27th Iranian Conference on Electrical Engineering (ICEE2019)

Day-Ahead Network-Constrained Scheduling of CHP and Wind Based Energy Systems Integrated with Hydrogen Storage Technology

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Abstract**—** The integration of renewable energy sources is vastly increased in recent decades considering environmental concerns and lack of fossil fuels. Such integration has appeared novel challenges in electrical energy systems according to their uncertain nature. The hydrogen energy storage (HES) system plays a significant role is power systems by converting extra wind power to the hydrogen using power to hydrogen (P2H) technology. In addition, the emerging technologies such as combined heat and power (CHP) units are effective in increasing the efficiency of power systems. This work presents a day-ahead scheduling scheme for CHP-HES based electrical energy networks with high integration of wind power sources. The effectiveness of the presented model is investigated by implementation on the IEEE 6-bus system. The impact of heat load increment has been studied on scheduling of generation plants, wind power dispatch and operation cost of the system. The simulation results prove that operation cost of the system and wind power curtailment have been decreased using the HES technology.

Keywords- Day-ahead network-constraint scheduling; wind energy;combined heat and power; hydrogen storage technology.

NOMENCLATURE

t	Time
i	Power plants
r	Wind turbine
h	HES
b,b'	Electric buses
j	Loads
L	Electricity system lines
NT	Number of hours
NP	Number of only power plants
$NCHP$	Number of CHP plants
NC	Number of total plants
NH	Number of HES
NR	Number of wind power plant
NQ	Number of heat load
NB	Number of electric buses
a_i, b_i, c_i	Cost function coefficient of total units
$a_i, b_i, c_i, d_i, e_i, f_i$	Coefficients of the CHP plant
SU_i	Start-up cost of thermal plant *i*
$P_i^{\max}, P_i^{\min}$	Min/Max generation capacity of thermal unit *i*
RU_i, RD_i	Ramp up/down power plant *i*
T_i^{On}, T_i^{Off}	Minimum up/down time of unit *i*
$P_{h,\max}^{HP}, P_{h,\max}^{PH}$	Upper limit of the corresponding modes
$P_{h,\min}^{HP}, P_{h,\min}^{PH}$	Lower limit of the corresponding modes
η_h^{PH}, η_h^{HP}	Generation/Storage efficiency of HES
$A_h^{\max}, A_h^{\min}$	Min/Max capacity of HES
$P_{r,t}^{f}$	forecasted wind power at time *t*
X_L	Reactance of line
$PF_L^{\max}$	Maximum capacity of line
$d_{j,t}$	Expected electric load
$HD_{q,t}$	Expected heat load
$P_{i,t}$	Power supply of plant *i*
$I_{i,t}$	Binary on/off status definer of unit *i*

$X^{on}_{i,t-1}, X^{off}_{i,t-1}$	On/off time of unit *i*
b^{PH}_{h}, c^{PH}_{h}	Cost function coefficient of HES in storage mode
$a^{HP}_{h}, b^{HP}_{h}, c^{HP}_{h}$	Cost coefficient of HES in supply mode
$I^{HP}_{h,t}, I^{PH}_{h,t}$	Binary supply/storage status definer of HES
$P^{PH}_{h,t}, P^{HP}_{h,t}$	Supplied/Stored hydrogen of hydrogen storage
$A_{h,t}$	Stored hydrogen of HES
$P_{r,t}$	Dispatched wind power
$H_{i,t}$	Generated heat of CHP
$PF_{L,t}$	Line flow at line *L*
$\delta_{b,t}$	Voltage angle of electric buses

I. INTRODUCTION

A significant attention has been absorbed to providing electrical energy using renewable energy in recent years such as wind power and photovoltaic systems. International challenges on climate revisions and emission of pollutant gases as well as limited sources of fossil fuels can be counted as the main reasons of high penetration of renewable energy in power networks [1]. Considering the latest reports by International Energy Agency (IEA), an annual generation of wind power equal to 2182 TWh will be attained by 2030 according to the statistics reported by [2]. On the other hand, the uncertainties of power supply using wind turbines and photovoltaic systems, researchers have proposed various solutions to overcome such dealings. In such area, the application of energy storage technologies have shown a practical solution that are used in different types such as pumped-hydro storage units [3], compressed air energy storage [4], electric vehicles [5] and hydrogen storage technology. Hydrogen storage system is able to store the extra power supplied by renewable energy sources by converting it to hydro using electrolysis process. The stored hydrogen can be utilized for late application via hydrogen-based gas turbines. The potential of using power-to-hydrogen (P2H) plants as energy storage facilities in power systems is considerable due to its capability to generate hydrogen from variable renewable sources [6, 7]. In addition, such storage technology takes advantage of fast responding that enables it to coordinate in ancillary services markets [8, 9].

