Sustainable Energy, Grids and Networks 31 (2022) 100751

Contents lists available at ScienceDirect

Sustainable Energy, Grids and Networks

journal homepage: www.elsevier.com/locate/segan

A centralized stochastic optimal dispatching strategy of networked multi-carrier microgrids considering transactive energy and integrated demand response: Application to water–energy nexus

Yasin Pezhmani [a], Morteza Zare Oskouei [b], Navid Rezaei [a,*], Hasan Mehrjerdi [b]

[a] Department of Electrical Engineering, University of Kurdistan, Sanandaj, Iran
[b] Department of Electrical Engineering, Qatar University, Doha, Qatar

ARTICLE INFO

Article history:
Received 22 September 2021
Received in revised form 22 April 2022
Accepted 28 April 2022
Available online 10 May 2022

Keywords:
Centralized operation
Integrated demand response program (DRP)
Networked multi-carrier microgrids (MCMGs)
Transactive energy management (TEM)
Water–energy nexus

ABSTRACT

Over a few decades, energy system operators have sought to achieve appropriate frameworks based on the water–energy nexus issues due to energy crises and the rapid growth of water demand. In this regard, multi-carrier microgrids (MCMGs) have been widely welcomed to implement water–energy nexus-related strategies to meet local energy and water demands. This paper presents a centralized stochastic optimization strategy for energy transactions in networked MCMGs to exploit the potential capabilities of the promoted energy conversion facilities in meeting electricity, thermal, and water demands at the lowest operating cost. To enhance the flexibility and operational cost of the system under severe uncertainties, the day-ahead scheduling of all individual MCMGs is carried out by a central operator with the consideration of transactive energy management (TEM) strategy and integrated demand response program (DRP). The MCMGs can purchase energy from the electricity and gas markets to supply demands and energize local generation resources, and also exchange electrical energy with each other under the TEM strategy. The uncertainties arising from the renewable power generation, energy demands, water demand, and electricity market prices are applied to the optimization model using a scenario-based method. The proposed strategy is formulated as the mixed-integer nonlinear programming problem and is solved under GAMS software. The effectiveness of the proposed strategy is validated using a test system consisting of three networked MCMGs. According to the obtained results, the central operator can reduce the total operating cost of the networked MCMGs considerably if employing the TEM strategy and integrated DRP.

1. Introduction

1.1. Motivation

Nowadays, rising global demand for freshwater, on the one hand, and limited freshwater resources, especially in arid areas, on the other hand, have highlighted the role of large-scale desalination plants in urban infrastructure development plans [1]. The desalination units consume relatively high electrical/thermal energy according to the procedure used in the process of separating water from salt [2,3]. Therefore, using the concept of water–energy nexus can help energy system operators to achieve a sustainable strategy for the operation of local energy systems. However, a lack of understanding of the interdependence between different energy components within an integrated energy system can lead to mismanagement or overuse of resources. To overcome this challenge, significant steps have been taken by various governments around the world. For example, in the United States, Ontario, South Africa, and China, the Energy and Water Research Integration Act has been regulated by energy system planners [4]. In addition, the utilization of renewable energy sources and energy storage systems has captured more attention in recent years [5]. Thanks to the recent advances in energy systems, the use of multi-carrier microgrids (MCMGs) is recognized as an appropriate framework for integrating different energy sources, e.g., electricity and heat, to meet local energy demands with a particular focus on economic issues [6,7]. MCMGs, which are equipped with different services, can improve the interdependencies between different suppliers and consumers in energy markets and help local energy system operators to enhance system flexibility and make cost-effective decisions to meet energy demands [8,9]. Therefore, it is crucial to provide a comprehensive decision-making approach to determine the optimal energy dispatch of MCMGs in coordination with promoted energy conversion facilities and advanced ancillary services to reach the expected potentials of MCMGs within the water–energy nexus issues.

* Corresponding author.
E-mail address: n.rezaei@uok.ac.ir (N. Rezaei).

https://doi.org/10.1016/j.segan.2022.100751
2352-4677/

Nomenclature

Acronyms

CHP	Combined heat and power
DRP	Demand response program
EDR	Electrical demand response
ESS	Energy storage system
FOR	Feasible operation region
MCMG	Multi-carrier microgrid
MINLP	Mixed-integer nonlinear programming
PV	Photovoltaic
RES	Renewable energy sources
TEM	Transactive energy management
TES	Thermal energy storage
WT	Wind turbine

Index

m	Index of MCMGs
s	Index of scenarios
t	Index of time intervals

Scenario-dependent parameters

$\lambda_{t,s}^{power}$	Electricity price at hour t and scenario s
$I_{t,s}$	Solar irradiance at hour t and scenario s
$\upsilon_{t,s}$	Wind speed at hour t and scenario s
$P_{t,s,m}^{load}$	Electrical demand of MCMG m at hour t and scenario s
$T_{t,s,m}^{load}$	Thermal demand of MCMG m at hour t and scenario s
$W_{t,s,m}^{load}$	Water demand of MCMG m at hour t and scenario s

Constants and parameters

N_m^{WT}	Number of wind turbines at MCMG m
Nm	Number of MCMGs
Ns	Number of scenarios
Nt	Number of time intervals
λ^{gas}	Natural gas price
$\lambda_m^{WT}/\lambda_m^{PV}$	Operational cost coefficient of wind turbines/solar panels
HR_m^{disch}/HR_m^{sc}	Required heat rate of CAES of MCMG m for discharging/simple-cycle mode
$VOM_m^{\exp}$	Variable operation and maintenance cost of expander of CAES of MCMG m
VOM_m^{c}	Variable operation and maintenance cost of compressor of CAES of MCMG m
$\lambda_m^{TDR}/\lambda_m^{WDR}$	Incentive payment of thermal/water DRP at MCMG m
$a_m, b_m, c_m, d_m, e_m, f_m$	Cost coefficients of CHP at MCMG m
C_m^{su}, C_m^{sd}	Start-up/shut-down cost of CHP unit of MCMG m
$\alpha_m, \beta_m, \gamma_m$	Cost coefficients of boiler at MCMG m
$T_m^{bo,\max}$	Maximum thermal energy generation of boiler at MCMG m
$\upsilon_{in}^{c}/\upsilon_{out}^{c}/\upsilon_{rated}$	Cut-in/cut-out/rated wind speed
I_{std}	Solar irradiance in standard environment
I_c	Certain irradiance point of PV system
P_{rated}^{pv}	Rated power generation of PV system
$P_m^{ch,min}/P_m^{ch,max}$	Minimum/maximum charging power of CAES at MCMG m
$P_m^{disch,min}/P_m^{disch,max}$	Minimum/maximum discharging power of CAES at MCMG m
$P_m^{sc,min}/P_m^{sc,max}$	Minimum/maximum power generation of CAES at MCMG m
$E_m^{CAES,min}/E_m^{CAES,max}$	Minimum/maximum energy level of CAES at MCMG m
$\eta_m^{CAES,ch}/\eta_m^{CAES,disch}$	Charging/discharging efficiency of CAES of MCMG m
$T_m^{ch,min}/T_m^{ch,max}$	Minimum/maximum charging power of TES at MCMG m
$T_m^{disch,min}/T_m^{disch,max}$	Minimum/maximum discharging power of TES at MCMG m
$T_m^{TES,min}/T_m^{TES,max}$	Minimum/maximum thermal energy level of TES at MCMG m
$\eta_m^{TES,sb}/\eta_m^{TES,ch}/\eta_m^{TES,disch}$	Stand by/charging/discharging efficiency of TES of MCMG m
$W_m^{ch,min}/W_m^{ch,max}$	Minimum/maximum charging water of water storage at MCMG m
$W_m^{disch,min}/W_m^{disch,max}$	Minimum/maximum discharging water of water storage at MCMG m
$L_m^{WS,min}/L_m^{WS,max}$	Minimum/maximum water level of water storage at MCMG m
L_m^{G}	The altitude of the location of water storage at MCMG m
A_m^{WS}	Cross-section of water storage of MCMG m
g	Gravity
ρ	The density of water
p_s	Probability of each scenario
η_m^{pump}	Efficiency of pump
$W_m^{WW,max}$	Maximum extracted water from water well of MCMG m
L_m^{WW}	Water well level
$W_m^{des,max}$	Maximum extracted water from water desalination unit of MCMG m
η_m^{des}	Energy efficiency of water desalination unit
$P^{Trans,max}$	Maximum exchanged power between two MCMGs
$P_m^{up,max}$	Maximum increased demand of shiftable loads of MCMG m
$P_m^{down,max}$	Maximum decreased demand of shiftable loads of MCMG m
D_m^{TDR}/D_m^{WDR}	Coefficient for load curtailment in thermal/water DRP

Binary variables

$V^{chp}_{t,m}$	Commitment status of CHP of MCMG *m*
$SU^{chp}_{t,m}/SD^{chp}_{t,m}$	Start-up/shut-down status of CHP of MCMG *m*
$B^{ch,CAES}_{t,s,m}/B^{disch,CAES}_{t,s,m}/$	Charging/discharging/ simple-cycle
$B^{sc,CAES}_{t,s,m}$	modes of CAES of MCMG *m*
$B^{ch,TES}_{t,s,m}/B^{disch,TES}_{t,s,m}$	Charging/discharging status of TES of MCMG *m*
$B^{ch,WS}_{t,m}/B^{disch,WS}_{t,m}$	Charging/discharging status of water storage of MCMG *m*
$B^{up,EDR}_{t,s,m}/B^{down,EDR}_{t,s,m}$	Binary variable for modeling increased/decreased demand in electrical DRP

Decision variables

$P^{load,EDR}_{t,s,m}/T^{load,TDR}_{t,s,m}/W^{load,WDR}_{t,s,m}$	Electrical/thermal/water demand of MCMG *m* at hour *t* and scenario *s* after DRP
$Cost^{MG}_{m}$	Operational cost of MCMG *m*
$Cost^{grid}_{t,s,m}$	Cost of purchasing power from the main grid at MCMG *m* at hour *t* and scenario *s*
$Cost^{RES}_{t,s,m}$	Operational cost of RES of MCMG *m* at hour *t* and scenario *s*
$Cost^{CAES}_{t,s,m}$	Operational cost of CAES of MCMG *m* at hour *t* and scenario *s*
$Cost^{TES}_{t,s,m}$	Operational cost of TES of MCMG *m* at hour *t* and scenario *s*
$Cost^{WS}_{t,s,m}$	Operational cost of water storage of MCMG *m* at hour *t* and scenario *s*
$Cost^{TDR}_{t,s,m}/Cost^{WDR}_{t,s,m}$	Cost of applying thermal/water DRP in MCMG *m* at hour *t* and scenario *s*
$Cost^{boiler}_{t,s,m}/Cost^{chp}_{t,s,m}$	Operational cost of boiler/CHP of MCMG *m* at hour *t* and scenario *s*
$P^{buy}_{t,s,m}$	The amount of power purchased from the main grid by MCMG *m* at hour *t* and scenario *s*
$P^{wt}_{t,s,m}/P^{pv}_{t,s,m}$	Power generation of WTs/PV systems of MCMG *m* at hour *t* and scenario *s*
$P^{ch}_{t,s,m}/P^{dsich}_{t,s,m}$	Charging/discharging power of CAES of MCMG *m* at hour *t* and scenario *s*
$P^{sc}_{t,s,m}$	Power generation in simple cycle mode by CAES of MCMG *m* at hour *t* and scenario *s*
$E^{CAES}_{t,s,m}$	Energy level of CAES of MCMG *m* at hour *t* and scenario *s*
$P^{chp}_{t,s,m}/T^{chp}_{t,s,m}$	Produced power/heat by CHP of MCMG *m* at hour *t* and scenario *s*
$T^{bo}_{t,s,m}$	Produced heat by boiler of MCMG *m* at hour *t* and scenario *s*
$T^{ch}_{t,s,m}/T^{dsich}_{t,s,m}$	Charging/discharging power of TES of MCMG *m* at hour *t* and scenario *s*
$T^{TES}_{t,s,m}$	Thermal energy level of TES of MCMG *m* at hour *t* and scenario *s*
$W^{ch}_{t,s,m}/W^{dsich}_{t,s,m}$	Charging/discharging water of water storage of MCMG *m* at hour *t* and scenario *s*
$L^{WS}_{t,s,m}$	Water level of water storage of MCMG *m* at hour *t* and scenario *s*
$P^{ws}_{t,s,m}$	Power consumption of water storage of MCMG *m* at hour *t* and scenario *s*
$W^{WW}_{t,s,m}$	The amount of water extracted from water well of MCMG *m* at hour *t* and scenario *s*
$P^{ww}_{t,s,m}$	Power consumption of water well of MCMG *m* at hour *t* and scenario *s*
$W^{des}_{t,s,m}$	The amount of water extracted from water desalination unit of MCMG *m* at hour *t* and scenario *s*
$P^{des}_{t,s,m}$	Power consumption of water desalination unit of MCMG *m* at hour *t* and scenario *s*
$P^{Trans}_{t,s,(m\leftrightarrow m+i)}$	Exchanged power between MCMGs at hour *t* and scenario *s*
$P^{up}_{t,s,m}/P^{down}_{t,s,m}$	Increased/decreased demand of shiftable load of MCMG *m* at hour *t* and scenario *s*
$T^{curt}_{t,s,m}/W^{curt}_{t,s,m}$	Load curtailment of thermal energy/water consumers of MCMG *m* at hour *t* and scenario *s*

1.2. Literature review

Herein, different studies on the optimal operation of MCMGs, which are used to meet the water and other energy demands, are briefly reviewed. Most of the conducted studies have been done to achieve the same objectives, namely operation cost savings and provide a wide range of energy forms, using various optimization techniques [10]. For instance, in [11], a day-ahead deterministic scheduling model was presented for water-heat-electrical flow management in the form of a MCMG with the aim of minimizing the total operation cost. In [12], a water–energy nexus approach was developed for a MCMG to meet the required energy demands of a cement plant following the objective of minimizing the operation cost and increasing the exergy efficiency. Authors of [13] presented a holistic framework for designing and optimizing a joint water and energy supply system in the context of a MCMG with a particular focus on the role of renewable energy sources (RES) in future energy systems. A stochastic decentralized framework was defined in [14] for optimal energy dispatching in a MCMG by relying on the uncertainties of demands and renewable power generation. The authors of [15] have proposed a mixed-integer linear programming (MILP) model for a smart water–energy MCMG with buildings and water distribution system. Also, an optimal dispatch model for a water–energy MCMG, which is equipped with different energy storage systems, has been proposed in [16]. In that paper, the impact of the employment of water and energy storage systems on the optimal scheduling of the proposed water–energy MCMG has been investigated. In [17], the concept of water–energy nexus was used for managing the behavior of a MCMG and the coordinated supply of electricity, water, and thermal demands considering photovoltaic (PV) system, desalination unit, combined heat and power (CHP), and gas boiler. In [18], a day-ahead economic dispatch model was presented to determine the optimal dispatch of a water–energy MCMG using the bivariate piecewise linear approximation. In [19], a co-optimization model was proposed for a water–energy MCMG at a community scale to participate in day-ahead energy markets considering different uncertain sources. Furthermore, in [20], a central optimization framework was developed for energy flow management in a MCMG in the presence of RES, energy storage systems (ESSs), and desalination unit to meet electrical and water demands.

