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Comprehensive method of natural gas pipeline efficiency evaluation based on energy and big data analysis

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ABSTRACT

Pipeline companies deploy a series of pipeline resource optimal configurations and efficiency enhancement strategies with the purpose of improving financial benefits. Thus far, pipeline owners and stakeholders have usually focused on efficiency evaluation processes based on the technological aspects of transmission. In this context, here we derive a pipeline efficiency evaluation method from the perspective of the pipeline energy input–output by monitoring the energy and transmission amount changes along the pipeline. The parameter of volumetric work, which is defined as the energy consumption required for transporting a certain amount of gas over a certain distance along the pipeline, measures the energy change except for the intrinsic energy and mechanical pressure energy. With no distribution stations being taken into consideration, the gas amount change due to the pipeline's self-energy consumption is regarded as the equivalent fuel gas while also considering the volumetric work change caused by gas consumption. Upon accounting for all factors via volumetric work and pressure energy, we utilise the input–output variation to develop a data envelopment analysis (DEA) model, which affords the relative efficiency via calculation and evaluation of the operating efficiency of the pipeline and related facilities. Subsequently, analytic hierarchy process (AHP) is introduced to determine the impact from different facilities. Our result, which presents the difference between the ideal objective efficiency and current efficiency based on the measured volumetric work can aid in identifying the most efficient situation. Here, we note that owing to factors such as the inlet pressure and equipment configuration, the first station usually exhibits lower efficiency than the other stations. In terms of energy for the whole pipeline, the efficiency (unit consumption) grows in inverse proportion to the transmission amount. In the final phase of the study, we consider an actual pipeline case study in our analysis and verify the practical utility of this method. Our results also indicate that the transmission efficiency and economic efficiency exhibit a trade-off relationship.

1. Introduction

Recent years have witnessed the rapid development of natural gas pipelines across the world in conjunction with economic growth. From the viewpoint of safety and economic aspects, pipelines are assumed as one of the most reasonable modes of petroleum and natural gas transport, particularly in cases of high demand over long distances [1]. In this regard, the West-East Natural Gas Pipeline System in China reportedly accounted for 41% of the nationwide natural gas consumption in 2017. Further, the natural gas demand of China in 2035 is forecasted to lie at a maximum value of $549.94 \times 10^6\ m^3$ [2]. Natural gas is mainly used for power generation, heating, transportation, and industrial production, and thus, it plays a critical role in the energy market [3]. In this context, previous research has indicated the severity of the problems of the lack of gas supply in instances such as pipeline failure and insufficient transport capacity in Europe [4]. However, research focused on pipeline operation performance is rare, particularly from the perspective of energy [5]. Although the pipeline efficiency determines the financial benefit of the pipeline itself, no significant pipeline assessment and research work has been carried in China thus far. With worldwide concerns regarding sustainable development and environmental issues, there is a critical focus on energy efficiency and environmental performance.

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Notation

$EFG_E =$	equivalent fuel gas
$C_E =$	electricity consumption ($kW{\cdot}h$)
$C_{EE} =$	electricity cost (Chinese Yuan)
$Q_{c,i} =$	gas consumption of station i (m^3)
$P_{EE,i} =$	electricity consumption for running station i ($kW{\cdot}h$)
$C_{EE,i} =$	electricity cost for running station i (Chinese Yuan)
$P_G =$	local unit price of natural gas (Chinese Yuan/m^3)
$W_v =$	total volumetric work ($m^3{\cdot}km$)
$W_C =$	current volumetric work ($m^3{\cdot}km$)
$\vec{Q}_i$	= gas flow at measurement station i (m^3)
$ms_i =$	milestone corresponding to station i (km)
$ms_0 =$	milestone corresponding to initial station (km)
$R_g =$	real gas constant ($J/(mol{\cdot}K)$)
$c_v =$	isochoric specific heat capacity ($J/(mol{\cdot}K)$)
$c_p =$	isobaric specific heat capacity ($J/(mol{\cdot}K)$)
$k_t =$	isothermal adiabatic exponent
$k_v =$	isochoric adiabatic exponent
$P_r =$	reduced pressure
$T_r =$	reduced temperature
$Z =$	compressibility factor

During the 15th United Nations Climate Change Conference in Copenhagen, PR China promised to reduce the carbon emission per unit GDP by 45% relative to that from 2005 to 2020.

Here, we note that oil and gas pipelines provide most of the oil and natural gas products to the market. Consequently, to reduce the energy cost, it is critical to ensure that the efficiency of the energy supply chain itself is optimal. In this regard, Sam et al. [6] performed an efficient coordinated control analysis based on energy supply and storage analysis in an attempt to decrease the pipeline energy cost. Further, many experts have conducted researches on efficiency measurement [7], efficiency improvement [8], and strategic planning [9–12]; however, these studies focus on policy and operating strategy rather than the technological aspects of pipeline operation.

The method of analysis of pipeline efficiency based on statistics of collected data is widely accepted [13,14]. In 2010, the Interstate Natural Gas Association of America pointed out that the main factors of pipeline efficiency enhancement were two types of efficiency: economic efficiency and transmission efficiency [15]. Economic efficiency is estimated by the fuel cost rate and gas transmission rate; on the other hand, transmission efficiency covers the thermal efficiency, hydraulic efficiency, and compressor efficiency. While this research proposes a novel concept of efficiency evaluation, we note here that developments characterised by our type of approach are still nascent.

The application of data envelopment analysis (DEA) to pipeline energy evaluation in China focuses mainly on electricity consumption and the turnover volume of a product oil pipeline [16]. Most efficiency evaluation studies on natural gas pipelines analyse the hydraulic and thermodynamic processes by means of flow simulations in the pipeline mechanism. Studies of the dynamic behaviour of natural gas flows in long transmission pipelines have also ignored the aspect of energy consumption [17]. Meanwhile, a study predicting the temperature distribution along the pipeline flow has attempted to isolate the energy change from the pipeline system [18]. However, energy efficiency evaluation without considering the pipeline system presents an incongruent and unrealistic scenario despite uniform application of the DEA model [19]. A review of recent energy efficiency evaluations based on DEA indicates that only 5.56% of research is focused on energy performance [20]. Other studies have conducted energy assessment with the use of different parameters on thermal power plants and provided monitoring solutions [21]. However, the application of big data to pipeline energy monitoring has not been studied thus far. In fact, very few studies have focused on the basic energy efficiency of a natural gas pipeline.

