first stage. In the second stage, the model evaluates the optimal scheduling problem for RT employing preventive actions. Finally, in the case of any contingent events, the third level will be executed utilizing RT actions at the third stage of the proposed optimization model, dealing with the corrective operational actions. Two different benchmarks, including 33 and 123 nodes, have been chosen to evaluate the performance of the TMGs and NTMGs investigated in this paper. The simulation outputs revealed that the proposed framework effectively leveraged the performance of the IMCES in both DA and RT markets; meanwhile, the cost reduction is equivalent to 20.37 % without the contribution of TMGs. Further, the model increased the RT flexibility index of IMCES by about 53.54 % concerning the DA flexibility index.

Nomenclature

Abbreviation	
ADMM	Alternating Direction Method of Multipliers
ARIMA	Autoregressive Integrated Moving Average
BG	Bidding Gain
CHP	Combined Heat and Power
CIC	Customer Interruption Cost
CSS	Cool energy Storage Systems
DA	Day-Ahead
DER	Distributed Energy Resource
DG	Distributed Generation
DRP	Demand Response Program
ECC	Electric Compression Chiller
EHC	Electrical, Heating, and Cooling
ESS	Electrical Energy Storage
ENSC	Energy Not Supplied Cost
FI	Flexibility Index

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GAMS	General Algebraic Modeling System
GB	Gas Boiler
HAC	Heating Absorption Chiller
IGDT	Information Gap Decision Theory
IMCES	Integrated Multi-Carrier Energy System
IMCESO	IMCES Operator
LCM	Local Cooling Market
LEM	Local Electricity Market
LFM	Local Flexibility Market
LHM	Local Heating Market
MILP	Mixed Integer Linear Programming
MINLP	Mixed Integer Non-Linear Programming
MU	Monetary Unit
MMU	Million MU
NTMG	Non-Transactive MicroGrids
PV	Photovoltaic system
PHEV	Plug-in Hybrid Electric Vehicle

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RI	Resiliency Index
RT	Real-Time
UDER	Utility-owned Distributed Energy Resource
TES	Thermal Energy Storage
TMGs	Transactive MicroGrids
TMGC	TMGs' Contributions
WT	Wind Turbines
5GDHC	5th Generation District Heating and Cooling System
Sets	
t	Set of time of simulation
s	Set of operating scenarios of IMCES
i	Set of utility-owned electrical DERs
j	Set of utility-owned heating energy DERs
k	Set of utility-owned cooling energy DERs
c	Set of bilateral contracts between TMGs and NTMGs
i'	Set of critical electrical loads
j'	Set of critical heating loads
k'	Set of critical cooling loads
i''	Set of IMCES's electrical loads
j''	Set of IMCES's heating loads
k''	Set of IMCES's cooling loads
l	Set of electrical TMG's DERs
m	Set of heating energy TMG's DERs
n	Set of cooling energy TMG's DERs
s'	Set of operating scenarios of NTMG
s''	Set of operating scenarios of IMCES
Parameters	
pr	Probability of scenario
$NTMGDA$	Number of TMG DA operating scenarios
$NTMG$	Number of TMG's electrical DER
$NIMCESDAS$	Number of IMCES DA operating scenarios
T	The time horizon of simulation
$NUEDER$	Number of utility-owned electrical DER
$NUHDER$	Number of utility-owned heating energy DER
$NUCDER$	Number of utility-owned cooling energy DER
$NXDAS$	Number of TMGs and NTMGs DA operating scenarios
NBC	Number of bilateral contracts between TMGs and NTMGs
$NCEL$	Number of critical electrical loads of IMCES
$NCHL$	Number of critical heating loads of IMCES
$NCCL$	Number of critical cooling loads of IMCES
NEL	Number of electrical loads of IMCES
NHL	Number of heating loads of IMCES
NCL	Number of cooling loads of IMCES
$P_{Critical}$	Electrical critical load of IMCES
$H_{Critical}$	Heating critical load of IMCES
$R_{Critical}$	Cooling critical load of IMCES
$\lambda_{t,c}^{Elec}, \lambda_{t,c}^{Heat}, \lambda_{t,c}^{Cool}$	The value of DA EHC energy bilateral contract prices of TMGs and NTMGs
$\pi^{Elec}, \pi^{Heat}, \pi^{Cool}$	Day-ahead LEM price, LHM price, and LFM price
$\pi_t^{Reac}, \pi_t^{Spinn}$	The value of procured reactive power and spinning reserve prices by TMG for IMCESO
$\xi^{Elec}, \xi^{Heat}, \xi^{Cool}$	The value of RT electrical, heating, and cooling energy bilateral contract prices of TMGs and NTMGs
$\nu_k^{Ramp}, \nu_k^{Reac}, \nu_k^{Heat}, \nu_k^{Cool}$	Real-time LFM price of ramp and reactive power, LHM price of heating energy, and LFM price of cooling energy
Variables	
C^{TMG}	Operating costs of TMG
C^{TES}	Operating cost thermal energy storage
C^{CHP}	Operating cost of CHP
C^{ESS}	Operating cost of ESS
C^{PV}	Operating cost of PV system
C^{WT}	Operating cost of WT system
C^{DG}	Operating cost of DG
C^{CSS}	Operating cost of CSS
C^{Boiler}	Operating cost of boiler
C^{HAC}	Operating cost of HAC
C^{ECC}	Operating cost of ECC
$C^{Purchase}$	Cost of energy purchased
B^{Sell}	Profit of energy sold
$Penalty$	Penalty cost for any mismatch any deviation from the accepted values of the DA/RT bidding process
$C_{IMCES}^{ELDRP}, C_{IMCES}^{CHDRP}, C_{IMCES}^{CDRP}$	Cost of electric DRP, heating energy DRP, and cooling energy DRP

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$g^{Elec}, g^{Heat}, g^{Cool}$	Volume of electrical, heating energy, and cooling energy transaction between TMGs and NTMGs through bilateral contract
$q^{Elec}, q^{Heat}, q^{Cool}$	Volume of energy transactions of TMG with IMCESO in the LEM, LHM, and LCM, respectively
q_t^{Reac}, q_t^{Spinn}	Volume of reactive power and procured spinning reserve by TMG for IMCESO
μ_k^{Ramp} and μ_k^{Reac}	TMG's ramp and reactive power transactions in the RT LFM with IMCESO
μ_k^{Heat}	TMG's heating energy transactions in the RT LHM with IMCESO
μ_k^{Cool}	TMG's cooling energy transactions in the RT LCM with IMCESO
$\phi^{Elec}, \phi^{Heat}, \phi^{Cool}$	The volume of RT electrical, heating energy, and cooling transactions between TMGs and NTMGs
BG	Bidding Gain
RI	Resiliency Index
$P^{TMG}(t)$	Active power generation of TMG
$H^{TMG}(t)$	Heating energy generation of TMG
$R^{TMG}(t)$	Cooling energy generation of TMG
$P^{UDER}(t)$	Active power generation of utility-owned electrical DER
$Q^{UDER}(t)$	Reactive power generation of utility-owned electrical DER
$H^{UDER}(t)$	Heating energy generation of utility-owned heating energy DER
$R^{UDER}(t)$	Cooling energy generation of utility-owned cooling energy DER
p^{E_Market}	The IMCES's electricity transactions with the electricity market
P_L	The electrical load of IMCES
p^{LOSS}	Electrical power loss of IMCES
H^{H_Market}	The IMCES's electricity transactions with the heating energy market
H_L	Heating load of IMCES
H^{LOSS}	Heating energy loss of IMCES
R^{C_Market}	The IMCES's cooling energy transactions with the cooling energy market
R_L	Cooling load of IMCES
R^{LOSS}	Cooling energy loss of IMCES

1. Introduction

The Integrated Multi-Carrier Energy System (IMCES) concept is highly utilized to reduce pollutant emissions, employ renewable energy resources, and increase energy conversion efficiency [1]. The IMCESs utilize the 5th Generation of District Heating and Cooling (5GDHC) conceptual design for exchanging energy carriers in heating and cooling markets [2]. Further, an IMCES can transact electrical, heating, and cooling energy carriers with Transactive MicroGrids (TMGs) to enhance its system's flexibility and resiliency. On the other side, the TMGs can transact multicarrier energy with Non-Transactive MicroGrids (NTMGs) to gain profit. The TMG may be an industrial town that is equipped with Combined Cooling, Heating, and Power (CCHP) facilities. Further, an NTMG may be a residential district that is utilizing Distributed Energy Resources (DERs) and transacting energy carriers with the neighboring TMG (see Fig. 11).

The energy transaction of TMGs and NTMGs can change the availability of TMGs' energy resources. Thus, the optimal resilient scheduling of IMCES considering energy transactions with TMGs should consider the energy transactions of NTMGs and TMGs, and TMGs and IMCES. Further, the external shock impacts on the IMCES should be considered in a preventive and corrective manner for the Day-Ahead (DA) and Real-Time (RT) operational scheduling horizons. The main challenge of the optimal resilient scheduling of IMCES is that the framework of TMGs, NTMGs, and IMCES multicarrier energy transactions, considering the flexibility of IMCES, should be determined, and the impact of external shocks on the system operational scheduling explored. Further, the optimal topologies of IMCES electrical, heating, and cooling systems in the preventive and corrective actions, considering TMGs' contributions, are another challenge in this field of research.

The operational planning of the IMCES has been extensively studied

in the literature, and it can be categorized into several groups: 1) The primary group endeavors to model the optimal scheduling of IMCES without modeling resiliency, and 2) The second group of papers models the resiliency of IMCESs.

As a first group paper, Ref. [3] presented a model for scheduling of IMCES for the energy and flexible ramp rates considering multi-energy demands. This paper presented that the integration of energy carrier systems could enhance the penetration factor of renewable DERs. Further, the generation and consumption uncertainties have been addressed. In addition, the complex three-stage model has been transformed into a single-stage optimization model, and to solve the new optimization model, a robust Information Gap Decision Theory (IGDT) model has been employed. Ref. [4] introduced a strategy for thermal energy transactions considering the flexibility constraints. The model utilized two leaders and one follower Stackelberg game process, and an iterative Nash equilibrium has been introduced to solve the operational planning problem of the multi-energy microgrids. In this regard, the optimization process consisted of two Stackelberg games that modeled the negotiations of leaders and followers. Finally, the Lagrange multiplier method was considered for the objective functions, and the iteration-based model was utilized to find the results. However, Refs. [3, 4] did not consider multi-energy Transactive MicroGrids (TMGs), Non-Transactive MicroGrids (NTMGs), and resilient IMCES optimal scheduling process for the DA and RT markets. The authors in Ref. [5] assessed a comprehensive optimization framework for the electrical and heating energy networks, considering the Peer-to-Peer (P2P) energy transactions in addition to addressing the flexibility market. To solve this complex problem, the Alternating Direction Method of Multipliers (ADMM) was used to deal with the operational planning problem. For validation of the proposed strategy, the 33-node test system with 16 P2P possible transactions has been chosen. A trading framework for electricity, heating, and carbon emission rights has been introduced in Ref. [6]. The model utilized the adaptive consensus-ADMM method to optimize the objective functions, and the results were compared with the ADMM and consensus-ADMM. Residential, industrial, and commercial multi-microgrids have been investigated to optimize energy purchasing costs, including the cost of electricity, heating energy, natural gas, and costs of emission pollution. Nevertheless, Refs. [5,6] did not model NTMGs' interactions with TMGs, the energy and flexibility service procurement of TMGs for the IMCES, and the multi-carrier energy markets. Ref. [7] explored an optimization procedure for interconnected energy hubs using a robust/IGDT algorithm. The bi-level model optimized the cooperative energy management in multi-carrier systems, addressing the optimal operation planning of the distribution system. The simulation results have been presented for an energy system including 30 energy hubs, and the proposed model optimized the scheduling of systems in 0.53 s. Ref. [8] introduced a novel framework in the field of operational planning of energy hubs with TMGs structure, considering different energy conversion technologies. The optimization process minimized the operating costs and pollutant emissions using Pareto front solution points. The model considered energy hubs, electric vehicle parking lots, electrical and heating energy facilities, and hydrogen energy conversion technology. Ref. [9] proposed an equilibrium problem with an equilibrium constraint process to hedge the risk of the local energy community. The flexibility constraints of energy resources were modeled, and the conditional value at risk model was employed to assess the risk-averse behavior of market participants. The developed and studied model consists of an interesting local energy community market in lower level 1, the distribution grid in lower level 2, and the energy community operator in the upper level, respectively. The outputs of simulations revealed that the P2P trading process increased the benefits of local energy community operators. However, Refs. [7–9] did not consider the TMGs and NTMGs multi-carrier energy transactions, resiliency assessment of IMCES, and the switching of electrical switches and heating and cooling energy systems control valves.

Ref. [10] introduced a framework for P2P energy transactions for complex multi-carrier energy systems. The operational planning of energy hubs was performed using a mixed integer programming process; meanwhile, the energy transactions between different sectors were carried out by the ADMM model. Ref. [11] proposed a model for trading energy in complex energy systems, considering Electric, Heating, and Cooling (EHC) systems, and gas markets. In the first step, each multi-carrier energy hub determined its power generation and energy consumption. Then, in the second step, the optimal bidding processes of energy hubs were considered. Ref. [12] proposed a chance-constrained programming optimization process for microgrids considering energy storage facilities. The electricity and heating energy markets were considered. Further, the solar power facilities and wind turbines were modeled. The overall energy cost was reduced by approximately 10.8 %. On the other hand, Refs. [10–12] did not optimize the TMGs and NTMGs energy transactions and assess the flexibility and resiliency of IMCES. Ref. [13] proposed a Mixed Integer Linear Programming (MILP) method for the commitment of electrical system energy resources, which consisted of frequency restoration and manual reserves. The optimization process minimized flexibility services procurement costs, renewable energy generation curtailment costs, thermal power plant operating costs, and electric vehicle commitment costs. Ref. [14] assessed an iterative game model for optimizing demand-side flexible service providers. The method consisted of a two-stage process. The first step optimized the offer curve of DERs, and the second step maximized the profit of the system's operator. Multiple offering scenarios were considered, and the results revealed that the pay-as-curved model was the best offering mechanism. Ref. [15] explored the flexibility of a system using a flexibility index. The optimization process utilized a heuristic optimization method, and the simulation result showed that the method supplied about 99.75 % and 99.31 % of the maximum values of the cooling and heating loads, respectively. However, Refs. [13–15] did not model NTMGs and TMGs energy interactions, the energy and flexibility service procurement of TMGs for the IMCES, and the flexibility and resiliency assessment of IMCES. Ref. [16] introduced a model that utilized the value of unserved energy, flexibility index, and the duration of insufficient flexibility criteria to optimize the contribution of DERs. Two metrics were considered in the model, which consisted of flexibility request and unserved flexibility. The expected unserved flexibility energy criteria assessed the procurement of the flexibility request signal. Ref. [17] proposed an automated demand response process for heat pumps, which introduced two models for loads: the fixed loads and the price-responsive loads. The behavior of loads was estimated using a predictive control process considering energy prices. The model was evaluated for Spain and Germany's electricity markets. The authors in Ref. [18] evaluated an extensive operational planning model to harvest clean energies and demand response aggregators as flexibility service providers. A two-stage optimization framework has been introduced to deal with the operational planning problem, while the profit maximization of the aggregators has been addressed at the lower stage, and the overall system's profits have been considered in the upper stage. The achievements confirm that the developed model could gain profit for the system and aggregators by about 74 % and 92 %, respectively, when they carried out the optimization independently. Ref. [19] introduced a reactive and active power optimization process considering the locational marginal pricing concept. In this case, the optimization model utilized a two-level problem. The upper stage is responsible for dispatching the system's resources, and the lower stage determines the market settlements. The duality theory and Big-M approach were utilized to recast the bi-level problem to a single-level optimization problem. Refs. [16–19] neither addressed the TMGs and NTMGs energy transactions, flexibility, and resiliency assessment of IMCES, nor the possibility of switching actions in the electrical and non-electrical energy systems.

The second group of papers models the resiliency of IMCESs. As a paper of the second group, Ref. [20] introduced a transactive framework

Table 1

A comparative taxonomy table highlighting the novelties and contributions of this study.

References		3	4	5	6	7	8	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	Proposed Approach
Bidding process of TMGs in DA and RT multi-carrier energy markets		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	✓
Integrated model for IMCES, TMGs, and NTMGs		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	✓
Modeling of resiliency in operational scheduling of IMCES considering flexibility services		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	✓
Operational scheduling of IMCES, TMGs, and NTMGs		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	✓
Method	MILP	x	x	x	x	x	✓	x	x	✓	x	x	✓	x	x	✓	✓	x	✓	x	x	x	✓
	MINLP	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	✓	✓	x	x
Model	Heuristic	✓	✓	✓	x	✓	x	✓	✓	✓	✓	✓	✓	✓	✓	✓	x	✓	x	x	x	✓	x
	Deterministic	x	✓	✓	✓	x	✓	x	✓	✓	✓	✓	✓	✓	✓	✓	x	✓	✓	✓	x	x	x
Objective Function	Stochastic	✓	x	x	x	✓	x	✓	x	x	x	x	x	x	x	x	✓	x	x	x	✓	✓	✓
	Revenue	x	x	x	x	✓	✓	✓	x	x	✓	x	x	x	✓	x	✓	x	x	x	x	x	✓
Uncertainty Model	Gen. Cost	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Storage Cost	✓	✓	✓	✓	✓	x	✓	x	x	x	x	x	x	x	x	✓	x	✓	x	✓	✓	✓
	Secu. Costs	✓	x	x	x	✓	x	x	x	x	x	x	x	x	x	x	✓	x	✓	✓	x	✓	✓
	TMGs cost	x	x	x	x	x	x	✓	x	x	x	x	x	x	x	x	✓	x	x	x	x	x	✓
	NTMGs costs	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	✓
	Ancillary service costs	✓	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	✓
	Heating and cooling flexibility costs	✓	✓	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	✓
	DA-Market	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	x	✓	✓	✓	✓	✓	✓	✓	✓	✓
Uncertainty Model	RT-Market	✓	x	x	x	x	x	x	x	x	x	x	x	✓	x	x	✓	x	x	x	x	x	✓
	BG index	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	✓
	Resiliency index	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	✓	x	✓
	Flexibility Index	x	x	x	x	x	x	x	x	x	x	✓	✓	x	x	x	x	x	x	x	x	x	✓
	Inter. Electricity	✓	✓	x	x	✓	✓	✓	✓	x	x	x	x	x	x	x	✓	x	x	x	✓	✓	✓

for multi-microgrids. The model considered the optimal bidding process of microgrids and determined the operational planning considering the resiliency of the system. Further, the process utilized the switching actions in the power distribution grid and cooling and heating valves. Ref. [21] introduced tri-level operational scheduling of IMCES considering the worst-case contingencies. The third stage is responsible for IMCES cost reduction strategies; meanwhile, the second stage deals with the worst-case contingencies. The first stage optimizes the electric and heating load restoration process. The model utilized a column-and-constraint generation optimization procedure. Ref. [22] explored a preventive optimization process for IMCES that consisted of multiple multi-carrier microgrids, considering the mobile storage facilities to enhance resiliency. The energy-not-supplied criterion was used as the main objective function of optimization, and an N-1 contingency model was considered for the external shock modeling. On the other hand, Refs. [20–22] did not model TMGs' interactions with NTMGs, the RT energy markets, and the energy and flexibility service procurement of TMGs for the IMCES. Ref. [23] proposed a Mixed Integer Non-Linear Programming (MINLP) optimization process for energy hub-based IMCES to minimize the energy not served for non-critical loads. It should be noted that the energy hub consisted of natural gas, heating, and electrical facilities. As the trade between operational cost and risk assessment is very important in operational planning problems, this feature has been investigated. Ref. [24] assessed a comprehensive model

to minimize both natural gas and electrical systems costs; meanwhile, maximize the resiliency of the system. Two indices were introduced to assess the system conditions, which consisted of the resiliency assessment index and the restoration index. Ref. [25] introduced a P2P energy exchange model for multi-carrier energy systems considering extreme conditions. The IMCES consisted of electrical, heating energy, and natural gas subsystems. The model simulated the tree representation of networking scenarios. However, Refs. [23–25] did not model the energy and flexibility service procurement of TMGs for the IMCES, TMGs, and NTMGs energy transactions, and resiliency assessment of IMCES.

As shown in Table 1, an integrated model that considers the DA and RT operational planning of IMCES, considering the energy and flexibility procurement of TMGs, and the multi-energy TMGs and NTMGs have a great added value compared to the current research works.

The contributions of this paper are fivefold.

- The impacts of multicarrier energy transactions of NTMGs and TMGs on the energy and flexibility service procurement of TMGs for the IMCES are explored,
- A bidding gain index is developed to assess the TMGs' profits,
- The resiliency and flexibility indices are proposed in this work for the IMCES,
- The optimal topology of EHC networks in preventive and corrective actions is presented,

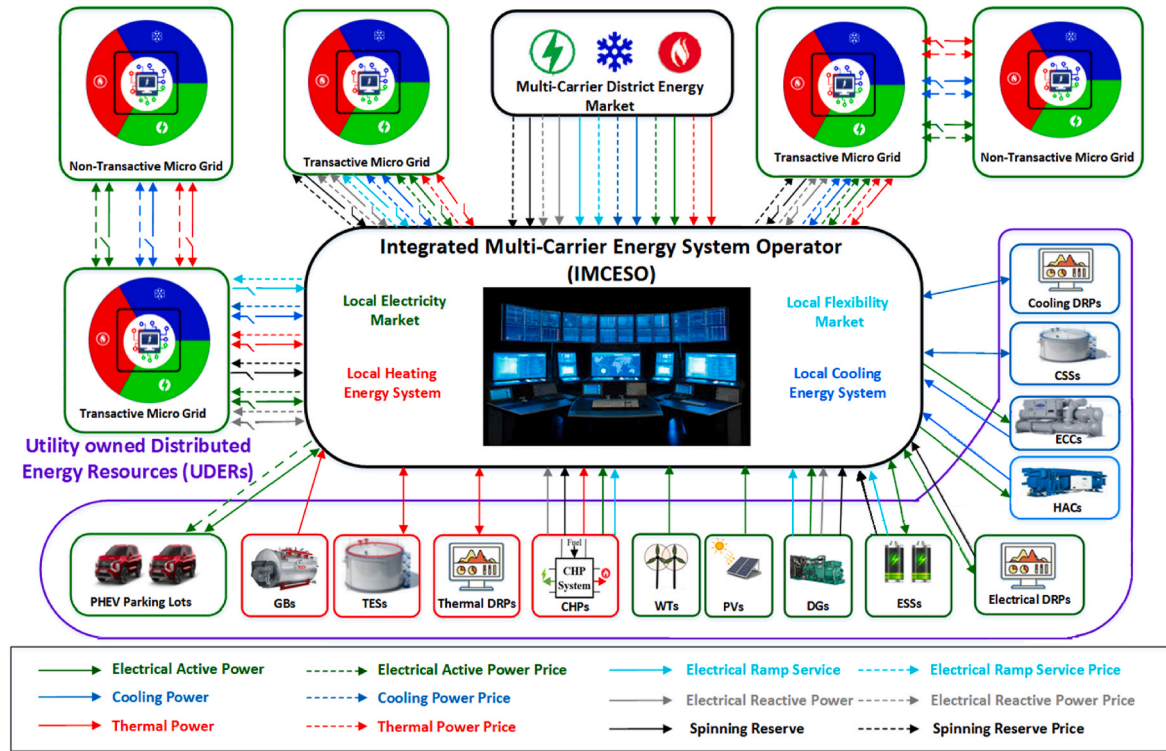


Fig. 1. IMCESO energy transactions with UDERs and TMGs.

