TẠP CHÍ KHOA HỌC
TRƯỜNG ĐẠI HỌC QUY NHƠN

Vận hành tối ưu hệ thống năng lượng (điện - gas) có xét đến năng lượng mặt trời, gió và hệ thống tích trữ trên cơ sở mô hình Energy Hub

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TÓM TẮT

Trong bài báo này, trung tâm năng lượng (Energy Hub) được xem như là một siêu nút kết nối giữa điện năng, khí tự nhiên, mặt trời và gió; sau đó thông qua các thiết bị chuyển đổi và hệ thống tích trữ năng lượng để đáp ứng nhu cầu sử dụng điện, nhiệt, và làm mát của phụ tải. Ngôn ngữ lập trình bậc cao GAMS được sử dụng để giải quyết vấn đề vận hành tối ưu mạng năng lượng (Energy Network - EN) với hàm mục tiêu tổng chi phí sử dụng năng lượng và phát thải nhà kính (NO_2, SO_2 và CO_2) nhỏ nhất. Ảnh hưởng của nguồn năng lượng phân tán, hệ thống tích trữ đến hiệu quả vận hành EN được đánh giá thông qua 04 kịch bản vận hành khác nhau. So sánh với hình thức cung cấp năng lượng điện truyền thống, kết quả tính toán cho thấy mô hình đề xuất đã làm thay đổi đáng kể đường đặc tính năng lượng điện và khí tự nhiên mua từ hệ thống; tăng hiệu quả khai thác và sử dụng tối ưu năng lượng so với hình thức cung cấp năng lượng chỉ sử dụng duy nhất một dạng năng lượng điện.

Từ khóa: *Khí tự nhiên, điện năng, mạng năng lượng, vận hành tối ưu, hệ thống tích trữ.*

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Optimal operation of the energy network (electricity - gas) considering solar, wind, and energy storages system based on energy hub modeling

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ABSTRACT

In this paper, the Energy Hub (EH) is considered as a super-node connecting different forms of energy including electricity, natural gas, solar energy, and wind energy; then through conversion equipment and energy storage systems meets the demand for electricity, heat, and cooling of small loads. GAMS is used to solve the optimal operation problem of Energy Network (EN) with the objective of minimizing the cost of energy and greenhouse emission (NO_2, SO_2 and CO_2). The effect of distributed energy, and energy storage systems on the performance of EN is assessed through four different operating scenarios. Compared to traditional electricity supply, the results showed that EN dramatically changed the characteristics of electricity consumption line chart and natural gas purchased from the system; thus, increasing efficiency and optimal use of energy compared to the conventional architecture of using a single energy source.

Keywords: *Natural gas, electricity, energy network, Optimal operation, Energy storages.*

1. INTRODUCTION

Depletion of energy resources and pressure of environmental pollution are two big problems for scientists. Nowadays, instead of using single energy systems,[1] combined energy systems are receiving strong attention.[2,3] The introduction of Energy Network (EN) concept[4-6] is considered a breakthrough to improve reliability, reduce pollution and encourage the development of energy systems. It also improves stability, and achieve the goal of economical and efficient use of energy.

Energy hub (EH)[1] is a model that has attracted the attention of researchers. EH is considered a multi-purpose system that combines capacity and load through a converter system.[7-8] Studies[9-11] address the problems of combining different energy forms through this model. In general, EH allows optimal connectivity between types of energy, considering storage devices, distribution sources, electric vehicles, etc.

Along with the establishment and development of EN and EH, renewable energy and energy storage technology are two solutions that continue to be researched and developed exstensively to confront increasing pressure from society's demand. The traditional form of energy distribution through the electricity system has proved significant efficiency of these two groups in terms of operation and energy saving.[12]

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The evaluation of the efficiency of renewable energy and Energy Storage System (ESS) to the independent EH optimal operation problem was introduced in studies.[13-15] However, for the EN model constructed from several EHs, their role and impacts have not been fully addressed. The operation problem has only been solved on the side of calculating the optimal capacity among EHs without calculating and comparing the efficiency between the energy network (electricity, heat, natural gas...) and traditional power network.