hydrogen dependent industrial sections or injection to natural gas system for gas consumers. Recently, various researches are focused on the coordination of HES and renewable resources [7]. The first effort toward coordination of HES and photovoltaic systems have been done in 1990 [8]. The installation of the first and largest wind-hydrogen system was accomplished in Utsira, Norway by cooperation of Norwegian energy company Norsk Hydro together with the German wind turbine manufacturer Enercon. This installation is capable to operate as an isolated electrical energy network with an availability of 90% [9]. Later, a project toward combination of HES to wind farm was proceeded in Nakskov Denmark in 2007 [10]. The impact of storage technologies has been discussed on the operation cost of electrical energy networks and the wind spillage. The authors have investigated the role of pumped hydro storage system in solving the stochastic unit commitment in [11] considering wind power generation. The authors have studied the effect of demand response and pumped hydro storage in optimal scheduling of power system for reducing the energy and reserve costs considering wind power uncertainties in [3]. The influence of power to gas storage technology have been analyzed in obtaining operation cost and wind power spillage in [12], where robust model of combined electricity and gas networks is studied. In [13], a stochastic model is proposed for network constrained energy and reserve market clearing problem taking into consideration plug-in electric vehicle parking lots and wind energy. Moreover, the authors have studied the cooperation of HES in obtaining optimal unit commitment problem of power systems taking into account wind power curtailment and system operation cost in [14].

Combined heat and power (CHP) plants have been practically utilized in industries to provide power and heat simultaneously that is accomplished by restoring the heat wasted in generation process. This approach is effective in decreasing the supply cost of heat and power demand and reducing the emission of air pollution gases. The reports show that using CHP units instead of conventional generation plants is influential in obtaining an efficiency up to 90% [15]. Moreover, such plants are capable to decrease the emission of pollutant gases almost 13-18%. The research around integration of CHP plants have been expanded in recent years that is focused in optimal short-term scheduling of CHP units [16], integration of CHP plants in micro-grids [17], unit commitment problem in the presence of CHP plants [18] and multi-objective energy management of CHP plants [19].

In this paper, a network-constrained day-ahead scheduling framework has been proposed for electrical energy systems based on CHP plants and HES technology. In addition, high integration of wind power production units has been considered. A mixed integer non-linear programming has been used for the proposed model to solve the problem using DICOPT solver in the GAMS environment. The introduced HES system in this paper is capable to convert the extra wind power generation to hydrogen and store it in the hydrogen tank. Then, the HES system converts the stored hydrogen to power by utilizing gas fired plants when wind power is low. Two case studied have considered in this paper which includes a: network-constrained problem for CHP-based systems in the presence of wind power generation, b: the effect of HES in network-constrained scheduling of CHP-based systems in the presence of wind power generation.

This paper is organized as follows: Section II proposes the problem formulation of the introduced model for day-ahead scheduling of the CHP-HES based electrical energy networks. The test system and simulation results are provided in Section III for analyzing the performance of the proposed model. Finally, the paper has been concluded in Section IV.

II. PROBLEM FORMULATION

The formulation of the proposed network-constrained day-ahead scheduling of the CHP-HES based power system is discussed in this section. The objective function of the problem includes fuel cost and start-up cost of the conventional and CHP plants generation plants, operation cost of the HES system in both generation and storage modes. The operation cost of the HES system in supply mode has a similar cost function of the conventional plants.

$$\min \sum_{t=1}^{NT} \left[\begin{array}{l} \sum_{i=1}^{NP} \left[F_i \ (P_{i,t}) + SUC_{i,t} \right] \\ + \sum_{i=1}^{NCHP} \left[F_i \ (P_{i,t}, H_{i,t}) + SUC_{i,t} \right] \\ + \sum_{h=1}^{NH} \left[F_h^{PH} \ (P_{h,t}^{PH}) + F_h^{HP} \ (P_{h,t}^{HP}) \right] \end{array} \right] \tag{1}$$