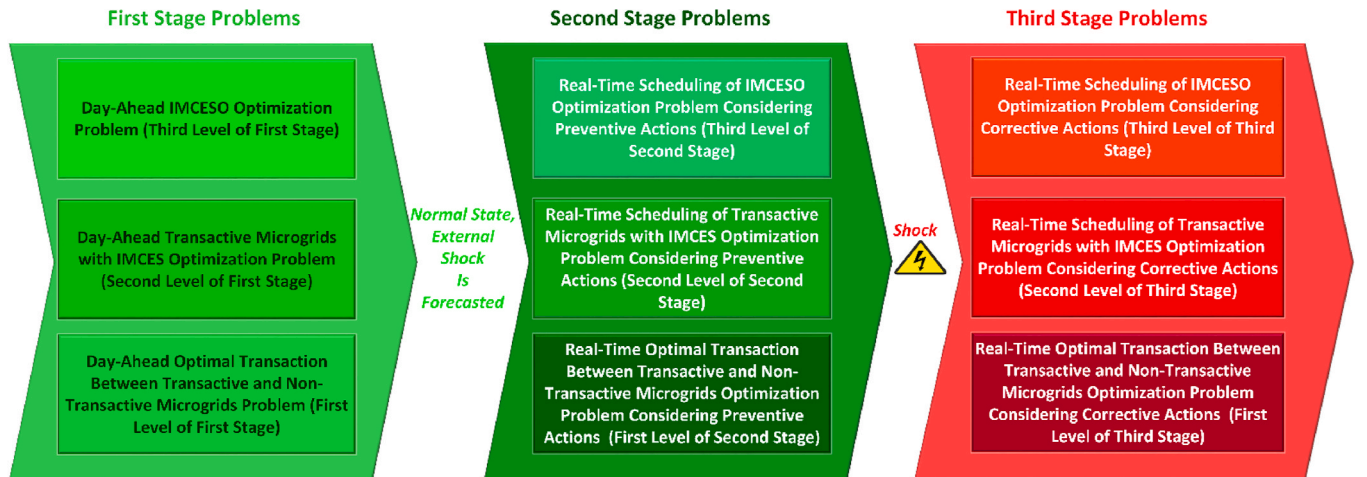


Fig. 2. The proposed levels and stages of the optimization process.

- The impacts of changing the multicarrier energy prices in the preventive and corrective actions of IMCES on the TMGs' bidding behaviors are assessed.

2. Mathematical problem formulation

The conceptual model for the energy and ancillary services transactions in an IMCES with EHC energy markets and TMGs has been presented in Fig. 1. The IMCES Operator (IMCESO) should schedule the Local Electricity Market (LEM), Local Flexibility Market (LFM), Local Heating Market (LHM), and Local Cooling Market (LCM) for the DA and RT horizons. The IMCESO can utilize EHC Demand Response Programs (DRPs) to manage its system and transact EHC energy with the corresponding regional markets. Active power, reactive power, spinning reserve, heating, and cooling energy carriers would be scheduled in the

DA market. Further, considering the ramp service, reactive power, active power, heating, and cooling energy carriers can be exchanged in the RT market following the LEM regulations. Finally, the ramp services are transacted in the LFM.

As shown in Fig. 1, the IMCESO may utilize parking lots with Plug-in Hybrid Electric Vehicle (PHEV), Electric Compression Chillers (ECCs), Distributed Generation (DG) facilities, Thermal Energy Storages (TESs), Combined Heat and Power (CHP) units, Gas Boilers (GBs), Heating Absorption Chillers (HACs), Cool energy Storage Systems (CSSs), Wind Turbines (WTs), PhotoVoltaic systems (PVs), and Electrical Energy Storages (ESSs) [26]. It is assumed that there are two types of microgrids: 1) the transactive microgrids (TMGs) that transact electricity, heating, and cooling energy with IMCESO, which can change the availability of energy resources, resiliency, and flexibility of IMCES operating conditions, and 2) NTMGs that have any energy transactions

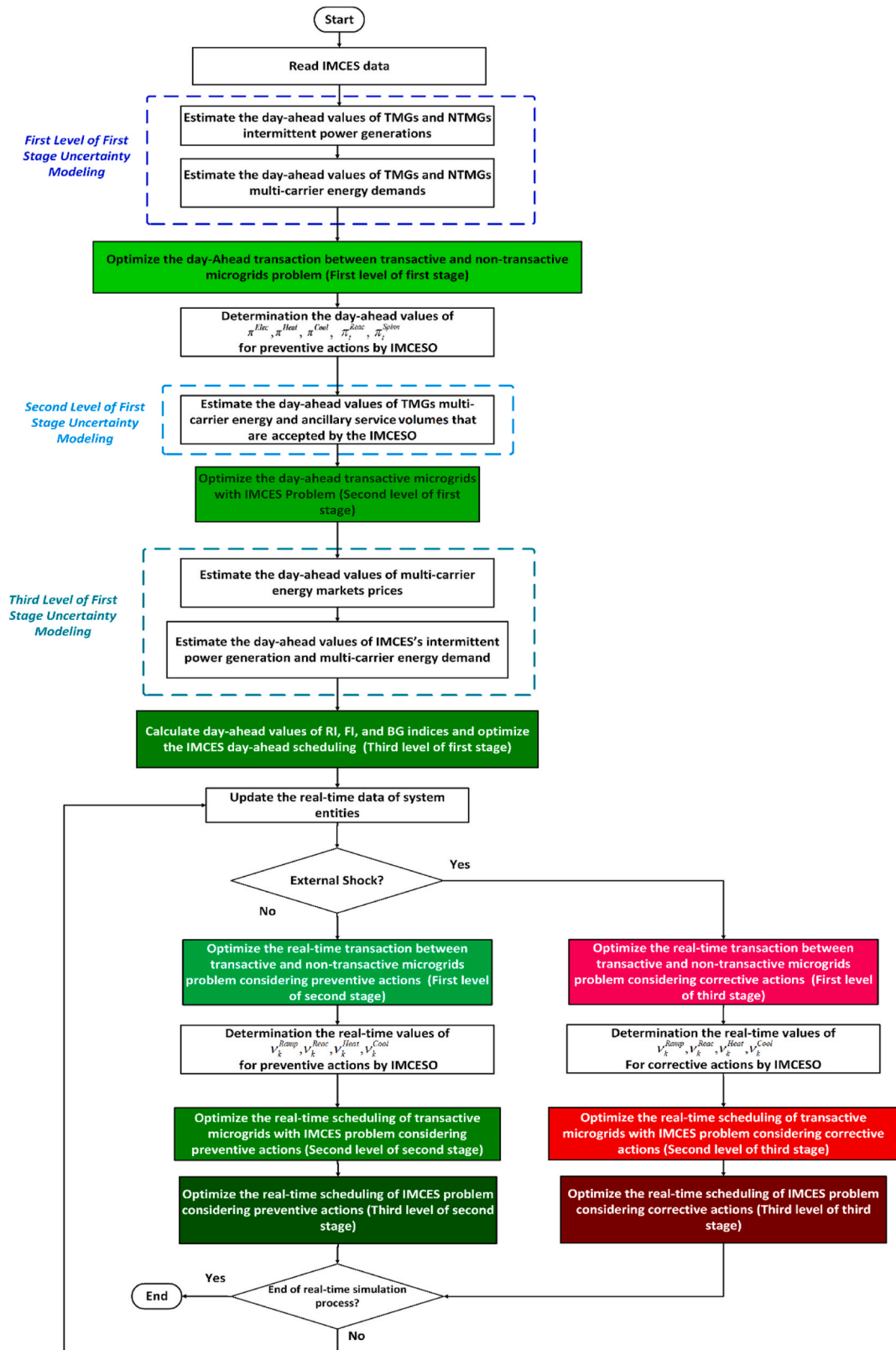


Fig. 3. The flowchart of the proposed method.

with IMCESO. However, this type of microgrid can transact energy with other TMGs. The TMGs are competing in the DA and RT markets to gain more profit.

It is assumed that the TMGs and NTMGs are transacting EHC energy. In addition, they can form cooperative MGs that endeavor to minimize

their operating costs through energy transactions. Finally, it is assumed that the microgrids' DERs consist of the same categories as the IMCES's DERs categories. More details for the microgrids' models have been addressed in Ref. [20]. It should be noted that the reconfiguration of the introduced IMCES could be achieved using proper switching actions and

control valves.

The cooperation mechanism of the TMGs and NTMGs consists of the first level of the first-stage optimization process for the day-ahead market and the first level of the second-stage optimization procedure for the real-time normal operation conditions. Finally, for the shock conditions, the TMGs and NTMGs are optimizing their cooperation process through the first level of the third stage optimization problem.

As shown in Fig. 2, the optimization process in the DA and RT horizons includes two different layers. In addition, the contingent event, introduced as the external shock, would be executed in the third layer. It is worth mentioning that each layer includes three corresponding levels. The full description of the layers and their corresponding levels is provided in the next sections.

2.1. Flexibility index

For assessing the impacts of the contribution of TMGs, a flexibility index for IMCES for the DA operational scheduling is defined as the DA Flexibility Index (FI^{DA}), which is proposed as (1):

$$FI^{DA} = \frac{\sum_{i=1}^{NUEDER} P_i^{UDER}(t)|_{No\ TMGCs} - \sum_{i=1}^{NUEDER} P_i^{UDER}(t)|_{With\ TMGCs}}{\sum_{i=1}^{NUEDER} P_i^{UDER}(t)|_{With\ TMGCs}} + \frac{\sum_{i=1}^{NUEDER} Q_i^{UDER}(t)|_{No\ TMGCs} - \sum_{i=1}^{NUEDER} Q_i^{UDER}(t)|_{With\ TMGCs}}{\sum_{i=1}^{NUEDER} Q_i^{UDER}(t)|_{With\ TMGCs}} + \frac{\sum_{j=1}^{NUHDER} H_j^{UDER}(t)|_{No\ TMGCs} - \sum_{j=1}^{NUHDER} H_j^{UDER}(t)|_{With\ TMGCs}}{\sum_{j=1}^{NUHDER} H_j^{UDER}(t)|_{With\ TMGCs}} + \frac{\sum_{k=1}^{NUCDER} R_k^{UDER}(t)|_{No\ TMGCs} - \sum_{k=1}^{NUCDER} R_k^{UDER}(t)|_{With\ TMGCs}}{\sum_{k=1}^{NUCDER} R_k^{UDER}(t)|_{With\ TMGCs}} \quad (1)$$

The first term of Eq. (1) presents the normalized value of the difference in active power generation of Utility-owned DERs (UDERs) without and with the TMGs' Contributions (TMGCs). The second term of

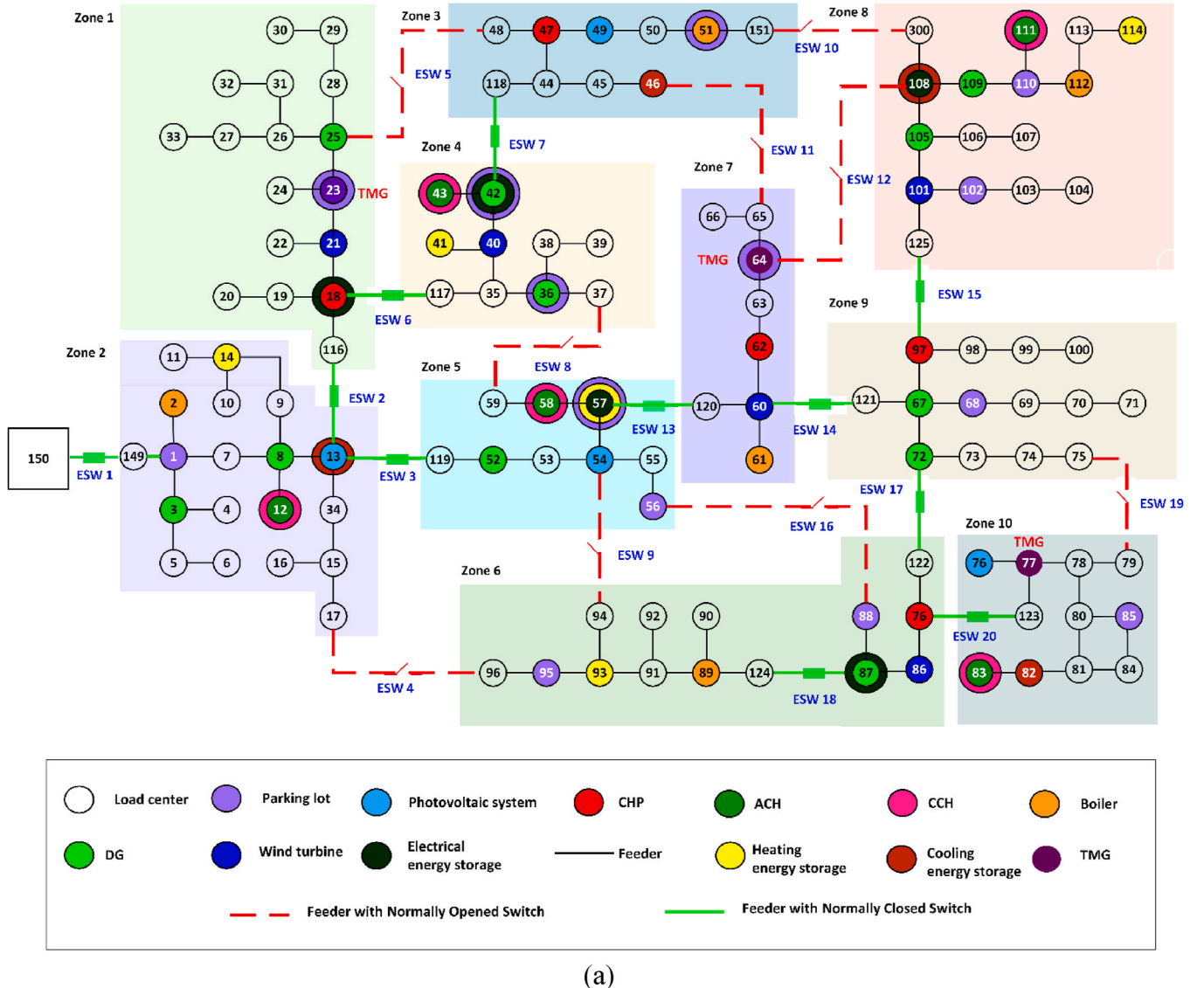
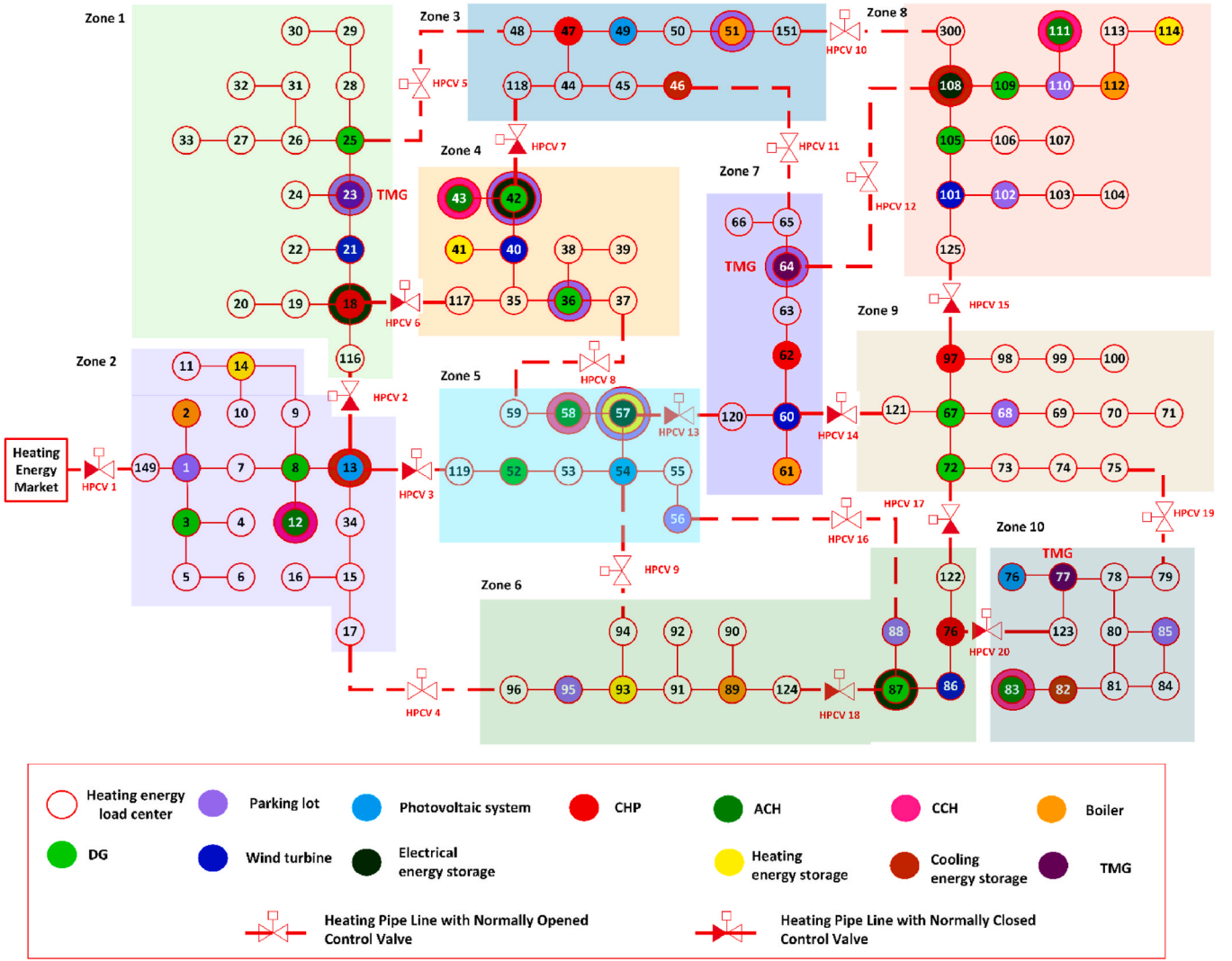


Fig. 4. (a) The electrical system, (b) The heating system, and (c) The cooling system of 123-bus IMCES.



(b)

Fig. 4. (continued).

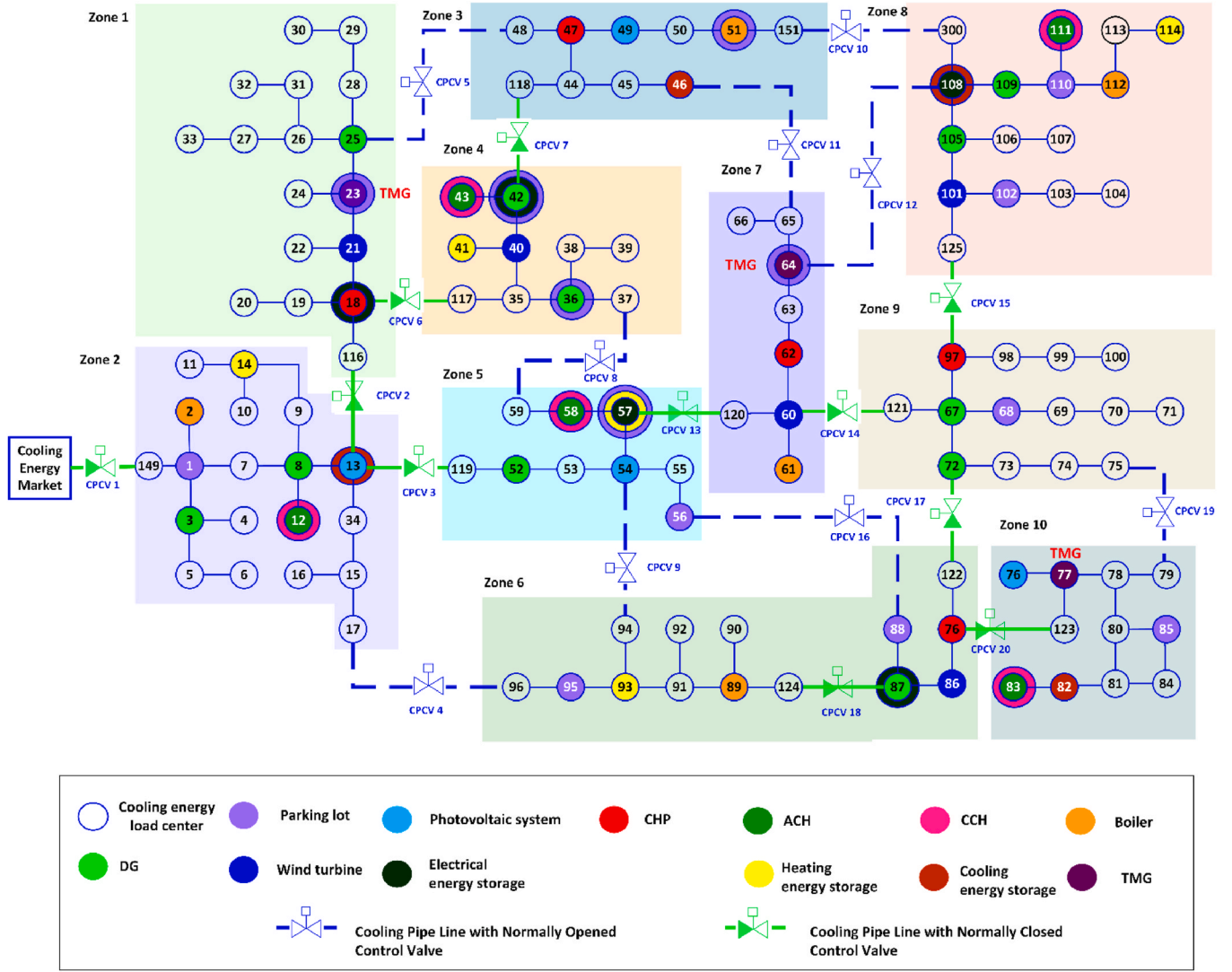
Eq. (1) calculates the normalized value of the difference in reactive power generation of UDERs without and with the TMGCs. The third term of Eq. (1) determines the normalized value of the difference in heating power generation of UDERs without and with the TMGCs. Finally, the fourth term of Eq. (1) presents the normalized value of the difference in cooling power generation of UDERs without and with the TMGCs. Based on Eq. (1), the higher values of FI^{DA} indicate that the IMCES's distributed energy resources produce less energy and ancillary services. Thus, there is a higher available capacity of the DERs in IMCES to supply the energy demands while the flexibility provision capability of the energy system is leveraged. Hence, the IMCES operator should endeavor to reach to higher value of FI^{DA} . However, the higher values of TMGs' contributions depend on the energy transactions between TMGs and NTMGs, which should be assessed by the IMCESO.

2.2. Day-ahead optimal transaction between transactive and non-transactive microgrids problem (first level of the first stage)

- Fig. 2 addresses the EHC transactions in TMGs and NTMGs through their interconnected networks. As mentioned earlier, TMGs and NTMGs can form cooperative groups to minimize their operating costs. In this case, the mathematical model of the cooperative group of TMGs and NTMGs can be presented as (2):

$$\begin{aligned}
 \text{Max } Z_X^{DA} = & \sum_{t=1}^T \sum_{s=1}^{NXDAS} \sum_{c=1}^{NBC} pr_s \cdot \left(\lambda_{t,c}^{Elect} \cdot g_{t,c}^{Elec} + \lambda_{t,c}^{Heat} \cdot g_{t,c}^{Heat} + \lambda_{t,c}^{Cool} \cdot g_{t,c}^{Cool} \right. \\
 & \left. - C_X^{Purchase} - \text{Penalty}^x \right) \forall X \\
 & \in \{TMGs, NTMGs\} \ \& \ \Omega \in \{TMGs \text{ and NTMGs feasible topologies}\}
 \end{aligned} \quad (2)$$

Eq. (2) consists of the profit of the electricity transaction of TMG with NTMG ($\lambda_{t,c}^{Elect} \cdot g_{t,c}^{Elec}$), the profit of the heating energy transaction of TMG with NTMG ($\lambda_{t,c}^{Heat} \cdot g_{t,c}^{Heat}$), the profit of the cooling transaction of TMG with NTMG ($\lambda_{t,c}^{Cool} \cdot g_{t,c}^{Cool}$), and the operating costs of TMGs and NTMGs ($C_X^{Purchase}$). Penalty^x is the penalty for any mismatch between the scheduled and actual energy transactions. It is assumed that each TMG can contract with NTMGs and determine the volume of electrical energy transaction ($g_{t,c}^{Elec}$), the volume of heating energy transaction ($g_{t,c}^{Heat}$), and the volume of cooling energy transaction ($g_{t,c}^{Cool}$), respectively. $\lambda_{t,c}^{Elect}$, $\lambda_{t,c}^{Heat}$, and $\lambda_{t,c}^{Cool}$ are the DA EHC energy transaction prices of TMGs and NTMGs, respectively, that TMG and NTMG are transacting energy carriers in their bilateral contracts. According to the assumptions, the TMGs can change the topology of the networks using switches and valves that



(c)

Fig. 4. (continued).

transact multi-carrier energy with the IMCES. The maximum capacity, the energy and mass constraints, charge, and discharge constraints of TMGs and NTMGs would be handled iteratively.

