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Optimal Operation of Integrated Energy Systems Considering Demand Response Program

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Abstract-*This study presents an optimal framework for the operation of integrated energy systems using demand response programs. The main goal of integrated energy systems is to optimally supply various demands using different energy carriers such as electricity, heating, and cooling. Considering the power market price, this work investigates the effects of multiple energy storage devices and demand response programs, including the time of use pricing, real-time pricing, and integrated demand response on optimal operation of energy hub. Moreover, impacts of different optimization methods are evaluated on the optimal scheduling of multi-carrier energy systems. Maximizing profits of selling electrical energy and minimizing the purchasing cost of input carrier energies are considered as objective functions to indicate bidirectional interchanges of energy hub systems with the power grid. To minimize the generation cost of energy carriers, a new quadratic objective function is also optimized using genetic algorithm. In this study, optimal operation of the energy hub based on the proposed quadratic objective function is an economic dispatch problem where the purchasing electrical power by the energy hub is considered as a load of the upstream grid. The optimization problem is implemented in the sample energy hub to indicate the effectiveness of different energy storage roles and applied demand response programs in the optimal operation of energy hub systems.*

Keyword: Integrated energy systems, Demand response, Linear optimization, Quadratic optimization, Energy storage

NOMENCLATURE

T	Index of time
E	Index of electricity
H	Index of heating energy
C	Index of cooling energy
RES	Index of renewable energy resources
WT	Index of wind Turbine
PV	Index of photovoltaic
ST	Index of solar thermal
x	Index of energy storage
$P_{e,in,ac,t}$	Total generated ac power
$P_{h,t}$	Total generated heating energy
$P_{c,t}$	Total generated cooling energy
$P_{grid,t}$	The purchased electrical power from the upstream grid (UG)
$P_{sell,t}$	The sold power to the power grid
$P_{gas,in,t}$	The total purchased natural gas
$P_{e,re,t}$	The generated electrical power by RES
$P_{e,GT,t}$	The produced electrical power by gas turbine
$u_{grid,t}$	The binary variable related to purchasing/selling electrical energy from/to UG
$u_{es,t}$	The binary variable related to battery electrical storage system (BESS)
$u_{hs,t}$	The binary variable related to heating electrical storage system (HESS)
$u_{cs,t}$	The binary variable related to cooling electrical storage system (CESS)
η_{trans}	Efficiency of transformer
η_{k}	Efficiency of inverter
$\eta_{e,GT}$	Efficiency of gas turbine for producing electricity
$\eta_{h,GT}$	Efficiency of gas turbine for producing heating energy
η_{HE}	Efficiency of heat exchanger
η_{GB}	Efficiency of gas boiler
C_{EC}	Efficiency of electrical chiller
C_{AC}	Efficiency of absorption chiller
P_{GT}^{max}	Electrical capacity of gas turbine
H_{GB}^{max}	Capacity of gas boiler
P_{EC}^{max}	Capacity of electrical chiller
P_{AC}^{max}	Capacity of absorption chiller
P_{grid}^{max}	Maximum purchased power from grid
P_{sell}^{max}	Maximum sold power to the UG
E_{es}^{min}	Minimum stored electrical energy in BSS
E_{hs}^{min}	Minimum stored heating energy in HSS

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Research Paper

E_{cs}^{min}	Minimum stored cooling energy in ISS
E_{es}^{max}	Maximum stored electrical energy in BSS
E_{hs}^{max}	Maximum stored heating energy in HSS
E_{cs}^{max}	Maximum stored cooling energy in ISS
$P_{es,dis}^{min}$	Maximum discharged power of BSS
$P_{hs,dis}^{max}$	Maximum discharged power of HSS
$P_{cs,dis}^{max}$	Maximum discharged power of ISS
$price_t^e$	Price of purchasing electrical energy
$price_t^{sell}$	Price of selling electrical energy
$price_t^{gas}$	Price of purchasing natural gas
$P_{e,demand,t}$	Electrical demand
$P_{h,demand,t}$	Heating demand
$P_{c,demand,t}$	Cooling demand
$P_{h,GT,t}$	The produced heating energy by gas turbine
$P_{h,GB,t}$	The produced heating energy by gas boiler
$P_{e,in,t}$	The actual purchasing power from the UG
$P_{WT,ac,t}$	The generated ac Power by WT
$P_{PV,dc,t}$	The generated dc Power by PV
$P_{h,ST,t}$	The generated heating energy by ST
$P_{h,HE,t}$	The produced heating energy by heat exchanger
$P_{c,EC,t}$	The produced cooling energy by electrical chiller
$P_{c,AC,t}$	The produced cooling energy by absorption chiller
$P_{AC,t}$	The consumed heating power by the absorption chiller
$P_{e,EC,t}$	The consumed power by the electrical chiller
$P_{GT,t}$	The consumed gas by the gas turbine
$P_{GB,t}$	The consumed gas by the gas boiler
$P_{e,dis,t}$	The discharge rate of BSS
$P_{h,dis,t}$	The discharge rate of HSS
$P_{c,dis,t}$	The discharge rate of ISS
$P_{e,ch,t}$	The charge rate of BSS
$P_{h,ch,t}$	The charge rate of HSS
$P_{c,ch,t}$	The charge rate of ISS
$E_{es,t}$	The stored electrical energy in BSS
$E_{hs,t}$	The stored heating energy in HSS
$E_{cs,t}$	The stored cooling energy in ISS