Where:

A. Constraints

a) Power plant constraints: The equality and inequality constraints of the studied problem includes operaion cost of the conventional and CHP plants (2)-(3), opertaion cost of the HES system (4)-(5), limitation of power generation (6), ramp rate (7)-(8), minimum on/off time units (9)-(10) and feasible operating region of the CHP units (11)-(14).

$$F_i \ (P_{i,t}) = \alpha_i P_{i,t}^2 + \beta_i P_{i,t} + c_i \quad i \in NP \tag{2}$$

$$\begin{aligned} F_i^c (P_{i,t}, H_{i,t}) &= a_i \times P_{i,t} + b_i \times (P_{i,t})^2 + c_i + \\ d_i \times H_{i,t} &+ e_i \times (H_{i,t})^2 + f_i \times H_{i,t} \times P_{i,t} \qquad i \in NCHP \end{aligned} \tag{3}$$

$$F_h^{PH} \ (P_{h,t}^{PH}) = b_h^{PH} P_{h,t}^{PH} + c_h^{PH} \tag{4}$$

$$F_h^{HP} \ (P_{h,t}^{HP}) = a_h^{HP} (P_{h,t}^{HP})^2 + b_h^{HP} P_{h,t}^{HP} + c_h^{HP} \tag{5}$$

$$P_i^{min} I_{i,t} \le P_{i,t} \le P_i^{max} I_{i,t} \tag{6}$$

$$P_{i,t} - P_{i,t-1} \le RU_i \tag{7}$$

$$P_{i,t-1} - P_{i,t} \le RD_i \tag{8}$$

$$(X_{i,t-1}^{on} - T_i^{on})(I_{i,t-1} - I_{i,t}) \ge 0 \tag{9}$$

$$(X_{i,t-1}^{off} - T_i^{off})(I_{i,t} - I_{i,t-1}) \ge 0 \tag{10}$$

$$P_{CHP,t} - P_{CHP}^A - \frac{P_{CHP}^A - P_{CHP}^B}{H_{CHP}^A - H_{CHP}^B} \times (H_{CHP,t} - H_{CHP}^A) \le 0 \tag{11}$$

$$\begin{aligned} & P_{CHP,t} - P_{CHP}^B - \frac{P_{CHP}^B - P_{CHP}^C}{H_{CHP}^B - H_{CHP}^C} \times \\ & (H_{CHP,t} - H_{CHP}^B) \ge -(1 - V_{CHP,t}) \times M \end{aligned} \tag{12}$$

$$\begin{aligned} & P_{CHP,t} - P_{CHP}^C - \frac{P_{CHP}^C - P_{CHP}^D}{H_{CHP}^C - H_{CHP}^D} \times \\ & (H_{CHP}^t - H_{CHP}^C) \ge -(1 - V_{CHP,t}) \times M \end{aligned} \tag{13}$$

$$0 \le H_{CHP,t} \le H_{CHP}^A \times I_{CHP,t} \tag{14}$$

The power and heat supplied by CHP units have bidirectional dependency. Such interconnection has been defined as feasible operating region (FOR), which is demonstrated in Fig. 1 for the studied CHP unit.

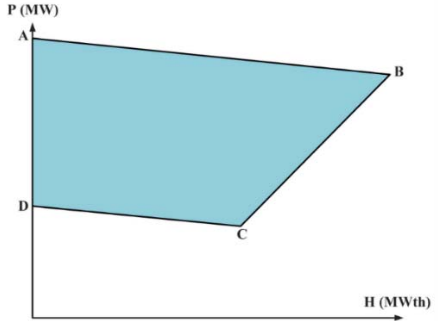

Fig. 1. FOR of the CHP plant

b) Hydrogen storage system constraints: The operation of HES system can be considered in generation, storage, or idle modes similar to other energy storage technologies that is defined by (15). The minimum and maximum limitations of the generated and stored hydrogen should be considred as (16) and (17). The hydrogen stored in the HES can be obtaine dusing (18), which should be limited to its lower and upper bounds as (19). Moreover, the intila and final value of the hydrogen stored in the HES system can be defined by using (20) and (21). Finally, the hydrogen utilized in other forms of energy can be defined by (22).