2.3. Day-ahead transactive microgrids with IMCES optimization problem (second level of the first stage)

After determining the energy transaction with NTMGs, the TMGs can transact active power, reactive power, and spinning reserve with IMCESO in the DA LEM. Further, the TMGs can transact multi-energy carriers with IMCESO in the DA LHM and LCM, respectively.

As mentioned earlier, the TMGs are competing with each other in the DA and RT markets to gain more profit. The TMGs can determine the volume of their energy transactions in the LEM (q^{Elec}), LHM (q^{Heat}), and LCM (q^{Cool}) that can be sold in the DA LEM price (π^{Elec}), LHM price (π^{Heat}), and LFM price (π^{Cool}), respectively. Thus, the TMG should maximize the following objective function for the DA optimization process, as Eq. (3):

$$\begin{aligned}
 \text{Max } \mathbb{Z}_{TMG}^{DA} = & \sum_{t=1}^T \sum_{s=1}^{NTMGDAS} \sum_{c=1}^{NBC} pr_s \cdot \left[\pi_t^{Elec} \cdot (q_t^{Elec} - g_{t,c}^{Elec}) + \lambda_{t,c}^{Elec} \cdot g_{t,c}^{Elec} \right. \\
 & + \pi_t^{Reac} \cdot q_t^{Reac} + \pi_t^{Spinn} \cdot q_t^{Spinn} + \pi_t^{Heat} \cdot (q_t^{Heat} - g_{t,c}^{Heat}) + \lambda_{t,c}^{Heat} \cdot g_{t,c}^{Heat} \\
 & \left. + \pi_t^{Cool} \cdot (q_t^{Cool} - g_{t,c}^{Cool}) + \lambda_{t,c}^{Cool} \cdot g_{t,c}^{Cool} - C^{TMG} - \text{Penalty}^{TMG,IMCESO} \right] \quad (3)
 \end{aligned}$$

Eq. (3) consists of the profit of electricity transaction of TMG with IMCESO ($\pi_t^{Elec} \cdot (q_t^{Elec} - g_{t,c}^{Elec})$), profit of active power transaction of TMG with NTMG ($\lambda_{t,c}^{Elec} \cdot g_{t,c}^{Elec}$), profit of reactive power transaction of TMG with IMCESO ($\pi_t^{Reac} \cdot q_t^{Reac}$), profit of spinning reserve transaction of TMG with IMCESO ($\pi_t^{Spinn} \cdot q_t^{Spinn}$), profit of heating energy transaction of TMG with IMCESO ($\pi_t^{Heat} \cdot (q_t^{Heat} - g_{t,c}^{Heat})$), profit of heating energy transaction of TMG with NTMG ($\lambda_{t,c}^{Heat} \cdot g_{t,c}^{Heat}$), profit of cooling transaction of TMG with IMCESO ($\pi_t^{Cool} \cdot (q_t^{Cool} - g_{t,c}^{Cool})$), profit of electricity transaction of TMG with NTMG ($\lambda_{t,c}^{Cool} \cdot g_{t,c}^{Cool}$), operating costs of TMG (C^{TMG}), and the penalty for any mismatch between the scheduled and actual energy transactions of TMG and IMCESO ($\text{Penalty}^{TMG,IMCESO}$), respectively.

Table 2
The simulation input data.

CHP	CHP1 = 0.1, CHP2 = 0.14, CHP3 = 0.07, CHP4 = 0.08, CHP5 = 0.09 MW (For 18, 47, 62, 76 and 97 bus). Consumption fuel cost respectively (MUs/kWh) = 0.18, 0.16, 0.17, 0.18, 0.19.
PhotoVoltaic system (PV)	Maintenance cost = 0.01 MUs/kWh. Photovoltaic arrays aggregated capacity (for 13, 49, 54, 76 and 108 bus) = 0.12 MW.
Wind Turbine (WT)	Maintenance cost = 0.015 MUs/kWh, Wind turbine aggregated capacity (for 21, 40, 60, 86 and 101 bus) = 0.12 MW.
Fossil fueled DG	DG1 = 0.12, DG2 = 0.14, DG3 = 0.1, DG4 = 0.18, DG5 = 0.2, DG6 = 0.18, DG7 = 0.2, DG8 = 0.32, DG9 = 0.24, DG10 = 0.1, DG11 = 0.18, DG12 = 0.15 MW (For 3, 8, 25, 36, 42, 52, 67, 72, 87, 105 and 109 bus), Consumption fuel cost respectively (MUs/kWh) = 0.0825, 0.0645, 0.0825, 0.0825, 0.0645, 0.0825, 0.0645, 0.0825, 0.0645, 0.0825, 0.0645.
Heating Absorption Chiller (HAC)	Maintenance cost (0.4 MW) = 1.2 MUs/kWh, COP = 0.8, Maintenance cost (0.48 MW) = 14.5 MUs/kWh, COP = 0.81, HAC (12, 43, 58) = 400 kW, HAC (83,111) = 480 kW.
Electric Compression Chiller (ECC)	Capacity: ECC1 = 0.52, ECC2 = 0.54, ECC3 = 0.66, ECC4 = 0.3, ECC5 = 0.88 MW (For 12, 43, 58, 83 and 111 bus) Maintenance cost respectively = 0.082, 0.064, 0.076, 0.082, 0.082 MUs/kWh, COP = 4.
Electrical Energy Storage (ESS)	Modules capacity = 50 kW (For 18, 42, 57, 87 and 108 bus), Type: Lead-acid battery, Efficiency = 0.9, Maintenance cost (ESS) = 0.001 MUs/kWh.
Thermal Energy Storage (TES) and Cooling Energy Storage (CSS)	CSS modules capacity = 50 kW (For 13, 46, 62, 82 and 108 bus), Maintenance cost (CSS) = 0.002 MUs/kWh, CSS type (ice storage), TES modules capacity = 50 kW (For 14, 41, 57, 93 and 114 bus), Maintenance cost (TES) = 0.002 MUs/kWh, TES type (hot water storage).
Boiler	Boiler Maintenance cost = 0.0725 MUs/kWh. Capacity = 0.22 MW

It is assumed that each TMG can transact energy with IMCESO and determine the volume of electrical energy transaction (q^{Elec}), the volume of heating energy transaction (q^{Heat}), and the volume of cooling energy transaction (q^{Cool}), respectively. π_t^{Elect} , π_t^{Heat} , and π_t^{Cool} are the value of EHC energy transactions hourly prices, respectively. It is very important

to note that the optimal volume of energy transactions between TMGs and NTMGs should be determined at the first level. Then, the optimal volume of energy transactions of TMGs and IMCESO can be calculated in the second level because there are two different markets. In the first level, the bilateral contracts are optimized, and in the second level, the DA LEM, LHM, and LCM are settled. The IMCESO can change the values of π_t^{Elect} , π_t^{Heat} , and π_t^{Cool} .

2.4. Day-ahead IMCESO optimization problem (third level of the first stage)

A Bidding Gain (BG) is proposed to assess the bidding strategy of TMGs considering their bilateral contracts with NTMGs. The BG is defined as Eq. (4):

$$BG_{TMGC} = \frac{\mathbb{Z}_{TMG}^{DA} | \text{With TMGCs} - \mathbb{Z}_{TMG}^{DA} | \text{No TMGCs}}{\mathbb{Z}_{TMG}^{DA} | \text{No TMGCs}} \quad (4)$$

Eq. (4) explore the value of TMG gain considering their TMGC and without TMGC conditions. The IMCESO can change the value of BG to increase the contribution of TMGs to enhance the flexibility and resiliency of its system. Further, a Resiliency Index (RI) is defined to evaluate the resiliency level of the system. The RI is proposed as (5):

$$RI|_{fixed} \Xi = \frac{\sum_{l=1}^{NCEL} P_{Critical}}{\left(\sum_{l=1}^{NEL} P_L - \sum_{l=1}^{NCEL} P_{Critical} \right)} + \frac{\sum_{j=1}^{NCHL} H_{Critical}}{\left(\sum_{j=1}^{NHL} H_L - \sum_{j=1}^{NCHL} H_{Critical} \right)} + \frac{\sum_{k=1}^{NCCL} R_{Critical}}{\left(\sum_{k=1}^{NCL} R_L - \sum_{k=1}^{NCCL} R_{Critical} \right)} \forall \Xi \in \{\text{IMCES feasible topologies}\} \quad (5)$$

The denominator of the first term of Eq. (5) is identical to the active power of supplied non-critical electrical loads. Thus, the first term of Eq. (5) indicates the ratio of the values of supplied critical electrical loads concerning the supplied non-critical electrical loads. The second term of Eq. (5) shows the ratio of the values of supplied critical heating loads concerning the supplied non-critical heating loads. Finally, the third term of Eq. (5) calculates the ratio of the values of supplied critical cooling loads concerning the supplied non-critical cooling loads. Thus, the higher values of RI indicate that a higher volume of critical loads is supplied in contingent conditions. Hence, the IMCES should reduce the values of not-supplied critical EHC loads that lead to an increase in the value of the resiliency index in contingent conditions.

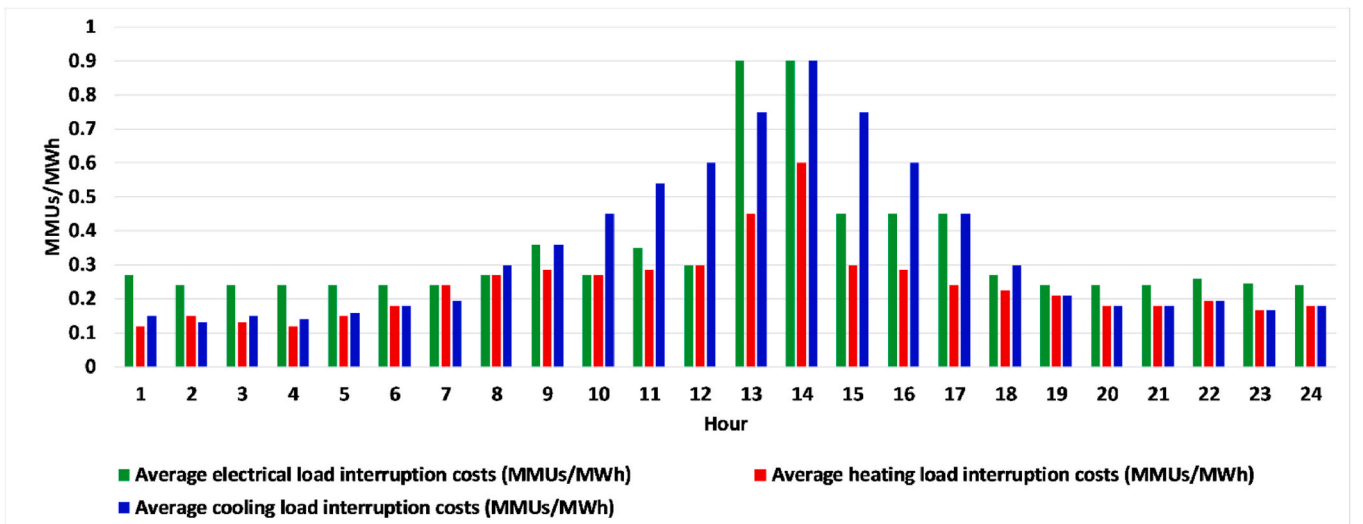


Fig. 5. The value of interruption costs for the EHC systems.

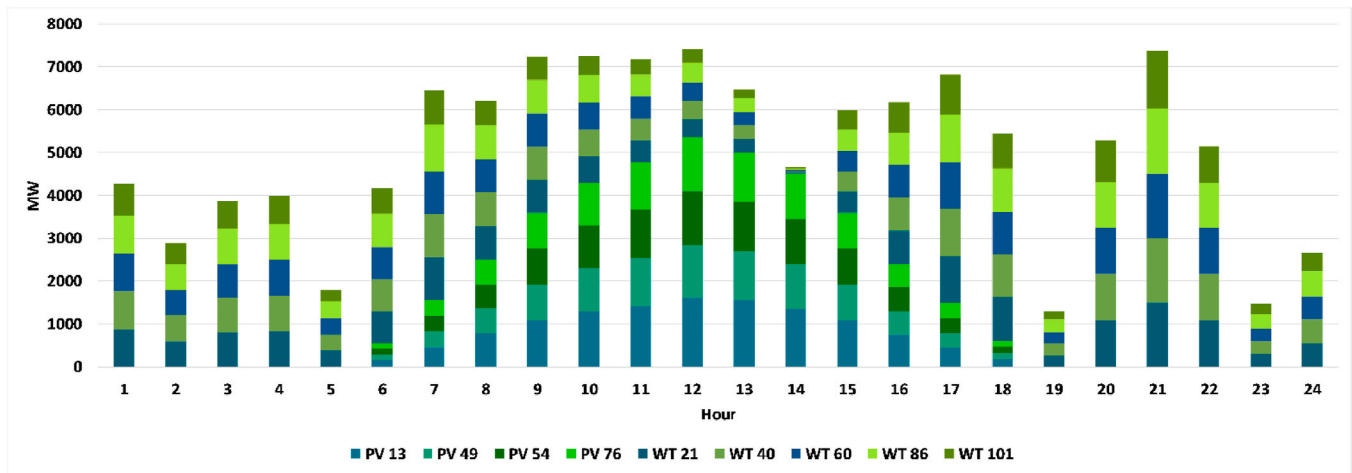


Fig. 6. The outputs of one of the reduced scenarios for the wind turbines and photovoltaic systems' electricity generation.

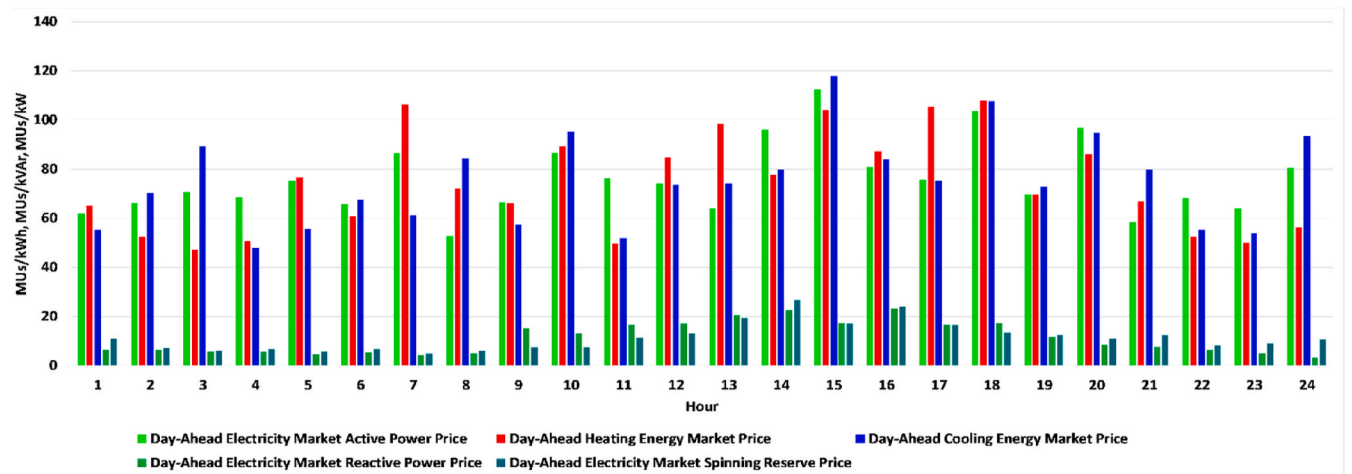


Fig. 7. The estimated hourly price for DA energy markets.

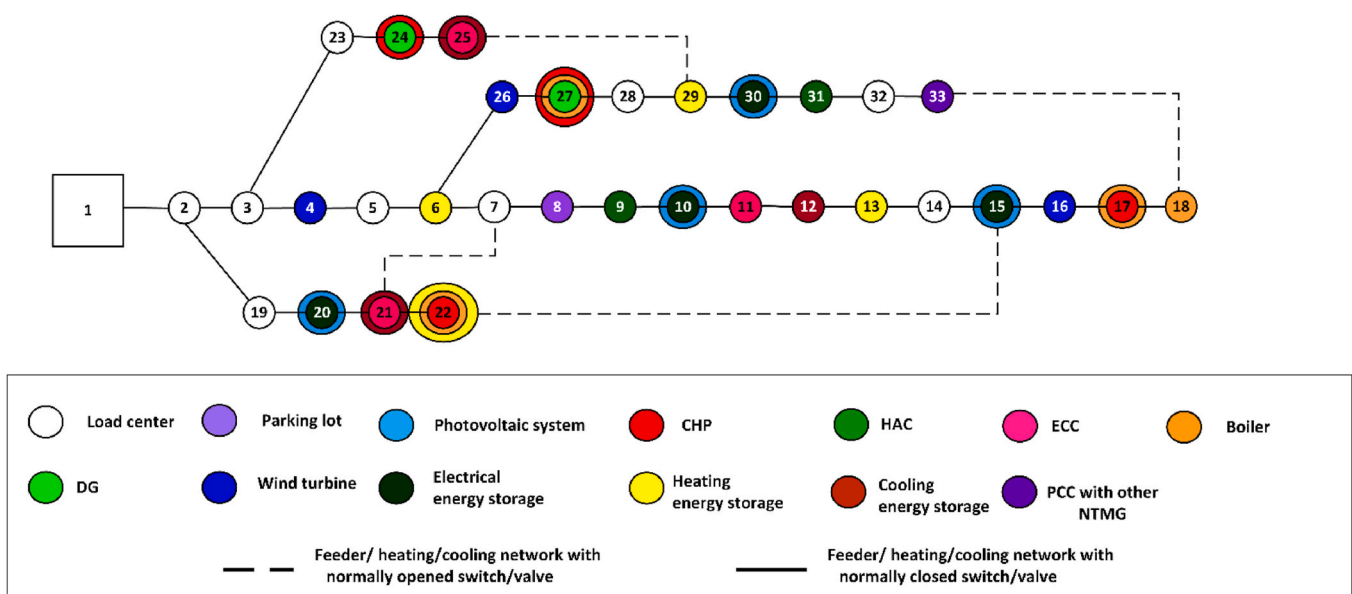


Fig. 8. The topology of TMG and NTMG.

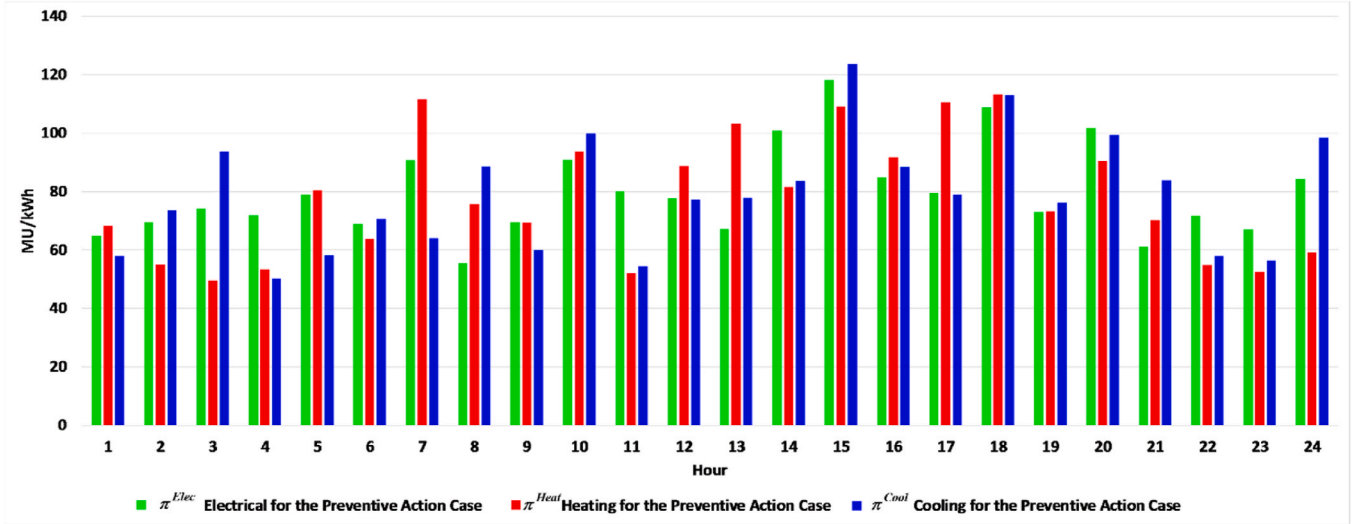


Fig. 9. The values of π^{Elec} , π^{Heat} , and π^{Cool} for preventive actions.

Thus, the objective function of the IMCES for the DA optimization process can be presented as (6):

$$\begin{aligned} \text{Min } Z_{IMCES}^{DA} = & \sum_{t=1}^T \sum_{s'=1}^{NIMCESDAS} pr_{s'} \cdot \left(W_1 \cdot \left(\begin{aligned} & C_{IMCES}^{DG} + C_{IMCES}^{CSS} + C_{IMCES}^{GB} + C_{IMCES}^{HAC} + C_{IMCES}^{PHEVPL} + C_{IMCES}^{TES} + C_{IMCES}^{CHP} \\ & + C_{IMCES}^{EES} + C_{IMCES}^{ECC} + C_{IMCES}^{PV} + C_{IMCES}^{WT} + C_{IMCES}^{Purchase} - B_{IMCES}^{Sell} + C_{IMCES}^{ELDRP} \\ & + C_{IMCES}^{HDRP} + C_{IMCES}^{CDRP} - \text{Penalty}^{TMG,IMCESO} + ENSCs \end{aligned} \right) \right. \\ & \left. - W_2 \cdot FI^{DA} - W_3 \cdot RI - W_4 \cdot BG_{TMGC} \right) \forall \Xi \in \{IMCES \text{ feasible topologies} \} \end{aligned} \quad (6)$$

Eq. (6) consists of the operating costs of DG (C_{IMCES}^{DG}), operating costs of CSS (C_{IMCES}^{CSS}), operating costs of boiler (C_{IMCES}^{GB}), operating costs of HAC (C_{IMCES}^{HAC}), operating costs of PHEV parking lots (C_{IMCES}^{PHEVPL}), operating costs of TES (C_{IMCES}^{TES}), operating costs of CHP (C_{IMCES}^{CHP}), operating costs of EES (C_{IMCES}^{EES}), operating costs of ECC (C_{IMCES}^{ECC}), operating costs of PV (C_{IMCES}^{PV}), operating costs of WT (C_{IMCES}^{WT}), costs of energy purchased ($C_{IMCES}^{Purchase}$), profits of the sold energy (B_{IMCES}^{Sell}), the costs of electrical, heating, and cooling energy DRP ($C_{IMCES}^{ELDRP} + C_{IMCES}^{HDRP} + C_{IMCES}^{CDRP}$), profits of TMG penalty ($\text{Penalty}^{TMG,IMCESO}$), the Energy Not Supplied Costs (ENSCs), the flexibility index ($W_2 \cdot FI^{DA}$), resiliency index ($W_3 \cdot RI$), and BG ($W_4 \cdot BG_{TMGC}$). The bidding gain is considered in the DA optimal scheduling process to encourage the TMGCs to procure energy and ancillary services in normal and external shock conditions.