Against this backdrop, we present a novel method for efficiency evaluation of natural gas pipeline operating processes. In order to ensure accuracy and credibility, we derive an efficiency estimation method from the basic definition of energy by using the ratio of the input to output energy including the internal energy of natural gas itself. The DEA is used to assess the effectiveness of the current efficiency of pipelines, and further, we determine the objective efficiency from current input conditions by utilising a case study of a functional pipeline operated by the China National Petroleum Corporation. In addition, we also consider the break-even point (BEP) and pipeline load rate in the financial analysis, which is of interest to oil and natural gas companies.

2. Methodology

A natural gas pipeline is a complex system which is characterised by several efficiency indices. Current efficiency evaluating methods are mostly based on characteristic methods of hydraulic and thermal simulations. Such efficiency analysis concentrates on the transmission parameters while ignoring the energy variation including energy cost and volume change along the pipeline. The efficiency corresponding to technical parameters cannot characterise the actual efficiency for different transmission amounts caused by the parameter changes. With the purpose of fundamentally evaluating the pipeline efficiency, the energy consumption (energy cost) of a certain gas transmission task can be studied to reveal the operating efficiency via a series of analyses. The parameter of equivalent fuel gas (EFG) indicates the energy cost of the transmission task. Further, unlike the EFG, the volumetric work numerically characterises the work of the gas amount and its transmission distance. Hence, via coupling of the EFG and volumetric work, it is possible to evaluate the specific energy cost for transmitting a unit volume of gas over a unit distance. After acquisition of the operating energy cost and gas variation at stations, the optimal operating situation can be estimated by means of the DEA and AHP method.

2.1. Definition and calculation of equivalent fuel gas

The natural-gas driven compressor of the pipeline system consumes the gas transmitted by the pipeline itself, but the energy source of the compressor is electricity from the external power grid. Thus, a unified criterion to evaluate the energy cost of the two sources is essential. Here, we ignore the efficiency diversity between a gas-driven compressor and electricity-driven compressor in converting the electricity consumption ($kW{\cdot}h$) into natural gas consumption (m^3). Thus, EFG can be expressed as

$$EFG_E = \frac{C_{EE}}{P_G} \tag{1}$$

here, $EFG_E =$ equivalent fuel gas.

$C_{EE} =$ cost of electricity
$P_G =$ price of natural gas

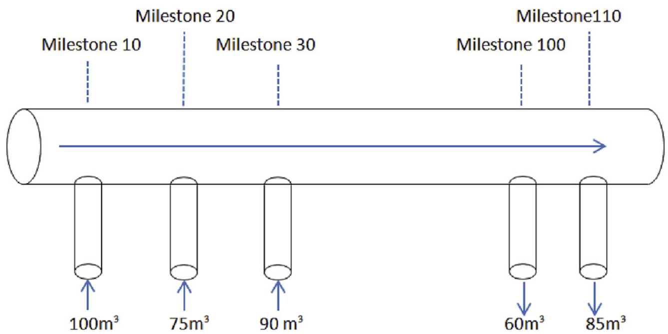

Fig. 1. Schematic of multi-input/output scenario.

Consequently, the electricity consumption is converted into gas consumption. The total EFG or EFG_T can be expressed as

$$EFG_T = \sum Q_{C,i} + \sum \frac{C_{EE,i}}{P_G}, \tag{2}$$

where, Qc,i = gas consumption of station i.

CEE,i = electricity cost of station j
PG = local unit price of natural gas

2.2. Volumetric work quantification

The concept of volumetric work was first introduced by the Williams Gas Pipeline Company in 2011, and it provides an index to indicate the equivalent operating energy of a monitoring pipeline [22]. Via introduction of the definition of volumetric work and equivalent gas consumption, pipeline efficiency assessment becomes possible in the energy domain, which is independent from the gas transmission amount.

The work (gas volume multiplied by distance) which characterises a certain amount of natural gas transmitted from the supplier to the market via the pipeline is defined as 'volumetric work'. In general, the amount of natural gas is measured in cube metres at pipeline measuring stations and city gate stations under standard conditions. With distance being measured in *km*, the unit of volumetric work is expressed as $m^3 \cdot km$.

The volumetric work can be calculated by installing measuring equipment at each station. A single input and output scenario is portrayed in Fig. 1. As shown in the figure, the task of transmitting 100 m^3 of natural gas is initiated from Milestone 10 to terminal Milestone 110, where the distance is 100 km. The volumetric work is simply calculated as the gas amount multiplied by the distance and measured as $10^4\, m^3\, km$. For each station, this method continues to serve well. In Fig. 1, volumetric work is calculated by assuming that the gas entering is positive, with gas distribution being negative.

The volumetric work before the outlet of the first station is zero because the gas has not been transmitted. To eliminate the pressure diversity impact from initial point, at each milestone station, the first milestone is not considered. The volumetric work pertaining to Fig. 1 can be expressed as 100 m^3 × (Milestone 10 − Milestone 10) − 75 m^3 × (Milestone 20 − Milestone 10) − 90 m^3 × (Milestone 30 − Milestone 10) + 60 m^3 × (Milestone 40 − Milestone 10) + 85 m^3 × (Milestone 50 − Milestone 10) = 2650 m^3 km.

Thus, the volumetric work of the whole system can be presented as below:

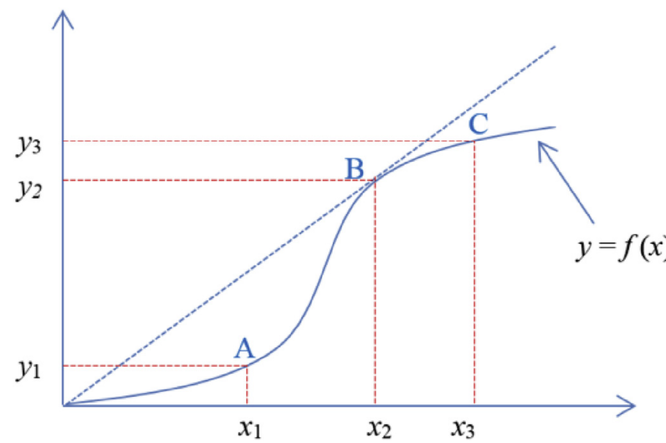

Fig. 2. Data envelopment function of single-input-and-output scenario.

$$W_v = \sum \vec{Q}_i \times (ms_i - ms_0) \tag{3}$$

Here, W_v = total volumetric work.

$\vec{Q}_i$ = gas flow at measurement station i
ms_i = milestone corresponding to station i
ms_0 = milestone corresponding to initial station

Thus, the pipeline efficiency can be expressed as below:

$$PER = \frac{EFG_P \cdot W_C}{EFG_C} \tag{4}$$

Here, PER = pipeline efficiency rating.

