Energy Proceedings
Vol 38, 2024
ISSN 2004-2965

Energy Station-Network Collaborative Planning of Integrated Energy System Based on Exergy-potential Constraints

Tianshuo ZHOU[1], Dan WANG[1,2*], Hongjie JIA[1,2], Yizhe LI[1], Jiawei LIU[1]

1 Key Laboratory of the Ministry of Education on Smart Power Grids (Tianjin University), Tianjin 300072, China

2 Key Laboratory of Smart Energy & Information Technology of Tianjin Municipality (Tianjin University), Tianjin 300072, China
(*Corresponding Author: wangdantjuee@tju.edu.cn)

ABSTRACT

Traditional research focuses on the quantity of energy while overlooking energy quality. Exergy-potential, as a critical state parameter for the energy quality of integrated energy system(IES), reflects the transport capability of effective energy. Based on the Exergy flow mechanism model of IES, this paper establishes an IES station-network joint planning model considering Exergy-potential constraints. The objective function is the minimization of the equivalent annual total cost, with Exergy-potential at IES nodes as new constraint conditions. The decision variables include the selection of energy pipelines and the 24-hour heat output of energy station equipment. Simultaneously, the accuracy and validity of the proposed method were validated in typical IES case studies. The results indicate that Exergy-potential constraints have an impact on the selection of energy pipelines and the capacity configuration of energy station equipment. Different Exergy-potential constraint conditions correspond to varying costs, and exergy loss for the planning scenarios.

Keywords: integrated energy system (IES), exergy flow, exergy-potential, Energy Station-Network Collaborative Planning

NONMENCLATURE

Abbreviations	
IES	Integrated Energy System
CHP	Combined Heat and Power
GB	Gas Boiler
EB	Electric Boiler
ES	Energy Station
ID	Number of Alternative Pipelines
Symbols	
h	Hour

1. INTRODUCTION

As the demands for energy transformation, upgrade, and high-quality development continue to advance, IES are gradually evolving in a direction where both energy quantity and energy quality are considered. Exergy, as a crucial state parameter introduced for studying energy quality, has garnered extensive attention across various fields, including mechanical, chemical, and biological domains.

Similarly, the issue of energy quality in IES is also receiving increasing attention[1]. Traditional analysis of IES, for the most part, relies on black-box models with the goal of enhancing overall exergy efficiency and reducing exergy losses within IES. Reference [2][3] incorporates exergy efficiency as one of the multi-objective functions in constructing the IES planning model. Reference [4] developed a multi-objective operational scheduling strategy for IES that takes exergy efficiency into account. Reference [5] defined the concept of energy quality in electrical systems.

Given that IES exhibits network attributes, traditional black-box models cannot dissect the distribution of effective energy(exergy) within IES, and they cannot accurately enhance the effective energy utilization at a specific location within IES. Therefore, in Reference [6], for the first time, an exergy flow mechanism model for IES was established, clearly illustrating the exergy distribution within IES. Simultaneously, the concept of exergy-potential was introduced for the first time to quantify the effective energy transport capability of a component within IES. Reference [7] further developed a unified exergy flow model for IES and initiated a preliminary discussion on the planning problem of energy station selection and sizing while considering energy quality. Reference [8] centered on energy quality as its objective and discussed

This is a paper for 15th International Conference on Applied Energy (ICAE2023), Dec. 3-7, 2023, Doha, Qatar.

the planning problem of IES considering the integration of renewable energy sources. Currently, there is no research discussing the planning problem of IES from the perspective of effective energy transport capability (exergy-potential).

In summary, this paper aims to enhance the effective energy transport capability at a specific juncture within IES and proposes an energy station-network collaborative planning of the IES method based on exergy-potential constraints. The discussion delves into the impact of introducing exergy-potential constraints for electrical nodes and thermal nodes on the planning outcomes within the IES planning model.

