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Coal-based synthetic natural gas vs. imported natural gas in China: a net energy perspective

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ABSTRACT

China has two choices to meet the gap between its gas demand and supply in the short term: coal-based synthetic natural gas and imported natural gas. China currently faces the following question: between coal-based synthetic natural gas and imported natural gas, which is the better choice for China? To provide a reference for policy makers and investors, this paper compares the energy efficiency of the Datang coal gasification project, which is the first demonstration project in China, with that of imported natural gas by an energy return on investment analysis. The results show that when the environmental inputs are not considered, the energy return on investment values of coal-based synthetic natural gas with different boundaries range from 1.7:1 to 6.9:1. The values of the total imported natural gas decreased from 14.5:1 in 2009 to 7.5:1 in 2014 and then increased to 9.2:1 in 2015. When the environmental inputs are considered, the energy return on investment values of coal-based synthetic natural gas and that of imported natural gas decrease to 1.4:1–3.4:1 and 5.9:1–9.6:1, respectively. Regardless of whether the environmental inputs are considered, imported natural gas generally has a better energy return on investment than coal-based synthetic natural gas. These results suggest that from a net energy perspective, policy makers and investors should encourage to import more natural gas and be prudent about developing the coal gasification industry.

1. Introduction

The demand for natural gas (NG) as a replacement for more expensive, less environmentally friendly, and less efficient fuels has increased significantly in China. However, due to soaring gas demand, domestic gas production cannot meet the demand (Fig. 1). As a result, China began importing liquefied NG (LNG) in 2006. In China, the gap between domestic production and demand will increase rapidly in the future; according to the BP energy outlook 2035 (BP, 2015), this gap is expected to increase to 254 billion cubic metres (bcm) in 2035.

China has two choices to meet the demand for gas. The use of China's relatively abundant coal reserves to produce synthetic natural gas (SNG) is one way to relieve the pressure that is associated with NG shortages. As of October 2013, the Chinese government has approved ten large SNG projects with a total capacity of 67.1 bcm/y (Li et al., 2014). The other choice is imported natural gas (ING). Fig. 2 shows China's supplies of ING from different countries via LNG and pipelines in 2014.

The development of SNG has been controversial. Prior to 2013, the Chinese central government maintained a restrictive policy on the development of SNG and halted all SNG development except for 4 selected demonstration projects. However, in March 2013, months before the commercial commencement of the first SNG demonstration plant, the Chinese government suddenly changed its cautious and restrictive policy on SNG and began encouraging its development (Yang, 2015). Parallel to its more positive attitude to SNG, the Chinese government started to stimulate the development of ING, i.e. by providing importers with subsidies. However, for a long time, China's NG prices have been determined by the government, which has resulted in imported gas prices being higher than the domestic market prices. ING companies are experiencing

List of abbreviations: BOG, boil-off gas; CIF, cost, insurance, and freight; EROI, energy return on investment; ENI, environmental inputs; FOB, free on board; GDP, gross domestic product; ING, imported natural gas; LNG, liquefied natural gas; IO, imported oil; LCA, life-cycle assessment; NG, natural gas; SNG, coal-based synthetic natural gas; PM, particulate matter; VOC, volatile organic compounds.

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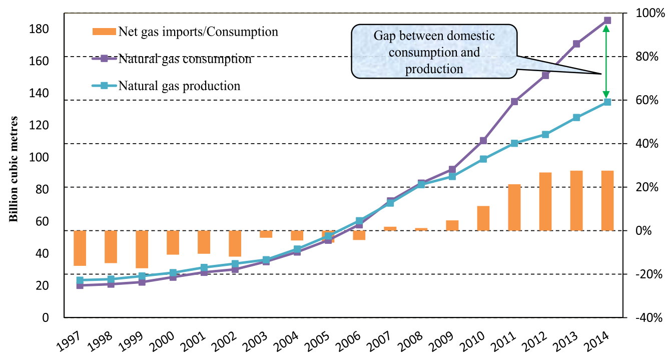

Fig. 1. Natural gas production and consumption in China.

standard was proposed by Murphy et al. (2011). The proposed standard included several boundaries, where different factors are included. This standard allows researchers to state which EROI they are referring to in their calculations. Atlason and Unnthorsson (2014a) presented a new EROI factor called the ideal EROI, or $EROI_{ide}$, which is the ratio between the inputs within the $EROI_{stnd}$ boundaries and the theoretical maximum output from a given system. $EROI_{ide}$ provides the theoretical upper boundary of the EROI of a given system and can be used to estimate the potential for improvement.

The EROI has been constantly improved in terms of the calculation method, boundary determination and applications. Many EROI studies have focused on oil and gas (Cleveland et al., 1984; Freise, 2011; Gagnon et al., 2009; Guilford et al., 2011; Hu et al.,

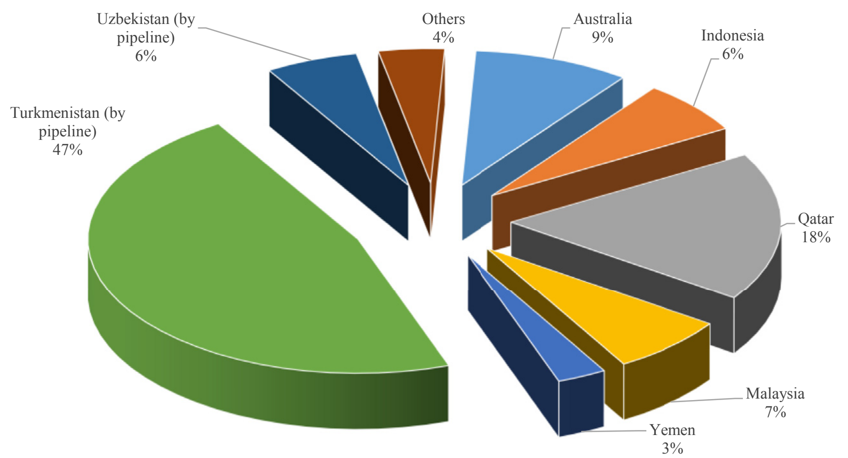

Fig. 2. Imported natural gas from different countries via LNG and pipelines in 2014.

2011, 2013). Almost all these analyses have shown that the EROI for oil and gas is high but is decreasing. Other papers have focused on other energy resources, such as coal (Cleveland et al., 1984; Hu et al., 2013), shale gas (Aucott and Melillo, 2013; Dale et al., 2013; Yaritani and Matsushima, 2014), tight gas (Sell et al., 2011), oil shale (Brandt, 2008, 2009; Cleveland and O'Connor, 2011), hydropower (Weißbach et al., 2013; Atlason and Unnthorsson, 2014b), wind (Brown and Ulgiati, 2002; Wagner and Pick, 2004), bio-fuels (Atlason and Unnthorsson, 2014b; Weißbach et al., 2013), wind (Brown and Ulgiati, 2002; Wagner and Pick, 2004), bio-fuels (Agostinho and Ortega, 2013; Aitken et al., 2014), and solar (Dale and Benson, 2013; Kubiszewski et al., 2009; Raugei et al., 2012). However, the peer-reviewed literature has paid only minimal attention to the EROIs of SNG ($EROI_{SNG}$) and ING ($EROI_{ING}$). Only a few papers have investigated the EROI of imported oil ($EROI_{IO}$), such as Hall et al. (2009) and Lambert et al. (2014). Moreover, the effects of environmental pollution control on the EROI have been ignored.

considerable losses because of the relatively low terminal ING prices (Kong et al., 2015). Currently, China is facing the following question: is SNG or ING the better choice for China?