EFG_P = past equivalent fuel gas
EFG_C = current equivalent fuel gas
W_C = current volumetric work

2.3. DEA optimisation in efficiency evaluation

DEA is an interdisciplinary optimisation [23] and evaluation method based on mathematics, operations research, economics, and management [24]. DEA is applied extensively for its accuracy of multi-input and output linear programming and evaluation. The Charnes–Cooper–Rhodes (CCR) model introduced by Charnes, Cooper, and Rhodes in 1978 defines the efficiency as the weighted sum of the output divided by the weighted sum of the input [25]. Thus, an evaluation method based on analysis of the input and output data of the decision-making unit (DMU) is developed for DMU effectiveness evaluation.

The production frontier forms the periphery of the production performance curve. In simple words, the production frontier is the optimal solution function. The production possibility set based on the C^2R model can be expressed as

Table 1
Random index of consistency.

n	1	2	3	4	5	6	7	8	9	10	11
R	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49	1.51

Table 2
Energy statistic for each month.

Station	Work (MJ/d)	Input Energy (MJ/d)	Efficiency	Work (MJ/d)	Input Energy (MJ/d)	Efficiency
January				July		
1	2130038	2695921	79.0%	1891911	2242103	84.4%
2	2479870	2709284	91.5%	2217577	2478830	89.5%
3	1583058	1752013	90.4%	1486534	1672355	88.9%
4	1947339	2083832	93.4%	1829605	1979172	92.4%
5	1993402	2220444	89.8%	1713121	2074360	82.6%
February				August		
1	2097444	2659	79.1%	1382914	1841263	75.1%
2	2456388	2691233	91.3%	1861735	2091818	89.0%
3	1660705	1809693	91.8%	1127749	1274847	88.5%
4	1915022	2132052	89.8%	1411074	1618400	87.2%
5	1841687	2061699	89.3%	1590872	1761450	90.3%
March				September		
1	1230511	1351959	91.0%	1304607	1564374	83.4%
2	0	0	–	0	0	–
3	861607	966209	89.2%	1047986	1244276	84.2%
4	0	0	–	0	0	–
5	1414658	1542002	91.7%	1372388	1601740	85.7%
April				October		
1	1021823	1220512	83.7%	1296374	1577369	82.2%
2	0	0	–	0	0	–
3	613659	741798	82.7%	1094260	1320936	82.8%
4	0	0	–	0	0	–
5	1111268	1256640	88.4%	1097170	1215526	90.3%
May				November		
1	731844	913644	80.1%	1917392	2468512	77.7%
2	1202845	1294875	929%	2281521	2464169	92.6%
3	0	0	–	1699530	1934012	87.9%
4	1150050	1288088	89.3%	2094421	2319310	90.3%
5	0	0	–	2408386	2738488	87.9%
June				December		
1	1215058	1366001	89.0%	2416581	2918332	82.8%
2	1031576	1121028	92.0%	2639271	2869233	92.0%
3	0	0	–	1718401	1886959	91.1%
4	1565940	1706401	91.8%	2196181	2454387	89.5%
5	877555	999600	87.8%	2438195	2665338	91.5%

$$\min\theta \quad s.t.\begin{cases}(\theta X_j, Y_j)\in T\\ \theta<1\end{cases} \tag{5}$$

If output Y_0 is constant and input X_0 does not reduce with proportion θ, the optimal solution of this linear programming is $\theta = 1$, or else the optimal solution is $\theta < 1$.

Technical effectiveness is a precondition for production evaluation for the reasons of physical constraints of equipment and technology. Scale effectiveness indicates that the output is maximal relative to the current input, and extra input can yield a significant increase in output, as indicated by point A in Fig. 2. Further, although point C corresponds to technical effectiveness, an abundant input does not yield a satisfactory outcome. An optimal solution (input and output relationship) is obtained at point B with a significant increase in output based on maximum technical effectiveness and optimal scale effectiveness relative to points A and C.

Analytic hierarchy process affords a quantitative analysis solution of the combined effects generated by multiple factors. To quantify the influence of N factors of a certain level on factor C of a higher level, a pairwise comparison matrix is introduced to calculate the weight vector.

$$A = \begin{bmatrix} \omega_1/\omega_1 & \dots & \omega_1/\omega_i & \dots & \omega_1/\omega_n \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \omega_j/\omega_1 & \dots & \omega_j/\omega_i & \dots & \omega_j/\omega_n \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \omega_n/\omega_1 & \dots & \omega_n/\omega_i & \dots & \omega_n/\omega_n \end{bmatrix} \tag{6}$$
$$a_{ij}\cdot a_{jk} = a_{ik}, i\in[1,n], j\in[1,n], k\in[1,n]$$

The eigenvalue λ of matrix A can be used for weight vector determination and performing consistency checks. A consistency check ensures that the eigenvalue can serve as the weight vector if the inconformity is not out of limits. The index of consistency C indicates the inconformity level of the matrix.

$$C = \frac{\lambda - n}{n-1}, \ n = \text{order of matrix} \tag{7}$$

A certain criterion is essential to determine the inconformity. Thus, a random index of consistency R is introduced into the calculation. According to Ref. [26], R can be determined as in Table 1.

When $n = 0$ and 1, $R = 0$ because the reciprocal matrices are the same. If $n \geq 3$ and the limit of inconformity which is defined as the consistency ratio CR (C/R) is less than 0.1, the eigenvalue vector can serve as the weight vector.

The DEA model is capable of evaluating the efficiency and estimating the optimal solution via DMU calculations after hierarchical analysis. Owing to the fundamental nature of the research, the mechanical energy and internal energy variation derived from the compressing process and transmission loss can be considered to suitably characterise the DMUs for the requirement of DEA application. The total energy change including the mechanical energy and internal energy along the pipeline can provide adequate parameters for DMU determination. Otherwise, the volume variation at the compressing stations and distribution stations usually characterise the energy transfer and loss at pivotal points. Consequently, an appropriate calculation method of energy variation deployed with volumetric work along the pipeline enables the

Table 3
Monthly pipe efficiency.