2. MODEL OF IES

2.1 Exergy flow mechanism model of power system

In energy quality analysis, electrical energy can be entirely converted into work or other forms of energy, making it high-quality energy that can be considered as exergy. Therefore, the active power of nodes in the electrical system is regarded as node exergy flow, the active power of lines as line exergy flow, and the active line losses as line exergy losses[7]. Thus, the steady-state models for energy flow and exergy flow in the power system can both be expressed as follows:

$$\begin{cases} e_i = U_i \sum_{j \in i} U_j \left(G_{ij} \cos\theta_{ij} + B_{ij} \sin\theta_{ij} \right) \\ Q_i = U_i \sum_{j \in i} U_j \left(G_{ij} \sin\theta_{ij} - B_{ij} \cos\theta_{ij} \right) \end{cases} \tag{1}$$

Where, U_i and U_j represent the voltage (exergy-potential p_{e}) at electrical nodes *i* and *j*, respectively. Other parameters can be referenced from literature [7].

2.2 Exergy flow mechanism model of natural gas system

The exergy flow mechanism model for natural gas systems primarily consists of node exergy flow balance equations and pressure-exergy flow equations[7]:

$$\boldsymbol{e}_{\mathrm{g,N}} = \boldsymbol{A}_{\mathrm{g}} \boldsymbol{e}_{\mathrm{g}}$$

$$\begin{cases} p_{\mathrm{pr1}} - p_{\mathrm{pr2}} = 11.7 \times 10^3 \dfrac{L_{\mathrm{g}}}{D_{\mathrm{g}}^5} (\dfrac{e_{\mathrm{g}}}{p_{\mathrm{g}}})^2 \\ p_{\mathrm{pr1}}^2 - p_{\mathrm{pr2}}^2 = 27.24 \dfrac{L_{\mathrm{g}}}{E^2 D_{\mathrm{g}}^{4.848}} (\dfrac{e_{\mathrm{g}}}{p_{\mathrm{g}}})^{1.848} \\ p_{\mathrm{pr1}}^2 - p_{\mathrm{pr2}}^2 = 18.43 \dfrac{L_{\mathrm{g}}}{E^2 D_{\mathrm{g}}^{4.854}} (\dfrac{e_{\mathrm{g}}}{p_{\mathrm{g}}})^{1.854} \end{cases} \tag{2}$$

Where, $\boldsymbol{e}_{\mathrm{g,N}}$ represents the source-load exergy of natural gas; $\boldsymbol{e}_{\mathrm{g}}$ represents the exergy flow in natural gas pipelines; p_{g} represents the exergy-potential of natural gas, which is considered constant in this paper; the following three are analogous to the Lacey-type exergy flow equation, the Polyflo-type exergy flow equation, and the Panhandle "A" type exergy flow equation, respectively.

2.3 Exergy flow mechanism model of thermal system

The thermal-exergy flow model[7] is as follows:

$$\begin{cases} T_{\mathrm{end}} - T_{\mathrm{a}} = (T_{\mathrm{start}} - T_{\mathrm{a}}) e^{-\frac{\lambda L}{C_{\mathrm{p}} \dot{m}_{\mathrm{h}}}} \\ \left(\sum \dot{m}_{\mathrm{out}} \right) T_{\mathrm{out}} = \sum \dot{m}_{\mathrm{in}} T_{\mathrm{in}} \\ e_{\mathrm{h,source}} = \mathrm{diag}\left(p_{\mathrm{s}} - p_{\mathrm{r}} \right) m_{\mathrm{h,q}} \\ e_{\mathrm{h,load}} = \mathrm{diag}\left(p_{\mathrm{s}} - p_{\mathrm{o}} \right) m_{\mathrm{h,q}} \\ p_{\mathrm{h}} = (T - T_{\mathrm{a}} \ln T - T_{\mathrm{a}} + T_{\mathrm{a}} \ln T_{\mathrm{a}}) c_{\mathrm{p}} \end{cases} \tag{3}$$

Where, $e_{\mathrm{h,source}}$ and $e_{\mathrm{h,load}}$ represent the exergy flows of heat sources and heat loads, respectively; p_{s}, p_{r}, and p_{o} represent the exergy-potentials of supply, return, and outlet nodes, respectively; p_{h} represents the exergy-potential corresponding to a node with a temperature of *T*.

