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Two-Stage Stochastic-based Scheduling of Multi-Energy Microgrids with Electric and Hydrogen Vehicles Charging Stations, considering transactions through pool market and bilateral contracts

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Abstract

In order to mitigate greenhouse gas emissions and improve energy efficiency, sustainable energy systems such as multi-energy microgrids (MEMGs) with the high penetration of renewable energy resources (RES) and satisfying different energy needs of consumers have received significant attention in recent years. MEMGs, by relying on renewable resources and energy storage systems along with energy conversion systems, play an essential role in sustainability of energy supply. However, renewable energies are uncertain due to the intermittent nature of solar and wind energy sources. Thus, optimal operation of the MEMGs with the consideration of the uncertainties of RES is necessary to achieve sustainability. In this paper, risk constrained scheduling of a MEMG is carried out with the presence of the PV, wind, biomass, electric vehicles (EVs) and hydrogen vehicles (HVs) charging stations, combined heat and power (CHP), boiler, hydrogen electrolyzer (HE), cryptocurrency miners (CMs), electrical, thermal and hydrogen storage systems, responsive demands. From the trading and business model side, the proposed MEMG optimized operation relies on bilateral contracts between producers and consumers and pool electricity markets. A two-stage stochastic programming method is used for considering the uncertainties of electrical, thermal and hydrogen demands, EV and HV charging stations load, CM load, PV and wind power, and the price of electricity purchased from the pool market. The proposed mixed integer linear programming (MILP) model is solved using the CPLEX solver in GAMS which guarantees to achieve a globally optimal solution. The results show that due to the certain prices of bilateral contracts, the possibility of transaction by bilateral contracts decreases the risk metric CVaR by 50.42%. The simulation results demonstrate that risk of high operation costs while considering flexibility sources, such as storages and demand response (DR) programs, is decreased by 5.45% and 4.6%, respectively. As far as operation costs are concerned, results reveal that using renewable resources decreases operation costs by 34.47%. Moreover, the operation cost is reduced by 5.94% and 4.57% in the presence of storage units and DR programs, respectively. In the same way, storages and DR programs decrease cost of purchased electricity by 13.47% and 14.46%, respectively.

Keywords: Two-stage stochastic model; hydrogen; Microgrids; Responsive demands; EV charging stations; hydrogen charging stations; Crypto miner; Risk.

Nomenclature

Acronyms

BPP	Biomass power plant
CHP	Combined heat and power
CM	Cryptocurrency miner
CVaR	Conditional value-at-risk
DR	Demand response
EV	Electric vehicle
HE	Hydrogen electrolyzer
EOC	Expected operation cost
HV	Hydrogen vehicle
MEMG	Multi-energy Microgrid
MG	Microgrid
MILP	Mixed-integer linear programming
MINLP	Mixed-integer nonlinear programming
P2G	Power-to-gas
PV	Photovoltaic
RD/U	Ramp-down/up
RES	Renewable energy resources
SS	Storage system
VaR	Value-at-risk

Indices

$boil$	Boiler
CHP	CHP
cr	Bilateral contract
$pool$	Pool market
$spill$	Spillage
ch	Charging mode of storage system
cm	Cryptocurrency miner
dch	Discharging mode of storage system
$evcs$	Electric vehicle charging station
$evcs$	Hydrogen vehicle charging station
E	Electric
H	Hydrogen
ini	Initial value
max	Maximum value
min	Minimum value
sh	Shed power
t	Time
s	Scenario

1. Introduction

With growing interest in decarbonizing energy systems and efforts to reduce carbon emissions, multi-energy Microgrids (MEMGs) have emerged as a valuable framework for integration of RES, energy conversion systems and also energy storage systems [1]. MEMGs are grid-connected or isolated energy networks that can provide a variety of energy carriers for consumers' needs by relying on non-renewable and RES, converters, energy storage systems and responsive demands. In other words, a MEMG is a developed structure of microgrid that can supply power, heat and hydrogen demands simultaneously. MEMGs can improve efficiency and reliability of power and energy systems by providing diverse energy carriers and relying on green energy sources. Therefore, the optimal operation of MEMGs with the presence of renewable energy sources is an efficient approach to decrease the cost of energy generation for supplying demands [2, 3].

RES, such as PV, wind and biomass [4, 5], are sustainable and clean resources that increase the reliability of the MEMGs, while reducing the operation cost. In modern energy systems, such as MEMGs, due to the high penetration of renewables, energy storage systems can reduce operation cost and load shedding and enhance power quality [6, 7]. Moreover, storage systems are employed in MEMGs to mitigate the variations of RES and improve the MEMGs efficiency [8-11], thus playing a remarkable role in optimal operation of MEMGs. Another approach to increase the MEMGs efficiency is the use of DR programs for the adaptation of the consumers load pattern to further balance generation and demand [12, 13] and increase flexibility [14].

The required reduction of greenhouse gas emissions posed by international targets and the consequent reduction of fossil fuels consumption has led to an increase in the use of zero emission vehicles such as electric and hydrogen vehicles. As a result, the energy system is also connected to electrical and green hydrogen mobility demand and relevant the electric vehicle charging stations (EVCSs) and hydrogen vehicle charging stations (HVCSs) will become significantly important in energy networks. Therefore, their optimal operation in MEMGs is of remarkable significance.

At the same time, using green hydrogen in transportation and energy sectors is emerging due to the positive environmental impacts and its storage potential [13, 15]. Because of the growing need for hydrogen in different sectors, the optimization problems of MEMGs with the presence of hydrogen based technologies such as electricity to hydrogen conversion systems and hydrogen storage systems have recently received a lot of attention [16].

Some studies have been conducted in the literature on the operation of MEMGs [17]. In Ref. [18], the optimal operation of an isolated MEMG with PV and wind sources, electrical and hydrogen storage systems, electrical and hydrogen demands, and electrical DR has been devised. The uncertainty of wind and PV energies and electrical demand has been considered using scenario-based stochastic model, and the operation problem of the MEMG with the consideration of tie lines and DGs outages has been formulated and solved. However, operation problem of the MEMG has been done without considering risk criteria. The results show high efficiency of MEMG structure in supplying power and hydrogen demand. In Ref. [19], scheduling of a grid-connected MEMG based on CCHP and P2G with wind energy, electrical and thermal storage systems, electrical, thermal and cooling demands, and, electrical and thermal DR has been performed. Uncertainties of wind energy as well as of electrical and thermal DR programs have been considered by using robust optimization, while uncertainty of electricity prices purchased from the network has not been taken into account. The results show that DR programs can reduce the operation cost.

In Ref. [20], scheduling of a grid-connected MEMG including electrical, heating and hydrogen demands, hydrogen storage system and plug-in electric vehicles has been conducted. In this case, the risk-based stochastic model, based on CVaR, has been utilized to represent the uncertainties of demands, PV production, and the price of electricity purchased from grid. Electricity has been purchased from pool market, while the role of bilateral contracts as a certain source of energy supply during operation of the MEMG has been ignored. The results of the integration of hydrogen storage and electric vehicles in the system indicate their impact in the reduction of operation cost. In Ref. [21], operation of a grid-connected MEMG with the PV source, hydrogen storage system, electrical, thermal, cooling and hydrogen demands has been presented. The uncertainties of PV production and electrical and thermal demands have been considered using a risk-based hybrid method. The simulation results indicate the effectiveness of suggested model. In Refs. [22-24], Information gap decision theory (IGDT) method has been applied to address the uncertainties of renewable energy sources, demands and electricity purchase price from grid while scheduling the MEMG. The results indicate the effectiveness of the employed method in providing a robust supply configuration under risk-based conditions.

In Ref. [25], the optimal scheduling of an isolated MEMG with PV and wind generations, hydrogen storage system, electrical and hydrogen demands and DR programs has been done. The uncertainties of wind and PV and electrical and hydrogen demands have been considered using interval optimization model. The analyses depict the efficiency of the presented method to handle uncertainties. However, the effect of risk on presented method and operation of MEMG has been neglected. In Ref. [26], optimal scheduling of a grid-connected transactive MEMG with PV and wind generations and electrical storage system has been carried out. In the studied model, uncertainties of PV and wind, and electrical demand have been considered using a stochastic method. Besides, uncertainty on electricity purchase price from market has been considered using a robust optimization model. In this study, storage losses have not been considered as well as costs associated with load shedding. The results of the system analysis show that DR programs can reduce the operation cost.

In Ref. [27], optimal scheduling of a MEMG with PV and wind resources, fuel cells, battery electric vehicle (BEV), electrical and hydrogen storage systems, electrical, thermal and cooling demands has been solved. The uncertainties of wind and PV generations, market prices and electric demand have been considered. The results demonstrate that the proposed model can decrease the operation cost and emissions. In Ref. [28], optimal operation of a grid-connected MEMG with PV and wind generations, Fuel Cell (FC), electrolyzer, microturbine, electrical and hydrogen storage systems, electrical demand and electrical DR has been devised. The uncertainties of renewable generations, market prices and electrical demand have been considered using a scenario-based stochastic model. The results show that employing DR programs and hydrogen storage can reduce operation.

In Ref. [29], the optimal operation of a grid-connected MEMG including PV, wind turbine, CHP, boiler, micro turbine and etc. has been done with the aim of reducing cost and emissions. The uncertainties of wind and PV generations, electricity price, thermal and electrical demands have been considered using a multi-objective stochastic model, although, the risk metric and bilateral contracts have not been considered. In Ref. [30], the optimal operation of an isolated MEMG with P2G storage, wind energy, thermal, electrical and gas loads from the risk-averse perspective has been done. In the problem formulation, electrical and gas DR programs and uncertainty of wind power generation have been considered. The uncertainty on demands has however been neglected. The main features of the researches performed in the literature on operation of MEMGs are summarized in Table 1.

Table 1. The main features of researches conducted on operation of MEMGs in literature

Ref.	Model	Uncertainty method	Mode		Multi-energy				Uncertainty						Risk-awareness	Risk metric	Bilateral contracts and pool market	Contingency	Storage systems			Demand response		
									Price	Generators		Demands												
			Islanded	Networked	Electrical	Thermal	Hydrogen	Cooling		PV	Wind	Electrical	Thermal	Hydrogen					Electrical	Thermal	Hydrogen	Electrical	Thermal	Hydrogen
[31]	MILP	Stochastic	×	✓	✓	×	×	×	✓	×	✓	✓	×	×	✓	CVaR	Pool market	×	✓	×	×	✓	×	×
[18]	MILP	Stochastic	✓	×	✓	×	✓	×	×	✓	✓	✓	×	×	×	×	×	✓	✓	×	✓	✓	×	×
[32]	MIQP	Two-stage Stochastic	×	✓	✓	×	×	×	✓	✓	✓	✓	×	×	✓	×	Pool market	×	✓	×	×	×	×	×
[19]	MINLP	Two-stage Robust	×	✓	✓	✓	×	✓	×	×	✓	×	×	×	×	×	×	×	✓	✓	×	✓	✓	×
[20]	MILP	stochastic	×	✓	✓	✓	✓	×	✓	✓	×	✓	✓	✓	✓	CVaR	Pool market	×	×	×	✓	×	×	×
[21]	MILP	Hybrid (stochastic/IGDT)	×	✓	✓	✓	✓	✓	×	✓	×	✓	✓	×	✓	×	Pool market	×	×	×	✓	×	×	×
[24]	MILP	IGDT	×	✓	✓	✓	×	×	✓	✓	✓	✓	✓	×	✓	×	Pool market	×	✓	✓	×	✓	✓	×
[25]	MILP	Interval optimization	✓	×	✓	×	✓	×	×	✓	✓	✓	×	✓	×	×	×	×	×	×	✓	✓	×	✓
[23]	MINLP	IGDT	×	✓	✓	×	×	×	✓	×	×	✓	×	×	✓	×	Pool market	×	✓	×	×	✓	×	×
[33]	MILP	Two-stage stochastic	×	✓	✓	×	✓	×	✓	×	✓	✓	×	✓	✓	CVaR	Pool market	×	✓	×	✓	✓	×	✓
[34]	MILP	Stochastic	×	✓	✓	×	×	×	✓	✓	✓	✓	×	×	✓	×	Pool market	×	✓	×	×	×	×	×
[22]	MILP	IGDT	×	✓	✓	×	×	×	✓	✓	✓	✓	×	×	✓	×	Pool market	×	✓	×	×	✓	×	×
[26]	MILP	Hybrid (stochastic/robust)	×	✓	✓	×	×	×	✓	✓	✓	✓	×	×	✓	×	Pool market	×	✓	×	×	✓	×	×
[35]	MILP	Stochastic/ Point Estimate Method (PEM)	×	✓	✓	×	×	×	✓	✓	✓	✓	×	×	×	×	Pool market	×	✓	×	×	✓	×	×
[27]	MILP	Hybrid (stochastic/robust)	×	✓	✓	✓	×	✓	✓	✓	✓	✓	×	×	✓	×	Pool market	×	✓	×	✓	✓	✓	×
[28]	MILP	Stochastic	×	✓	✓	×	×	×	✓	✓	✓	✓	×	×	✓	×	Pool market	×	✓	×	✓	✓	×	×
[29]	MILP	Stochastic	×	✓	✓	✓	×	×	✓	✓	✓	✓	×	×	×	×	Pool market	×	✓	✓	×	✓	×	×
This research	MILP	Two-stage stochastic	×	✓	✓	✓	✓	×	✓	✓	✓	✓	✓	✓	✓	CVaR	Bilateral contracts and Pool market	✓	✓	✓	✓	✓	✓	✓

By reviewing the literature and to the best of our knowledge, no research work has considered bilateral contracts in addition to pool market and PV, wind and biomass as renewable energy sources in the optimal operation problem formulation of MEMGs. When using renewable generation and purchasing electricity from the grid with uncertain prices, the energy system faces large uncertainty, thus bringing the risk of uncontrollability and unreliability of the system's operation. As a consequence, this may initiate unplanned, non-optimal and inefficient operational decisions and can expose the system to a risk of load shedding. In order to relieve these risks, in this paper, bilateral contracts are considered in the problem formulation as further source of certainty of supply. Moreover, when the operator faces uncertain demands, generations and energy prices during the operation, the presence of bilateral contracts as a certain source of supply can improve the flexibility of the energy system in achieving the optimal scheduling, thus relieving load shedding.

The decision variables related to the purchase of electricity from bilateral contracts are considered certain and are here-and-now decisions which are made to be made prior to the realizing the stochastic process and do not depend on the stochastic processes. While those related to demands, pool market prices and renewable energies, are affected by uncertainty and are to be considered wait-and-see decision variables which are made in real-time after uncertainties occur. Thus, the optimal scheduling problem of MEMGs must be considered as a two-stage stochastic model [36].

In this study, the risk constrained scheduling of a MEMG is carried out with the presence of PV, wind and biomass generation, EV and HV charging stations, and CMs loads, electrical storage system (ESS), hydrogen storage system (HSS), thermal storage system (TSS), responsive demands including electrical demand response (EDR), hydrogen demand response (HDR) and thermal demand response (TDR), bilateral contracts and pool market purchases.

In the presented model, the MEMG can purchase electricity from bilateral contracts and pool market. The uncertainties associated to the latter as well as to electric, thermal and hydrogen demands, EVCS and HVCS loads, CM load, PV and wind power, the price of electricity purchased from pool market are handled using two-stage stochastic method. The proposed MILP model is solved using the CPLEX solver in the GAMS which guarantees to achieve the global solution.

The main contributions of this paper are as follows:

- ✓ Risk constrained scheduling of a MEMG has been carried out with the consideration of the uncertainties.
- ✓ Bilateral contracts have been used as a certain source of electric energy, in addition to the pool market as an uncertain source and their impact on optimized operation of MEMG has been evaluated.
- ✓ Effect of different contingency events on the operation of MEMG has been studied.
- ✓ Effect of DR programs on operation cost of MEMG for demands of electrical, thermal and hydrogen has been assessed.

✓ Effect of storage systems by considering their storage loss on operation cost of MEMG has been discussed.

The rest of the paper is organized as follows. Section 2 describes the proposed model and the problem formulation. Section 3 describes solution methodology for the scheduling problem of MEMG. In section 4, simulation results are discussed, and section 5 presents conclusions.

2. Proposed model

This paper is focused on a grid-connected MEMG with CHP, HE, boiler, ESS, HSS and TSS which is composed of three energy networks of electrical, thermal and hydrogen, supplying electrical, thermal and hydrogen loads simultaneously. In addition to these, the MEMG supplies mobility loads (EVCS and HVCS loads) and CM load. The supply sources are those provided by pool market and bilateral contracts and those relying on local energy generation (RES, units of CHP, boiler and HE). The purchases from the pool market are considered as variables related to uncertain parameters, while purchases from bilateral contracts are considered as certain variable. Moreover, the presented MEMG uses RES of PV, wind and biomass to increase the flexibility. The studied MEMG is represented in Figure 1.

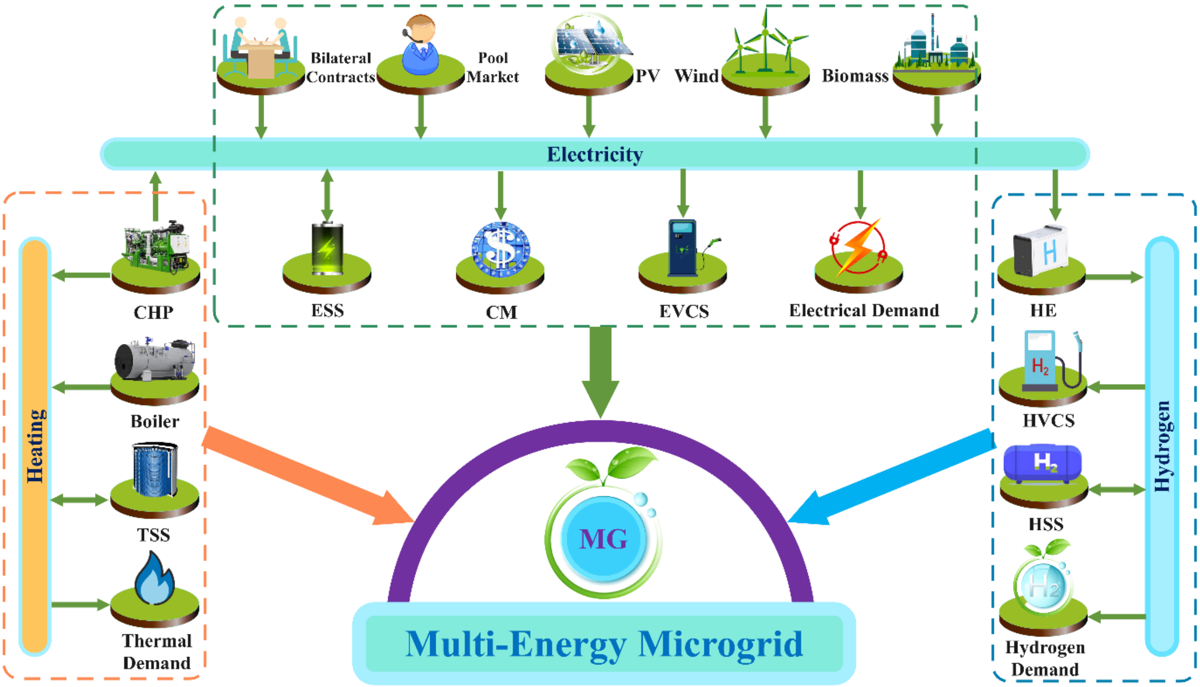

Fig.1. The scheme of the studied MEMG

Formulation of the proposed two-stage stochastic model for day-ahead risk constrained scheduling of a grid-connected MEMG with the aim of minimizing expected operation cost (EOC) is presented by Eqs. (1)-(60). Due to the space limitations, some parameters can be seen in Refs. [13, 37]. This formulation includes objective function and constraints.

