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Stochastic Assessment of the Renewable–Based Multiple Energy System in the Presence of Thermal Energy Market and Demand Response Program

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Abstract- *The impact of different energy storages on power systems has become more important due to the development of energy storage technologies. This paper optimizes the stochastic scheduling of a wind-based multiple energy system (MES) and evaluates the operation of the proposed system in combination with electrical and thermal demand-response programs and the three-mode CAES (TM-CAES) unit. The proposed wind-integrated MES consists of a TM-CAES unit, electrical boiler unit, and thermal storage system which can exchange thermal energy with the local thermal network and exchange electricity with the local grid. The electrical and thermal demands as well as wind farm generation are modeled as a scenario-based stochastic problem using the Monte Carlo simulation method. Afterwards, the computational burden is reduced by applying a proper scenario-reduction algorithm to initial scenarios. Finally, the proposed methodology is implemented to a case study to evaluate the effectiveness and appropriateness of the proposed method.*

Keyword: Three mode compressed air energy storage, thermal energy market, stochastic modeling, wind generation, demand response program, simple cycle generation.

NOMENCLATURE

Indices

t	Index of scheduling horizon, [1 to T].
ω	Index of scenarios, [1 to W].

Parameters

λ^{gas}	The natural gas price.
$\beta^{\exp./c}$	The expander/compressor operation and maintenance costs.
HRC	CAES system heat rate coefficient.
$\eta^{ch/dch}$	The charged/discharged state efficiency of the TM-CAES unit.
$E_{\max}^{ch}$	Maximum compressor range.
$E_{\max}^{dch}$	Maximum expander range.
$E_{Min/Max}^{CAES}$	Minimum and maximum stored power level of the TM-CAES unit.
η_{TES}	Efficiency of the standby mode of the thermal storage system.
$\eta_{TES}^{ch/dch}$	Efficiency of the charging and discharging modes of the thermal storage system.
$T_{Max}^{ch/dch}$	Rates of the maximum charging and discharging modes of the thermal storage system.
$T_{Min/Max}^{TES}$	Minimum and maximum ranges of stored energy in the thermal storage system.
η^{boiler}	The efficiency of the boiler.
$T^{boiler,Min/Max}$	The minimum/maximum output rates of the boiler.
$P^{E/T}$	The limitations of the imported and exported electrical and thermal energy.
$\lambda_{E}^{imp/\exp}$	The price of imported and exported electricity.
$\lambda_{T}^{imp/\exp}$	The price of imported/exported thermal energy.
DR^{Max}	The maximum level of participation factor of DR program.
TD^{Max}	The maximum level of increased demand percentage.
$VOLL$	Value of lost load.

Variables

Cost	Total operation cost of the proposed MES.
$C^{E/T}$	Costs of the imported electricity and thermal energy.
$R^{E/T}$	Revenues of the exported electricity and thermal energy.
C^{CAES}	Total cost of the TM-CAES unit.

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$E^{ch/dch}$	Consumption and generated energy in the charging and discharging modes.
E^{sc}	Generated electrical energy in the simple cycle mode.
E^{CAES}	Rates of stored energy in the TM-CAES unit.
$T^{ch/dch}$	Charging and discharging powers of the thermal storage system.
T^{TES}	Stored energy in the thermal storage system.
T^{boiler}	Thermal energy generated by electrical boiler
E^{boiler}	Input of boiler.
$E^{imp/\exp}$	Imported/exported electricity from/to local grid.
$T^{imp/\exp}$	Imported/exported thermal energy from/to local thermal network.
$R^{E/T}$	Revenues of the exported electricity and thermal energy.
$C^{E/T}$	Costs of the imported electricity and thermal energy.
$Load^{ADR}$	The amount of demands after implementing DR program.
DR	The participation factor of DR program.
$Load^{BDR}$	The load before implementing DR program.
I	The shifted demand.
D^{TRD}	The amount increased demand.
TD	The percentage of increased demand.
PC	Penalty cost.
EC	Curtailed electrical load.
TC	Curtailed thermal load.
P^{wind}	Power generation of wind farm.

1. INTRODUCTION

1.1. Motivation and literature review

In recent years, the significant development of storage technologies has provided more optimal operation methods for the scheduling of energy systems. On the other hand, renewable energy generation has attracted considerable attention. Therefore, using flexible storage technologies, the integration between various energy carriers and the use of renewable energy resources can make the operation of energy systems more optimal.

CAES is a mechanical energy storage considered as a large-scale storage that can store up to hundreds of megawatts. In the past years, various methods have attempted to realize the use of CAES. By classifying and comparing CAES processes, Reference [1] reviews various approaches. The classification and comparison with the extensive historical background on how CAES has progressed over time have been substantiated from the beginning to its latest advances.

