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Review

Coal-derived alternative fuels for vehicle use in China: A review

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ABSTRACT

The rapid growth of vehicle ownership in China has brought severe energy and environmental challenges. By referring to a wide range of existing studies and policy documents, this paper reviews the rationality, pathway choice, policy initiatives, barriers and opportunities of developing coal-derived alternative fuels in China, including methanol, Dimethyl Ether (DME) and Coal-to-Liquid (CTL). The review suggests that (a) the production of coal-derived alternative fuels faces the constraints of coal resource, water consumption and CO_2 emissions. China should develop coal-derived alternative fuels with full considerations of these constraints. (b) Coal can be utilized as vehicle fuel through multiple pathways, each pathway with significant trade-off among its energy, environmental and economical attributes. Some critical issues, such as the toxicity of methanol use, the life cycle Greenhouse Gas emissions from different pathways, are still not fully justified. Demonstration plays an essential role in justifying these issues and identifying the optimal technology pathway. (c) The demonstration of methanol use as vehicle fuel faces several major barriers. To further promote the demonstration progress, an essential step is to adjust the excise tax rate for fuel methanol. Besides, the government should consider to establish a number of fuel methanol closed-operation regions in the coal-rich provinces. (d) Driven by the fluctuations in oil prices and policy incentives, the established and planned CTL capacities have been growing very fast. To protect CTL plants from the impacts of oil price fluctuations or carbon tax, the government can consider to provide appropriate subsidies to CTL plants when necessary. (e) The DME fuel and vehicle technologies are more likely to be developed as technology reserves rather than mainstream technologies. Regional demonstration projects should be maintained to improve infrastructure and vehicle technology maturity.

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Abbreviations

CAAM	China Association of Automobile Manufacturers
CATARC	China Automotive Technology and Research Center
CCS	Carbon Capture and Storage
CN	Cetane Number
CNG	Compressed Natural Gas
CNOOC	China National Offshore Oil Corporation
CNPC	China National Petroleum Corporation
CI	Compression Ignition
COP	Conference of the Parties
CTL	Coal-to-Liquid
CTG	Coal-to-Gas
DCTL	Direct Coal-to-Liquid
DME	Dimethyl Ether
DMMn	Polyoxymethylene dimethyl ethers
ECU	Electronic Control Unit
GHG	Greenhouse Gas
HLB	High-Level methanol-gasoline Blend
ICE	Internal Combustion Engine
ICTL	Indirect Coal-to-Liquid
IGCC	Integrated Gasification Combined Cycle
INDC	Intended Nationally Determined Contributions
IPCC	Intergovernmental Panel on Climate Change
LHV	Lower Heating Value
LLB	Low-Level methanol-gasoline Blend
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
MIIT	Ministry of Industry and Information Technology
MOF	Ministry of Finance
NBS	National Bureau of Statistics
NDRC	National Development and Reform Commission
NEA	National Energy Administration
OEM	Original Equipment Manufacturer
RON	Research Octane Number
SAC	Standardization Administration of China
SI	Spark Ignition
Sinopec	China Petroleum & Chemical Corporation
tde	ton of diesel equivalent
tge	ton of gasoline equivalent
VAT	Value Added Tax

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1. Introduction

Driven by economic growth and urbanization process, China's vehicle market experienced rapid growth over the past decade, becoming the world's largest vehicle market since 2009. China's vehicle sales, including passenger vehicles, buses and trucks, increased from 2.1 million in 2000 to 23.5 million in 2014, with an annual growth rate of 19% (CAAM, 2015). Accordingly, China's vehicle stock reached 154 million in 2014. Nevertheless, China's vehicle ownership level was only 113 vehicles/thousand people in 2014, much lower than the level of the developed economies (OICA, 2015). Under such a circumstance, China's vehicle market is expected to experience further growth in the coming decades (Hao et al., 2011d).

Despite the fact that the increasing vehicle ownership has greatly improved travel welfare, it has caused severe negative externalities to the public, including traffic congestion, urban air pollution, CO_2 emissions and energy insecurity (IEA, 2015; IPCC, 2014). In China, vehicles are responsible for over 90% of gasoline consumption and around half of diesel consumption. Driven by vehicle ownership growth, the demand for oil increased dramatically (Hao et al., 2015a, 2015b). As China's domestic oil production has been almost maintained at the level of 200 million tons per year, the incremental oil demand has to be met by oil import. In 2014, China's dependence rate on oil import reached the historic high of 59.6%. This high dependence on oil import caused great concerns over energy security.

To reduce oil consumption by vehicles, China has followed two basic strategies, namely, reducing oil demand and finding alternatives to oil. From the perspective of reducing oil demand, China has implemented a multi-phase fuel consumption regulation for passenger vehicles, with a target of reaching 5 L/100 km in 2020. Meanwhile, energy-efficient vehicles are qualified for financial incentives such as subsidy and tax-exemption. Besides, policies on vehicle ownership and usage have been implemented to reduce transport demand (Hao et al., 2011a, 2011c). From the perspective of finding alternatives to oil, China has been promoting the uses of coal, natural gas and biomass derived vehicle fuels as alternatives to conventional gasoline and diesel (Salvi et al., 2013). The uses of electricity on electric vehicles and hydrogen on fuel cell vehicles have also been promoted (Hao et al., 2014b, 2015c).

Among these alternative fuel pathways, each pathway offers unique advantages and disadvantages. The identification of the 'best fuel' for vehicle use is not absolute, but depends on the perspective chosen. From the economic perspective, the conventional petroleum-based gasoline and diesel pathways offer comparative advantages due to their mature production technology and the existing widespread refueling infrastructures. From the environmental perspective, the low-carbon fuels, such as natural gas and bioethanol, offer the benefits of lower tailpipe emissions and life cycle Greenhouse Gas (GHG) emissions. Electricity and hydrogen are also preferable for their zero tailpipe emissions characteristics. From the energy security perspective, China is poor in oil and natural gas resources, but relatively rich in coal resource (Lu and Ma, 2004). Under such a circumstance, coal-derived alternative fuels become a preferable choice to enhance energy security. Actually, the Chinese government has been very interested in promoting the use of coal as alternative to oil.

With the development of coal chemical industry, coal can be potentially utilized as vehicle fuel through the following six pathways:

Methanol pathway: Coal → Methanol → SI (Spark Ignition)-ICE (Internal Combustion Engine) vehicle.

DME pathway: Coal → Dimethyl Ether (DME) → CI (Compression Ignition)-ICE vehicle.

DCTL pathway: Coal → Direct Coal-to-Liquid (DCTL) → CI-ICE vehicle.

ICTL pathway: Coal → Indirect Coal-to-Liquid (ICTL) → CI-ICE vehicle.

Electricity pathway: Coal → Electricity → Electric vehicle.

Hydrogen pathway: Coal → Hydrogen → Fuel cell vehicle.

It was estimated that the consumption of methanol as vehicle fuel reached over 6.0 million tons in 2013 (Chang, 2014). CTL production reached 1.2 million tons in 2014 (MIIT, 2015b), most of which was consumed by vehicles. Accordingly, the amount of gasoline and diesel replaced by methanol and CTL were around 2.8 and 1.2 million tons, which accounted for around 3.1% and 1.7% of total gasoline and diesel consumptions by vehicles in 2014. More specific decompositions of the fuel consumptions by vehicles in China can be found in relevant studies (Hao et al., 2015a, 2015b). With the development of China's coal chemical industry, the consumptions of coal-derived alternative fuels are expected to experience further growth in the future.

From an international perspective, there have been trails on developing coal-derived alternative fuels in many other countries. As early as in the World War II, Germany established 18 DCTL and 9 ICTL plants, with their productions meeting 90% of domestic gasoline demand (Dubey, 2008). However, these plants were mostly closed down after World War II. After that, the most significant progress was led by Sasol, South Africa's dominating energy company. Sasol's trial on CTL production was mostly driven by the international sanctions imposed on South Africa during the apartheid era and the government's unsuccessful looking for oil. Benefiting from the generous government subsidy, Sasol has made a great fortune through its CTL plants. Sasol established the Sasol Synfuel II and Sasol Synfuel III CTL plants in 1980 and 1984, with a total production capacity of 160,000 barrels per day (Gas-to-Liquids News, 2005). These two plants are still under operation nowadays. Driven by the oil crisis in the 1970s, countries like the U.S. also showed significant interests in developing CTL. Especially, over recent years, the use of CTL as jet fuel, which was estimated to be cost-effective and market-competitive, has become an emphasis of the energy research and development (NETL, 2015).

Technologically, coal can also be utilized to produce ethanol, which is another kind of vehicle alternative fuel. However, in reality, the use of coal-derived ethanol is very little. Globally and in China, ethanol is mainly derived from biomass. With Brazil as a representative, bioethanol has played an essential role in the transition of vehicle energy system. The progress of bioethanol application in the U.S. and China was also remarkable over the past decade. Global bioethanol consumption was estimated to increase from 0.35 EJ in 2000 to 1.78 EJ in 2012 (EIA, 2015). However, considering the scope of this study, the ethanol issues are not detailed in this paper.