According to Eq. (1), the objective function of the suggested model is a linear weighted sum of EOC and CVaR. [36].

$$OF = expcost_{MG} + \beta.CVaR \tag{1}$$

EOC of MEMG is given by (2).VaR and CVaR are defined by equations (3)-(5) below [38].

$$expcost_{MG} = \sum_{s} prob_s \, cost_{MG,s} \tag{2}$$

$$cost_{MG,s} - VaR \leq \theta_s \quad \forall s \tag{3}$$

$$\theta_s \geq 0 \quad \forall s \tag{4}$$

$$CVaR = VaR + \frac{\sum_s prob_s \, \theta_s}{1-\alpha} \tag{5}$$

According to equation (6), the operation cost of MEMG is given by addition of different terms. The cost of power and heat generated by CHP and boiler can be acquired by Eqs. (7) and (8), respectively. Eqs. (9) and (10) present load shedding cost of demands, and start-up and shut-down cost of components including CHP, boiler, HE and BPP. Eq. (11) can be used to calculate the total amount of incentives provided to demands. Using Eqs. (12), (13) and (14), incentives can be acquired [39].

$$\begin{aligned} COST_{MG,s} = {} & \sum_{cr}\sum_{t} PR_{cr,t} \, . P_{cr,t} + \sum_{t} PR_{pool,t,s} \, . P_{pool,t,s} + cost_{CHP,t,s} + cost_{boiler,t,s} + cost_{shed,s} \\ & + cost_{susd,s} + cost_{dr,s} + cost_{spill,s} - \sum_{t} (v_{BPP,t,s}.SU_{BPP} + m_{BPP,t,s}.SD_{BPP}) \quad \forall s \end{aligned} \tag{6}$$

$$cost_{CHP,t,s} = \sum_{t} b_{P,chp} P_{chp,t,s} + \sum_{t} b_{H,chp} H_{chp,t,s} \tag{7}$$

$$cost_{boiler,t,s} = \sum_{t} b_{boil} H_{boil,t,s} \tag{8}$$

$$cost_{shed,s} = \sum_{t} \left(LO_e . P_{sh,t,s} + LO_T . T_{sh,t,s} + LO_h . H_{sh,t,s} \right) \quad \forall s \tag{9}$$

$$\begin{aligned} cost_{susd,s} = {} & \sum_{t} \left(v_{CHP,t,s} . SU_{AC} + m_{CHP,t}, s . SD_{AC} \right) + \sum_{t} \left(v_{boil,t,s} . SU_{boil} + m_{boil,t,s} . SD_{boil} \right) \\ & + \sum_{t} \left(v_{HE,t,s} . SU_{HE} + m_{HE,t,s} . SD_{HE} \right) + \sum_{t} \left(v_{BPP,t,s} . SU_{BPP} + m_{BPP,t,s} . SD_{BPP} \right) \end{aligned} \tag{10}$$

$$cost_{dr,s} = cost_{Edr,s} + cost_{Tdr,s} + cost_{Hdr,s} \quad \forall t, \forall s \tag{11}$$

$$cost_{Edr,s} = \sum_{t} DRI_{Edr,t} \left(DR_{E,up,t,s} + DR_{E,down,t,s} \right) \quad \forall t, \forall s \tag{12}$$

$$cost_{Tdr,s} = \sum_{t} DRI_{Tdr,t} \left(DR_{T,up,t,s} + DR_{T,down,t,s} \right) \quad \forall t, \forall s \tag{13}$$

$$cost_{Hdr,s} = \sum_{t} DRI_{Hdr,t} \left(DR_{H,up,t,s} + DR_{H,down,t,s} \right) \quad \forall t, \forall s \tag{14}$$

The power acquired from pool market is constrained by an upper limitation as constraint (15). In accordance with the constraint (16), the power acquired through each bilateral contract is restricted Furthermore, as per constraint (17), the spilled power at any time is limited by the total power of PV and wind.

$$0 \leq P_{pool,t,s} \leq \overline{P}_{pool} \quad \forall t, \forall s \tag{15}$$

$$\underline{P_{cr}} u_{cr} \leq P_{cr,t} \leq \overline{P_{cr}} u_{cr} \quad \forall t \tag{16}$$

$$0 \leq P_{spill,t,s} \leq PV_{t,s} + W_{t,s} \quad \forall t, \forall s \tag{17}$$

Constraints (18)-(20) represent the balance constraints between generation and demands.

$$PV_{t,s} + WT_{t,s} + P_{chp,t,s} + P_{bpp,t,s} + \sum_{t} P_{cr,t} + P_{pool,t,s} + PS_{shed,t,s} + F_{ESS,dch,t,s} + DR_{e,down,t,s} \geq D_{e,t,s} + D_{evcs,t,s} + D_{cm,t,s} + DR_{e,up,t,s} + F_{ESS,ch,t,s} + P_{spill,t,s} + \frac{H_{HE},t,s}{Q_{HE}} \quad \forall t, \forall s \tag{18}$$

$$T_{boil,t,s} + TS_{shed,t,s} + F_{TSS,dch,t,s} + T_{CHP,t,s} + DR_{h,down,t,s} \geq D_{h,t,s} + DR_{h,up,t,s} + F_{TSS,ch,t,s} \quad \forall t, \forall s \tag{19}$$

$$H_{HE,t,s} + H_{shed,t,s} + H_{HSS,dch,t,s} + DR_{h,down,t,s} \geq D_{hy,t,s} + D_{hvcs,t,s} + DR_{h,up,t,s} + H_{HSS,ch,t,s} \quad \forall t, \forall s \tag{20}$$

Shift-up and shift-down constraints of electrical, thermal and hydrogen demands as responsive demands are obtained by constraints (21)-(24) [40, 41].

$$DR_{D,up,t,s} \leq DPF_{up}.D_{D,t,s}.n_{DR,D,up,t,s} \quad \forall t, \forall s \tag{21}$$

$$DR_{D,down,t,st} \leq DPF_{D,down}.D_{D,t,s}.n_{DR,D,down,t,s} \quad \forall t, \forall s \tag{22}$$

$$n_{DR,D,up,t,s} + n_{DR,D,down,t,s} \leq 1 \quad \forall t, \forall s \tag{23}$$

$$\sum_{t} DR_{D,up,t,s} = \sum_{t} DR_{D,down,t,s} \quad \forall s \tag{24}$$

Boiler operation is determined using constraints (25)-(31) [41, 42].

$$v_{boil,t,s} - m_{boil,t,s} = n_{boil,t,s} - n_{boil,t-1,s} \quad \forall s, \forall t \neq 1 \tag{25}$$

$$v_{boil,t,s} = 0 \quad \forall s, \ \forall t = 1 \tag{26}$$

$$m_{boil,t,s} = 1 - n_{boil,t,s} \quad \forall s, \ \forall t = 1 \tag{27}$$

$$v_{boil,t,s} + m_{boil,t,s} \leq 1 \quad \forall t, \forall s \tag{28}$$

$$H_{boil,min} u_{boil,t,s} \leq H_{boil,t,s} \leq H_{boil,max}\, u_{boil,t,s} \quad \forall t, \forall s \tag{29}$$

$$H_{boil,t+1,s} - H_{boil,t,s} \leq RU_{boil} \quad \forall s, \ \forall t \neq 24 \tag{30}$$

$$H_{boil,t-1,s} - H_{boil,t,s} \leq RD_{boil} \quad \forall s, \forall t \neq 1 \tag{31}$$

Operation of HE is determined using constraints (32)-(38) [43, 44].

$$v_{HE,t,s} - m_{HE,t,s} = n_{HE,t,s} - n_{HE,t-1,s} \quad \forall t, \forall s \neq 1 \tag{32}$$

$$v_{HE,t,s} = 0 \quad \forall s, \forall t = 1 \tag{33}$$

$$m_{HE,t,s} = 1 - n_{HE,t,s} \quad \forall s, \forall t = 1 \tag{34}$$

$$v_{HE,t,s} + m_{HE,t,s} \leq 1 \quad \forall s, \forall t \tag{35}$$

$$H_{HE,min} n_{HE,t,s} \leq H_{HE,t,s} \leq H_{HE,max}\, n_{HE,t,s} \quad \forall t, \forall s \tag{36}$$

$$H_{HE,t+1,s} - H_{HE,t,s} \leq RU_{HE} \quad \forall s, \forall t \neq 24 \tag{37}$$

$$H_{HE,t-1,s} - H_{FC,t,s} \leq RD_{HE} \quad \forall s, \forall t \neq 1 \tag{38}$$

In CHP operation, operation point is located at the FOR due to the relationship between power and heat. Constraints (39)-(43) are used to determine FOR of a CHP [45-47].

$$0 \leq P_{chp,t} \leq P_{chp,A} \,.\, k_{chp,t,s} \quad \forall t, \forall s \tag{39}$$

$$0 \leq T_{chp,t} \leq T_{chp,B} \,.\, k_{chp,t,s} \quad \forall t, \forall s \tag{40}$$

$$P_{chp,t,s} - P_{chp,A} - \frac{(P_{chp,A} - P_{chp,B})(T_{chp,t,s} - T_{chp,A})}{T_{chp,A} - T_{chp,B}} \leq 0 \quad \forall t, \forall s \tag{41}$$

$$P_{chp,t,s} - P_{chp,B} - \frac{(P_{chp,B} - P_{chp,C})(T_{chp,t,s} - T_{chp,B})}{T_{chp,B} - T_{chp,C}} \geq -M(1 - k_{chp,t,s}) \quad \forall t, \forall s \tag{42}$$

$$P_{chp,t,s} - P_{chp,C} - \frac{(P_{chp,C} - P_{chp,D})(T_{chp,t,s} - T_{chp,C})}{T_{chp,C} - T_{chp,D}} \geq -M(1 - k_{chp,t,s}) \quad \forall t, \forall s \tag{43}$$

Operation of BPP is determined using constraints (44)-(50) [37, 43].

$$v_{BPP,t} - m_{BPP,t} = n_{BPP,t} - n_{BPP,t-1} \quad \forall t \neq 1 \tag{44}$$

$$v_{BPP,t} = 0 \quad \forall t = 1 \tag{45}$$

$$m_{BPP,t} = 1 - n_{BPP,t} \quad \forall t = 1 \tag{46}$$

$$v_{BPP,t} + m_{BPP,t} \leq 1 \quad \forall t \tag{47}$$

$$BP_{BPP,min} k_{BPP,t} \leq BP_{BPP,t} \leq BP_{BPP,max}\, k_{BPP,t} \quad \forall t \tag{48}$$

$$BP_{BPP,t+1} - BP_{BPP,t} \leq RU_{BPP} \quad \forall t \neq 24 \tag{49}$$

$$BP_{BPP,t-1} - BP_{BPP,t} \leq RD_{BPP} \quad \forall t \neq 1 \tag{50}$$

Energy storage systems operation is determined using constraints (51)-(57) [6, 48-50].

$$n_{SS,ch,t,s} Fch_{SS,min} \leq F_{SS,ch,t,s} \leq n_{SS,ch,t,s} Fch_{SS,max} \quad \forall t, \forall s \tag{51}$$

$$n_{SS,dch,t,s} Fdch_{SS,min} \leq F_{SS,dch,t,s} \leq n_{SS,dch,t,s} Fdch_{SS,max} \quad \forall t, \forall s \tag{52}$$

$$R_{SS,min} \leq R_{SS,t,s} \leq R_{SS,max} \quad \forall t, \forall s \tag{53}$$

$$n_{SS,ch,t,s} + n_{SS,dch,t,s} \leq 1 \quad \forall t, \forall s \tag{54}$$

$$IE_{SS,ini} = R_{SS,end,s} \quad \forall s \tag{55}$$

$$R_{SS,t,s} = R_{SS,t-1,s} - \frac{F_{SS,dch,t,s}}{K_{SS,dch}} + K_{SS,ch} F_{SS,ch,t,s} - L_{SS}\left(\frac{R_{SS,t,s} + R_{SS,t-1,s}}{2}\right) \quad \forall t, \forall s \neq 1 \tag{56}$$

$$R_{SS,t,s} = IE_{SS,ini} - \frac{F_{SS,dch,t,s}}{K_{SS,dch}} + K_{SS,ch} F_{SS,ch,t,s} - L_{SS}\left(\frac{R_{SS,t,s} + R_{SS,t-1,s}}{2}\right) \quad \forall t, \forall s = 1 \tag{57}$$

In recent years, especially, crypto miners have become a type of high-consumption electric load, which can affect the performance of the power grid with their growing consumption. The significant increase in energy consumption of bitcoins, for instance, compared to previous years, shows the rapid growth of such loads in the energy network [51-53]. Therefore, CMs are considered as an uncertain demand in this study. Consumed power of miners at each time and each scenario is calculated as a portion of maximum considered load, as modeled by (58).

$$CML_{t,s} = PCML * TF_{cm,t,s} \quad \forall t, \forall s \tag{58}$$

Electric and hydrogen vehicles charging stations are sources that are able to supply energy for electric and hydrogen vehicles. During operation, these charging stations form a part of the electric and hydrogen load of the energy network. The growing increase of EVs and HVs will increase the load on the energy network. Thus, the consumed load of EV and HV charging stations is taken into account as uncertain demands. Consumed power of EVCS and HVCS at each time and each scenario is computed as a portion of maximum considered load, as per (59) and (60) [13, 54].

$$EVCSL_{t,s} = PEVCSL * TF_{evcs,t,s} \quad \forall t, \forall s \tag{59}$$

$$HVCSL_{t,s} = PHVCSL * TF_{hvcs,t,s} \quad \forall t, \forall s \tag{60}$$

3. Solution methodology of problem

In this paper, optimal operation of MEMG is solved as MILP model using CPLEX solver in the GAMS with the aim of minimizing linear weighted sum of EOC and CVaR and satisfying all constraints. In CPLEX solver, a branch and bound method is used for tackling LP and MILP models [55]. To manage uncertainty of pool market prices, PV and wind power, electrical, thermal and hydrogen demands, EVCS and HVCS loads, CM load, CHP and boiler power, charging/discharging power of storages and finally power of responsive demands, two-stage stochastic model is proposed. Due to the existence of here-and-now and wait-and-see decision variables in the considered MEMG, it is believed that two-stage stochastic model is a desirable option for optimal operation of the MEMG under study.

Generally, two types of decisions are recognized in the decision-making process of a two-stage stochastic model. In first-stage decisions or here-and-now decisions, in this case, decision-makings are made before the realizing the stochastic process, so these decisions do not depend on the scenarios and are not affected by uncertainties. In the subsequent optimization they come as scenario-independent input variables. While in second-stage decisions or wait-and-see decisions, decision-makings are made in real-time after realizing the uncertainties, so these decisions are determined by each realization vector of the stochastic process. In this case, a second-stage decision variable is presented for each scenario if the stochastic process is represented by a set of scenarios. More details about two-stage stochastic method can be found in [38].

Considering the standard deviation or forecast error of 5% and the uncertainties of PV, WT, EVCS, HVCS, CMs, demands of electrical, thermal and hydrogen, and pool market price during 24 hours as the mean, 3000 scenarios are generated. Due to the computational complexity, running time limit and large number of decision variables, 3000 scenarios are decreased to 10 scenarios using backward reduction algorithm based SCENRED module in GAMS. Refs. [56-58] show the more descriptions of the backward technique.

In the following, by taking into account the probabilities of 10 reduced scenarios, uncertainties of 216 input data, i.e., the uncertainties of PV, WT, EVCS, HVCS, CMs, demands of electrical, thermal and hydrogen, and pool market price during 24 hours and for 10 considered scenarios, considering CVaR criteria and finally setting value of weight factor, the scheduling problem of MEMG is solved with the aim of minimizing the objective function. Figure 2 shows the solution method of risk constrained scheduling problem of MEMG.

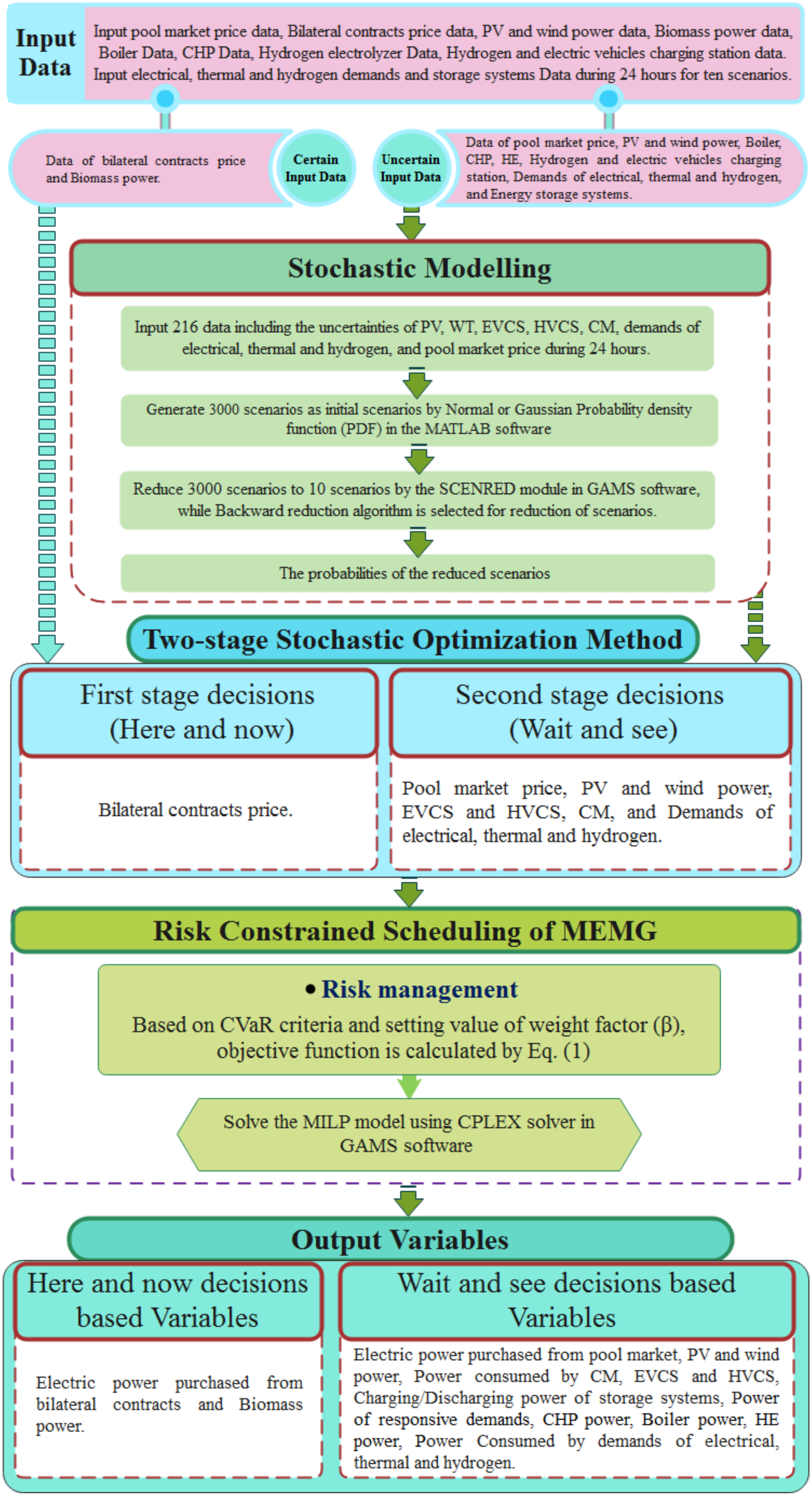

Fig.2. Solution methodology of risk constrained scheduling problem of MEMG

4. Simulation results

In this section, the simulation results of the proposed two-stage stochastic model and their analysis is provided. In the load shedding program, a portion of load or the entire load is removed by the operator in some cases, such as an imbalance between generation and load or etc. In this case, the MEMG operator must pay a fee to the consumer as to compensate for the cost of unsupplied load or the cost of lost load. Figure 3 depicts time factors of demands, PV and wind power and pool market price [59, 60]. The problem data are given in Tables 2-5 and Figure 4 [36, 61].

In subsection 4.1, operation costs of MEMG and also purchase of electricity from pool market and bilateral contracts are discussed. In subsections 4.2 and 4.3, effect of storage systems and DR programs on operation costs of MEMG is assessed. In Subsection 4.4, impact of contingency events on MEMG is studied, followed by effect of CM demand on operation cost in subsection 4.5.

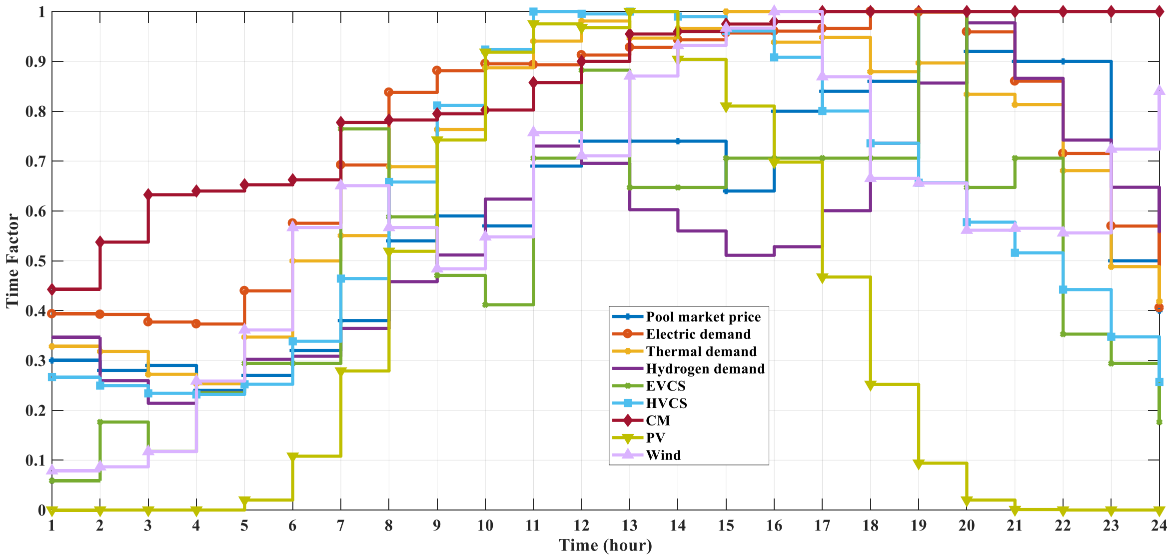

Fig.3. Time factors of demands, PV and wind power and pool market price [59, 60]

Table 2. Boiler data [61]

Heat cost coefficient ($)	Min. power (kW)	Max. power (kW)	Efficiency	RU (kW/h)	RD (kW/h)	SU cost ($)	SD cost ($)
8	0.06	0.25	0.9	0.04	0.25	10	10

Table 3. CHP data [61]

Power cost coefficient ($)	Heat cost coefficient ($)	Power RU (kW/h)	Power RD (kW/h)	Heat RU (kW/h)	Heat RD (kW/h)	SU cost ($)	SD cost ($)	A_p	A_h	B_p	B_h	C_p	C_h	D_p	D_h
27.5	8.5	1	1	0.2	0.2	5	5	5.5	0	4.42	1.5	0.98	0.62	1.16	0

Table 4. Input data of MEMG operation problem [36]

Max. purchasable electricity from pool market	1 MW	Electric DR incentive	10 $/MWh
TOU price of pool market	100 $/MWh	Hydrogen DR incentive	5 $/MWh
Peak electrical load	12 MW	Thermal DR incentive	4 $/MWh

Peak thermal load	1.2 MW	Biomass incentive	20 $/MWh
Peak hydrogen load	1.5 MW	Lost electrical load	250 $/MWh
Peak electric charging station	0.5 MW	Lost thermal load	250 $/MWh
Peak hydrogen charging station	0.2 MW	Lost hydrogen load	250 $/MWh
Peak Cryptocurrency miner load	0.6 MW	PV capacity	2.5 MW
Biomass capacity	0.08 MW	Wind capacity	3.2 MW
Participation factor for DR	0.2		

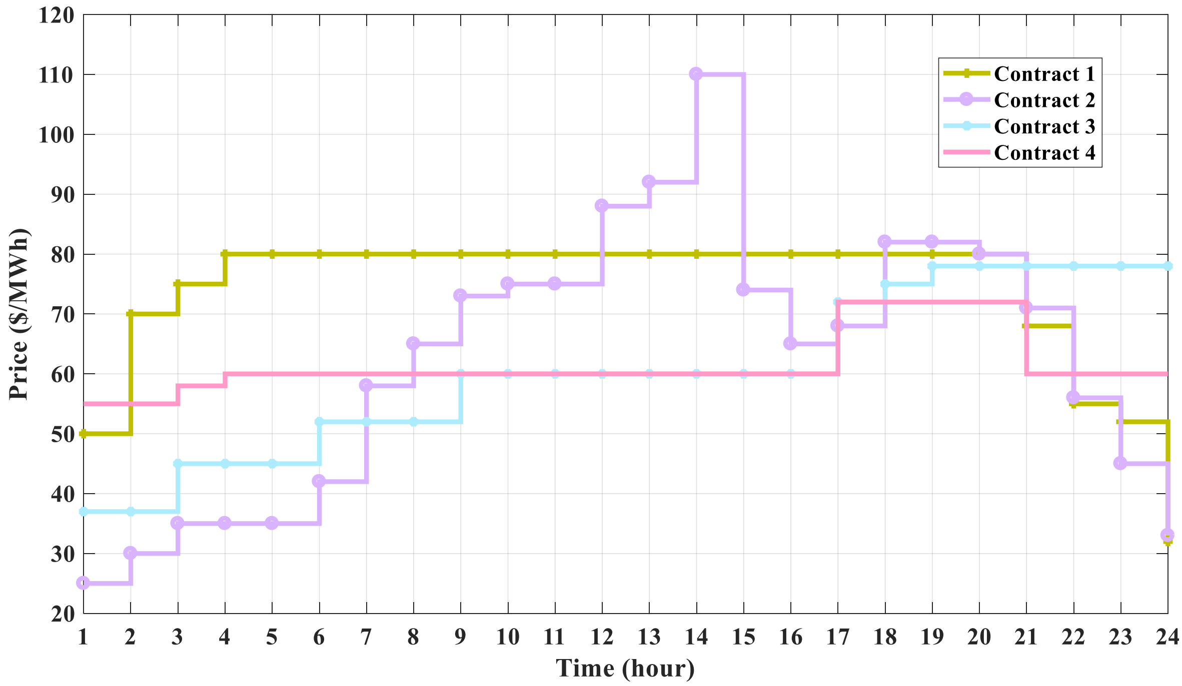

Fig.4. The prices of bilateral contracts [36]

Table 5. Minimum and maximum purchasable power through bilateral contracts [36]

Contract number	Minimum power (MW)	Maximum power (MW)
1	1.5	7
2	2	6
3	3	8
4	4	5.5

Table 6. Probability of reduced scenarios

Scenario number	1	2	3	4	5	6	7	8	9	10
Probability	0.239	0.150	0.075	0.058	0.073	0.064	0.063	0.140	0.073	0.064

Table 6 shows the probability value of ten reduced scenarios. Electrical, thermal and hydrogen demands, EVCS, HVCS, CM, PV and wind, and pool market price in scenarios reduced are shown in Figures 5-13.