Given the variable and unpredictable wind power, there is a need for flexible resources like demand response programs and energy storage systems, that can facilitate the integration of wind power. Accordingly, a multi stage stochastic method is presented in [2] to schedule the demand response program, bulk energy storages and conventional components, using wind energy integration is provided. So that the total cost of the operation and emission is minimized. A two-stage stochastic approach is presented in [3] to model the determination of operating reserves, as the main concern of operators in power systems which utilize wind power, in simultaneous energy and reserve market. Reference [4] presents a method for optimal operation of an hub concept. The residential different demands are supplied by the proposed hub system.

The impact of storage devices in electricity markets is an important issue in energy markets. The uncertain electricity price has an undeniable effect on the electrical energy market. In this regard, a risk-based operation strategy for a CAES system is presented in [5]. The uncertainty parameter is modeled by the information-gap decision theory (IGDT). Moreover, Reference [6] proposes a co-optimized dispatch model for CAES to determine the worth of providing operating reserves in the reserve markets. The CAES system coupled with wind energy is one of the best candidates in this case. The integration of this system with a combined cooling, heating, and power system is studied in [7]. The produced electrical energy is used to set up the compressors to provide the required compressed air to store in the storage.

In [8], a combined cooling, heating, and power (CCHP) unit which is operated with the CAES system is proposed, combining an ammonia-water absorption refrigeration system and a gas engine. In the proposed system, a design compromise between the exergy efficiency and cost of the final product is probed using a differential evolutionary algorithm. Furthermore, a CAES system with inter-cooling coupled with a integrated system is investigated in [9], comparing air cooling with an air compression refrigeration cycle. In addition, the modeling and control of a CAES system for wind turbines are proposed in [10]. This system absorbs excess power before power generation so that electrical components can be reduced for demand instead of supply. Reference [11], proposes a multi energy system which have various energy components such as combined heat and power (CHP) units and auxiliary boiler to model multi energy players in an optimal way. In [12], simultaneous behavior of a multi energy player used to collect a series of local energy systems and participate in wholesale electricity markets is probed. Reference [13] presents a bi-level optimization method to model distribution company as a price maker player in market due to its operational flexibility in active distribution grids.

The volatility of renewable energies such as wind energy has an undeniable effect on the operation of microgrids such as fluctuations in power flow and a direct effect on the performance of power systems [14]. These effects cause problems such as frequency fluctuations in the system [15]. In [16], the application of a superconducting magnetic energy storage controller is proposed to stabilize and control the flow of the electric current of wind-hybrid microgrids. This storage has the ability to increase the dynamic security of power systems. The dynamic performance of the prepared system is confirmed using the Sim-Power-Systems of MATLAB/Simulink. Also, the performance of a conventional gas-fired power generation company with a integration of CAES system and wind generation is optimized and compared in [17]. The optimization problem is modeled by a mixed-integer non-linear programming formulation. Numerical results showed that the use of the combined system yields a 43% higher operating profit and has 7.6% lower costs in the market environment. The energy hub system offers substantial benefits such as the flexibility to face the challenging effects of renewable energy sources for energy services. A wind generation integrated with energy hub based on a hybrid programming with multiple energy systems is developed in [18]. In the proposed system, wind power generation, the uncertainty of load forecasting, and the random outages of components are modeled by using hybrid methodology.

Another benefit of using a combination of renewable energies such as solar energy with energy storage systems is its less greenhouse gas emissions. Reference [19] integrates a storage system using solar cells to solve problems such as power fluctuations, and participating in the energy markets.

The intermittent nature of renewable energies is a significant challenge of using these kinds of energies. The stochastic method can be applied to model the intermittency of renewable energy generations. A comprehensive literary study on stochastic modeling and also the key features of microgrids and optimization tools for a microgrid are presented in [20]. These tools are employed to optimize the generation of renewable energies and buffer effects from energy storage systems. A stochastic model predictive control method is proposed in [21] for the microgrid management problem with regard to the three-node topology, including a renewable resource and an storage unit, customers, and a micro-gas generator for the electrical grid. Also, reference [22] develops microgrid management in a stochastic programming that manages microgrid operations by forecasts and stochastic techniques. The existence of elements such as controllable loads, distributed generators, distributed energy storage devices, and the intermittency of renewable energies' demand and generation complicates the operation of microgrids. The scheduling of microgrid energy is formulated by a stochastic problem in [23]. The purpose of this formulation is to minimize microgrid operational costs and power losses while maintaining consistency with the intermittency of renewable energy resources.

The demand-response program is an effective tool for providing financial and operational benefits to electricity customers, service providers, and grid operators, and can also provide a balance between supply and demand. In [24], a demand-response strategy is proposed to regulate frequency in a microgrid based on the communication between the instrument's control center and the responsive loads. This strategy is considered once with wind energy and one without wind energy. The authors of [25] modeled predicted wind speed and solar radiation errors by probabilistic distribution functions, and then the feasible renewable energy scenarios for day-ahead energy and reserve scheduling are generated using the Latin hypercube sampling. In the proposed method, all types of customers can participate in demand-response programs. In addition, a coordination algorithm between battery storage and demand response is proposed in [26] to provide smoother microgrid lines. Simulation results indicate that this coordination algorithm significantly reduces the volume of storage systems for the generation of renewable energies in microgrids and also improves the quality of the power system. Table 1 summarizes capability of the proposed method in modeling and different strategies.