Existing studies on coal-derived alternative fuels mostly focus on evaluating their energy, environmental and economical impacts. Liu et al. (2013) compared the properties of coal-derived methanol, DME, CTL from multiple aspects, resulting in a technology roadmap for the development of coal-derived alternative fuels in China. Regarding fuel methanol, Zhen and Wang (2015) summarized the thirteen methods of applying methanol in ICE vehicles. Chen et al. (2014) analyzed the development strategy of fuel methanol in China. They argued that the use of fuel methanol in China should be constrained in coal-rich regions. The basis for this argument is that in the coal-rich regions, the methanol transportation, storage and refueling infrastructures are quite mature, which implies a low fuel system transition cost. However, in other regions, the infrastructures are not mature enough to support the transition. Regarding DME, Park and Lee (2014) reviewed the use of DME in CI engine. They concluded that the use of DME offers the benefits of lower NO_x, HC and CO emissions. Zhang and Huang (2007) conducted life cycle assessment on the GHG emissions of coal-derived DME used on urban buses. They found that using coal through the DME pathway is more rational than through the CTL pathway from the GHG emissions perspective. CTL has received the highest attention from the research community. Ou et al. (2010) compared the GHG emissions of the CTL pathway and other coal-based pathways, and concluded that the CTL pathway significantly increases the life cycle GHG emissions compared with petroleum-based pathways. Xu et al. (2015) introduced the development of CTL technology and industry in China, and discussed their possible environmental impacts. Mantripragada and Rubin (2013a) evaluated the CO_2 impacts of CTL plants under multiple aspects. Besides coal-derived alternative fuels, other coal-derived products have also received attention from the research community (Xiang et al., 2015). Overall, researches have revealed the impacts of developing coal-derived alternative fuels in multiple dimensions. However, technology evaluation alone is not enough to answer the question of how China should develop coal-derived alternative fuels. Alternatively, this question can only be answered based on the comprehensive considerations on resource abundance, environmental impacts, technology pathway advantages and disadvantages, and market acceptance.

For these reasons, a comprehensive review on the development of coal-derived alternative fuels in China is conducted. This review aims to answer the questions of if China should develop coal-derived alternative fuels and, if so, on what scale, through what technology pathway, and based on what deployment strategy. The

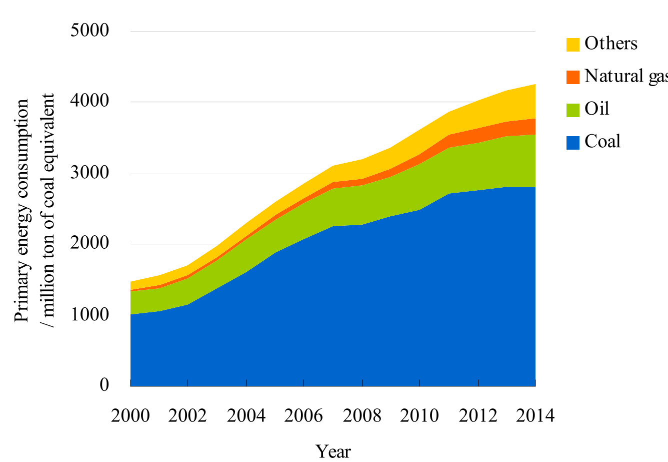

Fig. 1. Primary energy consumption in China from 2000 to 2014.

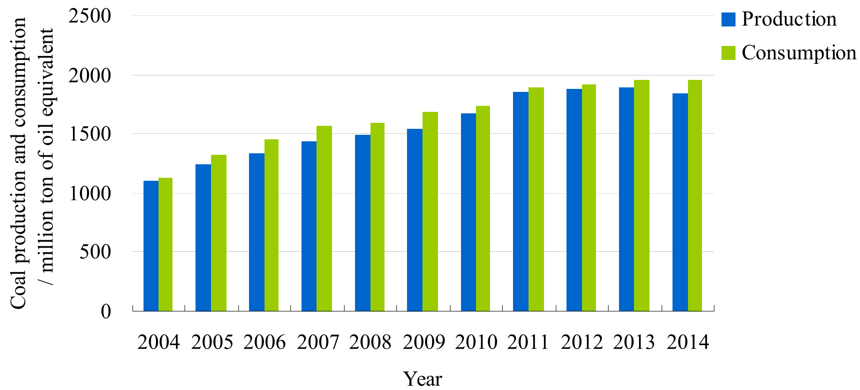

Fig. 2. Coal production and consumption in China over recent years. Note: [a] The gap between coal production and consumption was the net coal import.

review is organized as follows: the next section analyzes the rationality of developing coal-derived alternative fuels from the resource abundance perspective. Following this, the major promising technology pathways of utilizing coal as alternative fuels are compared. The subsequent section summarizes the policy initiatives China has taken to promote the use of coal-derived alternative fuels. Following this, barriers and opportunities for each alternative fuel are assessed. Policy implications are raised in the next section. The last section concludes the whole review.

2. Coal utilization in China

In this section, the current status of coal utilization in China is introduced. Based on this, the rationality of developing coal-derived alternative fuels is discussed.

2.1. *Coal resource, production and consumption*

China has relatively rich coal resources. The proved coal reserve in China was estimated to be 114.5 billion tons, 12.8% of global total (BP, 2015). As a comparison, the shares of China's proved oil and natural gas reserves are only 1.1% and 1.8% of global total (BP, 2015). Therefore, coal has long been playing the dominating role in China's energy system, as Fig. 1 shows (NBS, 2015a). As Fig. 2 shows, China's coal production and consumption experienced rapid growths over recent years, increasing by 67% and 74% within the last decade, respectively (NBS, 2015a). In 2014, China's coal consumption was 1962 million tons of oil equivalent, representing 66.0% of China's primary energy consumption, and 50.6% of global coal consumption (BP, 2015).

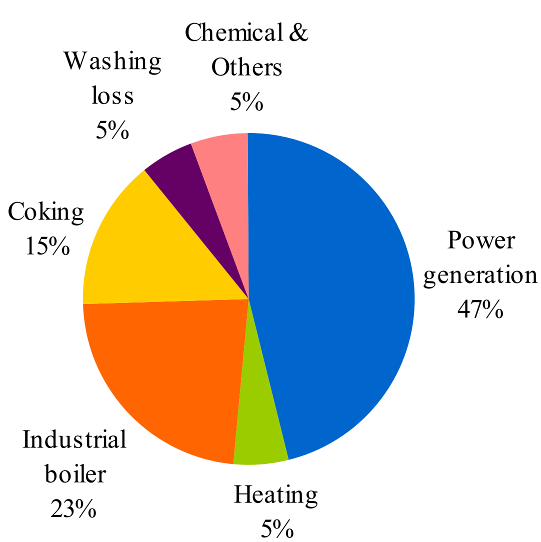

Fig. 3. Decomposition of coal consumption in China by utilizations in 2013.

Generally, power generation is the most efficient way of coal utilization, especially when coupled with high-efficiency generation technologies, such as Integrated Gasification Combined Cycle (IGCC), and emissions control technologies such as Carbon Capture and Storage (CCS). Based on this consideration, China has prioritized the use of coal for power generation. The share of electricity-coal out of total coal consumption is projected to increase from the current level of 46%–60% in 2020 (NBS, 2015a). Besides, coal is also the necessary material and energy feedstock for other industrial sectors. Other major forms of coal utilization include industrial boilers, coking and heating, which were responsible for 23%, 15%, and 5% of total coal consumption in 2013, as Fig. 3 shows (NBS, 2015a). Currently, coal consumption for chemical uses, except coking, is relatively in a small scale, accounting for less than 5% of total coal consumption.

Coal chemical industry is commonly conceptually categorized into traditional and modern coal chemical industries, as Fig. 4 shows. Traditional coal chemical industry includes the productions of coke, calcium carbide, ammonia, methanol, etc. These sectors have been established for a long time and are quite mature in technology. Modern coal chemical industry is based on C1 chemical knowledge, which refers to chemical production through the synthesis of materials containing one carbon atom, such as methane, methanol, etc. Modern coal chemical industry covers the productions of CTL, Coal-to-Gas (CTG), DME, olefin, ethylene glycol, etc (Xie et al., 2010).

From an international perspective, coal production and consumption are concentrated in several major countries. Following China, U.S. and India are the second and third largest coal-consuming countries, which accounted for 11.7% and 9.3% of global coal consumption in 2014, respectively (BP, 2015). As the energy situations in these countries are quite different, the utilizations of coal resource show significant disparities. In the U.S., around 95% of coal consumption is for power generation, with the other 5% for coking and other utilizations. The major reason behind this consumption pattern is that natural gas, as a cleaner primary energy, has already been widely used in power generation and other industrial sectors, which squeezes the space for coal utilization. Besides, the demand for coking in the U.S. is much lower than in China. Regarding India, the situation is much more similar to China. The coal consumptions attributed to power generation, coking and other utilizations are around 70%, 15% and 15%.