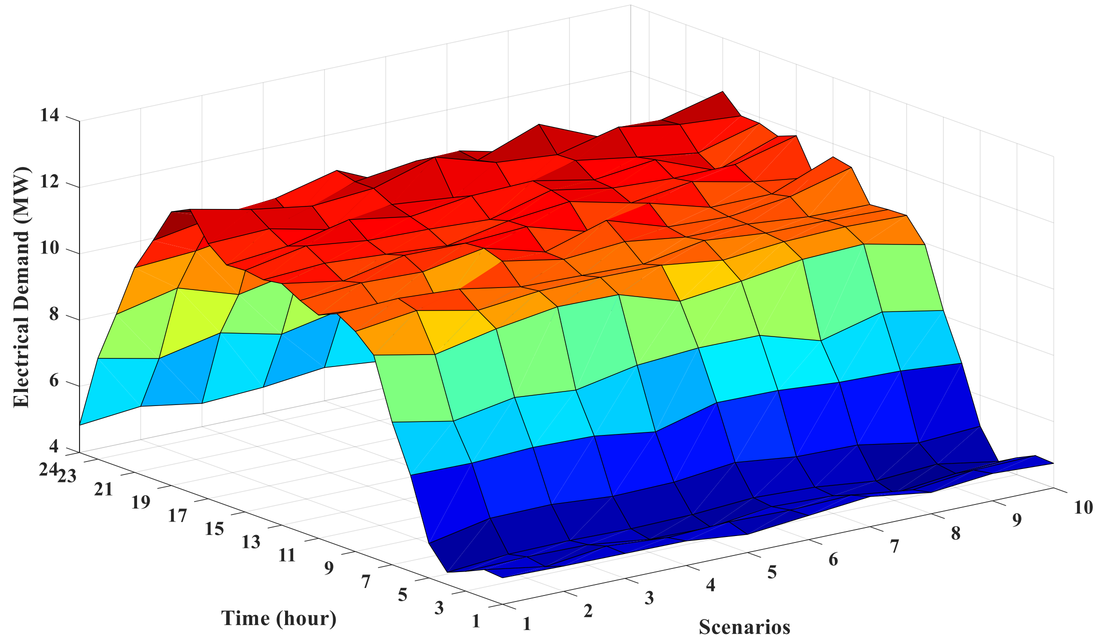

Fig.5. Electrical demand

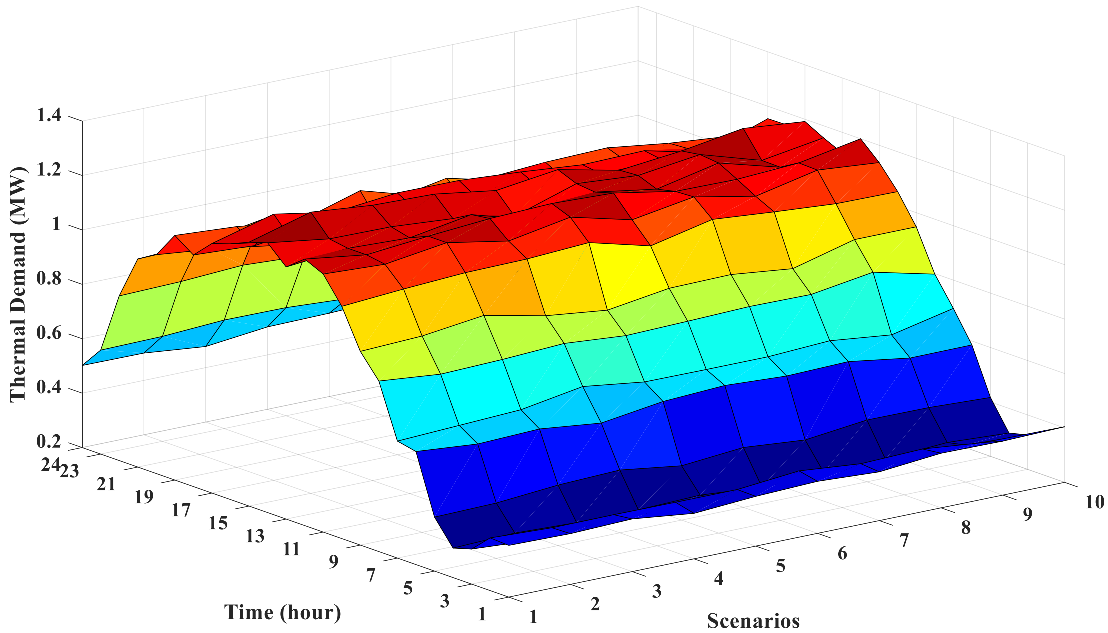

Fig.6. Thermal demand

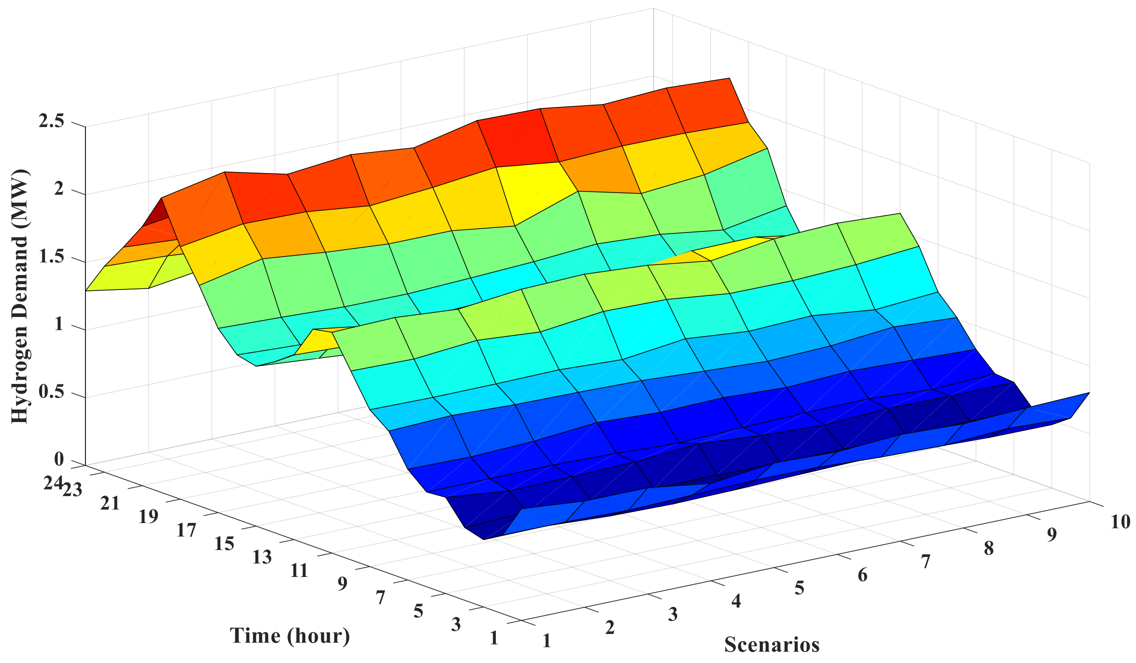

Fig.7. Hydrogen demand

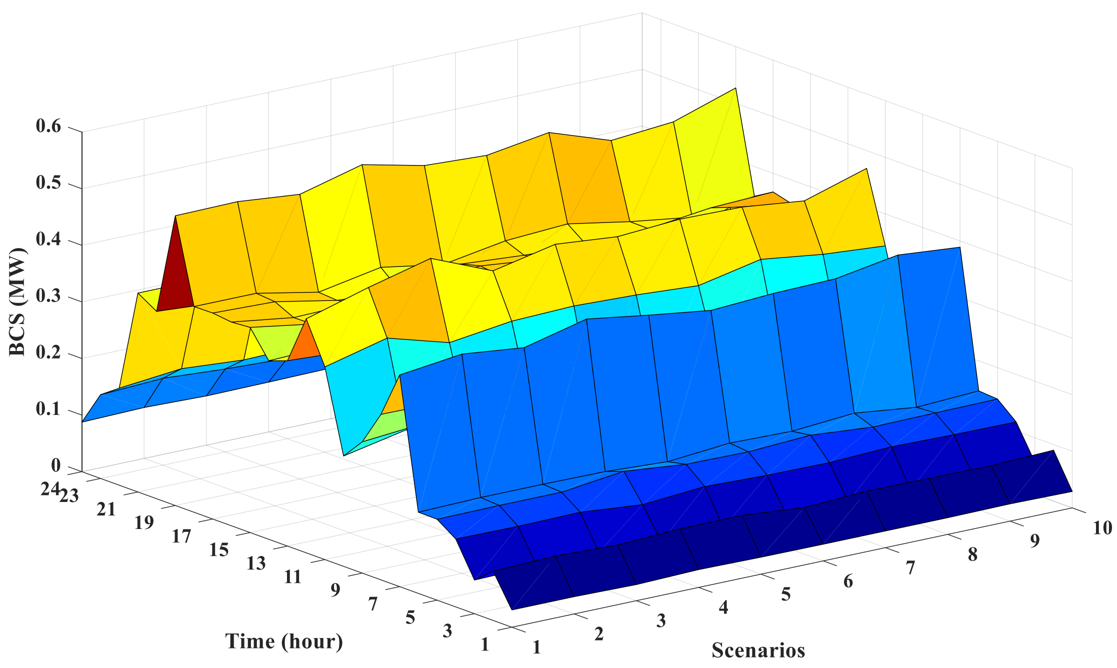

Fig.8. EVCS

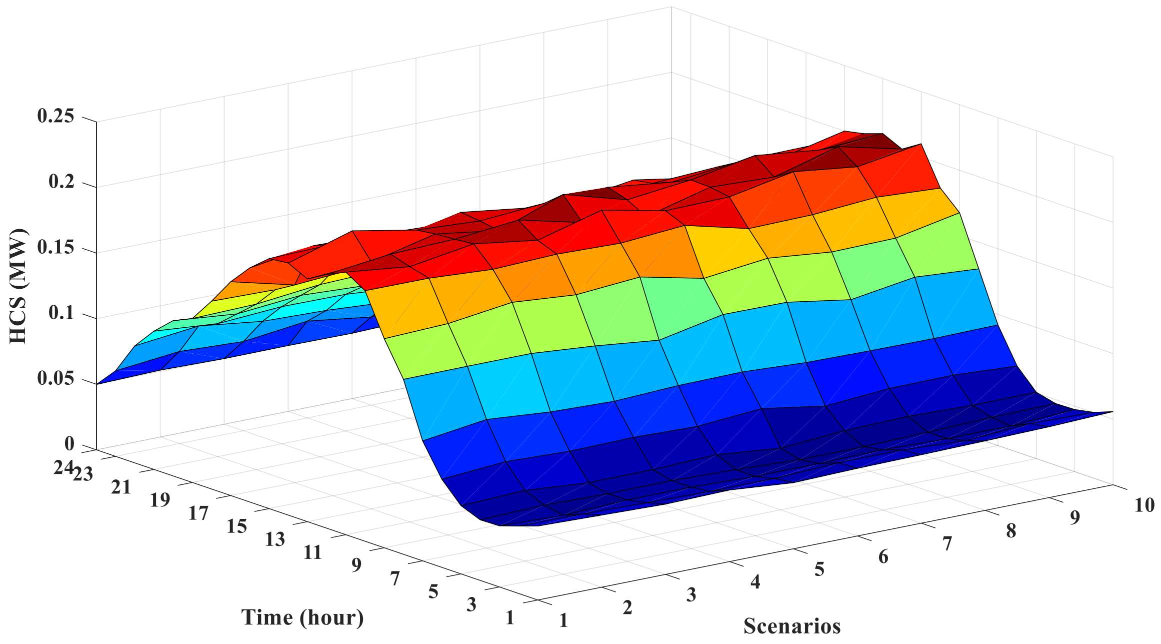

Fig.9. HVCS

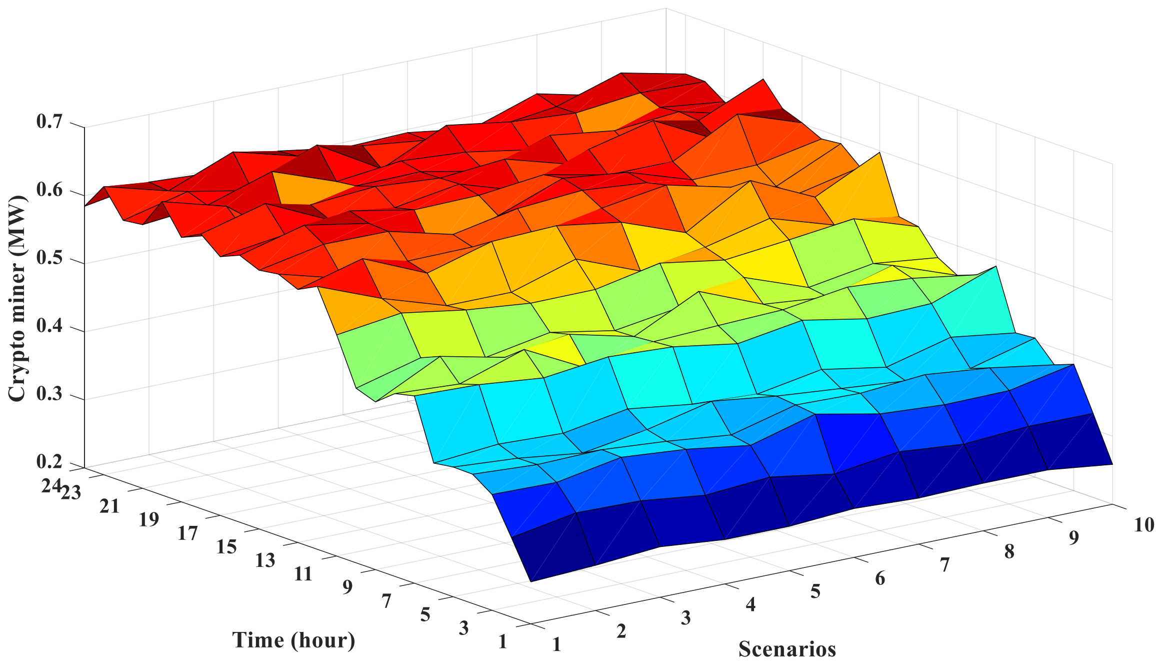

Fig.10. CM

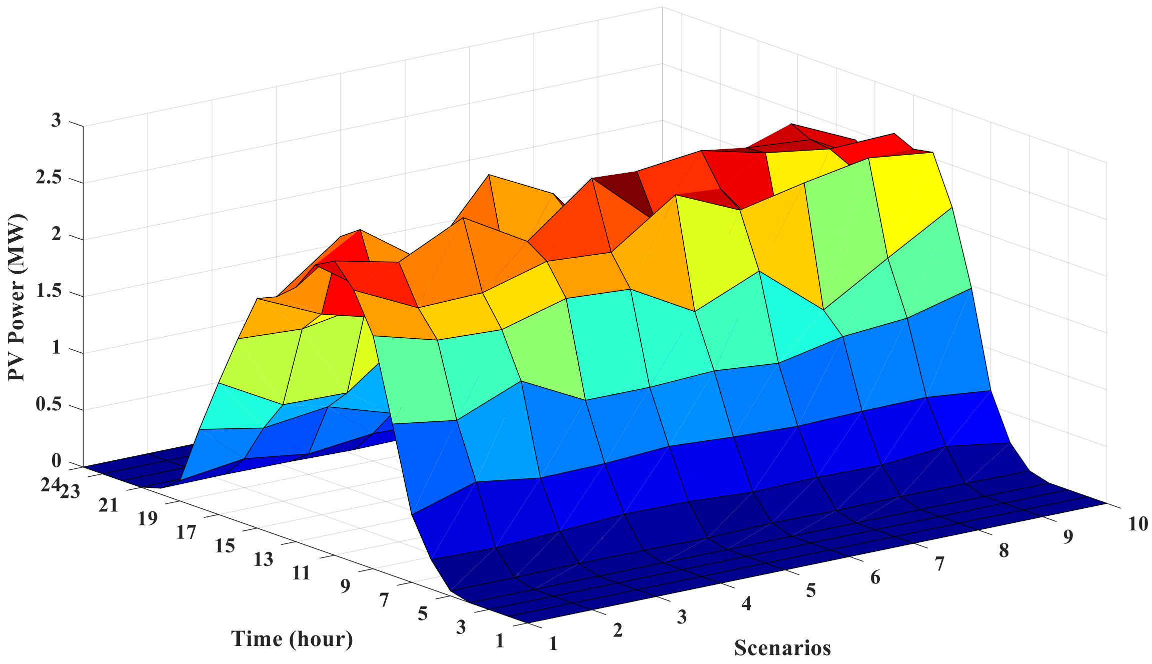

Fig.11. PV power

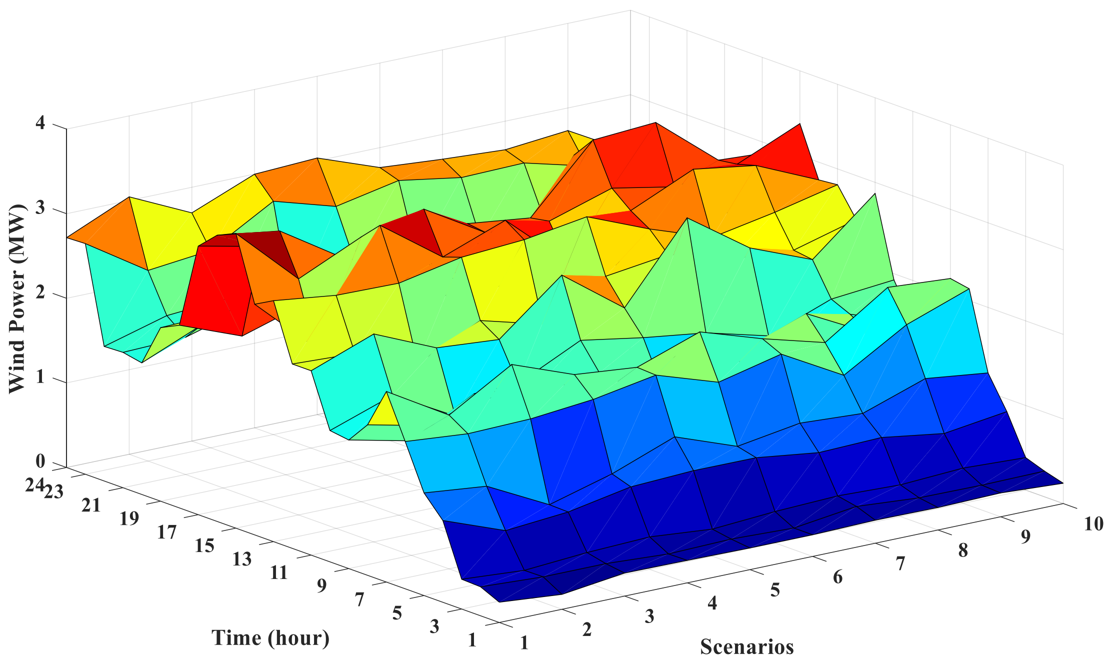

Fig.12. Wind power

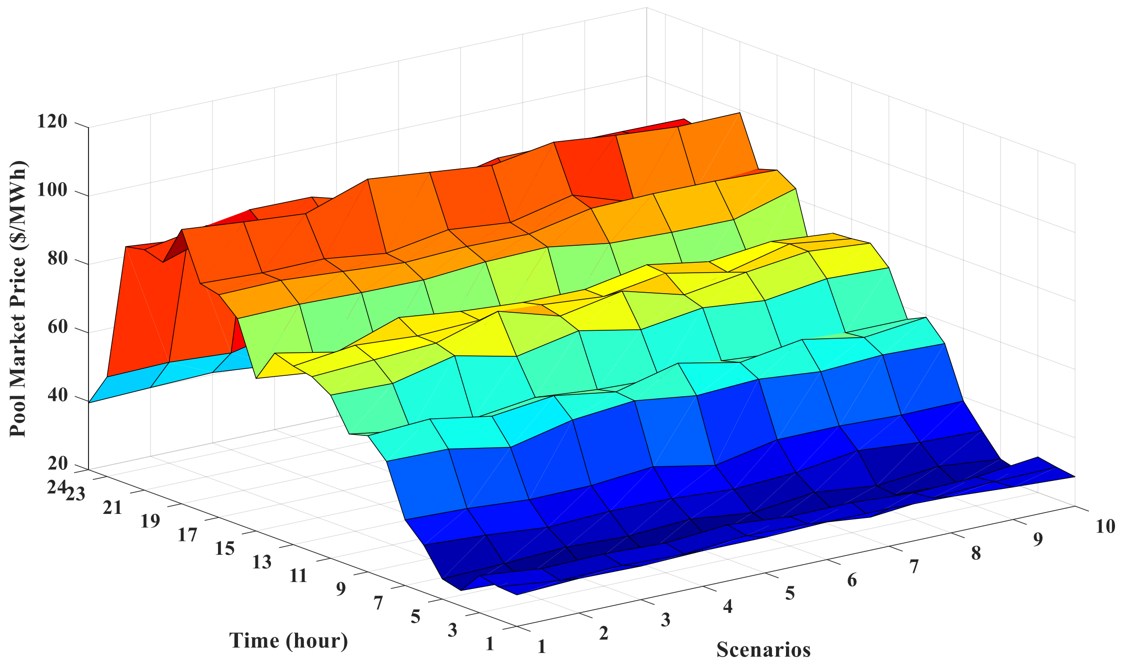

Fig.13. Pool market prices

4.1. Operation costs of MEMG

Table 7 illustrates the costs in different scenarios. As shown in Table 7, costs vary depending on generation and load in each scenario. Table 8 shows expected components of costs for studied MEMG. EOC of MEMG in Table 8 is equal to the weighted sum of operation costs in 10 scenarios. As it was mentioned above, bilateral contracts do not depend on scenarios. As shown in Table 7, thus, cost of electricity purchased from bilateral contracts is the same for all the scenarios. It is clear that in this case, there is no load shedding in operation of MEMG and all demands are fully met. Because in this case, the operator can purchase the needed power for supplying of all demands from the bilateral contracts, regardless of stochastic processes made by the forecast error, reducing the risk of high operation costs.