1.2. Contributions

In this paper, an optimal stochastic scheduling model is proposed for multi carrier energy system, which can provide thermal demand from energy market.

The proposed TM-CAES unit is fed by natural gas, also, this can create an ability for the MES to operate as a generator when the air storage is evacuated. Furthermore, the proposed MES can participate in thermal and electrical energy markets. Also, thermal demand response (TDR) beside electrical demand response (EDR) programs has been applied to obtain more efficient schedule for MES. The main contributions of current paper can be summarized as following:

1) The proposed method can manage the operation of the proposed wind based multi energy system in an optimal way with considering various flexible energy components.

2) A two stage stochastic method is applied to model the uncertain parameters.

3) The proposed TM-CAES can be operated in simple cycle, charging and discharging modes.

4) The proposed MES can provide the thermal demands from local thermal market.

5) TDR beside EDR programs is applied to reduce the operation cost of the proposed MES.

Table 1. Comparing the proposed MES unit with different previous energy systems.

References	Studied system	Uncertainty modelling	Flexible storage	Demand response	
				Electrical	Thermal
[11]	Multiple energy system	×	×	×	×
[12]	Multiple energy system	Scenario based	×	×	×
[13]	Electrical system	stochastic	×	✓	×
[34]	Multiple energy system	stochastic	×	×	×
[25]	Electrical system	-	×	✓	×
Proposed	Multiple energy system	stochastic	✓	✓	✓

2. STOCHASTIC PROGRAMMING

As it is mentioned previously, stochastic programming is an appropriate tool for modeling uncertainties related to unpredictable parameters such as renewable generations. In suggested stochastic optimization model, the first stage of decision making is decided before realizing the uncertainties. After that, when the random parameters are appeared, the second stage decisions begin to take place.

2.1. Scenario generation

Generally, for modeling the distribution of wind speed, the Weibull or Rayleigh PDF is used [27]. The Rayleigh PDF for wind speed υ is shown by (1):

$$PDF(v)=\left(\frac{v}{c^2}\right)\exp\left[-\left(\frac{v^2}{2c^2}\right)\right] \quad (1)$$

The wind turbine power generation is formulated as following:

$$p_\omega(v)=\begin{cases}0 & \text{if } v\le v_{in}^c \text{ or } v\ge v_{out}^c\\ \dfrac{v-v_{in}^c}{v_r-v_{in}^c}P_\omega^r & \text{if } v_{in}^c\le v\le v_r\\ P_\omega^r & \text{if } v_r\le v\le v_{out}^c\end{cases} \quad (2)$$

where v_r, v_{in}^c, v_{out}^c and P_ω^r represent rated wind speed, cut-in wind speed, cut-out wind speed and the rated output power of installed wind turbine respectively.

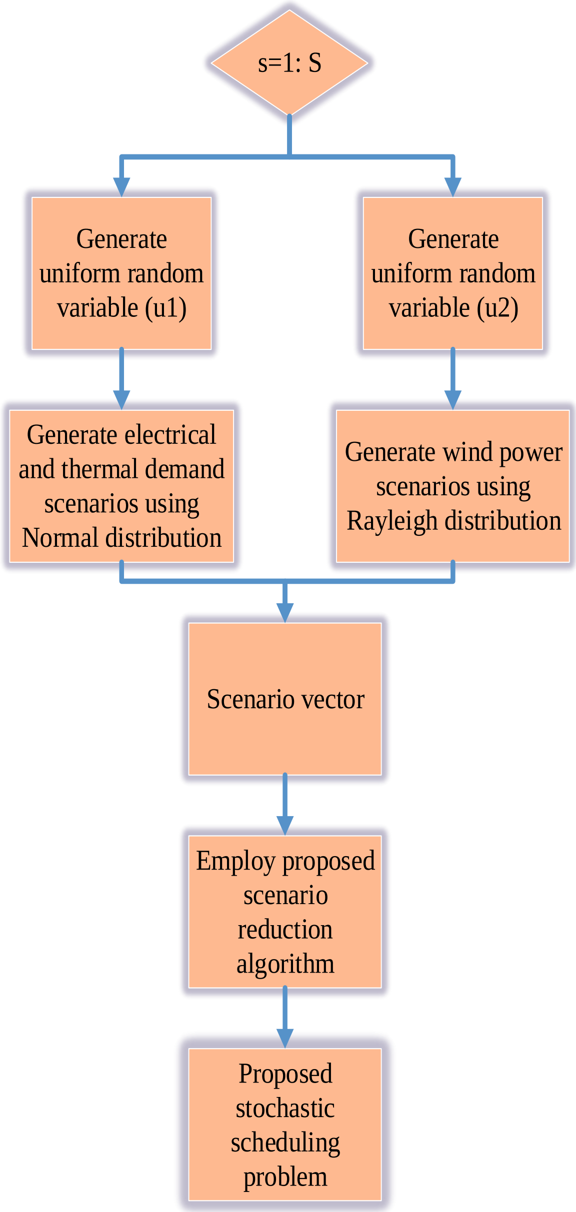

Fig. 1. Flowchart of the proposed scenario based stochastic scheduling procedure

Generally, the uncertainties relevant to electrical and thermal demands are modeled by using normal distribution [28]. In this paper, a set of possible scenarios by normal distribution is generated by using the Monte Carlo methodology.