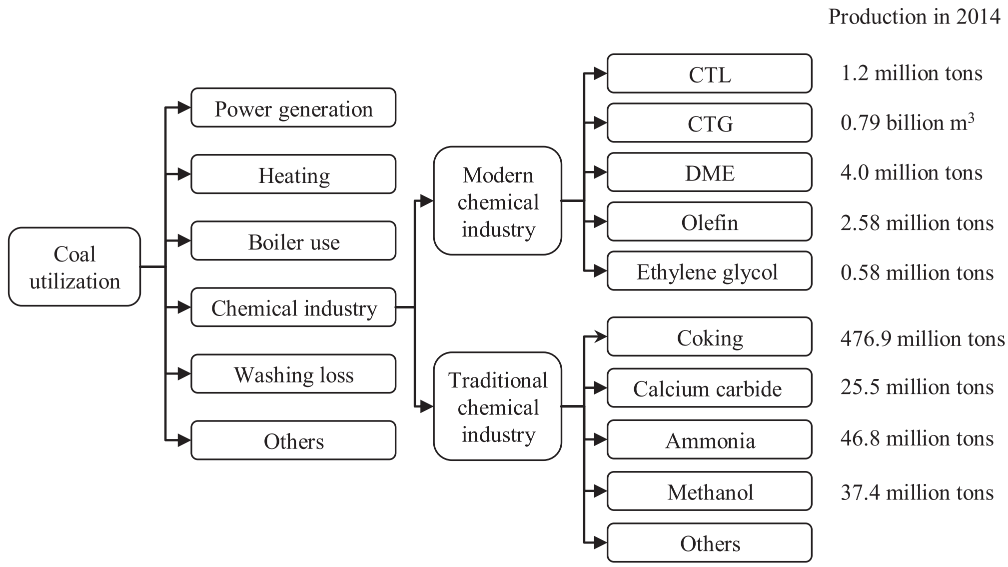

Fig. 4. Coal utilization pathways in China.

Especially, India is also showing interests in developing coal chemical industry over recent years.

2.2. Coal-derived alternative fuels

As mentioned above, the basic idea behind the development of coal-derived alternative fuels is to replace the use of the scarce oil resource with the relatively abundant coal resource. However, this is not an impeccable logic of utilizing coal resource. In fact, developing coal-derived alternative fuels faces severe resource, environmental and economical constraints.

First, as mentioned above, due to the fast increase of coal demand, China has become a net importer. On the consumption side, China's power generation and industrial boilers rely mainly on coal. Under such a circumstance, the amount of coal that can be utilized as feedstock to produce vehicle fuels is actually quite limited (Brathwaite et al., 2010). On the other hand, with China's booming natural gas production and import, natural gas has been more and more utilized as vehicle fuel (NDRC, 2012), which reduces the urgency of oil consumption replacement (Hao et al., 2011b, 2014a, 2012).

Second, the production of coal-derived alternative fuels is accompanied by considerable water consumption. It is estimated that the water consumptions for methanol, DME, DCTL and ICTL productions are 8.3t, 21.7t, 6.0t and 11.0t per ton product, respectively (Jin et al., 2012). However, the fact is that China's water resource distribution highly mismatches with coal resource distribution. China's coal resources distribute mainly in northwestern regions. But these regions are mostly poor in water. In other words, developing coal-derived alternative fuels in coal-rich regions faces great water resource constraint. Although this issue can be solved by transporting coal to water-rich regions, the additional transport cost and, in addition, emission of CO_2, will severely reduce the overall cost competitiveness of coal-derived alternative fuels.

To address the water issues, more and more water treatment, purification and recycling technologies have been employed to reduce water consumption and emissions from the coal chemical industry. For example, the Shenhua DCTL project is designed and built to be 'near-zero wastewater discharge', which was realized by establishing four wastewater treatment systems dedicated to

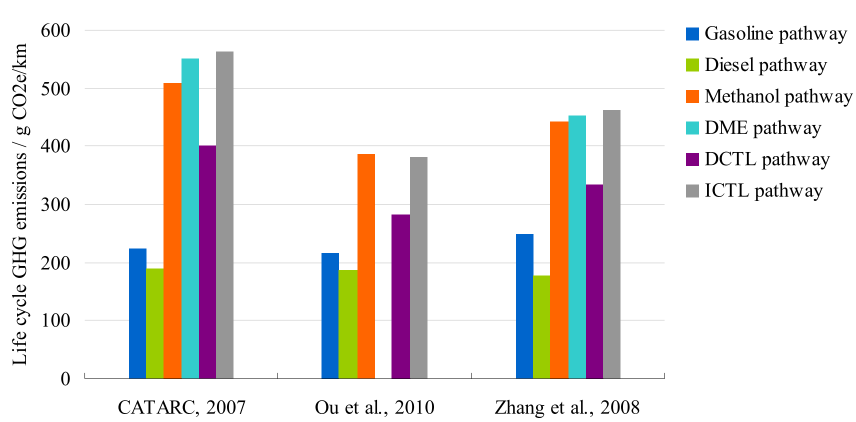

Fig. 5. Comparison of the life cycle GHG emissions of coal-derived alternative fuels. Notes: [a] The unit of g CO_{2e}/km denotes the life cycle GHG emissions (measured in g CO_2 equivalent) per kilometer the vehicle travels. [b] The research boundaries of the cited studies are a bit different. The CATARC (2007) study and the Zhang et al. (2008) study include GHG emissions from fuel cycle and vehicle end-use phase. The Ou et al. (2010) study includes not only GHG emissions from fuel cycle and vehicle end-use phase, but also GHG emissions from vehicle manufacturing. [c] The assumptions for the methanol pathway in the cited studies are different. The Zhang et al. (2008) study is based on the use of M85, while the other two studies are based on the use of M100.

dealing with high concentration organic wastewater, low concentration oily wastewater, salty wastewater, and wastewater containing catalyst, respectively. However, in actual operation, due to operation instability and the lack of experiences, these water treatment technologies normally do not function well. Besides, as the application of these water treatment technologies needs considerable capital investment and operation cost, most coal chemical companies are not willing to afford this burden.

Third, the life cycle GHG emissions of coal-derived alternative fuels are much higher than conventional petroleum products. Fig. 5 shows the life cycle GHG emissions from the use of coal-derived alternative fuels estimated by different studies (CATARC, 2007; Ou et al., 2010; Zhang et al., 2008). The life cycle GHG emissions of methanol, DME, DCTL and ICTL productions are 50%–200% higher than the conventional petroleum pathways. In the context of global GHG mitigation, China is facing great pressure from the global community in controlling GHG emissions (State Council, 2014b). As specified in the Intended Nationally Determined Contributions (INDC) China submitted to the Intergovernmental Panel on Climate Change (IPCC), China promises to peak its CO_2 emissions before 2030 (State Council, 2015). During the 21st session of the Conference of the Parties (COP21) held in Paris, President Xi reasserted this promise (Xi, 2015). The target of GHG mitigation is gaining higher and higher priority in the overall energy strategy. With the aim of reducing GHG emissions, China has considered reducing coal consumption as a major energy strategy (State Council, 2014a). Under such a circumstance, developing coal-derived alternative fuels is not in line with the GHG mitigation target.

It should be noted that with the development of CCS technologies, it becomes technologically possible to significantly reduce GHG emissions from the production of coal-derived alternative fuels. As reported by NETL (2009), the life cycle GHG emissions of CTL production equipped with CCS is lower than petroleum-derived fuels. However, the deployment of CCS technologies is accompanied by considerable cost increment. As estimated by Berg et al. (2007), an additional $10/barrel cost was expected when adding CCS to CTL plants.

Fourth, modern coal chemical industry faces great uncertainties in its economical feasibility. Modern coal chemical industry is capital-intensive. For example, the average investment intensity for ICTL project is around ¥15 billion (~$2.4 billion)/million ton capacity. From the cost-benefit perspective, such projects can only be rational when operating over a certain scale. However, as coal-derived alternative fuels are facing direct competition from conventional fuels, the market can be greatly affected by oil price fluctuations. Accordingly, there is a high possibility that the established production capacities can not be fully utilized, which implies huge losses to the society.

Based on these considerations, the Chinese government has been very cautious about the development of coal-derived alternative fuels. As Table 1 shows, since 2004, the government has launched a series of policy initiatives to regulate the development of coal chemical industry, with coal-derived alternative fuels as a focus (NDRC, 2006a, b, 2007a, b, 2008, 2009, 2011; NEA, 2013, 2014a, b, 2015; SDRC, 2013a, b; State Council, 2005, 2009). The essential ideas behind the documents are to strictly constrain the establishments of coal chemical projects, especially the CTL and CTG projects; and to encourage large, efficient projects and eliminate smaller, inefficient ones. For example, CTL projects with capacities of 1 million tons/year or lower, CTG projects with capacities of 2 billion m^3/year or lower, were prohibited to be established. Overall, although there is a high demand for developing coal-derived alternative fuels in China, this industry faces severe resource, environmental and economical constraints. Existing studies estimated that with all possible constraints accounted, the maximum amount of coal resource that can be allocated to produce alternative fuels is around 100–200 million tons per year (Liu et al., 2013).