Station	Outlet Pressure (MPa)	Inlet pressure (MPa)	Efficiency	Outlet Pressure (MPa)	Inlet pressure (MPa)	Efficiency
January				July		
1	9.16		63.6%	9.63		63.1%
2	9.35	5.82	73.8%	9.37	6.07	75.6%
3	9.34	6.90	67.9%	9.46	7.09	70.1%
4	9.29	6.35	67.6%	9.52	6.63	71.0%
5	9.11	6.28	78.2%	9.45	6.76	79.8%
6		7.12			7.54	
February				August		
1	9.03		63.7%	9.00		69.5%
2	9.22	5.75	74.4%	9.25	6.26	78.9%
3	9.45	6.86	69.6%	9.26	7.30	74.0%
4	9.58	6.57	70.1%	9.22	6.85	72.3%
5	9.56	6.72	80.2%	9.28	6.66	81.4%
6		7.67			7.55	
March				September		
1	9.58		73.1%	9.45		71.0%
2	–	–	–	–	–	–
3	9.09	7.00	68.0%	9.08	6.71	68.0%
4	–	–	–	–	–	–
5	9.32	6.18	90.6%	9.03	6.17	89.8%
6		8.44	–		8.11	
April				October		
1	8.99		76.0%	9.56		71.5%
2	–	–	–	–	–	–
3	8.36	6.83	72.9%	9.42	6.83	71.6%
4	–	–	–	–	–	–
5	8.66	6.10	92.0%	9.30	6.74	91.2%
6		7.97			8.48	
May				November		
1	9.00		72.7%	9.10		63.8%
2	9.28	6.54	74.0%	8.98	5.81	72.9%
3	–	–	–	9.05	6.55	66.2%
4	9.65	6.86	77.4%	8.99	5.99	64.8%
5	–	–		9.19	5.82	77.1%
6		7.47			7.08	
June				December		
1	9.16		79.4%	9.64		63.1%
2	9.48	7.27	66.7%	9.70	6.08	73.7%
3	–	–	–	9.68	7.15	66.7%
4	9.43	6.32	81.0%	9.60	6.45	64.8%
5	9.54	7.63	88.7%	9.54	6.22	76.1%
6		8.47			7.25	

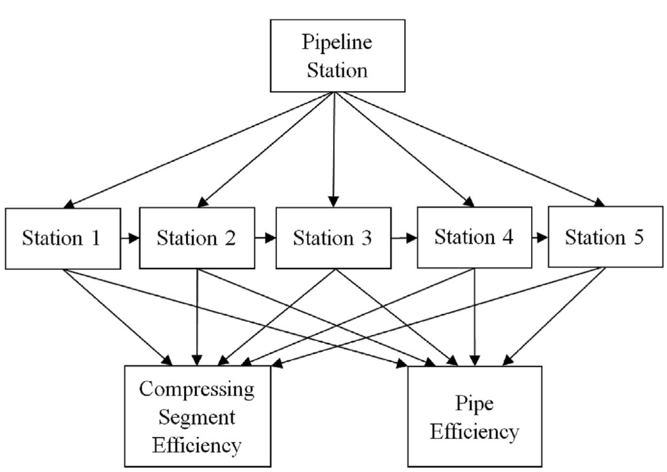

Fig. 3. Hierarchical structure of pipeline efficiency analysis.

feasibility and accuracy of our approach.

3. Calculation

The presence of numerous functional modules makes the pipeline system complex. Current research has introduced various efficiency evaluation indices, and in contrast, we apply a direct and effective method in this case with basic energy parameters [27]. We analyse the operating data of a main natural gas transmission pipeline (as collected by the China National Petroleum Corporation), and our efficiency analysis mainly concerns the compressing section and pipes because the largest amount of energy transfer occurs at these two sections. The energy changes are characterised by DMU change before and after DEA and AHP processing.

Based on the operation data including the gas transmission amount and self-consumption of the stations, we calculate the typical operating state for each month as the ambient temperature and gas supply demand vary monthly.

3.1. Compressing section efficiency calculation

Based on the operating parameters and physical properties of natural gas in the pipeline considered, we determine the critical

Table 4
The pipeline efficiency of January.

	Station	Compressing segment efficiency	Weight	Pipe efficiency	Weight	Station efficiency	Weight	Pipeline efficiency
Jan	1	79.0%	0.6	63.6%	0.4	72.84%	0.5128	77.7%
	2	91.5%	0.57	73.8%	0.43	83.89%	0.2615	
	3	90.4%	0.56	67.9%	0.44	80.50%	0.1289	
	4	93.4%	0.55	67.6%	0.45	81.79%	0.0634	
	5	89.8%	0.54	78.2%	0.46	84.46%	0.0333	
Feb	1	79.1%	0.6	63.7%	0.4	72.94%	0.5128	77.9%
	2	91.3%	0.57	74.4%	0.43	84.03%	0.2615	
	3	91.8%	0.56	69.6%	0.44	82.03%	0.1289	
	4	89.8%	0.55	70.1%	0.45	80.94%	0.0634	
	5	89.3%	0.54	80.2%	0.46	85.11%	0.0333	
Mar	1	91.0%	0.6	73.1%	0.4	83.85%	0.5128	83.5%
	2	–	–	–	–	–	–	
	3	89.2%	0.56	68.0%	0.44	79.88%	0.1289	
	4	–	–	–	–	–	–	
	5	91.7%	0.54	90.6%	0.46	91.18%	0.0333	
Apr	1	83.7%	0.6	75.9%	0.4	80.61%	0.5128	80.7%
	2	–	–	–	–	–	–	
	3	82.7%	0.56	72.9%	0.44	78.40%	0.1289	
	4	–	–	–	–	–	–	
	5	88.4%	0.54	92.1%	0.46	90.08%	0.0333	
May	1	80.0%	0.6	72.7%	0.4	79.76%	0.5128	81.5%
	2	92.9%	0.57	74.0%	0.43	84.76%	0.2615	
	3	–	–	–	–	–	–	
	4	89.3%	0.55	77.4%	0.45	83.95%	0.0634	
	5	–	–	–	–	–	–	
Jun	1	89.0%	0.6	79.4%	0.4	85.16%	0.5128	84.3%
	2	92.0%	0.57	66.7%	0.43	81.10%	0.2615	
	3	–	–	–	–	–	–	
	4	91.8%	0.55	81.0%	0.45	86.93%	0.0634	
	5	87.8%	0.54	88.7%	0.46	88.23%	0.0333	
Jul	1	84.4%	0.6	63.1%	0.4	75.88%	0.5128	79.1%
	2	89.5%	0.57	75.6%	0.43	83.52%	0.2615	
	3	88.9%	0.56	70.1%	0.44	80.63%	0.1289	
	4	92.4%	0.55	71.0%	0.45	82.77%	0.0634	
	5	82.6%	0.54	79.8%	0.46	81.31%	0.0333	
Aug	1	75.1%	0.6	69.5%	0.4	72.86%	0.5128	78.1%
	2	89.0%	0.57	78.9%	0.43	84.66%	0.2615	
	3	88.5%	0.56	74.0%	0.44	82.12%	0.1289	
	4	87.2%	0.55	72.3%	0.45	80.50%	0.0634	
	5	90.3%	0.54	81.4%	0.46	86.21%	0.0333	
Sep	1	83.4%	0.6	71.0%	0.4	78.43%	0.5128	78.7%
	2	–	–	–	–	–	–	
	3	84.2%	0.56	68.0%	0.44	77.07%	0.1289	
	4	–	–	–	–	–	–	
	5	85.7%	0.54	89.9%	0.46	84.46%	0.0333	
Oct	1	82.2%	0.6	71.5%	0.4	77.92%	0.5128	78.7%
	2	–	–	–	–	–	–	
	3	82.8%	0.56	71.6%	0.44	77.88%	0.1289	
	4	–	–	–	–	–	–	
	5	90.3%	0.54	91.2%	0.46	90.72%	0.0333	
Nov	1	77.7%	0.6	63.8%	0.4	72.14%	0.5128	76.9%
	2	92.6%	0.57	72.9%	0.43	84.13%	0.2615	
	3	87.9%	0.56	66.2%	0.44	78.35%	0.1289	
	4	90.3%	0.55	64.8%	0.45	78.83%	0.0634	
	5	87.8%	0.54	77.1%	0.46	82.93%	0.0333	
Dec	1	82.8%	0.6	63.1%	0.4	74.92%	0.5128	78.6%
	2	92.0%	0.57	73.7%	0.43	84.13%	0.2615	
	3	91.1%	0.56	67.7%	0.44	80.36%	0.1289	
	4	89.5%	0.55	64.8%	0.45	78.39%	0.0634	
	5	91.5%	0.54	76.1%	0.46	84.41%	0.0333	