Table 7. Operation costs of MEMG in different scenarios

Components ($)	**Scenarios**									
	S1	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S10**
Operation cost	8016.77	8225.26	8053.79	8082.71	7969.10	8255.57	7897.93	7942.21	7811.21	7901.79
Purchased electricity cost (Sum of purchased electricity cost from pool market and bilateral contracts)	4458.07	4665.85	4466.17	4559.13	4417.56	4664.88	4346.69	4384.34	4261.94	4331.62
Purchased electricity cost from pool market	351.66	559.45	359.76	452.72	311.15	558.47	240.28	277.93	155.54	225.22
Purchased electricity cost from bilateral contracts	4106.41	4106.41	4106.41	4106.41	4106.41	4106.41	4106.41	4106.41	4106.41	4106.41
Spillage cost	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CHP cost	3353.15	3352.61	3376.74	3318.50	3356.06	3377.83	3351.33	3349.20	3358.47	3363.31
Boiler cost	49.96	46.40	47.82	47.51	48.13	49.60	46.40	46.85	47.65	49.96

EDR cost	183.22	189.21	187.81	183.70	172.58	186.87	178.82	186.95	168.29	184.24
TDR cost	8.30	8.26	9.99	10.00	10.04	10.05	9.97	10.05	10.07	8.42
HDR cost	8.96	7.81	10.14	8.75	9.60	11.23	9.60	9.69	9.66	9.13
DR cost	200.48	205.28	207.94	202.45	192.22	208.15	198.40	206.70	188.02	201.79
Incentive for biomass	44.88	44.88	44.88	44.88	44.88	44.88	44.88	44.88	44.88	44.88

Table 8. Expected components of operation costs

Components ($)	**Values**
Exp. operation cost	8018.14
Purchased electricity cost (Sum of purchased electricity cost from pool market and bilateral contracts)	4461.77
Purchased electricity cost from pool market	359.47
Purchased electricity cost from bilateral contracts	4106.40
Exp. CHP cost	3351.63
Exp. boiler cost	48.08
Exp. spillage cost	-
Exp. total shed cost	-
Exp. start-up/shut-down cost	-
Exp. EDR cost	182.98
Exp. TDR cost	9.23
Exp. HDR cost	9.25
Exp. DR cost	201.47

As per Table 7, the sixth scenario has the maximum amount of the operation cost. In this scenario, the cost of electricity purchased from pool market and bilateral contracts accounts for 56.50% of the operation cost, 6.76% of the cost is related to the cost of electricity purchased from pool market and 49.74% is related to the cost of electricity purchased from bilateral contracts. It is clear that in all scenarios, the MEMG is able to supply the total demand and there is no shedding demand.

In contrast, the ninth scenario has the minimum amount of the operation cost. In ninth scenario, the cost of electricity purchased from pool market and bilateral contracts accounts for 54.57% of the operation cost, 2% of the cost is related to the cost of electricity purchased from pool market and 52.57% is related to the cost of electricity purchased from bilateral contracts. It can be seen from Table 7 that DR costs and cost of electricity purchased from pool market are at the lowest among the all scenarios. The reason for this is that the generation and load values are at their maximum and minimum with respect to the forecast values in this scenario. Thus, operation cost of MEMG is the lowest in this scenario.

Table 8 presents EOCs of MEMG. As per Table 8, the EOC is equal to $8018.14. In accordance with the Table 8, the cost of electricity purchased from pool market and bilateral contracts accounts for 55.64% of the operation cost. Figure 14 shows different components of MEMG operation costs. It can be seen that cost of electricity purchased from pool market in the sixth scenario is at its maximum, while the ninth scenario has the lowest cost among all scenarios.

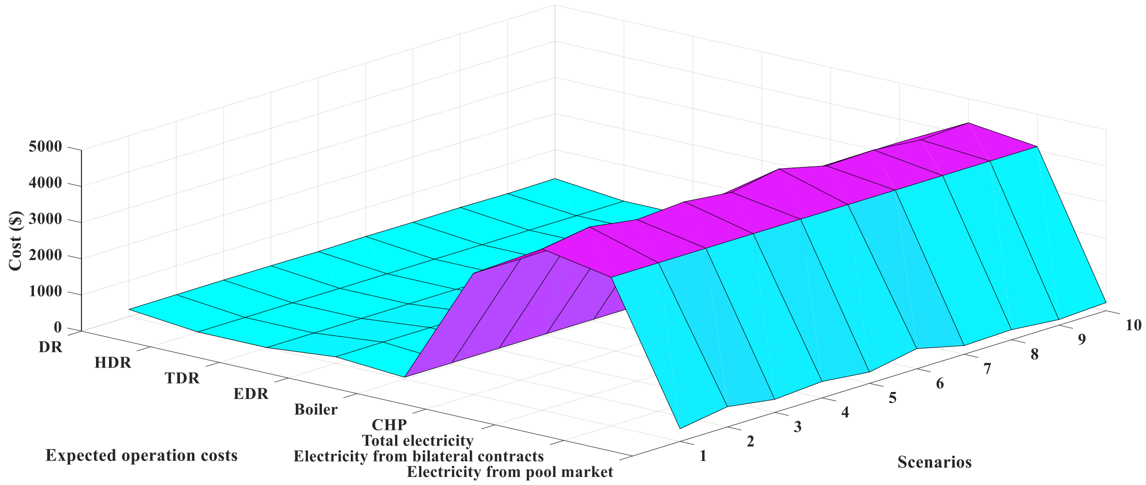

Fig.14. Components of operation costs of MEMG in different scenarios

Figure 15 shows the electric power generated by CHP during 24 hours in different scenarios.

As can be seen from Figure 15, MEMG uses maximum capacity of the CHP to generate electric power especially in hours 6-22. Although there are two other sources in MEMG including pool market and bilateral contracts for supplying loads. It is worth noting that the scheduling of these sources for production of electric energy depends on the peak load, cost of energy production, energy production capacity, storages, DR programs and etc. Also, Figures 16 and 17 display the thermal power generated by CHP and boiler during 24 hours in different scenarios, respectively.

As can be seen from Tables 2 and 3, the cost of thermal energy produced by the boiler and CHP is $8 and $8.5, respectively. Since the cost of producing thermal energy by the boiler is cheaper than the cost for CHP, the MEMG first uses all the capacity of the boiler to generate thermal energy and then receives the rest of the thermal energy needed for supplying loads from CHP. Therefore, as can be seen from Figure 16, the boiler operates at its full capacity in most hours of the day (hours 3-22).

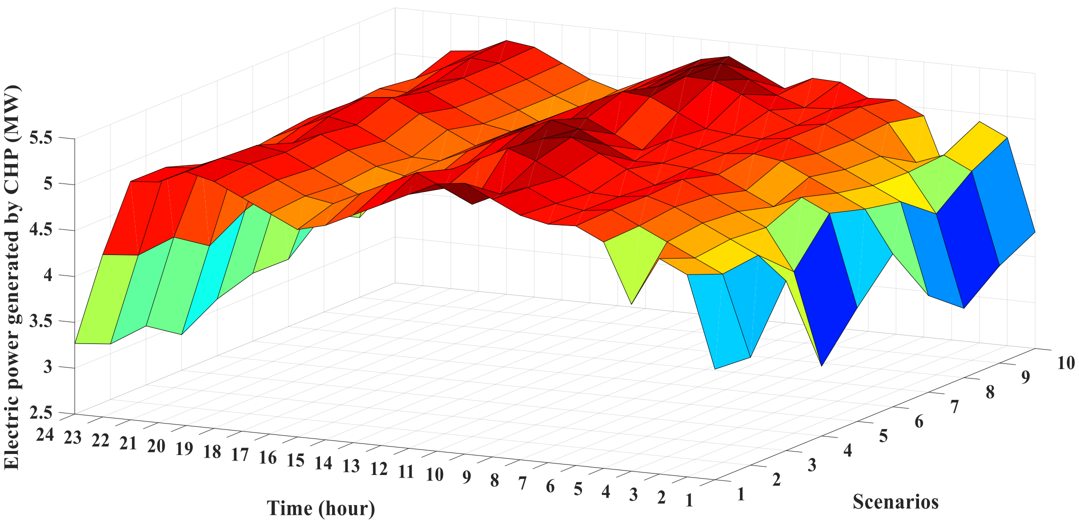

Fig.15. Electric power generated by CHP

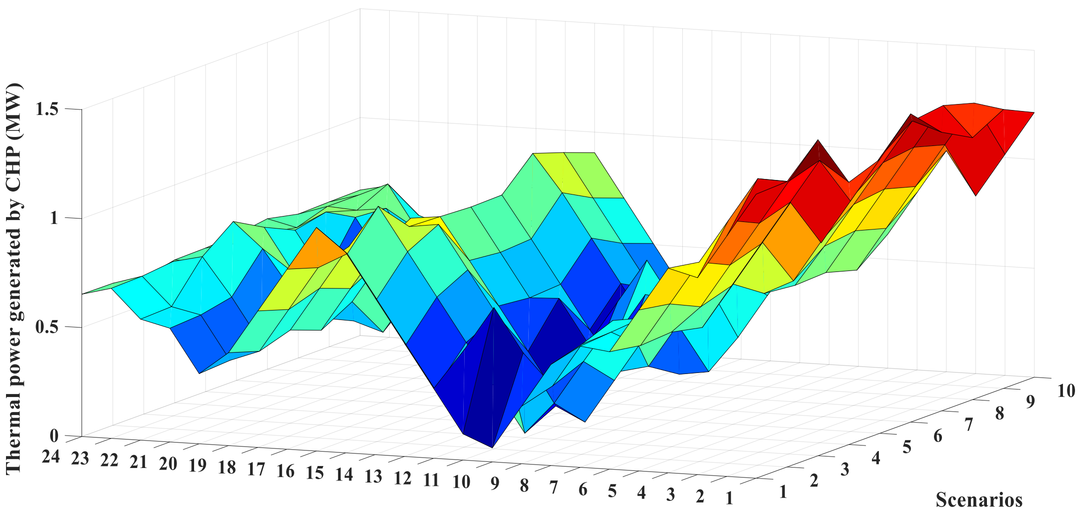

Fig.16. Thermal power generated by CHP

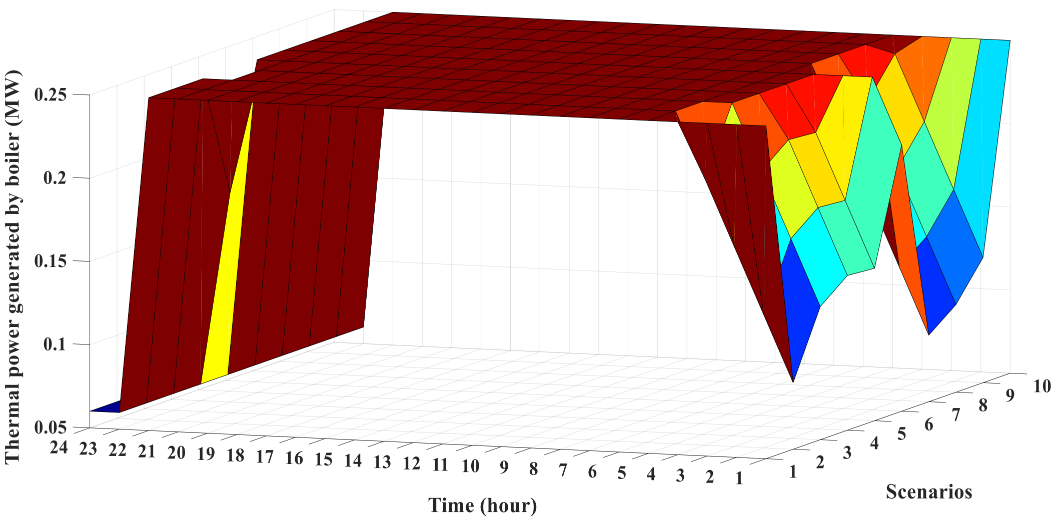

Fig.17. Thermal power generated by boiler

Figures 18-20 demonstrate the balance between load and generation for electrical, hydrogen and thermal energies in MEMG during 24 hours for 10 scenarios. Hour 1 represents interval between 0.00 AM to 1.00 AM, and hour 24 represents interval between 23.00 to 24.00.

In accordance with the Figure 18, at hour 1 and for scenario 1, generated power is 10.04 MW. 2.22 MW of the power generated is used to charge ESS; 0.96 MW shift-up occurred in electrical demand; 1.76 MW is used for supplying HE; and 4.80 MW, 0.26 MW and 0.03 MW are used to supply electric demand, CM and EVCS, respectively. Also, it can be found from Figure 18 that hour 16 in scenario 8 experiences the peak load among all scenarios, while power generated is 16.27 MW that consists of 6 MW power purchased from bilateral contract, 4.7 MW power produced by CHP, 3.6 MW power generated by wind and 1.97 MW power by PV. 1.91 MW of 16.27 MW generated power is used to charge ESS; 1.76 MW is used for supplying HE; and 11.7 MW, 0.57 MW and 0.33 MW are used to supply electric demand, CM and EVCS, respectively.

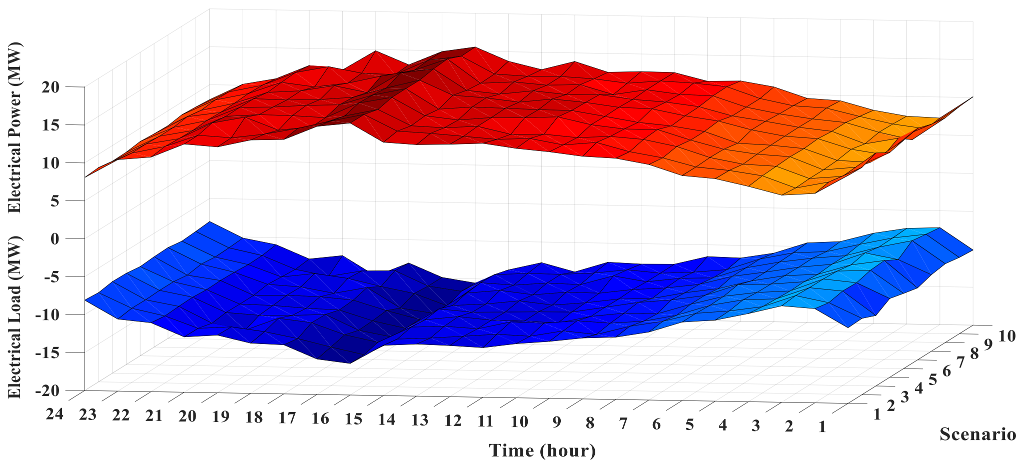

Fig.18. Electrical energy balance in MEMG

As per Figure 19, at hour 1 and for scenario 1, generated power is 1.5 MW that is produced by HE. 0.78 MW of the power generated is used to charge HSS; 0.11 MW shift-up occurred in hydrogen demand; and 0.55 MW and 0.06 MW are used to supply hydrogen demand and HVCS, respectively. It can be seen from Figure 19 that hour 20 in scenario 6 experiences the peak load among all scenarios, while power generated is 1.63 MW. 1.51 MW and 0.51 MW of the power generated is used to supply hydrogen demand and HVCS, respectively.

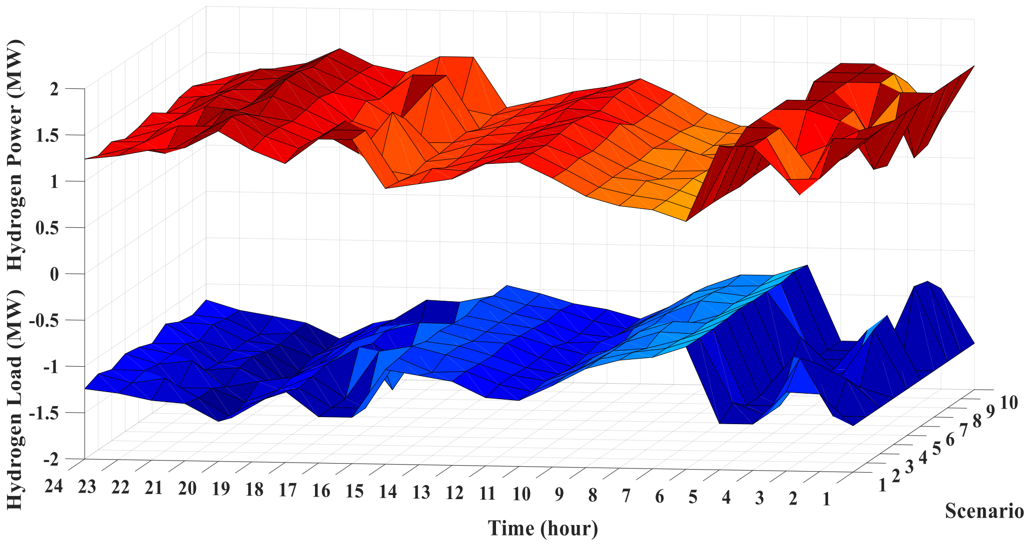

Fig.19. Hydrogen energy balance in MEMG

Figure 20 displays the balance between load and generation for thermal energy in MEMG during the 24 hours for 10 scenarios. Generally, there are two main generation sources of thermal energy in MEMG for supplying thermal loads, CHP and boiler, Although CHP produces the electricity in addition to the thermal energy. As per Figure 20, at hour 1 and for scenario 1, generated thermal power is 1.55 MW. 1.085 MW of the power generated is used to charge TSS; 0.078 MW shift-up occurred in thermal demand; and 0.39 MW is used for supplying thermal demand. It can be seen from Figure 20 that hour 1 in scenario 1 experiences the peak load among 10 scenarios during 24 hours.

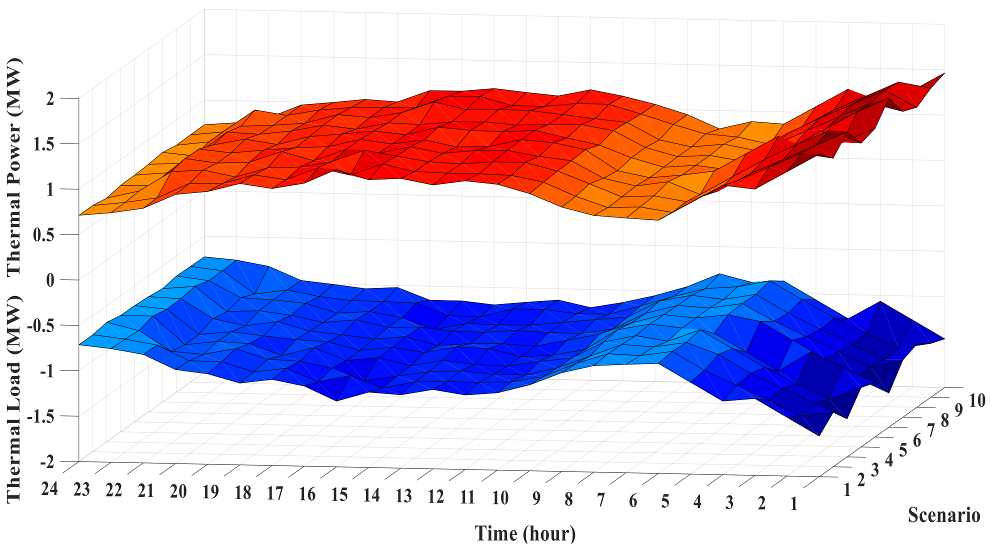

Fig.20. Thermal energy balance in MEMG

4.1.1. Purchase of electricity from pool market

In this study, pool market is one of sources of purchasing electrical energy. As per Table 8, expected purchased electricity cost from pool market is $359.47. Figures 21 and 22 show the electrical power purchased from pool market and its cost for different scenarios. It is obvious that the maximum purchased electricity from the pool market occurs in scenarios 2 and 6. Thus, cost of electricity purchased and operation cost of MEMG in these scenarios is higher than those in other scenarios.