$$\mathrm{PDF}(d) = \frac{1}{\sqrt{2\pi\sigma_d^2}} exp\left[-\frac{(d-\mu_d)^2}{2\sigma_d^2} \right] \quad (3)$$

2.2. Scenario reduction

Since the computational burden of the problem is related to number of scenarios to solve problems of stochastic programming optimization, it is necessary to implement a useful scenario reduction algorithm to solve large-scale problems. The proposed method offers a proper approximation of scenarios for the initial system. The SCENRED algorithm has been implemented for the scenario reduction process, presented by the GAMS [29]. SCENRED contains various scenario reduction methods. It should be noted that all variables without ω index are made in stage 1 and likewise, variables with ω index are scenario based and related to stage 2. Figure 1 presents the flowchart of the proposed scenario based optimal scheduling of the MES.

3. PROBLEM FORMULATION

3.1. Objective function

The objective function of the proposed wind-based MES is to minimize the total operation cost. The operation costs of the TM-CAES unit and boiler, the cost and revenue of exchanged electrical and thermal energies by local energy networks in scheduling horizon are the terms of the objective function (4).

$$Minimize \;\; \mathrm{Cost} = \sum_{\omega=1}^{W} \pi_\omega \times \begin{Bmatrix} C_\omega^{CAES} + C_\omega^{E} + C_\omega^{T} + \\ PC_\omega - R_\omega^{E} - R_\omega^{T} \end{Bmatrix} \quad (4)$$

3.2. Constraints of the TM-CAES unit

The proposed three mode compressed air energy storage system is fed by natural gas. Also, this can create the ability for the MES to operate as a generator when the air storage is evacuated. The output of the proposed TM-CAES system in the discharging and simple cycle modes is electrical energy. Equation (5) represents the total cost of the TM-CAES unit:

$$C_\omega^{CAES} = \sum_{t=1}^{T} \begin{bmatrix} \left(E_\omega^{ch}(t)\times\beta^{c}\right) + \\ \left(E_\omega^{dch}(t)\times(\beta^{\exp.} + HRC\times\lambda^{gas}(t))\right) + \\ \left(E_\omega^{sc}(t)\times(\beta^{c} + \beta^{\exp.} + HRC\times\lambda^{gas}(t))\right) \end{bmatrix} \quad (5)$$
$$\forall\omega,\ \forall t$$

where, the first term is cost of the compressor in the charging mode, the second term is the cost of discharging mode and the last term represents the cost of the simple generation mode. At the proposed TM-CAES unit, limitations of the simple cycle, charging and discharging modes are given by (6) - (8), respectively. The binary variables j^{ch} , j^{dch} and j^{sc} used in the following constraints make the charge, discharge, and simple cycle mode do not occur simultaneously.

$$0 \le E_\omega^{ch}(t) \le j_\omega^{ch}(t)\times E_{\max}^{ch} \qquad \forall\omega,\ \forall t \quad (6)$$

$$0 \le E_\omega^{dch}(t) \le j_\omega^{dch}(t)\times E_{\max}^{dch} \qquad \forall\omega,\ \forall t \quad (7)$$

$$0 \le E_\omega^{sc}(t) \le j_\omega^{sc}(t)\times E_{\max}^{dch} \qquad \forall\omega,\ \forall t \quad (8)$$

The proposed TM-CAES can only operate in one particular mode during the scheduling horizon. This can be presented as following:

$$j_\omega^{ch}(t) + j_\omega^{dch}(t) + j_\omega^{sc}(t) \le 1 \qquad \forall\omega,\ \forall t \quad (9)$$

Equations (10) to (11) represent the stored energy level equation and initial stored energy of the TM-CAES unit respectively.

$$E_\omega^{CAES}(t+1) = \left[E_\omega^{CAES}(t) + (E_\omega^{ch}(t)\times\eta^{ch}) - (E_\omega^{dch}(t)/\eta^{dch}) \right] \quad (10)$$
$$\forall\omega,\ \forall t$$

$$E_{Min}^{CAES} \le E_\omega^{CAES}(t) \le E_{Max}^{CAES} \qquad \forall\omega,\ \forall t \quad (11)$$

3.3. Constraints of the electrical boiler

The thermal energy generated by electrical boiler (EB) and its generation range are shown by (12) and (13), respectively.