In large areas, the EN has to supply a lot of loads. As a result, many EHs are connected on a large scale by distribution networks to provide energy to consumers. This paper focuses on solving the following three problems: *(1) Simultaneously analyse operational cost optimization problems in EH-using networks and the use of renewable resources in storage and distribution networks; (2) Ensure optimal network operation in all situations by considering the operational parameters and energy losses of both electricity and natural gas distribution networks; (3) Assess the impact of energy sources and storage devices on EN performance by comparing system energy consumption and emissions across four operating scenarios.*

The 22 kV distribution grid with 6 load nodes is the basis for the formation of EN. four scenarios considered include independent network operation and optimal operation of EN with the participation of solar, wind and ESS energy. The approach and solution to the problem are as follows: The energy center model (including concept, structure, mathematical description), energy balance problem and EN system structure will be introduced in part 2. Part 3 develops an optimal operation problem for EN with the objective function of minimizing energy costs and emission costs (SO_2, NO_2 and CO_2). Part 4 addresses the optimal operation problem using GAMS. Micro Energy Networks (MEN) optimization problem is considered with four different configurations to simultaneously meet the heat, electricity and cooling needs of 6 load nodes. The conclusion and suggestion for further research are presented in section 5.

2. ENERGY HUB & ENERGY NETWORK

2.1. Mô hình EH

The concept and structure of EH were introduced in study.[16] In general, EH is considered a node in an energy network with multiple inputs and outputs. The energy centers are described in Figure 1. In which, P, L denote the input and output energy of the respective energy forms. The EH model is used with n converters corresponding to efficiency *η1, η2*... to η_n.

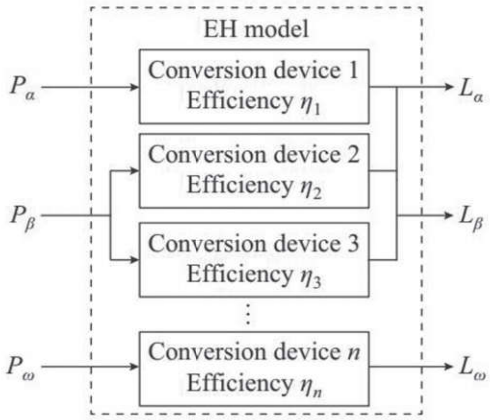

Figure 1. General structure of EH

2.2. Energy Network model

EN is an extensive definition of the power grid that combines natural gas and other forms of energy (Figure 2). Its advantages are (1) Promote applications of new and renewable energy sources; (2) Lower energy costs, emissions and load peaks while flexibly responding to load diversity; (3) Promote diversified and sustainable development of energy technology.

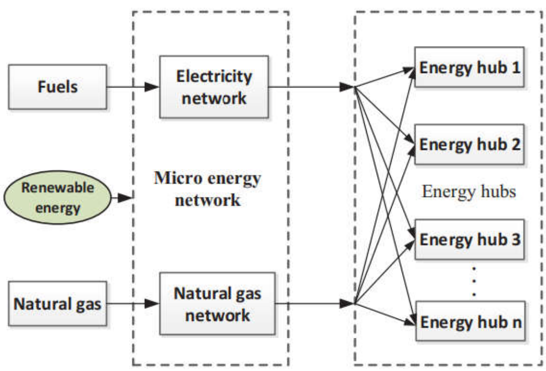

Figure 2. General structure of EN

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With the mentioned advantages, the research analyzes and proposes a model consisting of several EHs to link the electricity and natural gas networks with the structure as shown in Figure 2.