Another set of literature made a step further by considering the networked MCMGs from a water–energy nexus perspective. Given the increasing use of MCMGs in local energy systems, obtaining an operational model to integrate a large set of MCMGs to consciously participate in different energy markets will be one of the main challenges in future energy systems. To address this challenge, authors of [21] presented a centralized deterministic analysis of optimal energy dispatch in networked MCMGs considering economic aspects. In the same study, different energy conversion facilities, e.g., CHP, water storage, and water desalination unit, were considered along with transactive energy management (TEM) strategy to link energy and water supply systems as well as to increase the flexibility of networked MCMGs. The robust optimization framework was presented in [22], which avails a collaborative strategy for optimal operation of networked MCMGs in meeting electrical, thermal, and water demands. In that study, the price-based demand response program (DRP) was applied as an ancillary service to shift the electrical consumption from peak to off-peak intervals with the aim of minimizing total operation cost and dealing with uncertain sources. There are other studies, e.g., in [23,24], evaluating the effect of the implementation of incentive-based and/or time-based DRP on networked MCMGs performance. In these works, each MCMG strives to take advantage of the opportunities provided by responsive loads to minimize the operation cost with regard to the optimal performance of local resources and energy trade with local markets. Furthermore, in [25], a centralized stochastic approach was introduced to assess the networked MCMGs' flexibility by increasing the end-users accessibility to water and energy using large-scale desalination units, RES, and DRPs under probabilistic events. Authors of [26] proposed an interactive trading framework among multiple MCMGs to scrupulously manage the energy demands and optimize the operational cost by relying on the water–energy nexus issues. Moreover, authors of [27] attempted to derive an integrated energy management strategy for coupling local electricity and water–energy systems through networked MCMGs, which were equipped with water pumps, RES, and ESSs. In [28], a practical optimization approach was developed for the optimal allocation of water pumps in networked MCMGs, which met the water and electrical demands at the lowest energy cost by achieving optimal system configuration.

1.3. Research gaps and contributions

According to the surveyed studies, there are many interesting works on the co-optimization of networked MCMGs with special emphasis on water–energy nexus issues. Table 1 gives the technical features of the aforementioned studies in comparison with the present study. According to this table, the following research gaps can be identified in the existing literature:

- In some of the literature, e.g., [11,12,14], a water–energy flow model has been developed for the operation of a single MCMG, which is not appropriate for the operation of networked MCMGs equipped with various energy conversion facilities and does not lead to feasible solutions.
- There is no study on day-ahead economic dispatch of networked MCMGs, which has simultaneously deployed the advanced ancillary services, i.e., TEM strategy and integrated DRP, in collaboration with water–energy nexus issues.
- The impact of the utilization of tri-state compressed air energy storage (CAES) system on improving the economic performance and flexibility of the networked MCMGs in the presence of water storage systems, water desalination units, and RES has not been investigated.
- In all relevant studies, the opportunities to leverage differences between price-based and incentive-based DRPs have been ignored to manage the electrical, water, and thermal demands of networked MCMGs.
- The impact of different uncertain sources, i.e., electricity market price, energy demands, and RES output power, on the proposed decision-making strategies for networked MCMGs operations was not investigated in [11,12,18,21,28].

This study tries to address the aforementioned research gaps by applying a centralized stochastic optimization problem to manage water and energy flow within networked MCMGs. The main objectives of the proposed strategy lie in (1) exploiting each MCMG with minimum operation cost in the presence of the water–energy nexus issues; (2) enhancing the flexibility and operational cost of the MCMGs considering the advanced ancillary services; and (3) establishing a reliable interface between electricity and gas supply system and the energy demands, i.e., electricity, heat, and water. To the best of the authors' knowledge, the current study contributes to state of the art in the following manners:

- A comprehensive centralized decision-making approach is developed for the coordinated operation of networked MCMGs by establishing a stable connection between electrical, heat, and water supply systems by a central operator. In this regard, a stochastic mixed-integer nonlinear programming (MINLP) model is presented to determine the optimal day-ahead operation of networked MCMGs as well as to facilitate the coordinated operation of each MCMG and electricity and gas markets considering local energy conversion facilities.
- The TEM strategy is considered, as an emerging ancillary service, to create an energy exchanging platform for networked MCMGs that enables the central operator to carry out the electrical power dispatch scheduling in a unified manner to enhance the system flexibility.
- The simultaneous application of time-based and incentive-based DRPs along with TEM strategy is considered in day-ahead scheduling to manage the electrical, thermal, and water demands with the aim of minimizing the total operation cost of each MCMG.
- In addition to the above items, the proposed centralized stochastic optimization is extended based on the promoted energy conversion facilities, e.g., tri-state CAES system, water storage systems, large-scale desalination units, to assess these resources impacts on energy efficiency, enhance operational flexibility of the networked MCMGs, and mitigate the operational risks.
- The scenario-based stochastic approach is used to manage uncertainties arising from RES power generation, electricity market price, water demand, and energy demands in an effective and tractable manner.

The rest of this paper is organized as follows: Section 2 presents the proposed centralized stochastic model, including general concepts, objectives, ancillary services, and technical limits of each component of MCMGs. Numerical results and technical analysis are provided in Section 3. Finally, Section 4 concludes the paper and draws potential future studies.

2. Proposed centralized strategy for networked MCMGs

This paper presents a centralized approach for the optimal exploitation of networked MCMGs to respond to the water–energy nexus requirements. Establishing a proper connection between the MCMGs enables the central operator to utilize the capacity of

Table 1
Comparison of main contributions with previous studies.

References	Network structure		Energies exchanging between MCMGs (TEM)	DRP model			Optimization model
	Single-MCMG	Networked MCMGs		Electrical	Heat	Water	
[11]	✓	–	×	✓	✓	✓	Deterministic optimization method
[12,18]	✓	–	×	×	×	×	Deterministic optimization method
[14]	✓	–	×	✓	✓	×	Stochastic optimization method
[21]	–	✓	✓	×	×	×	Centralized deterministic optimization method
[22]	–	✓	×	✓	×	×	Centralized robust optimization method
[25]	–	✓	×	✓	×	×	Centralized stochastic optimization method
[27]	–	✓	×	×	×	×	Centralized stochastic optimization method
[28]	–	✓	×	✓	×	×	Centralized deterministic optimization method
Proposed strategy	–	✓	✓	✓	✓	✓	Centralized stochastic optimization method

different energy systems in providing water and energy demands. The schematic overview of the proposed strategy is shown in Fig. 1. As depicted in Fig. 1, the central operator purchases the required energy from the electricity and gas markets and delivers them to networked MCMGs. The electrical demands are economically dispatched between the electricity market, CHP units, PV systems, wind turbines, and tri-state CAES systems. In addition, the central operator can take advantage of the TEM strategy to satisfy the power balance limit in day-ahead decisions by overcoming the existing power mismatches under uncertain sources. On the other hand, water wells, water storage systems, and water desalination units are considered for supplying freshwater demands. Moreover, CHP units, gas boilers, and thermal energy storages (TESs) are used to provide thermal demands within networked MCMGs. The effect of the load shifting technique, as a prevalent price-based DRP, is investigated to manage responsive electrical loads. Also, the load curtailment option, as an incentive-based DRP, is applied to identify the optimal control strategy of responsive thermal and water demands. The comprehensive mathematical model of the presented strategy is provided in the following sub-sections.

2.1. Objective function

The objective function, represented by (1), aims to minimize the overall expected cost of the MCMGs, while satisfying all the technical and operational constraints of each individual MCMG. The operation cost of each MCMG is determined in (2). The cost of purchasing power from the main grid and the operation cost of RES are presented in (3) and (4), respectively. Also, the operation cost of CAES technologies is represented in (5). Eq. (6) calculates the cost associated with load curtailment in thermal DRP while the cost of water DRP is given in (7). The cost function of boilers and CHP units are presented by (8) and (9), respectively. In addition, the operation cost of thermal and water storage systems are represented in (10) and (11), respectively.

$$Min: F_m$$
$$F_m = Cost_m^{MG} \;\; ; \forall m \tag{1}$$

$$Cost_m^{MG} = \sum_{s=1}^{Ns} p_s \left[\sum_{t=1}^{Nt} \begin{matrix} Cost_{t,s,m}^{grid} + Cost_{t,s,m}^{RES} + Cost_{t,s,m}^{CAES} + Cost_{t,s,m}^{TDR} + Cost_{t,s,m}^{WDR} \\ + Cost_{t,s,m}^{boiler} + Cost_{t,s,m}^{chp} + Cost_{t,s,m}^{TES} + Cost_{t,s,m}^{WS} \end{matrix} \right] ; \forall m \tag{2}$$

$$Cost_{t,s,m}^{grid} = P_{t,s,m}^{buy}.\lambda_{t,s}^{power}; \forall t, s, m \tag{3}$$

$$Cost_{t,s,m}^{RES} = P_{t,s,m}^{wt}.\lambda_m^{wt} + P_{t,s,m}^{pv}.\lambda_m^{pv}; \forall t, s, m \tag{4}$$

$$Cost_{t,s,m}^{CAES} = P_{t,s,m}^{disch}\left(HR_m^{disch}.\lambda^{gas} + VOM_m^{\exp}\right) + P_{t,s,m}^{sc}\left(HR_m^{sc}.\lambda_t^{gas} + VOM_m^{\exp} + VOM_m^{c}\right) + P_{t,s,m}^{ch}.VOM_m^{c}; \forall t, s, m \tag{5}$$

$$Cost_{t,s,m}^{TDR} = T_{t,s,m}^{curt}.\lambda^{TDR}; \forall t, s, m \tag{6}$$

$$Cost_{t,s,m}^{WDR} = W_{t,s,m}^{curt}.\lambda^{WDR}; \forall t, s, m \tag{7}$$

$$Cost_{t,s,m}^{boiler} = \alpha_m.\left(T_{t,s,m}^{boiler}\right)^2 + \beta_m.T_{t,s,m}^{boiler} + \gamma_m; \forall t, s, m \tag{8}$$

$$Cost_{t,s,m}^{chp} = C_{t,s,m}^{opr} + C_m^{su}SU_{t,m}^{chp} + C_m^{sd}SD_{t,m}^{chp}; \forall t, s, m \tag{9}$$

$$Cost_{t,s,m}^{TES} = T_{t,s,m}^{disch}.\lambda_m^{TES}; \quad \forall t, s, m \tag{10}$$

$$Cost_{t,s,m}^{WS} = W_{t,s,m}^{disch}.\lambda_m^{WS}; \quad \forall t, s, m \tag{11}$$

2.2. CHP unit

The generation cost of the CHP unit is a non-linear function of its electrical and thermal output power as described in (12). The constraint associated with start-up and shut-down of CHP units is expressed in (13). In this work, the mutual dependency of the power and heat generation of CHP units are taken into account in (14)–(18) by using feasible operation region (FOR) [29,30]. Although in the reality, the FOR of CHP units is generally non-convex, in this paper, it is assumed that the FOR of CHP units is convex to avoid complexity. The convex FOR of CHP units is exhibited in Fig. 2. The area under the line AB is presented in (14), while the area above the line BC is expressed in (15). Also, the area over the line CD is indicated in (16). The upper and lower bounds of power and heat generation of CHP units are enforced by (17) and (18), respectively.

$$C_{t,s,m}^{opr} = a_m.\left(P_{t,s,m}^{chp}\right)^2 + b_m.P_{t,s,m}^{chp} + c_m + d_m.\left(T_{t,s,m}^{chp}\right)^2 + e_m.T_{t,s,m}^{chp} + f_m.\left(P_{t,s,m}^{chp}.T_{t,s,m}^{chp}\right); \forall t, s, m \tag{12}$$