The exergy flow mechanism model for thermal systems consists of a hydraulic model and a thermal-exergy flow model. The hydraulic model is widely used and will not be elaborated on here.

2.4 Energy station (exergy hub)

The exergy flow mechanism model for the energy station is represented using an exergy hub[7]:

$$\boldsymbol{e}_{\mathrm{out}} = \boldsymbol{C}_{\lambda} \boldsymbol{e}_{\mathrm{in}} \tag{4}$$

Where, $\boldsymbol{e}_{\mathrm{out}}$ represents the exergy column vector at the energy station's output ports; $\boldsymbol{e}_{\mathrm{in}}$ represents the exergy column vector at the energy station's input ports; $\boldsymbol{C}_{\lambda}$ is the exergy coupling matrix, which characterizes the relationship between exergy flows at the energy station's input and output ports.

2.5 Objective function

With the objective of minimizing the equivalent annual total cost of IES, where the costs encompass pipeline retrofit costs, energy station retrofit costs, equipment maintenance costs, energy purchase costs, and environmental costs, specifically expressed as:

$$\begin{gathered} f_1: \ \min \ C_{\mathrm{IES}} = C_{\mathrm{line}} + C_{\mathrm{es}} \\ C_{\mathrm{es}} = C_{\mathrm{inv}} + C_{\mathrm{mat}} + C_{\mathrm{opt}} + C_{\mathrm{CO_2}} \\ C_{\mathrm{line}} = C_{\mathrm{ele}} + C_{\mathrm{gas}} + C_{\mathrm{heat}} \end{gathered} \tag{5}$$

Where, C_{line} represents the pipeline retrofit costs, including the cable retrofit costs C_{ele}, natural gas pipeline retrofit costs C_{gas}, and thermal pipeline retrofit costs C_{heat}; C_{es} represents the energy station retrofit costs, comprising the annual equivalent investment cost of equipment C_{inv}, annual equipment maintenance cost C_{mat}, annual energy purchase cost C_{opt}, and annual environmental cost C_{CO_2}

2.6 Constraint

The constraint conditions encompass equipment constraints for the energy station, constraints related to energy pipelines, and node exergy-potential constraints.

2.6.1 Equipment constraints

Due to constraints such as budget limitations and available space, there are the following limitations on the planning capacity of energy equipment:

$$0 \le S_{\Omega} \le S_{\max,\Omega} \tag{6}$$

Where, $S_{\max,\Omega}$ represents the maximum allowable capacity for configuring Type Ω equipment.

There are constraints on the output of the primary equipment in the energy station as follows:

$$\begin{cases} 0 \le K \cdot \left(P_{\text{CHPe},t} + P_{\text{CHPh},t}\right) \le S_{\text{CHP}} \\ 0 \le K \cdot P_{\text{GBh},t} \le S_{\text{GB}} \\ 0 \le K \cdot P_{\text{EBh},t} \le S_{\text{EB}} \end{cases} \tag{7}$$

Where, $P_{\text{CHPe},t}$ and $P_{\text{CHPh},t}$ represent the electrical power output and thermal power output of the CHP system at time t on a typical day; $P_{\text{GBh},t}$ and $P_{\text{EBh},t}$ represent the thermal power outputs of the GB and EB systems at time t on a typical day.