Table 5
Load rate statistics.

Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Load rate	97.3%	97.3%	67.4%	62.5%	66.4%	74.8%	94.5%	88.9%	67.2%	67.1%	96.5%	104.3%

temperature as 191.05 K and the critical pressure as 4.641 MPa. Thus, the specific heat ratio $k = c_p/c_v = 1.6$, the adiabatic exponent $k_t = 1.38$, and $k_v = 1.54$.

The average inlet pressure is 6.5 MPa and the temperature is 293 K, whereas the reduced pressure P_r is 1.4 and the reduced temperature T_r is 1.54. Hence, the compressibility factor Z is 0.87.

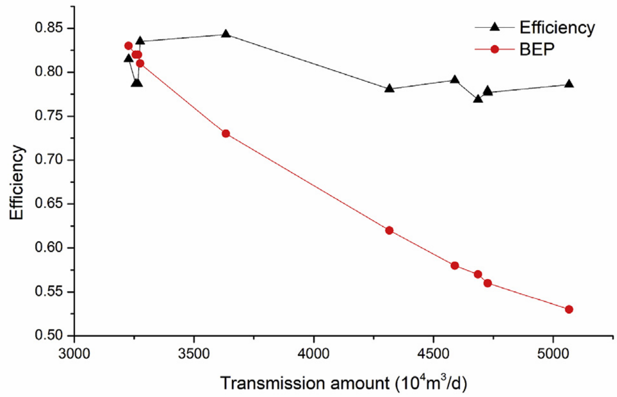

Fig. 4. Relationship between break-even point (BEP) and pipeline efficiency.

For ensuring that the pipeline parameters are in accordance with the estimation, the first 5 continuous stations without distribution are chosen as independent systems and numbered from 1 to 5 from upstream to downstream. Because the natural gas consumption of the compressors in these five stations is sufficiently small to be neglected, the input energy is evaluated as the total energy cost including gas and electricity consumption by the compressors. The energy consumption (input energy) including natural gas measured in m^3 and electricity measured in $kW{\cdot}h$ is converted into joules for unification. The compression work (output energy) is calculated via equation (3). Consequently, the efficiency can be simply obtained by its definition.

Here, we note that the essential energy is different from that used for various transmission tasks. Different gas transmission amounts and process arrangements ensure that the energy consumption is distinctive. Traditionally, the peak transmission amount is reached in winter because residential heating is utilised in this season, and on the other hand, the least transmission amount corresponds to spring. Including the median scenario in summer, these three typical transmission tasks can characterise the whole-year operating period.

Because of residential heating loads and natural gas power plant cost, the demand for natural gas peaks in December. The pipeline transports 47.27 million m^3 per day at its maximum transmission capacity, which is also its full capacity. Table 2 presents the average daily input and output energy based on the operating data collected by a supervisory control and data acquisition (SCADA) system.

In spring and autumn, the resulting comfortable climate makes residential heating and air-conditioning unnecessary. Consequently, natural gas consumption is more uniform than in winter. The objective transmission amount decreases to $30.36 \times 10^9\,m^3$. Because of this reduction in the transmission amount, the inlet pressure reduces to approximately 8.4 MPa at the downstream station. To reduce the energy cost and enable periodic checks at certain stations, a bypass strategy is implemented. From Table 1, we can infer that the natural gas from upstream bypasses Station 2 and Station 4 because of the small transmission amount at these stations. The functioning stations also do not operate under full-load conditions.

A peak electrical load occurs in summer with the high temperature. The resulting electrical consumption requires the output of all power plants under full operation. However, the gas consumption during summer is very small relative to winter. The objective transmission amount reaches a median value of 43.16 billion m^3.

3.2. Pipeline efficiency calculation

Owing to the occurrence of friction during gas transport, the useable energy (pressure) decreases continuously along the pipeline, and this pressure drop ultimately reflects as energy loss. The pressure energy and mechanical energy of a random cross-section along the pipeline can be utilised to overcome the friction loss. The useable energy both at the inlet and outlet cross-sections is considered for analysis as the initial status and final status by ignoring the complex flow process along the pipe. Via analysis of the difference between the ideal and actual conditions, the pipeline efficiency can be easily obtained. While there are theoretical formulas which describe and quantify the ideal condition, their modification based on the operation data becomes essential to determine the actual conditions.

In the ideal scenario, the available energy at any cross-section is

$$-\frac{dp}{\rho} = \lambda \frac{dx}{D}\frac{\omega^2}{2} + \frac{\omega^2}{2} + gh \tag{8}$$

The surplus pressure energy at any cross-section is

$$p_s = p + \frac{\rho\omega^2}{2} + \rho gh = p + \frac{8ZR_gTq^2}{\pi^2 d^4 p} + \rho gh \tag{9}$$

When the altitude difference along the pipeline segment of interest is less than 200 m, the potential energy of the gas itself can be ignored in the calculation process. Based on the collected data, we find that the reduced inlet pressure $P_r = 1.4$, the reduced inlet temperature $T_r = 1.53$, and further, the reduced outlet pressure $P_r = 2.05$, with the reduced outlet temperature $T_r = 1.7$.

The pipe efficiency is defined as the actual useable inlet pressure energy of the current station divided by the useable outlet pressure energy of the preceding station. Because Station 1 is the first station in this pipeline, the inlet pressure at this point is not available for analysis. Further, knowledge of the inlet pressure is essential for pipeline efficiency analysis from Station 5 to downstream. Table 3 lists the calculated pipe efficiency statistics.