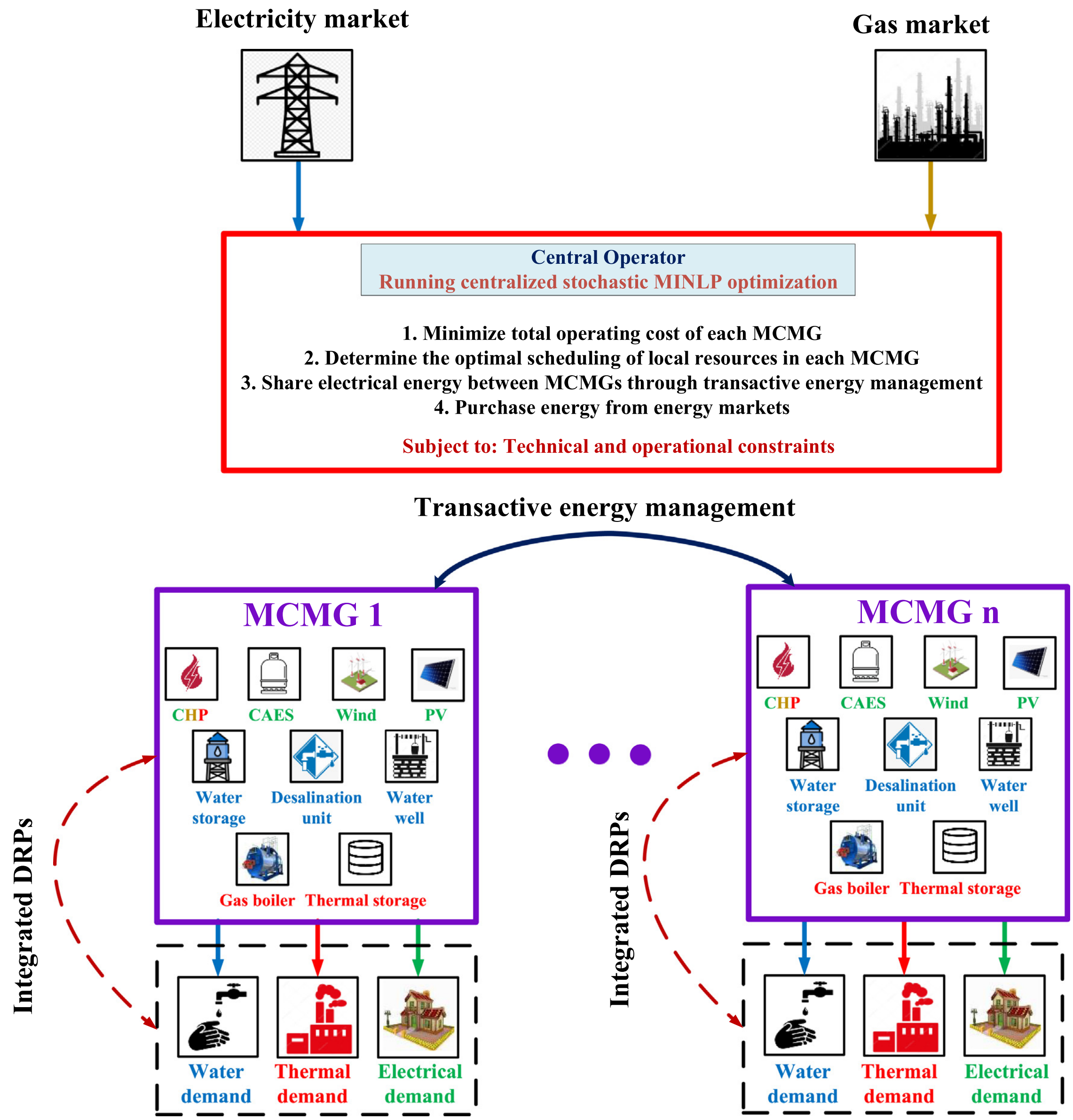

Fig. 1. Structure of centralized operation for networked MCMGs.

$$SU_{t,m}^{chp} - SD_{t,m}^{chp} = V_{t,m}^{chp} - V_{t-1,m}^{chp};\ \forall t > 1, \forall m \tag{13}$$

$$P_{t,s,m}^{chp} - P_{m,A}^{chp} - \frac{P_{m,A}^{chp} - P_{m,B}^{chp}}{T_{m,A}^{chp} - T_{m,B}^{chp}}\left[T_{t,s,m}^{chp} - T_{m,A}^{chp}\right] \le 0;\ \forall t, s, m \tag{14}$$

$$P_{t,s,m}^{chp} - P_{m,B}^{chp} - \frac{P_{m,B}^{chp} - P_{m,C}^{chp}}{T_{m,B}^{chp} - T_{m,C}^{chp}}\left[T_{t,s,m}^{chp} - T_{m,B}^{chp}\right] \ge -\left[1 - V_{t,m}^{chp}\right].M;\ \forall t, s, m \tag{15}$$

$$P_{t,s,m}^{chp} - P_{m,C}^{chp} - \frac{P_{m,C}^{chp} - P_{m,D}^{chp}}{T_{m,C}^{chp} - T_{m,D}^{chp}}\left[T_{t,s,m}^{chp} - T_{m,C}^{chp}\right] \ge -\left[1 - V_{t,m}^{chp}\right].M;\ \forall t, s, m \tag{16}$$

$$0 \le P_{t,s,m}^{chp} \le P_{m,A}^{chp}.V_{t,m}^{chp};\ \forall t, s, m \tag{17}$$

$$0 \le T_{t,s,m}^{chp} \le T_{m,B}^{chp}.V_{t,m}^{chp};\ \forall t, s, m \tag{18}$$

2.3. Boiler

A boiler could be employed if the thermal storage and CHP units are not able to satisfy thermal load, entirely, or when utilizing them is not economical. The limitation related to the heat generation of each boiler is expressed in (19).

$$0 \le T_{t,s,m}^{bo} \le T_{m}^{bo,max};\ \forall t, s, m \tag{19}$$

2.4. Wind turbines(WTs)

The power generation of wind turbines is highly uncertain and is formulated as a function of wind speed as represented in

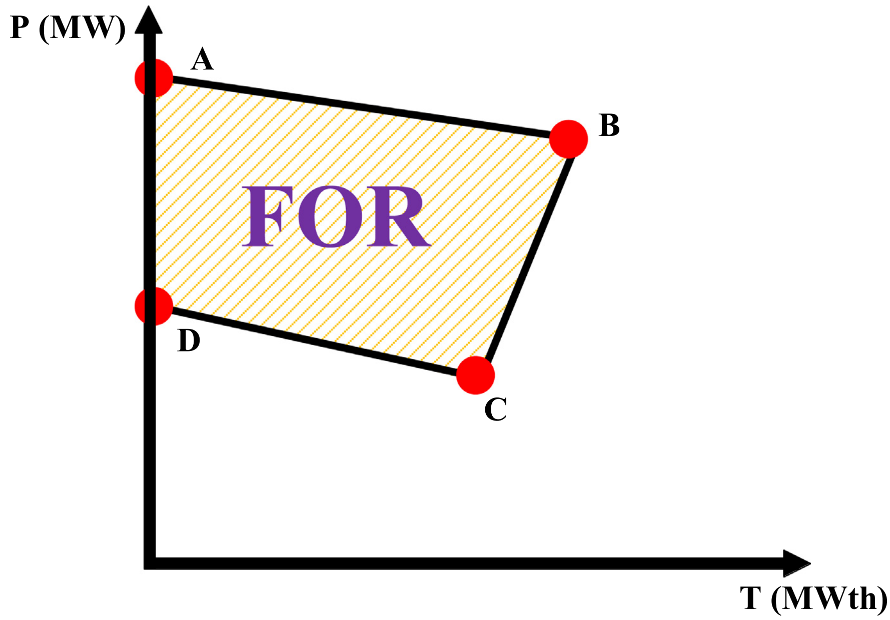

Fig. 2. FOR of CHP units [31].

(20) [32].

$$P^{wt}_{t,s,m} = N^{wt}_m \times \begin{cases} 0 & v_{t,s} < v^c_{in},\ v^c_{out} \le v_{t,s} \\ P^{wt}_{rated} \times (\dfrac{v_{t,s} - v^c_{in}}{v_{rated} - v^c_{in}})^3 & v^c_{in} \le v_{t,s} < v_{rated} \\ P^{wt}_{rated} & v_{rated} \le v_{t,s} < v^c_{out} \end{cases} ;\forall t, s, m \quad (20)$$

2.5. PV system

The generated power by PV systems can be calculated using (21). As can be seen, the defined function is dependent on solar radiation, i.e., $I_{t,s}$ [33].

$$P^{pv}_{t,s,m} = \begin{cases} P^{pv}_{rated}(\dfrac{I^2_{t,s}}{I_{std} I_C}) & I_{t,s} \le I_C \\ P^{pv}_{rated}(\dfrac{I^2_{t,s}}{I_{std}}) & I_C \le I_{t,s} \end{cases} ;\forall t, s, m \quad (21)$$

2.6. Tri-state CAES system

Tri-state CAES is recognized as a beneficial technology that could be employed to cope with the fluctuations of RES. This technology, which can operate in three modes including charging, discharging, and simple-cycle mode, makes the operation of the MCMGs cost-effective. The limitations of charging and discharging power of CAES are defined by (22) and (23), respectively. The constraint related to the power generated by CAES in simple-cycle mode is satisfied in (24). Each tri-state CAES unit is operated in only one of the charging, discharging, and simple-cycle modes at each time interval as shown in (25). Eq. (26) limits the capacity of tri-state CAES. Additionally, the amount of stored power in tri-state CAES at each hour is determined in (27).

$$P^{ch,min}_m.B^{ch,CAES}_{t,s,m} \le P^{ch}_{t,s,m} \le P^{ch,max}_m.B^{ch,CAES}_{t,s,m};\forall t, s, m \quad (22)$$

$$P^{disch,min}_m.B^{disch,CAES}_{t,s,m} \le P^{disch}_{t,s,m} \le P^{disch,max}_m.B^{disch,CAES}_{t,s,m};\forall t, s, m \quad (23)$$

$$P^{sc,min}_m.B^{sc,CAES}_{t,s,m} \le P^{sc}_{t,s,m} \le P^{sc,max}_m.B^{sc,CAES}_{t,s,m};\forall t, s, m \quad (24)$$

$$B^{ch,CAES}_{t,s,m} + B^{disch,CAES}_{t,s,m} + B^{sc,CAES}_{t,s,m} \le 1;\forall t, s, m \quad (25)$$

$$E^{CAES,min}_m \le E^{CAES}_{t,s,m} \le E^{CAES,max}_m;\forall t, s, m \quad (26)$$

$$E^{CAES}_{t,s,m} = E^{CAES}_{t-1,s,m} + \left(\eta^{CAES,ch}_m.P^{ch}_{t,s,m} - \frac{P^{disch}_{t,s,m}}{\eta^{CAES,disch}_m}\right)\Delta t;\forall t, s, m \quad (27)$$

2.7. TES system

Charging and discharging constraints of TES are clearly modeled in (28) and (29), respectively. Eq. (30) denotes that TES is not operated in charging and discharging mode, simultaneously. The capacity of TES is limited by (31). Moreover, the thermal energy balance of TES is presented in (32).

$$T^{ch,min}_m.B^{ch,TES}_{t,s,m} \le T^{ch}_{t,s,m} \le T^{ch,max}_m.B^{ch,TES}_{t,s,m};\forall t, s, m \quad (28)$$

$$T^{disch,min}_m.B^{disch,TES}_{t,s,m} \le T^{disch}_{t,s,m} \le T^{disch,max}_m.B^{disch,TES}_{t,s,m};\forall t, s, m \quad (29)$$

$$B^{ch,TES}_{t,s,m} + B^{disch,TES}_{t,s,m} \le 1;\forall t, s, m \quad (30)$$

$$T^{TES,min}_m \le T^{TES}_{t,s,m} \le T^{TES,max}_m;\forall t, s, m \quad (31)$$

$$T^{TES}_{t,s,m} = \eta^{TES,sb}_m.T^{TES}_{t-1,s,m} + \left(\eta^{TES,ch}_m.T^{ch}_{t,s,m} - \frac{T^{disch}_{t,s,m}}{\eta^{TES,disch}_m}\right)\Delta t;\forall t, s, m \quad (32)$$

2.8. Water storage

Water storage is employed in each MCMG to store water during low water demand hours and return it to the water consumers at peak hours when water demand rises. The structure of water storage is illustrated in Fig. 3. The mathematical constraints associated with charging and discharging of water storage are shown in (33) and (34), respectively. Water storage is excluded from simultaneous discharging and charging mode as indicated in (35). The limitation of water level in storage is presented in (36).

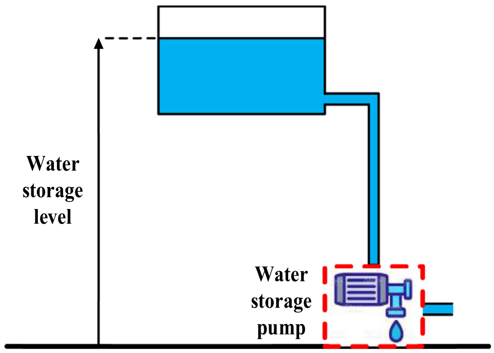

Fig. 3. The structure of water storage.

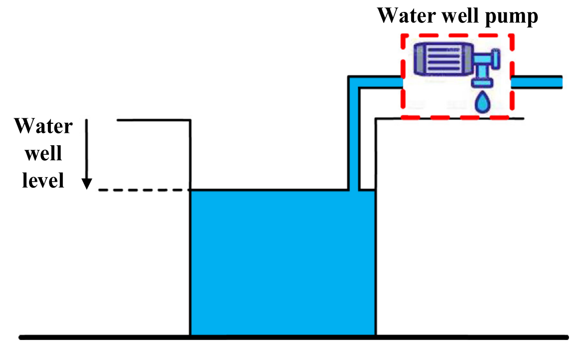

Fig. 4. The structure of water well.