A. Electric power balance constraint

This constraint can be presented as (7):

$$\mp \sum_{l=1}^{NTMG} P_l^{TMG}(t) + \sum_{i=1}^{NUEDER} P_i^{UEDER}(t) \mp P^{E_Market}(t) = \sum_{i'=1}^{NEL} P_{i'}^L(t) + P^{LOSS} \quad (7)$$

Eq. (7) represents the aggregated transacted electrical power with TMGs ($\sum_{l=1}^{NTMG} P_l^{TMG}(t)$), generated electrical power of UEDRs ($\sum_{i=1}^{NUEDER} P_i^{UEDER}(t)$), and the exported (imported) power to (from) the electricity market ($P^{E_Market}(t)$) must be identical to the aggregated active power of loads ($\sum_{i'=1}^{NEL} P_{i'}^L(t)$) and electrical power loss of IMCES (P^{LOSS}). The same formulation for reactive power should be considered.

B. Heating power balance constraint

This constraint can be presented as (8):

$$\mp \sum_{m=1}^{NTMG} H_m^{TMG}(t) + \sum_{j=1}^{NUHDER} H_j^{UEDER}(t) \mp H^{H_Market}(t) = \sum_{j'=1}^{NHL} H_{j'}^L(t) + H^{LOSS} \quad (8)$$

Eq. (8) represents that aggregated transacted heating power with TMGs ($\sum_{m=1}^{NTMG} H_m^{TMG}(t)$), generated heating power of UEDRs ($\sum_{j=1}^{NUHDER} H_j^{UEDER}(t)$), and the exported (imported) heating power to (from) heating market ($H^{H_Market}(t)$) must be identical to aggregated heating power of loads ($\sum_{j'=1}^{NHL} H_{j'}^L(t)$) and heating power loss of IMCES (H^{LOSS}).

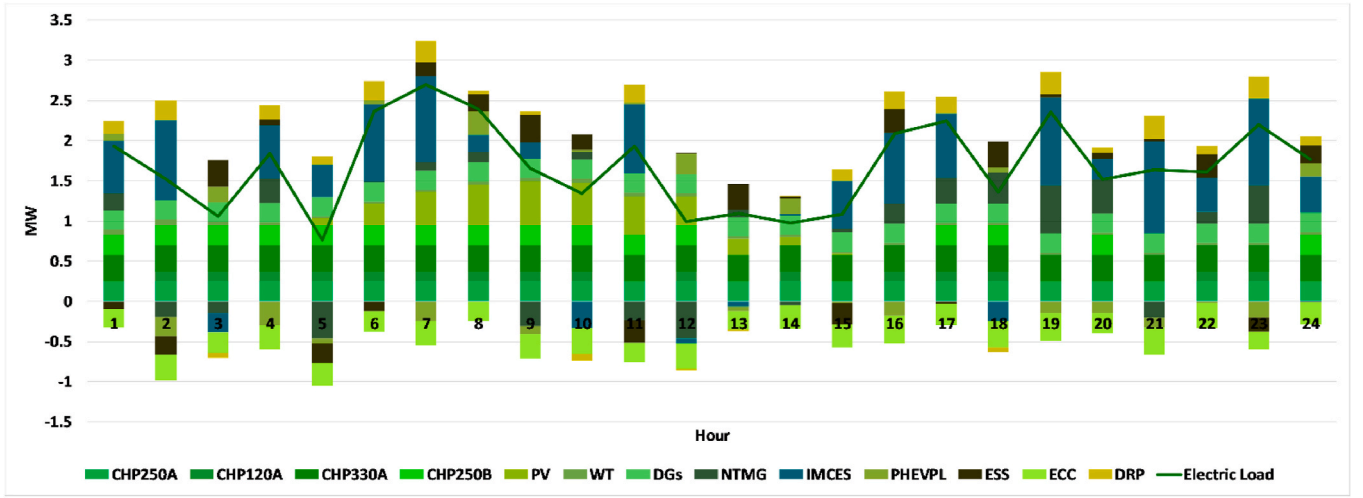
C. Cooling power balance constraint

This constraint can be formulated as (9):

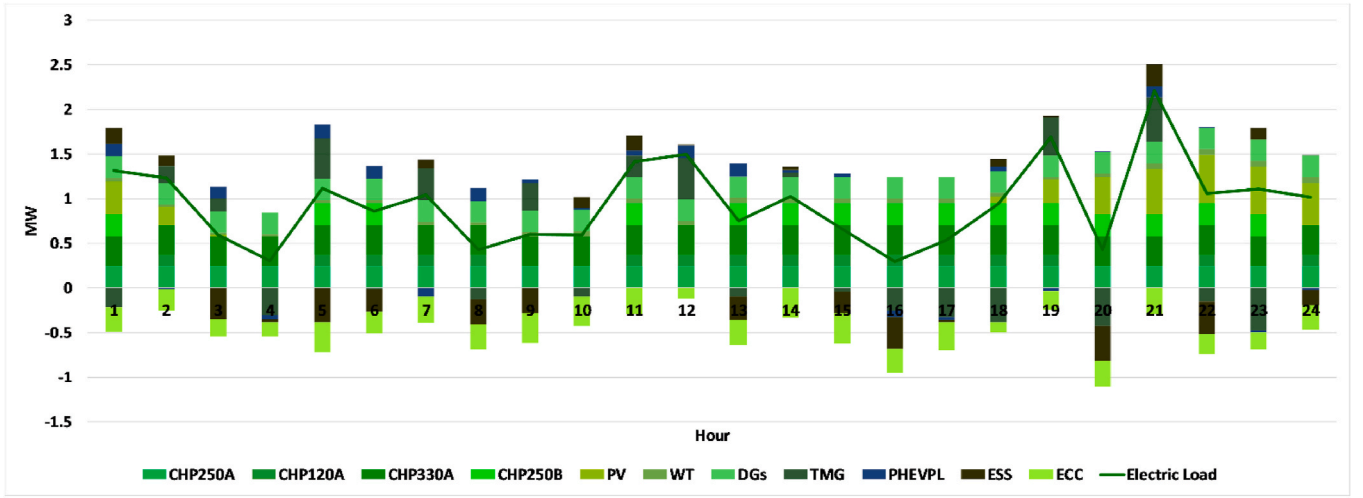
$$\mp \sum_{n=1}^{NTMG} R_n^{TMG}(t) + \sum_{k=1}^{NUCDER} R_k^{UEDER}(t) \mp R^{C_Market}(t) = \sum_{k'=1}^{NCL} R_{k'}^L(t) + R^{LOSS} \quad (9)$$

Eq. (9) represents that aggregated transacted cooling power with TMGs ($\sum_{n=1}^{NTMG} R_n^{TMG}(t)$), generated cooling power of UEDRs ($\sum_{k=1}^{NUCDER} R_k^{UEDER}(t)$), and the exported (imported) cooling power to (from) cooling market ($R^{C_Market}(t)$) must be identical to the aggregated cooling power of loads ($\sum_{k'=1}^{NCL} R_{k'}^L(t)$) and cooling power loss of IMCES (R^{LOSS}).

The constraints of facilities' maximum capacity, load flows, mass balance constraints, and charge and discharge constraints should be considered in the optimization process.



(a)



(b)

Fig. 10. (a) Optimal dispatch of distributed electrical energy resources of TMGs, their transactive energy, and electrical loads, (b) the optimal dispatch of distributed electrical energy resources of NTMGs, their transactive energy, and electrical loads.

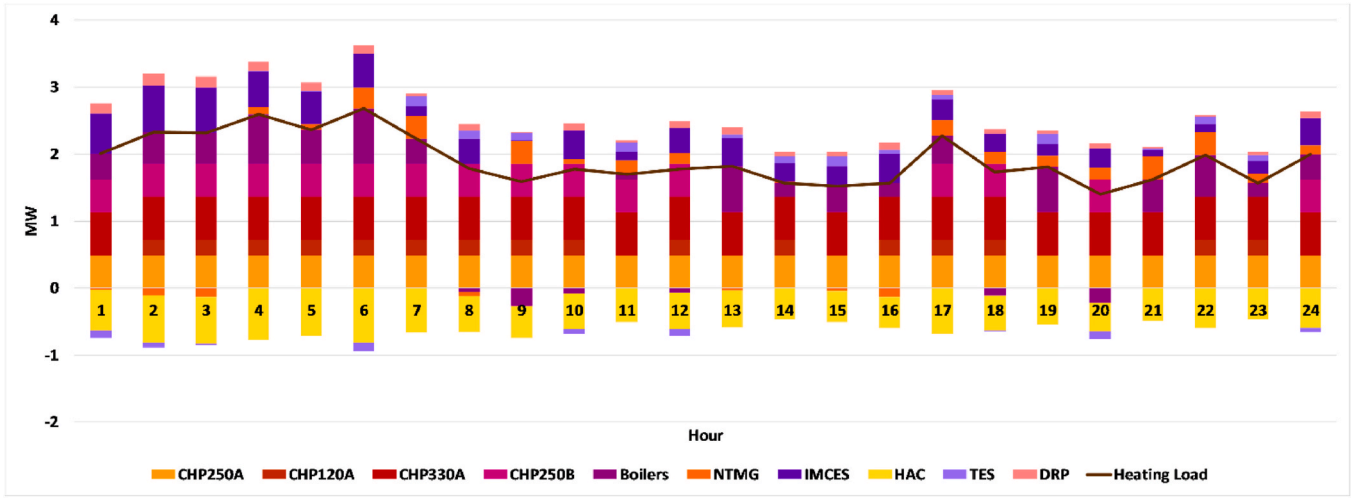
2.5. Real-time optimal transaction between transactive and non-transactive microgrids optimization problem considering preventive actions (first level of the second stage)

It is assumed that external shocks (such as storms) can be forecasted and announced by the responsible entities to the IMCESO, NTMGs, and TMGs. Thus, the TMGs, NTMGs, and IMCESO should manage their systems in a preventive manner. As mentioned earlier, the ramp service, reactive power, active power, and heating and cooling energy are transacted in the RT market. The active power and reactive power are transacted in the LEM. The heating energy and cooling energy carriers are transacted in LHM and LCM, respectively. Finally, the ramp services are transacted in the LFM.

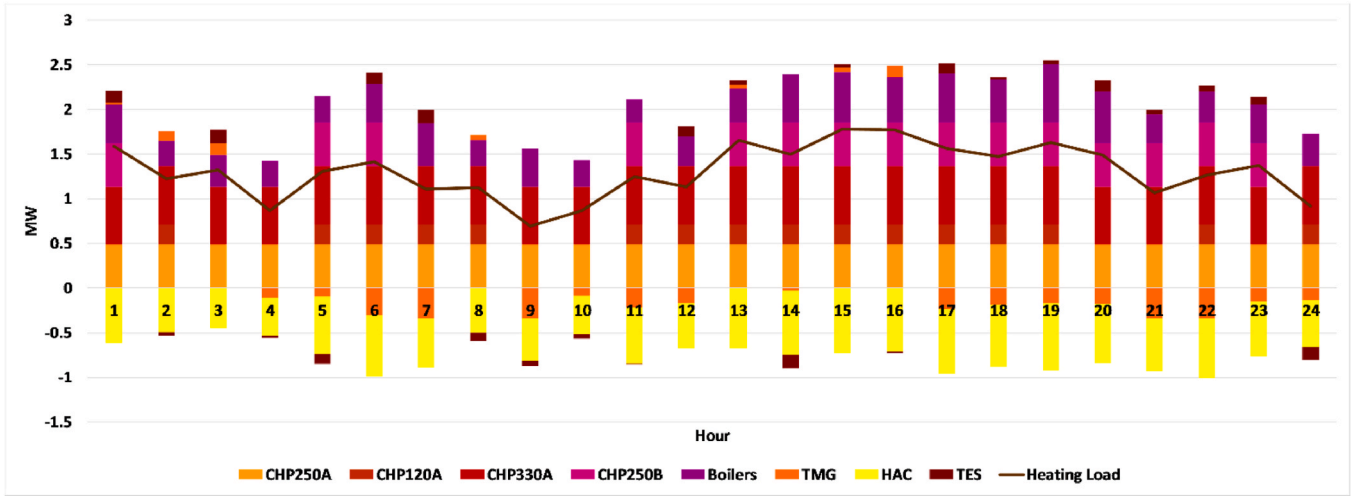
The TMGs and NTMGs can form cooperative groups to minimize their RT operating costs, considering the expected external shock. Further, they can change their topologies in a preventive manner against external shocks. Thus, the objective function of a cooperative group of TMGs and NTMGs can be proposed as (10):

$$\begin{aligned}
 \text{Max } Z_X^{\text{RT}} = & \sum_{k=1}^{96} \sum_{c=1}^{NBC} \left(\xi_{k,c}^{\text{Elect}} \cdot \phi_{k,c}^{\text{Elec}} + \xi_{k,c}^{\text{Heat}} \cdot \phi_{k,c}^{\text{Heat}} + \xi_{k,c}^{\text{Cool}} \cdot \phi_{k,c}^{\text{Cool}} - C_X^{\text{Purchase}} \right. \\
 & \left. - \text{Penalty}^X - \text{ENSCs}^X \right) \forall X \\
 & \in \{\text{TMGs, NTMGs}\} \ \& \ \forall \Omega \in \{\text{TMGs and NTMGs feasible topologies}\}
 \end{aligned} \quad (10)$$

Eq. (10) consists of the profit of the RT electricity transaction of TMG with NTMG ($\xi_{k,c}^{\text{Elect}} \cdot \phi_{k,c}^{\text{Elec}}$), the profit of the RT heating energy transaction of TMG with NTMG ($\xi_{k,c}^{\text{Heat}} \cdot \phi_{k,c}^{\text{Heat}}$), the profit of the RT cooling transaction of TMG with NTMG ($\xi_{k,c}^{\text{Cool}} \cdot \phi_{k,c}^{\text{Cool}}$), and the RT operating costs of TMGs and NTMGs (C_X^{Purchase}). Penalty^X is the penalty of any mismatch between the RT scheduled and actual energy transactions. ENSC is considered for probable external shock for the TMGs and NTMGs systems. The volume of the RT electrical energy transaction is equal to (ϕ^{Elec}), the volume of the RT heating energy transaction is equal to (ϕ^{Heat}), and the volume of the RT cooling energy transaction is equal to (ϕ^{Cool}), respectively. ξ^{Elect} ,



(a)



(b)

Fig. 11. (a) The optimal dispatch of distributed heating energy resources of TMGs, their transactive energy, and heating loads, (b) the optimal dispatch of distributed heating energy resources of NTMGs, their transactive energy, and heating loads.

ξ^{Heat} , and ξ^{Cool} are the values of the RT EHC energy transaction prices, respectively, that TMG and NTMG are transacting the energy carriers in their RT bilateral contracts. Further, Eq. (10) constraints are the same as Eq. (2) constraints.

2-6- Real-time scheduling of transactive microgrids with IMCES optimization problem considering preventive actions (Second level of the second stage)

The TMGs are transacting active power and reactive power with IMCESO in the RT LEM. Further, the TMGs can transact heating energy and cooling energy carriers with IMCESO in the RT LHM and RT LCM, respectively. Finally, some of the TMGs can procure ramp services for the IMCESO in the LFM. The TMGs should determine the number of their energy transactions in the RT LFM (μ_k^{Ramp} and μ_k^{Reac}), RT LHM (μ_k^{Heat}), and RT LCM (μ_k^{Cool}) that can be sold in RT LFM price (ν_k^{Ramp} , and ν_k^{Reac}), RT LHM price (ν_k^{Heat}), and RT LCM price (ν_k^{Cool}), respectively.

Thus, the objective function of TMGs for the RT optimization problem can be written as (11):

$$\begin{aligned}
 \text{Max } \mathcal{Z}_{TMG}^{RT} = & \sum_{k=1}^{96} \sum_{c=1}^{NBC} \left[\nu_k^{Ramp} \cdot \left(\mu_k^{Ramp} - \phi_{k,c}^{Elec} \right) + \xi_{k,c}^{Elect} \cdot \phi_{k,c}^{Elec} + \nu_k^{Reac} \cdot \mu_k^{Reac} \right. \\
 & + \nu_k^{Heat} \cdot \left(\mu_k^{Heat} - \phi_{k,c}^{Heat} \right) + \xi_{k,c}^{Heat} \cdot \phi_{k,c}^{Heat} + \nu_k^{Cool} \cdot \left(\mu_k^{Cool} - \phi_{k,c}^{Cool} \right) + \xi_{k,c}^{Cool} \cdot \phi_{k,c}^{Cool} \\
 & \left. - C^{TMG} - \text{Penalty}^{TMG,IMCESO} \right]
 \end{aligned} \quad (11)$$

Eq. (11) consists of the profit of the RT electricity transaction of TMG with IMCESO ($\nu_k^{Ramp} \cdot (\mu_k^{Ramp} - \phi_{k,c}^{Elec})$), the profit of the RT active power transaction of TMG with NTMG ($\xi_{k,c}^{Elect} \cdot \phi_{k,c}^{Elec}$), the profit of the RT reactive power transaction of TMG with IMCESO ($\nu_k^{Reac} \cdot \mu_k^{Reac}$), the profit of the RT heating energy transaction of TMG with IMCESO ($\nu_k^{Heat} \cdot (\mu_k^{Heat} - \phi_{k,c}^{Heat})$), the profit of the RT heating energy transaction of TMG with NTMG ($\xi_{k,c}^{Heat} \cdot \phi_{k,c}^{Heat}$), the profit of the RT cooling transaction of TMG with IMCESO ($\nu_k^{Cool} \cdot (\mu_k^{Cool} - \phi_{k,c}^{Cool})$), the profit of the RT electricity transaction of TMG with NTMG ($\xi_{k,c}^{Cool} \cdot \phi_{k,c}^{Cool}$), operating costs of TMG (C^{TMG}),

and the penalty of any mismatch between the RT scheduled and actual energy transactions of TMG and IMCESO ($Penalty^{TMG,IMCESO}$), respectively. Eq. (11) constraints are the same as Eq. (3) constraints.

2.6. Real-time scheduling of IMCESO optimization problem considering preventive actions (third level of the second stage)

For assessing the operating and structural flexibility of IMCESO in the RT horizon, an RT Flexibility Index (FI^{RT}) is proposed as (12):

$$FI^{RT} = \sum_{\Xi} \left(\frac{\sum_{i=1}^{NUEDER} RAMP_i^{UDER}(t)|_{No\ TMGCs} - \sum_{i=1}^{NUEDER} RAMP_i^{UDER}(t)|_{With\ TMGCs}}{\sum_{i=1}^{NUEDER} RAMP_i^{UDER}(t)|_{With\ TMGCs}} + \right. \\ \left. \frac{\sum_{i=1}^{NUEDER} Q_i^{UDER}(t)|_{No\ TMGCs} - \sum_{i=1}^{NUEDER} Q_i^{UDER}(t)|_{With\ TMGCs}}{\sum_{i=1}^{NUEDER} Q_i^{UDER}(t)|_{With\ TMGCs}} + \right. \\ \left. \frac{\sum_{j=1}^{NUHDER} H_j^{UDER}(t)|_{No\ TMGCs} - \sum_{j=1}^{NUHDER} H_j^{UDER}(t)|_{With\ TMGCs}}{\sum_{j=1}^{NUHDER} H_j^{UDER}(t)|_{With\ TMGCs}} + \right. \\ \left. \frac{\sum_{k=1}^{NUCDER} R_k^{UDER}(t)|_{No\ TMGCs} - \sum_{k=1}^{NUCDER} R_k^{UDER}(t)|_{With\ TMGCs}}{\sum_{k=1}^{NUCDER} R_k^{UDER}(t)|_{With\ TMGCs}} \right) \\ \forall \Xi \in \{IMCES\ feasible\ topologies\} \quad (12)$$

Based on Eq. (12), the higher values of FI^{RT} present that the distributed energy resources of IMCESO generate less energy and ancillary services, there is a higher available capacity of IMCESO's distributed energy resources to supply the energy system loads, and the flexibility of the energy system is increased.

The IMCESO can change the topologies of the IMCES's EHC systems to enhance the FI^{RT} , considering the TMGs' contributions. Thus, Eq. (12) considers all of the feasible topologies of IMCES that the IMCESO endeavors to enhance the flexibility of operation. Hence, the IMCESO's RT objective function can be written as (13):

$$Min\ S_{IMCES}^{RT} = \sum_{k=1}^{96} W_5 \cdot \left(\begin{aligned} &\Delta C_{IMCES}^{DG} + \Delta C_{IMCES}^{CSS} + \Delta C_{IMCES}^{GB} + \Delta C_{IMCES}^{HAC} + \Delta C_{IMCES}^{PHEVPL} + \Delta C_{IMCES}^{TES} + \Delta C_{IMCES}^{CHP} \\ &+ \Delta C_{IMCES}^{ESS} + \Delta C_{IMCES}^{ECC} + \Delta C_{IMCES}^{PV} + \Delta C_{IMCES}^{WT} + \Delta C_{IMCES}^{Purchase} - \Delta B_{IMCES}^{Sell} + \Delta C_{IMCES}^{ELDRP} \\ &+ \Delta C_{IMCES}^{HDP} + \Delta C_{IMCES}^{CDRP} - Penalty^{TMG,IMCESO} \end{aligned} \right) \\ - W_6 \cdot FI^{RT} - W_7 \cdot RI - W_8 \cdot BG_{TMGC} \quad \forall \Xi \in \{IMCES\ feasible\ topologies\} \quad (13)$$

Eq. (13) terms are the same as Eq. (6) terms and are not presented for the sake of space. The IMCESO can change the weighting factor W_8 to encourage TMGs to procure energy carriers for IMCES, considering preventive actions. The IMCESO can change the values of ν^{Ramp} , ν^{Reac} , ν^{Heat} , ν^{Cool} based on the RT IMCES energy balance and ancillary services conditions.

2.7. Real-time optimal transaction between transactive and non-transactive microgrids optimization problem considering corrective actions (first level of the third stage)

It is assumed that the IMCESO, TMGs, and NTMGs systems are planned and operated based on smart grid infrastructure, and the forecastable external shocks (such as storms) are announced by the responsible entities to the IMCESO, NTMGs, and TMGs. Thus, the TMGs, NTMGs, and IMCESO should manage their systems in a corrective manner after external shocks.