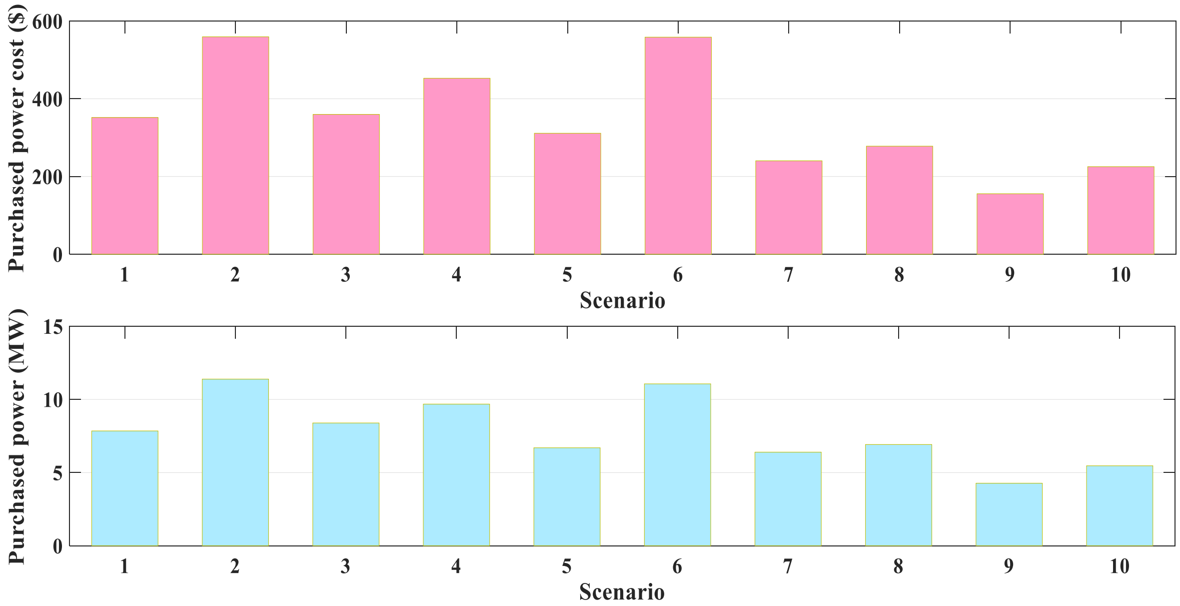

Fig.21. Power purchased from pool market and its cost

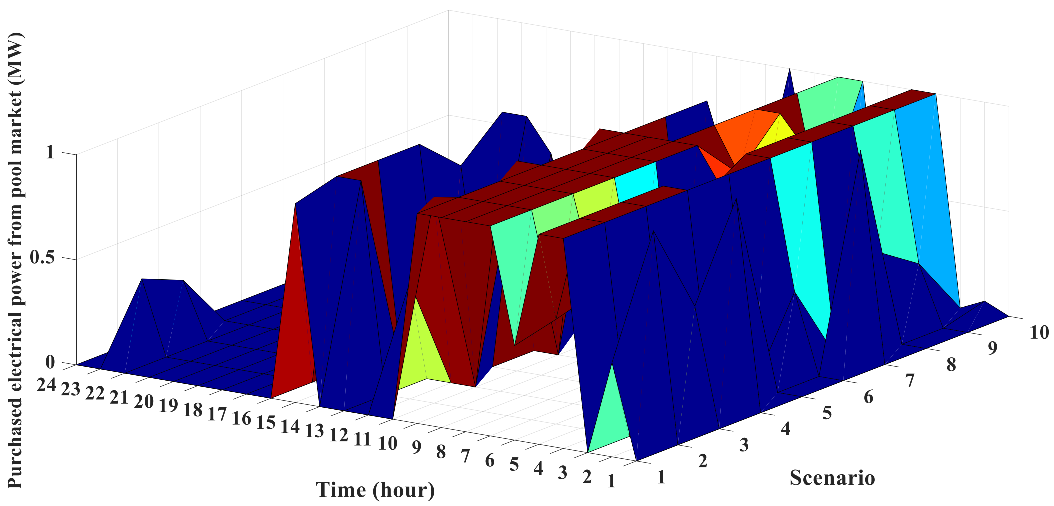

Fig.22. Purchased electric power from pool market along 24 hours in different scenarios

As it can be found from Figure 22, in hours 4-5 and 7-10, in around all scenarios, the maximum capacity of the pool market for supplying demands is used.

4.1.2. Purchase of electricity from bilateral contracts

The studied MEMG purchases the needed electricity for supplying demands from pool market and bilateral contract. As it was mentioned in section 4, 4 types of contracts are considered in this paper. It is obvious that different forms of purchase of electricity from bilateral contracts can occur depending on the operator's decision. In this regard, 4 cases for purchasing of power from bilateral contracts are taken into account.

In case 1, operator can only purchase electricity from one contract. In case 2, operator can decide to purchase electricity from any contract at any time. In case 3, operator can decide to purchase electricity from any contract at any time without the constraint of minimum purchasable power. In case 4, operator can only purchase electricity from one contract without the constraint of minimum purchasable power. In the following, each one of these case studies is studied.

1) Case 1

In case 1, operator can only purchase electricity from one contract. Figure 23 shows purchased power and cost of power purchased through bilateral contract #2. Among the 4 considered bilateral contracts, contract #2 is selected. According to the Figure 16, purchased power and cost of electricity purchased from bilateral contracts are 67.85 MW and $4106.4, respectively. The amount of demand minus renewable power principally affects the purchases from bilateral contracts, pool market and the performance of storages and DRs [62].

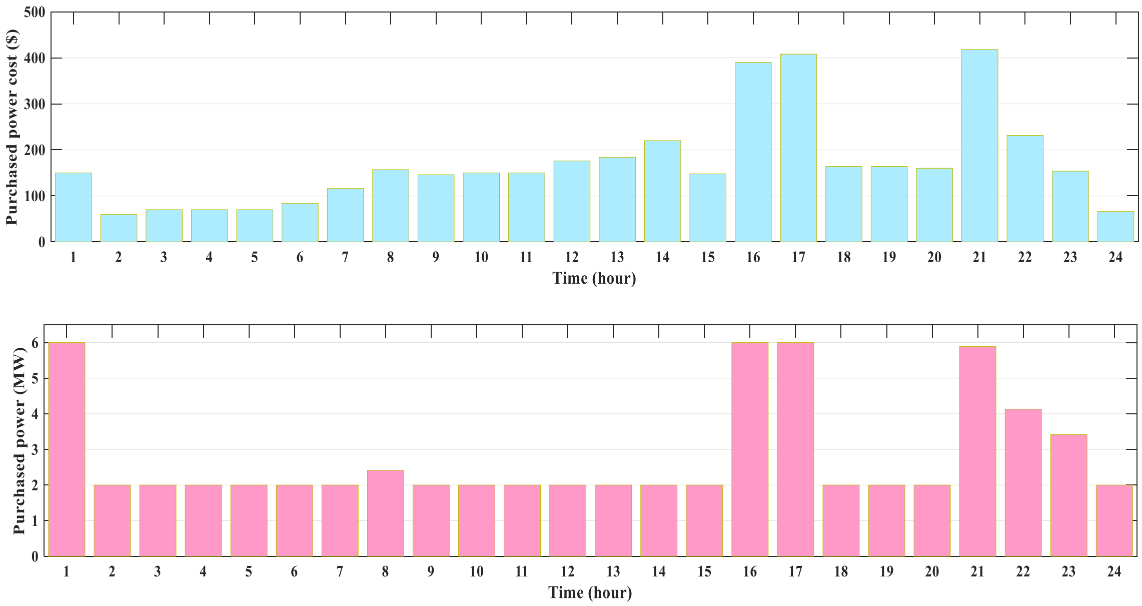

Fig.23. Power purchased and cost of power purchased through bilateral contracts in case 1

2) Case 2

In case 2, operator can decide to purchase electricity from any contract at any time. Figure 24 shows purchased power and cost of purchased power through bilateral contracts. It can be seen from Figure 24, all four contracts are selected. According to the Figure 24, purchased power and cost of electricity purchased from contract #1 are 3.91 MW and $215.57, purchased power and cost of electricity purchased from contract #2 are 14.91 MW and $496.87, purchased power and cost of electricity purchased from contract #3 are 25.97 MW and $1523.83, and purchased power and cost of electricity purchased from contract #4 are 9.5 MW and $618, respectively. It is clear that a high share of electricity is procured through contract #3.

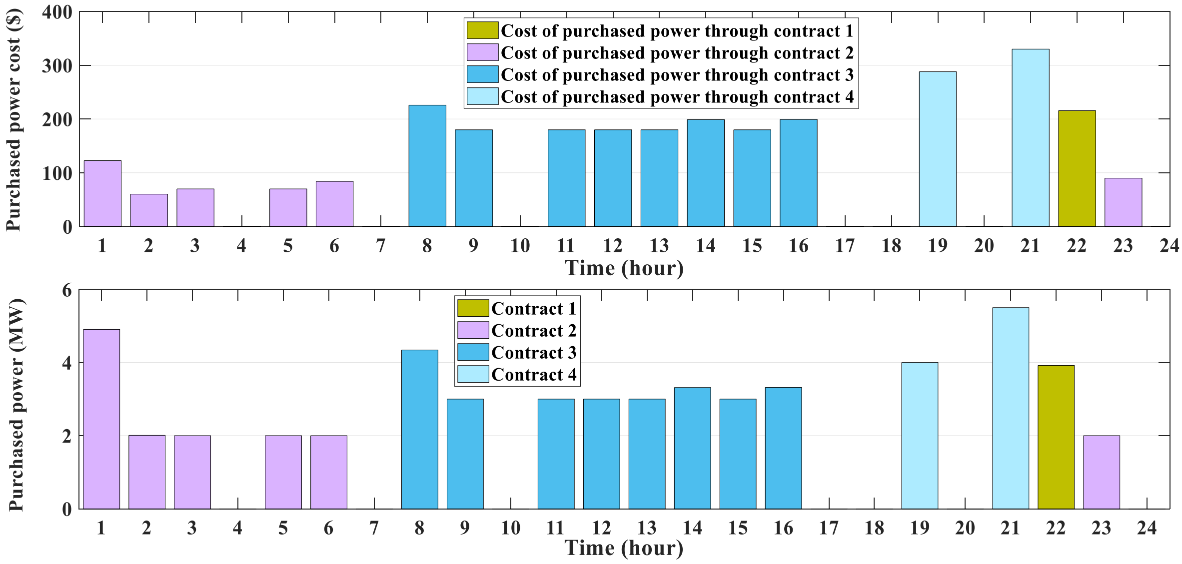

Fig.24. Power purchased and cost of power purchased through bilateral contracts in case 2

3) Case 3

In case 3, operator can decide to purchase electricity from any contract at any time without the constraint of minimum purchasable power. Figure 25 shows purchased power and cost of purchased power through bilateral contracts. It can be seen from Figure 18, all four contracts are selected. According to the Figure 25, purchased power and cost of electricity purchased from contract #1 are 3.79 MW and $208.67, purchased power and cost of electricity purchased from contract #2 are 15.07 MW and $517.43, purchased power and cost of electricity purchased from contract #3 are 27.20 MW and $1592.40, and purchased power and cost of electricity purchased from contract #4 are 7.514 MW and $475.03, respectively. It is clear that a high share of electricity is procured through contract #3.

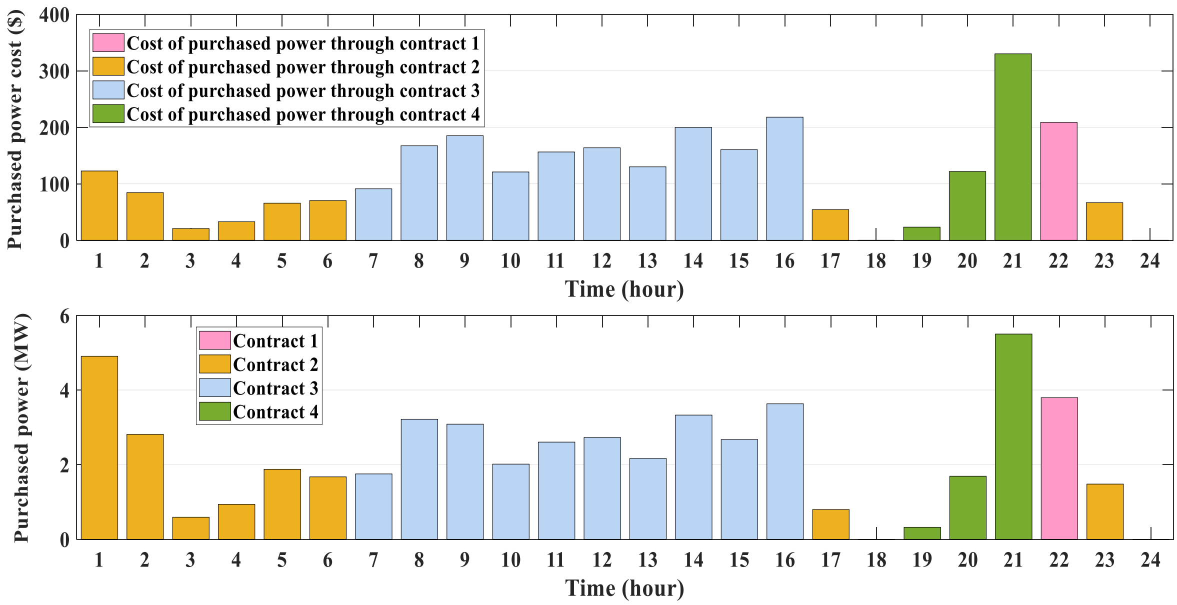

Fig.25. Power purchased and cost of power purchased through bilateral contracts in case 3

4) Case 4

In case 4, operator can only purchase electricity from one contract without the constraint of minimum purchasable power. Figure 19 shows purchased power and cost of purchased power through bilateral contracts. It can be seen from Figure 26, all four contracts are selected. According to the Figure 26, purchased power and cost of electricity purchased from contract #1 are 3.79 MW and $208.67, purchased power and cost of electricity purchased from contract #2 are 15.07 MW and $517.43, purchased power and cost of electricity purchased from contract #3 are 27.20 MW and $1592.40, and purchased power and cost of electricity purchased from contract #4 are 7.514 MW and $475.03, respectively. It is clear that a high share of electricity is procured through contract #3.

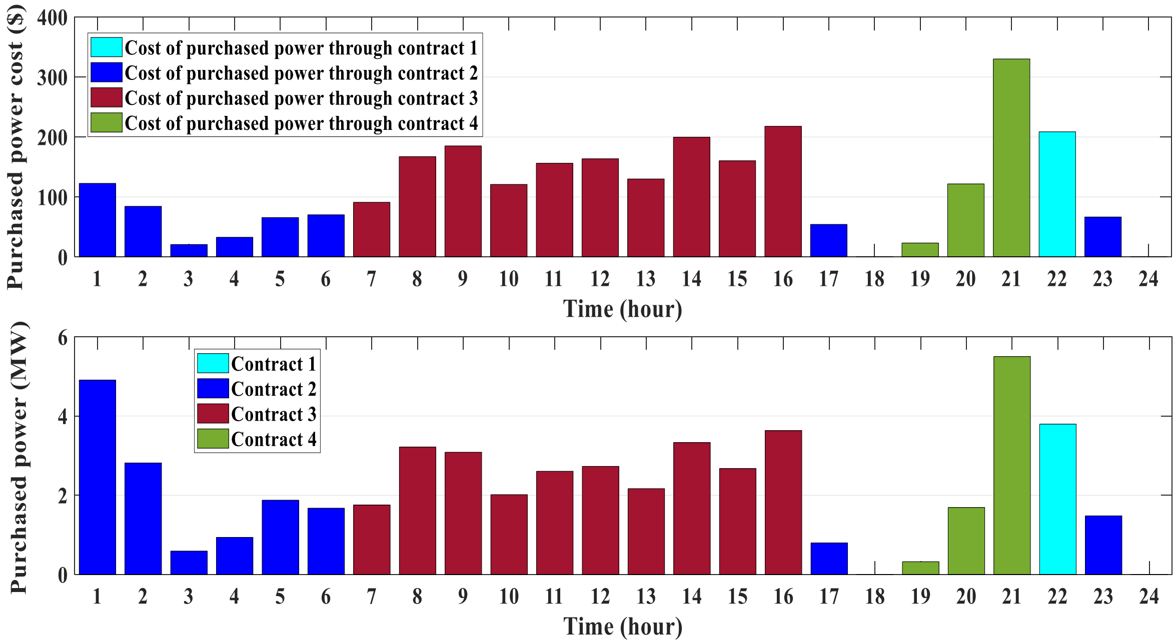

Fig.26. Power purchased and cost of power purchased through bilateral contracts in case 4

Figure 27 compares purchased power and cost of purchased power through bilateral contracts for 4 case studies. It can be seen from Figure 27 that the results obtained for cases 3 and 4 are exactly the same. The reason for this is the constraint of the minimum purchased power in two case studies. In other words, in these two case studies operator can purchase electricity from bilateral contract in order to optimal operation without the considering minimum purchasable power.

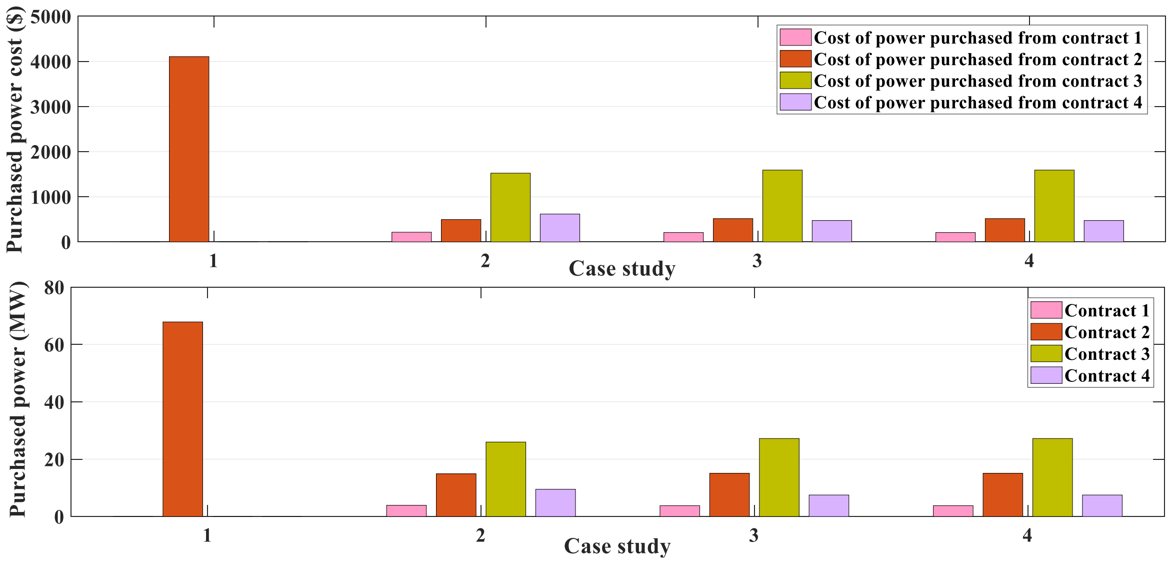

Fig.27. Power purchased and cost of power purchased through bilateral contracts for 4 cases

4.2. Effect of storage systems on operation costs

The systems improve the flexibility of MEMG in supplying demands and decrease costs of operation by charging and discharging in low-demand and high-demand hours, respectively

[6, 13]. In this case, storage systems reduce the negative effects of uncertainties in operation of MEMG. In the following, the impact of the storages on EOC of MEMG and CVaR are assessed. Table 9 shows the data of the storage systems.

Table 9. Input data of energy storage systems

	Storages		
	ESS	**TSS**	**HSS**
Min. charging power (MW)	0.05	0.05	0.05
Max. charging power (MW)	3	3	3
Min. discharging power (MW)	0.05	0.05	0.05
Max. discharging power (MW)	3	3	3
Charging efficiency	0.95	0.95	0.95
Discharge efficiency	0.95	0.95	0.95
Min. energy (MWh)	0.1	0.1	0.1
Max. energy (MWh)	4	4	4
Initial energy (MWh)	0.25	0.25	0.25
Storage loss factor	0.001	0.001	0.001

Figure 28 and Table 10 illustrate MEMG operation cost in a variety of storages and scenarios. As it was mentioned in section 4.1, 10 scenarios are considered in this study. According to Figure 28 and also Table 10, operation cost of MEMG for different combination of storage systems in ninth scenario is smaller than other scenarios. It is clear that the lowest cost in ninth scenario occurs when all energy storage systems are present. Also, it can be seen from Figure 28, the largest cost for all scenarios occurs when none of storage systems are present.