2.3. Established capacities

The methanol, DME and CTL productions in China over recent years are presented in Fig. 6 (MIIT, 2015b; NBS, 2015b). By 2014, the established methanol production capacity reached 68.9 million tons, most of which were coal-based capacities (CCIN, 2015). However, affected by low oil price, most established facilities were in the status of under production (Su et al., 2013). The actual methanol production was only 37.4 million tons in 2014, implying a capacity utilization rate of around 54%. Methanol is currently mainly consumed as feedstock for downstream chemical products, such as olefin, methanal, DME, acetic acid, among others. The consumption of methanol as vehicle fuel was estimated to be 6.0 million tons in 2013, accounting for around 15% of total methanol consumption (Chang, 2014).

The utilization rate of DME production capacity is even lower than methanol. By 2014, China's DME production capacity reached 14.9 million tons. However, the actual production was only 4.0 million tons, implying a capacity utilization rate of around 27% (Hu, 2015). DME is currently mainly consumed as the alternative to liquefied petroleum gas (LPG) for residential uses. Very little amount of DME is consumed as vehicle fuel.

China's CTL production capacity and actual production in 2014 reached 1.58 and 1.20 million tons, respectively (MIIT, 2015b). Table 2 summarizes China's initiated CTL projects. The Shenhua DCTL project located in Erdos, Inner Mongolia is the only commercialized DCTL project globally. Meanwhile, eight ICTL projects have been established or under construction. With all these CTL projects established as planned, China's total CTL production capacity is expected to reach around 20 million tons by 2020. This implies a total coal consumption of around 100 million tons as feedstock for CTL production.

3. Technology assessment

Coal can be utilized as vehicle fuel through diversified pathways. These pathways have different impacts on every aspect of the transport system, which is summarized in Table 3. The following sections will discuss the impacts in detail. As methanol and DME are used as alternatives to gasoline and diesel, the physical-chemical properties of these fuels are compared, as presented in Table 4.

3.1. Methanol pathway

Methanol can be derived through coal gasification and synthesis processes (Xie and Li, 2005). Low-Level methanol-gasoline Blend (LLB) can be used directly on conventional vehicles. Regarding high-Level methanol-gasoline Blend (HLB)/pure methanol, as their physical-chemical properties, such as LHV, theoretical air/fuel ratio, RON, change significantly compared with gasoline, they can only be used on modified or dedicated vehicles. The major vehicle modification needed is to install an additional Electronic Control Unit (ECU) on the fuel injection system, which adjusts the fuel injection timing and quantity so that the engine works in a mode that matches the physical-chemical property of the new fuel.

Compared with the CTL pathway, the major advantage of the methanol pathway is its higher overall energy efficiency. Given one unit of coal input, the vehicle mechanical work delivered through the methanol pathway is around 15% higher than the GTL pathway

Table 1
China's recent policy initiatives on coal chemical industry.

Year	Guidance document	Major points	References
2005	Guidance on promoting the healthy development of coal industry	To steadily promote the development of CTL and CTG projects To evaluate the resource impacts of CTL and CTG projects	State Council, 2005
2006	Notification on strengthening the management of coal chemical projects	CTL projects were suspended to be approved until the launch of national CTL development plan Coal chemical projects under certain scales were prohibited to be established: CTL projects with capacities of 3 million tons/year or lower Methanol and DME projects with capacities of 1 million tons/year or lower Olefin projects with capacities of 0.6 million tons/year or lower	NDRC, 2006b
2006	Mid-long term development plan of coal chemical industry (Exposure draft)	Targets for the coal chemical productions: Methanol: 16, 38, 66 million tons in 2010, 2015 and 2020 DME: 5, 12, 20 million tons in 2010, 2015 and 2020 CTL: 1.5, 10, 30 million tons in 2010, 2015 and 2020 Olefin: 1.4, 5, 8 million tons in 2010, 2015 and 2020	NDRC, 2006a
2007	The eleventh five-year plan on coal industry	CTL Projects to be established and demonstrated before 2010: 1 million tons/year DCTL project by using domestic independent technologies 3 million tons/year ICTL project by incorporating foreign mature technologies 0.16 million tons/year ICTL facility and 1 million tons/year ICTL project by using domestic independent technologies To establish financial incentives for the production and use of CTL, methanol and DME	NDRC, 2007b
2007	Coal industry policy	To moderately develop coal chemical industry in water-rich and coal-rich regions To restrict the development of coal chemical industry in water-scarce and coal-importing regions To prohibit the development of coal chemical industry in regions with insufficient environmental capacity	NDRC, 2007a
2008	Notification on strengthening the management of CTL projects	The Shenhua DCTL project can continue to be demonstrated The Shenhua ICTL project can only be started after careful evaluation and approval from the central government All other CTL projects must be halted	NDRC, 2008
2009	Restructuring and revitalization plan on petrochemical industry	The approval of modern coal chemical projects would be halted for three years	State Council, 2009
2009	Notification on restricting over capacity and duplicated construction, and guiding healthy industrial development	The approval of modern coal chemical projects would be halted for three years (in line with previous guidance)	NDRC, 2009
2011	Notification on regulating the development of coal chemical industry	Coal chemical projects under certain scales were prohibited to be established: Olefins projects with capacities of 0.5 million tons/year or lower Methanol projects with capacities of 1 million tons/year or lower DME projects with capacities of 1 million tons/year or lower CTL projects with capacities of 1 million tons/year or lower CTG projects with capacities of 2 billion m^3/year or lower Ethylene glycol projects with capacities of 0.2 million tons/year or lower	NDRC, 2011
2013	Coal industry policy (Revised version)	The principles of coal chemical industry development in the 2007 version of Coal Industry Policy were reiterated	NEA, 2013
2014	Notification on regulating the development of CTL and CTG industries	CTL and CTG projects can only be established with the approval from the central government CTL and CTG projects under certain scales were prohibited to be established: CTL projects with capacities of 1 million tons/year or lower CTG projects with capacities of 2 billion m^3/year or lower	NEA, 2014b
2014	Guidance on promoting the safe, green development and clean, efficient utilization of coal	Modern coal chemical industry should be developed moderately	NEA, 2014a
2015	Initiative on clean and efficient utilization of coal	Modern coal chemical industry should be developed moderately (in line with previous guidance) With successful demonstration, modern coal chemical projects should be further developed with integrated considerations	NEA, 2015

(Jin, 2015). Besides, methanol production technology has been developed for decades and is currently quite mature. The investment for a methanol plant is lower than a CTL plant on a unit production capacity basis. The tailpipe emissions of methanol vehicles can be lower than conventional vehicles. As summarized by Dhaliwal et al. (2000), compared with conventional gasoline vehicles, vehicles running on HLB realize 16%–61% HC reduction and a substantial reduction in non-aldehyde toxic compounds. Wei et al. (2008) reported that the use of M85 (85% methanol-15% gasoline blend) leads to a 25% reduction in CO and 80% reduction in NO_x compared with the use of pure gasoline.

The major disadvantage of the methanol pathway is the compatibility issues. The transport, storage and distribution of methanol depend on dedicated systems. For the uses of HLB/pure methanol, both existing infrastructure and vehicle fleet need significant modifications. This implies significant transition cost to the society. Besides, the toxicity issues of fuel methanol are still controversial. The use of HLB/pure methanol can cause vehicle problems like engine corrosion and difficulty in low-temperature starting, although they can be avoided by special treatments.

3.2. DME pathway

DME can be derived from coal through two major methods, the one-step method and two-step method. Most existing production facilities in China are based on the two-step method, namely, using coal to produce methanol as the first step, and to produce DME through methanol dehydration as the second step. DME is gaseous

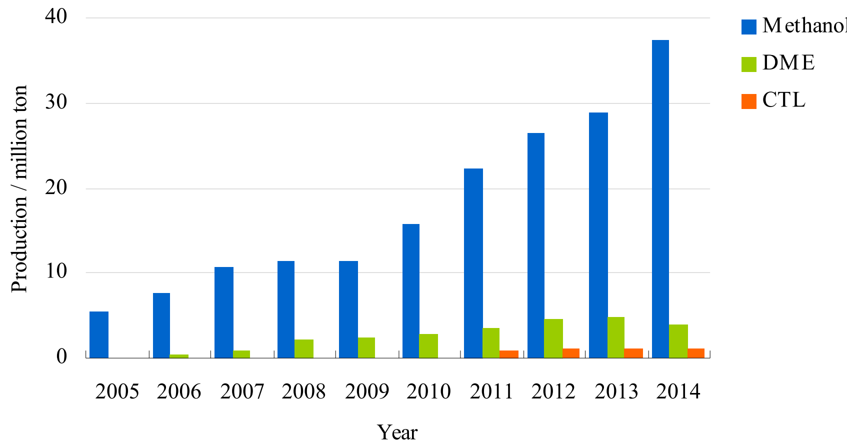

Fig. 6. Productions of methanol, DME and CTL in China over recent years.

Table 2
Established and planned CTL projects in China.