The power distribution of the power network can be through the basic node power balance equation:

$$\begin{cases} Q_{E,i}^{G} = Q_{E,i}^{D} + V_i \sum_{j=i}^{n_E} V_j \left(G_{E,ij} \cos\theta_{ij} + B_{E,ij} \sin\theta_{ij} \right) \\ P_{E,i}^{G} = P_{E,i}^{D} + V_i \sum_{j=i}^{n_E} V_j \left(G_{E,ij} \cos\theta_{ij} + B_{E,ij} \sin\theta_{ij} \right) \end{cases} \quad (1)$$

In which $P_{E,i}^{G}(t)$, $Q_{E,i}^{G}$ represent active and reactive power of the generator flows into the i-th node; $P_{E,i}^{D}(t), Q_{E,i}^{D}$ represent the active and reactive power of the electrical load at node *i*. V_i, V_j are the voltage values at node *i* and node *j*. $G_{E,ij}$, $B_{E,ij}$, and θ_{ij} are the active inductance, reactive inductance of the conductor, and phase difference from node *i* to *j* respectively. n_e is the number of nodes in the power network.

The natural gas network is supplied from gas plants or natural gas supply companies through pipelines, compressors and valve systems. The air flow in the gas line can be calculated according to the document:[17,18]

$$f_{ij}^{L} = k_{ij}^{L} sign(p_i, p_j) \sqrt{sign\left(p_i, p_j\right)\left(p_i^2 - p_j^2\right)} \quad (2)$$

Where, they are the natural gas flow rate and the coefficient of gas pipes from point i to j, respectively, p_i, p_j are the gas pressure at points i and j, respectively.

In the above Equation (2), $sign(p_i, p_j)$ represents the flow direction in the gas pipeline. The specific value is determined by Formula (3) as follows:

$$sign(p_i, p_j) = \begin{cases} +1, \text{ if } p_i > p_j \\ -1, \ else \end{cases} \quad (3)$$

Natural gas flow can be calculated based on the gas flow in the pipeline and the Gross Heating Value (GHV) of the gas according to the expression:

$$\begin{cases} P_{G,ij}^{L} = GHV \times f_{\text{ij}}^{L} \\ P_{G,ij}^{C} = GHV \times f_{\text{ij}}^{C} \end{cases} \quad (4)$$

Where, $P_{G,ij}^{L}$, $P_{G,ij}^{C}$ are the capacity of natural gas and pump pressure from point i to point j, respectively; K_{ij}^{C} is the compressor constant; f_{ij}^{L} is the natural gas flow from point i to j; f_{ij}^{C} is the pressure pump loss from point i to j. Then the gas balance equation is written as mathematical formula (5) as follows:

$$P_{G,i}^{S} = P_{G,\text{i}}^{D} + \sum_{j=1}^{n_g} P_{G,\text{ij}}^{C} + \sum_{j=1}^{n_g} P_{G,\text{ij}}^{L} \quad (5)$$

$P_{G,i}^{S}$ is the capacity of natural gas flowing into point i. $P_{G,\text{i}}^{D}$ is the natural gas power consumed at point i. n_g is the number of nodes of the natural gas network.

3. OPTIMAL MODEL

3.1. Proposed EH model

This study proposes an EN model as shown in Figure 3. EN is formed on the basis of a distribution grid (voltage level 22 kV), scale to meet the demand for electricity, heat and cool energy for 06 nodes load. The natural gas network and the electricity network are connected through EHs. Within the scope of the research model, applications from solar energy (can be exploited in the form of electricity through the solar thermal system and electricity through the photovoltaic battery system), wind power and electric ESS, heat, and cool are provided in the EH hubs. The energy storage system plays the role of storing and transmitting according to the optimal operating mode of MEN.

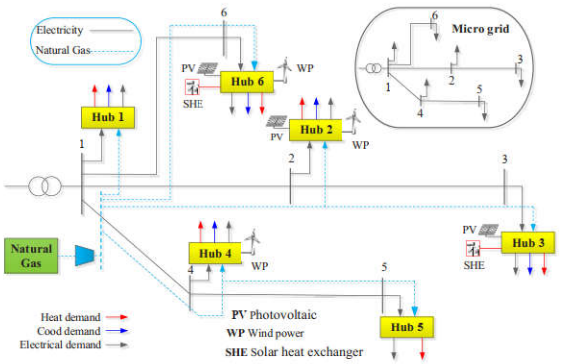

Figure 3. Proposed EN model

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3.2. EH structure

A general EH structure consisting of 12 devices is proposed in Figure 4. In which, the source group includes: electricity distribution system, natural gas system, distributed source (wind energy and solar energy); The group of conversion equipment includes: voltage transformer, Micro turbine (MT), Air Conditioned (AC), Gas boiler (GB), Absorption Chiller (ACh), solar heat exchanger (SHE) and Electric heater (EHe). The group of storage systems includes: Energy storage devices (Energy storage ES), thermal storage devices (Thermal Storage TS) and Ice storage-IS. Energy demand includes electricity, heat and cooling loads.