When an external shock occurs, the TMGs and NTMGs should restore their system using their unscathed DERs, changing their energy system topologies, and reconnecting their energy networks. In this condition, the TMGs and NTMGs should minimize their RT operating costs and Customer Interruption Costs (CICs). Thus, the objective function of TMGs and NTMGs as cooperative MGs can be proposed as (14):

$$Max\ Z_X^{RT'} = \sum_{k=1}^{96} \sum_{c=1}^{NBC} \left(\xi_{k,c}^{Elect} \cdot \phi_{k,c}^{Elec} + \xi_{k,c}^{Heat} \cdot \phi_{k,c}^{Heat} + \xi_{k,c}^{Cool} \cdot \phi_{k,c}^{Cool} - C_X^{Purchase} \right. \\ \left. - Penalty^X - CICs^X \right) \forall X \\ \in \{unscathed\ TMGs, NTMGs\} \ \&\forall \Psi \\ \in \{feasible\ TMGs\ and\ NTMGs\ interconnectd\ topologies\} \quad (14)$$

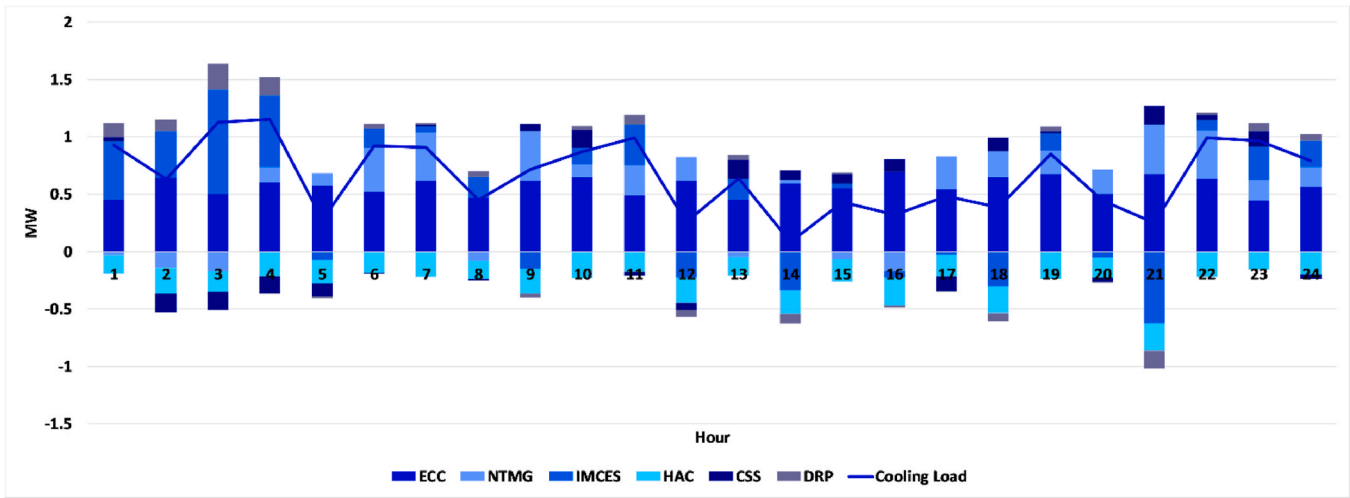
Eq. (14) terms are equal to Eq. (10) items. However, the CICs are considered for minimization. Further, the interconnected TMGs and NTMGs topologies are considered as Ψ . Finally, Eq. (14) constraints are the same as Eq. (10) constraints.

2.8. Real-time scheduling of transactive microgrids with IMCES optimization problem considering corrective actions (second level of the third stage)

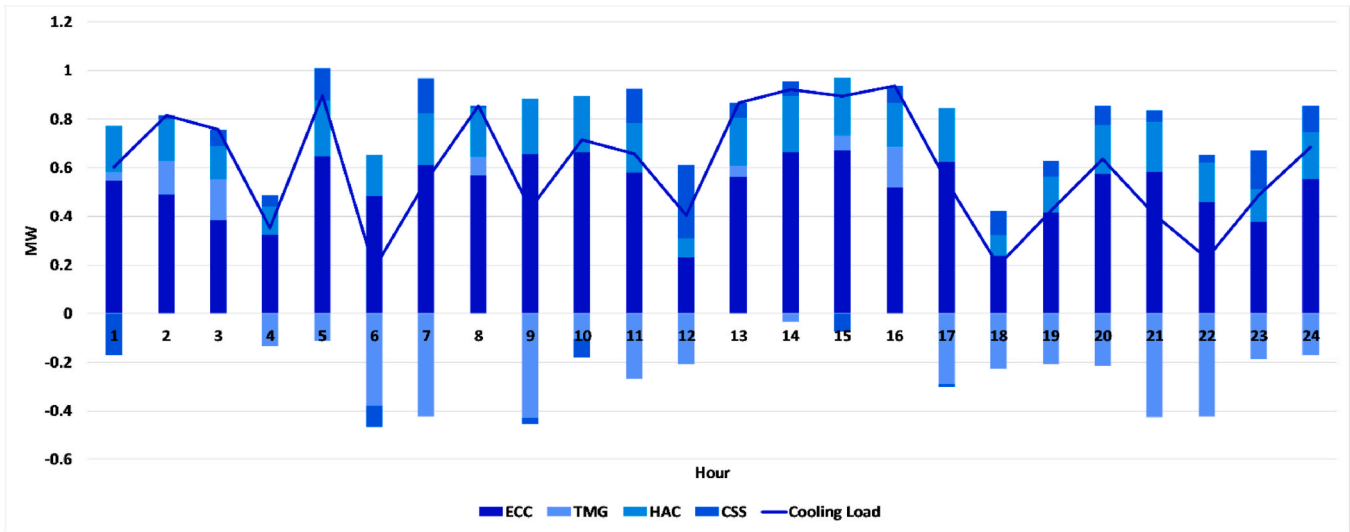
Based on the above discussion, the objective function of unscathed TMGs for the RT optimization problem considering corrective actions can be written as (15):

$$Max\ Z_{TMG}^{RT'} = \sum_{k=1}^{96} \sum_{c=1}^{NBC} \left[\nu_k^{Ramp} \cdot (\mu_k^{Ramp} - \phi_{k,c}^{Elec}) + \xi_{k,c}^{Elect} \cdot \phi_{k,c}^{Elec} + \nu_k^{Reac} \cdot \mu_k^{Reac} \right. \\ \left. + \nu_k^{Heat} \cdot (\mu_k^{Heat} - \phi_{k,c}^{Heat}) + \xi_{k,c}^{Heat} \cdot \phi_{k,c}^{Heat} + \nu_k^{Cool} \cdot (\mu_k^{Cool} - \phi_{k,c}^{Cool}) + \xi_{k,c}^{Cool} \cdot \phi_{k,c}^{Cool} \right. \\ \left. - C_{TMG}^{TMG} - CICs - Penalty^{TMG,IMCESO} \right] \forall \Psi \\ \in \{feasible\ unscathed\ TMGs\ and\ NTMGs\ interconnectd\ topologies\} \quad (15)$$

Eq. (15) terms are the same as Eq. (11) terms, except for the CICs



(a)



(b)

Fig. 12. (a) The optimal dispatch of distributed cooling energy resources of TMGs, their transactive energy, and cooling loads, (b) the optimal dispatch of distributed cooling energy resources of NTMGs, their transactive energy, and cooling loads.

term. Further, Eq. (15) should be solved considering the interconnected TMGs and NTMGs that are uncashed after occurring external shock. Eq. (15) constraints are the same as Eq. (11) constraints. In the corrective actions conditions, the IMCESO should change the values of ν^{Ramp} , ν^{Reac} , ν^{Heat} , ν^{Cool} based on the external shock intensity, RT IMCES energy bal-

2.9. Real-time scheduling of IMCESO optimization problem considering corrective actions (third level of the third stage)

The IMCESO's RT objective function can be written as (16):

$$\begin{aligned} \text{Min } \mathbb{S}_{IMCES}^{RT} = & \sum_{k=1}^{96} W_9 \cdot \left(\begin{aligned} & \Delta C_{IMCES}^{DG} + \Delta C_{IMCES}^{CSS} + \Delta C_{IMCES}^{GB} + \Delta C_{IMCES}^{HAC} + \Delta C_{IMCES}^{PHEVPL} + \Delta C_{IMCES}^{TES} + \Delta C_{IMCES}^{CHP} \\ & + \Delta C_{IMCES}^{ESS} + \Delta C_{IMCES}^{ECC} + \Delta C_{IMCES}^{PV} + \Delta C_{IMCES}^{WT} + \Delta C_{IMCES}^{Purchase} - \Delta B_{IMCES}^{Sell} + \Delta C_{IMCES}^{ELDRP} \\ & + \Delta C_{IMCES}^{HDRP} + \Delta C_{IMCES}^{CDRP} + CICS - \text{Penalty}^{TMG,IMCESO} \end{aligned} \right) \\ & - W_{10} \cdot FI^{RT} - W_{11} \cdot RI - W_{12} \cdot BG_{TMGC} \quad \forall \Xi \in \{IMCES \text{ feasible topologies}\} \end{aligned} \quad (16)$$

ance, and ancillary services conditions.

Eq. (16) terms are the same as Eq. (13) terms, except for the CICS

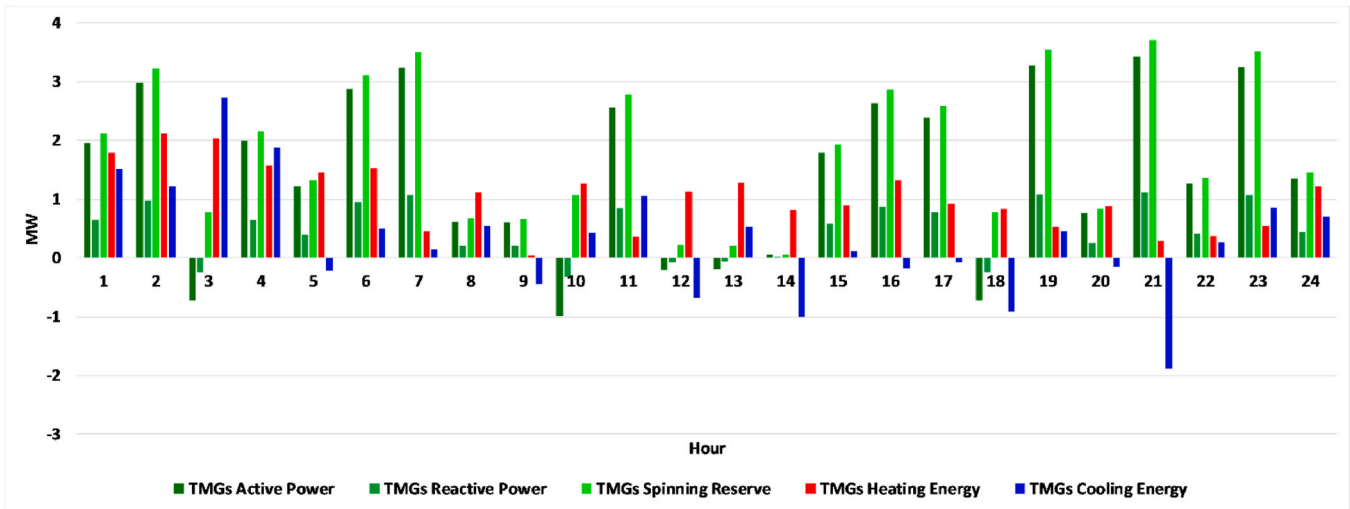


Fig. 13. The accepted values of aggregated TMGs' active power, reactive power, spinning reserve, heating energy, and cooling energy.

term. Further, Eq. (16) should be solved considering the unscathed IMCES's DERs after occurring external shock. The IMCESO can change the weighting factor W_{12} to encourage TMGs to contribute and procure energy carriers for IMCES after occurring external shock occurs.

3. Solution algorithm

The proposed model has multiple uncertainties, which consist of the following parameters.

- The day-ahead values of TMGs' and NTMGs' intermittent power generation,
- The day-ahead values of TMGs' and NTMGs' multi-carrier energy demand,
- The day-ahead volumes of TMG's energy and ancillary service that are accepted by the IMCESO,
- The day-ahead values of multi-carrier energy markets' prices,
- The day-ahead values of intermittent power generation and multi-carrier energy demand of IMCES.

The described uncertainties were modeled using Auto Regressive Integrated Moving Average (ARIMA) models, and the details of the ARIMA model are available in Ref. [27]. A generation/reduction process was performed. The weighting factors were considered equal to one. The proposed model was a mixed integer non-linear problem. The model was linearized, and the CPLEX solver was used to solve the problem. The AC load flow equations were linearized using Ref. [28]. The error of the linearization method was formulated as Eq. (17):

$$\varepsilon = [1 / \cos(\pi / 2^{\chi+1})] - 1 \quad (17)$$

where, χ was a parameter that determined the number of additional variables and constraints that were added to the constraint to linearize the AC load flow equations [28]. It was assumed: $\chi = 15$. Thus, the error of the linearization method was $\chi = 1.148973 \text{ E-}9$. The details of the linearizing process are available in Ref. [28] and are not presented for the sake of space. Further, the first, second, and third levels are mixed integer non-linear programs. Ref. [29] method was utilized to linearize the startup costs, ramping limits, and minimum up and down times constraints. The details of the linearizing process are available in Ref. [29] and are not presented for the sake of space.

As shown in Fig. 3, in the first level of the first stage, the optimization processes for multicarrier energy transactions between TMGs and NTMGs are performed considering the preventive actions. It is assumed that the IMCESO, TMGs, and NTMGs receive warnings about

forecastable external shocks within 24 intervals. Then, the second level is fulfilled to determine the optimal energy and ancillary service procurement by the TMGs for the IMCES. The optimization levels of the first and second stages are proposed based on the fact that the TMGs should determine the optimal day-head scheduling of their DERs and submit the DA bids/offers to the IMCESO database. At the second level, the optimal values of DA bids/offers of TMGs (from their viewpoints) can be determined. Hence, at the third level of the optimization model, the optimal DA scheduling of IMCES's DERs and electrical, heating, and cooling networks is determined. At this level, the DA values of RI , FI , and BG indices are determined, and the IMCES DA scheduling is optimized. Based on the linearization process of the objective functions, it is assumed that the quantity of the TMGs energy transactions with IMCESO in the LEM (q^{Elec}), LHM (q^{Heat}), and LCM (q^{Cool}) are linear functions of the DA LEM price (π^{Elec}), LHM price (π^{Heat}), and LFM price (π^{Cool}), respectively. The same assumptions are considered for the RT optimization process.

For RT operational scheduling, the data of the system should be updated. If there is no external shock, the first level of the second-stage optimization process should be executed. At this level, the optimal RT scheduling of TMGs and NTMGs considering preventive actions is determined. Then, at the second level of the second stage, the optimal bids/offers of TMGs for flexibility, heating, and cooling energy carriers' procurements are calculated. Finally, at the third level of the second stage, the optimal scheduling of IMCES is performed considering the preventive actions, and the optimal topology of the IMCES is determined. The RT values of RI and FI are determined at this level. During the RT updating data process, if any external shock is detected, the third-stage optimization procedures should be fulfilled. At the first level of the third stage, the optimal RT transactions of energy carriers between unscathed TMGs and NTMGs are determined. Then, at the second level of the third stage, the optimal RT bids/offers of TMGs to the IMCESO for corrective actions are calculated. Finally, at the third level of the third stage, the optimal scheduling of IMCES DERs and energy networks should be calculated.

4. Simulation results

Simulation results are provided considering a 123-bus system. Fig. 4 (a), (b), and (c) depict the electrical system, heating system, and cooling system of 123-bus IMCES, respectively.

The simulation input data are shown in Table 2. Fig. 5 presents the value of interruption costs for the EHC systems. MU stands for Monetary Unit, and MMUs represent the million MUs.

Table 3

The optimal switching of MCES with electrical switches and district heating and cooling control valves for 33 worst-case external shock conditions.

External Shock No.	External Shock Region	HPCV1	CPCV1	HPCV2	CPCV2	HPCV3	CPCV3	HPCV4	CPCV4	HPCV5	CPCV5	HPCV6	CPCV6	HPCV7	CPCV7	HPCV8	CPCV8	HPCV9	CPCV9	HPCV10	CPCV10
1	Cooling Market	✓	⊗	✓	✓	✓	✓	⊗	⊗	⊗	⊗	✓	✓	✓	✓	⊗	⊗	⊗	⊗	⊗	⊗
2	Heating Market	⊗	✓	✓	✓	✓	✓	⊗	⊗	⊗	⊗	✓	✓	✓	✓	⊗	⊗	⊗	⊗	⊗	⊗
3	Cooling in zone 1	✓	✓	✓	✓	✓	✓	⊗	✓	⊗	⊗	✓	✓	✓	✓	⊗	⊗	⊗	⊗	⊗	⊗
4	Heating in zone 1	✓	✓	✓	✓	✓	✓	✓	⊗	⊗	⊗	✓	✓	✓	✓	⊗	⊗	⊗	⊗	⊗	⊗
5	Cooling in zone 2	✓	✓	✓	✓	✓	✓	⊗	✓	⊗	⊗	✓	✓	✓	✓	⊗	⊗	⊗	⊗	⊗	⊗
6	Heating in zone 2	✓	✓	✓	✓	✓	✓	✓	⊗	⊗	⊗	✓	✓	✓	✓	⊗	⊗	⊗	⊗	⊗	⊗
7	Cooling in zone 3	✓	✓	✓	✓	✓	✓	⊗	⊗	⊗	✓	✓	✓	✓	✓	⊗	⊗	⊗	⊗	✓	✓
8	Heating in zone 3	✓	✓	✓	✓	✓	✓	⊗	⊗	⊗	⊗	✓	✓	✓	✓	⊗	⊗	⊗	⊗	✓	✓
9	Cooling in zone 4	✓	✓	✓	✓	✓	✓	⊗	⊗	⊗	⊗	✓	✓	✓	✓	⊗	✓	⊗	⊗	⊗	⊗
10	Heating in zone 4	✓	✓	✓	✓	✓	✓	⊗	⊗	⊗	⊗	✓	✓	✓	✓	✓	⊗	⊗	⊗	⊗	⊗
11	Cooling in zone 5	✓	✓	✓	✓	✓	✓	⊗	⊗	⊗	⊗	✓	✓	✓	✓	⊗	✓	⊗	⊗	⊗	⊗
12	Heating in zone 5	✓	✓	✓	✓	✓	✓	⊗	⊗	⊗	⊗	✓	✓	✓	✓	✓	⊗	⊗	⊗	⊗	⊗
Normal Operation		✓	✓	✓	✓	✓	✓	⊗	⊗	⊗	⊗	✓	✓	✓	✓	⊗	⊗	⊗	⊗	⊗	⊗
External Shock No.	External Shock Region	HPCV11	CPCV11	HPCV12	CPCV12	HPCV13	CPCV13	HPCV14	CPCV14	HPCV15	CPCV15	HPCV16	CPCV16	HPCV17	CPCV17	HPCV18	CPCV18	HPCV19	CPCV19	HPCV20	CPCV20
1	Cooling Market	⊗	⊗	⊗	⊗	✓	✓	✓	✓	✓	✓	⊗	⊗	✓	✓	✓	✓	⊗	⊗	✓	✓
2	Heating Market	⊗	⊗	⊗	⊗	✓	✓	✓	✓	✓	✓	⊗	⊗	✓	✓	✓	✓	⊗	⊗	✓	✓
3	Cooling in zone 1	⊗	⊗	⊗	⊗	✓	✓	✓	✓	✓	✓	⊗	⊗	✓	✓	✓	✓	⊗	⊗	✓	✓
4	Heating in zone 1	⊗	⊗	⊗	⊗	✓	✓	✓	✓	✓	✓	⊗	⊗	✓	✓	✓	✓	⊗	⊗	✓	✓
5	Cooling in zone 2	⊗	⊗	⊗	⊗	✓	✓	✓	✓	✓	✓	⊗	⊗	✓	✓	✓	✓	⊗	⊗	✓	✓
6	Heating in zone 2	⊗	⊗	⊗	⊗	✓	✓	✓	✓	✓	✓	⊗	⊗	✓	✓	✓	✓	⊗	⊗	✓	✓
7	Cooling in zone 3	⊗	⊗	⊗	⊗	✓	✓	✓	✓	✓	✓	⊗	⊗	✓	✓	✓	✓	⊗	⊗	✓	✓
8	Heating in zone 3	⊗	⊗	⊗	⊗	✓	✓	✓	✓	✓	✓	⊗	⊗	✓	✓	✓	✓	⊗	⊗	✓	✓
9	Cooling in zone 4	⊗	⊗	⊗	⊗	✓	✓	✓	✓	✓	✓	⊗	⊗	✓	✓	✓	✓	⊗	⊗	✓	✓
10	Heating in zone 4	⊗	⊗	⊗	⊗	✓	✓	✓	✓	✓	✓	⊗	⊗	✓	✓	✓	✓	⊗	⊗	✓	✓
11	Cooling in zone 5	⊗	⊗	⊗	⊗	✓	✓	✓	✓	✓	✓	⊗	⊗	✓	✓	✓	✓	⊗	⊗	✓	✓
12	Heating in zone 5	⊗	⊗	⊗	⊗	✓	✓	✓	✓	✓	✓	⊗	⊗	✓	✓	✓	✓	⊗	⊗	✓	✓
Normal Operation		⊗	⊗	⊗	⊗	✓	✓	✓	✓	✓	✓	⊗	⊗	✓	✓	✓	✓	⊗	⊗	✓	✓
External Shock No.	External Shock Region	HPCV1	CPCV1	HPCV2	CPCV2	HPCV3	CPCV3	HPCV4	CPCV4	HPCV5	CPCV5	HPCV6	CPCV6	HPCV7	CPCV7	HPCV8	CPCV8	HPCV9	CPCV9	HPCV10	CPCV10
13	Cooling in zone 6	⊗	⊗	⊗	⊗	✓	✓	✓	⊗	✓	✓	⊗	⊗	✓	✓	✓	✓	⊗	✓	⊗	⊗
14	Heating in zone 6	⊗	⊗	⊗	⊗	✓	✓	✓	⊗	✓	✓	⊗	⊗	✓	✓	✓	✓	✓	⊗	⊗	⊗
15	Cooling in zone 7	⊗	⊗	⊗	⊗	✓	✓	✓	✓	✓	✓	⊗	⊗	✓	✓	✓	✓	⊗	⊗	✓	✓
16	Heating in zone 7	⊗	⊗	⊗	⊗	✓	✓	✓	✓	✓	✓	⊗	⊗	✓	✓	✓	✓	⊗	⊗	✓	✓
17	Cooling in zone 8	⊗	⊗	⊗	⊗	✓	✓	✓	⊗	⊗	⊗	⊗	⊗	✓	✓	✓	✓	⊗	⊗	⊗	✓
18	Heating in zone 8	⊗	⊗	⊗	⊗	✓	✓	✓	⊗	⊗	⊗	⊗	⊗	✓	✓	✓	✓	⊗	⊗	✓	✓
19	Cooling in zone 9	⊗	⊗	⊗	⊗	✓	✓	✓	⊗	⊗	⊗	⊗	⊗	✓	✓	✓	✓	⊗	⊗	⊗	⊗
20	Heating in zone 9	⊗	⊗	⊗	⊗	✓	✓	✓	⊗	⊗	⊗	⊗	⊗	✓	✓	✓	✓	⊗	⊗	⊗	⊗
21	Cooling in zone 10	⊗	⊗	⊗	⊗	✓	✓	✓	⊗	⊗	⊗	⊗	⊗	✓	✓	✓	✓	⊗	⊗	⊗	⊗
22	Heating in zone 10	⊗	⊗	⊗	⊗	✓	✓	✓	⊗	⊗	⊗	⊗	⊗	✓	✓	✓	✓	⊗	⊗	⊗	⊗
Normal Operation		⊗	⊗	⊗	⊗	✓	✓	✓	⊗	⊗	⊗	⊗	⊗	✓	✓	✓	✓	⊗	⊗	⊗	⊗
External Shock No.	External Shock Region	HPCV11	CPCV11	HPCV12	CPCV12	HPCV13	CPCV13	HPCV14	CPCV14	HPCV15	CPCV15	HPCV16	CPCV16	HPCV17	CPCV17	HPCV18	CPCV18	HPCV19	CPCV19	HPCV20	CPCV20
13	Cooling in zone 6	⊗	⊗	⊗	⊗	✓	✓	✓	✓	✓	✓	⊗	⊗	✓	✓	✓	✓	⊗	⊗	✓	✓
14	Heating in zone 6	⊗	⊗	⊗	⊗	✓	✓	✓	✓	✓	✓	⊗	⊗	✓	✓	✓	✓	⊗	⊗	✓	✓
15	Cooling in zone 7	⊗	✓	⊗	⊗	✓	✓	✓	✓	✓	✓	⊗	⊗	✓	✓	✓	✓	⊗	⊗	✓	✓
16	Heating in zone 7	✓	⊗	⊗	⊗	✓	✓	✓	✓	✓	✓	⊗	⊗	✓	✓	✓	✓	⊗	⊗	✓	✓
17	Cooling in zone 8	⊗	⊗	⊗	✓	✓	✓	✓	✓	✓	✓	⊗	⊗	✓	✓	✓	✓	⊗	⊗	✓	✓
18	Heating in zone 8	⊗	⊗	✓	⊗	✓	✓	✓	✓	✓	✓	⊗	⊗	✓	✓	✓	✓	⊗	⊗	✓	✓
19	Cooling in zone 9	⊗	⊗	⊗	⊗	✓	✓	✓	✓	✓	✓	⊗	⊗	✓	✓	✓	✓	⊗	✓	✓	✓
20	Heating in zone 9	⊗	⊗	⊗	⊗	✓	✓	✓	✓	✓	✓	⊗	⊗	✓	✓	✓	✓	✓	⊗	✓	✓
21	Cooling in zone 10	⊗	⊗	⊗	⊗	✓	✓	✓	✓	✓	✓	⊗	⊗	✓	✓	✓	✓	⊗	✓	✓	✓
22	Heating in zone 10	⊗	⊗	⊗	⊗	✓	✓	✓	✓	✓	✓	⊗	⊗	✓	✓	✓	✓	✓	⊗	✓	✓
Normal Operation		⊗	⊗	⊗	⊗	✓	✓	✓	✓	✓	✓	⊗	⊗	✓	✓	✓	✓	⊗	⊗	✓	✓