In addition, the water level of storage at each hour is determined in (37). In fact, power is consumed by the water storage pump when the storage is in charging mode. The power consumption of the water storage is calculated by (38).

$$W_m^{ch,min}.B_{t,s,m}^{ch,WS} \leq W_{t,s,m}^{ch} \leq W_m^{ch,max}.B_{t,s,m}^{ch,WS};\ \forall t,s,m \tag{33}$$

$$W_m^{disch,min}.B_{t,s,m}^{disch,WS} \leq W_{t,s,m}^{disch} \leq W_m^{disch,max}.B_{t,s,m}^{disch,WS};\ \forall t,s,m \tag{34}$$

$$B_{t,s,m}^{ch,WS} + B_{t,s,m}^{disch,WS} \leq 1;\ \forall t,s,m \tag{35}$$

$$L_m^{WS,min} \leq L_{t,s,m}^{WS} \leq L_m^{WS,max};\ \forall t,s,m \tag{36}$$

$$L_{t,s,m}^{WS} = L_{t-1,s,m}^{WS} + \frac{W_{t,s,m}^{ch}}{A_m^{WS}} - \frac{W_{t,s,m}^{disch}}{A_m^{WS}};\ \forall t,s,m \tag{37}$$

$$P_{t,s,m}^{WS} = \frac{W_{t,s,m}^{ch}\left(L_{t,s,m}^{WS} + L_{t-1,s,m}^{WS} + L_m^{G}\right) g\rho}{2\eta_m^{pump}\left(3.6\times 10^9\right)};\ \forall t,s,m \tag{38}$$

2.9. Water well

The structure of the water well system is shown in Fig. 4. The operational constraints of the water well are given in (39) and (40). The constraint imposed on the amount of extracted water from the water well is presented in (39). Also, the amount of power that the water well pump consumes to extract water from the well can be calculated using (40). It should be noted that 3.6×10^9 in (40) is used for converting the consumed electricity in W unit during one second to electricity consumption in MW unit within one hour.

$$0 \leq W_{t,s,m}^{ww} \leq W_m^{ww,max};\ \forall t,s,m \tag{39}$$

$$P_{t,s,m}^{ww} = \frac{W_{t,s,m}^{ww} L_m^{ww} g\rho}{\eta_m^{pump}\left(3.6\times 10^9\right)};\ \forall t,s,m \tag{40}$$

2.10. Water desalination

To cope with the freshwater shortage, a water desalination unit, which consumes power for changing the brackish water into potable water, is utilized. The limitation related to the amount of extracted water from the water desalination unit is expressed in (41). Furthermore, the power consumption of a desalination unit is calculated in (42).

$$0 \leq W_{t,s,m}^{des} \leq W_m^{des,max};\ \forall t,s,m \tag{41}$$

$$P_{t,s,m}^{des} = \eta_m^{des} W_{t,s,m}^{des};\ \forall t,s,m \tag{42}$$

2.11. TEM strategy

In this study, TEM strategy, as a reliable and sustainable technique, is implemented to control the electrical energy sharing between MCMGs and boost the flexibility and stability of the system against uncertain parameters and unbalancing problems. In (43)–(45), the constraints associated with the TEM strategy are modeled. A similar strategy based on the peer-to-peer mechanism has been used in [34]. In that paper, the electrical energy can be traded between the multi-carrier energy hubs and the cost of purchasing or selling energy related to the peer-to-peer mechanism is taken into account. In other words, when a multi-carrier energy hub, imports electrical energy from another energy hub, it pays money. On the other hand, when a multi-carrier energy hub, exports electrical energy to another energy hub, it receives money from the power receiver multi-carrier energy hub. Nevertheless, in the transactive energy model of this paper, which is a simplified transactive energy model, no money is exchanged between MCMGs. This is because in this paper it is assumed that the total amount of power that is imported from MCMG i to MCMG j during 24 h equals the total amount of power that is exported to MCMG i from MCMG j during 24 h as stated in (46).

$$-P^{Trans,max} \leq P_{t,s,(m+i\leftrightarrow m)}^{Trans} \leq P^{Trans,max};\ \forall t,s,m,i=1,\ldots,Nm-1 \tag{43}$$

$$P_{t,s,(m\leftrightarrow m+i)}^{Trans} = -P_{t,s,(m+i\leftrightarrow m)}^{Trans};\ \forall t,s,m,i=1,\ldots,Nm-1 \tag{44}$$

$$\sum_{t=1}^{Nt} P_{t,s,(m\leftrightarrow m+i)}^{Trans} = \sum_{t=1}^{Nt} P_{t,s,(m+i\leftrightarrow m)}^{Trans};\ \forall s,m,i=1,\ldots,Nm-1 \tag{45}$$

2.12. Electrical DRP

In this work, the load shifting technique, which is recognized as a suitable DRP, is applied to decrease the operation cost of each MCMG. By employing this technique, the selective electrical loads of each MCMG are shifted from peak hours to off-peak hours. As described by (46) and (47), an increase or decrease of the electrical load must be within the predetermined limitations. Eq. (48) states that the consumer is not able to decrease or increase the shiftable load simultaneously. As represented by (49), the amounts of increased and decreased load must be equal at the end of the optimization period. In addition, the modified load pattern after employment of the load shifting technique is determined by (50).

$$0 \leq P_{t,s,m}^{up} \leq P_m^{up,max}.B_{t,s,m}^{up,EDR};\ \forall t,s,m \tag{46}$$

Table 2
The characteristic of CHP units.

Parameter	Value
a_m	0.0435
b_m	56
c_m	12.5
d_m	0.027
e_m	0.6
f_m	0.011
C_m^{su}	20
C_m^{sd}	20
Feasible region coordinates of CHP[P, H]	[2.47, 0], [2.15, 1.8], [0.81, 1.04], [0.98,0]

$$0 \le P_{t,s,m}^{down} \le P_m^{down,max}.B_{t,s,m}^{down,EDR};\ \forall t,s,m \tag{47}$$

$$B_{t,s,m}^{up,EDR} + B_{t,s,m}^{down,EDR} \le 1;\ \forall t,s,m \tag{48}$$

$$\sum_{t=1}^{Nt}\sum_{m=1}^{Nm} P_{t,s,m}^{up} = \sum_{t=1}^{Nt}\sum_{m=1}^{Nm} P_{t,s,m}^{down};\ \forall t,s,m \tag{49}$$

$$P_{t,s,m}^{load,EDR} = P_{t,s,m}^{load} + P_{t,s,m}^{up} - P_{t,s,m}^{down};\ \forall t,s,m \tag{50}$$

2.13. Thermal and water DRPs

As one of the important DRPs, load curtailment strategy is widely employed all over the world. With the implementation of this incentive-based strategy, both consumers and generation company operators attain economic advantages [35]. In this study, the basic load usage pattern of thermal and water demands is modified by employing incentive-based DRPs. Eqs. (51) and (52) describe the incentive-based thermal DRP used in this study. The amount of curtailed load of thermal energy demands is limited by (51). In addition, the modified thermal load after implementation of the thermal DRP is given in (52). Likewise, the constraints related to the incentive-based water DRP are represented in (53) and (54). Participation coefficients D_m^{TDR} and D_m^{WDR} are considered as 10% in this work.

$$0 \le T_{t,s,m}^{curt} \le D_m^{TDR}.T_{t,s,m}^{load};\ \forall t,s,m \tag{51}$$

$$T_{t,s,m}^{load,TDR} = T_{t,s,m}^{load} - T_{t,s,m}^{curt};\ \forall t,s,m \tag{52}$$

$$0 \le W_{t,s,m}^{curt} \le D_m^{WDR}.W_{t,s,m}^{load};\ \forall t,s,m \tag{53}$$

$$W_{t,s,m}^{load,WDR} = W_{t,s,m}^{load} - W_{t,s,m}^{curt};\ \forall t,s,m \tag{54}$$

2.14. Energy/Water balance

The electrical energy balance is formulated in (55). That constraint implies that the total power demand of each MCMG, which is the sum of electrical load after employing DRP and power consumption of water equipment, equals the obtained power from RES, CHP unit, CAES technology plus the power purchased from the electricity market. The power balance associated with the power consumption of water equipment is shown in (56). Furthermore, the thermal energy balance and water balance of each MCMG are represented in (57) and (58), respectively.

$$P_{t,s,m}^{buy} + P_{t,s,m}^{chp} + P_{t,s,m}^{pv} + P_{t,s,m}^{wt} + P_{t,s,m}^{disch} + P_{t,s,m}^{sc} - P_{t,s,m}^{ch} + \sum_{i=1}^{Nm-1} P_{t,s,(m\leftrightarrow m+i)}^{Trans} = P_{t,s,m}^{load,EDR} + P_{t,s,m}^{water};\ \forall t,s,m \tag{55}$$

Table 3
The input data of tri-state CAES technologies.

Parameter	Value
$P_m^{ch,min}/P_m^{disch,min}/P_m^{sc,min}$ (MW)	0
$P_m^{ch,max}/P_m^{disch,max}/P_m^{sc,max}$ (MW)	0.4
$E_m^{CAES,min}$(MWh)	0.24
$E_m^{CAES,max}$(MWh)	1.2
$\eta_m^{CAES,ch}$, $\eta_m^{CAES,disch}$	0.9
HR_m^{disch} (GJ/MWh)	0.4185
HR_m^{sc} (GJ/MWh)	0.8370
VOM^{exp}/VOM^{c} ($/MWh)	0.87

Table 4
The required parameters of water desalination units and water wells.

Parameter	Value
$W_m^{WW,max}$ (m^3)	65
L_m^{WW} (m)	10
$W_m^{des,max}$ (m^3)	160
η_m^{des}	3.0348

Table 5
The parameters associated with thermal and water storage systems.

Parameter	Value
$T_m^{ch,min}/T_m^{disch,min}$ (MWt)	0
$T_m^{ch,max}/T_m^{disch,max}$ (MWt)	0.5
$\eta_m^{TES,ch}$, $\eta_m^{TES,disch}$	0.9
$\eta_m^{TES,sb}$	0.95
$T_m^{TS,min}$ (MWth)	0
$T_m^{TS,max}$ (MWth)	6
$W_m^{ch,min}/W_m^{disch,min}$ (m^3)	0
$W_m^{ch,max}/W_m^{disch,max}$ (m^3)	15
$\eta_m^{WS,ch}$, $\eta_m^{WS,disch}$	0.9
$L_m^{WS,min}$ (m)	0
$L_m^{WS,max}$ (m)	45
A_m^{WS} (m^2)	4
L_m^{G} (m)	4
g (m/s^2)	9.8
ρ (kg/m^3)	1000
η_m^{pump}	0.85

$$P_{t,s,m}^{water} = P_{t,s,m}^{des} + P_{t,s,m}^{ww} + P_{t,s,m}^{WS};\ \forall t,s,m \tag{56}$$

$$T_{t,s,m}^{boiler} + T_{t,s,m}^{chp} + T_{t,s,m}^{disch} - T_{t,s,m}^{ch} = T_{t,s,m}^{load,TDR};\ \forall t,s,m \tag{57}$$

$$W_{t,s,m}^{des} + W_{t,s,m}^{ww} + W_{t,s,m}^{disch} - W_{t,s,m}^{ch} = W_{t,s,m}^{load,WDR};\ \forall t,s,m \tag{58}$$

3. Numerical results and technical analysis

In order to evaluate the functionality and befit of the proposed framework, a networked MCMGs system is considered as illustrated in Fig. 1. The proposed grid-connected system has three water, power, and heat-based networked MCMGs equipped with CHP units, boilers, WTs, PV systems, tri-state CAES systems, TES systems, water desalination units, water storage systems, and water wells with the aim of supply of different energy demands and water demands in the system in a cost-effective manner. The natural gas is purchased from the gas market as the fuel for the tri-state CAES system, CHP unit, and boiler of MCMGs. In addition, each MCMG can purchase power from the electricity market to effectively supply its electrical demands. Data for the forecasted electricity market price is given in [36]. In addition, the price of

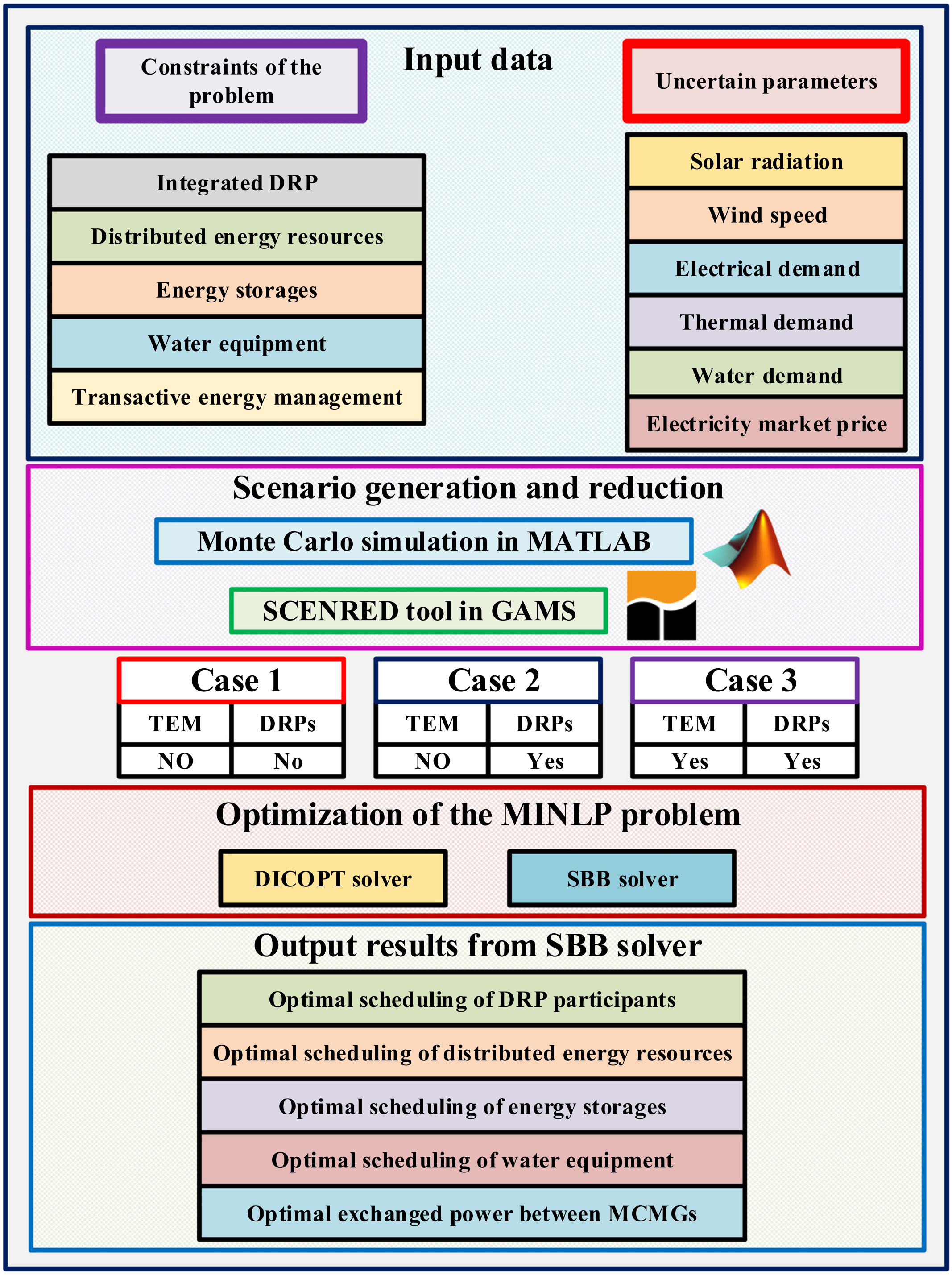

Fig. 5. The schematic diagram of the proposed stochastic model for scheduling problem of the MCMGs.