$$I_{h,t}^{H2P} + I_{h,t}^{P2H} \le 1 \tag{15}$$

$$P_{h,\min}^{PH} I_{h,t}^{PH} \le P_{h,t}^{PH} \le P_{h,\max}^{PH} I_{h,t}^{PH} \tag{16}$$

$$P_{h,\min}^{HP} I_{h,t}^{HP} \le P_{h,t}^{HP} \le P_{h,\max}^{HP} I_{h,t}^{HP} \tag{17}$$

$$A_{h,t} = A_{h,t\text{-}1} + \eta_h^{PH} P_{h,t}^{PH} - \frac{P_{h,t}^{HP}}{\eta_h^{HP}} - M_{h,t} \tag{18}$$

$$A_h^{\min} \le A_{h,t} \le A_h^{\max} \tag{19}$$

$$A_{h,0} = A_{h,in} \tag{20}$$

$$A_{h,0} = A_{h,NT} \tag{21}$$

$$0 \le M_{h,t} \le M_{h,\max} \tag{22}$$

c) Wind power constraint: Limit of dispatched wind power is can be formulated as (23).

$$0 \le P_{r,t} \le P_{r,t}^f \tag{23}$$

d) System constraints: Power balance in each bus of the electroical enerrgy system can be satisfied according to (24). Line power transmission and its limitations can be expres by (25) and (26). The heat balance of the system can be formulated by (27).

$$\sum_{i=1}^{NU_b} P_{i,t} + \sum_{r=1}^{NR_b} P_{r,t} + \sum_{k=1}^{NK_b} P_{h,t}^{HP} - \sum_{k=1}^{NK_b} P_{h,t}^{PH} - \sum_{j=1}^{NJ_b} d_{j,t} = \sum_{l=1}^{NL_b} PF_{L,t} \tag{24}$$

$$PF_{L,t} = \frac{\delta_{b,t} - \delta_{b^{'},t}}{X_L} \tag{25}$$

$$-PF_L^{max} \le PF_{L,t} \le PF_L^{max} \tag{26}$$

$$\sum_{i=1+NP}^{NC} H_{i,t} = \sum_{q=1}^{NQ} HD_{q,t} \tag{27}$$

III. CASE STUDY

The proposed model has been applied to a 6-bus network, which contains a CHP plant, 2 conventional thermal plants, 3 power load demands and 7 power transmission lines. The CHP plant has been located at bus 1, and two thermal plants G1 and G2 are installed at buses 2 and 6, respectively. The characteristics of the CHP plant and generation units are provided in Table I and Table II. In addition, a wind power generation unit and a HES are located at bus 5. The load demand and transmission lines data are adapted from [20]. The wind power output and forecasted heat load are shown in Fig. 2. The proposed network-constrained market clearing problem is modeled as a mixed integer non-linear programming method, and is solved using DICOPT solver in GAMS software environment. Two cases are considered in this section to verify the effectiveness of the proposed model:

Case 1: Network-constrained problem for CHP-based systems in the presence of wind power generation

Case 2: The effect of HES in network-constrained scheduling of CHP-based systems in the presence of wind power generation

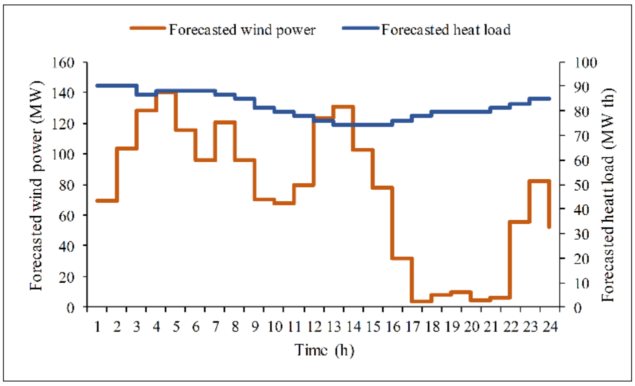

Fig. 2. The wind power output and forecasted heat load

Table I: Cost coefficients of the CHP and thermal units

	a (*$/MW^2*)	*b* (*$/MW*)	*c* (*$/h*)	*d* (*$/MWth^2*)	*e* (*$/MWth*)	*f* (*$/MWMWth*)
CHP	0.0345	14.5	110.41	0.03	4.2	0.031
G1	0.001	32.63	129.97	0	0	0
G2	0.005	17.7	137.41	0	0	0