To answer this question, this study compares the energetic performance of SNG and ING in China using an energy return on investment (EROI) analysis, which is a useful approach for assessing the availability of an energy source. This paper calculates the EROI for the Datang SNG project in Chifeng, Hexigten, Inner Mongolia, which was the first SNG demonstration project in China, and estimates the EROIs of ING from different countries to China.

2. Literature review

EROI is a method to calculate how much energy is returned from one unit of energy that is invested in an energy-producing activity, which allows one to evaluate the energy production physically rather than monetarily (Hall, 2011). The concept of EROI originated from ecology (Xu et al., 2014). The term EROI was first used by, and it subsequently received significant attention in the journal Science (Hu et al., 2013). EROI has more utility than other metrics because it allows the fuels to be ranked and estimates to be made of their changing ease of extraction over time, which can also be interpreted as the difference between the effects of technology and depletion.

The methodologies for calculating EROI have been widely variable. Specifically, published values of EROI for similar fuels are sometimes significantly different as a result of the use of different boundaries and variables (Hall et al., 2014). However, in 2011, a

3. Methods

The general EROI equation is given in Eq. (1).

$$EROI = \frac{\text{Energy returned(outputs)}}{\text{Energy required(inputs)}} \quad (1)$$

Because the numerator and denominator are usually in the same units, the ratio is dimensionless and is often expressed as x:1, such as 10:1.

3.1. EROI methods for SNG

The EROI equation has been applied to finding and/or producing energy (Grandell et al., 2011). However, it should not be used to compute conversion efficiency; i.e., converting from one form of energy to another, such as upgrading petroleum in a refinery or converting diesel to electricity (Hall, 2011; Murphy et al., 2011). Thus, this paper discusses the life-cycle assessment (LCA) process for SNG from coal extraction to SNG utilization (Fig. 3).

During the SNG production process, coal is first crushed and sometimes dried and is then fed into gasifier, in which the coal reacts under an oxygen shortage (Sha, 2015). The coal is first heated in a closed reaction chamber, where it undergoes a pyrolysis process at temperatures above 400 °C. During pyrolysis, a hydrogen-rich syngas is released, along with tar, phenols, and gaseous hydrocarbons (IEA, 2010). The char is then gasified, which releases gases, tar vapours and solid residues. The dominant reactions consist of the partial oxidation of char, which produces a synthesis gas with high fractions of H_2 and CO. The output of coal gasification includes SNG and by-products, which include naphtha, tar, sulphur, crude phenol, and crude ammonia. This paper considers the effect of the by-products on $EROI_{SNG}$.

Unlike coal and oil, which remain almost unchanged after long-distance transportation, NG (LNG or pipeline gas) may suffer losses during transportation (Lin et al., 2010). Therefore, the SNG losses during transportation will be estimated and excluded from the total energy outputs.

Self-use or internal energy is an important issue in the assessment of EROI. In the Datang SNG project, the fuel coal, low-pressure steam, and tail gases that are produced during coal liquefaction are burned in the combustor of a captive power plant to create electricity to meet on-site electricity requirements as well as a modest amount of additional electricity that is exported to the electricity grid. Several energy analysts have argued that these internally generated fuels should not be counted as energy inputs because they do not have opportunity costs; i.e., the society did not give something up to create these fuels, unlike the electricity that a SNG facility purchases from the grid. Conversely, the internal energy is used to perform useful work and is thus an essential energy expenditure that is required to produce the desired fuel. Given this controversy, the effect of the internal energy on $EROI_{SNG}$ will be discussed.

The $EROI_{SNG}$ with by-products and internal energy inputs ($EROI_{(1)}$), the $EROI_{SNG}$ without by-products and with internal energy inputs ($EROI_{(2)}$), the $EROI_{SNG}$ with by-products and without internal energy inputs ($EROI_{(3)}$), and the $EROI_{SNG}$ without by-products and internal energy inputs ($EROI_{(4)}$) are calculated using the following equations:

$$EROI_{(1)} = \frac{E_{ey} + E_{by} - L_t}{E_{extern} + E_{intern}} \tag{2}$$

$$EROI_{(2)} = \frac{E_{ey} - L_t}{E_{extern} + E_{intern}} \tag{3}$$

$$EROI_{(3)} = \frac{E_{ey} + E_{by} - L_t}{E_{extern}} \tag{4}$$

$$EROI_{(4)} = \frac{E_{ey} - L_t}{E_{extern}} \tag{5}$$

where E_{ey} and E_{by} refer to the energy products and by-products, respectively, L_t represents the SNG losses during transportation, and E_{extern} and E_{intern} refer to the external energy inputs and internal energy inputs, respectively.

3.2. EROI methods for ING

The EROI of imported fuel is the ratio between the energy value of the amount of fuel that is purchased with a US dollar relative to the amount of fuel that is required to generate a dollar's worth of goods and services (GDP). US dollars (or euros) are used because most oil companies do not accept local currencies. In 1986, Kaufmann derived an explicit method (Eq. (6)) to quantitatively assess the $EROI_{IO}$ (the subscript IO refers to imported oil) (Lambert et al., 2014):

$$EROI_{IO} = \frac{E_{OIL}}{(E_T/GDP) \times P_{OIL}} = \frac{E_{OIL}}{EI_{GDP} \times P_{OIL}} \tag{6}$$

where E_{OIL} is the unit energy content of oil, P_{OIL} is the price of imported oil, and EI_{GDP} is the economic intensity of an economy. Similar to Eq. (6), the $EROI_{ING}$ equation is as follows:

$$EROI_{ING} = \frac{E_{NG}}{EI_{GDP} \times P_{NG}} = \frac{E_{NG} \times M_p}{(E_T/GDP) \times P_{NG} \times M_p} = \frac{E_p}{E_{purch}} \tag{7}$$

where E_{NG} is equal to the unit energy content of NG, P_{NG} is the ING price, M_p is the amount of ING, E_T is the total energy consumption in GDP production, E_p is the total energy content of the purchased NG, and E_{purch} is the total energy input in the purchasing phase.

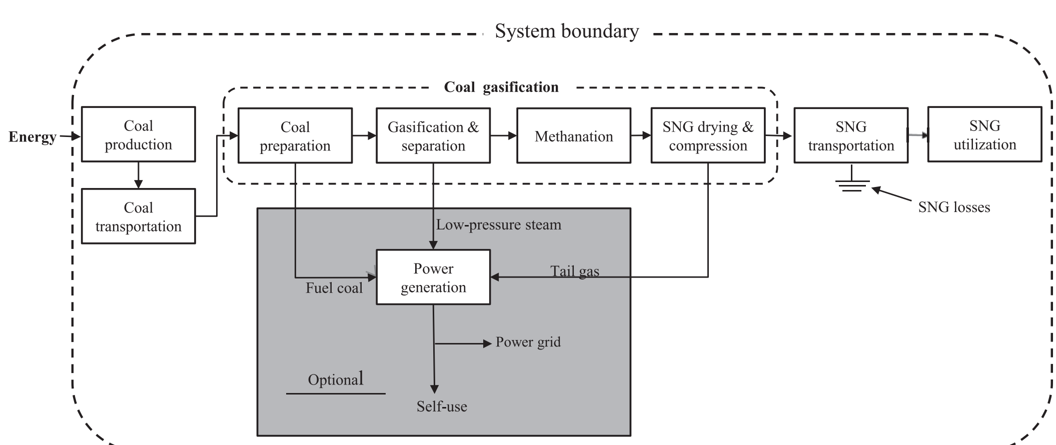

Fig. 3. The analysed life cycle of coal-based synthetic natural gas.