The pipe efficiency is drastically lower than that of the compressing segment because of friction, which induces significant energy loss along the length of the pipeline.

In summer, the efficiency does not change significantly relative to spring because the stations use a different operating strategy. The efficiency trend in summer also differs from that of winter. The rotation speed and flow rate change of the compressors also affect the efficiency. Consequently, the determination of identical conditions for efficiency analysis is impractical.

3.3. Analytic hierarchy process

According to actual operational conditions and theory, it is well known that the upstream stations afford greater efficiency than the downstream stations. Thus, the influence of the DMU of different stations is disparate regardless of the value. The schematic of the hierarchical structure is shown in Fig. 3.

As per the operating statuses of these stations in January, April, and August, the only two operating strategies of the pipeline are as follows: all 5 stations functioning and Stations 1, 3, and 5 functioning.

The pairwise comparison matrix of these five functioning stations is established based on previous DEA research [10] and can be expressed as below:

Table 6
Volumetric work.

	Station	Milestone (km)	Gas amount change ($10^4 m^3$)	Volumetric work ($m^3 \cdot km$)	Total volumetric work ($m^3 \cdot km$)
Jan	1	0	−4704.4	0	3739918
	2	181.5	22.7671	4132.23	
	3	315.14	14.7228	4639.71	
	4	495.32	17.5112	8673.67	
	5	666.02	18.6592	12427.4	
	6	801.19	4630.69	3710045	
Feb	1	0	−4703.7	0	3739337
	2	181.5	22.6154	4104.7	
	3	315.14	15.2075	4792.76	
	4	495.32	17.9164	8874.37	
	5	666.02	17.3252	11539.0	
	6	801.19	4630.66	3710027	
Mar	1	0	−3263.6	0	2609087
	2	181.5	0	0	
	3	315.14	8.1194	2558.73	
	4	495.32	0	0	
	5	666.02	12.958	8640.3	
	6	801.19	3242.56	2597898	
Apr	1	0	−3025.7	0	2419729
	2	181.5	0	0	
	3	315.14	6.2336	1964.44	
	4	495.32	0	0	
	5	666.02	10.56	7033.18	
	6	801.19	3008.95	2410732	
May	1	0	−3220.4	0	2570104
	2	181.5	10.88	1974.96	
	3	315.14	0	0	
	4	495.32	10.8242	5361.45	
	5	666.02	0	0	
	6	801.19	3198.71	2562768	
Jun	1	0	−3621.5	0	2890156
	2	181.5	9.4204	1709.8	
	3	315.14	0	0	
	4	495.32	14.3395	7102.66	
	5	666.02	8.4	5594.58	
	6	801.19	3589.36	2875749	
Jul	1	0	−4570.2	0	3634370
	2	181.5	20.8305	3780.74	
	3	315.14	14.0534	4428.76	
	4	495.32	16.6317	8238.03	
	5	666.02	17.4316	11609.8	
	6	801.19	4501.21	3606312	
Aug	1	0	−4300.5	0	3423266
	2	181.5	17.5783	3190.46	
	3	315.14	10.713	3376.07	
	4	495.32	13.6	6736.37	
	5	666.02	14.8021	9858.51	
	6	801.19	4243.83	3400104	
Sep	1	0	−3252.9	0	2599243
	2	181.5	0	0	
	3	315.14	10.4561	3295.11	
	4	495.32	0	0	
	5	666.02	13.46	8964.64	
	6	801.19	3228.94	2586983	
Oct	1	0	−3243.7	0	2592070
	2	181.5	0	0	
	3	315.14	11.1003	3498.13	
	4	495.32	0	0	
	5	666.02	10.2145	6803.07	
	6	801.19	3222.43	2581769	
Nov	1	0	−4665.3	0	3707939
	2	181.5	20.7073	3758.38	
	3	315.14	16.2522	5121.69	
	4	495.32	19.49	9653.81	
	5	666.02	23.0125	15326.81	
	6	801.19	4585.794	3674079	
Dec	1	0	−5041.5	0	4007181
	2	181.5	24.1112	4376.18	
	3	315.14	15.8568	4997.08	
	4	495.32	20.6251	10216.1	
	5	666.02	22.3978	14917.41	
	6	801.19	4958.485	3972674	

Table 7
Equivalent fuel gas statistics.

Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
EFG (10^4 m^3/d)	96.3	95.3	32.4	27.1	28.3	43.6	87.8	72.2	37.1	34.6	100.2	107.5

Table 8
Unit consumption data.

Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Unit consumption (10^{-5} $m^3/m^3\cdot km$)	2.6	2.57	1.25	1.12	1.1	1.52	2.43	2.12	1.43	1.34	2.73	2.72

We particularly analyse three representative scenarios (January, April, and August) as the typical transmission amounts and station configurations.

Table 9
Original decision-making unit conditions for January.

Station	Input 1	Input 2	Output 1	Output 2
1	2695921	9.16	2130038	5.82
2	2709284	9.35	2479870	6.90
3	1752013	9.34	1583058	6.35
4	2083832	9.29	1947339	6.28
5	2220444	9.11	1993402	7.12

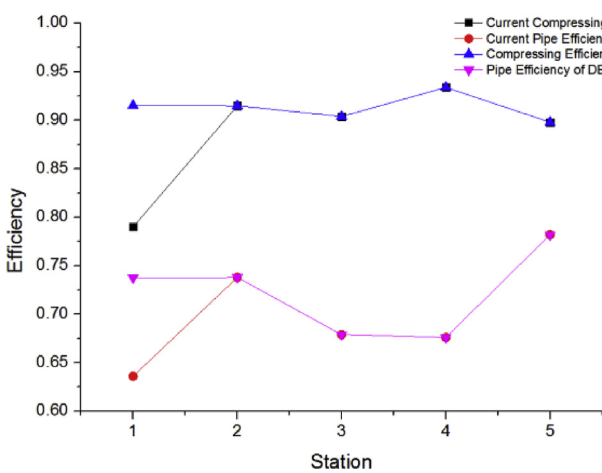

Fig. 5. Pipeline efficiency for January.

Table 10
Original decision-making unit conditions for April.

