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Implementation plan and impact of natural gas pipeline network transformation from volume metering to energy metering in China

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Abstract: The volume-based natural gas measurement system not only fails to accurately reflect the value of natural gas but also hinders fair trading and the long-term development of the market. This paper proposes specific implementation schemes for energy measurement systems from three aspects. It presents two methods for converting natural gas prices from volume measurement to energy measurement and three selection methods for reference heating values, resulting in a total of six combined implementation schemes. Taking a certain operational long-distance pipeline as an example, a simulation model is established using SPS to investigate the impact of the transition from a volume-based metering system to an energy-based metering system on the economic benefits of pipeline operator.

Keywords: natural gas; energy measurement; pipe network simulation; caloric value.

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1 Introduction

Amidst the rapid expansion of the natural gas market and the diversification of natural gas supply sources, China's natural gas pipeline network has transitioned towards a multi-source supply framework. Simultaneously, as the trend towards expanding pipeline networks and achieving a nationwide 'one network' progresses, the establishment of 'Pipeline China' signifies the formal segmentation of China's natural gas industry into production, transportation, and marketing phases. Despite this, China's prevailing measurement system remains predominantly volume measurement (VM). However, the adoption of an Energy Measurement System (EMS) has been facilitated by state policies, marking a significant advancement in the measurement and management of natural gas resources within China.

China's current metering and settlement model for natural gas trading is primarily based on Volume Measurement (VM). However, the Volume Measurement System (VMS) has limitations in accurately reflecting the value of natural gas and promoting fair trading practices. The energy produced from the combustion of natural gas can lead to unfair competition among different gas qualities on trading platforms, making it challenging to establish a reliable reference price for natural gas in China. To address this issue, in August 2018, China implemented a policy aimed at enhancing fairness and convenience in natural gas trade. This policy requires operators of pipeline network facilities to adopt Calorific Value (CV) and volume as the measurement standards for receiving and transmitting natural gas, with energy serving as the basis for trade settlement. In May 2019, supported by favourable policies, research and technological development in Energy Measurement (EM) advanced significantly towards full implementation. Currently, EM has been incorporated into international natural gas trade and large-scale gas transmission following LNG gasification. However, the specification of CV content is not included in current technical standards. As the pipeline network continues to expand, natural gas trade transactions have increased in frequency, leading to a gradual diversification of upstream gas sources and downstream pipeline network users. Traditional VM is inadequate in addressing the complexities inherent in centralised pipeline network control and fails to meet user requirements for gas quality. As a result, the adoption of EM becomes essential. However, it encounters the challenge of optimising the supply pattern while enhancing pipeline network operational profitability without compromising gas demand fulfilment for users. At the same time, with increasing downstream customer demand in China facilitated by pipeline interconnections and a nationwide 'one network' trend, pipeline network supply options are gradually diversifying. The use of EM can more accurately assess customer satisfaction with the quality of natural gas.

1.2 Related work

Energy Measurement (EM) involves quantifying the energy content of natural gas for settlement purposes, utilising volumetric measurement and measuring the calorific value of natural gas through its calorific content per unit volume and volume to calculate the total energy of natural gas flowing through the pipeline. Currently, international trade in natural gas is predominantly measured in terms of energy, encompassing Liquefied Natural Gas (LNG), natural gas spot, futures and options trading. Wu et al. (2018) observed that energy metering is also becoming a prevailing trend for gas pricing in China. Laib et al. (2021) highlighted gas metering as an issue requiring attention in Algeria. Foreign countries have adopted EMS earlier, and current research on natural gas EM primarily focuses on CV.

Haloua et al. (2016) employed an advanced calibration procedure that covers the entire measurement range to determine the CV and energy of natural gas. This extends the range of calorimeters in the field and ensures reliable calorific value measurements. In a similar vein, Kong et al. (2019) developed models for gas hydrodynamics in two different manifolds based on the process flow of a dual-source gas distribution station. They conducted a comparison of the mixing efficiency and CV of these models to provide a reference for measuring the CV of multiple gas sources. Kuz et al. (2021a, 2021b) developed a method for measuring gas energy using an indirect approach based on gas consumption volume, ambient air temperature around the gas metre, and gas CV. This method is based on assessments of regulatory requirements and technical possibilities for introducing gas metering into Ukrainian energy units. The researchers determined the CV of natural gas for specific months in Ukraine using predictive modelling methods. The results showed a relative error to the actual calorific value of natural gas of less than $\pm 1\%$, which is comparable to the measurement accuracy of domestic gas metres. Therefore, the model accurately describes CV changes and can serve as a basis for calculating gas parameters without measurement data. Furthermore, as a result of the growing prevalence of hydrogen blending, Dell'Isola et al. (2021) conducted an investigation into the changes in thermodynamic properties of gases with varying H₂ contents. They also delved into the impacts of injecting H₂ into gas networks on domestic gas metres.

In addition to investigating the calorific value and energy of natural gas, some scholars also focus on evaluating the uncertainty associated with calorific value measurement. Ficco et al. (2015) addressed measurement challenges related to the volume and energy of natural gas in order to mitigate inaccurate billing. They developed an uncertainty model for measuring the energy of natural gas, which was subsequently validated on a network in Italy. While EMS have been employed earlier in foreign countries with improvements in relevant policies, the current focus lies primarily on CV measurement technology and uncertainty evaluation. Therefore, this study primarily focuses on the analysis of technical aspects of natural gas energy settlement by examining domestic scholars such as Li (2017). Wang et al. (2018) conducted a study on the challenges encountered in implementing EM pricing for natural gas in China, addressing issues such as measurement interface, method, unit, gas price conversion and pipeline transportation pricing. They proposed solutions and implementation pathways

for the adoption of EM pricing for natural gas. Additionally, Xu et al. (2018) developed an energy metering method based on a multi-source pipeline network by leveraging the natural gas pipeline network topology and gas balance principle. This provides operational guidelines for the implementation and promotion of natural gas energy metering in China.

Lu et al. (2019) conducted a validation study on the feasibility of implementing energy management in urban gas distribution systems across two distinct cities and proposed a tailored approach for its implementation. China's exploration of energy management in the natural gas sector has been relatively recent, primarily focusing on investigating implementation strategies and their industry ramifications. Han (2019) developed a pricing scheme based on energy consumption, contingent upon the selection of natural gas energy units and pricing methodologies. Li et al. (2019) calculated the energy values of natural gas across various billing cycles, adhering to practices outlined in natural gas trade agreements and standards. They performed statistical analyses using field data from long-distance natural gas pipeline metering stations to evaluate the impact of different energy calculation methods on outcomes.

Cai and Jiang (2019) examined the transition from volumetric to energy-based natural gas measurement and its implications for pipeline operators, considering factors such as measurement precision, gas shortfall detection, index adjustments and pipeline transportation costs. They advocate for establishing standards for measuring components of mixtures with substantial variations and calculating the 'equilibrium RCV' for both volumetric and energy-based measurements. This, along with pipeline transportation pricing, would effectively safeguard the interests of stakeholders involved in procurement, transportation and marketing. Lu et al. (2019) conducted an assessment of the viability of implementing EM systems in urban gas distribution networks, using two distinct city types as case studies and proposed a tailored framework for urban gas EM. Chang and Duan (2020) conducted a comprehensive comparison of natural gas metering technologies at both domestic and international levels, analysing the significance and characteristics of natural gas metering while highlighting its advantages. Tan et al. (2021) introduced a scheme for pricing natural gas energy, outlining optional methods for price conversion, the selection of pricing units and the consideration of RCV. Huang et al. (2021) summarised the progress made in domestic natural gas EMS construction in terms of value tracing and EM standards. They analysed natural gas flow, determined CV, made informed decisions using intelligent technologies and applied these advancements.

In summary, concerning research on natural gas EM, foreign countries have previously adopted EMS, with refined relevant policies, now primarily emphasising CV measurement technology and uncertainty assessment. Domestic scholars predominantly concentrate on the technical feasibility and economic imperative of implementing EMS in China. They analyse and synthesise foreign EMS experiences and propose various energy measurement implementation strategies tailored to China's national circumstances. However, there remains a lack of systematic presentation of specific implementation strategies for establishing an EMS across the entire gas supply chain.

Furthermore, the impact of utilising different metering systems on the interests of pipeline operators has not been adequately addressed.

1.3 Contributions

- 1) This study presents two methods for transitioning natural gas pricing from VM to EM, along with three selection methods for RCV.
- 2) In this paper, a simulation model for the pipeline network has been developed and utilised to simulate the operational outcomes of various EM schemes within the pipeline network.
- 3) The study suggests multiple feasible EMS implementation plans and conducts qualitative and quantitative analysis of the impact of different measurement systems on the efficiency of pipeline operators. This analysis holds significant guidance for pipeline operators.