1. INTRODUCTION

With the development of technology, advances in the field of the smart grid have enabled to improve the efficient use of renewable energy resources and multi-carrier energy systems. In recent years, dependently operation of various forms of energy in smart grids has developed as integrated energy systems (IESs) to enhance the security and reliability of power systems.

The energy hub acts as an intermediate between various energy carriers and supplies different types of demand by purchasing, converting, and storing input carriers [1]. In addition, different load demands can be supplied by discharging power of battery electrical storages (BESs) [2], heating energy storages (HESs) [2], and cooling energy storages (CESs) [3,4]. For balancing between supply and demand, the contributions of converters and energy storage devices can be determined using operation of the energy hub optimally.

The optimal operation of an energy hub is defined as an optimization problem based on various objective functions and different decision variables. The main objective functions used in related works are minimizing the cost of purchasing energy such as electrical energy and natural gas from the power market [5] and maximizing profits of selling electrical energy [6]. These objective functions can be defined as operation costs. Moreover, the integrated energy system can be also operated optimally based on the investment cost [7], the emission cost [5, 8], the cost of implementing energy storage [7, 9] and the cost of executing demand response programs [7, 9-10]. Considering constraints related to the capacity of the converters [11] and transmission lines [1], these objective functions can be optimized through deterministic and uncertainty [12-14] approaches using different optimization algorithms such as mixed-integer linear programming, robust optimization, stochastic optimization, and genetic algorithms.

Demand response programs (DRPs) play a critical role in flatting the load curve, improving reliability, and reducing the total cost of customers and the cost of distribution companies. DR programs are categorized into incentive-based and price-based DRPs [15].

In price-based DR programs (PDRs), energy price changes according to demand and the customers reduce or shift their consumption in response to price variations. Also, the customer's participation in DR programs is increased by receiving financial persuasions from distribution companies in incentive-based DR programs. The time-of-use (TOU) [16-18] and real-time-pricing (RTP) rates [3, 5, 19] are the most famous PDRs. Moreover, economically operation of energy hub without TOU and RTP constraints is defined as the integrated demand response (IDR) [20]. These DRPs can be used for both electrical and heating loads [21]. On the other side, the electrical, heating and cooling demands are divided into responsive and non-responsive loads that the responsive loads only participate in DRPs [22-24].

In view of the above issues, this paper aims to study the optimal operation of an energy hub in two cases. In case I, a linear objective function is optimized for minimizing the customer's costs using linear programming and genetic algorithm by MATLAB and GAMS software. Furthermore, different DRPs are implemented and the effects of energy storage devices on the optimal operation of energy hub are evaluated in this study.

In case II, the power market price is not considered and a new quadratic objective function for energy hub based on generation cost of electrical energy and natural gas is optimized using the genetic algorithm. On the other hand, the input electrical power of the energy hub acts as a load in case II and the optimal operation of the integrated energy system is the same as the economic dispatch problem where the loss of the transmission line is ignored.

The rest of the paper is organized as follows. Section 2 describes mathematical models for the sample energy hub. The optimal scheduling of energy hub is expressed in Section 3. The optimization problem is simulated in Section 4. Finally, the conclusion is presented in Section 5.

2. ENERGY HUB MODELING

Energy hub is a framework for exhibiting integrated energy systems consists of different converters and energy storage devices. Fig.1 indicates the general structure of the energy hub.