Table 10. MEMG operation costs in different scenarios

Components ($)	**Scenarios**									
	S1	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S10**
No storage	8492.05	8690.17	8523.34	8560.85	8442.11	8718.74	8351.76	8405.75	8268.91	8350.09
Only ESS	8291.05	8500.77	8333.03	8365.01	8249.22	8541.17	8160.17	8212.49	8076.59	8167.76
Only TSS	8374.97	8577.86	8408.16	8445.72	8325.27	8607.45	8235.03	8291.70	8151.32	8236.35
Only HSS	8293.02	8492.33	8324.45	8358.08	8240.50	8531.98	8157.92	8212.78	8068.62	8161.15
TSS and HSS	8181.34	8385.77	8214.14	8251.27	8129.56	8422.09	8045.38	8103.10	7957.57	8051.36
ESS and TSS	8185.92	8394.43	8222.28	8259.56	8139.20	8428.97	8061.67	8109.35	7976.48	8066.81
ESS and HSS	8115.88	8328.50	8158.81	8187.40	8073.54	8365.99	7989.62	8039.54	7900.86	7993.94
ALL	8016.77	8225.26	8053.79	8082.71	7969.10	8255.57	7897.93	7942.21	7811.21	7901.79

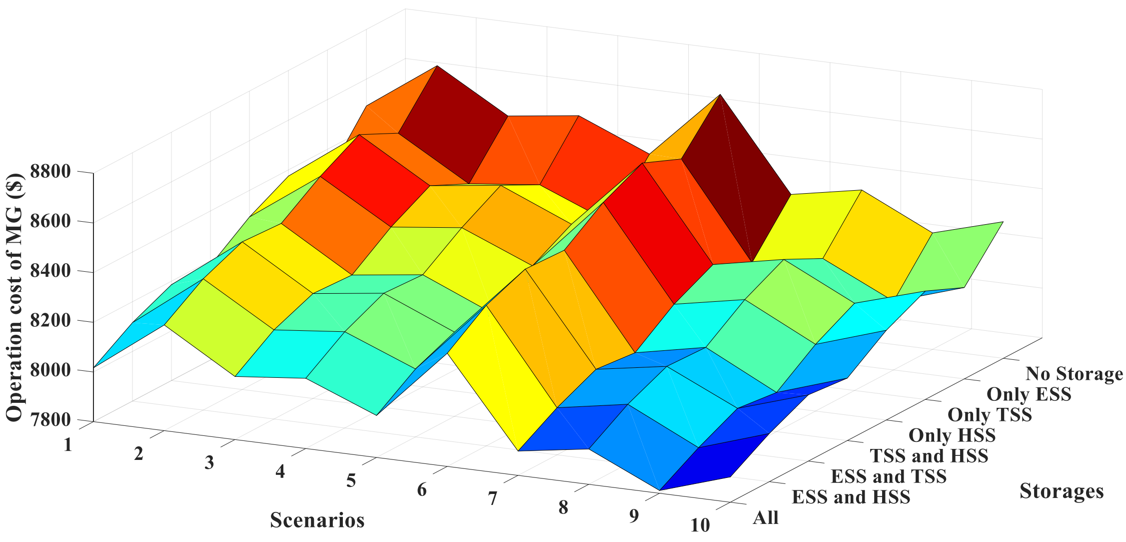

Fig.28. Operation cost of MEMG in different storages and scenarios

Figures 29-31 illustrate charging and discharging power of ESS, TSS and HSS at different times and scenarios, respectively. It can be seen from the Figures 29-31, ESS is charged in low-demand hours such as 1-6 and 15-18 and is discharged in high-demand hours such as 7-12 and 18-20; TSS is charged in low-demand hours such as 1-6 and is discharged in high-demand hours such as 7-22; and HSS is charged in low-demand hours such as 1-6 and is discharged in high-demand hours such as 7-14 and 16-21. In addition, it can be found from the figures, charging power of storages systems is higher in low-demand hours and discharging power of storages systems is lower in high-demand hours.

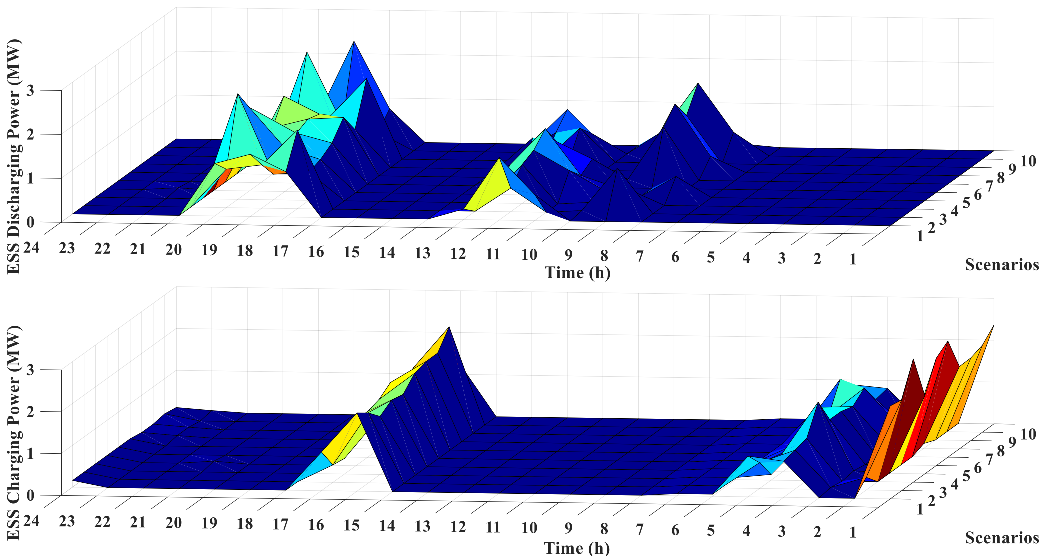

Fig.29. ESS power at different scenarios

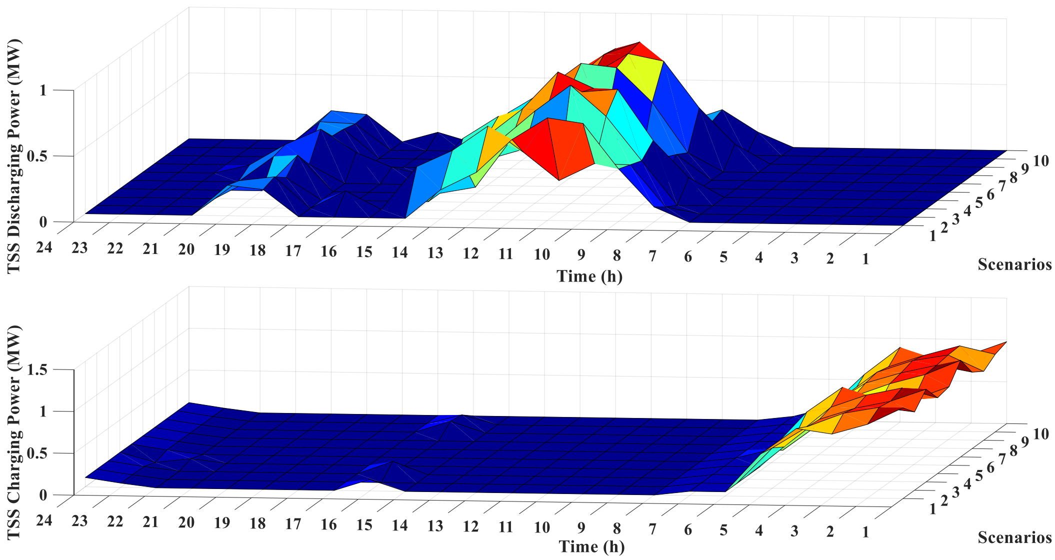

Fig.30. TSS charging power at different scenarios

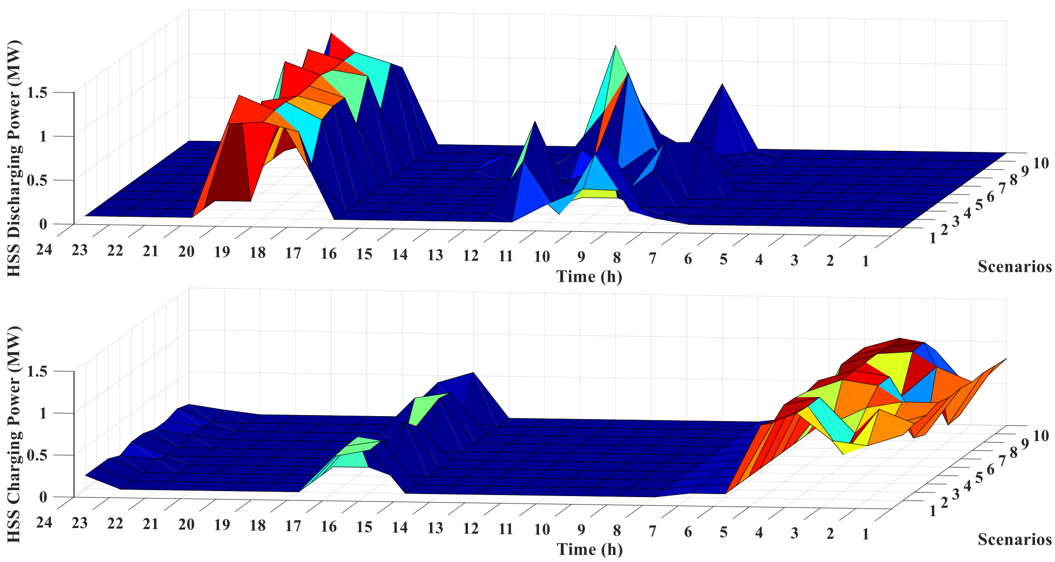

Fig.31. HSS charging power at different scenarios

Figure 32 shows the impact of storages on the operation cost of MEMG. It can be seen from Table 21, different combinations of the storages are used to evaluate their effect on EOCs of MEMG. It is obvious that the effect of different storages on the EOC of MEMG depends on different parameters such as the MEMG model studied, energy pricing patterns and so on. According to Figure 33, the EOC of MEMG without storages is $8484.18, while EOC of MEMG with all of the storages is $8018.14. In this case, EOC of MEMG with the presence of ESS, TSS and HSS storages is decreased by 2.26%, 1.36% and 2.32%, respectively. However, thermal storage system has smaller impact on the EOCs of MEMG compared to the ESS and HSS. It is clear that storages decrease EOC of MEMG by 6%.

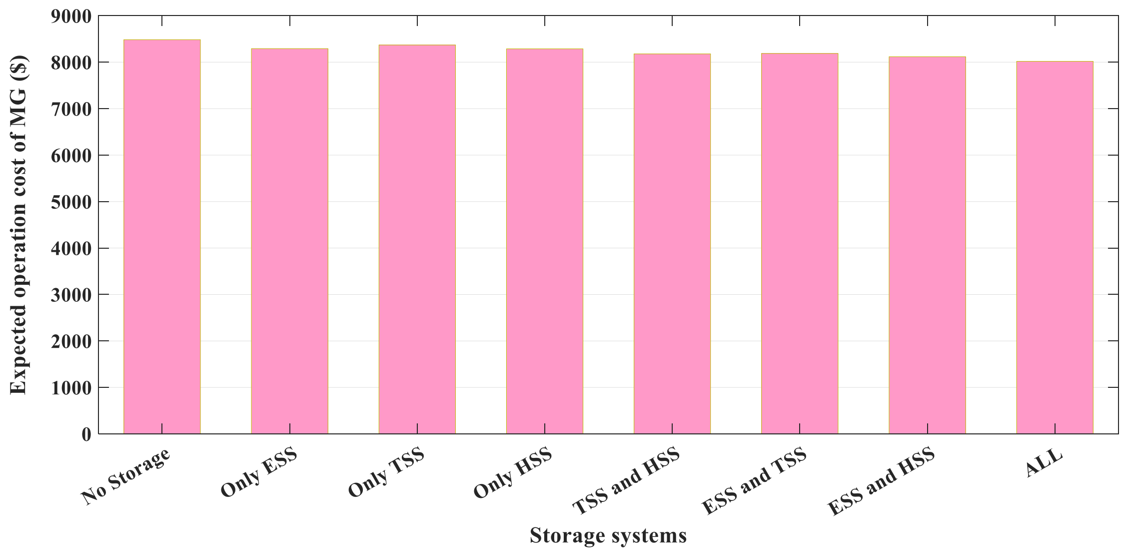

Fig.32. Effect of storages on EOC of MEMG

Figure 33 shows the impact of diverse storage systems on CVaR of MEMG operation cost. According to Figure 33, CVaR of operation cost without these systems is $8856.48, while CVaR of operation cost with all of the storages is $8718.73. It can be found that CVaR of operation cost of MEMG with the considering of ESS, TSS and HSS storages is decreased by 2.03%, 1.28% and 2.14%, respectively. As a result, storage systems reduce CVaR of MEMG operation cost, decreasing the risk of high operation costs.

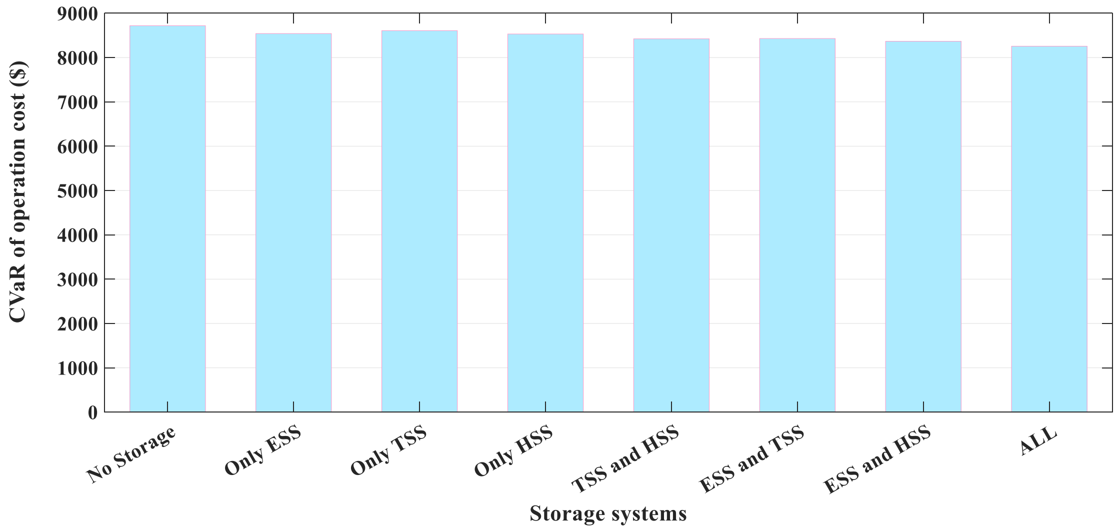

Fig.33. Effect of storages on CVaR of operation cost

Figure 34 illustrates the effect of storage systems on expected cost of electricity purchased from pool market, expected purchased electricity cost from bilateral contracts, and total expected cost of electricity purchased. According to Figure 34, total expected cost of electricity purchased without storages is $5156.60, while the cost by considering all of the storages is $4461.78. In this case, storage systems decrease expected purchased electricity costs by 13.47%.

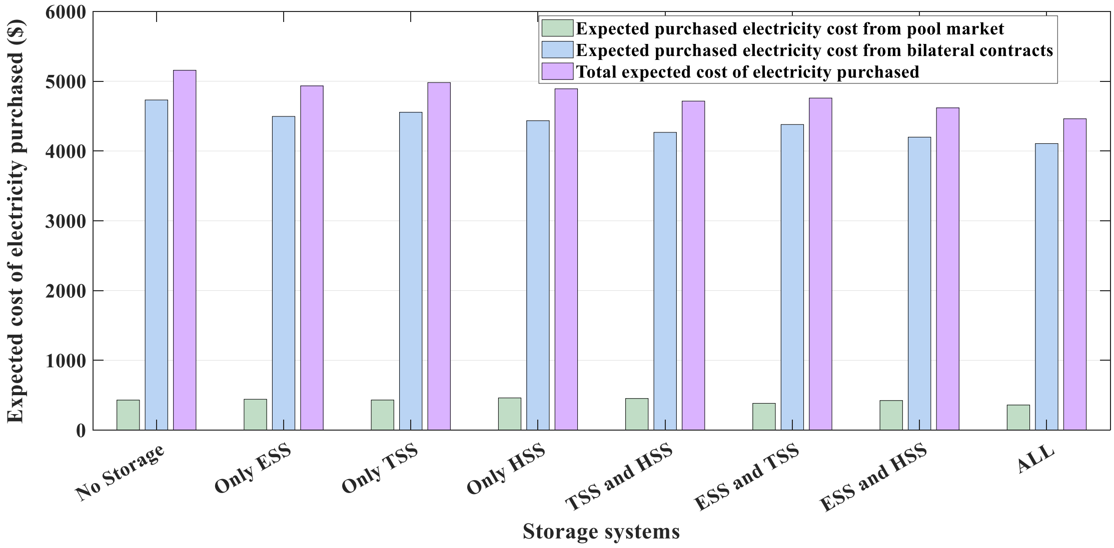

Fig.34. Effect of storages on expected cost of electricity purchased

As a result, storage systems decrease the costs of electricity purchased by charging at minimum price and load, and discharging at maximum price and load, reducing operation costs of MEMG.

4.3. Effect of DR programs on operation costs

In DR programs, demands are met in such a way that part of the demand shifts from peak demand hours and energy carrier prices to low demand and energy price times, reducing the operations cost of MEMG [6, 13]. In this section, the effect of electrical, thermal and hydrogen DR programs on different components of MEMG operations costs is evaluated. Figures 35-37 show the effect of DR on EOC of MEMG, CVaR of operation cost and expected cost of electricity purchased, respectively.

According to Figure 35, the EOC of MEMG without DRs is $8378.55, while EOC of MEMG with all of the DRs is $8018.14. In this case, EOC of MEMG with the presence of EDR, TDR and HDR programs is decreased by 3.57%, 0.3% and 0.7%, respectively. DR programs decrease EOC of MEMG by 4.57%. However, TDR program has smaller impact on the EOCs of MEMG compared to other programs.

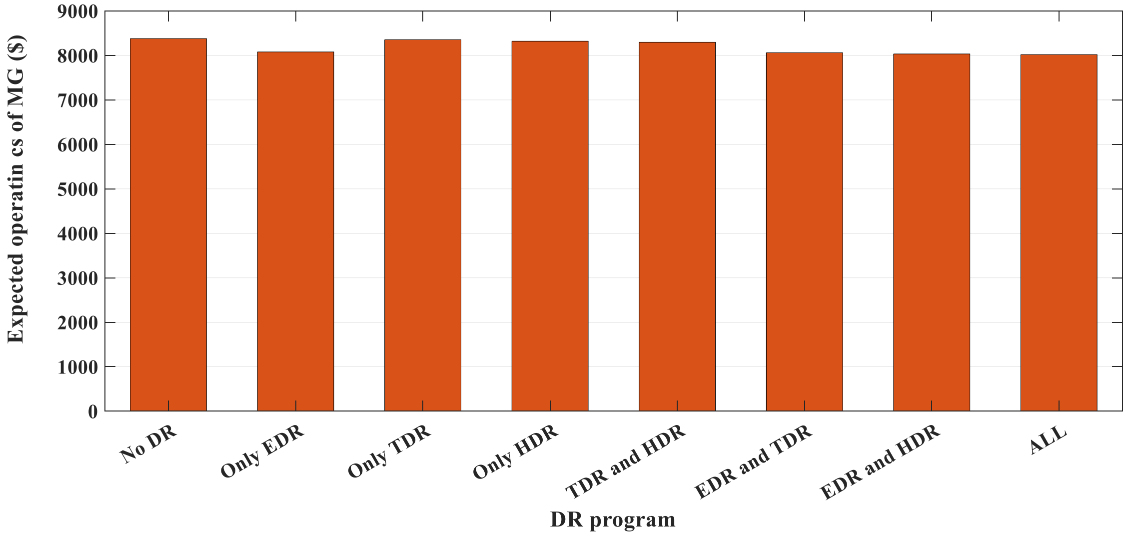

Fig.35. Impact of DR on EOC of MEMG

Figure 36 shows the impact of DR programs on CVaR of MEMG operation cost. According to Figure 36, CVaR of operation cost without these programs is $8709.86, while CVaR of operation cost with all of the DR programs is $8428.94. CVaR of MEMG operation cost for EDR, TDR and HDR programs is $8328.88, $8611.01 and $8570.11, respectively. In this case, CVaR of operation cost of MEMG with the presence of EDR, TDR and HDR programs is decreased by 3.55%, 0.29% and 0.76%, respectively. It is obvious that DR programs reduce CVaR of MEMG operation cost by 4.6%, decreasing the risk of the cost increment.

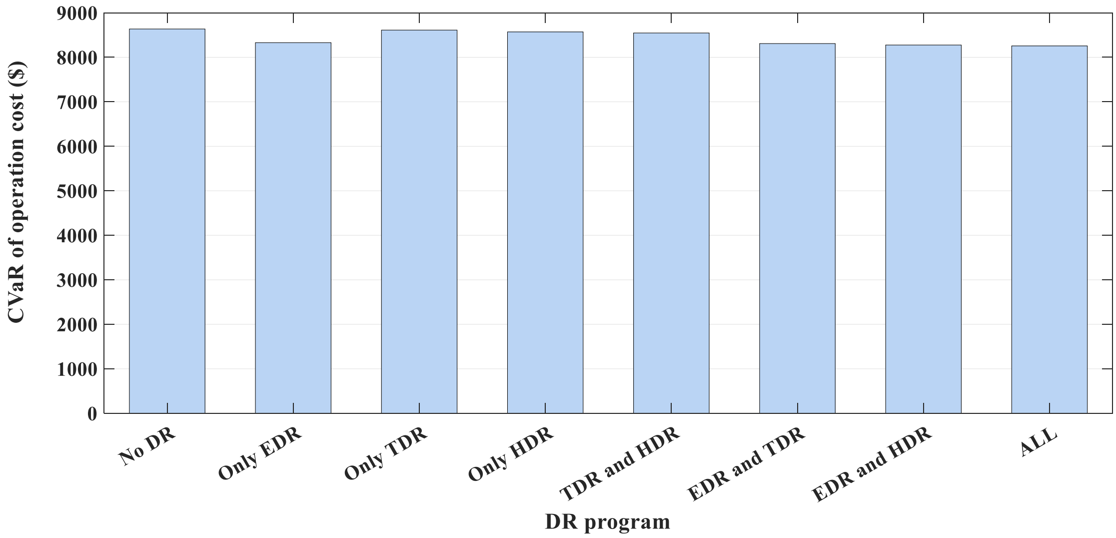

Fig.36. Effect of DR on CVaR of operation cost

Figure 37 indicates the effect of DR programs on expected purchased electricity cost from pool market, expected purchased electricity cost from bilateral contracts, and total expected cost of electricity purchased. According to Figure 37, total expected cost of electricity purchased without DRs is $5216.19, while the cost by considering all of the DRs is $4461.78. It is apparent that DR programs reduce expected cost of purchased electricity by 14.46%.