ING is used in four main phases: purchasing, international transportation, domestic transportation, and utilization (Fig. 4). Eq. (7) considers only the purchasing phase, and all the phases are considered in this paper. Moreover, the ING losses during transportation will be estimated and excluded from the total energy output. Therefore, the $EROI_{ING}$ can be calculated by Eq. (8):

$$EROI_{ING} = \frac{E_P - L_{it} - L_{dt}}{E_{purch} + E_{it} + E_{dt}} \quad (8)$$

where L_{it} and L_{dt} refer to the ING losses during international transportation and domestic transportation, respectively, and E_{it} and E_{dt} refer to the energy inputs during international transportation and domestic transportation, respectively.

When calculating the $EROI_{ING}$, we must also address the following factors. P_{NG} refers to P_1 (the price without C_{it} (the unit cost of international transportation)) or P_2 (the price with C_{it}). Here, $P_2 = P_1 + C_{it}$. For example, for imported LNG, the pricing mechanism includes free on board (FOB) and cost, insurance, and freight (CIF) (Sha, 2014). CIF includes C_{it}, but FOB does not. The $EROI_{ING}$ equation with P_1 is different from that with P_2, as is discussed in Appendix A.

3.3. Methodological framework for ENI

Energy systems also have external costs, most notably in the form of environmental and human health costs, which can be difficult to assess in energy terms. As shown in Fig. 5, the methodology comprises three steps:

- Step 1 (air emissions assessment): This step is an inventory and quantification of all the air emissions that occur along the energy supply life cycle. The atmospheric emissions are quantified for each process.
- Step 2 (monetary evaluation): In this paper, the monetary valuation of damage is calculated using an external cost factor, which is the marginal damage cost based on the willingness to pay to avoid the damage that is caused by environmental emissions (European Commission, 2003).
- Step 3 (ENI evaluation): External costs are expressed in terms of money. They must be multiplied by an index of energy intensity before being included in an EROI formula. Thus, a straightforward assessment of energy in physical units is possible. In this paper, EI_{GDP} is used to convert the dollar expenditures into energy.

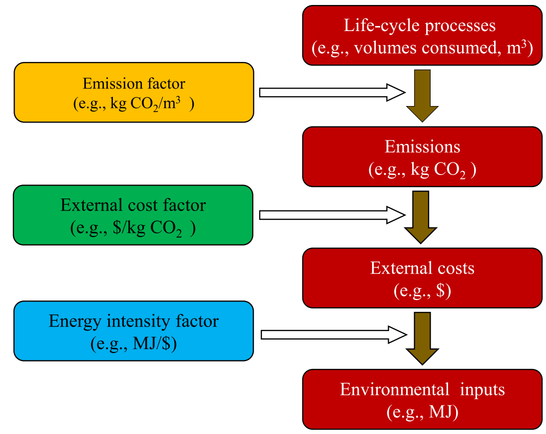

Fig. 5. Illustration of the environmental inputs calculation approach.

In general, the ENI can be calculated using Eq. (9):

$$ENI = \sum_i ENI_i = \sum_i \sum_j A_i \times EF_{ij} \times ECF_{ij} \times EI_{GDP} \quad (9)$$

where ENI_i is the environmental inputs at i (in \$), i is the life cycle stage, A_i is the activity data of life cycle i, EF_{ij} is the emissions factor of emission j (e.g., X kg CO_2), and ECF_{ij} is the external costs factor of emission j (e.g., \$/kg CO_2).

4. SNG energy output and inputs

In this section, this paper estimates the energy outputs in SNG production, energy losses in SNG transportation, and energy inputs in SNG's life-cycle stages.

4.1. Energy outputs in SNG production

Table 1 lists all the energy products and by-products of SNG production. SNG is an energy product, which is directly converted to heat units using the values in Table B1. The by-products are converted into heat units through the prices (Table B2) and the industrial energy intensity, which was approximately 20.5 MJ/\$ in 2015 (Xu et al., 2014).

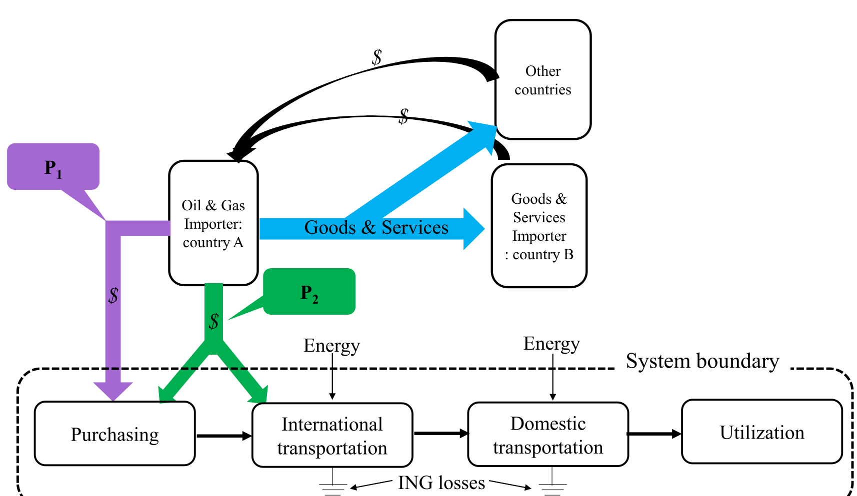

Fig. 4. The analysed life cycle of imported natural gas.

Table 1
Primary energy outputs per 10,000 m^3 of coal-based synthetic natural gas.

Output	Quantity	Unit	Output (MJ)	Output type
SNG	10,000	m^3	346,000	Energy
Naphtha	0.2532	t	15,817	By-product
Tar	1.272	t	5225	By-product
Sulphur	0.30009	t	1192	By-product
Crude phenol	0.144	t	2001	by-product
Crude ammonia	0.1314	t	696	By-product
Total without by-products	–	–	346×10^3	–
Total with by-products	–	–	371×10^3	–

4.2. SNG losses during transportation

The SNG that is produced by the Datang SNG project is transported approximately 448 km by pipeline to Beijing. The NG losses for gas transportation by pipeline usually result from fugitive emissions, flaring, and the gas that is used by fuel compressors to maintain the pressure in the gas line. The NG losses during pipeline transportation can be calculated as:

$$L_t = M_t \times D_t \times LR \tag{10}$$

where L_t is the volume of NG leakage (kg), M_t is the volume of NG transported (m^3), and LR is the loss rate from fugitive emissions, flaring and the gas that is used by the fuel compressors (kg/m^3). In this paper, the production of SNG is 10,000 m^3. According to Zhang et al. (2013), the loss rate from fugitive emissions and flaring is 1.23×10^{-6} kg/m^3 km. Ren (2015) estimates that to transport 120×10^8 m^3 of natural gas by the West–East Gas Pipeline, the fuel compressors use 1.28×10^5 kg of NG to maintain the pressure in the gas line at the appropriate level. The West–East Gas Pipeline is 3842 km long, so the unit natural gas consumption by the fuel compressors is 0.003×10^{-6} kg/m^3 km. LR can be calculated and is approximately 1.233×10^{-6} kg/m^3 km. According to Eq. (10), the value of L_t for SNG transportation is 7.7 m^3, which is equivalent to 266 MJ.

4.3. Energy inputs without ENI

4.3.1. Energy investment in coal extraction

Because Datang does not conduct an explicit accounting of energy consumption during the coal mining process, this paper estimates the energy investment using the average EROI of coal mining in China from Hu et al. (2013). To produce 10,000 m^3 of SNG products, 45.6 t of raw coal must be consumed, which is equivalent to 954×10^3 MJ. Hu et al. (2013) suggests that China's EROI of coal production is approximately 27. According to Eq. (1), the total energy input of coal production is approximately 35×10^3 MJ.