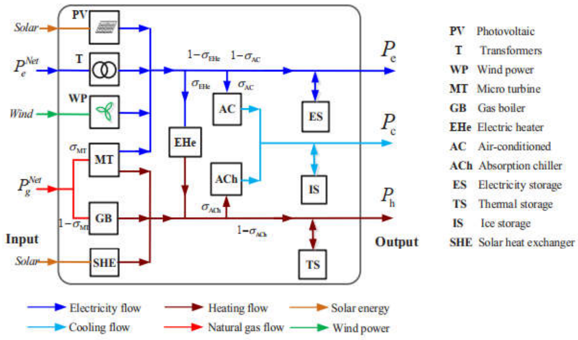


Figure 4. EH model structure

The relationship between input/output energy of the general EH model at the nth node is rewritten as mathematical formula (6).

$$
\begin{aligned}
L_{e,n}(t) &= \left[P_{e,n}(t)\eta^{T}_{e,n} + P_{g,n}(t)\nu_{MT,n}(t)\eta^{MT}_{ge,n} + P^{WP}_{e,n}(t) + P^{PV}_{e,n}(t)\right] \\
&\quad \times\left(1-\nu_{EHe,n}(t)\right)\left(1-\nu_{AC,n}(t)\right) + \left(P^{dis}_{ES,n}(t) - P^{ch}_{ES,n}(t)\right) \\
L_{h,n}(t) &= \left[\begin{array}{l} \left(P_{g,n}(t)\left(\nu_{MT,n}(t)\eta^{MT}_{gh,n} + (1-\nu_{MT,n}(t))\eta^{GB}_{h,n}\right) + P^{SHE}_{h,n}(t)\right) + \\ + \left(\begin{array}{l} P_{e,n}(t)\eta^{T}_{e,n} + P_{g,,n}(t)\nu_{MT,n}(t)\eta^{MT}_{ge,n} + P^{PW}_{e,n}(t) + \\ + P^{PV}_{e,n}(t) \end{array}\right)\eta^{EHe}_{h,n}\nu_{EHe,n}(t) \end{array}\right] \\
&\quad \times\left(1-\nu_{ACh,n}(t)\right) + \left(P^{dis}_{HS,n}(t) - P^{ch}_{HS,n}(t)\right) \\
L_{c,n}(t) &= \left[\begin{array}{l} \left(P_{g,n}(t)\left(\nu_{MT,n}\eta^{MT}_{gh,n} + (1-\sigma_{MT,n})\eta^{GB}_{h,n}\right) + P^{SHE}_{h,n}(t)\right) + \\ + \left(P_{e,n}(t)\eta^{T}_{e,n} + P_{g,n}(t)\nu_{MT,n}(t)\eta^{MT}_{ge,n} + P^{WP}_{e,n}(t) + P^{PV}_{e,n}(t)\right)\eta^{EHe}_{h,n}\nu_{EHe,n}(t) \end{array}\right]\nu_{ACh,n}\eta^{ACh}_{h,n} \\
&\quad + \left[P_{e,n}(t)\eta^{T}_{e,n} + P_{g,\mu^{T}_{e,n}}(t)\left(\nu_{MT,,n}(t)\eta^{MT}_{ge,n}\right) + P^{WP}_{e,n}(t) + P^{PV}_{e,n}(t)\right]\times \\
&\quad \left(1-\nu_{EHe,n}(t)\right)\nu_{AC,n}(t)\eta^{AC}_{e,n} + \left(P^{dis}_{CS,n}(t) - P^{ch}_{CS,n}(t)\right)
\end{aligned}
\quad (6)
$$