1.4 Paper organisation

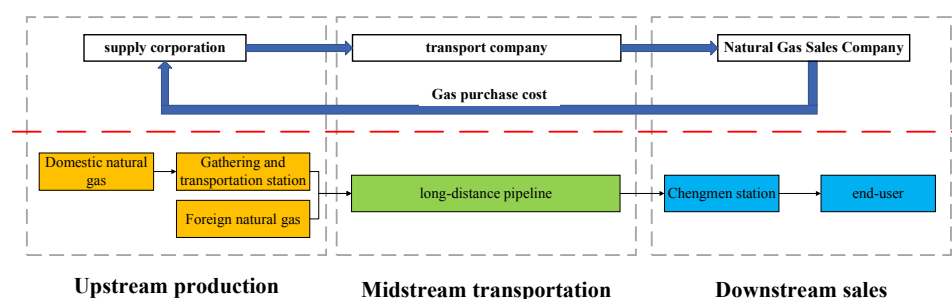
Section 2 studies outline the entire supply chain of natural gas and discusses the challenges associated with implementing EM. Section 3 details the implementation plan for EM. In Section 4, an SPS network simulation model is established to validate the operational outcomes of the network under various implementation plans. Finally, in Section 5, an analysis of gas sales revenue, gas purchase cost and pipeline transportation cost under different implementation plans is conducted based on the simulation results.

2 Problem description

2.1 Natural gas supply chain

As illustrated in Figure 1, the natural gas supply chain encompasses three principal components: upstream production, midstream transportation and downstream sales. This chain is tasked with the transportation of natural gas, originating from production or importation upstream, to downstream sales destinations. Upstream, natural gas suppliers manage raw material provision, exploration, extraction as well as the purification and processing of natural gas. Pipeline operators oversee the distribution of natural gas, which involves judiciously selecting gas sources and volumes from upstream suppliers based on contracts stipulating gas volume and quality requirements from downstream users. They are responsible for pipeline transmission duties, facilitating the delivery of natural gas to various natural gas marketers. Downstream, natural gas marketers oversee sales operations and strategise natural gas distribution plans.

Figure 1 Schematic diagram of the whole industrial chain of natural gas (see online version for colours)



By the end of 2019, the establishment of 'Pipeline China' signified a significant milestone in the reform of China's natural gas pipeline network system. This restructuring transformed the operational model of China's natural gas market into a regulatory framework characterised by 'regulating the middle and liberalising the two ends' and 'multiple gas suppliers + national pipeline network companies + multiple downstream users'. This framework, illustrated in Figure 2, is often referred to as the 'X+1+X' model. Here, the first 'X' denotes the diversification of upstream market entities and natural gas sources. The In conclusion, during the initial phase of the measurement system reform, it is advisable to opt for EMSI 2. This choice can mitigate the impact of the measurement system transformation on pipeline operators' operating profits and facilitate a smoother transition from Volumetric Metering (VM) to Energy Metering (EM). As the reforms progress and implementation matures, the adoption of EMSI 5 could be considered. This approach would accurately account for the carbon content of gas and enhance transaction transparency. '1' signifies the uniqueness of the natural gas midstream pipeline network transmission system, encompassing not only the national natural gas pipeline network but also provincial, regional and urban gas distribution networks. The second 'X' represents the diversification of distribution entities and end customers in the natural gas downstream market.

The natural gas supply chain encompasses diverse segments, including upstream suppliers' natural gas sales, midstream pipelines and natural gas purchases and sales by downstream marketers. The concurrent adoption of EM proves advantageous for overseeing each pricing segment, standardising and overseeing the entirety of the natural gas pricing system and harmonising with international price management standards. The implementation of EM and pricing schemes for each segment is depicted in Figure 3. Drawing from international practices, developed nations with significant natural gas reserves have implemented energy pricing across the production, transmission and distribution segments, underscoring the feasibility of simultaneous implementation across all segments.

Figure 2 ‘X+1+X’ operation mode of the natural gas industry (see online version for colours)

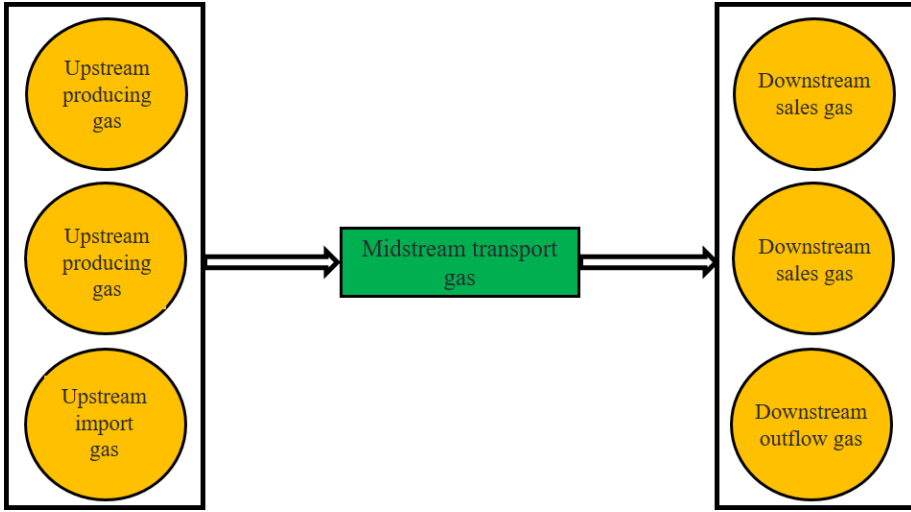
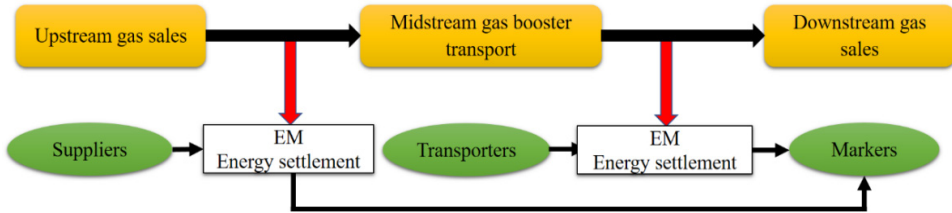


Figure 3 EM and pricing scheme implemented in each link of the natural gas supply chain (see online version for colours)



2.2 Pipeline operators

Operators now have a wider array of options due to the diversification of upstream gas sources. Suppliers determine the purchase price, enabling them to select more cost-effective natural gas in line with actual demand. In the downstream market, the diversification of end users leads to varying requirements for gas volume and CV. Operators must supply gas according to contractual obligations, and the price of gas supply fluctuates based on the Benchmark Gate Station Price (BGSP) set by the state. Additionally, pipeline operators incur costs associated with pipeline transmission and natural gas pressurisation. Consequently, the interests of upstream, midstream and downstream entities intersect and mutually constrain each other. Operators must devise detailed plans for procurement, transportation and sales to safeguard their interests.

2.3 Natural gas market pricing mechanism

Transportation modes, geographic location and costs all play crucial roles in shaping pricing mechanisms within the natural gas market. Competitive market pricing prevails in the North American market, whereas the European market utilises oil-related Long-

Term Agreement (LTA) prices and national equilibrium point prices. In the Asia-Pacific market, oil-related LTA prices are predominantly relied upon. China, on the other hand, predominantly employs government pricing for natural gas trading, which entails a fixed pricing method. However, Zhu et al. (2018) observed a gradual transition of China's gas pricing mechanism towards a market-based approach during the period of 2013–2018. In contrast, Hamied et al. (2020) conducted short-term forecasts of wholesale natural gas prices in Germany using relevant mathematical methods.

2.3.1 *Ex-factory natural gas price*

The prices of gases sourced from different origins exhibit variations, and even gases from the same source can experience substantial price fluctuations due to changes in the international landscape. The diverse prices of various gas sources present different appeals to users, prompting them to select more cost-effective and convenient options based on the prevailing prices of gases from different sources. Currently, China is in the process of gradually implementing natural gas EM methods, and fluctuations in natural gas prices will have a notable impact on pipeline operating parameters.

2.3.2 *Natural gas gate station price*

The price of a natural gas gate station represents the rate at which the operator supplies natural gas to downstream marketers at each station. Currently, the wholesale segment of natural gas sales can be categorised into regulated and non-regulated sales. Prices of non-regulated gas, as well as the gate prices of natural gas in provinces with competitive conditions, are determined by market dynamics. In regulated markets, the wholesale price of natural gas is known as a 'government-guided price', established through contracts between upstream suppliers and downstream purchasers within a predefined fluctuation range.

In May 2018, the National Development and Reform Commission (NDRC) standardised the management of gate station prices for various gas users and introduced management of Benchmark Gate Station Prices (BGSP). The provincial BGSPs are outlined in Table 1.