Project developer	Technology	Location	Status	Designed capacity million ton/year
Shenhua	DCTL	Erdos, Inner Mongolia	Operating since 2008	5.0
	ICTL	Ningdong, Ningxia	Under construction, ready in 2017	4.0
Yitai	ICTL	Yili, Xinjiang	Under construction, ready in 2016	1.0
	ICTL	Urumchi, Xinjiang	Under construction, ready in 2016	2.0
	ICTL	Erdos, Inner Mongolia	Under construction, ready in 2016	2.0
Lu'an	ICTL	Changzhi, Shanxi	Under construction, ready in 2016	1.8
Yankuang	ICTL	Yulin, Shaanxi	Operating since 2015	1.0
Yanchang	ICTL	Yulin, Shaanxi	Operating since 2015	0.15
Yufu	ICTL	Bijie, Guizhou	Under construction, ready in 2018	2.0
			Total planned	**18.95**

under normal temperature and pressure. Thus, DME can only be used through dedicated infrastructure and on dedicated vehicles. The major differences between DME vehicle and conventional diesel vehicle are the redesign of fuel supply system and the adjustment of engine working mode (Zhang and Huang, 2007). The DME pathway features the similar advantages with the methanol pathway, i.e., high energy efficiency and technology maturity, lower plant investment (Jin et al., 2012). On the other hand, DME vehicle and infrastructure technologies are still in the stage of demonstration. The technological barriers such as corrosion, engine power degradation, need to be further solved (Arcoumanis et al., 2008).

3.3. CTL pathway

CTL can be derived through both direct liquefaction and indirect liquefaction processes. Direct liquefaction is realized through coal hydrocracking under high temperature and pressure (Quignard et al., 2013). For indirect liquefaction, coal is firstly gasified into the mixture of hydrogen and carbon monoxide, which is then converted to oil through Fischer-Tropsch synthesis (Salkuyeh and Adams Ii, 2013; Sudiro and Bertucco, 2009). A detailed comparison between DCTL and ICTL can be found in Xie and Li (2005). The CTL pathway offers the benefit of complete compatibility with existing infrastructure and vehicle fleet, which implies a near-zero transition cost (Hao et al., 2010; Ogunkoya and Fang, 2015). However, from the fuel production perspective, CTL production technology is in the stage of mass demonstration, and still faces the uncertainties of energy efficiency, environmental impacts and economical feasibility. Compared with the methanol and DME pathways, the coal consumption, water consumption and CO_2 emissions of the CTL pathway are generally higher (Mantripragada and Rubin, 2013b). Besides, the investment for a CTL plant is higher than a methanol or DME plant on a unit production capacity basis.

3.4. Electricity pathway

Using coal to generate electricity and then to power electric vehicles is another pathway of utilizing coal as vehicle fuel. The electricity pathway offers the highest life cycle energy efficiency compared with other coal-based pathways. According to Jin (2015), with the same coal input, the vehicle mechanical work delivered through the electricity pathway is more than one time higher than the methanol pathway and about two times higher than the CTL pathway. Besides, electric vehicles feature zero tail-pipe emissions, which is critical for improving urban air quality. However, the current performance of electric vehicle is not comparable to conventional vehicles. Low driving range and long charging time are the major drawbacks, although they can be remedied through wide-spread charging infrastructures and the installation of high-capacity batteries. When comparing CO_2 emissions from the life cycle perspective, electric vehicles using coal power have higher CO_2 emissions than the petroleum-based pathways (Huo et al., 2010). Besides, the development of electric vehicles needs dedicated charging network. The cost of electric vehicles is significantly higher than conventional vehicles, all of which implies a high transition cost to the society.

3.5. Hydrogen pathway

Hydrogen can be derived through a variety of pathways, including those which are renewable. The coal-based pathway is one of the options. Hydrogen fuel can be used on fuel cell vehicles

Table 3
Comparison among the pathways of utilizing coal as vehicle fuel.

Fuel		Technology maturity	Vehicle performance	Vehicle compatibility	Infrastructure compatibility	Plant investment	Resource impact	Environmental impact
Methanol pathway	LLB	All associated technologies are quite mature	Comparable to conventional vehicles	Compatible with conventional vehicles	Special treatments needed for the transport, storage, distribution, and refueling infrastructures	Around ¥5 billion/million ton production capacity	Higher energy efficiency compared with CTL High water consumption	Low tailpipe emissions Controversial methanal emissions Life cycle GHG emissions 80%–120% higher than petroleum-based pathways
	HLB/pure methanol	All associated technologies are quite mature	Difficulty in low-temperature starting Corrosion problems	Engine retrofit needed Dedicated methanol tank needed				
DME pathway		DME vehicle and infrastructure technologies need further development	Comparable to conventional vehicles	Dedicated DME engine needed Dedicated DME tank needed	Dedicated DME infrastructures needed	Around ¥8 billion/million ton production capacity	Higher energy efficiency compared with CTL High water consumption	Low tailpipe emissions Life cycle GHG emissions 100%–200% higher than petroleum-based pathways
CTL pathway	DCTL	CTL production technologies need further demonstration	Comparable to conventional vehicles	Compatible with existing vehicle fleet	Compatible with existing infrastructures	Around ¥10 billion/million ton production capacity	Lower energy efficiency compared with methanol and DME High water consumption	Life cycle GHG emissions 50%–100% higher than petroleum-based pathways
	ICTL					Around ¥15 billion/million ton production capacity	Lower energy efficiency compared with methanol and DME High water consumption	Life cycle GHG emissions 100%–200% higher than petroleum-based pathways
Electricity pathway		Electric vehicle and charging infrastructure technologies need further improvement	Lower driving range (typically 100–300 km, depending on battery capacity) Long charging time	Based on battery-motor propulsion technology, with much higher cost than conventional vehicles	Dedicated charging infrastructures needed	No dedicated plant needed	Highest energy efficiency compared with other coal-based pathways Low water consumption	Zero tailpipe emissions Lowest life cycle GHG emissions compared with other coal-based pathways
Hydrogen pathway		Fuel cell vehicle and hydrogen infrastructure technologies need further development	Comparable to conventional vehicles	Based on fuel cell propulsion technology, with much higher cost than conventional vehicles	Dedicated hydrogen infrastructures needed	Data currently unavailable	Higher energy efficiency compared with other coal-based pathways	Zero tailpipe emissions Lower life cycle GHG emissions compared with other coal-based pathways

(Van Mierlo et al., 2006). Same with electric vehicles, fuel cell vehicles offer the benefit of zero tail-pipe emissions. However, the current hydrogen technologies are still not ready for mass deployment (Sharma and Ghoshal, 2015). The hydrogen production, transport, storage, distribution, refueling technologies, as well as the fuel cell technologies, still need to be further developed (Singh et al., 2015). Besides, the deployment of fuel cell vehicles has to be accompanied by a newly established hydrogen refueling network, and a much higher vehicle manufacturing cost, implying a high transition cost.

Based on the analysis above, it can be concluded that each technology pathway has its own advantages and disadvantages. The evaluation of the pathways depends critically on how the advantages and disadvantages are valued and balanced. The methanol and DME pathways offer the benefits of higher technology maturity and production efficiencies, while the disadvantages are lower compatibility with existing vehicle fleet and infrastructures (Chen, 2006; Jin, 2015; Xie and Li, 2005). In contrast, the CTL pathways, including DCTL and ICTL, show advantages in terms of compatibility with existing vehicle fleet and infrastructure, but the technology maturity and production efficiencies are lower (Cao, 2011). The electricity and hydrogen pathways have obvious advantages from the life cycle efficiency perspective, but their development depends critically on vehicle technology improvement and infrastructure deployment, which is far from maturity at the current stage.

Besides, some key concerns are yet to be clearly justified. For example, the potential impact of methanol use as vehicle fuel on human health is still very controversial. The use of methanol as vehicle fuel under normal conditions has generally been proved to be safe (Su, 2014). However, the use of methanol under a wider range of conditions, including different blend levels, different vehicle operating conditions, the possible accidents in methanol storage, distribution and refueling, still needs to be fully tested. The technology maturity of CTL is also a great concern. The Shenhua DCTL plant is the first-ever large-scale commercialized DCTL project globally. Although the facility has been reported to be operating in good condition since its establishment, the energy efficiency, environmental impact, water resource impact are still not fully disclosed. The operation stability and facility lifespan are not clear either.

An even more substantial concern is the unclear scientific facts behind these technology pathways. As Fig. 5 shows, the relative comparisons of technology pathways within each study are quite different, and can lead to different implications. For example, the Ou et al. (2010) study showed that the life cycle GHG emissions from the methanol pathway is higher than the ICTL pathway, which

Table 4
The physical-chemical properties of gasoline, methanol, diesel and DME.

	Unit	Gasoline	Methanol	Diesel	DME
Molecular formula		$C_5H_{12}-C_{12}H_{26}$	CH_3OH	$C_{10}H_{22}-C_{22}H_{46}$	CH_3OCH_3
Oxygen content		0	50%	0	34.8%
Density	kg/L	0.70–0.78	0.79	0.84–0.86	0.67
Boiling point	°C	30–220	64.7	180–370	−24.9
Autoignition temperature	°C	246–280	470	210	235
LHV [a]	MJ/kg	43.07	20.09	42.65	28.8
Theoretical air/fuel ratio		14.7	6.5	14.3	9.0
RON/CN [b]		90–97	108.7	40–55	55–60

Note:
[a] LHV: Lower Heating Value.
[b] RON: Research Octane Number (for gasoline and methanol); CN: Cetane Number (for diesel and DME).

implies that the ICTL pathway can be an absolutely better option than the methanol pathway. On the other hand, the CATARC (2007) study indicated a lower GHG emissions estimation for the methanol pathway than the ICTL pathway. This can be the basis for arguing that the methanol pathway is a better choice.