$$T_\omega^{boiler}(t) = \eta^{boiler}\times E_\omega^{boiler}(t) \qquad \forall\omega,\ \forall t \quad (12)$$

$$T^{boiler,Min} \le T_\omega^{boiler}(t) \le T^{boiler,Max} \qquad \forall\omega,\ \forall t \quad (13)$$

3.4. Constraints of the thermal energy storage

The thermal energy storage (TES) system is used to store thermal energy in off-peak times and exports it to the system in the peak times. The TES charge and discharge rates are shown by (14) and (15) respectively. Binary variables a and b prevent TES simultaneous charging and discharging.

$$0 \le T_\omega^{ch}(t) \le a_\omega(t)\times T_{Max}^{ch} \qquad \forall\omega,\ \forall t \quad (14)$$

$$0 \le T_\omega^{dch}(t) \le b_\omega(t)\times T_{Max}^{dch} \qquad \forall\omega,\ \forall t \quad (15)$$

$$a_\omega(t) + b_\omega(t) \le 1 \qquad \forall\omega,\ \forall t \quad (16)$$

The limitation of stored thermal energy in the storage and energy balance are shown in (17) and (18), respectively.

$$T_{\omega}^{TES}(t)=\Big[T_{\omega}^{TES}(t-1)\times\eta_{TES}+ \left(T_{\omega}^{ch}(t)\times\ \eta_{TES}^{ch}\right)-\left(T_{\omega}^{dch}(t)/\eta_{TES}^{dch}\right)\Big] \quad \forall\omega,\ \forall t \tag{17}$$

$$T_{Min}^{TES}\le T_{\omega}^{TES}(t)\le T_{Max}^{TES} \qquad \forall\omega,\ \forall t \tag{18}$$

3.5. Exchange electrical and thermal energies by local grid

Equations (19) and (20) illustrate the ranges of the exchanged electrical energy between the proposed MES and local grid. Importing and exporting electricity status are indicated by binary variables, x^{E} and y^{E} , respectively.

$$0\le E_{\omega}^{imp}(t)\le P^{E}\times x_{\omega}^{E}(t) \qquad \forall\omega,\ \forall t \tag{19}$$

$$0\le E_{\omega}^{\exp}(t)\le P^{E}\times y_{\omega}^{E}(t) \qquad \forall\omega,\ \forall t \tag{20}$$

$$x_{\omega}^{E}(t)+y_{\omega}^{E}(t)\le 1 \qquad \forall\omega,\ \forall t \tag{21}$$

Similar to exchanged electricity, limitations of the exchanged thermal energy with local grid are presented in (22)-(24).

$$0\le T_{\omega}^{imp}(t)\le P^{T}\times x_{\omega}^{T}(t) \qquad \forall\omega,\ \forall t \tag{22}$$

$$0\le T_{\omega}^{\exp}(t)\le P^{T}\times y_{\omega}^{T}(t) \qquad \forall\omega,\ \forall t \tag{23}$$

$$x_{\omega}^{T}(t)+y_{\omega}^{T}(t)\le 1 \qquad \forall\omega,\ \forall t \tag{24}$$

The revenues and costs of the exported and imported electrical and thermal energies to/from local networks are illustrated by (25)-(28), respectively.

$$R_{\omega}^{E}=\sum_{t=1}^{T}E_{\omega}^{\exp}(t)\times\lambda_{E}^{\exp}(t) \qquad \forall\omega,\ \forall t \tag{25}$$

$$C_{\omega}^{E}=\sum_{t=1}^{T}E_{\omega}^{imp}(t)\times\lambda_{E}^{imp}(t) \qquad \forall\omega,\ \forall t \tag{26}$$

$$R_{\omega}^{T}=\sum_{t=1}^{T}T_{\omega}^{\exp}(t)\times\lambda_{T}^{\exp}(t) \qquad \forall\omega,\ \forall t \tag{27}$$

$$C_{\omega}^{T}=\sum_{t=1}^{T}T_{\omega}^{imp}(t)\times\lambda_{T}^{imp}(t) \qquad \forall\omega,\ \forall t \tag{28}$$

3.6. Electrical and thermal demand response programs

In the current paper, the main purpose of the DR program is to shift the energy demands for the proposed system from peak prices to off-peak prices. It should be noted that the h and e as the superscript show the thermal and electrical demand response programs respectively. The following equation shows the final demand for the proposed system after applying the DR program.

$$Load_{\omega}^{ADR,h/e}(t)=\left(1-DR_{\omega}^{h/e}(t)\right)\times Load_{\omega}^{BDR,h/e}(t)+I_{\omega}^{h/e}(\mathrm{t}) \quad \forall\omega,\forall\mathrm{t} \tag{29}$$

The part of the energy demands that can be shifted to off-peak prices can be as follows:

$$DR_{\omega}^{h/e}(t)\le DR^{Max,h/e}(\mathrm{t}) \qquad \forall\omega,\forall\mathrm{t} \tag{30}$$