Table 1 Provinces (districts and municipalities) natural gas BGSP

<i>Province</i>	<i>BGSP (CNY/m³)</i>	<i>Province</i>	<i>BGSP (CNY/m³)</i>
Beijing	1.86	Hubei	1.82
Tianjin	1.86	Hunan	1.82
Hebei	1.84	Guangdong	2.04
Shanxi	1.77	Guangxi	1.87
Inner Mongolia	1.22	Hainan	1.52
Liaoning	1.84	Chongqing	1.52
Jilin	1.64	Sichuan	1.53
Heilongjiang	1.64	Guizhou	1.59
Shanghai	2.04	Yunnan	1.59
Jiangsu	2.02	Shaanxi	1.22
Zhejiang	2.03	Gansu	1.31

Table 1 Provinces (districts and municipalities) natural gas BGSP (continued)

<i>Province</i>	<i>BGSP (CNY/m³)</i>	<i>Province</i>	<i>BGSP (CNY/m³)</i>
Anhui	1.95	Ningxia	1.39
Jiangxi	1.82	Qinghai	1.15
Shandong	1.84	Xinjiang	1.03
Henan	1.87		

2.4 Pipeline operators

Currently, China employs two natural gas trade measurement and pricing systems: volumetric pricing and CV pricing, predominantly relying on volumetric pricing. However, this system deviates from the international mainstream EMS, revealing several issues across production, trade, consumption and other domains:

- 1) *Economic fairness*: The existing system lacks economic equity, hindering the formation of market prices.
- 2) *Market development impediment*: Diluting natural gas undermines market development.
- 3) *Quality differentiation challenge*: Integrating natural gas of varying qualities into the network poses challenges, impeding equitable access to the pipeline network.

EM is a technique employed to gauge the energy content of natural gas for computational purposes. It assesses the CV of natural gas using VM and computes the total energy conveyed through the pipeline using an associated formula.

There are various methods for determining the CV per unit of natural gas, encompassing both direct and indirect approaches. The direct method entails obtaining the CV of natural gas through combustion, whereas the indirect method entails measuring the components of natural gas via gas chromatography and computing the CV based on these components.

The indirect method of calculating total energy is now commonly used internationally. In GB/T22723-2008, ‘Determination of Natural Gas Energy’, it is pointed out that the EM of natural gas is completed through two unrelated measurements. The calculation equation is shown in equation (1):

$$E = Q \times H \quad (1)$$

In the equation, E is the energy of natural gas, MJ ; Q is the volume of natural gas in the standard state, m^3 ; H is the CV content of natural gas, MJ/m^3 .

Natural gas is a gas mixture containing many components, and the CV of natural gas varies from region to region and from one gas supply company to another for the same customer. Natural gas from a variety of sources, including imported LNG, self-produced conventional gas and unconventional gas, is transported through the pipeline network in China. Therefore, an EMS is necessary for the fair trading of natural gas. EM pricing not only promotes competition among various gas sources but also helps to introduce more market participants.

Therefore, it is necessary to adopt an EM mode, but there are problems in optimising the supply pattern and pipeline operation plan under the EMS. For this reason, it is

necessary to minimise the operating cost of the pipeline while meeting the gas demand of users and improving the operating profit of the pipeline.

3 EMS implementation program

The foreign natural gas metering system is shown in Table 2. According to the analysis of the existing measurement system in China, two main energy pricing methods are widely used at this stage. One is the direct energy pricing method, which is settled based on energy volumes. The other is the indirect energy pricing method, which adjusts the volume price based on CV.

Table 2 Pipeline gas export trade pricing in some countries

<i>Exporting country</i>	<i>Pricing method and unit</i>
Russia	The price of pipeline gas exported from Russia to Europe is usually priced by volume, with the unit of USD/Km ³ . However, the contract specifies a range of CV of natural gas per unit volume, below or above which the price of natural gas will need to be adjusted. Similar to China's natural gas imports from Central Asia.
Canada	The pipeline gas exported from Canada to the USA adopts the CV pricing method, with the unit of USD/MMBtu, and its price is fully based on Henry Hu's price.
Norway	The pipeline gas exported to Western Europe is priced in the form of CV, with the unit of Euro cents/kWh.
USA	Domestic natural gas consumption in the USA, including import price, wellhead price, pipeline transportation fee and final consumption, is all priced by CV. The prices of spot and futures transactions are also priced by CV, and the pricing unit is USD/MMBtu.
Britain	The natural gas transmission adopts a two-part system, consisting of a capacity fee and usage fee, all of which adopt CV measurement and pricing methods. The gas distribution company also implements CV measurement and pricing for the gas distribution fee, and the pricing unit is Pence/Kcal.
France	The French natural gas price adopts the CV measurement and pricing, and the pipeline transportation fee adopts the two-party system, and the pricing unit is Euro/MWh
Japan	Japan's natural gas supply is dependent on imported LNG, and has realised the integrated services of natural gas import, pipeline transmission and urban distribution. The user terminal price is measured and priced by CV, and the pricing unit is JPY/Kcal.
India	India's natural gas pricing mechanism is relatively complex, but it also adopts the CV pricing method. The pipeline transportation fee is also measured and priced by CV, and the pricing unit is generally Rs/MMBtu.

At the same time, EM and pricing are based on a certain period, and the CV accumulated in the natural gas during the period is settled uniformly, and the 'EM and energy pricing' method is adopted according to the principles of simplicity, practicality and smooth transition. The unit energy price may be the current volume price for the conversion of measurement units. The method for calculating the price of unit energy is $C_E = C_V / H$, where C_E represents the price of natural gas under energy measurement, C_V represents the price of natural gas under volume measurement, and H represents the CV of natural gas per unit volume. Accordingly, the establishment of an EMS for natural gas can be carried out in the following ways: (1) energy pricing unit selection; (2) conversion of natural gas

purchase, transportation, and sales prices and (3) national RCV selection. At the same time, EM and pricing are based on a certain period, and the CV accumulated in the natural gas during the period is settled uniformly. The ‘EM and energy pricing’ method is adopted according to the principles of simplicity, practicality and smooth transition.

3.1 EM unit selection

The choice of natural gas EM units is one to comply with China’s legal units of measurement, and the other is easy for society and the public to recognise and accept. Currently, the main units of natural gas EM worldwide are Btu, therm, cal, J and kWh. Among them, Btu, kWh and J are the three most widely used energy units; therm is mainly applied in the UK and cal measurement is used in Japan and the Taiwan Province of China. According to our natural gas metering requirements, the available units of measurement are kWh, J, MJ and GJ.

3.2 Natural gas purchase, transportation and sales price conversion method

The pricing of natural gas involves multiple stakeholders with distinct economic interests. To ensure the smooth implementation of metering and pricing system reforms, it is essential to determine the price conversion method scientifically and reasonably while maintaining the overall stability of natural gas prices.

Moreover, using different metering and pricing systems for pipeline transportation and commercial gas transactions can increase workload. With the national reform of the pipeline network operation mechanism aimed at ‘separating pipeline transmission and sales’ and the gas price reform objective of ‘liberalising the two ends and controlling the middle’, ex-factory and transportation prices are separated from the gate price and settled independently. Similarly, as European and American countries transition from volume-based metering and pricing to energy-based metering and pricing, natural gas pipeline transportation is also unified under energy-based metering and pricing. In consideration of standardisation and operational convenience, the current pipeline transportation prices are also converted into energy-based prices to reasonably safeguard the interests of all parties involved in purchasing, transporting and selling natural gas.

The price conversion method can involve various price conversion equations, which are established by identifying a fundamental parameter that quantifies the CV contained in each cubic metre of natural gas. Subsequently, the unit price of natural gas by volume is converted into a unit price of CV that represents the energy content of the natural gas. In essence, after specifying the natural gas price under a certain RCV, all natural gas prices should be converted according to the price standard corresponding to the CV. If the RCV is higher, the energy price derived from the current volume price is relatively lower, and vice-versa.

3.2.1 Natural gas price conversion 1 (NGPC1)

The state-administered energy-based price schedule for natural gas in all provinces and municipalities and long-distance pipelines determines the CV contained in a unit volume of natural gas and establishes a national standard CV. China uses the CV benchmark to directly convert the prices in the existing BGSP schedule and pipeline transportation price schedule in a uniform manner, resulting in a natural gas energy-based price schedule. Under this method, the natural gas purchase price, sales price and transportation price are transformed as shown in equations (2), (3) and (4), respectively.

$$C_{E,purchase}^{NGPC1} = \frac{C_{V,purchase}}{H_0} \times 1000 \quad (2)$$

In the equation, $C_{E,purchase}^{NGPC1}$ is the purchase price of natural gas under the EM in NGPC 1, CNY/GJ; $C_{V,purchase}$ is the purchase price of natural gas under VM, CNY/m³; H_0 is the RCV of natural gas price converted from volume pricing to energy pricing, MJ/m³.

$$C_{E,sell}^{NGPC1} = \frac{C_{V,sell}}{H_0} \times 1000 \quad (3)$$

In the equation, $C_{E,sell}^{NGPC1}$ is the sales price of natural gas under the EM when using NGPC 1, CNY/GJ; $C_{V,sell}$ is the provinces and municipalities BGSP, CNY/m³.

$$C_{E,pipe}^{NGPC1} = \frac{C_{V,pipe}}{H_0} \quad (4)$$

In the equation, $C_{E,pipe}^{NGPC1}$ is the pipeline transmission price of natural gas under EM when using NGPC 1, CNY/GJ; $C_{V,pipe}$ is the price of natural gas pipeline transportation under VM, CNY/m³.