External Shock No.	External Shock Region	HPCV1	CPCV1	HPCV2	CPCV2	HPCV3	CPCV3	HPCV4	CPCV4	HPCV5	CPCV5	HPCV6	CPCV6	HPCV7	CPCV7	HPCV8	CPCV8	HPCV9	CPCV9	HPCV10	CPCV10
23	Electricity Market	✓	✓	✓	✓	✓	✓	⊗	⊗	⊗	⊗	✓	✓	✓	✓	⊗	⊗	⊗	⊗	⊗	⊗
24	Electric in zone 1	✓	✓	✓	✓	✓	✓	⊗	✓	⊗	⊗	✓	✓	✓	✓	⊗	⊗	⊗	⊗	⊗	⊗
25	Electric in zone 2	✓	✓	✓	✓	✓	✓	⊗	✓	⊗	⊗	✓	✓	✓	✓	⊗	⊗	⊗	⊗	⊗	⊗
26	Electric in zone 3	✓	✓	✓	✓	✓	✓	⊗	⊗	⊗	⊗	✓	✓	✓	✓	⊗	⊗	⊗	⊗	✓	✓
27	Electric in zone 4	✓	✓	✓	✓	✓	✓	⊗	⊗	⊗	⊗	✓	✓	✓	✓	⊗	⊗	⊗	⊗	⊗	⊗
28	Electric in zone 5	✓	✓	✓	✓	✓	✓	⊗	⊗	⊗	⊗	✓	✓	✓	✓	⊗	⊗	⊗	⊗	⊗	⊗
29	Electric in zone 6	⊗	⊗	⊗	⊗	✓	✓	⊗	✓	✓	✓	⊗	⊗	✓	✓	✓	✓	⊗	✓	⊗	⊗
30	Electric in zone 7	⊗	⊗	⊗	⊗	✓	✓	⊗	✓	✓	✓	⊗	⊗	✓	✓	✓	✓	⊗	⊗	✓	✓
31	Electric in zone 8	⊗	⊗	⊗	⊗	✓	✓	⊗	⊗	✓	✓	⊗	⊗	✓	✓	✓	✓	⊗	⊗	⊗	✓
32	Electric in zone 9	⊗	⊗	⊗	⊗	✓	✓	⊗	⊗	✓	✓	⊗	⊗	✓	✓	✓	✓	⊗	⊗	⊗	⊗
33	Electric in zone 10	⊗	⊗	⊗	⊗	✓	✓	⊗	⊗	✓	✓	⊗	⊗	✓	✓	✓	✓	⊗	⊗	⊗	⊗
Normal Operation		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
External Shock No.	External Shock Region	HPCV11	CPCV11	HPCV12	CPCV12	HPCV13	CPCV13	HPCV14	CPCV14	HPCV15	CPCV15	HPCV16	CPCV16	HPCV17	CPCV17	HPCV18	CPCV18	HPCV19	CPCV19	HPCV20	CPCV20
23	Electricity Market	⊗	⊗	⊗	⊗	✓	✓	✓	✓	✓	✓	⊗	⊗	✓	✓	✓	✓	⊗	⊗	✓	✓
24	Electric in zone 1	⊗	⊗	⊗	⊗	✓	✓	✓	✓	✓	✓	⊗	⊗	✓	✓	✓	✓	⊗	⊗	✓	✓
25	Electric in zone 2	⊗	⊗	⊗	⊗	✓	✓	✓	✓	✓	✓	⊗	⊗	✓	✓	✓	✓	⊗	⊗	✓	✓
26	Electric in zone 3	⊗	⊗	⊗	⊗	✓	✓	✓	✓	✓	✓	⊗	⊗	✓	✓	✓	✓	⊗	⊗	✓	✓
27	Electric in zone 4	⊗	⊗	⊗	⊗	✓	✓	✓	✓	✓	✓	⊗	⊗	✓	✓	✓	✓	⊗	⊗	✓	✓
28	Electric in zone 5	⊗	⊗	⊗	⊗	✓	✓	✓	✓	✓	✓	⊗	⊗	✓	✓	✓	✓	⊗	⊗	✓	✓
29	Electric in zone 6	⊗	⊗	⊗	⊗	✓	✓	✓	✓	✓	✓	⊗	⊗	✓	✓	✓	✓	⊗	⊗	✓	✓
30	Electric in zone 7	✓	⊗	⊗	⊗	✓	✓	✓	✓	✓	✓	⊗	⊗	✓	✓	✓	✓	⊗	⊗	✓	✓
31	Electric in zone 8	⊗	⊗	✓	⊗	✓	✓	✓	✓	✓	✓	⊗	⊗	✓	✓	✓	✓	⊗	⊗	✓	✓
32	Electric in zone 9	⊗	⊗	⊗	⊗	✓	✓	✓	✓	✓	✓	⊗	⊗	✓	✓	✓	✓	⊗	✓	✓	✓
33	Electric in zone 10	⊗	⊗	⊗	⊗	✓	✓	✓	✓	✓	✓	⊗	⊗	✓	✓	✓	✓	⊗	✓	✓	✓
Normal Operation		⊗	⊗	⊗	⊗	✓	✓	✓	✓	✓	✓	⊗	⊗	✓	✓	✓	✓	⊗	⊗	✓	✓
External Shock No.	External Shock Region	ESW1	ESW2	ESW3	ESW4	ESW5	ESW6	ESW7	ESW8	ESW9	ESW10	ESW11	ESW12	ESW13	ESW14	ESW15	ESW16	ESW17	ESW18	ESW19	ESW20
23	Electricity Market	⊗	✓	✓	✓	⊗	✓	✓	⊗	⊗	⊗	⊗	⊗	✓	✓	✓	⊗	✓	✓	⊗	✓
24	Electric in zone 1	✓	✓	✓	⊗	✓	✓	✓	⊗	⊗	⊗	⊗	⊗	✓	✓	✓	⊗	✓	✓	⊗	✓
25	Electric in zone 2	✓	✓	✓	✓	⊗	✓	✓	⊗	⊗	⊗	⊗	⊗	✓	✓	✓	⊗	✓	✓	⊗	✓
26	Electric in zone 3	✓	✓	✓	⊗	✓	✓	✓	⊗	⊗	⊗	✓	⊗	✓	✓	✓	⊗	✓	✓	⊗	✓
27	Electric in zone 4	✓	✓	✓	⊗	⊗	✓	✓	✓	⊗	⊗	⊗	⊗	✓	✓	✓	⊗	✓	✓	⊗	✓
28	Electric in zone 5	✓	✓	✓	⊗	⊗	✓	✓	⊗	✓	⊗	⊗	⊗	✓	✓	✓	✓	✓	✓	⊗	✓
29	Electric in zone 6	✓	✓	✓	✓	⊗	✓	✓	⊗	✓	⊗	⊗	⊗	✓	✓	✓	⊗	✓	✓	⊗	✓
30	Electric in zone 7	✓	✓	✓	⊗	⊗	✓	✓	⊗	⊗	⊗	✓	✓	✓	✓	✓	⊗	✓	✓	⊗	✓
31	Electric in zone 8	✓	✓	✓	⊗	⊗	✓	✓	⊗	⊗	✓	⊗	✓	✓	✓	✓	⊗	✓	✓	⊗	✓
32	Electric in zone 9	✓	✓	✓	⊗	⊗	✓	✓	⊗	⊗	⊗	⊗	⊗	✓	✓	✓	⊗	✓	✓	✓	✓
33	Electric in zone 10	✓	✓	✓	⊗	⊗	✓	✓	⊗	⊗	⊗	⊗	⊗	✓	✓	✓	⊗	✓	✓	✓	✓
Normal Operation		✓	✓	✓	⊗	⊗	✓	✓	⊗	⊗	⊗	⊗	⊗	✓	✓	✓	⊗	✓	✓	⊗	✓

The scenario generation and reduction processes were carried out, and 1500 scenarios were generated for the uncertainties. Then, these scenarios were reduced to 15 scenarios for each of them. It was presumed that the topologies of heating and cooling systems were the same as the topologies of the electrical system.

Fig. 6 shows the outputs of one of the reduced scenarios for the wind turbines and photovoltaic systems' electricity generation.

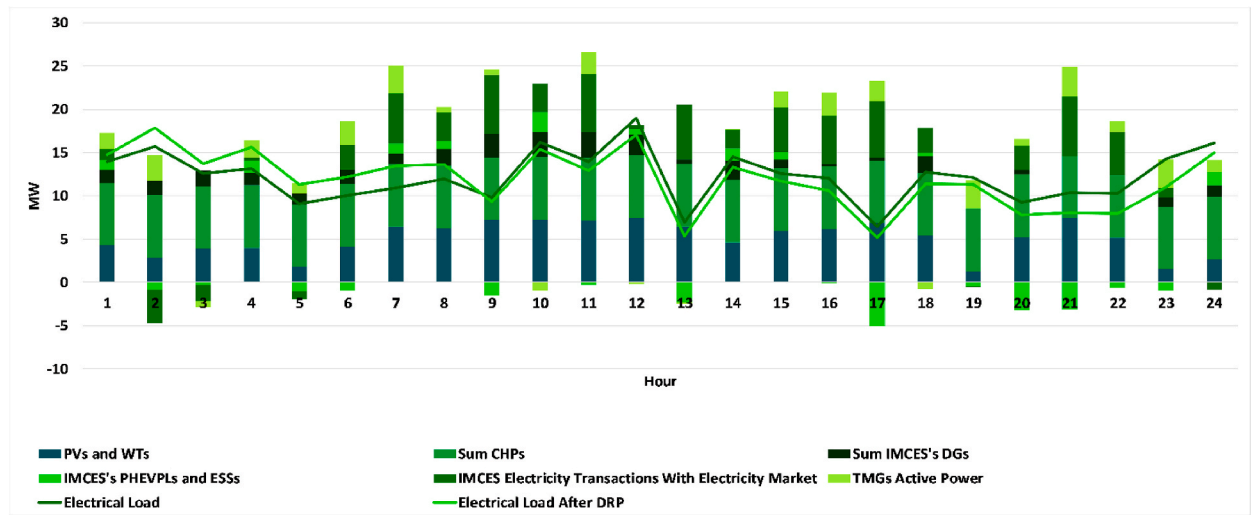
The estimated hourly price for DA energy markets for one of the reduced scenarios is shown in Fig. 7.

The 33-bus system is considered as NTMG and TMG. Further, the 123-bus test system is considered as an IES. Fig. 8 presents the topology of TMG and NTMG, where the 33-bus test system was considered as TMG and NTMG. The detailed data of 33-bus TMG and NTMG are available in

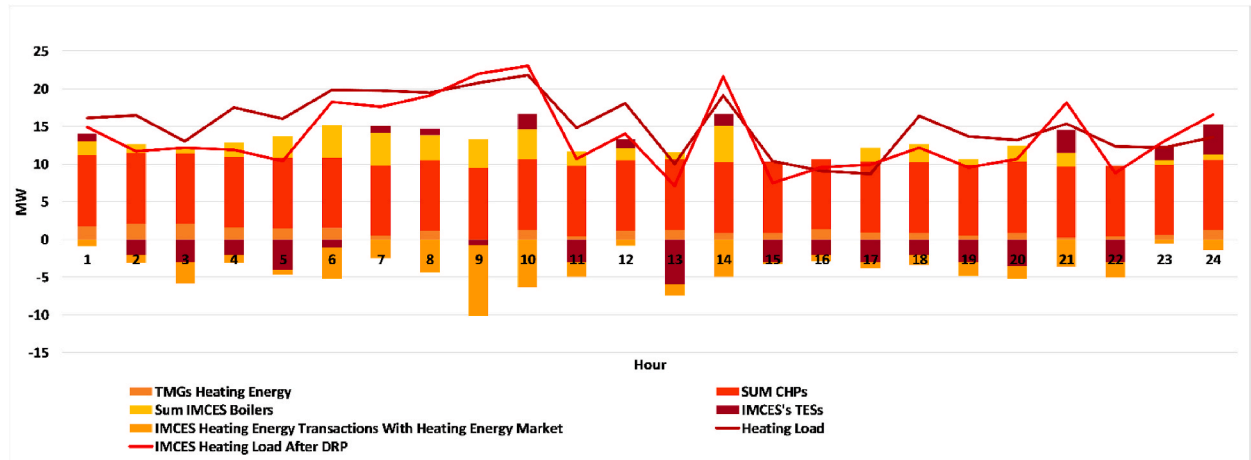
Ref. [30]. It was assumed that each TMG is connected to the NTMG through the bus 33. Further, each TMG was connected to the IMCES through the TMG's bus 1.

The IMCESO determined the values of π^{Elect} , π^{Heat} , and π^{Cool} , respectively for preventive actions. Fig. 9 presents the values of π^{Elect} , π^{Heat} , and π^{Cool} for DA preventive actions. It is assumed that the values of π_t^{Reac} , and π_t^{Spinn} are 18 % and 25 % of π^{Elect} for each hour (see Fig. 10).

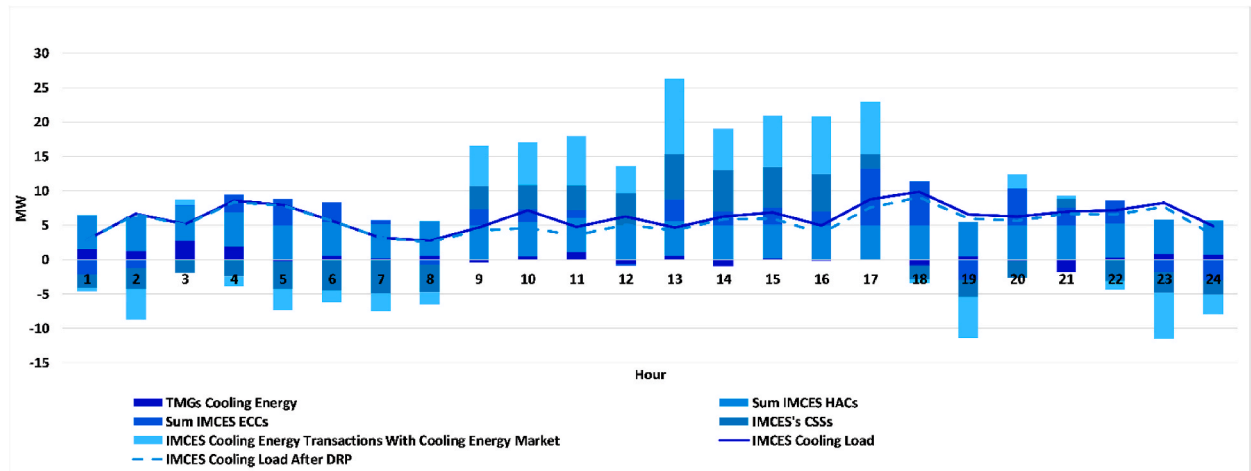
The average values of π^{Elect} , π^{Heat} , and π^{Cool} for preventive actions were about 79.62 MU/kWh, 77.96 MU/kWh, and 78.6 MU/kWh, respectively. At first, the DA optimal transaction between transactive and non-transactive microgrids (first level of the first stage) optimization process was carried out. Fig. 10 (a) presents the optimal dispatch of distributed electrical energy resources of one of the TMGs, the



(a)

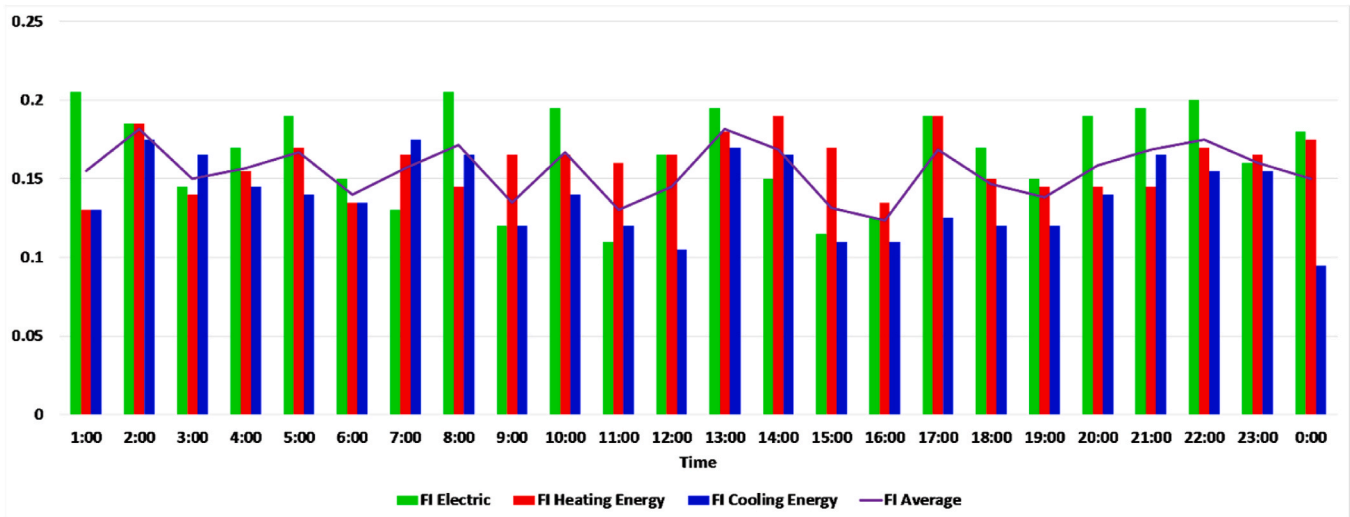


(b)

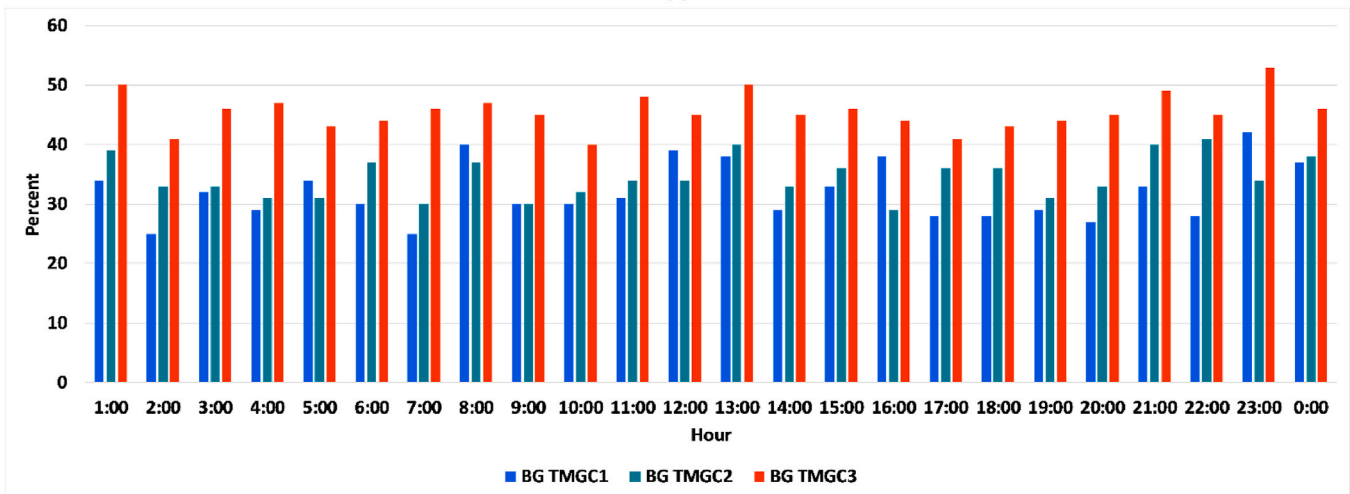


(c)

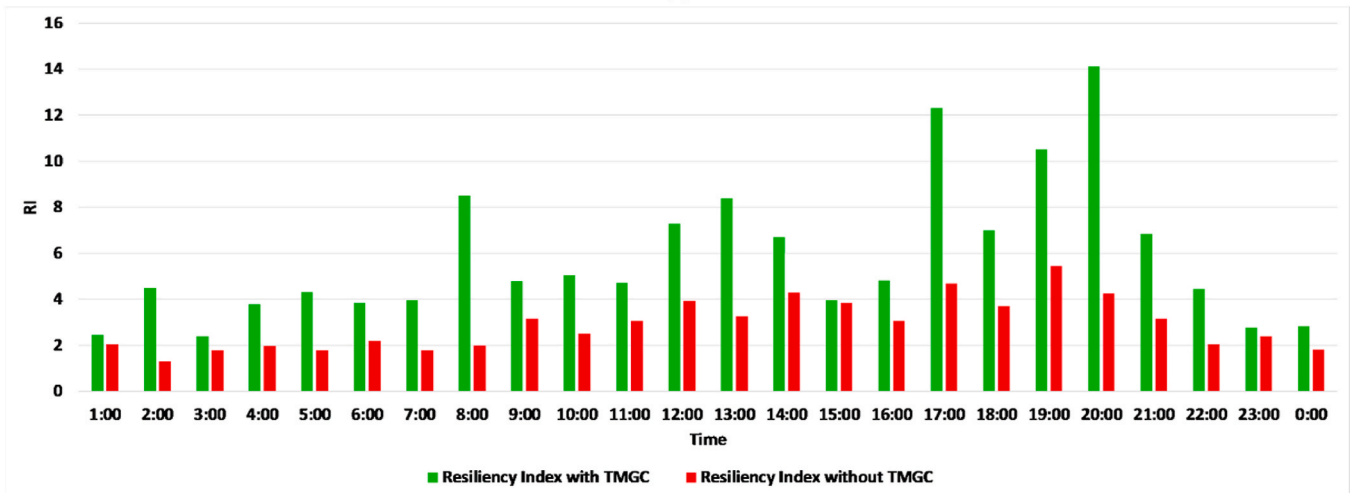
Fig. 14. (a) Optimal dispatch of distributed electrical energy resources of the IMCESO, the transactive energy with TMGs, and electrical load, (b) optimal dispatch of distributed heating energy resources of the IMCESO, the transactive heating energy with TMGs, and heating load, (c) optimal dispatch of distributed cooling energy resources of the IMCESO, the transactive cooling energy with TMGs, and cooling load.