Due to the different perspectives into the advantage-disadvantage balances, and due to the insufficient scientific evidences, there have been great controversies over how coal should be used as vehicle fuel in China. Major opinions can be generally divided into the pro-methanol & DME camp and the pro-CTL camp, each camp with strong arguments and numerous powerful supporters. Under such a circumstance, the most urgent work is not to determine what technology pathway to choose, but to stimulate the demonstration processes, and the associated data and evidence collections. Through the demonstration processes, the uncertainties of technologies can be gradually understood and reduced. The evaluation of different technology pathways can be more solid with more demonstration data incorporated. All these works contribute to providing evidences for determining the optimal technology pathway.

Specifically, the demonstration of methanol use as vehicle fuel is currently encountering significant barriers, which should be cleared using policy instruments. The demonstration of CTL plants, especially the ICTL plants, has already been in a great scale. The further establishment of CTL plants should be strictly restricted before a total confidence on the technology maturity. The demonstration of DME use as vehicle fuel is still in very small scale, and should be promoted to improve vehicle and infrastructure technology maturity. As the electricity and hydrogen pathways are much larger topics concerning a total transition of the transport energy system (Jaramillo et al., 2009), this paper does not go deep into these two technology pathways.

4. Policy initiatives

In this section, the policy initiatives China has launched to promote the use of coal-derived alternative fuels are comprehensively reviewed.

4.1. Methanol

Both the central and many local governments have made great efforts in promoting the use of methanol as vehicle fuel. The promotion was firstly initiated in some coal-rich provinces, with Shanxi as the representative (SPG, 2014). In 2002, Shanxi province announced the M15 (15% methanol-85% gasoline blend) demonstration program (SPG, 2002). Four prefecture-level cities, Taiyuan, Yangquan, Linfen, Jincheng, were included in the demonstration program. Sinopec Shanxi company and its branches in the four demonstration cities were required to provide M15 fuel in their refueling stations. In 2004, the demonstration program was expanded to cover seven more cities, Datong, Shuozhou, Xinzhou, Jinzhong, Changzhi, Yuncheng, Lvliang (SPG, 2004). Each newly covered city was required to have 20 refueling stations providing M15 fuel. In 2005, the demonstration program in three cities, Yangquan, Linfen, Jincheng, evolved into the closed-operation mode (SPG, 2005). Namely, all refueling stations in the closed-operation regions were mandated to provide M15 fuel only. Besides, the use of M100 (pure methanol) started to be demonstrated in the taxi fleet. At the same time, several local standards on methanol use were established (SPBQTS, 2008).

On the national level, Ministry of Industry and Information Technology (MIIT) is the major campaigner behind fuel methanol use. In 2012, MIIT launched the M85 and M100 demonstration program in Shanxi, Shaanxi and Shanghai (MIIT, 2012). In 2014, the demonstration program was expanded to cover two more provinces, Guizhou and Gansu (MIIT, 2015a). The demonstration program focused on evaluating the technology maturity, human health and environmental impacts of M85 and M100 uses. By far, China has issued two national standards on fuel methanol, which are Fuel methanol for motor vehicles (GB/T 23,510-2009) and Methanol gasoline (M85) for motor vehicles (GB/T 23799-2009) (SAC, 2009a, b). The highly anticipated national standard for M15 is under discussion and is expected to be available in the near future.

4.2. DME

The use of DME as vehicle fuel is still in the stage of small-scale demonstration. Shanghai is the first city launching DME demonstration program starting in 2008. The demonstration program included ten DME transit buses operating on a local route. These DME transit buses were developed by Shanghai Jiaotong University. In particular, the first DME refueling station was established to support the demonstration program. After that, Linyi of Shandong province started a DME demonstration program in 2009, with a few DME transit buses operating on a local route. In 2011, China launched the national standard of Dimethyl ether for motor vehicle fuel (GB/T 26605-2011) (SAC, 2011), which is the first national standard regarding the use of DME as vehicle fuel.

4.3. CTL

The establishment of CTL projects is under the strict control from the government. CTL projects can only be established after the approval from both the local and central governments. Therefore, the policy on project approval has substantial impact on the development of CTL industry. The government's attitude towards CTL industry experienced dramatic changes over the past decade (Rong and Victor, 2011). In an exposure draft on coal chemical industry development by National Development and Reform

Commission (NDRC) in 2006, CTL production was projected to reach 30 million tons in 2020. This target implied that 10% of national gasoline and diesel consumption will be replaced by CTL in 2020. Encouraged by this ambitious target, China's coal chemical companies showed extremely high passion on initiating plans on CTL projects. However, with the issues of water scarcity, unreasonable and redundant constructions emerging, NDRC reversed the previous attitude and greatly tightened the project approval policy. In the 2008, 2009, 2011 and 2014 announcements on coal chemical industry development, NDRC emphasized repeatedly that small-scale CTL projects are strictly prohibited (NDRC, 2008, 2009, 2011; NEA, 2014b). Even large-scale CTL projects can only be approved with full justification. Under such a circumstance, the current CTL industry scale in China is lower than previously projected.

5. Barriers and opportunities

In this section, the barriers and opportunities related to the commercialization of coal-derived alternative fuels are discussed.

5.1. Fuel producer perspective

From the perspective of the fuel producers, the motivation to produce a certain kind of fuel is basically determined by the production profitability. Fig. 7 presents the estimations of the costs and profits of producing fuel methanol, DME, DCTL and ICTL. As the profits of producing coal-derived alternative fuels are very sensitive to oil price, two time points, Jun 2014 and Mar 2015, with different oil prices are chosen to be compared. These two time points generally represent the times when oil price was at the high point (Jun, 2014) and low point (Mar, 2015). The major assumptions behind the estimations are based on several published literature and reports, as listed in Table 5 (AsiaChem, 2014; Haarlemmer et al., 2014; Jin et al., 2012; Li et al., 2015; Liu et al., 2010; Shen, 2008; Zong, 2008).

According to the estimation, production of fuel methanol offers relatively lower profit. In Jun, 2014, when oil price was at the high point, the profit of producing methanol is around ¥500/t, which is far lower than producing other coal-derived alternative fuels. The major reason behind the low profit is the high excise tax imposed on fuel methanol (MOF, 2008, 2014a, b; 2015; State Council, 2008). The excise tax rate for fuel methanol is set to be the same as gasoline, which is ¥1.00/L in Jun 2014, equivalent to ¥1266/t. During the same period, the excise tax for diesel is ¥0.80/L, equivalent to ¥941/t. Therefore, although the LHV of fuel methanol (20.1 MJ/kg) is only around half of diesel (42.7 MJ/kg), the excise tax for fuel methanol is over 30% higher than diesel.

Between Jun 2014 and Mar 2015, China increased the excise tax rate for three times. The excise tax rates for gasoline and diesel in Mar 2015 were ¥1.52/L and ¥1.20/L, over 50% higher than the tax rates in Jun 2014. At the same time, affected by the collapse of international oil price, China's domestic gasoline and diesel trade prices fell steeply. Under such a circumstance, methanol production faces severe losses. According to the estimation, the loss of producing fuel methanol in Mar 2015 is around ¥1300/t. This loss estimation is supported by the intensive reports on the heavy deficit of fuel methanol companies.

Currently, the volume of DME produced as vehicle fuel is very little. The excise tax rate and price formation mechanism do not actually exist. In this estimation, the excise tax rate and price of DME as vehicle fuel are determined by referring to diesel. Namely, excise tax is assumed to be the same with diesel (¥941/t in Jun 2014 and ¥1411/t in Mar 2015). DME price is determined by referring to diesel price on a LHV equivalent basis (ORNL, 2011; SAC, 2008). According to the estimation, the profit of producing DME as vehicle fuel is around ¥1000/t and ¥-500/t in Jun 2014 and Mar 2015, respectively. It should be noted that although the profitability of DME production is relatively better than methanol production, DME production also faces considerable losses when oil price is at the low point.

The profitability of producing CTL is estimated to be better than methanol and DME, or in other words, more resilient to oil price changes. When oil price is at the high point, the profits of producing DCTL and ICTL are around ¥2000/t. The profit of ICTL production is slightly higher than DCTL production. Even at the point when oil price was low and the excise tax rate was increased, CTL production can basically maintain profit and loss balance. Sasol Ltd, the largest coal chemical company in South Africa, estimated that ICTL shows cost competitiveness when oil price is higher than $45/barrel. This estimation was based on the condition in South Africa. Domestic estimations for the oil price threshold generally range between $60–80/barrel. Other existing estimations generally fall within this range (van Vliet et al., 2009). Besides, from the perspective of the local governments, the establishment of CTL plants stimulates local economy growth and employment (Qi et al., 2012). This explains why the coal chemical companies and local governments showed high passion at establishing CTL projects (Erturk, 2011; Sangeeta et al., 2014). However, the profitability of CTL production is not absolute, with the failure of some CTL projects in the U.S. as an example (Fantazzini and Maggi, 2015; Vallentin, 2008).