A BGSP list and a pipeline transportation price list make up the price list for this method, which is based on natural gas energy. It has the advantage that after the implementation of EM, the natural gas gate prices and pipeline transportation prices in each province are strictly enforced directly according to the price list and are simple and easy to implement, and the provinces have a clear basis for controlling natural gas prices and are easy to regulate. The disadvantage is the workload of calculating the average calorific value of each place in the initial stage, which may not accurately reflect the actual value. This could lead to an unfair distribution of benefits during the handover.

3.2.2 Natural gas price conversion 2 (NGPC 2)

The RCV of the national management of natural gas price conversion is to announce the CV contained in a unit of natural gas volume to the society and then use the CV benchmark to calculate the price of each transaction and service according to the actual CV, which is equivalent to completely liberalising the control of sales price. Based on NGPC 1, the method adds a price volatility coefficient, shown in equation (5). This coefficient shows how much the actual traded CV of natural gas for each customer changes from the national benchmark CV. The conversion equations for natural gas purchase price, sales price, and transportation price are shown in equations (6), (7) and (8), respectively.

$$w = \frac{H_{act} - H_0}{H_0} \times 100\% \quad (5)$$

In the equation, w is the price fluctuation coefficient; H_{act} is the actual gas CV of each pipeline of users everywhere, MJ/m³.

$$C_{E,purchase}^{NGPC2} = \frac{C_{V,purchase}}{H_0} (1 + w) \times 1000 \quad (6)$$

In the equation, $C_{E,purchase}^{NGPC2}$ is the purchase price of natural gas under EM when using NGPC 2, CNY/GJ.

$$C_{E,sell}^{NGPC2} = \frac{C_{V,sell}}{H_0} (1 + w) \times 1000 \quad (7)$$

In the equation, $C_{E,sell}^{NGPC2}$ is the selling price of natural gas under the EM when using NGPC 2, CNY/GJ.

$$C_{E,pipe}^{NGPC2} = \frac{C_{V,pipe}}{H_0} \quad (8)$$

In the equation, $C_{E,pipe}^{NGPC2}$ is the price of natural gas pipeline transmission under EM when using NGPC 2, CNY/GJ.

This method solely establishes a CV benchmark. Its advantage lies in enabling each user to determine the settlement price based on the actual CV of gas post-implementation of EM. This approach can effectively capture the value distinctions among different CVs of natural gas and will be adopted concurrently with the progression of marketisation and energy-based pricing. However, a notable drawback is that various gas sources and pipelines independently set their prices, potentially resulting in significant price disparities at present. This situation could lead to market price confusion and pose challenges for regulation. Currently, conditions are not yet conducive to the full marketisation of prices.

3.3 RCV selection method

There are two primary purposes for the RCV: one is to designate the RCV for price conversion, wherein a specific RCV is set to establish the price level of natural gas and other natural gas will be priced based on their CV content, thereby correlating higher CV natural gas with higher prices. The second purpose is to ensure that natural gas meets the required CV when entering the pipeline network; hence, the CV of natural gas needs to be adjusted within a certain range before being transmitted through the long-distance natural gas pipeline network.

This study examines the utilisation of RCV based on the following three principles: (1) A unified method is strictly followed nationwide to determine and implement the RCV uniformly; (2) The selected RCV should align with the actual CV and its developmental trajectory in China to the greatest extent possible and (3) The chosen RCV should comply with national directives and standard specifications and withstand industry supervision during implementation. Combining the actual CV in China with relevant government document requirements, the optional RCVs are presented in Table 3.

3.3.1 RCV selection method 1 (RCVS 1)

Using the national average CV as the RCV offers the advantage of minimal change in the overall benefit situation post-implementation of price conversion. This approach is well-founded and readily accepted and acknowledged by the industry and society. However, a drawback arises from the significant variation in the CV of natural gas from oil and gas fields across different regions of China, leading to disparities in the national

average CV. The National Development and Reform Commission (NDRC) has gathered data on the compliance capacity of natural gas from fields operated by PetroChina, Sinopec and CNOOC, as well as imported gas and sales, resulting in three sets of compliance capacity data. Among these, the average CV of domestically sourced natural gas, excluding imported gas, closely reflects the actual situation in China. Consequently, the average domestic CV of 36.86 MJ/m³ has been chosen as the RCV.

Table 3 RCV selection method and basis

Number	Available options		CV	Basis
1	National average CV	Average domestic CV	36.86MJ/m ³	The baseline CV is close to the actual CV
		Average CV of domestic gas and imported gas	37.04MJ/m ³	
		Average CV of all-natural in China	37.31MJ/m ³	
2	Standards proposed by NDRC	The low CV standard proposed by NDRC	33.49MJ/m ³	The CV standard proposed by NDRC
		The high CV standard proposed by the NDRC	36.84MJ/m ³	
3	National standard	National standard before 2018	36 MJ/m ³	National class I gas quality standard
		2018 new national standard	34 MJ/m ³	

3.3.2 RCV selection method 2 (RCVS 2)

The RCV is derived from the CV standard proposed by the National Development and Reform Commission (NDRC). The national standard ‘GB17820-2012 Natural Gas’ categorises natural gas into three classes (refer to Table 4) and establishes the minimum limit of gross CV. The high heating value (HHV) not only aligns with the CV of most oil and gas fields in China but is also comparable to the CV of commercial natural gas in many countries globally. Selecting this CV offers the advantage of NDRC endorsement, ensuring long-term implementation. With an HHV of approximately 36.84 MJ/m³, it presents a more suitable option with a smaller increase compared to volumetric pricing. Conversely, the low calorific value, around 33.49 MJ/m³, poses the disadvantage of being lower in value and not matching China’s actual calorific content. Opting for this CV could lead to a rise in actual prices, complicating implementation efforts.

Table 4 Gas quality requirements of three standards for pipeline natural gas

	Class I	Class II	Class III
HHV (MJ/m ³)	≥36	≥31.4	≥31.4
Total sulphur content (mg/m ³)	≤60	≤200	≤350
H ₂ S (mg·m ⁻³)	≤6	≤20	≤350
CO ₂ (%)	≤2.0%	≤3.0%	-

3.3.3 RCV selection method 3 (RCVS 3)

The RCV is derived from the national standard CV of Class I gas. Prior to 2018, the national standard CV for Class I gas was 36 MJ/m³. Selecting this CV offers the advantage of being closely aligned with the actual CV and the standard adopted by the

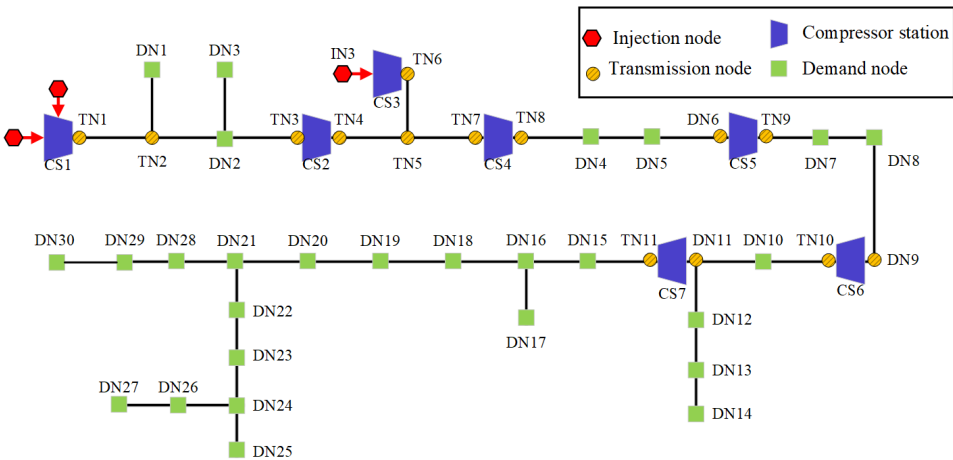
United States. However, the drawback is that this value is not utilised in the updated national standard. In the new national standard implemented in 2018, the CV for Class I gas was revised to 34 MJ/m³. Despite being the latest standard and providing a more adequate basis, this CV is generally lower and does not reflect the actual CV content in China. Opting for this CV as the RCV could result in a significant price hike and market volatility, posing challenges to implementation. Considering the duration of industry standard implementation, similarity to the average CV in China, and the impact on benefit changes due to price conversion, it is recommended to select the national Class I gas standard of 36 MJ/m³ before 2018 as the RCV.

4 Case study

4.1 Establishment of pipe network simulation model

Using the SPS, component tracking functions can be implemented to determine the CV at downstream demand nodes. This enables the prediction of the operating profit of the natural gas industry chain following the transition from volume-based to energy-based metering systems. A domestic long-distance pipeline serving multiple gas sources and users (referred to as MSNGP1) is chosen as the model case study. The pipeline network structure model is depicted in Figure 4, excluding valves and pipeline connecting elements. MSNGP1 comprises 3 gas sources, 30 gas delivery stations and 7 distributing stations (with compressors as the main equipment). Although the MSNGP1 measurement system currently utilises VM, variations in gas quality and CV from different sources necessitate energy metering to facilitate more convenient and transparent natural gas trading, garnering mutual acceptance from transaction stakeholders. Presently, the existing volume-based metering system of the pipeline enterprise possesses the requisite hardware foundation for energy metering. Transitioning from VM to energy metering does not necessitate additional hardware investment for the pipeline enterprise.