Table II: Technical characteristics of the CHP and thermal units

	P_{min} (*MW*)	P_{max} (*MW*)	H_{min} (*MWth*)	H_{max} (*MWth*)	*Initial status (h)*	*MUT (h)*	*MDT (h)*
CHP	68	207	0	150	4	1	1
G1	10	100	0	0	-3	2	3
G2	10	20	0	0	-1	1	1

Case 1: In this case, the HES is not considered in the network-constrained scheduling problem. The power dispatch of the generation units during the scheduling time interval is depicted in Fig. 3. As seen in this figure, the CHP units has been participated in power generation at whole time interval. The plant G1 as the most expensive plant has been cooperated only when wind power generation is low and the system is in on-peak hours. The plant G2 has been participated in power supply with its maximum capacity (i.e., 20 MW) at medium and on-peak hours since it has lower generation cost than plant G1. The operation cost of case 1 is $95667.331 that includes $84000.78 for CHP operation cost. The cost of production the whole plants is $11666.54 in this case. In addition, the effect of heat load increment on wind power dispatch and generation plants power dispatch has been provided in Table III and Fig. 4. As it is obvious from the obtained results, the minimum power generation of CHP plant has been increased in the beginning of scheduling time interval by increasing the heat load, which is due to feasible operating region of the CHP plant. This is effective in curtailment of wind power at these time intervals and consequently increment of operation cost of the system. In addition, the power generation of CHP plant has been decreased at *t=16 h to t=21 h* due to feasible operating region of the CHP unit, which is resulted to higher cooperation of expensive plants. This is done in a way that the wind power curtailment has increased form 221.92 MW to 249.207 MW by increasing the heat demand by 10%. Accordingly, the operation cost of plants has been increased from $11666.54 to $12447.452, which resulted in increment of total operation cost of the system.

Case 2: In this case, the HES is taken into account in the network-constrained scheduling. The characteristics of the HESS, which has a maximum capacity of 30 MW, are provided in Table IV. As seen in Fig. 5, the HES has stored the extra wind power at begging of the scheduling time horizon at *t=2 h to t=7 h*. This is accomplished by converting the extra power to hydrogen using the P2H technology, and storing it in hydrogen tank, which can be seen in increment of the wind power dispatch in Table V. Then, the stored hydrogen is converted to the power at on-peak hours as seen in Fig. 6. In these time intervals, the plant G1 is not participated in power supply that the HESS is in generation mode. It is notable that HES is in ideal mode at *t=17 h to t=18 h* since the power generation of plant G1 is greater than the capacity of HES. Accordingly, it is economical that HES operates at generation mode when the plant G1 is not participated in power supply because this plant has constant cost. The operation cost of the system in this case is \$92509.79, which is decreased remarkably with respect to case 1.

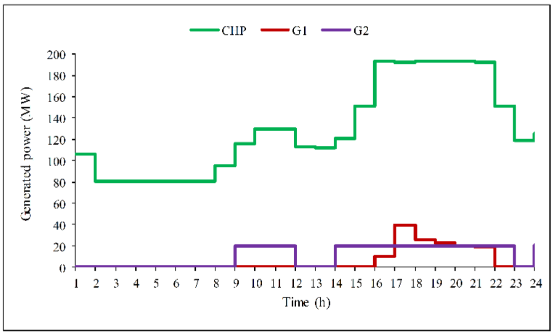

Fig. 3. The power dispatch of the generation units during the scheduling time interval

Table III. The effect of heat load increment on generation plants power dispatch

	Power dispatch in 1.1 forecasted heat load			Power dispatch in forecasted heat load		
Hour	G1	G2	G3	G1	G2	G3
1	105.59	0	0	105.59	.	.
2	89.57	0	0	81.00	.	.
3	82.67	0	0	81.00	.	.
4	86.12	0	0	81.00	.	.
5	86.12	0	0	81.00	.	.
6	86.12	0	0	81.00	.	.
7	82.67	0	0	81.00	.	.
8	94.90	0	0	94.90	.	.
9	115.36	0	20.00	115.36	.	20.00
10	129.60	0	20.00	129.60	.	20.00
11	129.41	0	20.00	129.41	.	20.00
12	113.30	0	0	113.30	.	.
13	111.58	0	0	111.58	.	.
14	121.20	0	20.00	121.20	.	20.00
15	150.86	0	20.00	150.86	.	20.00
16	191.97	11.81	20.00	193.47	10.31	20.00
17	191.63	40.36	20.00	192.60	39.39	20.00
18	191.28	27.45	20.00	192.85	25.88	20.00
19	191.28	24.68	20.00	192.85	23.11	20.00
20	191.28	21.06	20.00	192.85	19.49	20.00
21	190.942	20.36	20.00	192.54	18.76	20.00
22	151.14	0	20.00	151.14	.	20.00
23	99.05	0	20.00	119.05	.	.
24	124.75	0	20.00	124.75	.	20.00