4.3.2. Energy investment in coal transportation

The coal that is consumed by the Datang SNG project is obtained from the Shengli East-NO.2 coalfield, which is an open pit mine. A total of 45.6 t of coal is transported, and the average distance that the raw coal moves from the coal mine to the SNG plant is approximately 180 km. The traffic intensity by railway in China is 0.24 MJ/t km (Ou et al., 2011). Therefore, the energy input of the coal transportation is approximately 1972 MJ.

4.3.3. Energy investment in SNG production

There are three types of energy inputs: fuel inputs, raw material inputs, and other costs. The fuel inputs (fuel coal and purchased electricity) are converted directly into heat units using the conversion factors (Table 2). The raw material inputs (sodium hydroxide, methanol, diisopropyl ether, catalyst, and water) are converted to joules by multiplying the amount of raw material by the price and then by the industrial energy intensity. The other costs (purchases of equipment and instruments) are converted to physical quantities according to the industrial energy intensity.

4.3.4. Energy investment in SNG transportation

The distance from the Datang SNG project to Beijing is approximately 448 km. Ou et al. (2011) reported that the traffic intensity by pipeline is 0.372 MJ/t km. Therefore, the energy input of transporting 10,000 m^3 of SNG is 1200 MJ.

Table 2 lists the inputs, including the fuel, raw materials, and other costs, that are needed to produce 10,000 m^3 of SNG. The energy input is classified into either direct energy input (E_{direct}) or indirect energy input (E_{indirect}) and either E_{extern} or E_{intern}.

4.4. ENI for SNG life-cycle

The emissions of CO_2, CO, CH_4, volatile organic compounds (VOC), SO_2, NO_x, and particulate matter (PM) are considered. The emissions boundary for SNG (Fig. 6) includes five stages: coal mining, coal transportation, SNG production, SNG transportation, and utilization.

The values of EF_j of the air emissions of each life cycle stage of SNG are presented in Table B3 (Li et al., 2014, 2016a; Man et al., 2014). This paper assumes that the SNG is used for heating. The ECF_j values of the emissions that were used in this study were summarized by Li et al. (2014) from different works (Table 3). The EI_{GDP} values in Fig. 7 were also adjusted based on constant 2010 prices.

The values of ENI for different emissions in each life cycle stage are calculated using Eq. (9) using the data that are given in Fig. 8. The SNG production stage requires nearly 58% of the ENI, and 57.6% of the ENI is used to control the CO_2 emissions. The second biggest component of the ENI is coal mining (40%), of which 88% is used to reduce the environmental impacts of the PM emissions.

5. ING energy output and inputs

In this section, this paper estimates the energy content of purchased NG, ING losses in international and domestic transportation, and energy inputs in ING's life-cycle stages.

5.1. Energy content of purchased NG

Data about the NG that is purchased by China (Table B4) are available from Wind Information (2015). The data cover the period from 2009 to 2015 (the 2015 data are only for the first seven months). The energy content of the purchased NG in Table B5 is equal to the volume of purchased NG multiplied by the energy conversion factor (Table B1).

5.2. ING losses during international transportation

Gas from Turkmenistan and Uzbekistan is imported through the China–Mid Asia gas pipeline (Zhang et al., 2016). The values of M_{it} from these two countries are listed in Table B4. D_{it} is shown in Table B6. LR is 1.233×10^{-6} kg/m^3 km (Zhang et al., 2013). The values of L_{it} are calculated using Eq. (10) as shown in Table B7.

Unlike Turkmenistan and Uzbekistan, ING transportation from Australia, Indonesia, Qatar, Malaysia, and Yemen relies on LNG tankers. NG losses for gas transportation by tankers result from boil-off gas (BOG) (Zakaria et al., 2013). LNG is vaporized because of the transfer of heat from the surroundings to the cryogenic LNG, which generates BOG in LNG tankers. The BOG may be consumed by the carrier itself, which causes a loss of LNG due to transportation. Therefore, L_{it} is equal to BOG and can be calculated using Eq. (11):

Table 2
Primary energy inputs per 10,000 m^3 of coal-based synthetic natural gas.

Input	Quantity	Unit	Input (MJ)	Input type
Coal production	–	–	35×10^3	E_{extern}
Coal transportation	–	–	1972	E_{extern}
SNG production	–	–	–	–
E_{direct}	–	–	–	–
Fuel coal	3789	t	145×10^3	E_{intern}
Purchased electricity	847	kW h	5870	E_{extern}
$E_{material}$	–	–	–	–
Sodium hydroxide	9×10^{-3}	t	34	E_{extern}
Methanol	24×10^{-3}	t	238	E_{extern}
Diisopropyl ether	5.25×10^{-3}	t	165	E_{extern}
Circulating water pharmacy	3.825×10^{-3}		50	
Catalyst	0.575×10^{-3}	t	12	E_{extern}
Water	67.25	t	888	E_{extern}
$E_{indirect}$	–	–	–	–
Equipment and instrument purchase	394.9	$	8080	E_{extern}
SNG transportation			1200	
Total (with E_{intern})	–	–	199×10^3	–
Total (without E_{intern})	–	–	54×10^3	–

$$L_{it} = BOG = M_{it}\left[1 - (1 - BR)^{\frac{D_{it}}{S \times 24}}\right] \quad (11)$$

where BOG is the BOG that is produced during transportation by LNG tankers (m^3), M_{it} is the volume of NG that is transported (m^3), BR is the boil-off rate, which indicates the percentage of LNG that must be boiled off to keep the LNG temperature constant as heat is added (x%/day; e.g., 0.5%/d), D_{it} is the distance of international transportation (km), and S is the speed of the LNG tanker (km/h).

The values of M_{it} are listed in Table B4, and the values of D_{it} are shown in Table B6. According to Lin et al. (2010), for large LNG carriers, BR is usually between 0.05 and 0.1%/d with an average value of 0.075%/d. Chu (2000) collected information on approximately 108 LNG ships and found that the operating speeds were 32.4–37 km/h. The average speed was 34.7 km/h, and this value is used in this paper. L_{it} can be calculated by Eq. (11) as shown in Table B7.

5.3. ING losses during domestic transportation

M_{it} is equal to the purchased NG (Table B5) minus NG losses during international transportation (Table B7). LR is 1.233×10^{-6} kg/m^3 km (Zhang et al., 2013), and L_{dt} (Table B8) is calculated using Eq. (10).

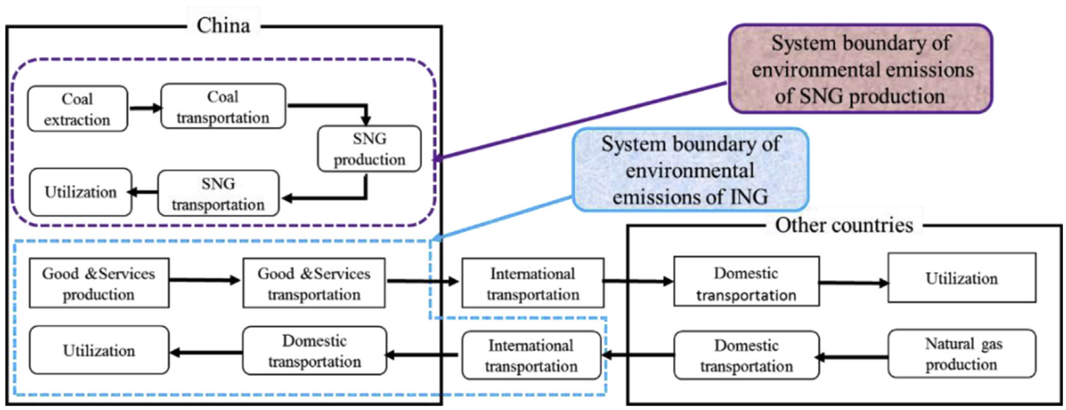

Fig. 6. The analysed life cycle of air emissions.