2.6.2 Energy pipeline constraints

The upper limits of the power flow $S_{\max}$, natural gas flow $Q_{\max}$, and thermal flow $M_{\max}$ for each pipeline should be greater than their respective carrying capacities:

$$\begin{cases} S_i < S_{\max} \\ Q_i < Q_{\max} \\ M_i < M_{\max} \end{cases} \tag{8}$$

Where, S_i represents the electrical line's carrying capacity; Q_i represents the thermal pipeline's carrying capacity; M_i represents the natural gas pipeline's carrying capacity.

2.6.3 Node exergy-potential constraints

Considering the enhancement or maintenance of the local effective energy transport capability within IES to a certain level, the exergy-potential of nodes within IES is subject to the following constraints:

$$\begin{cases} p_{\text{e},t} \ge p_{\text{e,TGT}} \\ p_{\text{g},t} \ge p_{\text{g,TGT}} \\ p_{\text{h},t} \ge p_{\text{h,TGT}} \end{cases} \tag{9}$$

Where, $p_{\text{e},t}$, $p_{\text{g},t}$, and $p_{\text{h},t}$ represent the exergy-potentials of the electrical, natural gas, and thermal systems at time t on a typical day; $p_{\text{e,TGT}}$, $p_{\text{g,TGT}}$, and $p_{\text{h,TGT}}$ represent the target values for the exergy-potentials of the electrical, natural gas, and thermal systems' nodes.

3. CASE STUDY

3.1 Case introduction

This case study is based on a typical IES, as shown in Figure 1, which comprises a 6-node electrical system, a 7-node natural gas system, an 8-node thermal system, and an energy station. The system parameters for the current year are as documented in reference[9]. Within the energy station, there are cogeneration units (CHP), an electric boiler (EB), and a gas boiler (GB) that provide heat for the thermal system. Among them, the CHP unit has a gas-to-heat conversion efficiency of 0.45 and a gas-to-electricity conversion efficiency of 0.35, the GB unit has an efficiency of 0.85, and the EB unit has an efficiency of 0.95.

The available expansion planning options for electric cables, natural gas pipe, and thermal pipe are presented in Table 1-Table 3.

Table 1 The expansion types of electric cable

ID	Type	Resistance [W/km]	Reactance [W/km]	Capacity [kVA]	Cost [$/m]
1	YJLV 1*25	0.87	0.12	300	150
2	YJLV 1*35	0.62	0.11	650	180
3	YJLV 1*50	0.44	0.11	950	220
4	YJLV 1*70	0.31	0.10	1450	250
5	YJLV 1*95	0.23	0.10	1950	300
6	YJLV 1*120	0.18	0.09	2350	330
7	YJLV 1*150	0.14	0.09	2800	370
8	YJLV 1*185	0.12	0.09	3200	400
9	YJLV 1*240	0.09	0.09	3950	450
10	YJLV 1*300	0.07	0.08	4550	520
11	YJLV 1*400	0.05	0.08	5550	610
12	YJLV 1*500	0.03	0.08	6250	710
13	YJLV 1*630	0.02	0.07	7050	830
14	YJLV 1*800	0.01	0.05	10000	900