(a)



(b)



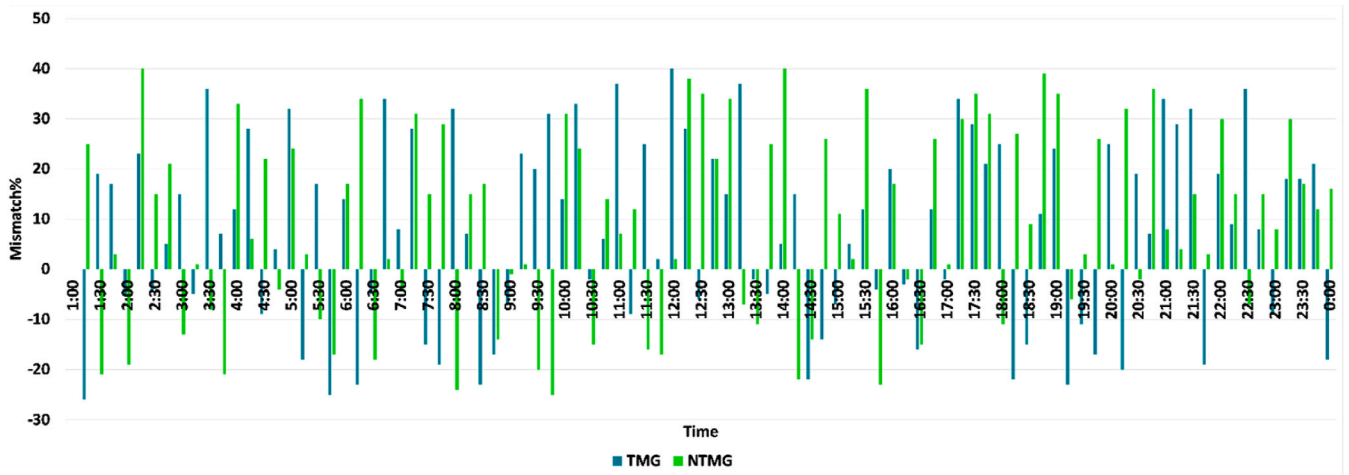
(c)

Fig. 15. (a) The values of the DA flexibility index (FI^{DA}), (b) bidding gain (BG), and (c) resiliency index (RI).

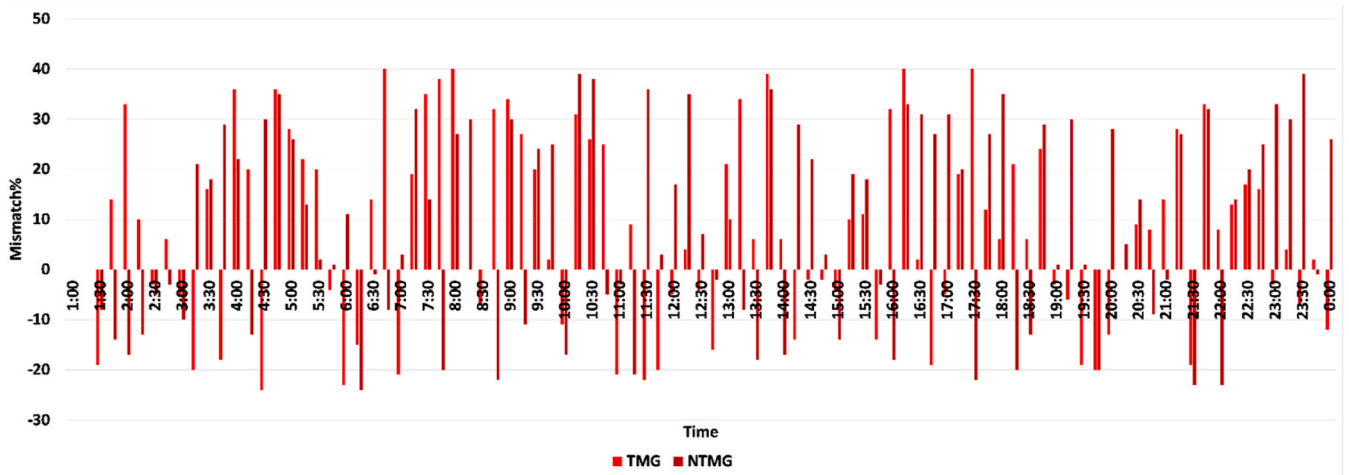
transactive energy to the NTMG, and the electrical load. As can be seen in Fig. 10 (a), aggregated electricity generation of CHPs, PVs, WTs, and DGs of TMG were about 19.84 MWh, 3.47 MWh, 0.818 MWh, and 5.76 MWh, respectively. Further, the aggregated electricity consumptions of

TMG and its ECCs were about 40.41 MWh and 6.88 MWh, respectively. Finally, the TMG participated in DRP, and the aggregated electricity consumption reduction was about 2.94 MWh.

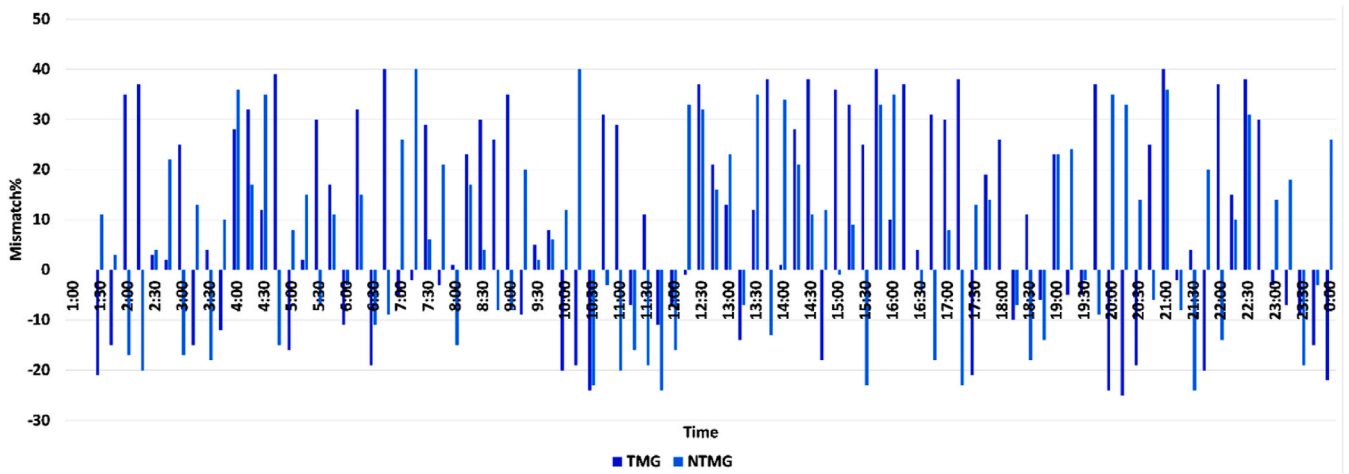
Fig. 10 (b) depicts the optimal dispatch of distributed electrical



(a)



(b)



(c)

Fig. 16. The aggregated values of the mismatches of TMG and NTMGs (a) electrical loads, (b) heating energy loads, and (c) cooling energy loads.

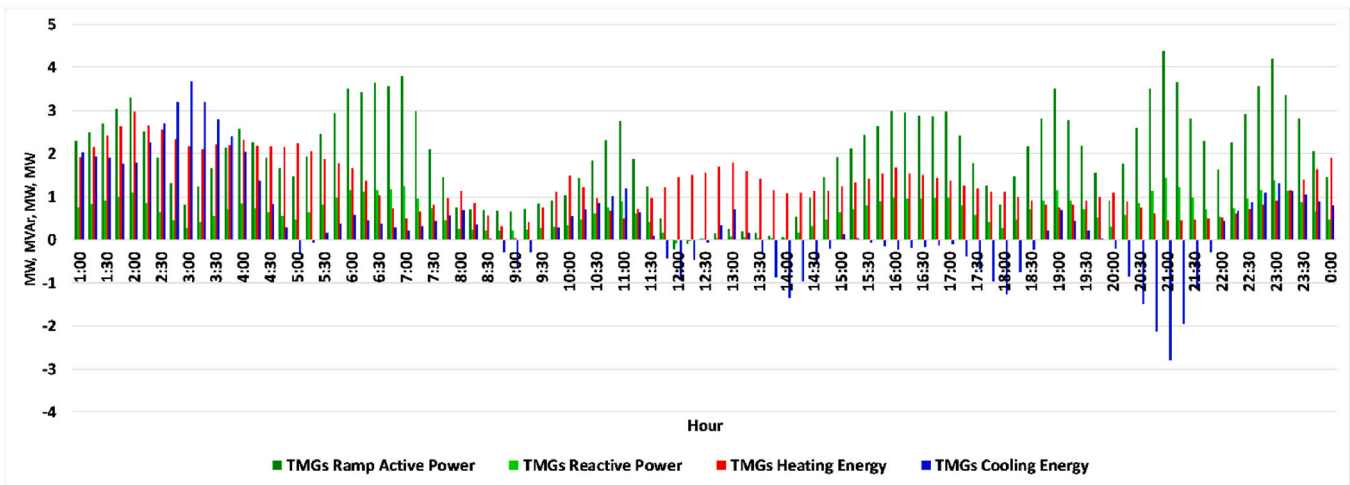


Fig. 17. The average values of accepted RT TMGs' ramp service, reactive power, heating energy, and cooling energy.

energy resources of NTMGs, their transactive energy, and electrical loads. As can be seen in Fig. 10 (b), aggregated electricity generation of CHPs, PVs, WTs, and DGs of NTMG were about 19.59 MWh, 3.37 MWh, 1.1 MWh, and 5.75 MWh, respectively. Further, the aggregated electricity consumptions of NTMG and its ECCs were about 22.73 MWh and 6.21 MWh, respectively.

Fig. 11 (a) shows the optimal dispatch of distributed heating energy resources of one of the TMGs, the transactive heating energy, and the heating load. As shown in Fig. 11 (a), the aggregated heating energy generations of CHPs and boilers were about 38.68 MWh and 7.31 MWh, respectively. Further, the aggregated heating energy consumptions of TMG and its HACs were about 46 MWh and 13.8 MWh, respectively. Finally, the TMG participated in DRP, and the aggregated heating energy consumption reduction was about 2.06 MWh. Fig. 11 (b) presents the optimal dispatch of distributed heating energy resources of one of the NTMG, the transactive heating energy, and the heating load. As shown in Fig. 11 (b), the aggregated heating energy generations of CHPs and boilers were about 38.2 MWh and 9.89 MWh, respectively. Further, the aggregated heating energy consumptions of NTMG and its HACs were about 31.39 MWh and 14.43 MWh, respectively.

Fig. 12 (a) depicts the optimal dispatch of distributed cooling energy resources of one of the TMGs, the transactive cooling energy, and the cooling load. As shown in Fig. 12 (a), the aggregated cooling energy generation of ECCs and HACs were about 13.76 MWh and 4.81 MWh, respectively. Further, the aggregated cooling energy consumption of TMG was about 15.88 MWh. Finally, the TMG participated in DRP and the aggregated cooling energy consumption reduction was about 0.617 MWh.

Fig. 12 (b) presents the optimal dispatch of distributed cooling energy resources of one of the NTMG, the transactive cooling energy, and the cooling load. As shown in Fig. 12 (b), the aggregated cooling energy generations of ECCs and HACs were about 12.43 MWh and 4.35 MWh, respectively. Further, the aggregated cooling energy consumption of NTMG was about 14.44 MWh.

Then, the DA transactive microgrids with IMCES optimization (second level of the first stage) procedure was performed (see Fig. 12). Fig. 13 presents the accepted values of aggregated TMGs' active power, reactive power, spinning reserve, heating energy, and cooling energy. As shown in Fig. 13, the aggregated values of TMGs' active power, reactive power, spinning reserve, heating energy, and cooling energy were about 35.39 MWh, 11.63 MVarh, 44.45 MVA, 24.77 MW, and 7.41 MW, respectively.

Hence, the DA IMCESO optimization process (third level of the first stage) was fulfilled. The optimal topology of the 123-bus system in normal preventive condition is presented in Table 3, and its results will

be discussed in the following paragraphs. Fig. 14 (a) presents the optimal dispatch of distributed electrical energy resources of the IMCESO, the transactive energy with TMGs, and the electrical load. As shown in Fig. 14 (a), the aggregated electricity generations of CHPs, PVs and WTs, and DGs of IMCES were about 173.36 MWh, 121.59 MWh, and 32.66 MWh, respectively. Moreover, aggregated electricity consumptions of IMCES and TMGs transactive electricity energy were about 285.63 MWh and 35.39 MWh, respectively. Finally, the aggregated electricity consumption reduction of IMCES using DRP was about 8.1 MWh.

Fig. 14 (b) shows the optimal dispatch of distributed heating energy resources of the IMCESO, the transactive heating energy with TMGs, and the heating load. As shown in Fig. 14 (b), the aggregated heating energy generations of CHPs and boilers were about 225.07 MWh and 48.15 MWh, respectively. Further, the aggregated heating energy consumptions of IMCES and TMGs transactive heating energy were about 367.77 MWh and 24.77 MWh, respectively. Finally, the aggregated heating energy consumption reduction of IMCES using DRP was about 37.29 MWh.

Fig. 14 (c) depicts the optimal dispatch of distributed cooling energy resources of the IMCESO, the transactive cooling energy with TMGs, and the cooling load. As shown in Fig. 14 (c), the aggregated cooling energy generations of ECCs and HACs were about 38.69 MWh and 119.23 MWh, respectively. Further, the aggregated cooling energy consumptions of IMCES and TMGs transactive cooling energy were about 146.38 MWh and 7.41 MWh, respectively. Finally, the aggregated cooling energy consumption reduction of IMCES using DRP was about 15.63 MWh.

Fig. 15. (a), (b), and (c) present the values of the DA flexibility index (FI^{DA}), bidding gain (BG), and resiliency index (RI), respectively. As shown in Fig. 15 (a), the minimum and maximum values of electrical FI^{DA} were about 0.11 and 0.205, respectively. Further, the minimum and maximum values of heating energy FI^{DA} were about 0.13 and 0.19, respectively. Finally, the minimum and maximum values of cooling energy FI^{DA} were about 0.095 and 0.175, respectively. The average value of average FI^{DA} was about 0.155.

As shown in Fig. 15 (b), the maximum and average values of TMG1's bidding gain were about 42 % and 32.01 %, respectively. Further, the maximum and average values of TMG2's bidding gain were about 41 % and 34.5 %, respectively. Finally, the maximum and average values of TMG3's bidding gain were about 53 % and 45.54 %, respectively. It can be concluded that the proposed method successfully increased the profits of TMGs to procure energy and ancillary services for the IMCESO.

As shown in Fig. 15 (c), the average values of the resiliency index without and with TMGC were about 2.89 and 5.84, respectively. Further, the minimum and maximum values of the resiliency index

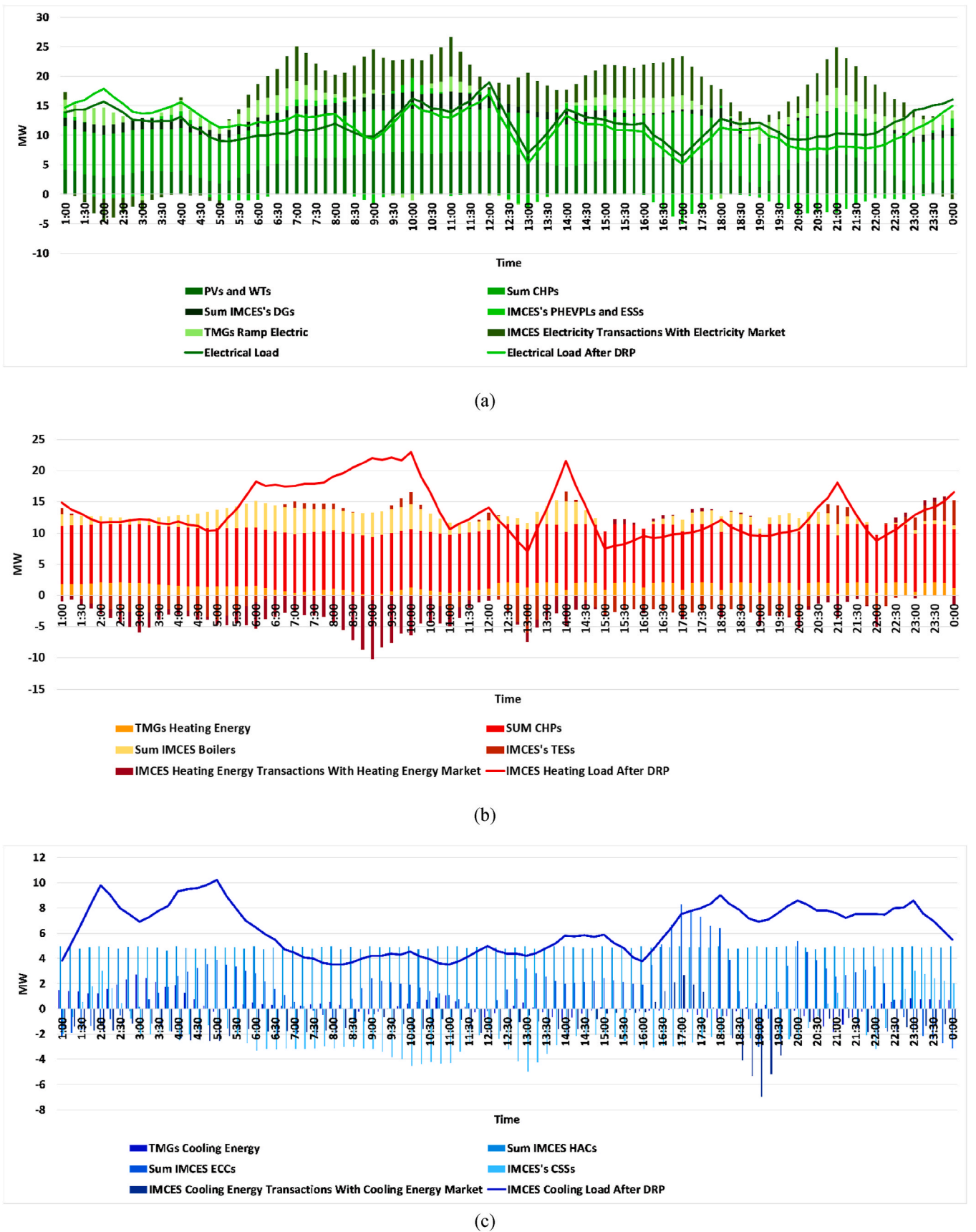
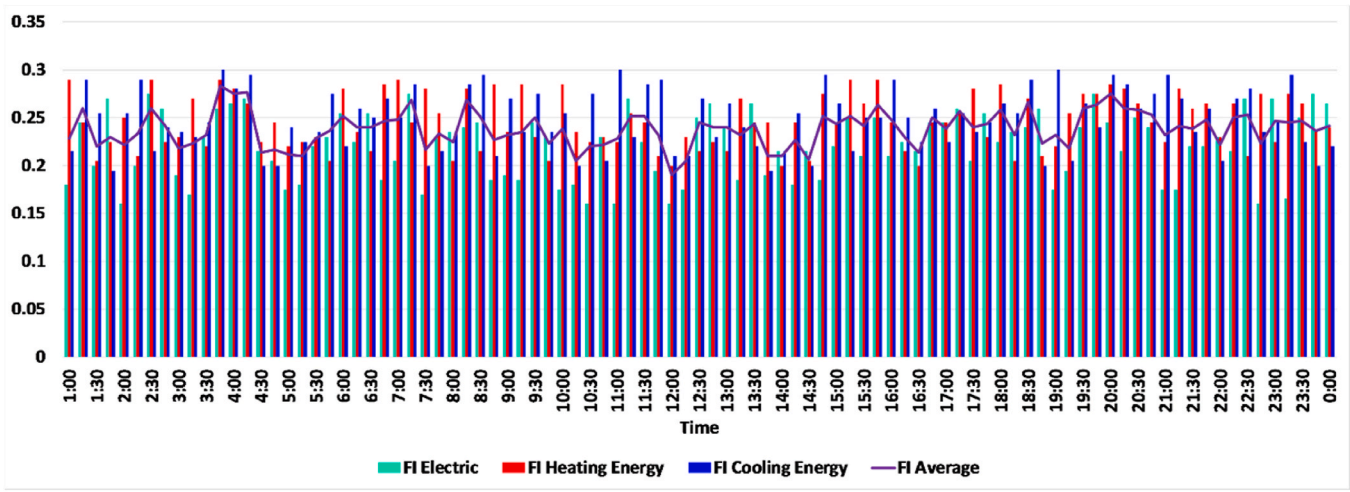
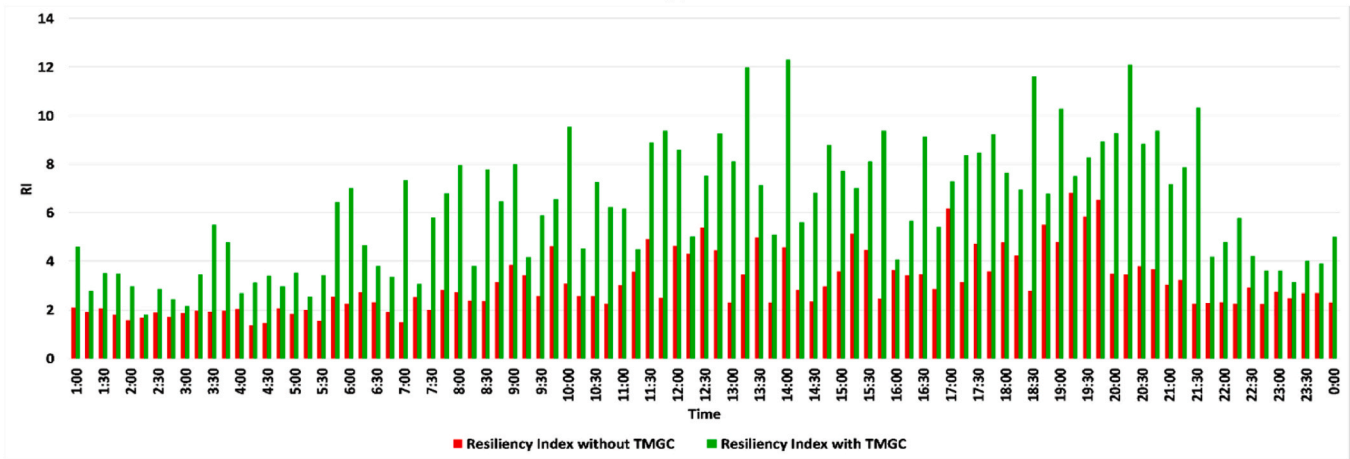


Fig. 18. (a) Optimal RT dispatch of distributed electrical energy resources of the IMCESO, the transactive energy with TMGs, and electrical load considering preventive actions, (b) Optimal RT dispatch of distributed heating energy resources of the IMCESO, the transactive heating energy with TMGs, and heating load considering preventive actions, (c) Optimal RT dispatch of distributed cooling energy resources of the IMCESO, the transactive cooling energy with TMGs, and cooling load considering preventive actions.



(a)

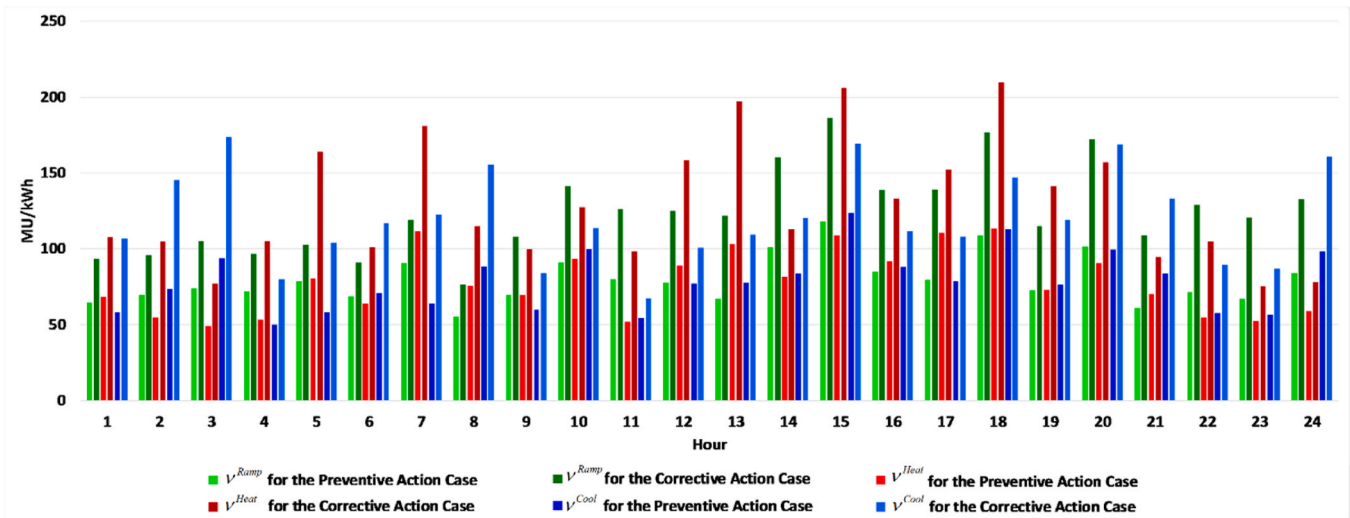


(b)

Fig. 19. (a) The values of the RT flexibility index (FI^{RT}), and (b) resiliency index (RI).

without TMGC were about 1.27 and 5.54, respectively. Finally, the minimum and maximum values of the resiliency index with TMGC were about 2.4 and 14.12, respectively. Thus, the suggested model enhanced the average value of the DA resiliency index by around 102 %.