Table 3
The external costs factors of air emissions.

	CO_2	CO	CH_4	VOC	SO_2	NO_x	PM
ECF_j (US$/kg)	0.032	0.68	0.24	3.58	4.01	5.23	11.84

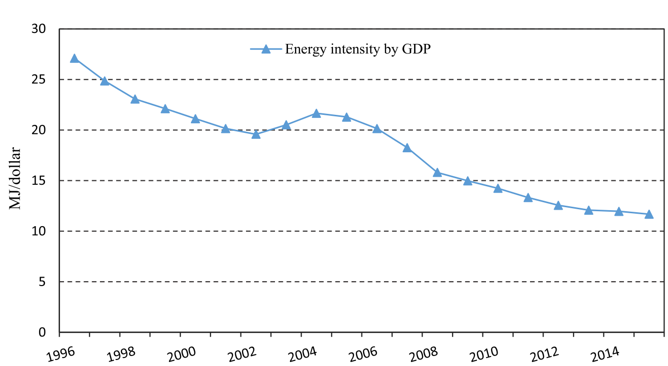

Fig. 7. Energy intensity by GDP in China.

5.4. Energy inputs without ENI

5.4.1. Energy investment in purchasing and international transportation

The ING price (Table B9), including C_{it}, is available from Wind Information (2015). This paper used Eq. (A.8) to create a time series of the energy inputs that are used in purchasing and international transportation (Table B10).

5.4.2. Energy investment in domestic transportation

The domestic transportation of ING relies on gas pipelines (Weijermars, 2015). The traffic intensity by pipeline is 0.372 MJ/t km (Ou et al., 2011). The average distances of domestic transportation for pipeline gas and LNG from the border to Beijing are approximately 3500 km and 1400 km, respectively. M_{dt} is calculated using Eq. (A.4). The energy investment in domestic transportation that is shown in Table B11 is calculated using Eq. (A.2).

5.5. ENI for the ING life cycle

Obtaining ING includes two steps. In step 1, dollars are obtained by exporting goods and services. In step 2, the dollars are spent to import NG. The emissions that are associated with the production and transportation of goods and services in step 1 and the domestic

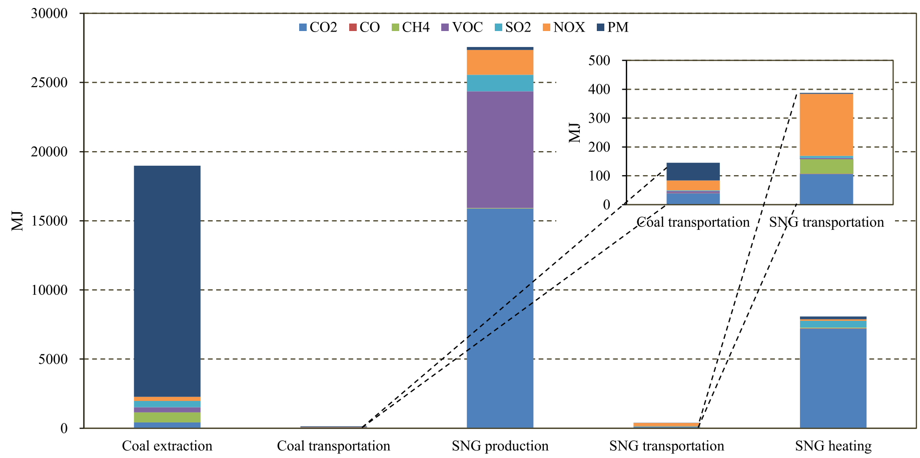

Fig. 8. Environmental inputs for the SNG life cycle.

transportation and utilization of ING in step 2 are produced in China; thus, they are within the life cycle boundary (Fig. 6). Because exported goods and services are used to satisfy other countries' demands, these countries are responsible for the emissions that result from international transportation. Conversely, the emissions from the international transportation of ING must be considered because the gas is used to meet China's demands for economic and social development. The air emissions from other processes are excluded because they occur in other countries.

Similar to the SNG, this paper assumes that the ING is used for heating. The EF_j values of the air emissions of each of the SNG's life cycle stages (Table B12) are taken from Li et al. (2014), Cristea et al. (2013), Zhang et al. (2015), and LMT (2015). The ENI values of different emissions in each life cycle stage are calculated using Eq. (9), and the ENI values of ING from different countries are given in Fig. 9. Most of the ENI is used in the processes of ING heating and international transportation. The ENI of the heating process contributes most of the ING life cycle; it accounts for more than 50% of the total ENI. The ENI of international transportation ranks second and corresponded to approximately 20% of the ENI life cycle in 2014. Controlling CO_2 emissions is responsible for most of the ENI, or approximately 68% of the ING life cycle.

6. $EROI_{SNG}$ and $EROI_{ING}$ results

$EROI_{SNG}$ and $EROI_{ING}$ are calculated using Eqs. (2)–(5) and Eq. (A.9), respectively, and are presented in Fig. 10. For SNG, $EROI_{(3)}$ has the greatest value (approximately 6.9:1), followed by $EROI_{(4)}$ (6.4:1), $EROI_{(1)}$ (1.9:1), and $EROI_{(2)}$ (1.7:1). When the by-products are considered, $EROI_{SNG}$ increases by 7.8–11.8%. The internal