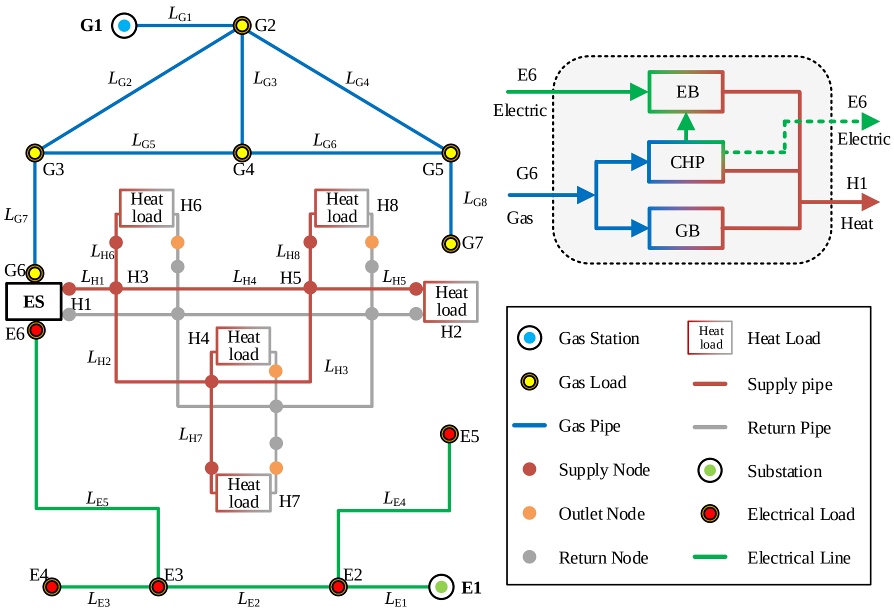


Fig. 1. Topological diagram of the case

Table 2 The expansion types of natural gas pipe

ID	Type	Diameter [mm]	Capacity [m³/h]	Cost [$/m]
1	DN-40	40	162.77	210.2460
2	DN-50	50	254.34	354.1690
3	DN-70	70	498.5	429.5300
4	DN-80	80	651.11	508.5440
5	DN-100	106	1017.36	645.5010
6	DN-125	131	1589.62	765.5700
7	DN-150	156	2289.06	910.6790
8	DN-200	207	4069.44	1259.7610
9	DN-225	245	5150.38	1366.5400
10	DN-250	259	6358.5	1518.2780
11	DN-300	309	9156.24	1940.8700

Table 3 The expansion types of thermal pipe

ID	Type	Diameter [mm]	Heat-transfer coefficient λ	Capacity (kg/s)	Cost [$/m]
1	DH-40	40	0.28	1.01	210.2460
2	DH-50	50	0.26	1.57	354.1690
3	DH-65	66.5	0.24	2.65	429.5300
4	DH-80	80	0.22	5.03	508.5440
5	DH-100	106	0.20	9.42	645.5010
6	DH-125	131	0.18	14.72	765.5700
7	DH-150	156	0.16	24.74	910.6790
8	DH-200	207	0.14	50.26	1259.7610

The typical daily load profiles for the current year are shown in Figure 2(a) through Figure 2(c). It is assumed that in the target planning year, the typical daily electrical load, natural gas load, and thermal load have increased by a factor of 2, 1.85, and 1.8, respectively. The purchase prices for electricity and natural gas are depicted in Figure 2(d).

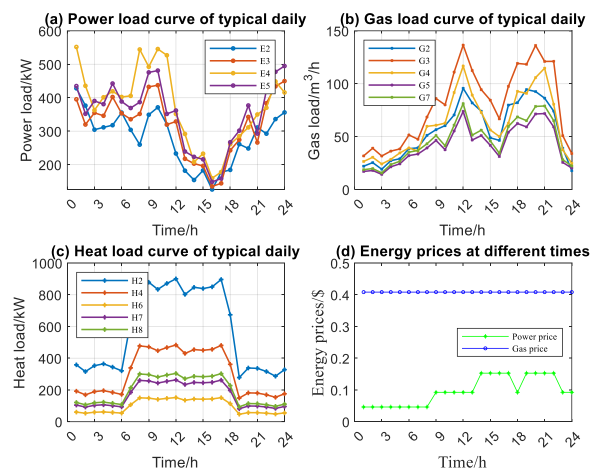


Fig. 2. Current annual load curve and energy prices

3.2 *Result analysis*

With the selection of expansion models for 5 cables, 8 natural gas pipelines, and 8 thermal pipelines, along with the typical daily 24-hour heat output of CHP and EB, a total of 69 decision variables were formed. Using the exergy-potential of thermal nodes or electrical nodes as constraints, a single-objective energy station-network collaborative planning model was constructed to minimize the equivalent annual total cost. Three planning scenarios were obtained as follows:

- Case 1: Without exergy-potential constraints.
- Case 2: Imposing a constraint on thermal node H3 with a return node exergy-potential $p_{h,r(3)}$ >10.35 J/kg.