The amount of shifted energy demands in each period of scheduling after the use of the DR program and the demand transference constrained can be formulated as follows:

$$D_{\omega}^{TRD,h/e}(t)=I_{\omega}^{h/e}(t)-\left(DR_{\omega}^{h/e}(t)\times Load_{\omega}^{BDR,h/e}(t)\right) \quad \forall\omega,\forall\mathrm{t} \tag{31}$$

$$TD_{\omega}^{h/e}(t)\le TD^{Max,h/e}(\mathrm{t}) \qquad \forall\omega,\forall\mathrm{t} \tag{32}$$

$$\left|D_{\omega}^{TRD,h/e}(t)\right|\le TD_{\omega}^{h/e}(t)\times Load_{\omega}^{BDR,h/e}(\mathrm{t}) \quad \forall\omega,\forall\mathrm{t} \tag{33}$$

However, the amount of shifted demand can be different in each scheduling time block. Also, in this paper, the sum of all time blocks energy demand before and after applying the DR program is unchangeable. Thus, this system can cover all of its energy needs at a lower cost.

$$\sum_{t=1}^{T}I_{\omega}^{h/e}(t)=\sum_{t=1}^{T}\left(DR_{\omega}^{h/e}(t)\times Load_{\omega}^{BDR,h/e}(t)\right) \quad \forall\omega,\forall\mathrm{t} \tag{34}$$

3.7. Penalty cost

The cost of the curtailed loads based on value of lost loads (VOLLs) is defined by (29):

$$PC_{\omega}=\sum_{t=1}^{T}VOLL_{E}\times EC_{\omega}(t)+VOLL_{T}\times TC_{\omega}(t) \quad \forall\omega,\ \forall t \tag{35}$$

where, EC and TC are the electrical and thermal unsupplied demands, respectively.

3.8. Energy balancing constraints

The following equations show that the generated electricity and thermal energy by the proposed MES equipment and the local electrical and thermal grids must satisfy the electrical and thermal demands in each scenarios and the scheduling horizon.

$$Load_{\omega}^{AEDR}(t)-EC_{\omega}(t)\leq E_{\omega}^{sc}(t)+E_{\omega}^{dch}(t)-E_{\omega}^{ch}(t)-E_{\omega}^{boiler}(t)+E_{\omega}^{imp}(t)-E_{\omega}^{\exp}+P_{\omega}^{wind}(t) \quad \forall\omega,\ \forall t \tag{36}$$

$$Load_{\omega}^{ATDR}-TC_{\omega}(t)\leq T_{\omega}^{boiler}(t)+T_{\omega}^{dch}(t)-T_{\omega}^{ch}(t)+T_{\omega}^{imp}(t)-T_{\omega}^{\exp}(t) \quad \forall\omega,\ \forall t \tag{37}$$

In addition, $Load^{AEDR}$ and $Load^{ATDR}$ are the electrical and thermal demands after applying DR programs.

4. ASSUMPTION AND SIMULATION RESULT

In this section, the effectiveness of the stochastic programming model for proposed wind-based MES is evaluated. The proposed system consists of a wind farm, a TM-CAES unit, an EB unit and thermal storage system. The proposed energy system can provide the thermal demands from local thermal market. The structure of the proposed MES is indicated in Fig. 2.

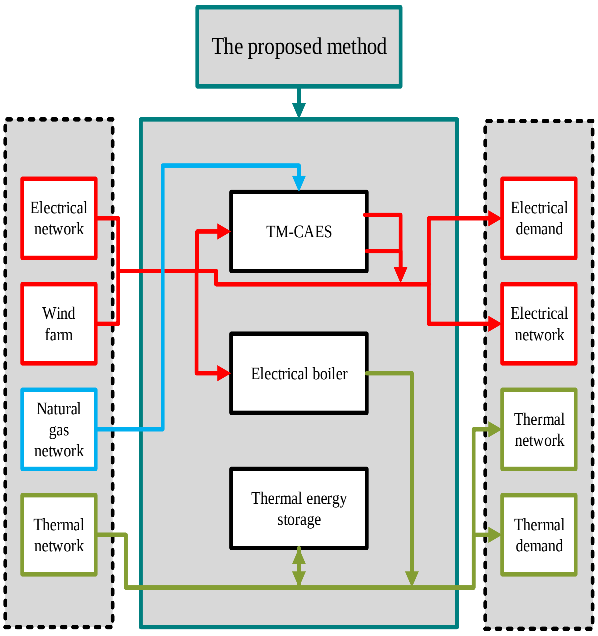

Fig. 2. Structure of the proposed wind integrated MES

4.1. Assumptions

The parameters of the EB unit are shown in Table 2. The parameters of the TM-CAES and TES unit are provided in Table 3 and Table 4, respectively. The specifications of the proposed CAES system can be taken from [30]. Figure 3 shows the gas, electrical and thermal energies' prices in 24 hours of a day. In addition, the prices' base value of the natural gas, electrical and thermal energies are chosen 16\$/MWh, 20\$/MWh and 32\$/MWh, respectively. Furthermore, the exported electrical and thermal energies' prices are assumed to be $1.5\times\lambda_t^{E,p}$ and $1.2\times\lambda_t^{H,p}$, respectively. The average VOLLs for electricity and thermal demands are considered to be 50 \$/MWh and 30 \$/MWh, respectively.