As shown in fig.1, a portion of input carriers including electrical energy, natural gas, and heating energy supplies output loads directly. Another portion of the input energy is delivered to the converters. After converting both size and type of input carriers, the load demands are provided through the output port. The input energies can be also stored by storage devices to reduce the purchasing cost of energy from the power market.

In this paper, the structure in fig.2 is used for modeling the energy hub [25]. As can be seen in fig. 2, the understudied energy hub is composed of electrical, heating and cooling parts that will be explained in future subsections.

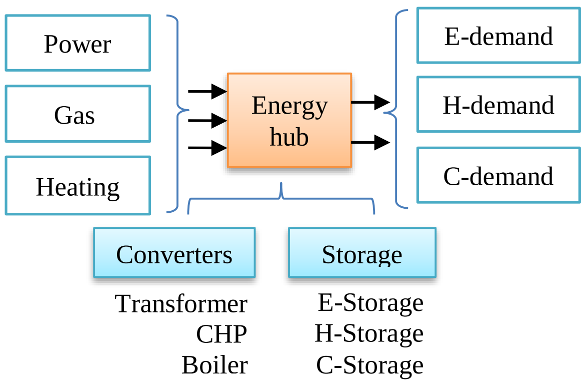

Fig.1. The general structure of the energy hub

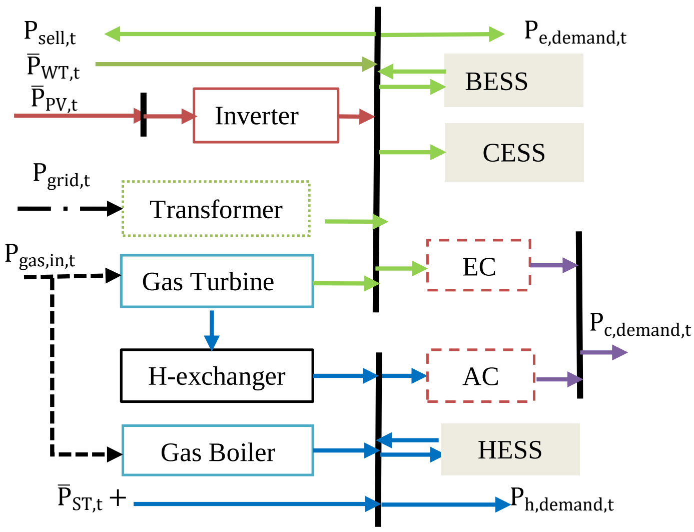

Fig.2. Schematic of understudied energy hub [25, 26]

2.1. Electrical System

The input of the electrical system in the energy hub ($P_{e,in,ac,t}$) is supplied by the sum of the input electrical energy from the power market ($P_{e,in,t}$), output power of renewable energy resources ($P_{e,re,t}$) and the produced electrical power by the gas turbine. The input electrical energy ($P_{e,in,t}$) is obtained from multiplying the efficiency of the transformer (η_{trans}) by the purchasing electrical energy ($P_{grid,t}$) expressed as Eq. (2). On the other side, a portion of ac electrical power is generated by the gas turbine ($P_{e,GT,t}$) based on Eq. (3). In the studied energy hub, both wind turbines and photovoltaic panels are used as electrical renewable resources according to Eq. (4). The dc output electrical power of PV is transferred to ac power using inverters.

$$P_{e,in,ac,t} = P_{e,in,t} + P_{e,GT,t} + P_{e,re,t} \quad (1)$$

$$P_{e,in,t} = \eta_{trans} \times P_{grid,t} \quad (2)$$

$$P_{e,GT,t} = P_{GT,t} \times \eta_{e,GT} \quad (3)$$

$$P_{e,re,t} = P_{WT,ac,t} + \eta_k \times P_{PV,dc,t} \quad (4)$$

Also, the excess generated electricity can be sold to the power grid ($P_{sell,t}$). Since the electrical chiller is used to supply the cooling demand in this structure, the input power of the electrical chiller ($P_{e,EC,t}$) should be supplied by the electrical system in the energy hub. Therefore, the power balance constraint in the electrical system will be as follows:

$$P_{e,in,ac,t} - P_{sell,t} - P_{e,EC,t} = P_{e,demand,t} \quad (5)$$

2.2. Heating System

The main input carriers of the studied energy hub are electrical power and natural gas. The input natural gas ($P_{gas,in,t}$) is split between gas turbine and gas boiler according to Eq.(6). Both the gas turbine and gas boiler generate heat from natural gas as Eq. (7) and Eq. (8). On the other hand, the gas turbine generates heat in addition to electrical energy according to Eq. (8). The heating exchanger is used in the energy hub for changing the temperature of produced heating by the gas turbine ($P_{h,GT,t}$) based on Eq. (9). The Total generated heat ($P_{h,t}$) is calculated according to Eq. (10). Also, a portion of the required heating demand can be supplied by the solar thermal expressed as $P_{h,ST,t}$.

$$P_{gas,in,t} = P_{GT,t} + P_{GB,t} \quad (6)$$

$$P_{h,GB,t} = P_{GB,t} \times \eta_{GB} \quad (7)$$

$$P_{h,GT,t} = P_{GT,t} \times \eta_{h,GT} \quad (8)$$

$$P_{h,HE,t} = P_{h,GT,t} \times \eta_{HE} \quad (9)$$

$$P_{h,t} = P_{h,GB,t} + P_{h,ST,t} + P_{h,HE,t} \quad (10)$$

The total amount of produced heating power must supply heating demand and the required input of absorption chiller as follows:

$$P_{h,t} - P_{h,AC,t} = P_{h,demand,t} \quad (11)$$

2.3. Cooling System

Total cooling energy is provided either through an electric chiller or through an absorption chiller according to Eq. (12). The required input of electrical chiller and heating input of absorption chiller are produced using the electrical system and heating energy hub stated above, respectively.

$$P_{c,t} = P_{c,EC,t} + P_{c,AC,t} \quad (12)$$

$$P_{c,EC,t} = C_{EC} \times P_{e,EC,t} \quad (13)$$

$$P_{c,AC,t} = C_{AC} \times P_{h,AC,t} \quad (14)$$

2.4. Energy storage systems (ESSs)

The ESSs store energy with low price at non-peak hours and inject energy into the power grid at peak hours. The dynamic model of energy storage devices is shown in Eq. (15). In the following equations, x refers to BESs, HESs, and CESs. Also, the capacity and charging/discharging power of energy storage devices are limited according to Eqns. (16)-(18). The binary variable $u_{xs,t}$ is used in Eqns.(17)-(18) to avoid charging and discharging ESSs, simultaneously. $u_{xs,t}$ is equal to 1 if energy storage is charging at t-th time interval.

$$E_{xs,t+1} = E_{xs,t} + \left(P_{x,ch,t} \times \eta_{xs,ch} - \frac{P_{x,dis,t}}{\eta_{xs,dis}}\right) \quad (15)$$

$$E_{xs}^{min} \le E_{xs,t} \le E_{xs}^{max} \quad (16)$$

$$P_{x,ch,t} \le u_{xs,t} \times P_{xs,ch}^{max} \quad (17)$$

$$P_{x,dis,t} \le (1 - u_{xs,t}) \times P_{xs,dis}^{max} \quad (18)$$

With storage devices, the electrical, heating and cooling balance constraint in the energy hub will be as follows:

$$P_{e,in,ac,t} + P_{e,dis,t} - P_{e,ch,t} - P_{c,ch,t} - P_{sell,t} - P_{e,EC,t} - P_{e,demand,t} \quad (19)$$

$$P_{h,t} + P_{h,dis,t} - P_{h,ch,t} - P_{h,AC,t} = P_{h,demand,t} \quad (20)$$

$$P_{c,t} + P_{c,dis,t} = P_{c,demand,t} \quad (21)$$

According to the above equations, the optimal operation of the studied energy hub will be illustrated in section 3.

3. OPTIMAL OPERATION OF ENERGY HUB

The main goal of optimal operation of energy hub is minimizing the total costs of integrated energy systems such that the constraints related to the capacity of converters and capacity of distribution systems are established. In this problem, the energy hub is optimally operated in two cases with following decision variables.

$$\{P_{e,in,t}, P_{sell,t}, P_{e,GT,t}, P_{h,GB,t}, P_{c,EC,t}, P_{c,AC,t}, P_{h,HE,t}\}$$

Case I: Minimizing the purchasing costs of electrical energy and natural gas and maximizing the profits of selling extra electricity to the power grid are the main objective functions in this work. The linear combination of these objective functions can be indicated as (22).