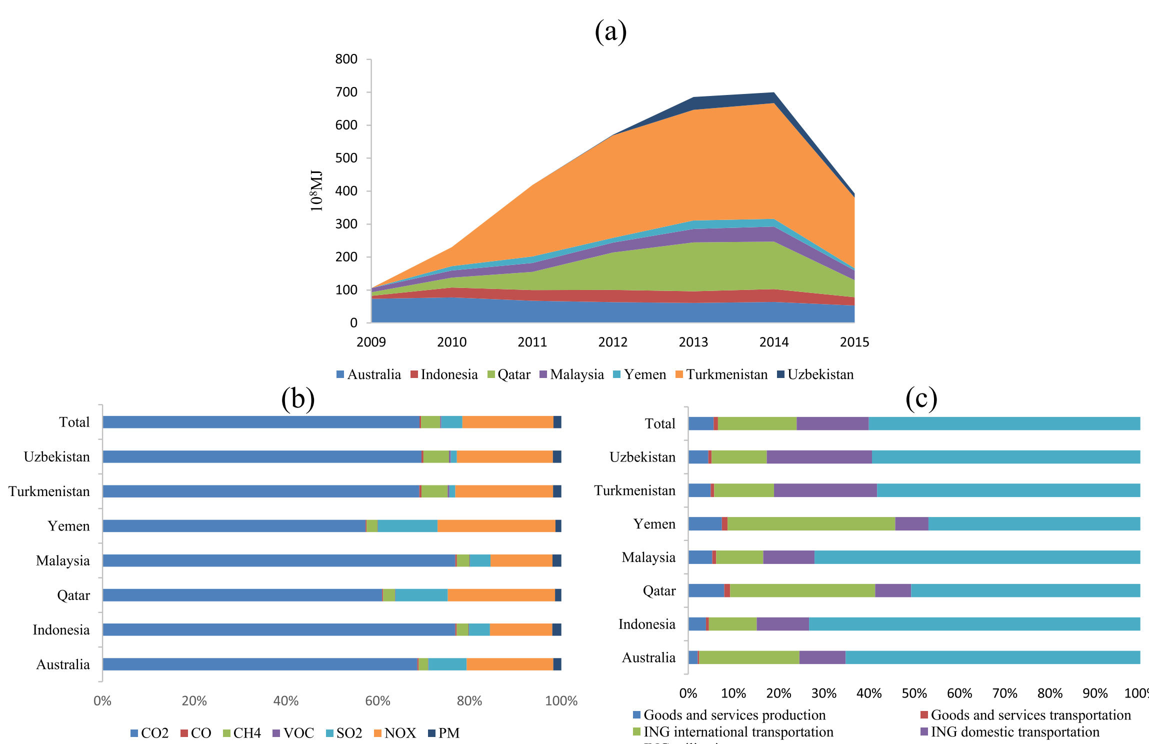

Fig. 9. Environmental inputs for the ING life cycle: (a) total environmental inputs, (b) environmental inputs from air emissions, and (c) environmental inputs from the life cycle process.

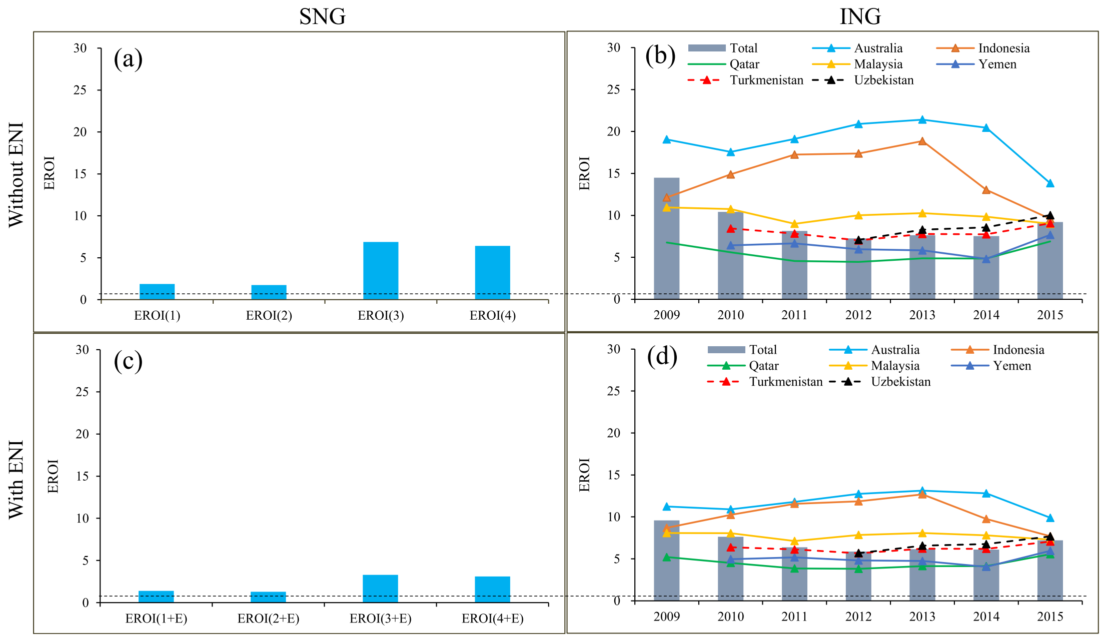

Fig. 10. $EROI_{SNG}$ and $EROI_{ING}$ results: (a) $EROI_{SNG}$ without ENI, (b) $EROI_{ING}$ without ENI, (c) $EROI_{SNG}$ with ENI, and (d) $EROI_{ING}$ with ENI.

energy has a substantially larger effect on $EROI_{SNG}$ than the by-products. When the internal energy is not considered, $EROI_{SNG}$ increases by 2.6–2.8 times. The $EROI_{(1+E)}$ ($EROI_{(1)}$ with ENI), $EROI_{(2+E)}$ ($EROI_{(2)}$ with ENI), $EROI_{(3+E)}$ ($EROI_{(3)}$ with ENI), and $EROI_{(4+E)}$ ($EROI_{(4)}$ with ENI) are 1.5:1, 1.4:1, 3.4:1, and 3.2:1, respectively. Compared with $EROI_{(1)}$, $EROI_{(2)}$, $EROI_{(3)}$, and $EROI_{(4)}$, these values are 21.7%, 21.7%, 50.6%, and 50.6% lower, respectively.

When the ENI is not considered, $EROI_{ING}$ exhibits a generally decreasing trend. $EROI_{total}$ (the EROI of total ING) decreased from 14.5:1 in 2009 to 7.5:1 in 2014 and then increased to 9.2. $EROI_{Australia}$ (in this paper, $EROI_{country}$ indicates the value of $EROI_{ING}$ from a country; e.g., $EROI_{Australia}$ means the value of $EROI_{ING}$ from Australia) has the largest value; it decreased from 19.1:1 in 2009 to 17.6:1 in 2010, increased to 21.4:1 in 2013, and decreased to 13.8:1 in 2015. Similar to $EROI_{Australia}$, $EROI_{Indonesia}$ increased during 2009–2012 and began to decline in 2013. $EROI_{Turkmenistan}$ and $EROI_{Uzbekistan}$ show similar trends and values to $EROI_{total}$. $EROI_{Qatar}$ and $EROI_{Yemen}$ also have similar trends relative to $EROI_{total}$, although the former values are 19.4–54.6% lower than the latter. $EROI_{ING}$ with ENI exhibits similar trends as $EROI_{ING}$ without ENI; however, the former is 19.2–46.8% lower than the latter. For example, because of ENI, $EROI_{Australia}$ in 2015 declined by 30.5% from 13.8:1 to 9.9:1.

The variation of the $EROI_{ING}$ from 2009 to 2015 is due to the change of the ING price. If the ING price increases, more energy is consumed to produce goods for export to generate dollars for importing NG, which means that more energy is used in the purchasing phase and vice versa. For example, the ING price from Indonesia decreased from 0.36 dollar/m^3 in 2009 to 0.28 dollar/m^3 in 2013 and then increased to 0.64 dollar/m^3 in 2015. Correspondingly, $EROI_{Indonesia}$ exhibited an increasing trend in 2009–2013 and decreased in 2014–2015.

$EROI_{SNG}$ is generally lower than $EROI_{ING}$, and the latter has a better net energy return. Without considering the ENI, $EROI_{(1)}$ and $EROI_{(2)}$ are near the break-even point (EROI = 1), which is far lower than $EROI_{total}$ and $EROI_{ING}$ from each exporter. $EROI_{(3)}$ and $EROI_{(4)}$ were similar to $EROI_{Qatar}$ and $EROI_{Yemen}$ from 2009 to 2014, whereas in 2015, $EROI_{Qatar}$ and $EROI_{Yemen}$ increased to 6.9:1 and 7.7:1, respectively, which is higher than $EROI_{(3)}$ and $EROI_{(4)}$. When ENI is included in the total energy inputs, $EROI_{(1+E)}$, $EROI_{(2+E)}$, $EROI_{(3+E)}$, and $EROI_{(4+E)}$ are significantly lower than $EROI_{total}$ and $EROI_{ING}$ from different countries.