- Case 3: Imposing a constraint on electrical node E3 with a node exergy-potential $p_{e(3)}$ >12.64 kV.

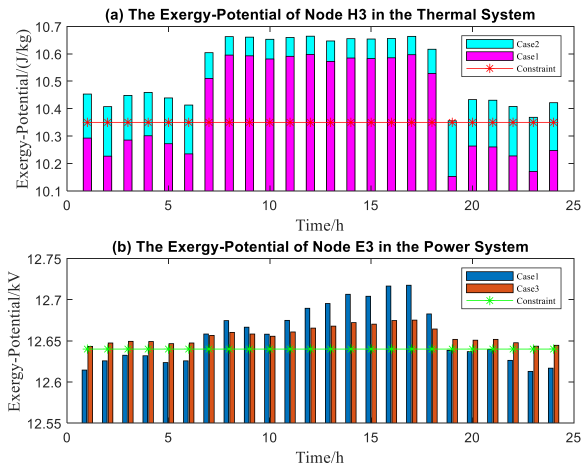


Fig. 3. The node exergy-potential on typical day

Figure 3 presents the comparative exergy-potential graphs for thermal node H3 on a typical day in both case 1 and case 2, as well as the exergy-potential comparison for electrical node E3 on a typical day in case 1 and case 3. Compared to case 1, cases 2 and 3 consistently have higher exergy-potential at typical daily time points, exceeding the specified constraints, and ensuring that the effective energy transport capacity of this node trends toward stability.

Table 4 Comparison of planning results

Planning results of Pipe(cables)			
Pipe	**case 1**	**case 2**	**case 3**
L_{E1}	3→7	3→14	3→13
L_{E2}	3→7	3→13	3→12
L_{E3}	1→4	1→13	1→11
L_{E4}	1→4	1→13	1→11
L_{E5}	1→9	1→13	1→11
L_{G1}	4→7	4→10	4→9
L_{G2}	1→4	1→10	1→9
L_{G3}	1→3	1→10	1→9
L_{G4}	1→3	1→10	1→9
L_{G5}	1→11	1→10	1→9
L_{G6}	1→11	1→10	1→9
L_{G7}	1→5	1→10	1→9
L_{G8}	1→1	1→10	1→9
L_{H1}	3→7	3→7	3→7
L_{H2}	3→6	3→7	3→7
L_{H3}	2→4	2→8	2→7
L_{H4}	2→5	2→8	2→7
L_{H5}	4→5	4→8	4→7
L_{H6}	1→3	1→7	1→6
L_{H7}	2→4	2→8	2→7
L_{H8}	2→4	2→8	2→7
Planning results of energy conversion equipment (kW)			
CHP	7498.2063	7056.7078	6726.4265
EB	0	158.6643	243.3009
GB	6.1215	126.4755	239.7814
Equivalent annual total cost of IES ($)			
case 1	**case 2**	**case 3**	
10989195.0084	15293033.8456	14414736.2542	
The exergy loss of the pipe and cable (kW)			
case 1	**case 2**	**case 3**	
2628107.2868	131836.18288	157539.9355	

The planning schemes for the three options are presented in Table 4.

1) In terms of pipeline expansion, case 1 demonstrates better cost-effectiveness with a more conservative extension of the pipelines (cables). In terms of equipment capacity configuration at the energy station, both case 2 and case 3 adopt a coordinated supply of CHP, EB, and GB.
2) Case 2 and case 3, constrained by the exergy-potential at nodes, opt for larger capacity pipelines (cables), but their cost-effectiveness is inferior. Case 2 opted for a larger capacity pipeline because, in accordance with temperature equation (3), as the heat transfer coefficient λ increases, the terminal node temperature T decreases, leading to a lower exergy-potential. Consequently, a pipeline model with a smaller heat transfer coefficient would be preferred.
3) The presence of exergy-potential constraints significantly reduces the exergy loss of the pipelines and cables in both case 2 and case 3.