$$OF_{case\ I} = \sum_{t=1}^{24} price_t^{e} \times P_{grid,t} + \sum_{t=1}^{24} price_t^{gas} \times P_{gas,in,t} - \sum_{t=1}^{24} price_t^{sell} \times P_{sell,t} \quad (22)$$

Case II: As a new method, if generation costs of input carriers including electricity and natural gas are considered as objective functions instead of customer's costs, the optimization is defined as a quadratic program and solved by nonlinear optimization methods such as the genetic algorithm. The objective function is determined in case II according to (23).

$$OF_{case\ II} = \sum_{t=1}^{24}(\alpha_e \times P_{grid,t}^2 + \beta_e \times P_{grid,t} + \gamma_e) + \sum_{t=1}^{24}(\alpha_g \times P_{gas,in,t}^2 + \beta_g \times P_{gas,in,t} + \gamma_g) \quad (23)$$

3.1. Constraints of Optimization Problem

The purchasing and selling electrical energy are respectively restricted according to Eq. (24) and Eq. (25) where $u_{grid,t}$ is equal to 1 if the electrical power is purchased from the UG at t-th time interval. Also, the constraints related to the capacity of converters such as the gas turbine, gas boiler, electrical chiller, and absorption chiller are defined as Eqns. (26)-(29).

$$P_{grid,t} \le P_{grid}^{max} \times u_{grid,t} \quad (24)$$

$$P_{sell,t} \le P_{sell}^{max} \times (1 - u_{grid,t}) \quad (25)$$

$$P_{e,GT,t} \le P_{GT}^{max} \quad (26)$$

$$P_{h,GB,t} \le H_{GB}^{max} \quad (27)$$

$$P_{c,EC,t} \le P_{EC}^{max} \quad (28)$$

$$P_{c,AC,t} \le P_{AC}^{max} \quad (29)$$

3.2. Demand Response Program (DRP)

In demand response programs, consumers change their consumption curves by decreasing and shifting their demand in response to the price's variations. The following equations are the key constraints of the time of use rate of DR program in the optimal operation of the energy hub. The new load curve can be written as Eq. (30). The sum of total transferred power in the daily DR program will be zero according to Eq. (32).

$$P_{e,demand,t,new} = P_{e,demand,t} + P_{e,shift,t} \quad (30)$$

$$|P_{e,shift,t}| \le E^{max} \times P_{e,demand,t} \quad (31)$$

$$\sum_{t=1}^{24} P_{e,shift,t} = 0 \quad (32)$$

Also, the new load pattern after implementation of the real-time DRP can be expressed as (33), where E is the demand-price elasticity coefficient.

$$P_{e,demand,t,new} = P_{e,demand,t}\left[1 + E \times \left(\frac{price_t^e - price_t^{e,base}}{price_t^{e,base}}\right)\right] \quad (33)$$

4. SIMULATION RESULTS

In this paper, two cases for optimal operation of the studied energy hub are simulated. In case I, a linear objective function is optimized by genetic algorithm and linear programming using GAMS and MATLAB software. This linear objective function is based on the purchasing cost of input carriers including electricity and natural gas. In case II, the genetic algorithm is used to optimize a quadratic objective function based on the generation cost of electrical energy and natural gas. The simulation results of case II are indicated in subsection 4.2. The data for electrical, heating and cooling demands are shown in fig.3.

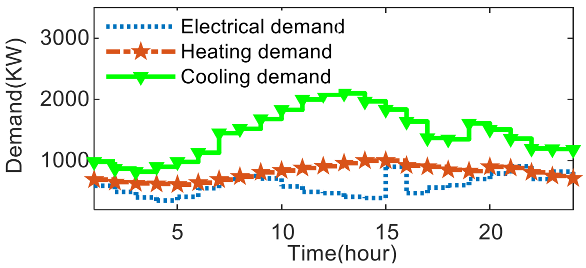

Fig.3. Electrical, heating and cooling demands

4.1. Case I: Simulation Results with Linear Objective Function

In this case, the objective function is optimized using linear programming and genetic algorithm. The total costs of different optimization methods are shown in table 1. The total cost of energy hub without ESSs using renewable energy sources (RES) is decreased by 8.95%, 7.79 % and 7.41% compared to optimization problem without RES by MILP (using MATLAB and GAMS) and genetic algorithm, respectively. Thus, it can be realized that the use of renewable energy resources can be led to a decrease in the cost of the energy hub.

