Optimal operation of a multi-energy hub for minimal energy usage cost

Jianquan Liang¹, Rui Huang²,³, Panbao Wang²,³,⁴, Jian Zhang¹, Wei Sun¹ and Dianguo Xu²,³

¹ State Grid Heilongjiang Electric Power Company Limited, Electric Power Research Institute, Harbin 150036, China;
² Harbin Institute of Technology, Harbin 150001, China;
³ Heilongjiang Industrial Technology Research Institute, Harbin 150028, China
⁴ Email: wangpanbao@hit.edu.cn

Abstract. This paper proposes a management model of a Multi-Energy Hub (MEH), which is an essential part in the Energy Network. Energy Hub (EH) is a collection of various energy conversion devices and energy storage elements. It can be regarded as the transmission node in the Energy Internet. In this paper, an EH containing Combined heat and power (CHP), electrical heat pump, electricity storage system and heat storage system is studied. In this paper, a new EH model is proposed which is different from the modelling method based on the original EH concept. The proposed method focuses on the practical application field. The optimal model and management of the proposed EH components focusing on the minimal energy usage cost is modelled as a mixed-integer non-linear optimization problem calculated by General Algebraic Modelling System (GAMS) software. Also, in order to be closer to the practical application, the electricity storage system optimization has been considered. The battery life loss is equivalent to the daily energy storage loss cost. The simulation results show that the proposed model is more economical than the traditional model and the maximum depth of discharge (DOD) has less influence on the battery life. However, value of maximum DOD effects the operational cost.

1. Introduction

Recently, with the high demand of clean and efficient way of using the energy, Multi-Energy Interconnected Network (MEIN) has gained more and more attractions. Energy Hub (EH) has emerged as an inevitable part of Multi-Energy Interconnected Network as it expedites the integration of energy converters (e.g., PV, wind power generation, CHP technologies), storage units (e.g., batteries, ultra-capacitors and thermal energy storage technologies), and various types of energy demand with an improved flexibility, reliability and efficiency [1-4].

Researches on the EH model focus on guaranteeing the optimal performance with different load types in the MEIN [5, 6]. The common modelling method of EH is to divide the internal equipment into power conversion equipment and energy storage equipment [7-9]. In [10], four forms of energy, electricity, and natural gas, local heat and wood chips, input EH and suffer through a series of conversions of internal conversion equipment. Finally, the EH outputs electricity, cooling and heat according to the consumer demand. However, it didn’t consider the energy reutilization equipment, all of the conversions are from the primary energy to demand energy, and excess energy will be stored in energy storage devices. Common reutilization equipment, such as heat pump and warmer haven’t been...
considered. The literature [11] considers the reutilization equipment, electric heat pump (EHP). But the electricity it needs is from either the grid or the electrical energy storage (ESS). The extra electricity generated by the CHP must be stored in the ESS before it can be utilized instead of direct use, which reduces the efficiency of the whole system.

The energy storage device plays a role of peak load shaving in the energy system, an important branch is the optimization of the ESS. In the optimization of the ESS, the most consideration is the attenuation of battery life [12-14]. However, there is no literature that considers energy storage optimization in the EH model.

Therefore, in this study, a practical framework of EH containing primary energy converter, reutilization energy converter, electrical energy storage and thermal energy storage is been introduced and modelled which enhance the flexibility and efficiency of energy delivery points. A mathematical mixed-integer non-linear model is established with the objective function of minimizing the operation cost of energy purchased from electricity and natural gas grid and the daily energy storage loss cost. The comparative studies of common EH model and the proposed model is also studied. The GAMS high-level programming language is used to solve the optimal operating problems.

2. Energy Hub structure and modelling

2.1. System structure

The structure with control infrastructure of considered energy hub is illustrated in Figure 1. The energy hub system consists of input and output energy carrier ports, primary and reutilization energy conversion devices and energy storages.

It can be seen that the energy hub can buy electricity/natural gas through the corresponding grids. The components of the energy hub are combined heat and power system (CHP), electric heat pump (EHP), electricity storage system (ESS) and Heat storage system (HSS). CHP can consume natural gas to produce electricity and heating. EHP is another heating producer which consumes the electricity from CHP, ESS or grid. Besides, EHP can also supply the cooling demands. ESS and HSS are the storage system used to store the extra electrical and thermal energy separately. Details of the parameters in the figure are described in the following section.

**Figure 1.** Structure of considered energy hub.

2.2. System modelling

According to [3], the energy conversion between different types of energy inside the EH can be expressed through the mixed matrix (1)
where $P(1,\ldots,m)$ represents the input energy and $L(1,\ldots,n)$ represents the output energy.