3.3. Mathematical model

3.3.1. Objective function

The optimal operation problem EN with the proposed objective function is the total cost of energy (the cost of purchasing electricity and natural gas from the system and the total cost of CO_2, SO_2, and NO_2 emissions of the MT and GB equipment for a period of 1 day (24 hours)) is the smallest:

$$Min \sum_{t=1}^{24}\left[P_{\sum_e}(t)c^{Net}_{e}(t) + P_{\sum_g}(t)c^{Net}_{g}(t) + C_{MT} + C_{GB}\right] \quad (7)$$

$$C_{MT} = \left(\sum_{n=1}^{6}\sum_{em}^{3} c_{em}EF^{MT}_{em}P^{MT}_{g,n}(t)\right);\; C_{GB} = \left(\sum_{n=1}^{6}\sum_{em}^{3} c_{em}EF^{GB}_{em}P^{GB}_{g,n}(t)\right)$$

In Eq (7), $P_{\sum_e}(t)$, $P_{\sum_e}(t)$, $P_{\sum_g}(t)$ are the total energy including electricity and natural gas purchased from the respective external system at time *t*; EF^{MT}_{em}, EF^{GB}_{em} are the emission factors of MT and GB, respectively.

3.3.2. Mathematical constraints

a. Transmission power limit

System limitations include limits on active power, reactive power and node voltage in the grid. The pressure and compression ratio in the natural gas network are as follows:

$$\begin{cases} p_{ck}^{\min} \le p_{ck} \le p_{ck}^{\max} \\ p,V_i^{\min} \le p,V_i \le p,V_i^{\max} \\ P,Q_{E,i}^{G,\min} \le P,Q_{E,i}^{G} \le P,Q_{E,i}^{G,\max} \end{cases} \tag{8}$$

b. Technical limits of EH

The constraint of energy balance for the corresponding EH at the nth node is introduced in part 2 by the mathematical Formula (6). Other constraints include: Limiting the input power of electricity and natural gas at the nth center; the mathematical formula (9) expresses the transition limits for AC, MT, ACh and EHe according to the state variable $v_{\mathrm{AC},n}(t)$, $v_{\mathrm{MT},n}(t)$, $v_{\mathrm{ACh},n}(t)$, $v_{\mathrm{EHe},n}(t)$ at time t of the n-th center respectively.

$$\begin{cases} \sigma_{\mathrm{AC}}(t),\ \sigma_{\mathrm{MT}}(t),\ \sigma_{\mathrm{ACh}}(t),\ \sigma_{\mathrm{Ehe}}(t)\ \in [0,\ 1] \\ P_{\text{e-g},n}(t) \le P_{\text{e-g},n}^{max} \end{cases} \tag{9}$$

c. Energy Storage System - ESS

The system of energy storage devices in EN uses three types of storage devices simultaneously: ES, TS, and IS respectively at the nth EH. Primarily, the principle of discharge and its effects are the same. Considering each nth EH at the t-th hour of the day, the energy storage system is investigated through the charging process and the corresponding energy loss factor $\rho_{\text{e,h,c-n}}^{\text{ES,TS,CS-loss}}$:

$$\begin{cases} \begin{cases} \psi_{\mathrm{ES.TS,IS}\,(n)}^{\mathrm{ch,dis}}(t) P_{\mathrm{ES.TS,IS}\,(n)}^{\mathrm{ch,dis}}(t) > 0 \Leftrightarrow \psi_{\mathrm{ES.TS,IS}\,(n)}^{\mathrm{ch}}(t) = 1 \\ \psi_{\mathrm{ES.TS,IS}\,(n)}^{\mathrm{dis}}(t) + \psi_{\mathrm{ES.TS,IS}\,(n)}^{\mathrm{ch}}(t) = 1 \\ \psi_{\mathrm{ES.TS,IS}\,(n)}^{\mathrm{dis}}(t) \times \psi_{\mathrm{ES.TS,IS}\,(n)}^{\mathrm{ch}}(t) = 0 \end{cases} \\ 0 \le P_{\mathrm{ES,HS},CS\,(n)}^{\mathrm{ch,dis}}(t) \le P_{\mathrm{ES,HS},CS\,(n)}^{\text{ch,dis-Max}} \\ P_{\mathrm{e,h,c}\,(n)}^{\text{ES,TS,CS-loss}}(t) = \rho_{\mathrm{e,h,c}\,(n)}^{\text{ES,TS,CS-loss}} P_{\mathrm{e,h,c}\,(n)}^{\mathrm{ES,HS,CS}}(t) \\ P_{\mathrm{e,h,c}\,(n)}^{\text{ES,HS,CS-Min}} \le P_{\mathrm{e,h,c}\,(n)}^{\mathrm{ES,HS,CS}}(t) \le P_{\mathrm{e,h,c}\,(n)}^{\text{ES,HS,CS-Max}} \\ P_{\mathrm{e,h,c}\,(n)}^{\mathrm{ES,HS,CS}}(t) = P_{\mathrm{e,h,c}\,(n)}^{\mathrm{ES,HS,CS}}(t-1) + P_{\mathrm{ES,HS,CS}\,(n)}^{\mathrm{ch}}(t) \\ \qquad - P_{\mathrm{ES,HS,CS}\,(n)}^{\mathrm{dis}}(t) - P_{\mathrm{ES,HS,CS}\,(n)}^{\mathrm{loss}}(t) \end{cases} \tag{10}$$

Constraint on energy balance in calculation cycle T=24 hours (due to the characteristic of discharge power that often repeats on a 1-day cycle):

$$P_{\mathrm{e,h,c}\,(n)}^{\mathrm{ES,HS,CS}}(0) = P_{\mathrm{e,h,c}(n)}^{\mathrm{ES,HS,CS}}(\mathrm{T}) \tag{11}$$

d. Energy price

Energy price including electricity and gas prices is the determining factor of the objective function (9). Where the price of natural gas is constant[18] introduced in Expression (12). The electricity tariff is determined according to the Time-Of-Use (TOU) tariff.[17]

$$c_{\mathrm{g}}^{\mathrm{Net}}(t) = \mathrm{const} \quad [\$/\mathrm{kWh}] \tag{12}$$

4. CALCULATION RESULTS

Four different operating scenarios (OS) for EN are proposed in Table 2 to assess the role and impact of renewable energy (solar and wind) and ESS on model performance as follows:

Table 1. Operating scenarios

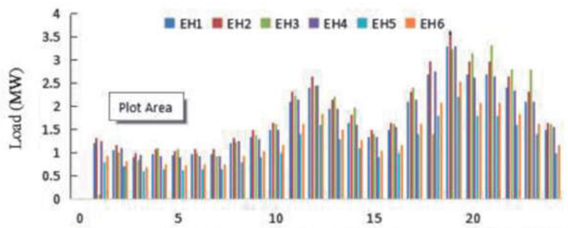
OS	Electricity network	Natural gas network	Solar wind	ESS (ES, HS, CS)
1	v			
2	v	v		
3	v	v	v	
4	v	v	v	v

4.1. Calculation data

The parameters for EN are as follows: the limited power from the power system through the transformer is 20 MVA, the rated voltage is 22 kV. The allowable voltage is [0.9-1.1]. The natural gas system has a nominal capacity of 20 MW for EN. The base pressure of the natural gas network is 10 bar.

4.1.1. Load data

Load parameters including power, heat and cooling demand based on[7, 8] are as follows:



a/ Demands for electricity in a single day.