Table 2. The parameters of electrical boiler unit

Maximum capacity (MW)	Minimum capacity (MW)	Efficiency (%)
18	2	80

Table 3. The specifications of the TM-CAES unit

Maximum stored energy (MWh)	Expander maximum range (MW)	Compressor maximum range (MW)	Charging efficiency (%)	Discharging efficiency (%)
300	20	15	85	90

Table 4. The characteristics of the thermal energy storage

Maximum energy (MWh)	Maximum charging/discharging Range (MW)	Charging/ discharging efficiency (%)	Standby Efficiency (%)
20	5	95	97

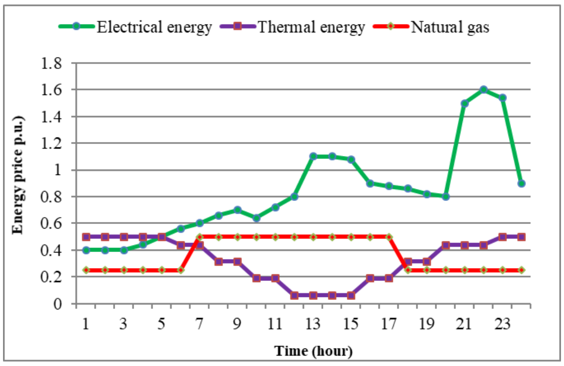

Fig. 3. Variations of electricity, thermal energy and natural gas price in 24 hours of a typical day

4.2. Scenario data

The capacity of the wind farm is considered 40 MW. Also, the specifications of wind turbine are taken from [31]. The base values of thermal and electrical energy demands are considered 22.5 MW and 37.5 MW, respectively. In addition, the energy demands forecasting standard deviations are assumed to be 5% of the mean value. The variations of the proposed MES electrical and thermal demands in different scheduling hours are presented in Fig. 4. Also, the MC model is applied to generate 1000 scenarios which have equal probabilities. Afterward, the number of the initial scenarios are reduced to 10 by applying fast backward reduction program from SCENRED/GAMS [32]. Table 5 indicates the probabilities of the each reduced scenarios. Finally, with respect to all mentioned assumptions, the proposed MILP problem is solved by the CPLEX solver using the GAMS platform [33].

Table 5. Probability of each scenario after scenario reduction

Scenario	1	2	3	4	5
Probability	0.041	0.055	0.244	0.151	0.090
Scenario	6	7	8	9	10
Probability	0.063	0.088	0.080	0.096	0.092

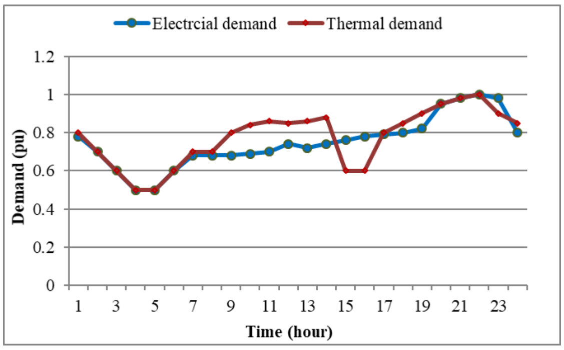

Fig. 4. The variation of electrical and thermal demands in a day.

4.3. Results and discussions on impact of demand response program on operation cost

This subsection investigates the electrical and thermal DR programs on the scheduling of the MES. The proposed demand response program with different participation factor is implemented on scheduling of MES to study the proposed system behavior. In order to investigate the utility of the demand response programs on the proposed system operation, the DR program with several steps of TD^{Max} and DR^{Max} is implemented on the MES. From Table 6, it is clear that, the total operation cost of the system decreased from 6324.10$ to 4321.95$ when the participation and increased demand factors are increased from 0% to 30%, a reduction by about 29%. In addition, there is no penalty cost due to high VOLLs and costs of load curtailment in the fourth step. By increasing the TD^{Max} and DR^{Max} from 0 to 0.1, the penalty cost is reduced from 131.55$ to 43.83$, a reduction by about 66%. Moreover, the cost of imported electricity from network decreases by increasing of TD^{Max} and DR^{Max}, but in the fourth step of the DR program, the amount of the imported electricity increases because of raising the proposed system ability to export more electricity in peak time and as a result, the revenue of exported electrical energy increases. In addition, the revenue of the exported thermal energy has been increased from 96.65$ to 142.22$ in the first step of the demands participation factors increasing.