Then the proposed EH model based on Figure 1 can be expressed as:

$$
\begin{bmatrix}
L_1^c \\
L_2^c \\
\vdots \\
L_n^c \\
\end{bmatrix} =
\begin{bmatrix}
C_{11} & C_{12} & \cdots & C_{1n} \\
C_{21} & C_{22} & \cdots & C_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
C_{n1} & C_{n2} & \cdots & C_{nn} \\
\end{bmatrix}
\begin{bmatrix}
P_1 \\
P_2 \\
\vdots \\
P_n \\
\end{bmatrix}
$$

(1)

(2)

where the output energies $L_t^c$, $L_t^e$, $L_t^h$ respectively represent the demands for electricity, cooling and heat. The input energies $P_{t,NET,e}$ and $P_{t,NET,g}$ are from electrical grid and natural gas network respectively. $\eta_{CHP}^e$, $\eta_{CHP}^h$, $\eta_{EHP}^c$ and $\eta_{EHP}^h$ are the conversion efficiency of CHP and EHP. Both of them can produce two types of energy, the subscript of $\eta$ shows the form of the energy output by the device. $\lambda_{EHP}$ is the dispatch ratio of electricity conversion via EHP device. The electrical storage charge/discharge devices are donated by $P_{t,ESS,CH}/P_{t,ESS,DIS}$. Similarly, $P_{t,ESS,IN}$ and $P_{t,ESS,OUT}$ represent the input and output power of the heat storage system.

2.3. System operation

2.3.1 Objective function. In the proposed model, it should be noted that this model is in small scales. Compared with large scales issues concerning optimal operation of energy hub in small scales have more importance. In that case, the objective function of the proposed model is set to minimize the total operational cost of purchasing electricity and natural gas, which can be expressed as:

$$
\text{Cost}(t) = \sum_j (c_{t,NET,e} \cdot P_{t,NET,e} + c_{t,NET,g} \cdot P_{t,NET,g}) + c_{loss}
$$

(3)

where $c_{t,NET,e}$ and $c_{t,NET,g}$ are the energy prices. $c_{loss}$ is the energy storage daily loss cost which is described in detail in the following section.

2.3.2 Constraints. Usually, constraints include load constraint, power balance constraint, capacity constraint and energy storage devices constraint. Since the load constraint has been described before and variables about other devices do not appear in the constraint, this section focuses on the conversion constraint and the energy storage device constraint.

The basis of the EH model operation is based on the ability to control the flow of EHP device. The constraint of this variable is introduced in the expression (4)

$$
0 \leq \lambda_{EHP} \leq 1
$$

(4)

For the energy storage devices constraint, there are two types of energy in the proposed model needed to be restrained. Take electric as an example, the amount of stored electricity $E_{t,ESS}$ depends on the amount of its charge power, discharge power and the stored electricity in former time interval as expressed in (5). Energy losses $E_{loss}$ during charge/discharge limits are introduced in the expression (6). The capacity limit is considered in (7), where $E_{min}$ and $E_{Max}$ are the minimum and maximum allowable power of the electrical storage. The initial state of the storage is shown in (8). Also, the charging and discharging rate should be limited as expressed in (9), (10).

$$
E_{t,ESS} = E_{t-1,ESS} + E_{t,CH} - E_{t,DIS} - E_{t,loss}
$$

(5)
\[ E_{t}^{\text{loss}} = \eta_{\text{ESS}} \cdot E_{t}^{\text{ESS}} \]  
\[ E_{t}^{\text{ESS}} \leq E_{t}^{\text{ESS}} \leq E_{t}^{\text{ESS}} \]  
\[ E_{t}^{\text{Min}} = E_{t}^{\text{ESS}} \]  
\[ 0 \leq E_{t}^{\text{ESS},\text{ch}} \leq E_{t}^{\text{ESS},\text{ch}} \]  
\[ 0 \leq E_{t}^{\text{ESS},\text{dis}} \leq E_{t}^{\text{ESS},\text{dis}} \]  

In a similar way, the heat storage system has the following constraints:

\[ H_{t}^{\text{HSS}} = H_{t}^{\text{HSS}} + H_{t}^{\text{in}} - H_{t}^{\text{out}} - H_{t}^{\text{loss}} \]  
\[ H_{t}^{\text{loss}} = \eta_{\text{HSS}} \cdot H_{t}^{\text{HSS}} \]  
\[ H_{t}^{\text{Min}} \leq H_{t}^{\text{HSS}} \leq H_{t}^{\text{Max}} \]  
\[ H_{t}^{\text{Min}} = H_{t}^{\text{HSS}} \]  
\[ 0 \leq H_{t}^{\text{HSS},\text{in}} \leq H_{t}^{\text{HSS},\text{in}} \]  
\[ 0 \leq H_{t}^{\text{HSS},\text{out}} \leq H_{t}^{\text{HSS},\text{out}} \]  