natural gas is considered as 0.11 $/kg [37]. The characteristics of CHP units are presented in Table 2 [38]. The information for the technical parameters of boilers, WTs, and PV systems are taken from [39]. The input data for CAES systems is presented in Table 3, while the required parameters related to water desalination units and water wells are given in Table 4 [21,40]. In addition, the parameters associated with thermal and water storage systems are listed in Table 5 [41,42]. It should be noted that the assumed data for water demand and energy demands of MCMGs are hypothetical. In this paper, the uncertainties related to the demand for water, electricity, and thermal energy as well as power generation of RES and electricity market price are taken into account by a scenario-based approach. In this regard, one hundred scenarios are generated through employing Monte Carlo simulation, and then to reduce the number of generated scenarios, SCENRED tool in GAMS software is employed. Therefore, the number of generated scenarios is reduced to ten scenarios, and consequently, the computational time of the problem is considerably reduced. In addition, in this paper, the duration of each time interval t is one hour, and the number of time intervals, which is represented by Nt, is 24.

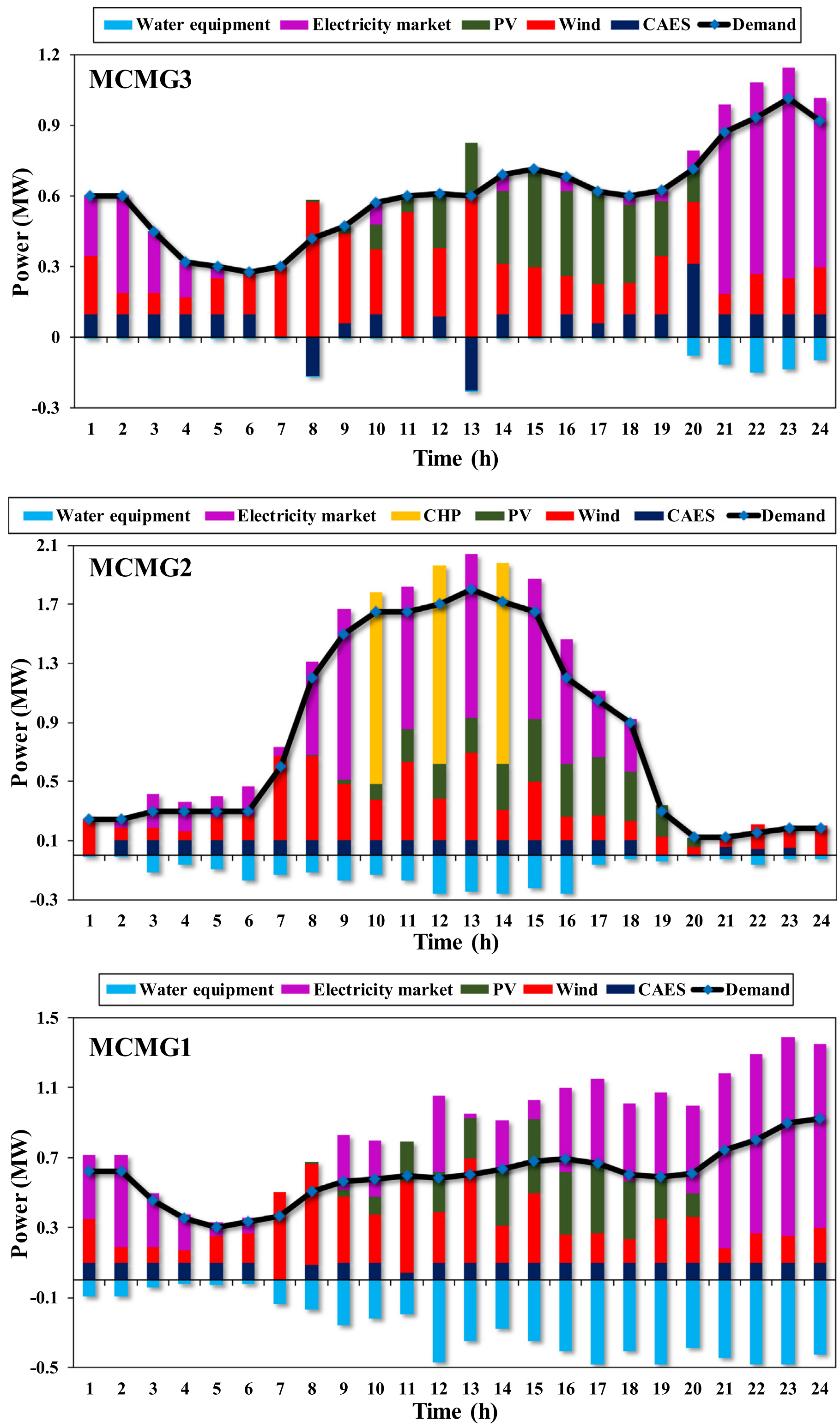

Fig. 6. The electrical energy balance of each MCMG in case 1.

The proposed framework is an MINLP problem because of existing the nonlinear equations associated with CHP units, boilers, and water storage systems. In this study, the SBB and DICOPT solvers are used in GAMS software to solve the proposed MINLP problem. The main reason for employing two solvers for solving the presented optimization problem is to prove the acceptable optimality range of the obtained results. Nevertheless, in this section, the numerical results of the SBB solver are analyzed and discussed due to the fact that all the extracted results are almost the same in the two mentioned solvers. To show how TEM

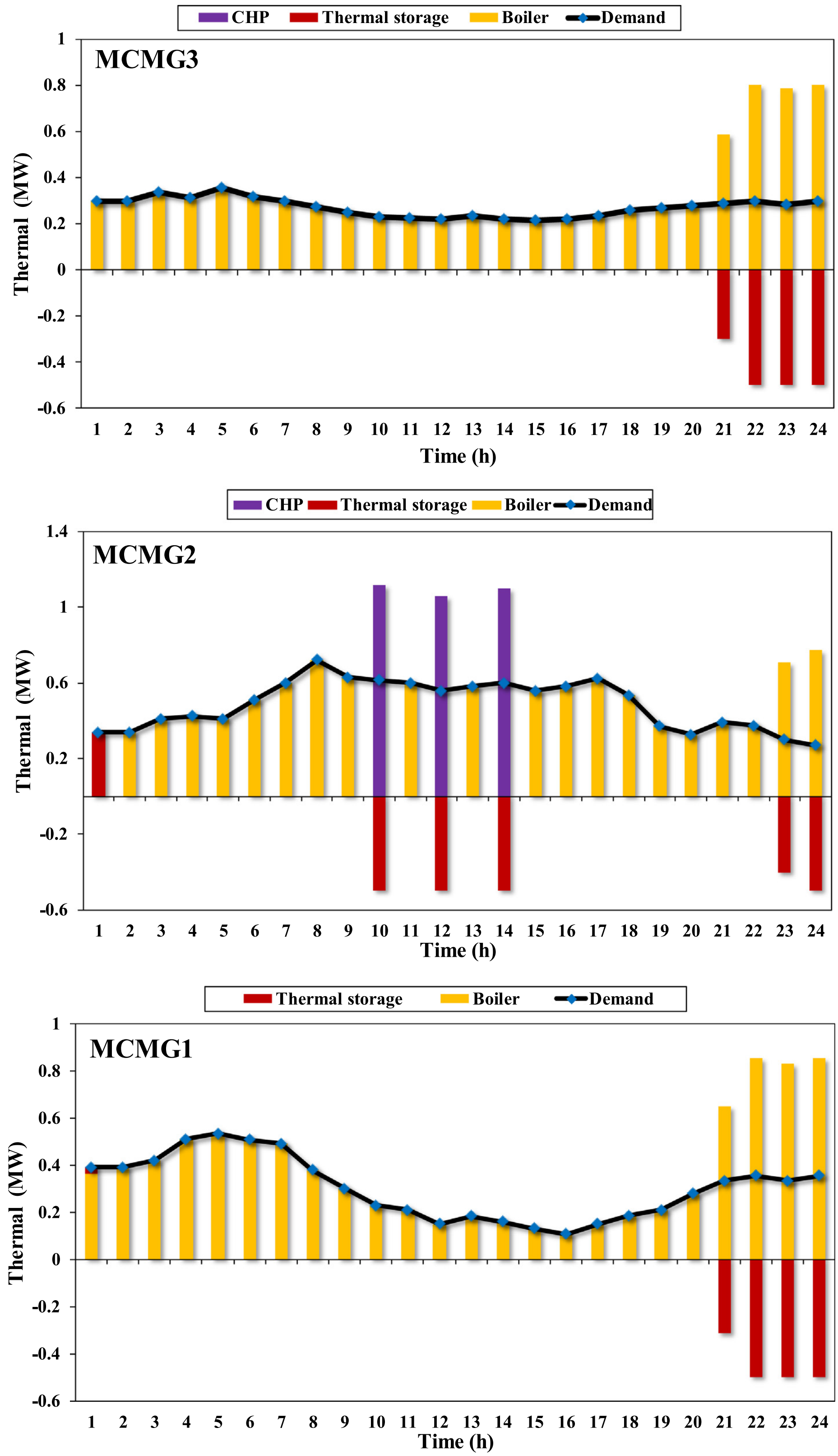

Fig. 7. The thermal energy balance of each MCMG in case 1.

strategy and integrated demand response affect the MCMGs' operation, the simulation results are evaluated in three case studies as follows:

- Case 1: Neglecting TEM strategy and integrated DRP;
- Case 2: Neglecting TEM strategy and considering integrated DRP;
- Case 3: Considering TEM strategy and integrated DRP.

The schematic of the proposed model for the scheduling problem of the MCMGs under multiple uncertainties is shown in Fig. 5.

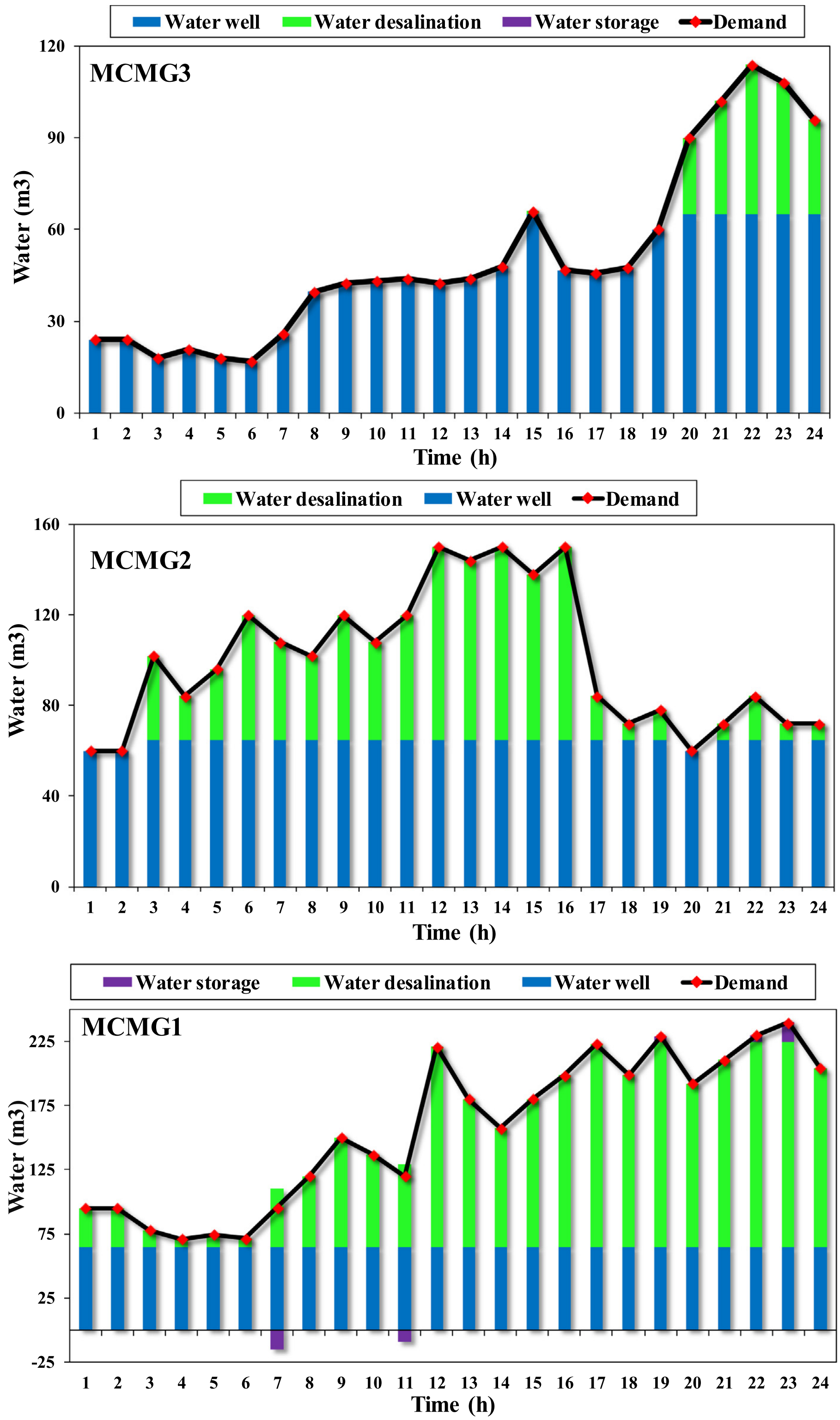

Fig. 8. The water balance of each MCMG in case 1.