It should be noted that the estimation of costs and profits of producing coal-derived alternative fuels are based on the current tax scheme. The most possible factor that can have substantial impact on the profitability of producing coal-derived alternative fuels is the implementation of carbon tax. As the life cycle CO_2 emissions of producing coal-derived alternative fuels are significantly higher than the corresponding petroleum-derived fuels, the

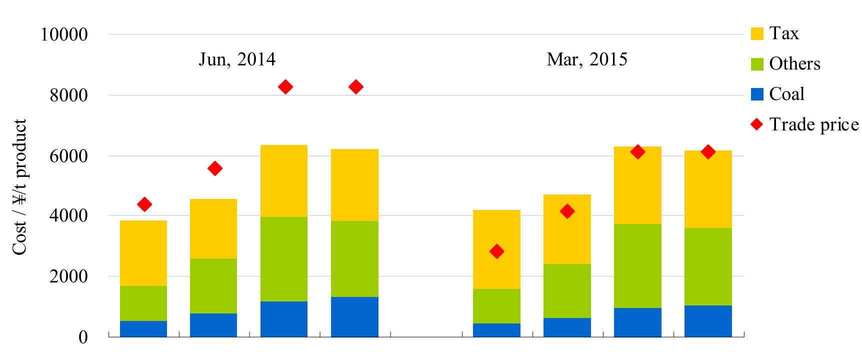

Fig. 7. Cost breakdown of producing coal-derived alternative fuels.

Table 5
Major assumptions behind the estimations of production costs of coal-derived alternative fuels.

		Unit	Time point	Methanol	DME	DCTL	ICTL
Plant design capacity		million ton product/year		0.8	0.5	1.0	0.18
Coal consumption [a]	Coal for liquidation	t coal/t product		–	–	2.0	–
	Coal for gasification	t coal/t product		1.6	2.3	1.2	3.6
	Steam coal	t coal/t product		0.4	0.6	0.6	1.1
Other cost [b]		¥/t product		1123	1785	2770	2530
Taxation [c]	Excise tax	¥/t product	Jun, 2014	1266	941	941	941
			Mar, 2015	1924	1411	1411	1411
	VAT [d]	% of price		14.5%			
	Other tax	% of the sum of excise tax and VAT		12%			
Coal price (before VAT) [e]	Coal for liquidation	¥/t coal	Jun, 2014	350			
			Mar, 2015	277			
	Coal for gasification	¥/t coal	Jun, 2014	300			
			Mar, 2015	238			
	Steam coal	¥/t coal	Jun, 2014	210			
			Mar, 2015	193			
Product price [f]		¥/t product	Jun, 2014	4376	5590	8255	8255
			Mar, 2015	2853	4141	6115	6115
Profit		¥/t product	Jun, 2014	559	1046	1901	2025
			Mar, 2015	−1347	−544	−185	−51

Notes:
[a] The assumptions for coal consumptions are based on several published literatures and reports.
[b] The item of 'other cost' covers facility depreciation cost, operation cost, labor cost, etc., which are estimated based on published literatures and reports.
[c] The item of 'other tax' covers urban construction tax, education surtax, local education surtax, which are 7%, 3% and 2% of the sum of excise tax and VAT.
[d] VAT: Value Added Tax.
[e] The prices for all types of coals (before VAT) are assumed based on the reported market trade prices.
[f] Methanol and DME prices are derived by referring to gasoline and diesel prices on an energy equivalent basis. CTL price is assumed to be the same with diesel price.

implementation of carbon tax can severely harm the cost competitiveness of coal-derived alternative fuels. In other words, the implementation of carbon tax will substantially challenge the market feasibility of coal-derived alternative fuels. Although technologies such as CCS can help to reduce CO_2 emissions, the price is an increase in production cost, which will also reduce the market competitiveness of coal-derived alternative fuels (Bassano et al., 2014; Mantripragada and Rubin, 2011).

5.2. Refueling station operator perspective

From the perspective of the refueling station operators, CTL is a more preferable and acceptable option than methanol and DME. CTL is completely compatible with existing refueling infrastructures, which implies a burden-free transition. Besides, CTL features high cetane number, which helps to improve fuel quality when blended with conventional diesel.

Fuel methanol is not fully compatible with existing refueling infrastructure. Special treatment is needed to make the infrastructure work with methanol, which implies additional cost and high inconvenience to the refueling station operators. Besides, there is a trade-off relationship between fuel methanol and gasoline sales. Higher sales of fuel methanol imply lower sales of gasoline, which reduces the profit of the oil companies. As a considerable share of the existing refueling stations are the branches of the oil companies, the sales of methanol faces resistance from these stakeholders. The concerns of the consumers on the toxicity and methanal emissions of fuel methanol is another factor the refueling stations have to consider (Wang et al., 2015). To provide fuel methanol instead of pure gasoline can lead to loss of consumers. Under such a circumstance, most refueling stations are not quite positive in promoting the use of fuel methanol. Currently, the number of refueling stations providing LLB, HLB or pure methanol is very low.

It should be noted that although most refueling stations ostensibly do not provide fuel methanol, methanol is actually being used as vehicle fuel in large quantity. It is frequently reported that refueling station operators blended methanol into gasoline secretly and sold the blend as pure gasoline. By taking the benefit of the lower per volume price of methanol, the refueling stations obtained considerable illegal revenue.

DME is not compatible with existing refueling infrastructure. As the vehicle technology, economical feasibility issues are yet to be solved, the establishment of DME refueling stations faces high risks. This is why DME refueling stations have rarely been established.

5.3. Consumer perspective

The following discussions focus on LLB, HLB/pure methanol, and DME, respectively. As CTL makes little difference to the consumers compared with conventional oil products, the consumer issues related to CTL can be ignored.

5.3.1. LLB

From the consumer perspective, the benefit of using LLB is the lower fuel price. However, the difference between the blend price and pure gasoline price is very small, normally lower than 5%. For moderate drivers with driving intensity of around 10,000 km/year, the cost reduction can be almost ignored. Meanwhile, due to the lack of public education, there is a common misconception that methanol's toxicity and the methanal emissions from methanol vehicle can do harm to human health. Based on these considerations, the public has considerable resistance on fuel methanol use.

5.3.2. HLB/pure methanol

HLB/pure methanol can only be used on modified or dedicated methanol vehicles. As alternative to gasoline vehicles, methanol vehicles face the challenge from another major alternative to gasoline vehicles, the Compressed Natural Gas (CNG) vehicles. Compared with conventional gasoline vehicles, both methanol vehicles and CNG vehicles show certain economical advantages. When taxi drivers or private passenger vehicle owners consider reducing driving cost by shifting to alternative vehicle technologies, they basically have to choose between these two options. After decades of developments of both methanol vehicles and CNG vehicles, it turns out that the development of CNG vehicles overwhelmed methanol vehicles. By the end of 2014, there were an estimated number of 4.4 million CNG vehicles in China, substantially higher than methanol vehicle stock. The market preference of CNG vehicles over methanol vehicles can be interpreted from several aspects.

Fig. 8 shows the comparison among vehicle-use gasoline, methanol and CNG prices from 2013 to 2015 (CHINACIR, 2015; NDRC, 2015). The prices of the three fuels are all converted to ¥/ton of gasoline equivalent (tge) on a LHV equivalent basis. Gasoline price is based on statistics. Fuel methanol price is estimated by counting up market methanol price and excise tax. The price of vehicle-use CNG in China is recommended to be linked to the price of 90# gasoline with a ratio of 0.75:1 (NDRC, 2007c, 2010). Regionally, the actual ratio generally ranges between 0.60:1 and 0.80:1. In this estimation, CNG price is converted based on the ratio of 0.75:1. The comparison suggests that both methanol and CNG have certain price advantages over gasoline. However, the price advantage of CNG is much more significant than methanol. Besides, the price advantage of methanol over gasoline is not stable, with the price of fuel methanol higher than gasoline at some time points. In contrast, as vehicle-use CNG price is linked to gasoline price, CNG has a stable price advantage over gasoline.

Besides, from the infrastructure aspect, the current number of CNG refueling stations is significantly higher than methanol refueling stations. This is basically a reflection of the refueling demand from the vehicle side. Moreover, the major CNG suppliers and infrastructure builders are China's big-three petroleum companies, China National Petroleum Corporation (CNPC), China Petroleum & Chemical Corporation (Sinopec), and China National Offshore Oil Corporation (CNOOC). They have strong willingness and financial capacities to promote the deployment of CNG refueling stations. As a contrast, the stakeholders behind the methanol refueling stations, the methanol enterprises, are far less powerful.