Station	Input 1	Input 2	Output 1	Output 2
1	1220512	8.99	1021823	6.83
2	0	0	0	0
3	741798	8.36	613659	6.10
4	0	0	0	0
5	1256640	8.66	1111268	7.97

$$A=\begin{bmatrix}1 & 3 & 5 & 7 & 9\\ 1/3 & 1 & 3 & 5 & 7\\ 1/5 & 1/3 & 1 & 3 & 5\\ 1/7 & 1/5 & 1/3 & 1 & 3\\ 1/9 & 1/7 & 1/5 & 1/3 & 1\end{bmatrix}$$

The eigenvalue$\lambda = 5.2375$ is introduced for consistency checking

$$C = (5.2375-5)/(5-1) = 0.059375$$

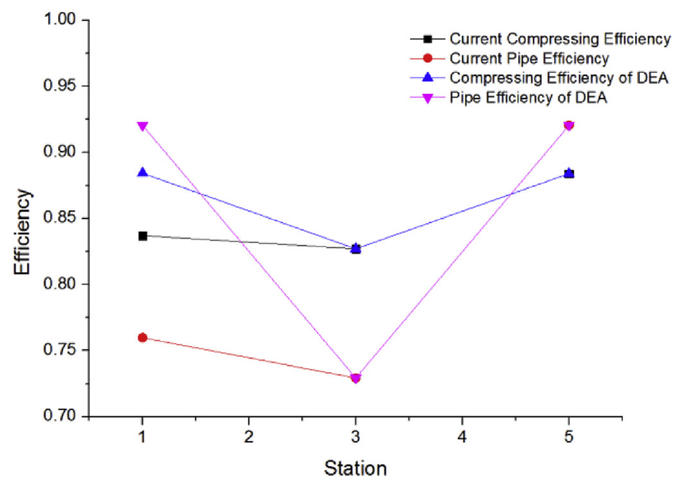

Fig. 6. Pipeline efficiency for April.

Table 11
Original decision-making unit conditions for August.

Station	Input 1	Input 2	Output 1	Output 2
1	1841263	9.00	1382914	6.26
2	2091818	9.25	1861735	7.30
3	1274847	9.26	1127749	6.85
4	1618400	9.22	1411074	6.66
5	1761450	9.28	1590872	7.55

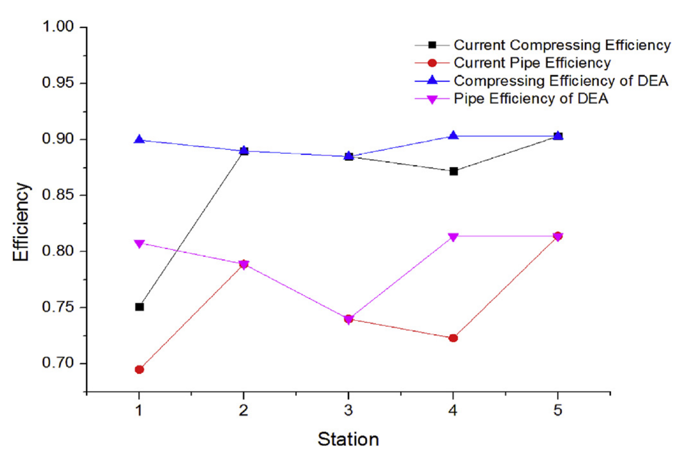

Fig. 7. Pipeline efficiency in August.

The random index of consistency R is equal to 1.12 according to Table 1, and thus, we have

Table 12
Objective efficiency.

	Station	Compressing segment efficiency	Weight	Pipe efficiency	Weight	Station efficiency	Weight	Pipeline efficiency
Jan	1	91.5%	0.6	73.76	0.4	84.42%	0.5128	83.6%
	2	91.5%	0.57	73.8%	0.43	83.89%	0.2615	
	3	90.4%	0.56	67.9%	0.44	80.50%	0.1289	
	4	93.4%	0.55	67.6%	0.45	81.79%	0.0634	
	5	89.8%	0.54	78.2%	0.46	84.46%	0.0333	
Apr	1	88.4%	0.6	92.1%	0.4	89.99%	0.7352	87.5%
	2	–	–	–	–	–	–	
	3	82.7%	0.56	72.9%	0.44	78.40%	0.2067	
	4	–	–	–	–	–	–	
	5	88.4%	0.54	92.1%	0.46	90.08%	0.0581	
Aug	1	90.0%	0.6	80.8%	0.4	86.29%	0.5128	85.3%
	2	89.0%	0.57	78.9%	0.43	84.66%	0.2615	
	3	88.5%	0.56	74.0%	0.44	82.12%	0.1289	
	4	90.3%	0.55	81.4%	0.45	86.29%	0.0634	
	5	90.3%	0.54	81.4%	0.46	86.21%	0.0333	

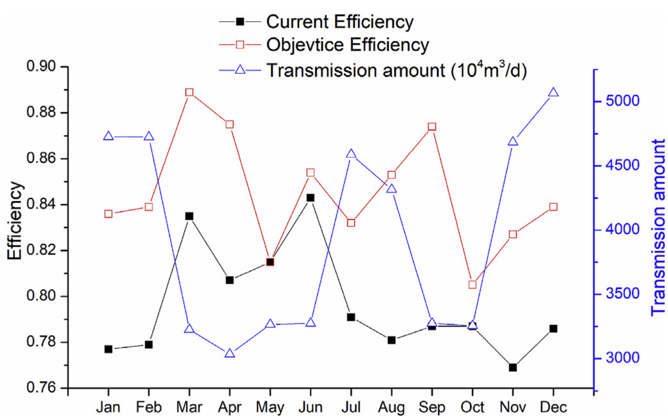

Fig. 8. Relationship between efficiency and unit consumption.

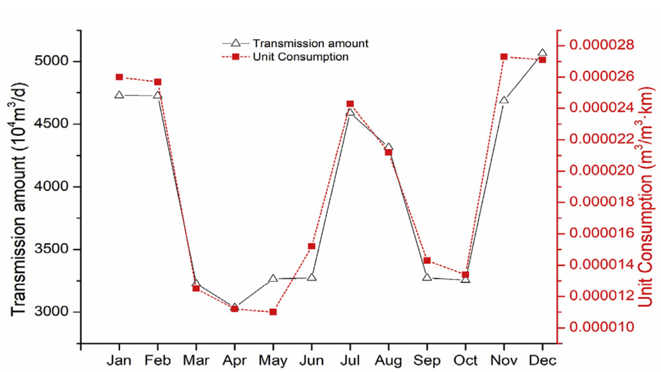

Fig. 9. Relationship between unit consumption and transmission amount.

$CR = C/R = 0.053 < 0.1$

The eigenvector can be used as the weight vector because the inconsistency is acceptable. Now, we have

$\omega = [0.5128, 0.2615, 0.1289, 0.0634, 0{,}333]^{\mathrm{T}}$

Similarly, the pairwise comparison matrix of the three-station scenario is

$$A = \begin{bmatrix} 1 & 5 & 9 \\ 1/5 & 1 & 5 \\ 1/9 & 1/5 & 1 \end{bmatrix}$$

The eigenvalue $\lambda = 3.0171$ is introduced for consistency checking. Thus, we have

$C = (3.0171-3)/(3-1) = 0.00855$

The random index of consistency R is equal to 0.58 according to Table 1, and thus, we have

$CR = C/R = 0.0147 < 0.1$

Again, the eigenvector can be used as the weight vector because the inconsistency is acceptable.