The MINLP problem was coded and solved in GAMS software on a PC with a 1.8 GHz Intel Core i5 processor with 4 GB RAM. Also, the execution time for the proposed stochastic MINLP model was 521 ms.

3.1. Case 1

In this case, integrated DRP and TEM strategies have not been considered in the proposed model. The electrical energy balance of each MCMG is indicated in Fig. 6. In this figure, "water equipment" represents the amount of power that the water desalination unit, water well pump, and water storage pump of each MCMG consume. As demonstrated in this figure, MCMG1 and MCMG3 import power from the main grid at midnight and the early morning (t = 1–5), when the output power of PV panels is zero, and also the amount of power by wind turbines is low. Additionally, the amount of power that MCMG1 and MCMG3

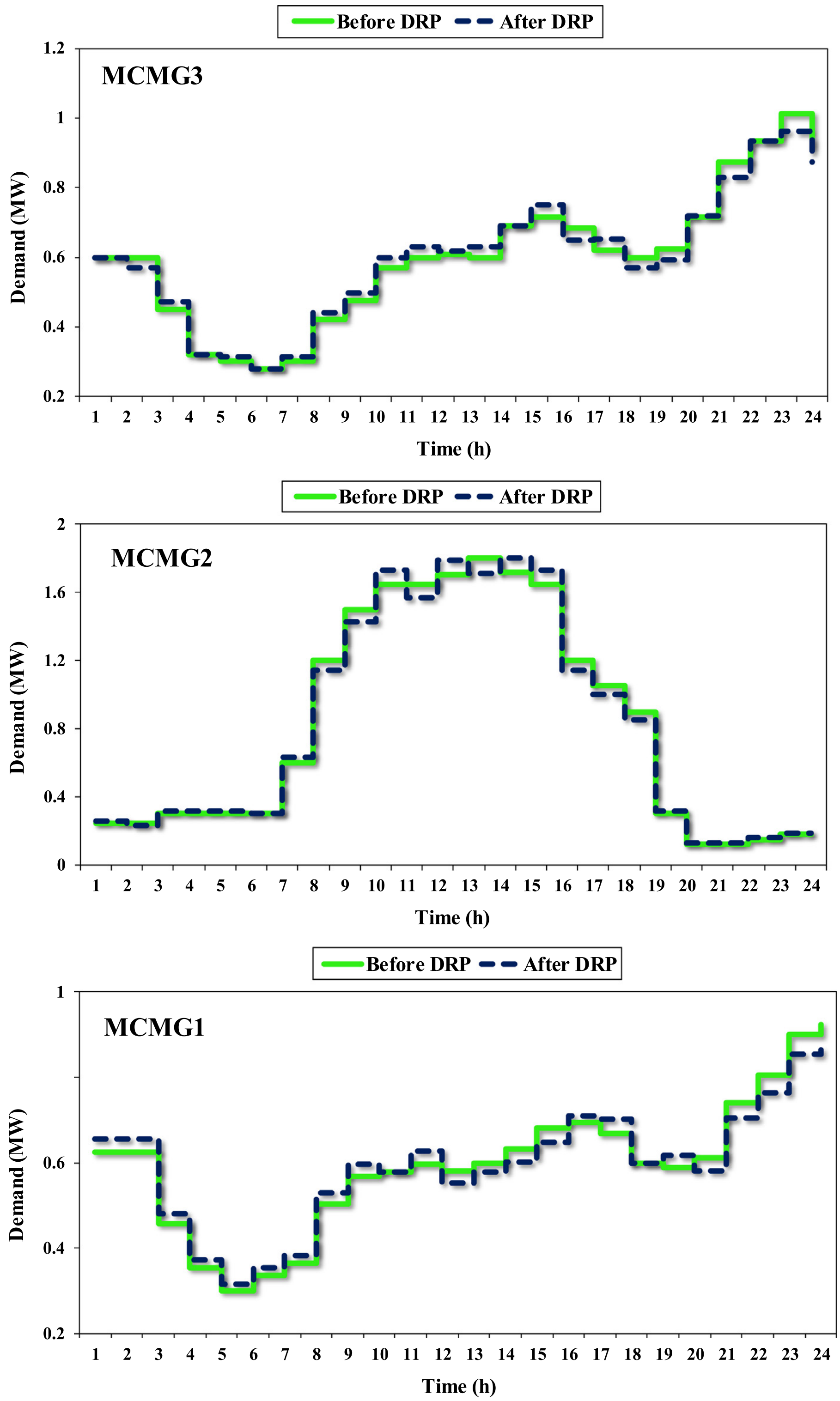

Fig. 9. The power demand profile before and after the employment of load shifting technique in case 2.

purchase from the main grid starts to be increased at t = 20 due to the fact that the electrical demand in these MCMGs is high from t = 21 till the end of the day, and the power outputs of RES are at the lowest level at night. However, the employment of flexible technologies like the CAES system alongside the use of RES to supply electrical load at peak hours is more economical for MCMGs than purchasing expensive electrical energy from the electricity market. Accordingly, at hours 10, 12, and 14, when the electricity price and demand are relatively high in comparison with initial and final hours, MCMG2 does not import power from the main grid and therefore the power demand is supplied by CHP unit, CAES system, and RES.

The thermal energy balance of each MCMG is depicted in Fig. 7. As indicated in this figure, boilers of MCMG1 and MCMG3 are continuously participating in heat generation at all hours. This is because the use of boilers to generate heat is more economical

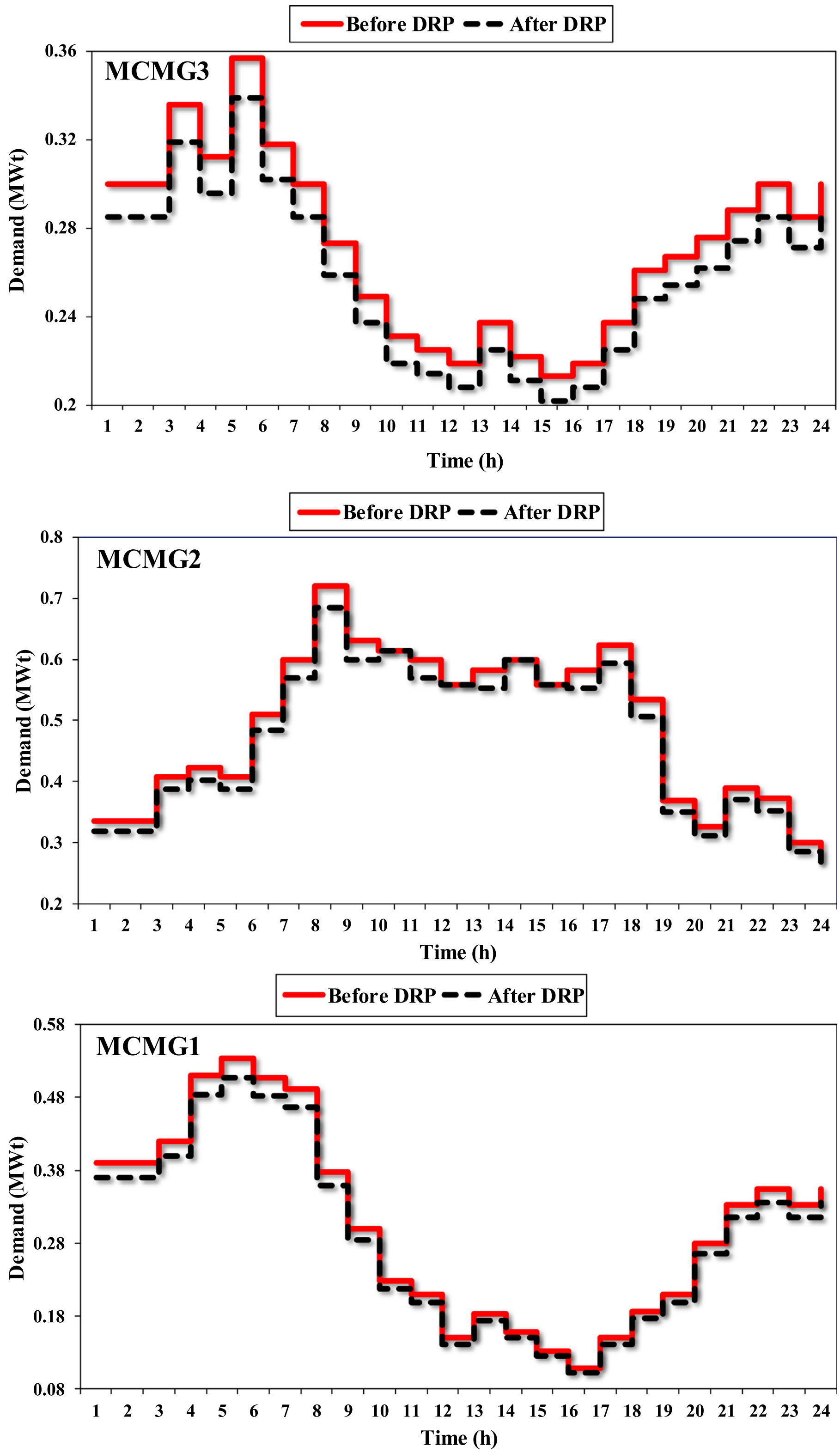

Fig. 10. The impact of performing incentive-based DRP on the thermal load of the MCMGs in case 2.

for the system operator. Additionally, the CHP unit alongside the boiler has participated in thermal energy generation of MCMG2 at hours 10, 12, and 14 due to the feasible operation region characteristic to cover a portion of thermal energy demand. It should be noted that thermal storage systems of MCMGs are charged at final hours due to the fact that the initial and final energy levels of storage systems must be the same. In other words, since a portion of stored heat in the thermal storage systems is wasted at each hour, thermal storage systems are charged at final hours, and therefore, the energy level of thermal storage systems at final hours would be equal to the amount of stored heat at the initial hour.

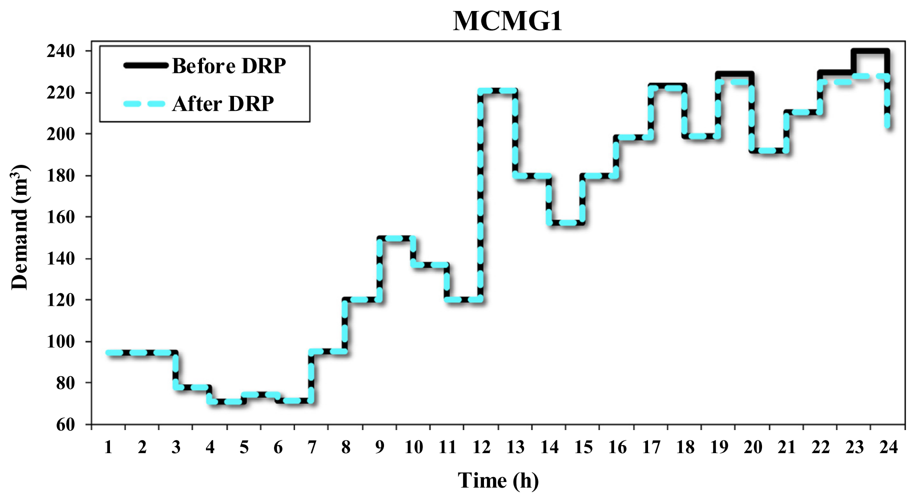

Fig. 11. The water consumption of MCMG1 before and after applying incentive-based water DRP in case 2.

Fig. 8 demonstrates the water balance in each MCMG. According to this figure, water wells have an irrefutable role in supplying the water demand of MCMGs and they are continuously committed at all hours because the employment of these facilities is more economical for MCMGs in comparison with the use of water desalination units. In other words, compared to water desalination units, the power consumption of water well pumps is lower. Nevertheless, when the water well and water storage are not able to meet water demand entirely, the water desalination unit is employed. In addition, the water storage of MCMG1 stores water at hours t = 7 and t = 11, when water demand is low and then it is discharged at hours t = 19, t = 22, and t = 23, when water demand is at a high level.

3.2. Case 2

In this case, integrated DRP is implemented to boost the economic performance of the MCMGs, while TEM strategy is neglected in the proposed model. Fig. 9 exhibits the power demand profile before and after the employment of the load shifting technique. With the use of the load shifting technique as a price-based DRP, flexible power consumers of each MCMG shift a portion of their load in peak-hours to lower price hours in response to the fluctuations of the electricity market price, as shown in Fig. 8. For example, a portion of the electrical load of MCMG1 is shifted down at t = 21–24 because the electricity market price is high at these hours. However, a shift up happens for a portion of the electrical load of MCMG1 at hours t = 1−9, due to the low price of electricity at this period. Also, the flexible power consumers of MCMG 2 and MCMG3 shift down a portion of their load at peak periods such as t = 16 and t = 18, and their load increases at hours t = 3, t = 5, and t = 7 in response to the low price of electricity at these hours. In fact, the effective potential of shiftable loads is used by MCMGs aiming to effectively decrease the total operational cost of the networked system.