Li et al. (2016a) estimated that $EROI_{SNG}$ for municipal heating is between 1.6 and 2.1, which is similar to our EROI estimates for SNG with the internal energy. Ding et al. (2013), Karellas et al. (2012), and Li et al. (2016b) estimated $EROI_{SNG}$ at 0.4–0.7, which is slightly lower than our estimate. The differences between the results of these previous papers and this study are the result of using different boundaries. Despite the differences, all the papers recognize that the energy efficiency of SNG is low. Until now, no studies have estimated $EROI_{ING}$, and only a few papers have focused on $EROI_{IO}$. Lambert et al. (2014) found two $EROI_{IO}$ peaks in China. The latest occurred in 1998, after which it began to decrease. Lambert et al. (2014) and this paper show that the EROI of obtaining oil and gas through trade has decreased.

7. Conclusions and policy implications

This paper systematically analysed the EROI of the Datang SNG project and the EROI of ING to China from different exporters to provide a reference for policy makers and investors. The following conclusions can be drawn from our results:

(1) For SNG, the values of $EROI_{(1)}$, $EROI_{(2)}$, $EROI_{(3)}$, and $EROI_{(4)}$ were 1.9:1, 1.7:1, 6.9:1, and 6.4:1, respectively. These values indicate that the system boundaries have important effects on the results of energy analyses.
(2) In general, $EROI_{ING}$ exhibited a decreasing trend. $EROI_{ING}$ of total imports decreased from 14.5:1 in 2009 to 7.5:1 in 2014 and then increased to 9.2:1 in 2015. The values of $EROI_{ING}$ from different exporters in 2015 ranged from 6.9:1 to 13.8:1.
(3) When ENI was considered, $EROI_{SNG}$ and $EROI_{ING}$ decreased to 1.4:1–3.4:1 and 5.9:1–9.6:1, respectively.
(4) Regardless of the environmental inputs, $EROI_{SNG}$ was generally lower than $EROI_{ING}$, but the latter had a better net energy return.

Based on these results, several suggestions are proposed as follows:

(1) Encouraging the development of ING. ING may have a better energy return than SNG. Therefore, to fill the gap between the gas demand and supply, the government should take measures to increase ING. The most appropriate measure is to rationalize the domestic NG pricing mechanisms. The rationalization of NG prices would stimulate enterprises to look for energy efficiency options first. Moreover, the government should provide additional subsidies to support the construction of import infrastructure, including NG pipelines, LNG tankers, and LNG-receiving terminals.

(2) Optimizing the sources of ING. Based on the values of $EROI_{ING}$, which are different for different exporters, importers could optimize the sources of ING. If the $EROI_{ING}$ from one country is higher than that of another, importing NG from that country is more energy efficient, and the importer should increase imports from that country from a net energy perspective. We do not suggest that the importer should import all the NG from that country even if that country could completely satisfy the import demand because it is unwise to rely on a single source. Here, $EROI_{Australia}$ is higher than that of other countries; thus, China should increase its ING from Australia.

(3) Promoting energy efficiency. Except for a very minor increase in 2015, China's $EROI_{ING}$ has continued to decrease steadily. In the past, the process of developing fuel-intensive domestic industries to generate exports has worked reasonably well for China when the price of ING was low compared to the prices of exports. However, the trends that are suggested by our data imply that if the increasing LNG prices that have been observed over the past several years, and hence the declining $EROI_{ING}$, continue, China and its ability to produce goods will be substantially affected. Therefore, China's policy decisions should focus on improving the energy infrastructure and promoting energy efficiency.

(4) Developing coal gasification technology. The low $EROI_{SNG}$ value means that any increases in production will not meaningfully affect the net energy that is available to society; accordingly, SNG should not currently be developed on a large scale in China. However, the government should continue to support research on coal gasification technology. The difference between $EROI_{ide}$ and the current $EROI_{SNG}$ may be large because the Chinese SNG industry is in its infancy and coal gasification technology is not mature. Thus, additional improvements can be expected from further research funding.

(5) Developing environmental technologies. SNG emits more air pollution than traditional energy. Air emissions in the ING trade are also large. Although some technologies, such as carbon capture and storage, are available to control emissions, the use of such technologies will also increase the energy investment, which could have a considerable negative impact on EROI. As environmental pollution increases, environmental technology will be required in energy production. Therefore, the government should investigate additional methods for developing environmental technologies with lower costs and less energy consumption.

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Appendix A

(1) The equation of $EROI_{ING}$ with P_1

If the importers do not pay the freight to the sellers, they can use their own transportation vehicles to transport ING to their countries or pay money (US dollars) to international transportation companies to transport the ING to their countries.

If international transportation is performed using their own vehicles, E_{it} can be calculated using Eq. (A.1):

$$E_{it} = D_{it} \times M_{it} \times T_{it} \tag{A.1}$$

where D_{it}, M_{it}, and T_{it} refer to the distance, amount, and traffic intensity of international transportation, respectively.

The domestic transportation of ING is usually performed by domestic transportation companies; thus, E_{dt} can be calculated using Eq. (A.2):

$$E_{dt} = D_{dt} \times M_{dt} \times T_{dt} \tag{A.2}$$

where D_{dt}, M_{dt}, and T_{dt} refer to the distance, amount, and traffic intensity of domestic transportation, respectively.

The relationship between M_p and M_{it} (M_{dt}) is represented by Eqs. (A.3) and (A.4).

$$M_{it} = M_p \tag{A.3}$$

$$M_{dt} = M_{it} - L_{it} = M_p - L_{it} \tag{A.4}$$

By substituting Eqs. (A.1)–(A.4) into Eq. (8), $EROI_{ING}$ can be obtained as follows:

$$EROI_{ING} = \frac{E_p - L_{it} - L_{dt}}{EI_{GDP} \times P_1 \times M_p + D_{it} \times M_p \times T_{it} + D_{dt} \times (M_p - L_{it}) \times T_{dt}} \tag{A.5}$$

If international transportation is performed by international transportation companies, the importers must pay US dollars to these companies; therefore, E_{it} should be calculated using Eq. (A.6).

$$E_{it} = EI_{GDP} \times C_{it} \times M_{it} \tag{A.6}$$

By substituting Eqs. (A.2), (A.3), (A.4), and (A.6) into Eq. (8), $EROI_{ING}$ can be obtained according to Eq. (A.7).

$$EROI_{ING} = \frac{E_p - L_{it} - L_{dt}}{EI_{GDP} \times (P_1 + C_{it}) \times M_p + D_{dt} \times (M_p - L_{it}) \times T_{dt}} \tag{A.7}$$

(2) The equation of $EROI_{ING}$ with P_2

Under P_2, the ING price that is paid to the exporters includes the cost of the ING's international transportation. Thus:

$$E_{purch} + E_{it} = EI_{GDP} \times P_2 \times M_p \tag{A.8}$$

By substituting Eqs. (A.2), (A.4), and (A.8) into Eq. (8), $EROI_{ING}$ can be obtained as follows:

$$EROI_{ING} = \frac{E_p - L_{it} - L_{dt}}{EI_{GDP} \times P_2 \times M_p + D_{dt} \times (M_p - L_{it}) \times T_{dt}} \tag{A.9}$$

Appendix B

Table B1
Conversion factors from physical units to thermal units.

Fuel	Average calorific value
Natural gas	34.6 MJ/m^3
Clean coal	26.0–29.1 MJ/kg
Raw coal	20.9 MJ/kg
Diesel	42.7 MJ/kg
Gasoline	43.1 MJ/kg
Electricity	3.6 MJ/kW h

Table B2
Prices of by-products and raw materials.