Figure 4 Structure of pipeline MSNGP1 (see online version for colours)



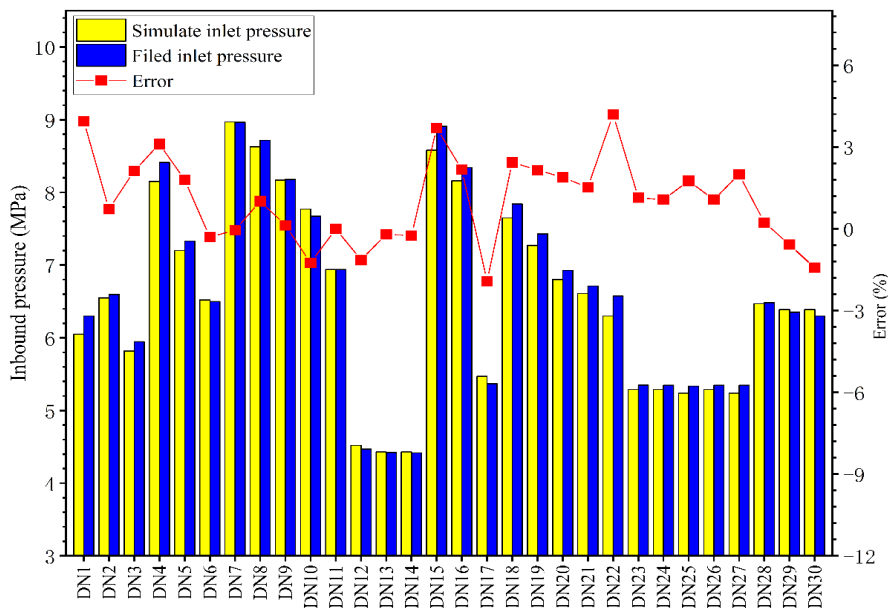
This simulation is set as a pressure constraint at air source IN1, which is 7.2 MPa. The air source IN2 is set as flow restriction, which is $700 \times 10^4 \text{ m}^3/\text{d}$. The air source IN3 is set as a flow constraint, which is $1638 \times 10^4 \text{ m}^3/\text{d}$. The total demand flow is $4326.17 \times 10^4 \text{ m}^3/\text{d}$. The compressor startup scheme is set as follows: 4 compressors at CS3, 1 compressor at CS2, 2 compressors at CS4 and 2 compressors at CS5. Each compressor is subject to outlet pressure constraints, and the pressure is set according to the actual site data. The heat transfer mode of the model is thermal mode, the gas state equation is BWRS and the TRACK function is selected to realise component tracking.

4.2 Verify the pipe network simulation model

Using the SPS simulation, the inlet pressure at each distribution station and the inlet and outlet pressures at each compressor station were logged. Subsequently, the software simulation outcomes were juxtaposed with field operation data, depicted in Figures 5 and 7, respectively.

As illustrated in Figure 5, the simulated inlet pressure marginally undershoots the actual field inlet pressure. Consequently, the SPS-simulated inlet pressure between dispensing stations DN1 and DN6 is lower compared to the field inlet pressure. Pressure levels from DN11 to DN14 tend to equalise at the distribution station. Owing to a slightly elevated pressure increment from the compressor preceding distribution station DN15, the simulated inlet pressure from DN15 to DN27 is less than the actual on-site inlet pressure. The maximum error at the pipeline distribution station is 4.2%, occurring at DN22. Error margins across each distribution station of the pipeline range from 0 to 4.2%, indicating an overall favourable simulation outcome for the pipeline network.

Figure 5 Comparison of inbound pressure of gas transmission station (see online version for colours)



As depicted in Figure 6, the inlet pressure errors for CS1 and CS6 stand at 0.3% and 0.13%, respectively, while the outlet pressure errors are 0.75% and 0.55%, respectively, demonstrating minimal discrepancies. CS3 serves as the pressurisation facility for gas source IN3. At CS2, the simulated outbound pressure exceeds the actual pressure by 0.124 MPa, resulting in a corresponding decrease in simulated inbound pressure at CS4 by 0.096 MPa. In order to meet the flow requirements of subsequent stations, the simulated boost pressure registers 0.291 MPa higher than the actual on-site pressure, with an error of 3.36%. The inlet pressure errors for CS5 and CS7 are 0.31% and 0.17%, respectively, while the outlet pressure errors are 0.00% and 0.18%, respectively, indicating relatively minor deviations.

Figure 6 Comparison of pressure in and out of the compressor station (see online version for colours)

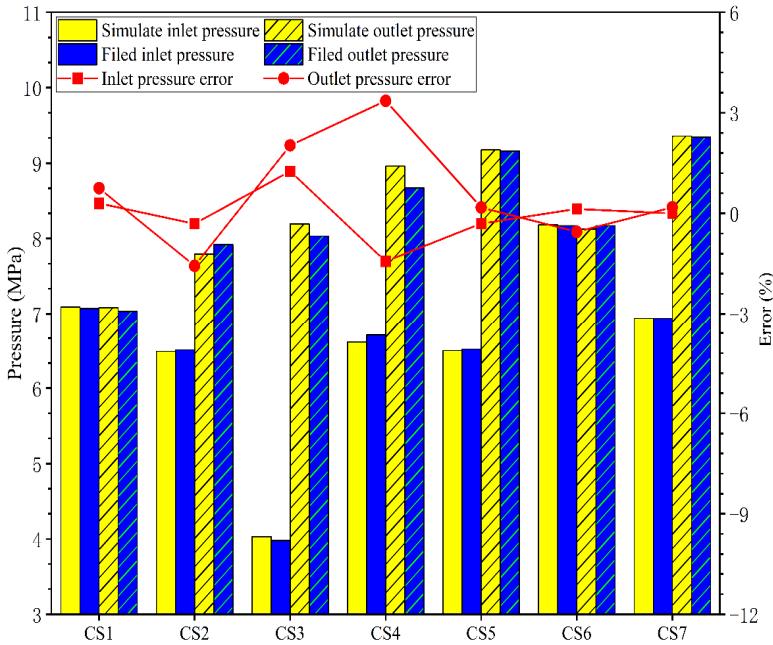
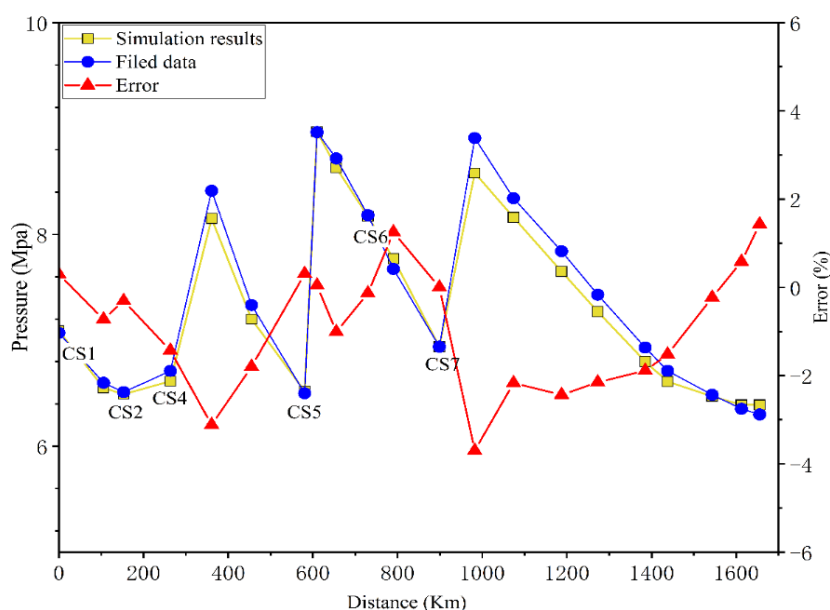


Figure 7 compares the simulated incoming pressure at the pipeline trunk line's main stations with the actual data from the field. As depicted in Figure 7, the mainline pipeline pressure in the SPS simulation model exhibits a lower reading compared to the field pressure, with the most significant discrepancy occurring at CS7 of the compressor station, where the error reaches 3.70%. Several factors contribute to this disparity: (1) Variations exist between the compressor parameters in the simulation model and the actual compressor performance on-site and (2) The simulation model assumes constant pipe friction, whereas real-world pipelines undergo changes in friction over time due to prolonged usage. Upon comparing the actual monitoring data of the pipeline with the simulation results from the SPS software, it is evident that the simulation outcomes align closely with the field's operational data, with differences below 5%, falling within an acceptable error margin. This test confirms the reliability and accuracy of the constructed pipeline network model.