In the second stage, the IMCESO determined the values of $\nu_k^{Ramp} \nu_k^{Reac}$, ν_k^{Heat} , and ν_k^{Cool} respectively, for preventive actions. It is assumed that the values of $\nu_k^{Ramp} \nu_k^{Reac}$, ν_k^{Heat} , and ν_k^{Cool} are the same as their corre-

Fig. 20. The values of ν_k^{Ramp} , ν_k^{Heat} , and ν_k^{Cool} for corrective actions.

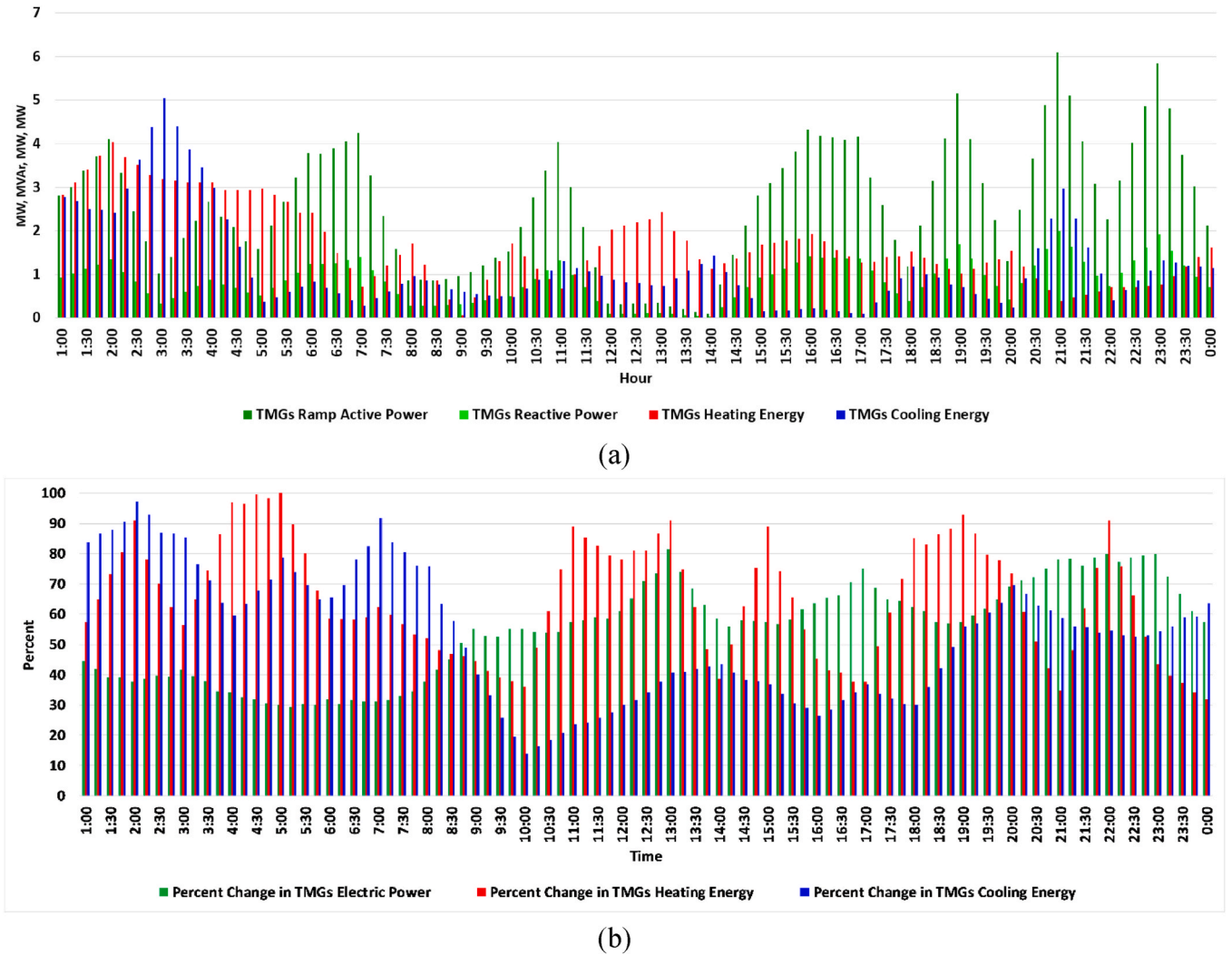


Fig. 21. (a) The average values of accepted RT TMGs' ramp service, reactive power, heating energy, and cooling energy for corrective actions, (b) the percent of the increase in the accepted RT TMGs' ramp service, reactive power, heating energy, and cooling energy for corrective actions.

sponding values of DA markets. Further, the optimization process of the RT optimal transaction between transactive and non-transactive microgrids (first level of the second stage) was performed. Fig. 16 (a), (b), and (c) depict aggregated values of the mismatches of TMGs' and NTMGs' electrical, heating, and cooling energy loads, respectively.

Hence, the proposed optimization process of the second level (RT scheduling of transactive microgrids with IMCES optimization problem) of the second stage was carried out.

As shown in Fig. 17, the average values of accepted RT TMGs' ramp service, reactive power, heating energy, and cooling energy were about 1.961 MWh, 0.645 MVarh, 1.3 MW, and 0.34 MW, respectively.

Then, the RT scheduling of the IMCESO optimization process, considering preventive actions (third level of the second stage), was executed. Fig. 18 (a) presents the optimal RT dispatch of distributed electrical energy resources of the IMCESO, the transactive energy with TMGs, and the electrical load considering preventive actions. As shown in Fig. 18 (a), the aggregated RT electricity generations of CHPs, PVs and WTs, and DGs of IMCES were about 167.72 MWh, 117 MWh, and 31.06 MWh, respectively. Further, the aggregated RT electricity consumptions of IMCES and TMGs transactive electricity energy were about 269.78 MWh and 33.47 MWh, respectively. Finally, the aggregated RT electricity consumption reduction of IMCES using DRP was about 7.89 MWh.

Fig. 18 (b) shows the optimal RT dispatch of distributed heating

energy resources of the IMCESO, the transactive heating energy with TMGs, and the heating load considering preventive actions. As shown in Fig. 18 (b), the aggregated RT heating energy generations of CHPs and boilers were about 218.04 MWh and 46.22 MWh, respectively. Further, the aggregated RT heating energy consumptions of IMCES and TMGs transactive heating energy were about 313.35 MWh and 34.31 MWh, respectively.

Fig. 18 (c) depicts the optimal RT dispatch of distributed cooling energy resources of the IMCESO, the transactive cooling energy with TMGs, and the cooling load considering preventive actions. As shown in Fig. 18 (c), the aggregated RT cooling energy generations of ECCs and HACs were about 40.1 MWh and 113.41 MWh, respectively. Further, the aggregated RT cooling energy consumptions of IMCES and TMGs transactive cooling energy were about 146.49 MWh and 6.4 MWh, respectively.

Fig. 19 (a) and (b) present the values of the RT flexibility index (FI^{RT}) and the resiliency index, respectively. As shown in Fig. 19 (a), the minimum and maximum values of electrical FI^{RT} were about 0.16 and 0.275, respectively. Further, the minimum and maximum values of heating energy FI^{RT} were about 0.2 and 0.29, respectively. Finally, the minimum and maximum values of cooling energy FI^{RT} were about 0.196 and 0.3, respectively. The average value of average FI^{RT} was about 0.238. Thus, it can be concluded that the proposed method increased the RT flexibility index of IMCES by about 53.54 % concerning the day-

ahead flexibility index. As shown in Fig. 19 (b), the average values of the RT resiliency index without and with TMGC were about 3.5 and 6.97, respectively. Further, the minimum and maximum values of the RT resiliency index without TMGC were about 2.24 and 6.8, respectively. Finally, the minimum and maximum values of the RT resiliency index with TMGC were about 3.13 and 12.08, respectively. Thus, the suggested model enhanced the average value of the RT resiliency index by around 99.14 %.

The IMCESO determined the optimal status of electrical switches and heating and control valves in a preventive manner. It was considered that there were 33 most critical external shocks for the IMCES. Table 3 displays the optimal switching of MCES with electric switches and cooling and heating valves for 33 external shock conditions.

Based on Table 3 results that present the optimal switching of MCES with electrical switches and district heating and cooling control valves for 33 worst-case external shock conditions, the topology of EHC systems is determined. Thus, the RT simulation can be performed. At first, the simulation processes for RT optimal transaction between transactive and non-transactive microgrids optimization problem considering corrective actions (first level of the third stage) and the RT scheduling of transactive microgrids with IMCES optimization problem considering corrective actions (second level of the third stage) were carried out. It was assumed that the worst-case external shock scenario corresponded to the combination of external shocks (3, 4, 19, 20, 34).

Then, the IMCESO determined the values of ν_k^{Ramp} , ν_k^{Heat} , and ν_k^{Cool} , respectively, for corrective actions considering the RT IMCES energy balance and ancillary services conditions. It is assumed that the values of ν_k^{Reac} , and ν_k^{Spin} are 18 % and 25 % of ν_k^{Elect} . Fig. 20 presents the values of ν_k^{Ramp} , ν_k^{Heat} , and ν_k^{Cool} for preventive and corrective actions.

The average values of ν_k^{Ramp} , ν_k^{Heat} , and ν_k^{Cool} for corrective actions were about 124.23 MU/kWh, 129.26 MU/kWh, and 120.61 MU/kWh, respectively. Thus, the IMCESO increased average values of ν_k^{Ramp} , ν_k^{Heat} , and ν_k^{Cool} for corrective actions by about 55.7 %, 65.83 %, and 54.85 %, respectively, concerning the values of preventive actions. Fig. 21 (a) shows that the average values of accepted RT TMGs' ramp service, reactive power, heating energy, and cooling energy were about 2.6 MWh, 0.856 MVarh, 1.18 MW, and 1.18 MW, respectively. Fig. 21 (b) depicts the percent increase in the accepted RT TMGs' ramp service, reactive power, heating energy, and cooling energy for corrective actions. As shown in Fig. 21 (b), the minimum and maximum values of the increase in the accepted RT TMGs' ramp service were about 29.38 % and 81.57 %, respectively. Further, the minimum and maximum values of the increase in the accepted RT TMGs' heating energy were about 31.96 % and 103.84 %, respectively. Finally, the minimum and maximum values of the increase in the accepted RT TMGs' cooling energy were about 13.99 % and 97.31 %, respectively. The average values of the increase in the accepted RT TMGs' reactive power, heating energy, and cooling energy were about 54.98 %, 65.25 %, and 53.21 %, respectively.

Finally, the simulation process of RT scheduling of the IMCESO optimization problem, considering corrective actions (third level of the third stage), was fulfilled. Fig. 22 (a) shows the optimal RT dispatch of distributed electrical energy resources of the IMCESO, the transactive energy with TMGs, and the electrical load considering corrective actions. As can be seen in Fig. 22 (a), the aggregated RT electricity generations of CHPs, PVs, WTs, and DGs of IMCES were about 154.86 MWh, 116.96 MWh, and 34.07 MWh, respectively. Moreover, the aggregated RT electricity consumptions of IMCES and TMGs transactive electricity energy were about 262.02 MWh and 60.64 MWh, respectively. Finally, the aggregated RT electricity consumption reduction of IMCES using DRP was about 15.21 MWh. By comparing the values of Figs. 22 (a) and Fig. 18 (a), it can be concluded that the changes in aggregated RT electricity generations of CHPs and DGs of IMCES were about -7.67 % and 9.69 %, respectively, based on the fact that the CHPs of scathed zones were out of order.

Fig. 22 (b) presents the optimal RT dispatch of distributed heating

energy resources of the IMCESO, the transactive heating energy with TMGs, and the heating load considering corrective actions. As shown in Fig. 22 (b), the aggregated RT heating energy generations of CHPs and boilers were about 200.28 MWh and 57.74 MWh, respectively. By comparing the values of Figs. 22 (b) and Fig. 18 (b), it can be concluded that the changes in aggregated RT heating energy generation of CHPs and boilers of IMCES were about -8.14 % and 24.92 %, respectively, based on the fact that the CHPs of scathed zones were out of order. Moreover, the aggregated RT heating energy consumptions of IMCES and TMGs transactive heating energy were about 289.53 MWh and 39.16 MWh, respectively.

Fig. 22 (c) depicts the optimal RT dispatch of distributed cooling energy resources of the IMCESO, the transactive cooling energy with TMGs, and the cooling load considering corrective actions. As shown in Fig. 22 (c), the aggregated RT cooling energy generations of ECCs and HACs were about 70.64 MWh and 105.73 MWh, respectively. Further, the aggregated RT cooling energy consumptions of IMCES and TMGs transactive cooling energy were about 142.2 MWh and 27.62 MWh, respectively. By comparing the values of Figs. 22 (c) and Fig. 18 (c), it can be concluded that the changes in aggregated RT cooling energy generation of ECCs and HACs of IMCES were about 76.15 % and -6.71 %, respectively.

Table 4 shows the DA and RT operating costs of the EHC energy systems of IMCES with and without TMGC. As shown in Table 4, the aggregated DA costs of EHC systems of IMCES for the case without TMGC were increased by about 23 %, 28 %, and 19 %, respectively, concerning the TMGC case. Further, the aggregated RT costs of EHC systems of IMCES for the second case were increased by about 12 %, 14 %, and 15 %, respectively, concerning the TMGC case.

Table 5 presents the aggregated day-ahead costs and profits of TMGs for the cases without and with TMGC. As shown in Tables 5 and it can be concluded that the proposed method increased the aggregated DA and RT TMGs' profits by about 1.19E+06 MUs.

In conclusion, the proposed process increased the resiliency and flexibility of IMCES. Further, the method successfully determined the optimal scheduling of IMCES, TMGs, and NTMGs, considering the coupling constraints of electrical, heating energy, and cooling energy systems.

5. Conclusion

This paper introduced an integrated framework for analyzing the impacts of TMG's energy and ancillary service procurement for the IMCES in the DA and RT energy markets. The proposed model had three-stage optimization procedures for the DA and RT operational scheduling of IMCES, TMGs, and NTMGs, considering the EHC markets. The TMGs could transact electrical, heating, and cooling energy and ancillary services with the IMCES in the day-ahead and real-time markets. The transactions of electrical, heating, and cooling energy carriers between TMGs and NTMGs could change the availability of energy resources of TMGs. Further, it was assumed that the IMCESO, TMGs, and NTMGs systems were planned and operated based on smart grid infrastructure, and the forecastable external shocks (such as storms) were announced by the responsible entities. Thus, the TMGs, NTMGs, and IMCESO should manage their systems in a preventive manner before the occurrence of external shocks and perform corrective actions after tolerating external shocks. Thus, the first stage problem consisted of the following three levels: the DA optimization process of NTMGs and TMGs bilateral contracts (first level of the first stage), TMGs' contribution for energy and ancillary service procurement for IMCESO (second level of the first stage), and the IMCES (third level of the first stage), respectively. Further, the RT optimization procedure considering preventive actions consisted of the following three levels: the RT optimization process of NTMGs and TMGs bilateral contracts (first level of the second stage), TMGs' contribution for energy and ancillary service procurement for IMCESO (second level of the second stage), and the IMCES (third level of

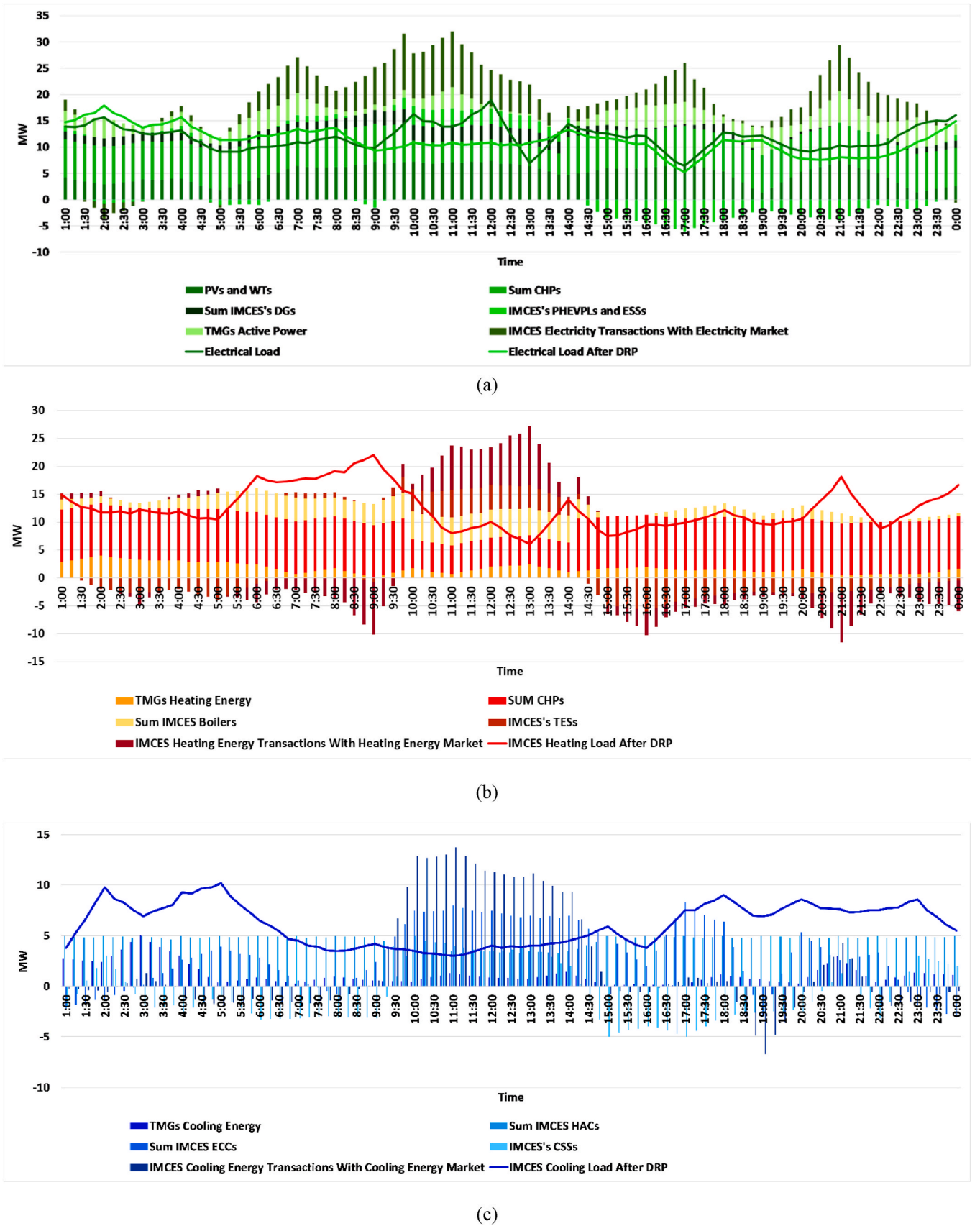


Fig. 22. (a) Optimal RT dispatch of distributed electrical energy resources of the IMCESO, the transactive energy with TMGs, and electrical load considering corrective actions, (b) Optimal RT dispatch of distributed heating energy resources of the IMCESO, the transactive heating energy with TMGs, and heating load considering corrective actions, (c) Optimal RT dispatch of distributed cooling energy resources of the IMCESO, the transactive cooling energy with TMGs, and cooling load considering corrective actions.

Table 4

The hourly DA and RT costs of IMCES for the without and with TMGC cases.

	With TMGC	Without TMGC
Day-Ahead IMCES's Electrical System Costs (MUs)	8.72E+05	1.07E+06
Day-Ahead IMCES's Heating Energy System Costs (MUs)	8.53E+05	1.09E+06
Day-Ahead IMCES's Cooling Energy System Costs (MUs)	8.19E+05	9.75E+05
Real-Time IMCES's Electrical System Costs (MUs)	4.51E+05	5.05E+05
Real-Time IMCES's Heating Energy System Costs (MUs)	2.95E+05	3.36E+05
Real-Time IMCES's Cooling Energy System Costs (MUs)	4.39E+05	5.05E+05
Aggregated costs (MUs)	3.73E+06	4.49E+06

Table 5

The hourly DA and RT costs and profits of TMGs for the cases without and with TMG contributions.

	With TMGC	Without TMGC
Total Day-Ahead TMGs' Electrical System Costs (MUs)	3.89E+05	3.54E+05
Total Day-Ahead TMGs' Electrical System Benefits (MUs)	1.20E+05	–
Total Day-Ahead TMGs' Heating Energy System Costs (MUs)	1.48E+05	1.01E+05
Total Day-Ahead TMGs' Heating Energy System Benefits (MUs)	1.77E+05	–
Total Day-Ahead TMGs' Cooling Energy System Costs (MUs)	1.34E+05	1.17E+05
Total Day-Ahead TMGs' Cooling Energy System Benefits (MUs)	1.63E+05	–
Total Real-Time TMGs' Electrical System Costs (MUs)	3.12E+05	2.65E+05
Total Real-Time TMGs' Electrical System Benefits (MUs)	4.36E+05	–
Total Real-Time TMGs' Heating Energy System Costs (MUs)	1.15E+05	9.85E+04
Total Real-Time TMGs' Heating Energy System Benefits (MUs)	1.53E+05	–
Total Real-Time TMGs' Cooling Energy System Costs (MUs)	1.23E+05	9.50E+04
Total Real-Time TMGs' Cooling Energy System Benefits (MUs)	1.42E+05	–

the second stage), respectively. Finally, the RT optimization procedure considering corrective actions consisted of the following three levels: the RT optimization process of NTMGs and TMGs bilateral contracts (first level of the third stage), TMGs' contribution for energy and ancillary service procurement for IMCESO (second level of the third stage), and the IMCES (third level of the third stage), respectively. The proposed model utilized three indices that explored the bidding gain of TMGs, the resiliency, and the flexibility of the IMCES. The optimization utilized a linearization process, and the CPLEX solver of the General Algebraic Modeling System (GAMS) was used to solve the problem. The case study was carried out for the 123-bus system as IMCES and the 33-bus system as TMG and NTMG. The output results revealed that the proposed method reduced the aggregated DA costs of EHC systems of IMCES by about 23 %, 28 %, and 19 %, concerning the case without TMGs' contribution. Further, the optimization process reduced the aggregated RT costs of EHC systems of IMCES by about 12 %, 14 %, and 15 %, respectively, concerning the case without TMGs' contribution. In addition, the output results presented that the proposed model increased the average value of the DA and RT resiliency index by about 102 % and 99.14 %, respectively. Further, the proposed method increased the RT flexibility index of IMCES by about 53.54 % concerning the day-ahead flexibility index. Finally, the proposed method successfully increased the average values of profits of TMG1, TMG2, and TMG3 by about 42 %, 41 %, and 53 %, respectively.

For future work, the authors are working on the modeling of the emergency demand response program to incorporate into the suggested model.

CRediT authorship contribution statement

Hadi Shahcheraghi: Software, Data curation, Writing – original draft, Investigation. **Mehrdad Setayesh Nazar:** Supervision, Conceptualization, Visualization, Methodology. **Mohammad Sadeh Javadi:** Formal analysis, Validation. **João P.S. Catalão:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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