$\omega = [0.7352, 0.2067, 0.0581]^{\mathrm{T}}$

From Table 4, we note that the pipeline efficiency in January approaches the empirical value. In the pipeline design stage, technological considerations mainly include the station equipment. Thus, as the primary equipment, the compressing segment is designed to achieve its optimal operating status.

Meanwhile, we note that owing to the small transmission amount in spring and autumn, only three or four stations usually function. The efficiency of the compressing segment in these cases is lower than in winter but the pipe efficiency exhibits just the opposite trend. A small transmission amount corresponds to a relatively low friction loss along the pipeline but the compressing segment must handle the transmission amount, and therefore, the compressor rotation speed is far from optimal.

3.4. Load rate and break-even point

The parameter of load rate can indicate the change in the operating efficiency from the viewpoint of the technological aspects. The load rate is simply defined as the current transmission amount divided the designed transmission amount (Table 5).

A low load rate indicates underutilisation of the pipeline and excessive investment. Meanwhile, the break-even point (BEP) indicates the financial status based on the operating technological conditions.

Here, we mention that the pipeline under study cost CNPC 140 billion China Yuan (21.9 billion US dollars) during the engineering, procurement, and construction (EPC) process, and it is expected to serve for 30 years with additional operating expenses. Thus, the BEP is expected to change proportionally with the transmission amount. Based on the current operating financial situation of this pipeline, the gross profit is calculated as approximately 0.5 Chinese Yuan (CNY) per m^3. Fig. 4 shows the change in BEP as a function of the transmission amount and efficiency. The efficiency difference is small relative to the BEP variation with the transmission amount. In terms of financial considerations, a higher load rate of the pipeline contributes to more profit without significantly influencing the technological aspects.

4. Results and discussion

The parameter of volumetric work describes the energy cost based on the energy consumption and transmission amount. The volumetric work data are listed in Table 6. The calculation of the volumetric work for each transmission amount enables the DEA to estimate the pipeline efficiency.

The five stations of this pipeline are all equipped with combustion gas turbines to drive the compressors. Thus, the EFG corresponds to the practical gas consumption of the five compressing stations. Meanwhile, from Table 7, we note that the EFG is measured in units of $10^4\,m^3$ per day to eliminate imbalance across different days of different months.

The unit consumption signifies the transmission energy cost per cubic metre of gas based on the transmission amount and distance, and it is measured in units of $m^3/m^3\cdot km$, which is defined as the natural gas consumption divided by the volumetric work (Table 8).

According to the current situation, the five stations and each outlet pipe to the downstream stations perfectly take the positions of the DMUs for DEA (Table 9). Each DMU consists of two inputs (input 1: compressing input work measured in units of 10^4 J and input 2: gas outlet energy measured in MPa) and two outputs (output 1: compressing output work measured in units of 10^4 J and output 2: gas inlet energy measured in MPa). Based on DEA principles, the optimal condition is obtained from the current operating condition.

As shown in Fig. 5, both the compressing output work and pipe inlet pressure energy are expected to be greater than the corresponding ones of the current situation. A more suitable configuration of compressors and operating status may enhance the compressing output work. Consequently, the gas outlet energy will increase simultaneously and influence the whole pipeline into a new equilibrium state.

Similarly, the DMU conditions for April are listed in Table 10.

As shown in Fig. 6, a smaller transmission amount changes the result slightly. As more operation modes of the compressing segment are available under smaller transmission amounts, the compressing efficiency approaches the optimal scenario relative to the case of larger transmission amounts. Owing to the bypass operating strategy implemented at Stations 2 and 4, the current pipeline efficiency between Stations 1 and Station 3 affords greater room for improvement as regards the large friction loss owing to smaller pressure along the pipe. However, a low efficiency does signify high cost because high efficiency may require more input energy.

The DMU data for August are listed in Table 11.

In August (Fig. 7), Stations 1 and 4 are relatively inefficient under the median transmission amount. The efficiency of Station 1 is far below the objective result as there is surplus input energy and insufficient gas inlet energy. Lesser values of the compressing output work and gas inlet energy at Station 4 reduce the efficiency below the objective result.

Based on the objective efficiency, the pipeline efficiency is recalculated as below (Table 12).

From the results, we note that compressing segment of Station 1 usually operates under effectively non-DEA conditions because the relatively large transmission amount requires more energy to overcome the low inlet pressure relative to the downstream stations. Thus, the main efficiency enhancement from the DEA result is realised at the first station. The small transmission amount of Station 1 in April indicates that the compressor rotation speed may not adapt to the flow rate.

The current efficiency of each month also indicates the possibility of efficiency improvement (Fig. 8). The relatively low efficiency in January exhibits a minimal difference from the objective result. The unit consumption is inversely proportional to the efficiency with a significantly greater change.

Hence, based on previous discussion, we can express the relationship between unit consumption and efficiency as below:

In Fig. 9, we note that the trend of unit consumption changes in conformance with the transmission amount change by a similar level. Although a lower transmission amount corresponds to lesser energy per cubic meter, while the fixed investment is constant and the operating cost (except for energy consumption) remains almost unchanged, the resulting economic efficiency compensates for higher transmission amounts.

5. Conclusion

We developed a pipeline efficiency evaluation method focusing on the energy aspect based on factors reflecting a weighted combination of both the compressing segment and the pipe. This new method is capable of explicitly estimating the efficiency as per the most basic definition obtained from the relationships of input and output energy. The DEA principle is deployed in the efficiency evaluation process for the purpose of determining the optimal result. Because the method avoids the need for complex hydraulic and thermodynamic calculations along the pipe, it is more adaptable for long-distance gas transmission pipelines.

We applied the method using the case study of a practical pipeline with its acquired operating data. According to the calculated result, the pipeline efficiency based on our definition was estimated as ~80%. With the DEA method, the objective efficiency of each unit under effective non-DEA conditions is obtained based on the current transmission amount. The quantitative DEA calculation reveals the difference between the current efficiency and the objective result for efficiency enhancement.

Furthermore, we note here that a very large amount of money is invested into pipeline construction, and thus, a large transmission amount corresponds to a more reasonable economic performance even when the unit transmission cost is higher relative to the low-transmission-amount scenario.

Although the method promises an effective approach for pipeline efficiency evaluation, we plan to further research on systematic optimisation and technological optimisation measures in detail. Owing to the interactive influence of the input and output values of each DMU, the overall efficiency improvement requires systematic optimisation involving all DMUs.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.energy.2019.116069.

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