Table.1. The comparison of total cost of energy hub by different optimization algorithms in case I

Total cost	Mixed integer linear programming with MATLAB (YALMIP)	Mixed integer linear programming with GAMS	Genetic algorithm
Total cost by IDRP without renewable energy source ($)	22516.7688	22534.5164	21779
Total cost by IDRP with renewable energy sources ($)	20500.5857	20778.3581	20165

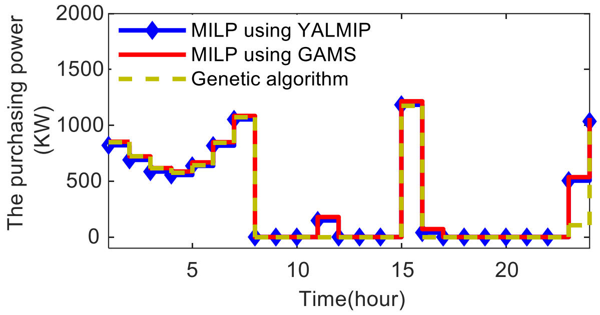

Fig.4. The comparing between the purchasing electrical power by MILP and genetic algorithm in case I

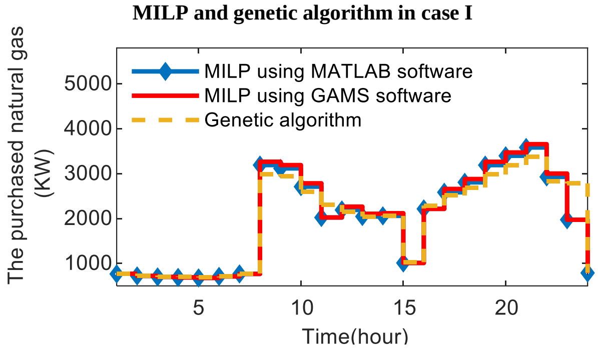

Fig.5. The comparison between the purchased natural gas by MILP and genetic algorithm in case I

The total cost arising from the genetic algorithm has the lowest value compared to the mixed-integer linear programming which is executed by MATLAB and GAMS software. Fig. 4 and Fig. 5 respectively indicate the purchasing electrical power and the purchased natural gas in case I without energy storage. As can be seen, the results of mixed-integer linear programming by GAMS software are almost the same as the results of MATLAB software and genetic algorithm.

Since the heating demand is only provided through the gas boiler and gas turbine without considering the energy storage devices, the fixed natural gas is purchased from the distribution system at 1:00 -8:00 a.m. The purchasing natural gas is low in this time interval because the heating demand has the minimum fixed value at 1:00-8:00. Considering the high efficiency of gas boiler compared to the gas-heating efficiency of the gas turbine, the upper portion of the purchasing gas is converted to the heating energy using the gas boiler. Furthermore, the produced electrical power using the gas turbine has a low value because of the low gas-electricity efficiency and the low portion of its input natural gas. So, the produced power by the gas turbine cannot supply the electrical and cooling demands and it is required to purchase the high value of electrical energy from the power market according to Fig. 4. Since the electrical and cooling demands are decreasing at 1:00-5:00 a.m., the purchasing power is reduced in this time interval. On the other side, the electrical demand is at the first peak during 8:00-9:00 a.m. Thus, the maximum power is purchased in this period. The purchased natural gas is increased during 8:00-16:00 because the electrical, heating and cooling demands are increased. During 8:00-11:00 a.m. and 11:00-15:00 p.m., the whole of electrical and heating demands is supplied using the gas turbine and gas boiler. So, it is not needed to purchase extra electrical power. As can be seen in Fig. 4 and Fig. 5, the maximum electrical power and the minimum natural gas are purchased when the electrical, heating and cooling demands have the peak value. This paper also evaluates the effects of three different energy storages (electrical, heating and cooling) on the optimal operation of the studied energy hub. The simulation is executed in case I using GAMS software. As can be seen in Fig. 6, the interchanged electrical power with the grid is increased if the electrical, heating and cooling energy storage devices are used in the studied energy hub. This increase in purchasing power is due to the charging of electrical energy storage. Also, the cooling energy storage has not the key effects on the optimal operation of the energy hub. Considering the cooling storage, the purchasing electrical energy is almost the same as the case in which there aren't any storage devices in the energy hub. Fig. 7 indicates the effects of ESSs on the purchased natural gas. The value of purchased natural gas is decreased using ESSs almost at the whole of time intervals.