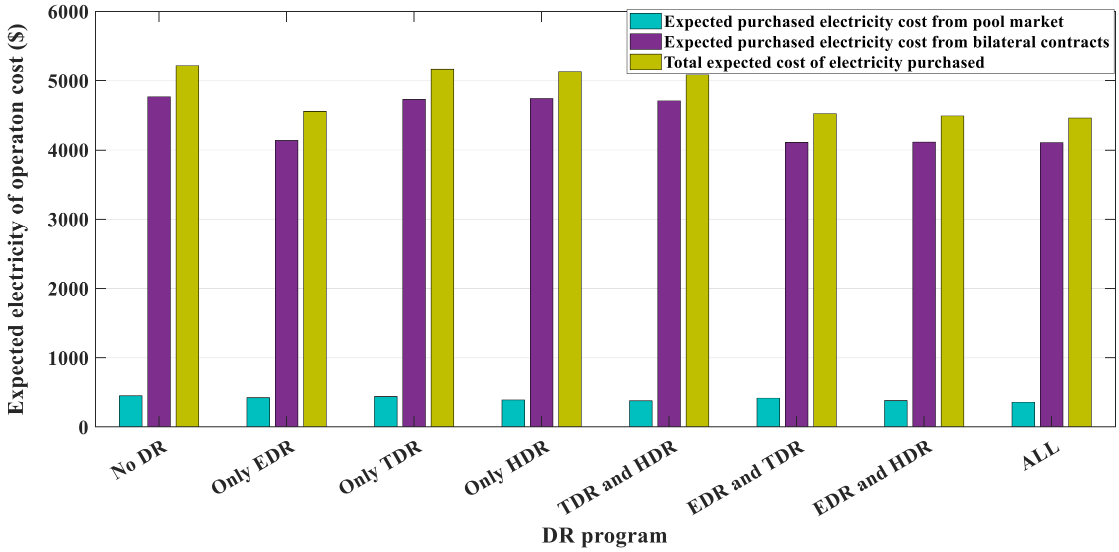

Fig.37. Effect of DR on expected cost of purchased electricity

Overall, the analysis of the above results shows that DR programs assist the continuous use of renewable sources and reduce the amount of purchased electricity and power spillage with shift-up and shift-down the demands, reducing the operation costs of MEMG. Figures 38-40 show the shift-up/down in demands. For electric demand, the shift-up at hours 1-8 and 22-24, and the shift down at hours 17-22 are observed. The same can be explained for other demands [13].

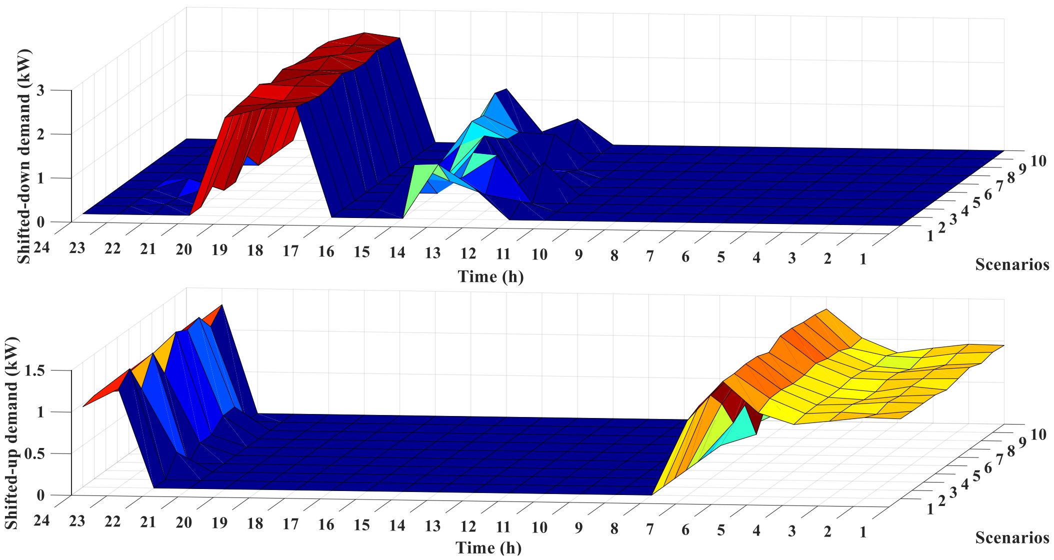

Fig.38. Shifted-up and down electric demand

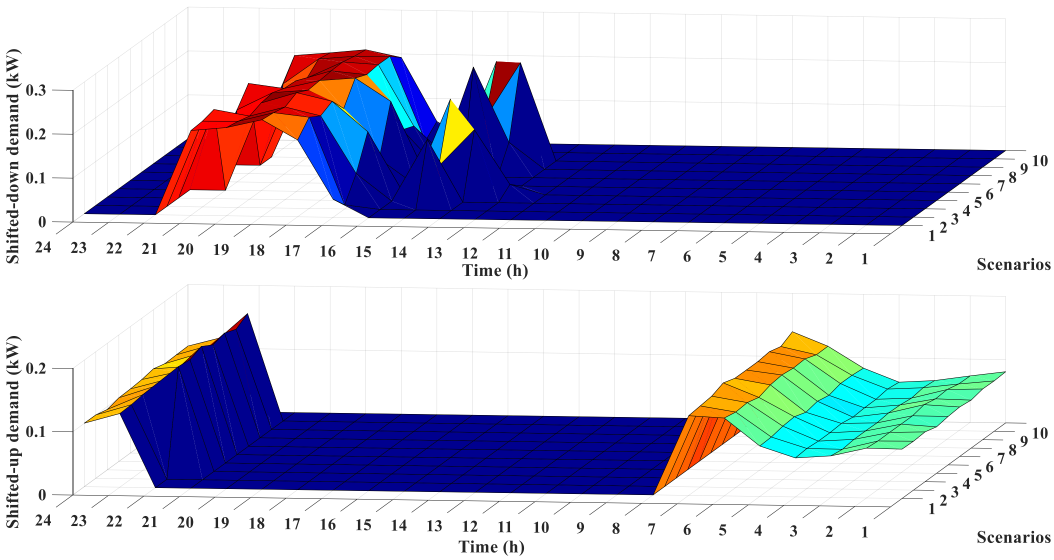

Fig.39. Shifted-up and down thermal demand

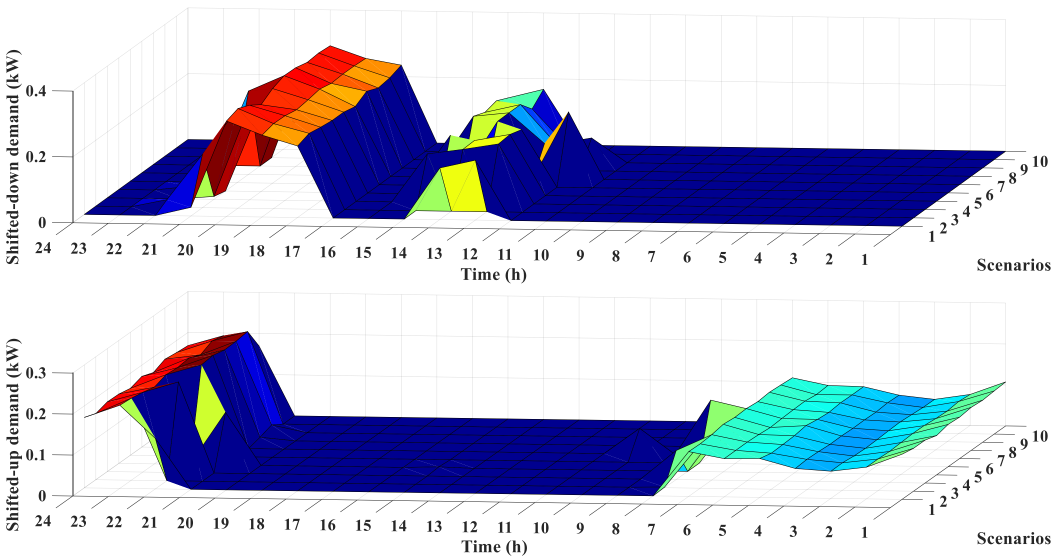

Fig.40. Shifted-up and down hydrogen demand

4.4. Effect of contingency events on the MEMG operation

Over the operation of MEMG, contingency events including outage of different components or unavailability of sources may occur. Therefore, study of MEMG performance in these events and also assessment of their effect on scheduling of MEMG in order to reduce load shedding and operation costs is of considerable importance. In the following, effect of events on MEMG is presented.

In this section, effect of outage of components for just hours 22-24 per day on operation of MEMG is assessed. In contingent events, equipment is exited. Table 11 shows the MEMG operation costs in the different contingencies.

Table 11. Components of MEMG operation costs in different events

Exp. cost components ($)	Normal operation	Outage		
		Boiler	CHP	Electrolyzer
Exp. operation cost	8018.14	8033.04	8860.16	8211.05
Purchased electricity cost (Sum of purchased electricity cost from pool market and bilateral contracts)	4461.77	4471.71	5919.22	4662.73
Exp. Purchased electricity cost from pool market	359.47	359.33	551.01	440.43
Purchased electricity cost from bilateral contracts	4106.40	4116.49	5373.58	4226.53
Exp. CHP cost	3351.63	3350.00	2729.65	3331.67
Exp. boiler cost	48.08	44.84	51.07	47.98
Exp. spillage cost	-	-	0.053	-
Exp. total shed cost	-	-	-	-
Exp. start-up/shut-down cost	-	9.99	4.99	3.99
Exp. EDR cost	182.98	183.18	183.31	190.09
Exp. TDR cost	9.23	8.87	6.48	10.02
Exp. HDR cost	9.25	9.27	10.19	9.37
Exp. DR cost	201.47	201.33	199.99	209.49

As shown in Table 11, no event or outage of equipment in hours 22-24 leads to load shedding, and all demands are supplied completely. In this case, EOC of MEMG for outage of boiler, CHP and electrolyzer is $8033.04, $8860.16 and $8211.05, respectively. It is clear that EOC in case of CHP exit is higher than that for other cases. The reason for that is that when CHP is exited, the electrical and thermal energy required for supplying electrical, thermal and hydrogen loads must be supplied from pool market, bilateral contracts and boiler, respectively. It can be seen from Table 11, expected purchased electricity cost from pool market and bilateral contracts is $551.01 and $5373.58 in case of CHP exit, respectively. These values indicate the increase of 53.28% and 30.85% in expected purchased electricity cost from pool market and bilateral contracts in case of CHP exit compared to the case of normal operation.

In the following, effect of unavailability or out of service of sources for just hours 22-24 per day on operation of MEMG is studied. Table 12 shows the MEMG operation costs in the different contingencies.

Table 12. Components of MEMG operation costs in different events

Exp. cost components ($)	Normal operation	Unavailability						
		PV	Wind	PV and Wind	Biomass	Pool market	Bilateral contracts	Pool market and bilateral contracts
Exp. operation cost	8018.14	8018.14	8296.97	8296.97	8037.87	8018.32	7847.99	7868.99
Purchased electricity cost (Sum of purchased electricity cost from pool market and bilateral contracts)	4461.77	4461.77	4666.64	4666.64	4466.62	4463.27	4245.55	4257.38
Exp. Purchased electricity cost from pool market	359.47	359.47	363.23	363.23	359.0	361.20	218.62	170.98
Purchased electricity cost from bilateral contracts	4106.40	4106.40	4307.71	4307.71	4111.64	4106.17	4030.96	4090.49
Exp. CHP cost	3351.63	3351.63	3424.61	3424.61	3356.87	3351.63	3393.47	3392.17
Exp. boiler cost	48.08	48.08	50.59	50.59	48.12	48.08	47.06	47.09
Exp. spillage cost	-	-	-	-	-	-	-	-
Exp. total shed cost	-	-	-	-	-	-	-	-
Exp. start-up/shut-down cost	-	-	-	-	3.99	-	-	-
Exp. EDR cost	182.98	182.98	181.81	181.81	182.98	181.63	187.08	196.94
Exp. TDR cost	9.23	9.23	8.74	8.74	9.2323	9.23	7.86	7.28
Exp. HDR cost	9.25	9.25	9.38	9.38	9.25	9.28	11.78	12.96
Exp. DR cost	201.47	201.47	199.95	199.95	201.47	200.15	206.73	217.19

As shown in Table 12, no contingency event or unavailability of sources in hours 22-24 leads to load shedding, and all demands are supplied completely. In this case, EOC of MEMG for unavailability of PV, unavailability of wind, simultaneous unavailability of PV and Wind, unavailability of Biomass, unavailability of pool market, unavailability of bilateral contracts and finally simultaneous unavailability of pool market and bilateral contracts is $8018.14, $8296.97, $8296.97, $8037.87, $8018.32, $7847.99 and $7868.99, respectively. It is clear that EOC in case of unavailability of PV is higher than that for other cases. The reason for that is that when PV is not available, the electrical energy required for supplying electrical, thermal and hydrogen loads must be supplied by pool market, bilateral contracts, boiler and CHP. It can be seen from Table 12, expected purchased electricity cost from pool market and bilateral contracts is $363.23 and $4307.71 in case of unavailability of wind, respectively. It is worth stating that operation costs of MEMG in the case of unavailability of PV are equal the normal operation. Because PV has no electricity generated in the case of normal operation during hours 22-24 and therefore its unavailability in these hours do not increase the operation costs of MEMG.

In addition, in case of unavailability of pool market and bilateral contracts, expected DR cost show increase of 7.80% compared with the case of normal operation. Figure 41 shows the shift-up/down electric demand in case of unavailability of pool market and bilateral contracts.

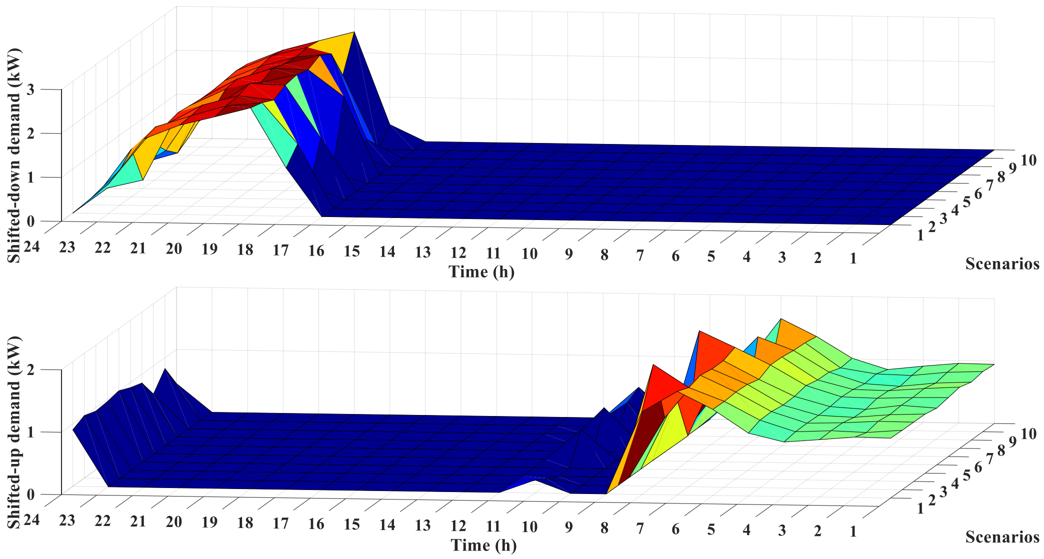

Fig.41. Shifted-up and down electric demand in case of unavailability of pool market and bilateral contracts

According to Figure 41, shifted-up/down in electric demand in case of unavailability of pool market and bilateral contracts is higher than that for other cases. The increase of shifted-up/down electric demand in the case of pool market and bilateral contracts exit compared to the case of normal operation is due to the reduction of purchased electric energy and increase of unsupplied load.

In this section, effect of outages of components for 24 hours or one day on MEMG operation is studied. Table 13 shows the MEMG operation costs in the different contingencies.

Table 13. Components of MEMG operation costs in different events

Exp. cost components ($)	Normal operation	Outage		
		Boiler	CHP	Electrolyzer
Exp. operation cost	8018.14	8143.90	15014.33	12365.16
Purchased electricity cost (Sum of purchased electricity cost from pool market and bilateral contracts)	4461.77	4669.10	11315.65	3334.39
Exp. Purchased electricity cost from pool market	359.47	449.94	236.82	157.05
Purchased electricity cost from bilateral contracts	4106.40	4223.38	11089.92	3180.52
Exp. CHP cost	3351.63	3305.15	-	3112.54
Exp. boiler cost	48.08	-	53.28	3112.54
Exp. spillage cost	-	-	0.17	-
Exp. electric shed cost	-	-	-	-
Exp. thermal shed cost	-	-	3499.12	-
Exp. hydrogen shed cost	-	-	-	5713.08
Exp. total shed cost	-		3499.12	5713.08
Exp. start-up/shut-down cost	-	9.99	5.00	3.99
Exp. EDR cost	182.98	184.92	175.17	190.82
Exp. TDR cost	9.23	9.65	0.00	9.01
Exp. HDR cost	9.25	9.94	10.78	0
Exp. DR cost	201.47	204.50	185.95	199.83

As shown in Table 13, outage of CHP and electrolyzer lead to thermal and hydrogen load shedding, respectively. While, electric demand is fully supplied. When CHP is exited, MEMG supplies needed electric energy for supplying electric demand from bilateral contracts. In this case, EOC of MEMG for outage of boiler, CHP and electrolyzer is $8143.90, $15014.33 and $12365.16, respectively. It is clear that EOC in case of CHP exit is higher than that for other cases. The reason for that is that when CHP is exited, the electrical and thermal energy required for supplying electrical, thermal and hydrogen loads must be supplied from bilateral contracts and boiler, respectively. It can be seen from Table 13, expected purchased electricity cost from bilateral contracts is $11089.92 in case of CHP outage. This value indicate the increase of 170.06% in expected purchased electricity cost from bilateral contracts compared to the case of normal operation.

In the following, effect of unavailability or out of service of sources for 24 hours or one day on MEMG operation is studied. In these conditions, source is unavailable for different reasons. For instance, the performance of the PV and wind units depends on the weather conditions. By reduction in solar radiation and wind speed, the MEMG faces a shortage in power generation. In this regard, seven contingent events including unavailability of PV, unavailability of wind, simultaneous unavailability of PV and wind, unavailability of biomass, unavailability of pool market, unavailability of bilateral contracts and finally simultaneous unavailability of pool market and bilateral contracts are considered, and the scheduling of MEMG under these events is evaluated. Table 14 shows the MEMG operation costs in the different contingency events.

Table 14. Components of MEMG operation costs in different events

Exp. cost components ($)	Normal operation	Unavailability							
		PV	Wind	Biomass	PV and Wind	PV, Wind and Biomass	Pool market	Bilateral contracts	Pool market and bilateral contracts
Exp. operation cost	8018.14	9442.96	10720.39	8182.9	12061.28	12237.05	8176.30	15699.75	19870.68
Purchased electricity cost (Sum of purchased electricity cost from pool market and bilateral contracts)	4461.77	5924.87	7025.89	4565.38	8371.12	8500.08	4735.51	1411.33	-
Exp. Purchased electricity	359.47	145.30	270.73	437.03	375.91	404.19	-	1411.33	-

cost from pool market									
Purchased electricity cost from bilateral contracts	4106.40	5785.36	6761.92	4132.48	8003.21	8103.99	4740.25	-	-
Exp. CHP cost	3351.63	3322.69	3452.30	3365.22	3453.69	3456.33	3277.81	3465.14	3467.41
Exp. boiler cost	48.08	44.59	52.72	48.48	52.32	52.97	45.25	53.13	53.13
Exp. spillage cost	-	-	-		-	-	0.04	-	-
Exp. electric shed cost	-	-	-		-	-	-	5552.49	10833.72
Exp. thermal shed cost	-	-	-		-	-	-	-	-
Exp. hydrogen shed cost	-	-	-		-	-	-	5093.07	5447.59
Exp. total shed cost	-	-	-		-	-	-	10645.56	16281.32
Exp. start-up/shut-down cost	-	-	-		-	-	-	6.99	6.99
Exp. EDR cost	182.98	175.97	215.58	185.01	205.56	204.21	142.44	153.67	100.10
Exp. TDR cost	9.23	8.23	7.18	9.29	11.00	11.08	9.82	7.41	5.93
Exp. HDR cost	9.25	11.45	11.56	9.51	12.43	12.36	10.26	1.35	0.61
Exp. DR cost	201.47	195.64	234.33	203.82	228.99	227.66	162.52	162.43	106.64
CVaR of operation cost	8255.57	9669.27	10815.71	8430.19	12185.03	12360.91	8365.99	16672.18	20856.47

As shown in Table 14, unavailability of bilateral contracts and also simultaneous unavailability of pool market and bilateral contracts lead to just electric and hydrogen load shedding, respectively, while thermal demand is fully met. In other cases, there is no load shedding and all demands are supplied completely. In this case, EOC of MEMG for unavailability of PV, unavailability of wind, unavailability of biomass, simultaneous unavailability of PV and wind, simultaneous unavailability of PV, wind and biomass, unavailability of pool market, unavailability of bilateral contracts and finally simultaneous unavailability of pool market and bilateral contracts is \$9442.96, \$10720.39, \$8182.9, \$12061.28, \$12237.05, \$8176.3, \$15699.75 and \$19870.68, respectively. These values show the increase of 17.77%, 33.7%, 50.42%, 2.05%, 1.97%, 95.8% and 147.82% in MEMG operation costs with respect to the normal operation costs. It can be found from Table 15 that RES (PV, wind and biomass) can decrease operation costs by 34.47%.

The increase of 17.77% and 33.7% of operation costs in case of unavailability of PV and wind is due to the increase in purchasing electricity from bilateral contracts, and the increase of 50.42% of operation costs in case of unavailability of PV and wind simultaneously is due to the increase in the purchase of electricity from the pool market and bilateral contracts. Therefore, in case of unavailability of PV and wind, the electricity required by MEMG is provided by the pool market and bilateral contracts.

The increase of 1.97% of operation costs in case of unavailability of pool market is due to the increase in purchasing electricity from bilateral contracts. The increase of 95.8% in case of unavailability of bilateral contracts is due to the increase in purchasing electricity from pool market, the increase of CHP and boiler costs, and electric and hydrogen load shedding costs. The increase of 147.82% of operation costs in case of simultaneous unavailability of pool market and bilateral contracts is due to the increase of CHP and boiler costs, and electric and hydrogen load shedding costs.