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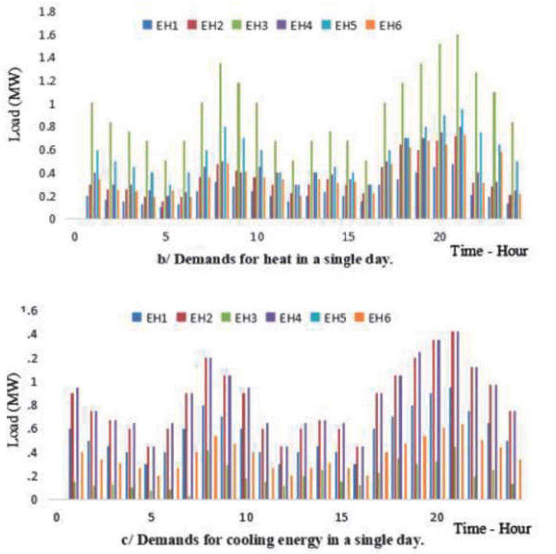


Figure 5. Demand for energy consumption

4.1.2. Energy price

Real-time energy prices are shown in Figure 6, where electricity prices are determined according to the TOU tariff[17] while natural gas prices are assumed to be constant:[18]

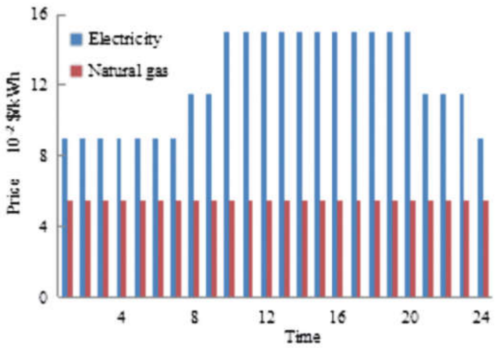


Figure 6. Prices of electricity and natural gas

4.1.3. System parameters

The parameters of 06 HubEH are presented in Table 2, the parameters of electricity and natural gas networks in Table 3:

Table 2. EH parameters

μ_e^{T}	μ_{ge}^{MT}	μ_{gh}^{MT}	$P_h^{HS\text{-}max}$ (MWh)	$\rho_h^{HS,\text{-}loss}$ (MW)	μ_h^{HS} (MW)
0.95	0.4	0.5	4.2	0.02	0.96
$P_{ES}^{dis\text{-}max}$ (MW)	$P_e^{ES\text{-}min}$ (MW)	$P_c^{ES\text{-}max}$ (MWh)	$\eta_{h,n}^{EHe}$	$P_{ES}^{ch\text{-}max}$ (MW)	$P_{HS}^{dis\text{-}max}$ (MW)
0.45	0.05	4.2	0.90	0.45	0.45
μ_h^{GB}	μ_h^{ACh}	μ_e^{AC}	$\rho_e^{ES\text{-}loss}$	μ_e^{ES}	$P_{HS}^{ch\text{-}max}$ (MW)
0.9	0.85	0.8	0.02	0.93	0.45

Table 3. Parameters of Electricity and Natural Gas Networks

Electricity network					Fuel gas heating value
Line	R_E (Ω)	X (Ω)	B_E 10^{-3}S	L km	k
1-2	0.096	0.108	0.130	1.2	7
2-3	0.072	0.081	0.0972	0.9	9
1-4	0.12	0.135	0.162	1.5	6
4-5	0.084	0.0945	0.1134	1.5	8
1-6	0.144	0.162	0.1944	1.8	5

4.1.4. Distributed sources

The distribution characteristics of PV, SHE and WP in a typical day are shown in Figure 7.

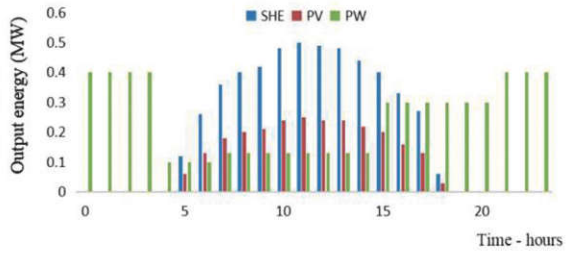
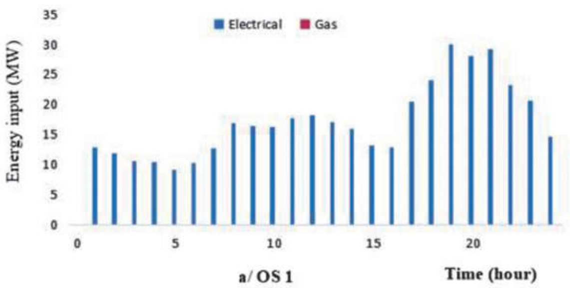


Figure 7. Transmit power of distributed sources

4.2. Optimal calculation results

The GAMS (MINOS) programming language[19] is used to compute the EN optimization with the objective function (7) and the constraints from (1) to (12). Calculation results for optimal operation with four different scenarios are presented in Table 4.