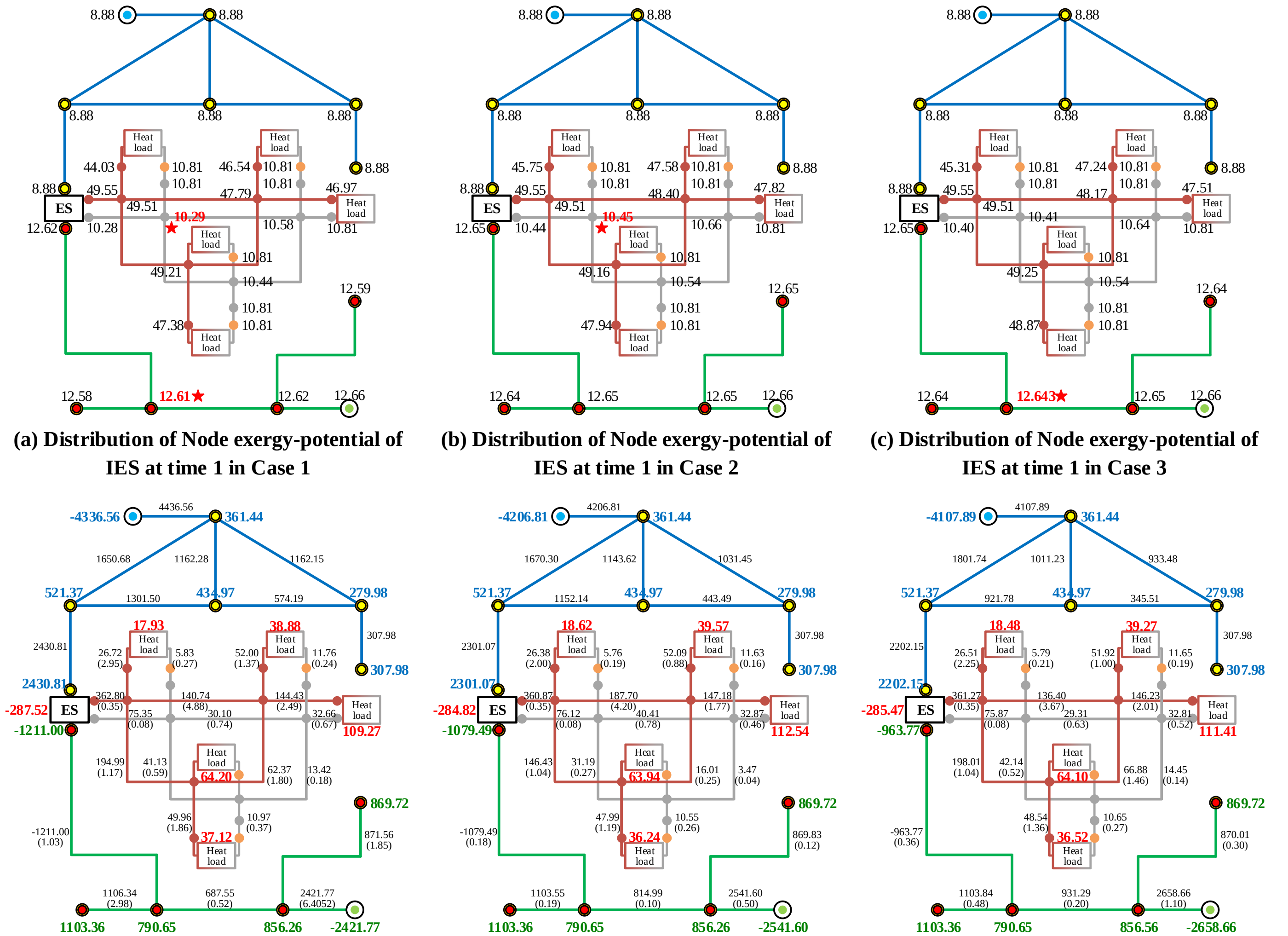
The distribution of exergy-potential and exergy flow for the three cases at the same moment is shown in Figure 4. It can be seen that the presence of exergy constraints not only reduces exergy losses in the energy pipeline but also decreases reliance on natural gas, thereby increasing the utilization of electricity.