It is obvious that EOC in case of simultaneous unavailability of pool market and bilateral contracts is higher than that for other cases, followed by unavailability of bilateral contracts. The reason for this increase is that when bilateral contracts is not available, the electrical energy required for supplying electrical and hydrogen loads must be supplied by pool market and CHP. In such conditions, pool market and CHP can supply some of the electrical energy required by MEMG according to their maximum capacity. However, rest of unsupplied load must be shed.

In addition, expected DR cost shows an increase of 16.33% compared to the case of normal operation in case of unavailability of wind. As shown in Table 14, due to the certain prices of bilateral contracts, the possibility of transaction by bilateral contracts decreases the risk metric CVaR by 50.42%. Figure 42 shows the shift-up/down electric demand in this case. It is obvious that shifted-up/down electric demand in case of unavailability of wind is higher than that for other cases. The reason for this increase compared to the normal operation is due to the unavailability of wind and increase of unsupplied load.

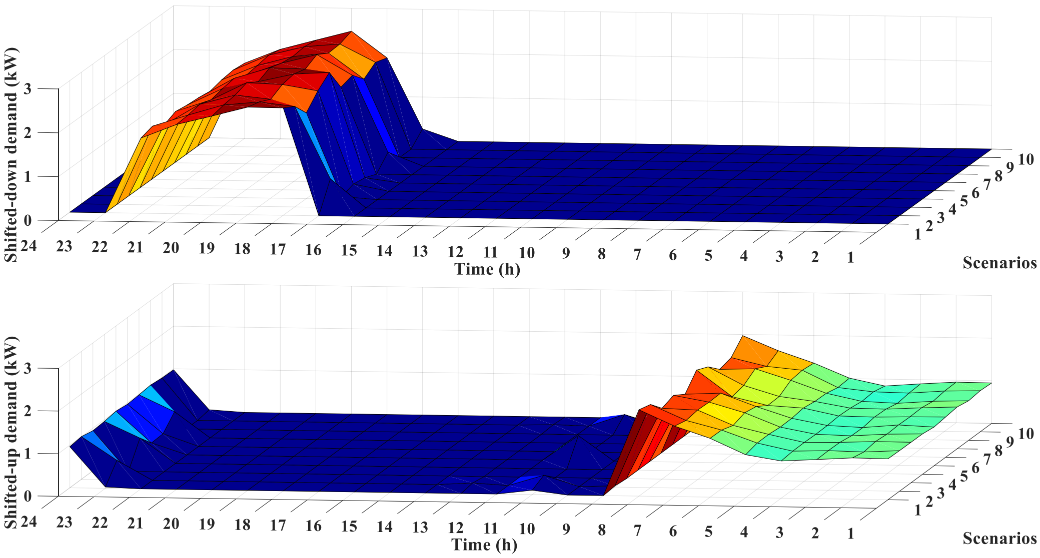

Fig.42. Shifted-up and down electric demand in unavailability of wind

It can be seen from Table 14 that bilateral contracts play the effective role in supplying demands over the operation of MEMG. Table 15 shows the MEMG operation costs in case of unavailability of bilateral contracts in considered scenarios.

Table 15. MEMG operation costs considering unavailability of bilateral contracts

Components	Scenarios									
	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
Operation cost ($)	15664.26	16526.73	16017.37	15904.40	15468.60	16672.18	15232.62	15325.74	14835.96	15136.24
Purchased electricity cost (Sum of purchased electricity cost from pool market and bilateral contracts) ($)	1409.57	1399.90	1389.50	1410.20	1413.60	1402.53	1423.40	1428.00	1425.32	1435.27
Purchased electricity cost from pool market ($)	1409.57	1399.90	1389.50	1410.20	1413.60	1402.53	1423.40	1428.00	1425.32	1435.27
Purchased electricity cost from bilateral contracts ($)	-	-	-	-	-	-	-	-	-	-
Unsupplied electrical load (MW)	22.05	25.32	23.64	23.53	21.26	25.92	20.22	20.69	18.63	19.81
Electrical load shedding cost ($)	5509.29	6331.75	5907.21	5883.88	5315.31	6480.26	5050.83	5171.14	4657.84	4949.42
Unsupplied thermal load (MW)	-	-	-	-	-	-	-	-	-	-
Unsupplied hydrogen load (MW)	20.38	20.58	20.31	19.86	20.33	20.58	20.42	20.34	20.42	20.37
Hydrogen load shedding cost ($)	5098.03	5148.10	5080.74	4966.09	5086.67	5145.24	5108.25	5086.68	5106.55	5093.55
Total unsupplied load (MW)	42.43	45.92	43.95	43.40	41.61	46.50	40.64	41.03	39.06	40.17
Total load shedding cost ($)	10607.5	11480.0	10987.5	10850.0	10402.5	11625.0	10160.0	10257.5	9765.0	10042.5

As per Table 15, MEMG operation cost in the ninth scenario is smaller than other scenarios while the cost in sixth scenario is the highest. It can be found from Table 15 that the ninth scenario has the lowest operation cost since it has the lowest load shedding cost, while the sixth scenario has the highest load shedding and operation cost. In the ninth scenario, total unsupplied load including unsupplied electrical load (18.63 MW) and unsupplied hydrogen load (20.42 MW) is 39.05 MW that is the lowest value of unsupplied load among ten scenarios. In sixth scenario, total unsupplied load including unsupplied electrical load (25.92 MW) and unsupplied hydrogen demand (20.58 MW) is 46.50 MW that is the highest value of unsupplied load among the all scenarios.

Table 16 shows electrical energy balance in MEMG in case of unavailability of bilateral contracts in different scenarios. According to Table 16, electrical energy generated in MEMG cannot supply all demands, resulting in electrical load shedding of 22.05, 25.32, 23.64, 23.53, 21.26, 25.92, 20.22, 20.69, 18.63 and 19.81 MW for ten scenarios, respectively. Although the amount of unsupplied electrical load is accounted for only 8.92%, 10.27%, 9.65%, 9.49%, 8.56%, 10.47%, 8.17%, 8.43%, 7.58% and 7.99% of the total electrical load for 10 scenarios, respectively and rest of the electrical load is supplied, completely. It is worth stating that unsupplied electrical load is accounted for a small share of the electric demand, while EVCS, CM, ESS charging power, shifted-up electrical demand and HE are fully met.

Table 16. Electrical energy balance in MEMG in case of unavailability of bilateral contracts

Components (MW)	**Scenarios**									
	S1	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S10**
	Electrical load									
Electric demand	215.69	215.75	214.84	216.36	216.64	217.45	215.92	214.13	214.13	214.84
EVCS	6.13	6.21	6.09	6.25	6.20	6.12	6.14	6.10	6.13	6.26
CM	12.18	12.30	12.17	12.14	12.13	12.25	12.19	12.11	12.20	12.25
ESS charging power	2.47	1.70	1.46	2.12	2.39	1.35	2.32	2.52	2.47	3.31
Shifted-up electrical demand	7.69	7.67	7.32	7.88	8.06	7.65	7.80	7.40	7.68	8.17
HE	3.00	2.83	2.87	3.16	2.82	2.73	2.93	2.94	2.94	2.92
Total electrical load	*247.16*	*246.46*	*244.75*	*247.91*	*248.24*	*247.55*	*247.3*	*245.2*	*245.55*	*247.75*
	Electrical generation									
Pool market	23.14	23.00	23.00	23.00	23.00	23.12	23.23	23.55	23.25	23.60
PV	21.83	21.14	20.70	22.04	22.60	21.93	22.22	21.83	22.60	22.70
Wind	46.33	43.90	44.91	45.95	47.34	43.92	47.78	45.67	47.29	46.59
Biomass	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24
CHP	121.77	121.74	121.71	121.46	121.69	121.62	121.82	121.67	121.74	121.81
ESS discharging power	2.11	1.45	1.23	1.81	2.05	1.15	1.99	2.15	2.12	2.83
Shifted-down electrical demand	7.69	7.67	7.32	7.88	8.06	7.65	7.80	7.40	7.68	8.17
Total electrical generation	*225.11*	*221.14*	*221.11*	*224.38*	*226.98*	*221.63*	*227.08*	*224.51*	*226.92*	*227.94*
	Electrical energy balance									
Total	*-22.05*	*-25.32*	*-23.64*	*-23.53*	*-21.26*	*-25.92*	*-20.22*	*-20.69*	*-18.63*	*-19.81*
	Unsupplied electrical load									
Electrical load shedding	22.05	25.32	23.64	23.53	21.26	25.92	20.22	20.69	18.63	19.81

Table 17 displays hydrogen energy balance in MEMG in case of unavailability of bilateral contracts. It can be seen from Table 17, hydrogen energy generated in MEMG can not supply a large share of hydrogen load due to the unavailability of bilateral contracts, resulting in hydrogen load shedding of 20.38, 20.58, 20.31, 19.86, 20.33, 20.58, 20.42, 20.34, 20.42 and 20.37 MW for ten scenarios, respectively.

Table 17. Hydrogen energy balance in MEMG in case of unavailability of bilateral contracts

Components (MW)	**Scenarios**									
	S1	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S10**
	Hydrogen load									
Hydrogen demand	20.00	20.04	19.78	19.58	19.79	19.96	19.95	19.89	19.96	19.86

HVCS	2.89	2.92	2.93	2.93	2.91	2.90	2.93	2.91	2.92	2.95
HSS charging power	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16
Shifted-up hydrogen demand	0.17	0.16	0.17	0.17	0.16	0.17	0.16	0.17	0.17	0.17
Total hydrogen load	*23.22*	*23.28*	*23.04*	*22.84*	*23.02*	*23.19*	*23.2*	*23.13*	*23.21*	*23.14*
	Hydrogen generation									
HE	2.55	2.41	2.44	2.69	2.40	2.32	2.49	2.50	2.50	2.48
HSS discharging power	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
Shifted-down hydrogen demand	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17
Total hydrogen generation	*2.84*	*2.7*	*2.73*	*2.98*	*2.69*	*2.61*	*2.78*	*2.79*	*2.79*	*2.77*
	Hydrogen energy balance									
Total	*-20.38*	*-20.58*	*-20.31*	*-19.86*	*-20.33*	*-20.58*	*-20.42*	*-20.34*	*-20.42*	*-20.37*
	Unsupplied electrical load									
Hydrogen load shedding	20.38	20.58	20.31	19.86	20.33	20.58	20.42	20.34	20.42	20.37

As a result, unavailability of bilateral contracts will led to electrical and hydrogen load shedding in all scenarios due to the influential role of this source of purchasing electrical energy in the studied MEMG. However, this influence on hydrogen load is much more than electric load.

In the following, a case can be considered in which the studied MEMG faces with simultaneous unavailability of pool market and bilateral contracts. In this case, the MEMG is not connected to grid and can only use its internal resources such as renewables energy resources to supply loads. In other words, no electricity is purchased from the grid in this case. Table 18 shows the MEMG operation costs in case of simultaneous unavailability of pool market and bilateral contracts in considered scenarios.

Table 18. MEMG operation costs considering unavailability of pool market and bilateral contracts

Components	**Scenarios**									
	S1	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S10**
Operation cost ($)	19830.41	20677.44	20188.46	20034.79	19597.70	20856.48	19409.27	19559.47	19005.86	19366.49
Purchased electricity cost from pool market ($)	-	-	-	-	-	-	-	-	-	-
Purchased electricity cost from bilateral contracts ($)	-	-	-	-	-	-	-	-	-	-
Purchased electricity cost (Sum of purchased electricity cost from pool market and bilateral contracts) ($)	-	-	-	-	-	-	-	-	-	-
Unsupplied electrical load (MW)	43.14	46.53	44.93	44.43	42.42	47.32	41.30	41.79	39.75	40.91
Electrical load shedding cost ($)	10784.56	11633.67	11231.93	11108.52	10605.40	11830.53	10326.03	10446.99	9937.76	10227.46
Unsupplied thermal load (MW)	-	-	-	-	-	-	-	-	-	-
Unsupplied hydrogen load (MW)	21.81	21.82	21.52	21.32	21.55	21.76	21.94	22.05	21.89	22.14
Hydrogen load shedding cost ($)	5453.66	5455.19	5382.69	5332.04	5389.09	5440.08	5484.79	5513.17	5474.87	5536.17
Total unsupplied load (MW)	64.95	68.36	66.46	65.76	63.98	69.08	63.24	63.84	61.65	63.05
Total load shedding cost ($)	16237.5	17090.0	16615.0	16440.0	15995.0	17270.0	15810.0	15960.0	15412.5	15762.5

It can be found from Table 18 that ninth and sixth scenarios have the lowest and highest load shedding costs among the other scenarios ($15412.5 and $17270, respectively). In all scenarios, unsupplied load is related to electrical load and hydrogen load. In ninth scenario, total unsupplied load including unsupplied electrical load (39.75 MW) and unsupplied hydrogen load (21.90 MW) is 61.65 MW. Total load shedding cost in ninth scenario is equal to 61.65*250=15412.5. In sixth scenario, total unsupplied load including unsupplied electrical load (47.32 MW) and unsupplied hydrogen demand (21.76 MW) is 69.08 MW. Total load shedding cost in ninth scenario is equal to 69.08*250=17270 MW.

Table 19 shows electrical energy balance in MEMG in case of unavailability of pool market and bilateral contracts. According to Table 19, electrical energy generated in MEMG can not supply all demands, resulting in electrical load shedding of 43.14, 46.53, 44.93, 44.43, 42.42, 47.32, 41.30, 41.79, 39.75 and 40.91 MW for ten scenarios, respectively. Although the amount of unsupplied electrical load is accounted for only 17.91%, 19.34%, 18.82%, 18.37%, 17.50%, 19.55%, 17.15%, 17.47%, 16.61% and 17.01% of the total electrical load for 10 scenarios, respectively and rest of the electrical load is supplied, completely. It is worth stating that unsupplied electrical load is accounted for a small share of the electric demand, while EVCS, CM, ESS charging power, shifted-up electrical demand and HE are fully met.

Table 19. Electrical energy balance in MEMG in case of unavailability of pool market and bilateral contracts

Components (MW)	**Scenarios**									
	S1	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S10**
	Electrical load									
Electric demand	215.69	215.75	214.84	216.36	216.64	217.45	215.92	214.13	214.13	214.84
EVCS	6.13	6.21	6.09	6.25	6.20	6.12	6.14	6.10	6.13	6.26
CM	12.18	12.30	12.17	12.14	12.13	12.25	12.19	12.11	12.20	12.25
ESS charging power	0.72	0.28	0.30	0.49	0.70	0.32	0.28	0.66	0.83	0.95
Shifted-up electrical demand	4.95	4.75	4.10	5.32	5.45	4.69	5.27	5.36	4.97	5.46
HE	1.32	1.39	1.45	1.44	1.40	1.35	1.16	0.93	1.21	0.84
Total electrical load	240.79	240.47	238.73	241.79	242.31	241.97	240.78	239.15	239.29	240.47
	Electrical generation									
PV	21.83	21.14	20.70	22.04	22.60	21.93	22.22	21.83	22.60	22.70
Wind	46.33	43.90	44.91	45.95	47.34	43.92	47.78	45.67	47.29	46.59
Biomass	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24	2.24
CHP	121.90	121.89	121.84	121.62	121.88	121.81	121.92	121.85	121.91	121.89
ESS discharging power	0.60	0.21	0.23	0.40	0.58	0.25	0.21	0.55	0.70	0.81
Shifted-down electrical demand	4.95	4.75	4.10	5.32	5.45	4.69	5.27	5.36	4.97	5.46
Total electrical generation	197.85	194.13	194.02	197.57	200.09	194.84	199.64	197.5	199.71	199.69
	Electrical energy balance									
Total	-43.14	-46.53	-44.93	-44.43	-42.42	-47.32	-41.30	-41.79	-39.75	-40.91
	Unsupplied electrical load									
Electrical load shedding	43.14	46.53	44.93	44.43	42.42	47.32	41.30	41.79	39.75	40.91

Table 20 shows hydrogen energy balance in MEMG in case of unavailability of pool market and bilateral contracts. It can be seen from Table 20 that hydrogen energy generated in MEMG does not supply a large share of hydrogen load due to the unavailability of pool market and bilateral contracts, resulting in hydrogen load shedding of 21.81, 21.82, 21.52, 21.32, 21.55, 21.76, 21.94, 22.05, 21.89 and 22.14 MW for ten scenarios, respectively.

Table 20. Hydrogen energy balance in MEMG in case of unavailability of pool market and bilateral contracts

Components (MW)	**Scenarios**									
	S1	**S2**	**S3**	**S4**	**S5**	**S6**	**S7**	**S8**	**S9**	**S10**
	Hydrogen load									
Hydrogen demand	20.00	20.04	19.78	19.58	19.79	19.96	19.95	19.89	19.96	19.86
HVCS	2.89	2.92	2.93	2.93	2.91	2.90	2.93	2.91	2.92	2.95
HSS charging power	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16

Shifted-up hydrogen demand	0.05	0.16	0.17	0.17	0.16	0.07	0.00	0.00	0.00	0.00
Total hydrogen load	23.1	23.28	23.04	22.84	23.02	23.09	23.04	22.96	23.04	22.97
	Hydrogen generation									
HE	1.12	1.18	1.23	1.23	1.19	1.14	0.98	0.79	1.03	0.71
HSS discharging power	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
Shifted-down hydrogen demand	0.05	0.16	0.17	0.17	0.16	0.07	0.00	0.00	0.00	0.00
Total hydrogen generation	1.29	1.46	1.52	1.52	1.47	1.33	1.1	0.91	1.15	0.83
	Hydrogen energy balance									
Total	-21.81	-21.82	-21.52	-21.32	-21.55	-21.76	-21.94	-22.05	-21.89	-22.14
	Unsupplied electrical load									
Hydrogen load shedding	21.81	21.82	21.52	21.32	21.55	21.76	21.94	22.05	21.89	22.14

As a result, by examining Tables 18-20, it can be found that despite the occurrence of load shedding and the presence of unsupplied electrical and hydrogen load in MEMG in this case, a significant share of the MEMG load is supplied by RES. In fact, although the two main sources of MEMG electricity supply, pool market and bilateral contracts, are not available in this case, the MEMG can still supply a major share of the load by relying on renewable sources, storage systems and DR programs. According to the Table 15, renewables can supply 29.23%, 27.97%, 28.42%, 29.04%, 29.78%, 28.13%, 30%, 29.16%, 30.14% and 29.74% of electrical load in 10 scenarios respectively, in case of unavailability of pool market and bilateral contracts. RES addition to storage systems and DR programs can increase the flexibility of the MEMG.

4.5. Effect of crypto miner (CM) demand on operation cost

The use of digital currency production equipment is increasing rapidly. Since this equipment consumes a lot of electrical energy, they impose a lot of load on the power grid. Therefore, it is necessary to predict the increase of such loads and prepare the network to deal their load. In this regard, Table 21 shows the impact of CM demand on EOC, CVaR and load shedding cost. As per Table 21, if the demand level of CM increases during the operation of MEMG, grid can supply demand completely in such a way that the increase in load will not lead to any load shedding.

Table 21. Effect of CM demand on EOC, CVaR and load shedding cost

CM demand (MW)	EOC ($)	CVaR ($)	Shed cost ($)
0.6	8018.14	8255.57	
0.8	8251.18	8501.44	-
1	8495.04	8745.84	-
1.2	8741.02	8994.19	-
1.4	8988.41	9246.38	-
1.6	9236.52	9462.23	-
1.8	9461.32	9687.74	-
2	9686.76	9914.76	-
2.2	9917.70	10146.23	-
2.4	10150.75	10378.90	-

5. Conclusions

In this paper, a two-stage stochastic model has been proposed for risk constrained scheduling of components in a MEMG including renewable resources, EV and HV charging stations, CHP, boiler, HE, CM, ESS, TSS, HSS, DR programs and pool market, while the MEMG is connected to bilateral contracts as an energy source with certain price. The uncertainties of demands, EVCS and HVCS, CM, PV and wind power, and the price of electricity purchased from pool market have been taken into account. The proposed MILP model is solved using the CPLEX solver in the GAMS which guarantees to achieve the global solution. In this work, the effects of bilateral contracts, RES, contingency events, energy storage systems, DR programs and CMs on operation costs of MEMG have been studied.

The results of the study on the effect of contingency events on operation of MEMG indicate that the unavailability of bilateral contracts will result in electrical and hydrogen load shedding in all scenarios due to the key role of this source in purchasing electrical energy in the studied MEMG. Furthermore, the simulation results of simultaneous unavailability effect of bilateral contracts and pool market on operation of MEMG show that despite the occurring of load shedding and the presence of unsupplied electrical and hydrogen load in MEMG, the considerable share of the MEMG load is supplied by RES. In fact, although the two main sources of MEMG electricity supply, pool market and bilateral contracts, are not available, the MEMG can still supply the major share of the load by relying on storages, DR programs and especially renewable energy sources. According to the results, RES including PV, wind and biomass energies can decrease operation costs and also costs of purchased electricity by 34.47% and 47.50%, respectively.

The results show that storages can decrease the cost by 5.94%. It is obvious that energy storage systems can reduce the EOC by 5.94%. Moreover, it can be seen that the CVaR with the considering of storages is decreased by 5.45%. It is interesting that storage systems decrease expected costs of purchased electricity by 13.47%.

According to the findings, EDR, TDR and HDR programs decrease the operation cost of MEMG by 3.57%, 0.3% and 0.7%, respectively. CVaR of operation cost of MEMG with the presence of EDR, TDR and HDR programs is decreased by 3.55%, 0.29% and 0.76%, respectively. In general, DR programs reduce operation cost and CVaR of operation cost by 4.57% and 4.6%, respectively. It is apparent that DR programs decrease expected cost of purchased electricity by 14.46%.

From comparing the results of effect of storage systems and DR programs on MEMG, it can be concluded that the storage systems and DR programs can reduce EOC by 10.51%, CVaR of operation cost by 10.05% and expected cost of purchased electricity 27.93%, respectively. Storage systems have more effect on decreasing the operation cost and CVaR of operation cost, while the effect of DR programs on reducing the cost of purchased electricity is significant.

Declaration of conflict of interest

The author declares that there is no conflict of interest for this research.

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