Figure 7 Comparison of pressure drop in main lines (see online version for colours)

5 Result and discussion

5.1 Gas sales income impact analysis

Comparing the advantages and disadvantages of the two gas price conversion methods, NGPC 1 stands out for its simplicity and ease of implementation, making it more feasible, particularly during the initial stages of gas EM and pricing implementation. With NGPC 1, the current volumetric price of natural gas for each customer type at every metering station is directly converted to an energy price using equation (2). Subsequently, the billing and settlement units of natural gas, represented in CNY/GJ, select the RCV under each of the three methods. By substituting the high-level calorific value of the natural gas and the prevailing natural gas benchmark gate price in China into the price conversion equation, the natural gas BGSP for energy billing under EMSI 1, EMSI 2 and EMSI 3 in the province is determined.

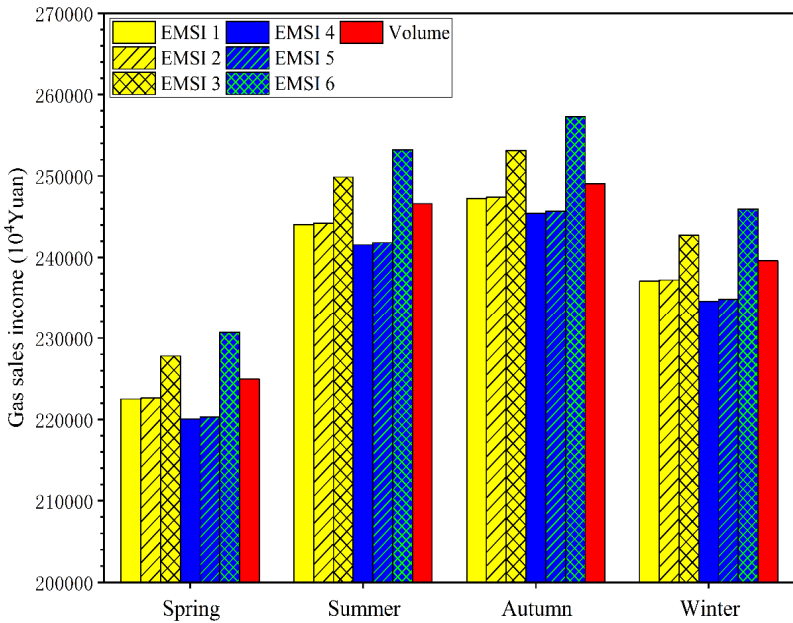
On the other hand, NGPC 2 presents challenges in implementation. To ensure stable market prices, it is advisable to initially adopt a downstream province as the implementation unit for calorific value pricing. This involves combining the actual calorific value of gas from the province across different quarters with the RCV established by the state to ascertain the settlement price. Utilising the SPS software alongside monthly source gas quality data from different quarters facilitates simulations. The high calorific value of pipeline MSNGP1 downstream of the province is calculated based on these simulation results. Subsequently, the current volumetric price of natural gas used by each user type at every metering handover site is directly converted into an energy price. Using CNY/GJ as the pricing and settlement unit after conversion, the RCV under each of the three methods is selected, and the BGSP of natural gas for energy

pricing is determined by substituting the HHV of natural gas for each quarter in the province and the current BGSP of natural gas in China into equations (3) and (7). Field data is then employed to calculate the gas consumption of the city downstream of the MSGNP1 pipeline across various quarters and months, with Table 6 documenting the average HHV, gas consumption and BGSP of the city in different seasons.

The monthly gas sales revenue for each quarter under the VMS implementation and various EMS implementation schemes is illustrated in Figure 8. It is evident from the figure that the quarterly gas sales revenue for EMSI 1, EMSI 2, EMSI 4 and EMSI 5 is lower compared to the gas sales revenue under VMS. Both EMSI 1 and EMSI 4 employ the RCV selection RCVS 1 (36.86 MJ/m^3), while EMSI 2 and EMSI 5 adopt RCV selection RCVS 2 (36.84 MJ/m^3). These selections surpass the CV content of the three gas sources in the MSGNP1 pipeline. Consequently, after the conversion of gas sales price from the VMS price to the EM price, the established energy price falls below the original VMS price level. The utilisation of RCVS 1 and RCVS 2 significantly diminishes enterprise gas sales income.

Contrastingly, EMSI 3 and EMSI 6 utilise the CV (36 MJ/m^3) of RCVS 3, which is the CV stipulated in the national standard prior to 2018 and primarily serves to confine the range of pipeline transmission CV. Given that most gas fields across the country exhibit CVs higher than this value, the EM price established by this CV exceeds the initial VMS price level, thereby augmenting gas sales income.

Figure 8 Total monthly gas sales revenue of downstream users in each quarter under different implementation plans of VMS and EMS (see online version for colours)



Through a comprehensive comparison of the gas sales revenue between NGPC 1 and NGPC 2, it becomes apparent that the gas sales revenue utilising EMSI 1 and EMSI 2 under NGPC 1 surpasses that utilising EMSI 4 and EMSI 5 under NGPC 2 in each quarter. NGPC 2 introduces a new price fluctuation coefficient, denoted as 'w', to depict the disparity between the actual CV accepted by downstream users and the RCV.

As depicted in Figure 8 for EMSI 4 and EMSI 5, the actual CV accepted by downstream users is lower than the RCV. Consequently, the EM price set by NGPC 1 is adjusted to better reflect the fairness of price setting, albeit at the expense of further diminishing gas sales income.

5.2 Scheme description

As mentioned earlier, the combination of two natural gas price conversion methods and three forms of RCV selection yields a total of six natural gas EMS implementation schemes. Utilising SPS software, the economic efficiency of pipeline operations is analysed based on different EMS implementation schemes, using a city in China as a case study, as outlined in Table 5.

Table 5 Combination of six implementation schemes of natural gas EMS

<i>EMS implementation scheme</i>	<i>Natural gas price conversion method</i>	<i>RCV selection method</i>
EMSI 1	NGPC 1	RCVS 1
EMSI 2	NGPC 1	RCVS 2
EMSI 3	NGPC 1	RCVS 3
EMSI 4	NGPC 2	RCVS 1
EMSI 5	NGPC 2	RCVS 2
EMSI 6	NGPC 2	RCVS 3

Table 6 Relevant parameters of natural gas in the province under different quarters

<i>Season</i>	<i>Average HHV (MJ/m³)</i>	<i>Gas consumption (m³)</i>	<i>BGSP (CNY/GJ)</i>					
			<i>EMSI 1</i>	<i>EMSI 2</i>	<i>EMSI 3</i>	<i>EMSI 4</i>	<i>EMSI 5</i>	<i>EMSI 6</i>
Spring	36.13	8944.98				40.69	40.73	42.65
Summer	36.15	6373.99	41.51	41.53	42.5	40.71	40.75	42.68
Autumn	36.27	7496.49				40.85	40.89	42.82
Winter	36.19	10005.92				40.76	40.8	42.72

5.3 Gas purchase cost impact analysis

5.3.1 Gas purchase price conversion under EMS

The gas supplier initially sets the gas purchase price according to volume and subsequently determines the EM price based on the CV of the gas supplied. Table 7 presents the calculation of the gas purchase price for each gas source under the six EMS implementation scenarios, based on actual VM price and CV at the site, utilising equations (5) and (7).

5.3.2 Calculation of gas purchase cost under different measurement systems

The purchased gas costs are calculated for different quarters based on the purchased gas prices and purchased gas volumes for each gas source, as shown in Table 8.

Table 7 Gas purchase price under different measurement systems

Season	Gas source	Gas source purchase price						
		VM (CNY/m ³)	EM (CNY/GJ)					
			EMSI 1	EMSI 2	EMSI 3	EMSI 4	EMSI 5	EMSI 6
Spring	Gas source 1					37.00	37.04	38.79
	Gas source 2	1.39	37.71	37.73	38.61	37.76	37.80	39.59
	Gas source 3					37.37	37.41	39.18
Summer	Gas source 1					37.02	37.07	38.81
	Gas source 2	1.39	37.71	37.73	38.61	37.76	37.80	39.59
	Gas source 3					37.40	37.44	39.21
Autumn	Gas source 1					37.16	37.20	38.95
	Gas source 2	1.39	37.71	37.73	38.61	37.91	37.96	39.75
	Gas source 3					37.55	37.59	39.36
Winter	Gas source 1					36.71	36.75	38.48
	Gas source 2	1.39	37.71	37.73	38.61	37.55	37.59	39.36
	Gas source 3					37.36	37.40	39.17

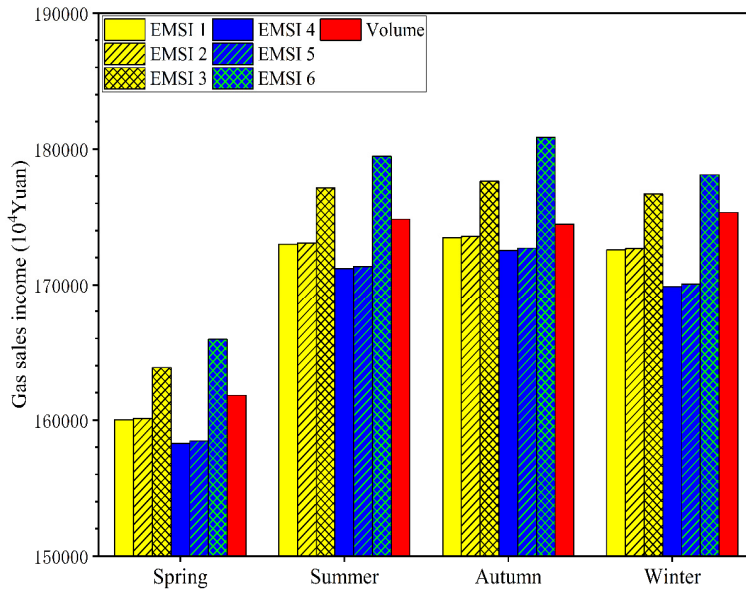
Table 8 Monthly gas purchase cost in each quarter under the same measurement system (10⁴ CNY)