For the equations for the ESS battery life model. Equation (17) represents the State of Charge (SOC). Also, the Depth of Discharge (DOD) is given in (18). It should be noted that \( DOD^{\text{eq}} \) is the energy storage cycle discharge depth where \( y_{t}^{E} \) is the 0-1 variables marking the charge-discharge cycle action at \( t \). \( T_{\text{cycl}} \) represents the cycle life of the energy storage element while \( T_{\text{ini}} \) represents the rating cycle life. \( N_{\text{eq}} \) is the equivalent number of full cycles per day. The detailed design and selection process can be found in reference [12].

\[ SOC_{t} = \frac{E_{t}^{\text{ESS}}}{E_{t}^{\text{Max}}} \]  
\[ DOD_{t} = 1 - SOC_{t} \]  
\[ DOD_{t}^{\text{eq}} = DOD_{t} \cdot y_{t}^{E} \]  
\[ y_{t}^{E} = \max \{ y_{t}^{\text{ESS},\text{ch,p}} - y_{t}^{\text{ESS},\text{dis,p}}, 0 \} \]  
\[ T_{\text{cycl}} \leq T_{\text{ini}} \]  
\[ T_{\text{cycl}} = \frac{1591}{365 \cdot N_{\text{eq}}} \]  
\[ N_{\text{eq}} = \sum_{t} 1591 \cdot DOD_{t}^{\text{eq}}^{-2.5} \]  

3. Simulation results

In this paper, GAMS programming language is used to validate the proposed model. The considered energy hub is a grid-connected system with a 400kW CHP, a 128kW EHP. The efficiency for CHP unit depends on operating conditions as reported in [15]. The CHP unit is modelled by specific linear equations to describe the feasible operating regions (FOR). The simulation parameters are given in Table 1. Table 2 lists the characteristics of the storage devices. Demands based on school residential consumers during 24hours of a day are given in Figure 2.

Figure 3 show the (a) electricity, (b) heat and (c) cooling supply of the proposed EH model. It can be seen that, the electricity is supplied by CHP, ESS and needs to buy electricity from grid since the electricity demand is higher than system can supply. The extra heat generated is stored in the HSS for later use needed. Comparative results among traditional energy network, common EH operation in and the proposed EH operation are shown in Figure 3(d), which indicates that the proposed EH model reduces the operational cost and improve the efficiency.
Besides, in order to study the effect of maximum discharge depth ($DOD_{\text{max}}$) on cycle life, different values of $DOD_{\text{max}}$ are chosen listed in Table 3. It can be seen that $DOD_{\text{max}}$ has less influence of cycle life. However, too limited discharge depth makes the problem unsolvable.

**Table 1. Simulation parameters*.**

| Units               | Parameters | CHP   | EHP   | **cost**b |
|---------------------|------------|-------|-------|-----------|
|                     | Electrical Efficiency & Thermal Efficiency | $\eta_{\text{CHP}}^C$ & $\eta_{\text{CHP}}^T$ | $\eta_{\text{EHP}}^C$ & $\eta_{\text{EHP}}^T$ | $c_{\text{NET}}^e$ | $c_{\text{NET}}^g$ |
| Values              | 0.5        | 0.7   | 3.13  | 4.13      | 0.52       | 0.28       |

* Efficiency of CHP and EHP is selected according to [15].

b Electricity price and natural gas price are decided according to the latest policy of Harbin.

**Figure 2.** Demands for whole consumers in EH system area.

**Figure 3.** The supply of the proposed EH model: (a) electricity, (b) heat and (c) cooling and (d) the comparative result.
Table 2. Storage devices characteristics.

| Parameters | Units | ESS | HSS |
|------------|-------|-----|-----|
| Efficiency | $\eta^{\text{ESS}}$ | 0.9 | 0.9 |
| Maximum Power | $E_{\text{Max}}^{\text{ESS}}$ | 2400 kW | 2400 kW |
| Minimum Power | $E_{\text{Min}}^{\text{ESS}}$ | 600 kW | 600 kW |
| Efficiency | $\eta^{\text{HSS}}$ | 0.9 | 0.9 |
| Maximum Power | $H_{\text{Max}}^{\text{HSS}}$ | 2400 kW | 2400 kW |
| Minimum Power | $E_{\text{Min}}^{\text{ESS}}$ | 600 kW | 600 kW |