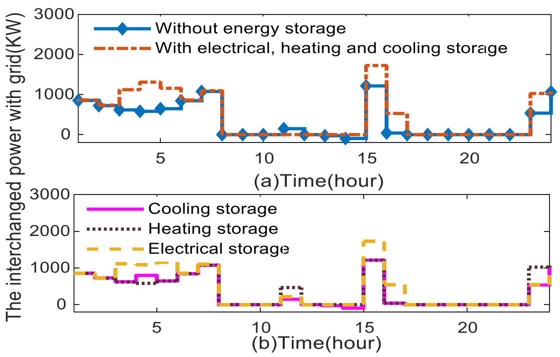

Fig.6. Effects of energy storage devices on the purchasing electrical power in case I (a) Available capacity of ESSs (b) Different types of ESSs

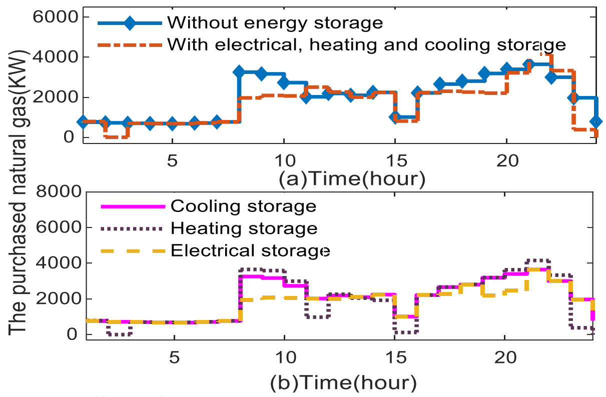

Fig.7. Effects of energy storage devices on the purchased natural gas in case I (a) Available capacity of ESSs (b) Different types of ESSs

As shown in Fig. 6, high electrical energy is interchanged with the power grid at time intervals with low demands and low prices. Also in non-peak hours, the purchased natural gas is low compared to hours with high demand according to Fig. 7.

The impacts of different energy storage devices on the total cost of energy hub are shown in Table 2. As can be seen in Table 2, the total cost of the energy hub is decreased using electrical, heating and cooling storage devices from 20778.35 $ to 19914.10 $. The minimum effect on the total cost is related to cooling energy storage. Thus, the cost arising from cooling energy storage is almost the same as the case in which energy storage devices have not been considered. This fact can be realized using Fig. 6 and Fig. 7. The structure of the studied energy hub is the same as [25] with the only difference that the uncertainty of the market price is ignored and deterministic planning is only considered. In Ref. [25], the operation cost of the energy hub in the deterministic case without demand response programs is equal to 20765.02 $ which is almost the same as the cost in this paper. The operation cost is calculated by the sum of the cost of purchasing electrical power and natural gas and the profit of exported electricity to the power grid.

Table 2.The comparison of the total cost of energy hub using different energy storage devices in case I

Total cost with different energy storages by IDRP ($)	Linear programming by MATLAB (YALMIP) ($)	Linear programming by GAMS ($)
Without energy storage	20500	20778.3581
With cooling energy storage	20475.2924	20854.2115
With heating energy storage	19777.6746	20348.97093
With electrical energy storage	19554.204	20168.31506
With electrical, cooling and heating energy storages	18889.9	19914.1047

Table 3.The comparison of the total cost of energy hub using different demand response programs in case I

Total cost with ES by DRP	MILP by GAMS($)	MILP in [25]($)
Time of use pricing	19706.578	20578.01
Real time pricing	19680.0271	20425.91
Integrated demand response program	19914.10	20765.02

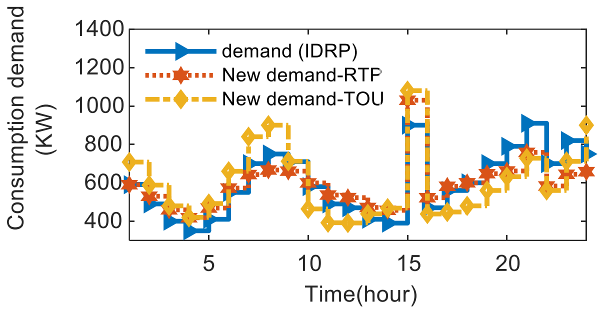

Fig.8. The load curve after implementing TOU/RTP rates of DRPs and IDRPs in case I using GAMS software