The impact of performing incentive-based DRP on the thermal load of the MCMGs is depicted in Fig. 10. As can be observed in this figure, a portion of the thermal load of each MCMG is curtailed at all hours. This is due to the fact that the incentive price provided by the operator of the MCMGs motivates the thermal energy consumers to participate in the incentive-based DRP and curtail a portion of their thermal load. Therefore, the incentive-based DRP participants benefit from the reward associated with load curtailment. In addition, since the heat demand of the MCMGs is decreased after the implementation of price-based DRP, the total heat generation in each MCMG is decreased, which results in a reduction of the total operational cost of the networked MCMGs, and the applicability of the incentive-based thermal DRP is proved. Fig. 11 shows the water consumption of MCMG1 before and after applying incentive-based water DRP. Obviously, it can be concluded that load curtailment happens at hours 19, 22, and 23, when water demand is high, and accordingly, at these peak hours the operational cost of MCMG1 is decreased due to the decrement of power consumption of the water desalination unit.

3.3. Case 3

In this case, not only integrated DRP is implemented but also TEM strategy is performed in the proposed framework. The impact of considering TEM strategy and integrated DRP on the purchase of power from the electricity market is illustrated in Fig. 12. As expected, the amount of power imported from the main grid has been decreased in most hours in comparison with cases 1 and 2. This decrement has roots in the participation of flexible loads of the MCMGs in integrated DRP as well as consideration of TEM strategy. In other words, each MCMG compensates the power shortages by means of electricity generation units of other MCMGs or participation of its flexible loads in DRPs instead of purchasing power from the electricity market. The amounts of exchanged electrical energy between MCMGs using the TEM strategy are presented in Table 6. In fact, the TEM strategy is performed in a way that the operational cost of the MCMGs is effectively decreased.

As mentioned before, the SBB and DICOPT solvers are employed in GAMS software to solve the proposed MINLP problem. In order to prove the acceptable optimality range of the obtained results, the operational cost of the MCMGs in different cases, which has been extracted from running the two mentioned solvers, is presented in Table 7. By taking a look at this table, it can be concluded that all the extracted results are almost the same in the two mentioned solvers and hence the acceptable optimality range of the obtained results is proved. Fig. 13 shows the total amount of power that MCMGs purchase from the electricity market. As shown in this figure, the uncertain behavior of uncertain parameters has a pivotal impact on the amount of electricity that MCMGs import from the main grid. The price of electricity and the power generation of RESs in scenario 9 is less than those of scenario 6, and accordingly, the MCMGs purchase more power

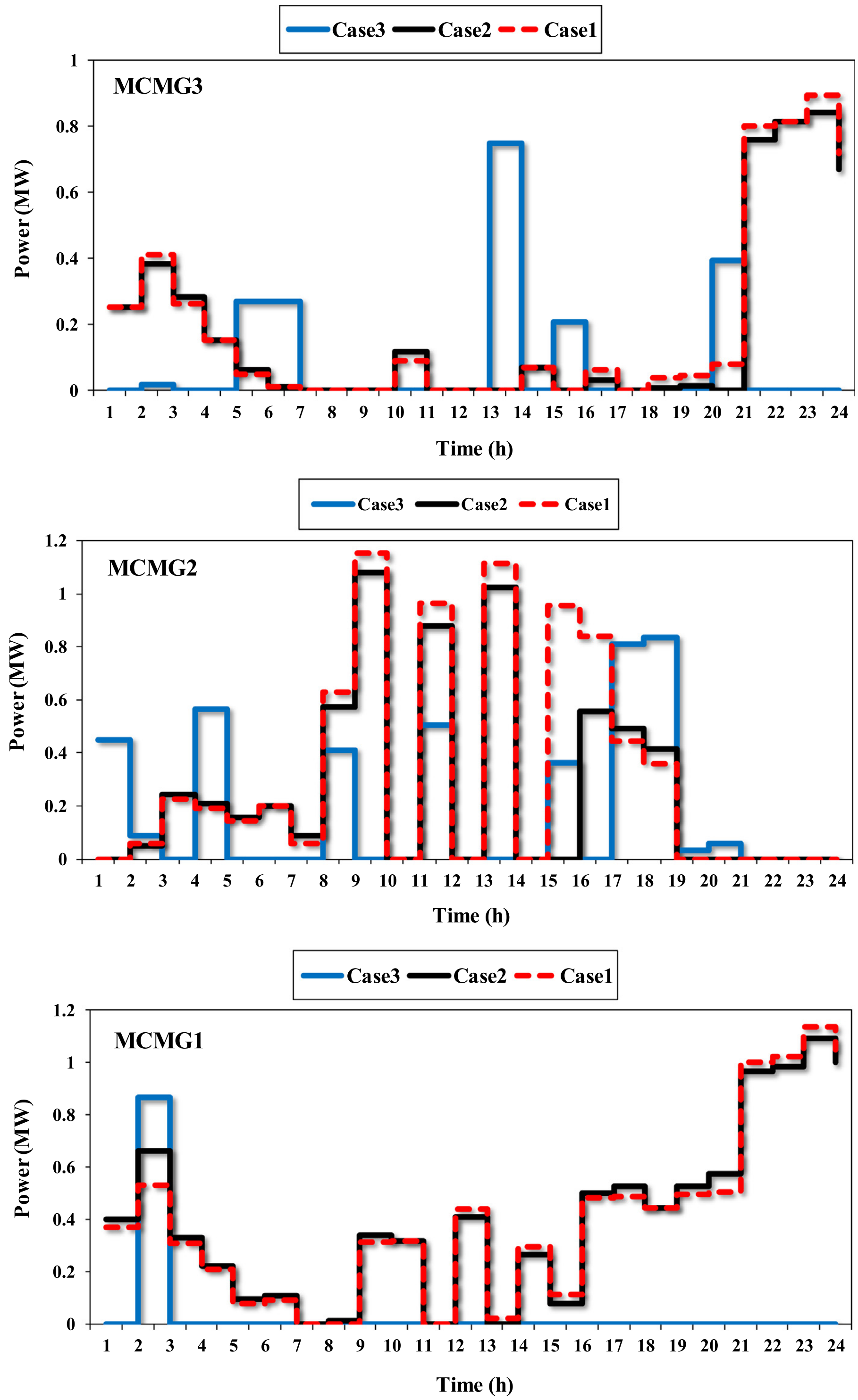

Fig. 12. The impact of TEM strategy and integrated DRP on the purchase of power from the electricity market.

from the electricity market in scenario 9 in comparison with scenario 6. Fig. 14 demonstrates the sensitivity of the operational cost of the MCMGs to the price of natural gas. The obtained results in different prices of natural gas implies that the total operational cost of MCMGs is gradually increased, when the price of natural gas is changed from 0.11 $/kg to 0.27 $/kg.

The contribution of each MCMG in the operational cost of the networked system in different cases is exhibited in Fig. 15. Obviously, in case 3, MCMG2 has the most impact on the total operational cost by 41% and the share of MCMGs 1 and 3 are 36% and 23%, respectively. In cases 1 and 2, the operational cost of MCMG1 is more than that of two other MCMGs. Additionally, MCMG3, which has the lowest operational cost among the networked system, covers 25% and 24% of the total operational cost of the system in cases 1 and 2, respectively.

4. Conclusion

It is undeniable that optimization and development of water and energy sectors in a cooperative manner are challenging issues

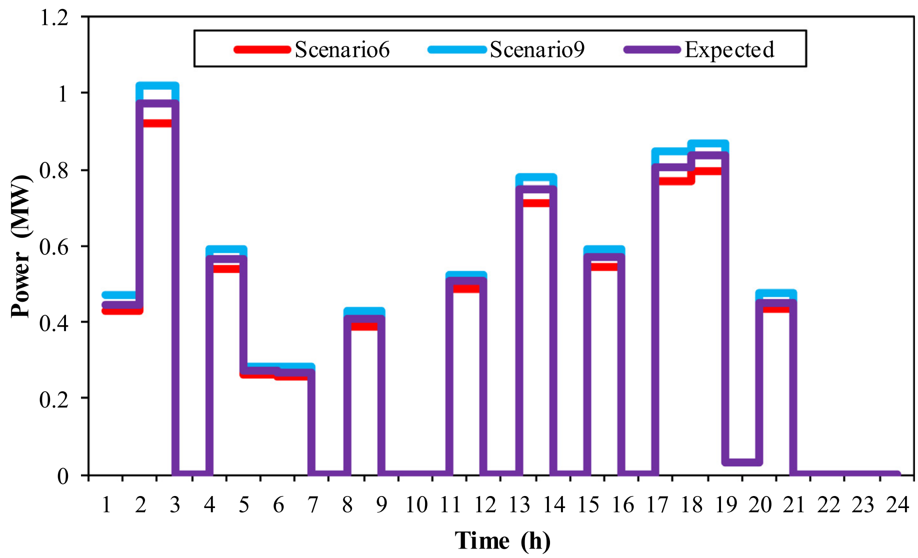

Fig. 13. Total amount of purchased power from the main grid.

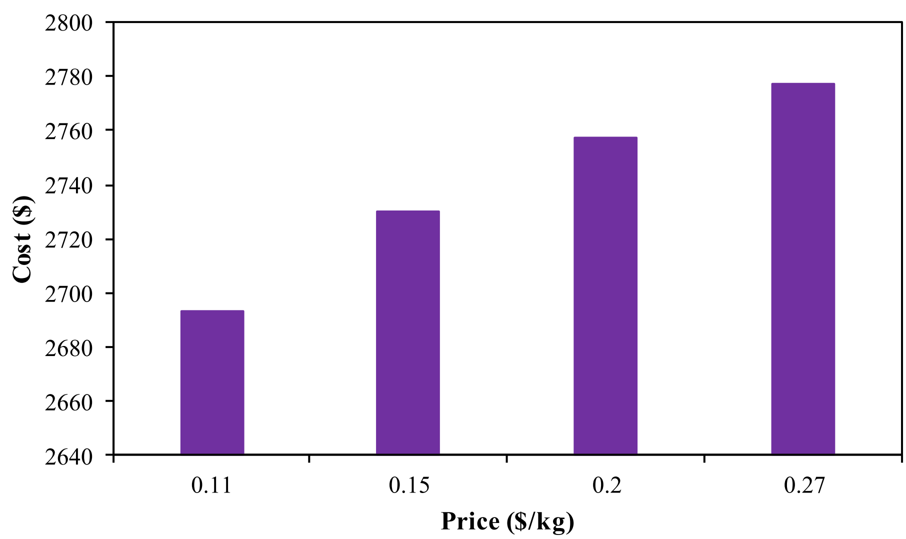

Fig. 14. The impact of the price of natural gas on the operational cost of the MCMGs.

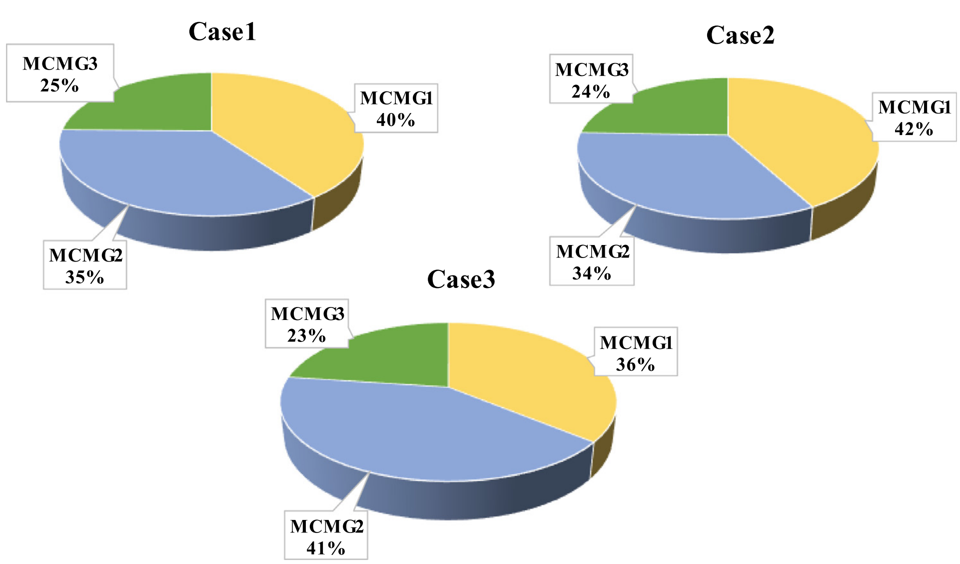

Fig. 15. Contribution of each MCMG in the operational cost of the networked system in different cases.

Table 6
The amounts of exchanged power between MCMGs in case 3.

Time interval	$P^{Trans}_{t,s,1\to 2}$ (MW)	$P^{Trans}_{t,s,1\to 3}$ (MW)	$P^{Trans}_{t,s,2\to 1}$ (MW)	$P^{Trans}_{t,s,2\to 3}$ (MW)	$P^{Trans}_{t,s,3\to 1}$ (MW)	$P^{Trans}_{t,s,3\to 2}$ (MW)
1	−0.293	−0.045	0.293	0.268	0.045	−0.268
2	0.324	0.013	−0.324	0.353	−0.013	−0.353
3	0.311	0.215	−0.311	0.07	−0.215	−0.07
4	−0.4	0.212	0.4	−0.042	−0.212	0.042
5	0.000595	−0.064	−0.000595	−0.144	0.064	0.144
6	0.034	−0.107	−0.034	−0.16	0.107	0.16
7	0.005	0.191	−0.005	−0.551	−0.191	0.551
8	−1.015	1.051	1.015	−1.235	−1.051	1.235
9	−0.071	−0.24	0.071	0.199	0.24	−0.199
10	−0.713	0.365	0.713	−0.245	−0.365	0.245
11	−0.192	0.312	0.192	−0.567	−0.312	0.567
12	−0.935	0.469	0.935	−0.478	−0.469	0.478
13	0.507	−0.5	−0.507	−0.607	0.5	0.607
14	0.868	−1.195	−0.868	−0.491	1.195	0.491
15	0.178	−0.032	−0.178	−0.413	0.032	0.413
16	−0.567	0.087	0.567	−0.021	−0.087	0.021
17	−0.29	−0.197	0.29	0.124	0.197	−0.124
18	−0.351	−0.165	0.351	0.172	0.165	−0.172
19	−0.129	−0.366	0.129	0.381	0.366	−0.381
20	0.063	−0.536	−0.063	0.501	0.536	−0.501
21	0.693	0.119	−0.693	0.728	−0.119	−0.728
22	0.665	0.147	−0.665	0.716	−0.147	−0.716
23	0.686	0.21	−0.686	0.735	−0.21	−0.735
24	0.619	0.056	−0.619	0.707	−0.056	−0.707

Table 7
Comparison of the obtained results under SBB and DICOPT solvers.