Season	VM	EM					
		EMSI 1	EMSI 2	EMSI 3	EMSI 4	EMSI 5	EMSI 6
Spring	161814	160033	160120	163856	158281	158452	165933
Summer	174841	172998	173092	177131	171183	171369	179460
Autumn	174455	173482	173576	177626	172524	172711	180865
Winter	175339	172583	172677	176706	169886	170071	178100

5.3.3 Comparative of gas purchase costs under different measurement systems

Figure 9 illustrates the monthly costs of purchased gas for each quarter under the VMS and various EMS implementation scenarios. In EMSI 1, EMSI 2, EMSI 4 and EMSI 5, the gas prices are lower compared to the VMS condition. This reduction is attributed to the fact that the CVs of the three gas sources in the MSNGP1 pipeline are lower than the CV benchmarks (RCVS 1 and 2) set in the RCV selections, resulting in lower total gas costs. However, EMSI 4 and EMSI 5 incorporate a price volatility factor, ‘w’, in the natural gas purchase prices, reflecting the difference between the average CV of the supplied gas and the quarterly RCV. This discrepancy may cause economic losses for suppliers providing low-CV natural gas while incentivising the production of HHV gas. Conversely, EMSI 3 and EMSI 6 raise the price level of EM gas purchases due to the selection of a low RCV, leading to higher gas purchase costs.

Figure 9 Monthly gas purchase cost in each quarter under the VMS and different EMS implementation plans (see online version for colours)



5.4 Analysis of impact on pipeline transportation cost

5.4.1 Price conversion of pipeline transportation under EMS

Currently, China still implements the pipeline transportation pricing mode based on VM, which essentially remains volume-based. For determining the pipeline transmission price under VM for the main pipelines operated by pipeline MSNGP 1, equation (4) of NGPC 1 is utilised to convert the transmission price from the corresponding VMS. The results are tabulated in Table 9. Pipeline MSNGP 1 is segmented into 30 pipeline sections based on the location of each distribution station and branch line. Using the pipeline volume and CV data, the transmission price under VMS is converted using equation (8) of NGPC 2. The results are presented in Table 10.

Table 9 Pipeline transmission price under the EMS in the implementation of price conversion NGPC 1

<i>EMS implementation plan</i>	<i>Pipeline transmission price (CNY/(GJ·km))</i>
EMSI 1	0.01037
EMSI 2	0.01038
EMSI 3	0.01062

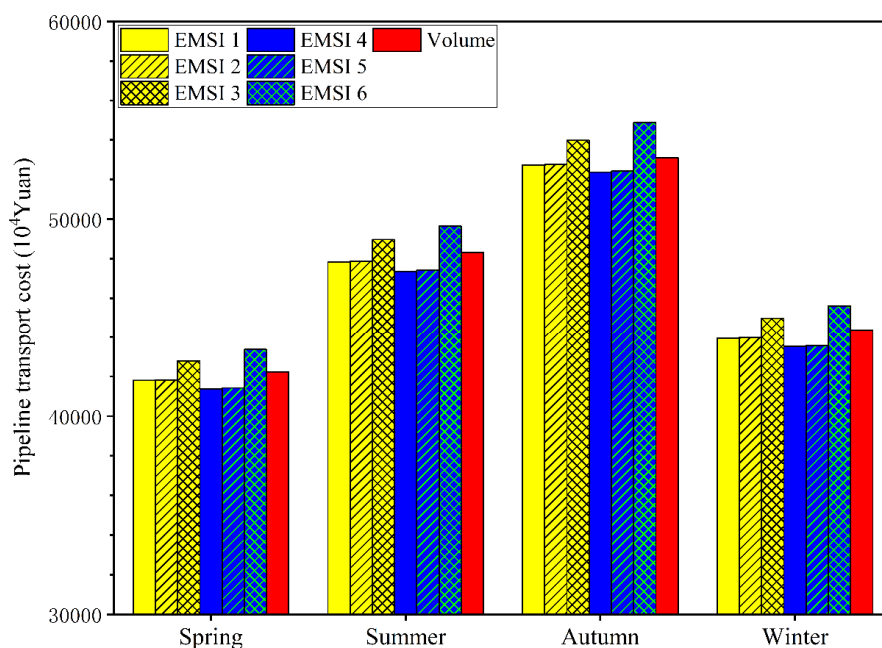
Table 10 Monthly pipeline transmission price in each quarter under the EMS of price conversion NGPC 2

Pipe section number		Pipe transmission price (CNY/(GJ.m))											
Pipe start point	Pipe end point	EMSI 4				EMSI 5				EMSI 6			
		Spring	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter	Spring	Summer	Autumn	Winter
Pipe trunk line	TN1	10.27	10.28	10.77	10.27	10.28	10.77	10.3	10.31	10.79	10.27	10.28	10.77
	TN5	10.27	10.28	10.77	10.27	10.28	10.77	10.3	10.32	10.8	10.28	10.29	10.77
	TN2	10.17	10.18	10.66	10.17	10.19	10.67	10.21	10.22	10.7	10.19	10.2	10.68
Pipe branch line	DN2	10.27	10.28	10.77	10.27	10.28	10.77	10.3	10.31	10.79	10.27	10.28	10.77
	TN6	10.28	9.52	9.95	10.29	9.53	9.96	10.33	9.56	10	10.28	9.52	9.95
	DN11	10.27	10.28	10.77	10.27	10.28	10.77	10.3	10.32	10.8	10.28	10.29	10.77
	DN16	10.27	10.28	10.77	10.27	10.28	10.77	10.3	10.32	10.8	10.28	10.29	10.77
	DN21	10.27	10.28	10.77	10.27	10.28	10.77	10.3	10.32	10.8	10.28	10.29	10.77
	DN24	10.27	10.28	10.77	10.27	10.28	10.77	10.3	10.32	10.8	10.28	10.29	10.77
	DN25	10.27	10.28	10.77	10.27	10.28	10.77	10.3	10.32	10.8	10.28	10.29	10.77
	DN27	10.27	10.28	10.77	10.27	10.28	10.77	10.3	10.32	10.8	10.28	10.29	10.77

5.4.2 Analysis of pipeline transmission costs under different measurement system

Using the pipeline pricing under VM for pipeline MSNGP1, the monthly pipeline costs are computed for different quarters under VM. By considering the pipeline transmission price under VM and the CV of gas transmission in each pipeline section, the quarterly and single-monthly pipeline transmission costs for each implementation scenario under different EMS are determined. The quarterly and single-monthly pipeline costs under the volume system and various EMS implementations are illustrated in Figure 10.

Figure 10 Quarterly pipeline transport costs under the VMS and different EMS (see online version for colours)



It can be seen from Figure 10 that the pipeline transportation cost of EMSI 1, EMSI 2, EMSI 4 and EMSI 5 is lower than the pipeline transportation cost under VM, and the pipeline transportation cost of EMSI 3 and EMSI 6 is higher than the pipeline transportation cost under VM. The pipeline transportation price under VM is determined according to the relevant pipeline transportation pricing model, and the EM price is converted on this basis, which has the same impact as the EMS on the gas sales revenue and gas purchase cost. The same reasons lead to the lower pipeline transportation cost of EMSI 4 and EMSI 5 than that of EMSI 1 and EMSI 2, and the higher pipeline transportation cost of EMSI 3 and EMSI 6 than that of VM.

5.5 Analysis of the impact of EM system on operating profit

5.5.1 Profit calculation under different measurement systems

Table 11 illustrates the computation of operational profitability within the volumetric metering system and the quarterly operational profitability across the six implementation alternatives for the energy metering system.