Moreover, both time of use (TOU) and real-time pricing (RTP) rates of DRPs are simulated according to formulation 3.2 and compared to the integrated demand response program (IDRP). The energy hub is optimally operated without constraints related to DRPs in IDRPs by determining the type and size of input carriers. The total costs of energy hub arising from different demand response programs are compared in table 3. According to Table 3, cost is decreased using RTP and TOU rates of DRP compared to the integrated demand response program. As a result, the most effective DRP method is RTP demand response program that is correctly approved by Ref. [25].

The load curve after implemention of demand response programs is shown in Fig. 8. As can be seen, real-time pricing and time of use demand response programs are more effective than IDRP because the load is decreased at time intervals with high demand using RTP and TOU. Since the customers can shift their consumption to time intervals with lower demand, the amount of load is also increased at non-peak hours. The effectiveness of TOU and RTP rates of DRP is demonstrated in Table 3. According to Fig. 8, the new demand curve arising from the RTP demand response program is close to the actual load pattern. This concern indicates the effective performance of RTP compared to TOU.

4.2. Case II: Simulation Results with a Quadratic Objective Function

In case II, a quadratic objective function based on the generation cost of input carriers is optimized using the genetic algorithm. Considering the generation cost of electrical power, the optimal operation of the studied energy hub is the same as the economic dispatch problem where the loss of the transmission line is ignored. Furthermore, the quadratic objective function is approximated to the linear function and it is compared with case I. The simulation results are shown in Fig. 9 and Fig. 10.

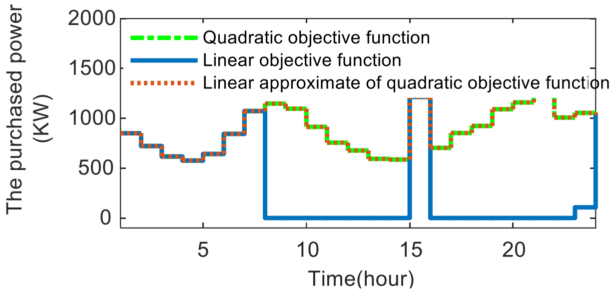

Fig.9. the purchased electrical energy in case II using the genetic algorithm

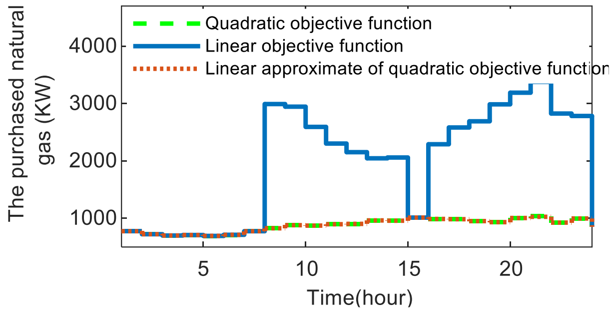

Fig.10. the purchased natural gas in case II using the genetic algorithm

The result of the quadratic optimization problem is the same as the result arising from linear approximated objective function. Also, the purchased electrical energy obtained from the quadratic problem is more than case I at 8:00-15:00 and 16:00-24:00. In case I, the objective function is defined as multiplying the purchasing electrical power by retail price while in case II, the power market price is not considered.

5. CONCLUSION

The optimal operation of the sample energy hub is proposed in two different and separate cases based on linear and quadratic programming in this paper. Considering the cost of purchasing input carriers from the market and the bidirectional interchanges between energy hub and power grid, a linear objective function is optimized using GAMS, YALMIP and genetic algorithm in case I.

Moreover, various demand response programs such as time of use and real-time pricing are implemented in this study. As a result, RTP is the most effective method to decrease or shift the customer’s consumption according to price variations. Furthermore, three energy storage devices including BES, HES, and CES are used to reduce the costs of customers. Reducing the purchased natural gas and improving the bidirectional interchanges with the power grid are the main results of using storage devices. In the other case, a new objective function based on the quadratic generation cost of electricity and natural gas is solved using the genetic algorithm. Also, the quadratic objective function is approximated to the linear function. The result of the linear approximated objective function is the same as the quadratic optimization problem, and the simulation results indicate suitable performance of the energy hub.

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