4.4. Assessment impact of demand response programs on TM-CAES unit operation

The simple cycle, charging and discharging modes' powers for $TD^{Max} = DR^{Max} = 0.1$ and $TD^{Max} = DR^{Max} = 0.30$ are shown in Fig. 5 and Fig. 6 respectively. As it is clear in Fig. 5 and Fig. 6, more electrical energy can be stored in the TM-CAES and sell it in peak price times to energy networks in $TD^{Max} = DR^{Max} = 0.30$ mode in comparison with $TD^{Max} = DR^{Max} = 0.1$ mode. The simple cycle, charging and discharging modes' power rates increase in the $TD^{Max} = DR^{Max} = 0.30$ condition, because of the flexibility of the proposed system to optimal operation in the different conditions.

Table 6. The proposed system optimal scheduling results for different DR program parameters.

DR^{Max}	0.0	0.10	0.20	0.30
TD^{Max}	0.0	0.10	0.20	0.30
Operation cost ($)	6324.10	5625.50	5072.18	4321.95
Penalty cost ($)	131.55	43.83	35.15	0.00
Cost of imported electricity ($)	3831.21	3741.92	3534.90	3949.53
Revenue of exported electricity ($)	1835.90	2238.87	2655.73	4831.51
Cost of imported thermal energy ($)	3429.08	3368.11	3328.87	3496.87
Revenue of exported thermal energy ($)	96.65	142.22	197.59	245.93

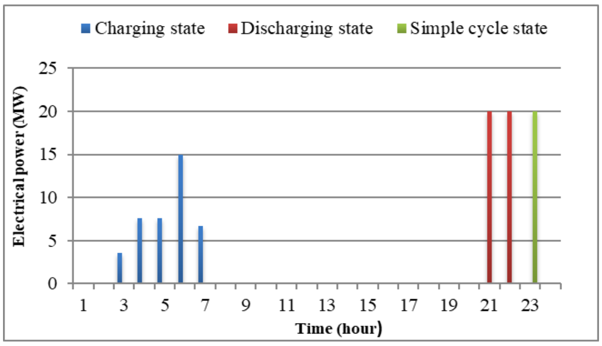

Fig. 5. TM-CAES system charging, discharging and simple cycle mode power for $TD^{Max} = DR^{Max} = 0.1$.

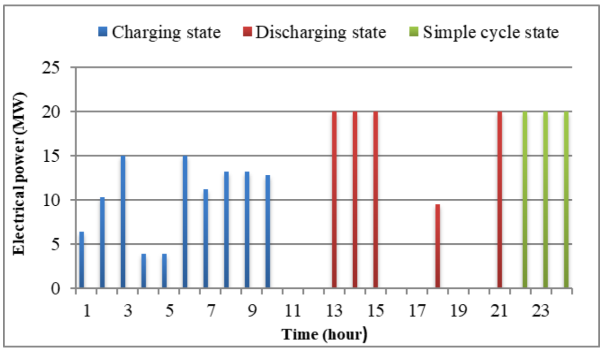

Fig. 6. TM-CAES system charging, discharging and simple cycle mode power for $TD^{Max} = DR^{Max} = 0.3$.

4.5. Discussions on impact of simple cycle mode on the proposed system

In this subsection, in order to analyse the effectiveness of the proposed model, two different case studies are defined. It should be noted that TD^{Max} and DR^{Max} are considered to be 30% for both electrical and thermal demand response programs in the both case studies.

As it is clear in Table 7, total operation cost decreases considerable in the proposed MES with considering three mode CAES unit in comparison with two mode CAES. The total cost of the proposed system decreases from 4507.93$ to 4321.95$, by about 4.1% reduction of the total cost. Moreover, the costs of the imported electrical energy decreases from 4048.12$ to 3949.53$ and thermal energy decreases from 3640.27$ to 3496.87$ in comparison with case study I. Results of the case study II indicate that adding simple cycle generation mode is capable for increasing the revenue of the exported electrical and thermal energies till 40% compared to the first case study.

Table 7. Operation costs of the proposed system in case study I and II conditions.

Case study	CAES	TM-CAES	Operation cost ($)	Penalty cost ($)
I	✔	✖	4507.93	0.30
II	✖	✔	4321.95	0.00
Case study	**Cost of imported electricity ($)**	**Revenue of exported electricity ($)**	**Cost of imported thermal energy ($)**	**Revenue of exported thermal energy ($)**
I	4048.12	3506.84	3640.27	93.70
II	3949.53	4831.51	3496.87	245.93

5. CONCLUSION

In the current paper, a stochastic model to optimal management of the wind integrated MES is proposed. Uncertainties related to thermal and electrical demands and wind generation are modeled by Monte Carlo procedure, afterward an efficient scenario reduction method is used to decrease the scenarios. The proposed system is assessed in combination with TM-CAES unit, EDR and TDR programs in the thermal and electrical energy markets environment. Total cost of the proposed system with TM-CAES unit decreases about 4.1% in comparison with two mode CAES. The proposed stochastic model has been investigated in a proper case study and the numerical results show the utility and appropriateness of the proposed method and impacts of the demand response programs on wind based MES scheduling problem. As future work, the management of uncertain parameters in optimal scheduling problem of the MES by the risk management methods can be studied.

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