4. CONCLUSIONS

This paper introduces the concept of exergy-potential for the first time as a constraint in the IES energy station-grid collaborative planning model. It provides an initial discussion of the impact of exergy-potential on IES planning schemes. Subsequent work will involve more detailed planning and design for practical engineering projects.

ACKNOWLEDGEMENT

This work was supported by National Natural Science Foundation of China (No. 51977141), National Key R&D Program of China (No. 2018YFB0905000), Science and Technology Project of SGCC (No. SGTJDK00DWJS1800232). This study was conducted in cooperation of APPLIED ENERGY UNiLAB-DEM: Distributed Energy & Microgrid. UNiLAB is an



(a) Distribution of Node exergy-potential of IES at time 1 in Case 1

(b) Distribution of Node exergy-potential of IES at time 1 in Case 2

(c) Distribution of Node exergy-potential of IES at time 1 in Case 3

(d) Distribution of Exergy flow of IES at time 1 in Case 1

(e) Distribution of Exergy flow of IES at time 1 in Case 2

(f) Distribution of Exergy flow of IES at time 1 in Case 3

Fig. 4. The distribution of exergy-potential and exergy flow for three cases

international virtual lab of collective intelligence in Applied Energy.

DECLARATION OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All authors read and approved the final manuscript.

REFERENCE

[1] WANG Dan, ZHOU Tianshuo, LI Jiaxi, et al. Theory and Application of High-Exergy Integrated Energy System for Energy Transition[J]. Automation of Electric Power Systems, 2022,46(17):114-131.

[2] HU Xiao, ZHANG Heng, CHEN Dongwen, et al. Multi-objective planning for integrated energy systems considering both exergy efficiency and economy[J]. Energy, 2020, 197: 117155.

[3] WANG Yongli, HUANG Feifei, TAO Siyi, et al. Multi-objective planning of regional integrated energy system aiming at exergy efficiency and economy[J]. Applied Energy, 2022, 306: 118120.

[4] CHEN Cong, SHEN Xinwei, XIA Tian, et al. Multi-objective optimal dispatch method for integrated energy system considering exergy efficiency[J]. Automation of Electric Power Systems, 2019, 43(12): 60-67.

[5] Zhang Xiaoping, YAN Zuanhong. Energy Quality: A Definition[J]. IEEE Open Access Journal of Power and Energy, 2020,7:430-440.

[6] LI Jiaxi, WANG Dan, JIA Hongjie. Exergy flow mechanism and analysis method for integrated energy system[J]. Automation of Electric Power Systems, 2022, 46(12):163-173.

[7] LI Jiaxi, WANG Dan, JIA Hongjie, et al. Mechanism Analysis and Unified Calculation Model of Exergy

Flow Distribution in Regional Integrated Energy System[J]. Applied Energy, 2022,324:119725.

[8] ZHOU Tianshuo, WANG Dan, LI Jiaxi, et al, Multi-objective planning for integrated energy systems considering both energy quality and renewable energy[C]. 2023 IEEE Power & Energy Society General Meeting (PESGM). Orlando, Florida, USA, 16 – 20 July 2023.

[9] LI Jiaxi, WANG Dan, ZHOU Tianshuo, et al. Exergy Flow Calculation Model for Integrated Energy System[J]. Automation of Electric Power Systems, 2022,46(24): 45-56.