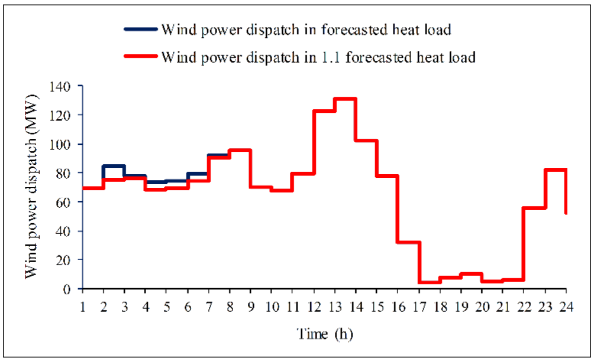

Fig. 4. The effect of heat load increment on wind power dispatch and generation plants power dispatch

Table IV. The characteristics of the HES

Mode	a (\$/MW^2)	b (\$/MW)	c (\$/h)	P_{max}	P_{min}	η
Generation	153.4	15.60	0.0027	30	10	0.80
Storage	0	1.41	0.125	30	10	0.6

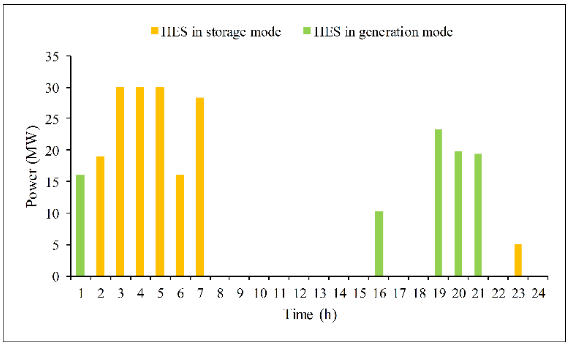

Fig. 5. Operation of the HES in case 2

Table V. Wind power dispatch in cases

Hour	Wind power dispatch in case 2	Wind power dispatch in case 1
2	103.200	84.150
3	97.670	77.670
4	93.730	73.730
5	94.060	74.060
6	95.600	79.480
7	112.390	92.390

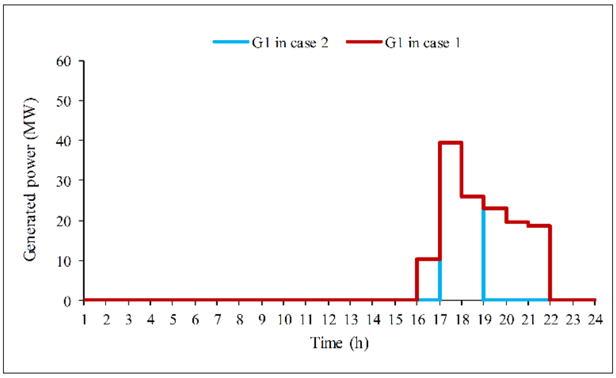

Fig. 6. Power generation of G1 in cases 1 and 2

IV. CONCLUSION

This paper presented a network-constrained day-ahead scheduling problem for electrical energy systems based on CHP units with high integration of wind power supply. The proposed model has been considered as a mixed integer non-linear programming, which was solved using DICOPT solver in the GAMS environment. A HES system was introduced in this paper to convert the extra wind power to hydrogen and stored it in the hydrogen tank. The stored energy was utilized when wind power is low, which was converted to power by utilizing gas fired plants based on hydrogen. The obtained analysis showed that the increment of heat load demand of the system has a considerable effect on increasing the curtailment of wind power and system operation cost. In addition, the investigation of the role of HES system proved that the curtailment of wind power and system operation cost were decreased considering HES system.

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