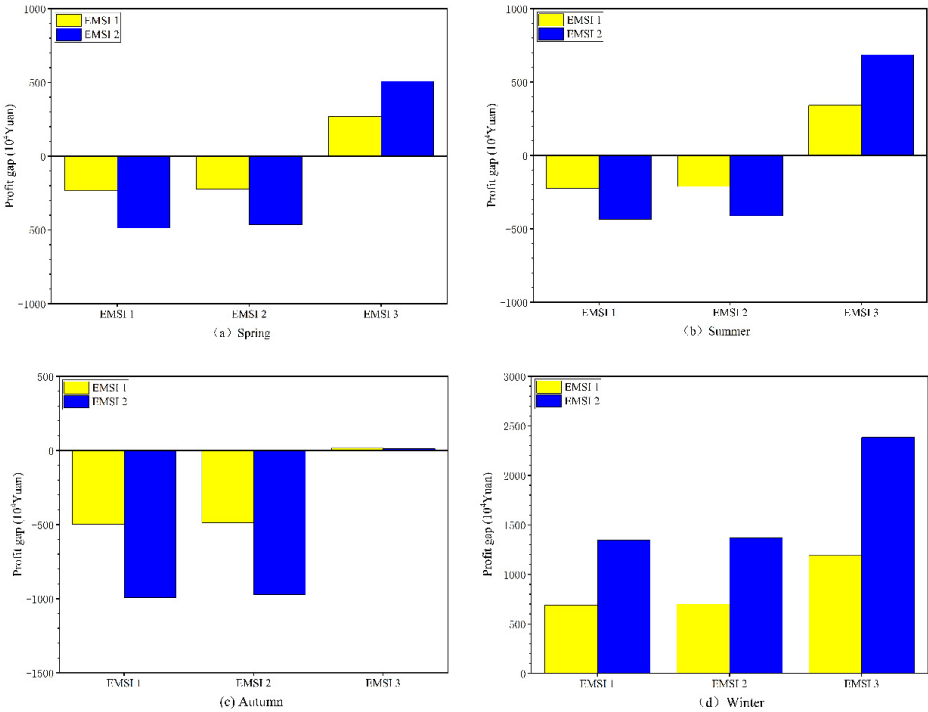
Table 11 Monthly profit of each quarter under different implementation schemes of VMS and EMS (10^4 CNY)

Season	VM	EM					
		EMSI 1	EMSI 2	EMSI 3	EMSI 4	EMSI 5	EMSI 6
Spring	20888.36	20657.16	20666.67	21157.98	20401.54	20423.05	21396.01
Summer	23450.53	23226.98	23239.6	23791.82	23013.68	23038.69	24136.17
Autumn	21531.07	21032.78	21044.49	21546.82	20537.56	20560.35	21542.27
Winter	19873.46	20563.81	20574.76	21064.29	21221.42	21244.07	22256.71

5.5.2 Profit analysis under different measurement systems

According to the profit difference under different measurement systems in each quarter in Table 11, the calculation results are shown in Figure 11 (operating profit difference = operating profit under the EMS-operating profit under the VMS).

Figure 11 Balance of operating profit for the same quarter (see online version for colours)



It can be seen from Figure 11 that when RCVS 1 and RCVS 2 are used as the RCV, except in winter, the operating profit when using the EMS is lower than that when using the VMS. The average CV at the MSNGP1 gas source of the pipeline is 36.62MJ/m^3 , while the RCV of RCVS 1 is 36.86MJ/m^3 , and the RCV of RCVS 2 is 36.84MJ/m^3 , which are higher than the average CV of the three gas sources. The CV selection based on RCVS 1 and RCVS 2 will reduce the gas sales revenue of the operator in the model. The RCV of RCVS 2 is slightly lower than the RCV of RCVS 1, which is closer to the average CV of the three gas sources. The price conversion can be better implemented, and RCVS 2 only causes a small change in operating profit. If RCVS 3 is used, the use of the EMS will make the operator gain more operating profits than the use of the VMS. This is because the RCV of RCVS 3 is 36 MJ/m^3 , which is 0.62 MJ/m^3 lower than the average CV at the MSNGP1 gas source of the pipeline. This means that the CV of each million cubic metres of natural gas burned is 620 GJ. Taking the price of Shanghai Gate Station as an example, 56.67 (CNY/GJ), the difference between the two sales of gas is 35,100 CNY. Selecting the RCV of RCVS 3 will bring more operating profits to operators, but the level of 36 MJ/m^3 as the RCV is relatively low, which is still inconsistent with the average calorific value of China and is less likely to be selected.

By analysing the operating profit variance for each quarter depicted in Figure 11, it becomes evident that only during winter does the operational profit under EM, utilising RCVS 1 and RCVS 2, surpass that of VM. Winter months typically witness lower natural gas CV from upstream sources alongside heightened downstream gas demand, thereby amplifying gas sales revenue under EM, mitigating gas purchase and pipeline transportation costs, and consequently boosting operational profit through various contributing factors.

When comparing the two gas price conversion methodologies, it is apparent that the overall operational profit difference is greater when employing gas price conversion NGPC 2 compared to NGPC 1. Although NGPC 2 more accurately reflects the value of gas with differing CVs in setting gas sales prices across provinces, it also precipitates significant fluctuations in gas prices, impacting the gas market and posing challenges for regulation. Additionally, the utilisation of NGPC 2 entails intricate calculations. Therefore, it is advisable to opt for NGPC 2 as the natural gas price conversion method once the natural gas capacity measurement and pricing reform policy mature further.

In conclusion, during the initial phase of the measurement system reform, it is advisable to opt for EMSI 2. This choice can mitigate the impact of the measurement system transformation on pipeline operators' operating profits and facilitate a smoother transition from VM to EM. As the reforms progress and implementation matures, the adoption of EMSI 5 could be considered. This approach would accurately account for the carbon content of gas and enhance transaction transparency.

6 Conclusions

Drawing upon an examination of diverse metering systems in natural gas transactions and the natural gas supply chain, this study presents six specific scenarios for implementing energy management across three domains: natural gas procurement, transportation and distribution. Employing SPS software, a simulation of a long-distance domestic pipeline is conducted. Subsequently, the CV of each downstream gas

transmission node is computed, and the economic benefits of the pipeline operator under both EMS and VM are compared.

- 1 The research conducts a comparative analysis of various measurement systems for natural gas trading, advocating that EMS can more accurately reflect the value derived from natural gas combustion, thereby facilitating measurement and pricing in domestic and international natural gas trading contexts.
- 2 Two methodologies are proposed for transitioning natural gas prices from volumetric to energy-based metering, alongside three choices for RCV.
- 3 Following an examination of international energy management units and considering our national context, it is suggested to adopt CNY/GJ as the pricing unit in natural gas transactions and CNY/kWh as the pricing unit for low purchase and sales units provided by urban gas management enterprises.
- 4 The study indicates that in selecting the RCV, a higher CV of pipeline gas compared to the RCV results in greater profit for the operator.
- 5 After comparing and analysing operator benefits under different energy metering implementation scenarios, it is recommended to initially adopt price conversion NGPC 1 during the initial stage of energy metering method implementation and transition to price conversion NGPC 2 during the intermediate stage.

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Nomenclature (Abbreviations)

CV	Calorific Value
EM	Energy Measurement
EMS	Energy Measurement System
VM	Volume Measurement
VMS	Volume Measurement System
RCV	Reference Calorific Value
BGSP	Benchmark Gate Station Price
NDRC	National Development and Reform Commission
HHV	Higher Heating Value
MSNGP 1	A domestic long-distance pipeline with multiple gas sources and users in service
NGPC 1	Natural Gas Price Conversion method 1
NGPC 2	Natural Gas Price Conversion method 2
RCVS 1	Reference Calorific Value Selection method 1
RCVS 2	Reference Calorific Value Selection method 2

Nomenclature (Abbreviations) (continued)

RCVS 3	Reference Calorific Value Selection method 3
EMSI 1	Natural gas price conversion should choose method 1 and reference calorific value choose method 1
EMSI 2	Natural gas price conversion should choose method 1 and reference calorific value choose method 2
EMSI 3	Natural gas price conversion should choose method 1 and reference calorific value choose method 3
EMSI 4	Natural gas price conversion should choose method 2 and reference calorific value choose method 1
EMSI 5	Natural gas price conversion should choose method 2 and reference calorific value choose method 2
EMSI 6	Natural gas price conversion should choose method 2 and reference calorific value choose method 3

Parameters

H	The calorific value content of natural gas, MJ/m ³ .
H_0	The reference calorific value of natural gas from volume pricing to energy pricing, MJ/m ³
$C_{V,purchase}$	The purchase price of natural gas under volume measurement, CNY/m ³
$C_{V,sell}$	The price in the price list of benchmark gate stations in provinces, cities and districts, CNY/m ³
w	The price fluctuation coefficient
$C_{V,pipe}$	The prices in the gas pipeline transportation price list under volume measurement, CNY/(km ³ ·km)
H_{act}	The actual gas calorific value of each pipe for each customer in each place, MJ/m ³
$C_{E,purchase}^{NGPC1}$	The purchase price of natural gas under energy measurement when using NGPC 1, CNY/GJ
$C_{E,purchase}^{NGPC2}$	The purchase price of natural gas under energy measurement when using NGPC 2, CNY/GJ
$C_{E,sell}^{NGPC1}$	The sales price of natural gas under energy measurement when using NGPC 1, CNY/GJ
$C_{E,sell}^{NGPC2}$	The sales price of natural gas under energy measurement when using NGPC 2, CNY/GJ
$C_{E,pipe}^{NGPC1}$	The natural gas pipeline transmission price under energy measurement when using NGPC 1, CNY/(GJ·km)
$C_{E,pipe}^{NGPC2}$	The natural gas pipeline transmission price under energy measurement when using NGPC 2, CNY/(GJ·km)