	Price ($/t)
Naphtha	771
Tar	255
Sulphur	194
Crude phenol	677
Crude ammonia	258
Sodium hydroxide	182
Methanol	484
Diisopropyl ether	1532
Circulating water pharmacy	645
Catalyst	1048
Water	0.65

Table B3
The emissions factors of air emissions.

	CO_2	CO	CH_4	VOC	SO_2	NO_x	PM
Coal mining, kg/t	2.48E+01	7.67E-03	5.68E+00	1.90E-01	2.14E-01	1.08E-01	2.65E+00
Railway transport, kg/t km	1.27E-02	2.50E-05	N/A	1.80E-05	8.00E-06	6.73E-05	5.40E-05
SNG production, kg/m^3	4.25E+00	3.11E-05	1.57E-03	2.02E-02	2.55E-03	2.94E-03	1.53E-04
Pipeline transport, kg/m^3 km	6.34E-05	7.15E-08	3.90E-06	2.25E-08	3.46E-08	7.87E-07	5.49E-09
SNG heating, kg/m^3	1.93E+00	3.50E-04	1.78E-03	N/A	1.04E-03	1.92E-04	1.40E-04

Table B4
Natural gas purchased by China (10^9 kg).

	2009	2010	2011	2012	2013	2014	2015
Australia	3.5	3.9	3.6	3.6	3.6	3.8	3.2
Indonesia	0.5	1.7	2	2.4	2.4	2.6	1.7
Qatar	0.4	1.2	2.3	5	6.8	6.7	2.5
Malaysia	0.7	1.2	1.6	1.9	2.7	3	2
Yemen	0	0.5	0.8	0.6	1.1	1	0.3
Turkmenistan	0	2.6	10.4	15.7	17.7	18.7	11.8
Uzbekistan	0	0	0	0.1	2.1	1.8	0.7
Total	5.5	11.9	22.6	30.5	37.8	40.4	22.6

Table B5
Energy contents of natural gas purchased (10^9 MJ).

	2009	2010	2011	2012	2013	2014	2015
Australia	200.1	223.0	205.8	205.8	205.8	217.3	183.0
Indonesia	28.6	97.2	114.4	137.2	137.2	148.7	97.2
Qatar	22.9	68.6	131.5	285.9	388.8	383.1	143.0
Malaysia	40.0	68.6	91.5	108.6	154.4	171.5	114.4
Yemen	0.0	28.6	45.7	34.3	62.9	57.2	17.2
Turkmenistan	0.0	148.7	594.7	897.7	1012.1	1069.3	674.7
Uzbekistan	0.0	0.0	0.0	5.7	120.1	102.9	40.0
Total	314.5	680.4	1292	1744	2161	2310	1292

Table B6
Distances of international transportation.

	Distance (km)
Australia–China	4372
Indonesia–China	1866
Qatar–China	8136
Malaysia–China	1866
Yemen–China	10143
Turkmenistan–China	2006
Uzbekistan–China	1818

Table B7
Natural gas losses during international transportation (10^8 MJ).

	2009	2010	2011	2012	2013	2014	2015
Australia	7.8	8.7	8.0	8.0	8.0	8.4	7.1
Indonesia	0.5	1.6	1.9	2.3	2.3	2.5	1.6
Qatar	1.7	5.1	9.7	21.0	28.5	28.1	10.5
Malaysia	0.7	1.1	1.5	1.8	2.5	2.8	1.9
Yemen	0.0	2.6	4.2	3.1	5.7	5.2	1.5
Turkmenistan	0.0	5.1	20.5	31.0	34.9	36.9	23.3
Uzbekistan	0.0	0.0	0.0	0.2	3.7	3.2	1.2
Total	10.6	24.3	45.8	67.3	85.7	87.1	47.2

Table B8
Natural gas losses in domestic transportation (10^8 MJ).

	2009	2010	2011	2012	2013	2014	2015
Australia	4.8	5.3	4.9	4.9	4.9	5.2	4.4
Indonesia	0.7	2.3	2.7	3.3	3.3	3.6	2.3
Qatar	0.5	1.6	3.2	6.8	9.3	9.1	3.4
Malaysia	1.0	1.7	2.2	2.6	3.7	4.1	2.7
Yemen	0.0	0.7	1.1	0.8	1.5	1.4	0.4
Turkmenistan	0.0	8.9	35.7	53.8	60.7	64.1	40.5
Uzbekistan	0.0	0.0	0.0	0.4	7.2	6.2	2.4
Total	7.0	20.6	49.8	72.7	90.6	93.7	56.1

Table B9
The prices of imported natural gas from different exporters (dollar/kg).

	2009	2010	2011	2012	2013	2014	2015
Australia	0.16	0.19	0.18	0.18	0.18	0.19	0.31
Indonesia	0.26	0.23	0.21	0.22	0.20	0.33	0.46
Qatar	0.52	0.67	0.88	0.97	0.92	0.93	0.65
Malaysia	0.33	0.34	0.44	0.42	0.42	0.44	0.49
Yemen	–	0.55	0.59	0.72	0.75	0.90	0.66
Turkmenistan	–	0.38	0.45	0.54	0.50	0.50	0.43
Uzbekistan	–	–	–	0.48	0.46	0.45	0.35
Total	0.23	0.34	0.46	0.55	0.54	0.56	0.45

Table B10
Energy investments in purchasing and international transportation (10^9 MJ).

	2009	2010	2011	2012	2013	2014	2015
Australia	8.6	10.6	8.8	7.9	7.7	8.6	11.5
Indonesia	2.1	5.6	5.6	6.6	6.0	10.0	9.2
Qatar	3.1	11.5	27.3	60.9	75.3	74.7	19.2
Malaysia	3.3	5.7	9.3	9.8	13.6	15.8	11.6
Yemen	0.0	4.1	6.4	5.4	10.1	11.2	2.1
Turkmenistan	0.0	14.1	62.0	106.8	106.2	112.9	58.8
Uzbekistan	0.0	0.0	0.0	0.7	11.6	9.6	3.0
Total	18.9	57.1	138.7	210.7	246.3	268.9	118.0

Table B11
Energy investments in domestic transportation (10^9 MJ).

	2009	2010	2011	2012	2013	2014	2015
Australia	1.81	2.02	1.87	1.87	1.87	1.97	1.66
Indonesia	0.26	0.88	1.04	1.25	1.25	1.35	0.88
Qatar	0.21	0.62	1.19	2.59	3.52	3.46	1.29
Malaysia	0.36	0.63	0.83	0.99	1.40	1.56	1.04
Yemen	0.00	0.26	0.42	0.31	0.57	0.51	0.15
Turkmenistan	0.00	3.38	13.50	20.38	22.96	24.26	15.32
Uzbekistan	0.00	0.00	0.00	0.14	2.72	2.34	0.91
Total	2.65	7.80	18.84	27.51	34.29	35.46	21.25

Table B12
The emissions factors of air emissions.

	CO_2	CO	CH_4	VOC	SO_2	NO_x	PM
Export production, kg/$	3.75E-01	N/A	8.74E-03	N/A	N/A	2.48E-04	N/A
Export transportation, kg/$	6.20E-02	N/A	1.44E-03	N/A	N/A	4.10E-05	N/A
LNG carrier, kg/t km	2.69E-02	N/A	N/A	N/A	5.90E-04	7.40E-04	N/A
NG pipeline transportation kg/m^3 km	6.34E-05	7.15E-08	3.90E-06	2.25E-08	3.46E-08	7.87E-07	5.49E-09
NG heating, kg/m^3	1.93E+00	3.50E-04	1.78E-03	N/A	1.80E-04	1.76E-04	1.40E-04

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