The results of optimal calculation of input energy in four scenarios are shown in Figure 8.



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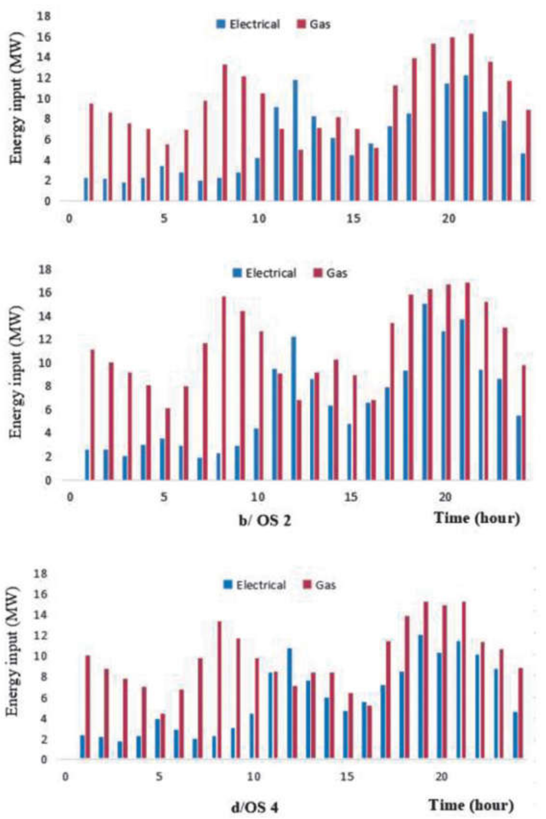

Figure 8. Electric and natural gas energy (input) in 4 OSs

The above results show that: The combination of several EHs forms an EN structure (including solar, wind and ESS) that responds appropriately and flexibly to the diversity of loads. The optimal results show that the optimal model can respond to changes in electricity prices and surcharges; at the same time, it allows the adjustment of renewable energy sources according to time and season.

Table 4. Costs comparison among 4 OSs

Calculation results	OS 1	OS 2	OS 3	OS 4
Total operation cost ($/day)	52653	38297	34335	33782
Total operation cost ($/day)	8.48	5.21	4.42	3.38
Total operation cost ($/day)	857	721	615	528
Total operation cost ($/day)	0	799	688	589

The comparison of four different EN scenarios clarified the role and impact of ESS, solar and wind on model performance by reducing the total cost categories (Table 4): operation, loss and pollution. In particular, if we compare OS 4 with OS 1, the total operating cost of OS 4 is reduced by 35.84%, the total loss is reduced by 60.14%; Therefore, cutting electricity demand during peak hours will help improve the urgent need for upgrading and renovating the power network.

The additional investment costs for the natural gas, PV, SHE and wind turbine networks are quite high but will be offset by EN's cost-effective performance. The results demonstrate that the proposed EN model contributes significantly to the study of future multi-energy systems that integrate renewable energy and energy storage systems.

5. CONCLUSION

Based on the energy center model, this research proposes the optimal operation between the power system and the natural gas network with the integration of solar, wind and energy storage systems.

The research analyzed the energy consumption of the whole system and emissions through four operating scenarios to assess the impact of distributed energy sources, energy storage devices on the performance of EN. Compared with the operation of the traditional grid model, the proposed model has significant advantages and provides a theoretical foundation for optimizing the operation of a system integrating various energy forms.

The results show that the EH structure in the energy network has a significant influence on operational efficiency. Therefore, further research is required on the optimal operation strategy for each EH and the optimization of the EH structure within the entire energy network.

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