Table 3. The influence of maximum discharge depth on storage life.

| $DOD_{\text{max}}$ | $T_{\text{cyc}}$ |
|---------------------|-----------------|
| 0.8                 | 10              |
| 0.75                | 10              |
| 0.5                 | 10              |
| 0.3                 | Without solution |

4. Conclusions
This paper proposed a more practical EH model considering the primary energy conversion device, the reutilization conversion device and the storage devices based on the energy network structure and optimal operation. The proposed EH model also incorporates the management problem of optimal scheduling of energy. The optimal scheduling is calculated based on minimum energy purchase and battery loss costs. The simulation results demonstrate that the proposed EH work in a sustainable way and the operational cost is lower than the operation of common EH and much lower than the operation of traditional network. Besides the maximum depth of discharge (DOD) has less influence on the battery life. However, value of maximum DOD affects the operational cost.

Acknowledgement
This work was supported by the Science and Technology Project of State Grid Heilongjiang Electric Power Company Limited (Research on Cooperative Operation and Efficient Optimization Technology of Multi-Energy Supplement System, SGHLDK00PJJS2000130).

References
[1] Lee S H, Kang Y C, and Park J 2016 Optimal operation of multiple dgs in dc distribution system to improve system efficiency *IEEE Transactions on Industry Applications* 52 3673-81
[2] Mohammadi M, Noorollahi Y, Mohammadi-ivatloo B, Hosseinzadeh M, Yousefi H, and Khorasani S T 2018 Optimal management of energy hubs and smart energy hubs a review *Renewable and Sustainable Energy Reviews* 89 33-50
[3] Geidl M, Koeppel G, Favre-Perrod P, Klockl B, Andersson G, and Frohlich K 2007 Energy hubs for the future *IEEE Power and Energy Magazine* 5 24-30
[4] Orehoung K, Evins R, and Dorer V 2015 Integration of decentralized energy systems in neighbourhoods using the energy hub approach *Applied Energy* 154 277-89
[5] Fan H, Chen Q, Liu W, Li J, and Chen Y 2016 Optimal scheduling for energy hub in power markets *Innovative Smart Grid Technologies-Asia* 127-31
[6] Fan H, Chen Q, Liu W, Li J, and Chen Y 2016 Optimal scheduling for energy hub in power markets 2016 *IEEE Innovative Smart Grid Technologies - Asia, ISGT-Asia 2016, November 28, 2016 - December 1, 2016* 0 127-31
[7] Ha T-T, Zhang Y-J, Hao J-B, and Pham T H A 2017 Optimal operation of energy hub with different structures for minimal energy usage cost *2nd International Conference on Power and Renewable Energy* 31-36
[8] Bai L, Li F, Cui H, Jiang T, Sun H, and Zhu J 2016 Interval optimization based operating strategy for gas-electricity integrated energy systems considering demand response and wind uncertainty *Applied Energy* 167 270-79
[9] Dogaheh Z R, and Puig V 2018 Optimal operation of a residential energy hub 7th International Conference on Systems and Control 105-10

[10] Teimourzadeh Baboli P, Yazdani Damavandi M, Parsa Moghaddam M, and Haghifam M R 2015 A mixed integer modeling of micro energy-hub system IEEE Power and Energy Society General Meeting

[11] Javadi M S, Anvari-Moghaddam A, and Guerrero J M 2017 Optimal scheduling of a multi-carrier energy hub supplemented by battery energy storage systems 2017 IEEE International Conference on Environment and Electrical Engineering and 2017 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe) 1-6

[12] Alharbi H, and Bhattacharya K 2018 Stochastic optimal planning of battery energy storage systems for isolated microgrids IEEE Transactions on Sustainable Energy 9 211-27

[13] Groppi D, Astiaso Garcia D, Lo Basso G, Cumo F, and De Santoli L 2018 Analysing economic and environmental sustainability related to the use of battery and hydrogen energy storages for increasing the energy independence of small islands Energy Conversion and Management 177 64-76

[14] Dufo-López R, Bernal-Agustín J L, Yusta-Loyo J M, Domínguez-Navarro J A, Ramírez-Rosado I J, Lujano J, and Aso I 2011 Multi-objective optimization minimizing cost and life cycle emissions of stand-alone pv–wind–diesel systems with batteries storage Applied Energy 88 4033-41

[15] Ma T, Wu J, and Hao L 2017 Energy flow modeling and optimal operation analysis of the micro energy grid based on energy hub Energy Conversion and Management 133 292-306