	Case1		Case2		Case3	
Solver	SBB	DICOPT	SBB	DICOPT	SBB	DICOPT
Total operational cost ($)	4102.10	4095.73	3951.11	3948.32	2693.76	2692.29

for researchers. This paper proposed a centralized optimal dispatching strategy for a number of networked multi-carrier microgrids (MCMGs) considering multiple uncertainties. The MCMGs, which participate in electricity and gas markets to supply energy and water demands, and energize local generation resources, consist of combined heat and power units, boilers, wind turbines, solar panels, compressed air energy storage systems, thermal storage systems, water desalination units, water storage systems, and water wells. An energy exchanging platform was created for the MCMGs by a central operator through applying transactive energy management (TEM) strategy. Meanwhile, with the implementation of an integrated demand response program (DRP), the demand-side management process for the MCMGs was effectively facilitated. A scenario generation and reduction method was used to incorporate the uncertainties associated with renewable power generation, energy and water demands, and electricity market prices into the optimization model. With the employment of the SBB and DICOPT solvers in GAMS software for solving the proposed mixed-integer nonlinear programming (MINLP) problem, the acceptable optimality range of the obtained results was proved. In addition, a test system consisting of three networked MCMGs was considered to evaluate the validity of the proposed framework. The extracted results indicated that:

- The implementation of integrated DRP based on load shifting technique and load curtailment strategy results in cost saving for the MCMGs.
- The consideration of TEM strategy, which realizes free power sharing for the networked MCMGs, reduces the operational cost of the system considerably.
- Water wells have a pivotal role in supplying the water demand of MCMGs in a cost-effective manner.

The optimal operation of MCMGs in the islanded mode and considering contingencies are left for our future works.

CRediT authorship contribution statement

Yasin Pezhmani: Formal analysis, Writing – original draft, Writing – review & editing, Software. **Morteza Zare Oskouei:** Visualization, Investigation, Data curation. **Navid Rezaei:** Supervision, Project administration, Validation. **Hasan Mehrjerdi:** Methodology, Conceptualization, Resources.

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.

References

[1] S.A. Makkeh, A. Ahmadi, F. Esmaeilion, M.A. Ehyaei, Energy, exergy and exergoeconomic optimization of a cogeneration system integrated with parabolic trough collector-wind turbine with desalination, J. Cleaner Prod. 273 (2020) 123122, http://dx.doi.org/10.1016/j.jclepro.2020.123122.

[2] X. Fan, W. Zhang, W. Chen, B. Chen, Land–water–energy nexus in agricultural management for greenhouse gas mitigation, Appl. Energy 265 (2020) 114796, http://dx.doi.org/10.1016/j.apenergy.2020.114796.

[3] B. Anand, R. Shankar, S. Murugavelh, W. Rivera, K. Midhun Prasad, R. Nagarajan, A review on solar photovoltaic thermal integrated desalination technologies, Renew. Sustain. Energy Rev. 141 (2021) 110787, http://dx.doi.org/10.1016/j.rser.2021.110787.

[4] J. Dai, et al., Water-energy nexus: A review of methods and tools for macro-assessment, Appl. Energy 210 (2018) 393–408, http://dx.doi.org/10.1016/j.apenergy.2017.08.243.

[5] S.A. Mansouri, A. Ahmarinejad, E. Nematbakhsh, M.S. Javadi, A.R. Jordehi, J.P. Catalão, Energy management in microgrids including smart homes: A multi-objective approach, Sustainable Cities Soc. 69 (2021) 102852.

[6] M.Z. Oskouei, M.A. Mirzaei, B. Mohammadi-Ivatloo, M. Shafiee, M. Marzband, A. Anvari-Moghaddam, A hybrid robust-stochastic approach to evaluate the profit of a multi-energy retailer in tri-layer energy markets, Energy 214 (2021) 118948.

[7] A. Mansour-Saatloo, et al., Robust decentralized optimization of multi-microgrids integrated with power-to-x technologies, Appl. Energy 304 (2021) 117635.

[8] M.Z. Oskouei, B. Mohammadi-Ivatloo, M. Abapour, M. Shafiee, A. Anvari-Moghaddam, Techno-economic and environmental assessment of the coordinated operation of regional grid-connected energy hubs considering high penetration of wind power, J. Cleaner Prod. 280 (2021) 124275.

[9] S.A. Mansouri, M.S. Javadi, A. Ahmarinejad, E. Nematbakhsh, A. Zare, J.P. Catalão, A coordinated energy management framework for industrial, residential and commercial energy hubs considering demand response programs, Sustain. Energy Technol. Assess. 47 (2021) 101376.

[10] M.Z. Oskouei, B. Mohammadi-ivatloo, M. Abapour, M. Shafiee, A. Anvari-Moghaddam, Strategic operation of a virtual energy hub with the provision of advanced ancillary services in industrial parks, IEEE Trans. Sustain. Energy (2021) 1, http://dx.doi.org/10.1109/TSTE.2021.3079256.

[11] F. Jabari, H. Jabari, B. Mohammadi-ivatloo, J. Ghafouri, Optimal short-term coordination of water-heat-power nexus incorporating plug-in electric vehicles and real-time demand response programs, Energy 174 (2019) 708–723, http://dx.doi.org/10.1016/j.energy.2019.02.132.

[12] M. Mostafavi Sani, A. Noorpoor, M. Shafie-Pour Motlagh, Optimal model development of energy hub to supply water, heating and electrical demands of a cement factory, Energy 177 (2019) 574–592, http://dx.doi.org/10.1016/j.energy.2019.03.043.

[13] H. Mehrjerdi, Modeling and optimization of an island water-energy nexus powered by a hybrid solar-wind renewable system, Energy 197 (2020) 117217, http://dx.doi.org/10.1016/j.energy.2020.117217.

[14] M.J. Salehpour, A.M. Alishavandi, M.J. Hossain, S.M. Hosseini Rostami, J. Wang, X. Yu, A stochastic decentralized model for the privately interactive operation of a multi-carrier energy system, Sustainable Cities Soc. 64 (2021) 102551, http://dx.doi.org/10.1016/j.scs.2020.102551.

[15] F. Moazeni, J. Khazaei, A. Asrari, Step towards energy-water smart microgrids; buildings thermal energy and water demand management embedded in economic dispatch, IEEE Trans. Smart Grid (2021).

[16] F. Jalilian, M.A. Mirzaei, K. Zare, B. Mohammadi-Ivatloo, M. Marzband, A. Anvari-Moghaddam, Multi-energy microgrids: An optimal despatch model for water-energy nexus, Sustainable Cities Soc. 77 (2022) 103573.

[17] M.A. Mohamed, A. Almalaq, E.M. Awwad, M.A. El-Meligy, M. Sharaf, Z.M. Ali, An effective energy management approach within a smart island considering water-energy hub, IEEE Trans. Ind. Appl. (2020) 1, http://dx.doi.org/10.1109/TIA.2020.3000704.

[18] F. Moazeni, J. Khazaei, Optimal operation of water-energy microgrids; a mixed integer linear programming formulation, J. Cleaner Prod. 275 (2020) 122776, http://dx.doi.org/10.1016/j.jclepro.2020.122776.

[19] F. Moazeni, J. Khazaei, J.P. Pera Mendes, Maximizing energy efficiency of islanded micro water-energy nexus using co-optimization of water demand and energy consumption, Appl. Energy 266 (2020) 114863, http://dx.doi.org/10.1016/j.apenergy.2020.114863.

[20] F. Moazeni, J. Khazaei, Dynamic economic dispatch of islanded water-energy microgrids with smart building thermal energy management system, Appl. Energy 276 (2020) 115422, http://dx.doi.org/10.1016/j.apenergy.2020.115422.

[21] M.J. Vahid Pakdel, F. Sohrabi, B. Mohammadi-Ivatloo, Multi-objective optimization of energy and water management in networked hubs considering transactive energy, J. Cleaner Prod. 266 (2020) 121936, http://dx.doi.org/10.1016/j.jclepro.2020.121936.

[22] B. Poursmaeil, P. Hosseinpour Najmi, S. Najafi Ravadanegh, Interconnected-energy hubs robust energy management and scheduling in the presence of electric vehicles considering uncertainties, J. Cleaner Prod. 316 (2021) 128167, http://dx.doi.org/10.1016/j.jclepro.2021.128167.

[23] X. Luo, Y. Liu, P. Feng, Y. Gao, Z. Guo, Optimization of a solar-based integrated energy system considering interaction between generation, network, and demand side, Appl. Energy 294 (2021) 116931, http://dx.doi.org/10.1016/j.apenergy.2021.116931.

[24] A. Rezaee Jordehi, Economic dispatch in grid-connected and heat network-connected CHP microgrids with storage systems and responsive loads considering reliability and uncertainties, Sustainable Cities Soc. 73 (2021) 103101, http://dx.doi.org/10.1016/j.scs.2021.103101.

[25] J. Najafi, A. Peiravi, A. Anvari-Moghaddam, J.M. Guerrero, An efficient interactive framework for improving resilience of power-water distribution systems with multiple privately-owned microgrids, Int. J. Electr. Power Energy Syst. 116 (2020) 105550, http://dx.doi.org/10.1016/j.ijepes.2019.105550.

[26] F. Moazeni, J. Khazaei, Interactive nonlinear multiobjective optimal design of water distribution systems using Pareto navigator technique, Sustainable Cities Soc. 73 (2021) 103110, http://dx.doi.org/10.1016/j.scs.2021.103110.

[27] L. Edmonds, M. Derby, M. Hill, H. Wu, Coordinated operation of water and electricity distribution networks with variable renewable energy and distribution locational marginal pricing, Renew. Energy 177 (2021) 1438–1450, http://dx.doi.org/10.1016/j.renene.2021.05.168.

[28] F. Moazeni, J. Khazaei, Optimal energy management of water-energy networks via optimal placement of pumps-as-turbines and demand response through water storage tanks, Appl. Energy 283 (2021) 116335, http://dx.doi.org/10.1016/j.apenergy.2020.116335.

[29] Y. Pezhmani, M.A. Mirzaei, K. Zare, B. Mohammadi-Ivatloo, Robust self-scheduling of a virtual multi-energy plant in thermal and electricity markets in the presence of multi-energy flexible technologies, Int. J. Energy Res. (2021).

[30] N. Rezaei, Y. Pezhmani, A. Khazali, Economic-environmental risk-averse optimal heat and power energy management of a grid-connected multi microgrid system considering demand response and bidding strategy, Energy 240 (2022) 122844.

[31] B. Mohammadi-Ivatloo, M. Moradi-Dalvand, A. Rabiee, Combined heat and power economic dispatch problem solution using particle swarm optimization with time varying acceleration coefficients, Electr. Power Syst. Res. 95 (2013) 9–18.

[32] S. Hadayeghparast, A.S. Farsangi, H. Shayanfar, Day-ahead stochastic multi-objective economic/emission operational scheduling of a large scale virtual power plant, Energy 172 (2019) 630–646.

[33] S. Ghaemi, J. Salehi, F. Hamzeh Aghdam, Risk aversion energy management in the networked microgrids with presence of renewable generation using decentralised optimisation approach, IET Renew. Power Gener. 13 (7) (2019) 1050–1061.

[34] M.S. Javadi, A.E. Nezhad, A.R. Jordehi, M. Gough, S.F. Santos, J.P. Catalão, Transactive energy framework in multi-carrier energy hubs: A fully decentralized model, Energy 238 (2022) 121717.

[35] N. Rezaei, Y. Pezhmani, Optimal islanding operation of hydrogen integrated multi-microgrids considering uncertainty and unexpected outages, J. Energy Storage 49 (2022) 104142, http://dx.doi.org/10.1016/j.est.2022.104142.

[36] M. Jadidbonab, E. Babaei, B. Mohammadi-ivatloo, Cvar-constrained scheduling strategy for smart multi carrier energy hub considering demand response and compressed air energy storage, Energy 174 (2019) 1238–1250, http://dx.doi.org/10.1016/j.energy.2019.02.048.

[37] M. Yan, N. Zhang, X. Ai, M. Shahidehpour, C. Kang, J. Wen, Robust two-stage regional-district scheduling of multi-carrier energy systems with a large penetration of wind power, IEEE Trans. Sustain. Energy 10 (3) (2018) 1227–1239.

[38] M. Nazari-Heris, S. Abapour, B. Mohammadi-Ivatloo, Optimal economic dispatch of FC-CHP based heat and power micro-grids, Appl. Therm. Eng. 114 (2017) 756–769, http://dx.doi.org/10.1016/j.applthermaleng.2016.12.016.

[39] S. Hadayeghparast, A. SoltaniNejad Farsangi, H. Shayanfar, Day-ahead stochastic multi-objective economic/emission operational scheduling of a large scale virtual power plant, Energy 172 (2019) 630–646, http://dx.doi.org/10.1016/j.energy.2019.01.143.

[40] S. Nojavan, A. Najafi-Ghalelou, M. Majidi, K. Zare, Optimal bidding and offering strategies of merchant compressed air energy storage in deregulated electricity market using robust optimization approach, Energy 142 (2018) 250–257.

[41] A. Mansour-Saatloo, M.A. Mirzaei, B. Mohammadi-Ivatloo, K. Zare, A risk-averse hybrid approach for optimal participation of power-to-hydrogen technology-based multi-energy microgrid in multi-energy markets, Sustainable Cities Soc. 63 (2020) 102421.

[42] M.J.V. Pakdel, F. Sohrabi, B. Mohammadi-Ivatloo, Multi-objective optimization of energy and water management in networked hubs considering transactive energy, J. Cleaner Prod. 266 (2020) 121936.