Although fuel methanol shows disadvantages in fuel price and infrastructure terms, methanol vehicle has generally better performance than CNG vehicles. The retrofit cost of methanol vehicles is ¥500–1000 per vehicle, significantly lower than the retrofit cost of CNG vehicles, which is ¥3000–5000 per vehicle. The performance of methanol vehicle is closer to conventional vehicle, on condition that retrofit quality can be ensured. CNG vehicles face the defects of engine power degradation, corrosions, lower driving range due to the limited CNG storage capacity, and smaller luggage space due to the space occupied by the gas tank. However, the advantage in vehicle term is not strong enough to balance the disadvantages in fuel price and infrastructure terms.

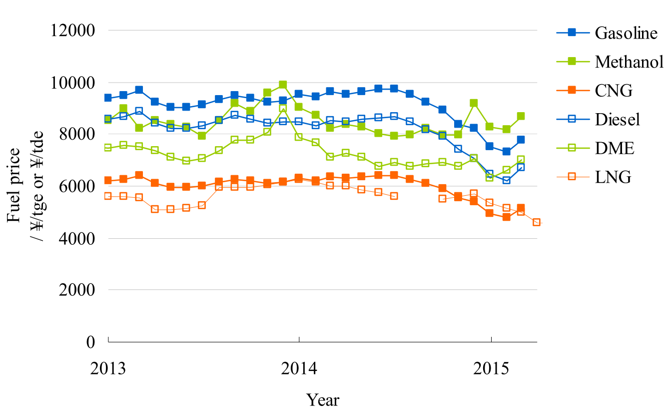

Fig. 8. Comparison of the prices of different vehicle fuels in China.

5.3.3. DME

Similar with methanol vehicles, the development of DME vehicles faces the challenge from Liquefied Natural Gas (LNG) vehicles, which are both potential alternatives to diesel vehicles. Fig. 8 also illustrates the comparison of vehicle-use diesel, DME and LNG prices from 2013 to 2015. All the prices are converted to ¥/ton of diesel equivalent (tde) on a LHV equivalent basis. Diesel price is based on statistics. Fuel DME price is estimated by counting up market DME price and excise tax as assumed above. LNG price is based on the reported price from one of China's representative LNG providers, the Shenzhen Dapeng LNG Company (Dapeng LNG, 2015). The prices of all three fuels have experienced considerable fluctuations. For most of the time, the price of DME is about 10%–20% lower than diesel. However, compared with LNG, the price of DME is generally higher. Under such a circumstance, the market has preferred LNG to DME as alternative to diesel. It should be noted that during 2010 and 2014, the DME market was mostly in the situation of oversupply, which drove the DME price to very low level. If DME price recovers to the level of over ¥6000/t, even its cost competitiveness to diesel can not be guaranteed.

Meanwhile, technology readiness is another major barrier for DME use as vehicle fuel. Currently, few Original Equipment Manufacturers (OEM) have the capacity or plan to produce DME vehicle models. The dozens of DME vehicles in demonstration are mostly research prototypes rather than mature commercialized productions.

6. Policy implications

Based on the analysis above, the development of coal-derived alternative fuels in China can not be completely left to the market. The government should play an essential role in regulating the development of this industry. Specifically, policy framework should be established in controlling the overall industry scale, designing the optimal technology roadmap, and promoting the demonstration processes, which are discussed below in detail.

(1) China's coal-derived alternative fuels should be developed with full considerations of resource, environmental, and economical constraints. The major rationality behind the development of coal-derived alternative fuels is to reduce oil consumption. However, although China's coal resource is relatively richer than oil and natural gas, coal supply is tight due to the large demand from power generation and industrial sectors. As mentioned above, the development of coal-derived alternative fuels faces the challenges of water shortage and CO_2 constraint. As a capital-intensive industry, coal-derived alternative fuel projects need huge investment to deploy. The rapid expansions of methanol, DME and CTL production capacities over the past decade were mainly driven by the high oil price and the associated highly expected profit. This has resulted in excessive methanol and DME production capacities. In particular, driven by the steep fall of oil price in recent years, most methanol and DME facilities are in the status of under production.

Based on these considerations, the government should have a strong control over the development of the coal-derived alternative fuel industry, rather than leave an unrestricted market. The overall industry scale should be maintained at the level of 100–200 million tons of coal consumption per year. Dedicated and explicit guidance on the deployment of production capacities should be established, with planning on both temporal and spatial dimensions. Existing production capacities should be optimized, with inefficient and small-scale capacities gradually phased out. The newly planned projects should only be approved after comprehensive considerations of technology maturity, energy efficiency, water and environmental impacts.

(2) Based on the comparison of the different pathways through which coal can be used as vehicle fuel, each pathway shows significant trade-off among its energy, environmental and economical attributes. This has resulted in great controversies on what pathway to choose in developing coal-derived alternative fuels. Besides, some scientific facts are far from being fully justified, such as the toxicity issues of methanol use, the technology maturity of CTL projects, the life cycle GHG emissions comparisons among the pathways, etc. Based on existing knowledge, it is difficult to confidently identify the optimal technology pathway.

Under such a circumstance, demonstration plays an essential role in justifying the scientific facts and identifying the optimal technology pathway. Policy instruments should be utilized to promote or regulate the demonstration progresses. Under the demonstration programs, it is important that a transparent data reporting and disclosure system can be established. Key technical indices, such as the coal consumption, water consumption, facility investment, facility lifespan, etc, should be available for public scrutiny. With updated data and information, the scientific community should be encouraged to conduct further assessments of the energy, environmental and economical impacts for each technology pathway.

Besides, a more complete set of codes and standards should be established based on the demonstration experiences. For example, the national standards for LLB should be timely established, especially the standard for M15 fuel. Due to the lack of national standards and the associated supervision and inspection mechanisms, the current LLB quality is not well regulated. Low-quality fuel can cause several possible engine problems, including engine power degradation, corrosion, etc, which severely harmed the reputation and social acceptance of fuel methanol. Besides, the standards regarding the safety issues of methanol production, transport, storage, distribution, refueling and on-vehicle use should be timely established.

(3) Compared with the CTL pathway, the methanol pathway offers the benefits of higher technology maturity, higher overall life cycle energy efficiency, and low vehicle emissions. The major disadvantage of the methanol pathway is that the transport, distribution, storage and refueling infrastructures for methanol are not fully compatible with existing infrastructures. Besides, the toxicity of methanol, the methanal emissions and their possible impacts on human health is still not fully justified. The demonstration of methanol use as vehicle fuel faces several major barriers. The profit of producing fuel methanol is relatively lower than other coal-derived alternative fuels, which reduces the motivation of fuel methanol producers. The infrastructure operators also lack motivations to promote the use of fuel methanol. Besides, the cost competitiveness of LLB, HLB and pure methanol are lower compared with other alternatives to gasoline, such as CNG.

To further promote the demonstration progress, an essential step is to adjust the excise tax rate for fuel methanol. Currently, the excise tax rate for fuel methanol is set to be the same with gasoline, ¥1.52/L. This tax rate is unfair from the energy content perspective, because the per-volume energy content of fuel methanol is only around half of gasoline. Especially when considering the role of fuel methanol as a strategic alternative to gasoline, the excise tax rate for fuel methanol should be set at an even lower level than gasoline. The high excise tax rate is the major reason behind the low profit of the whole fuel methanol industry chain. By reducing the excise tax rate to a reasonable level, the generated profit can be shared among different entities all over the industry chain, including the methanol producers, retailers, and consumers, etc. This will substantially increase the market competitiveness of fuel methanol.

The government can consider to establish a number of province-level fuel methanol closed-operation regions, limited in the coal-rich provinces. In the closed-operation regions, all refueling stations are mandated to provide fuel methanol, either in the form of LLB, HLB or pure methanol. The possible candidate provinces include Shanxi, Shaanxi, Inner Mongolia, etc. On one hand, this ensures that the refueling station operators have to be open to the methanol companies, regardless of the stakeholder considerations. On the other hand, the methanol distribution and storage networks in these provinces are relatively mature, which reduces the infrastructure transition cost.

Besides, the government needs to strengthen the public education to establish correct public attitude towards fuel methanol, especially regarding their environmental impacts. Regarding the competition from CNG vehicles, methanol vehicles should be positioned as a complement to CNG vehicles. For example, in regions where natural gas supply can not be well guaranteed, methanol vehicles can play a major role as alternative to conventional gasoline vehicles.

(4) The major advantage of the CTL pathway is its complete compatibility with existing infrastructure. The disadvantages include technology immaturity, lower energy efficiency, etc. The major concern of CTL demonstration is that driven by temporary high oil price and policy incentives in the past few years, the established and planned capacities have been growing too fast. This may cause systematic risks, potentially caused by technical problems or excessive use of coal and water resources.

To regulate the demonstration progress of CTL projects, the government should strictly control the deployment of CTL projects. A consistent tight approval policy on CTL projects is strongly recommended. Through the operation of existing CTL facilities, technology maturity should be further tested and improved, especially for the DCTL technology. Besides, facility and operation costs should be further reduced.

Besides, different from methanol which has a wide range of utilities besides being used as fuel, CTL is a single-utility product. The production of CTL is less flexible and more likely to be affected by carbon tax or oil price fluctuations. With regard of the huge investment in the CTL plants, it would be a great waste of investment if established facilities can not operate at full capacity. To protect CTL plants from possible negative impacts, the government can consider to provide appropriate subsidies to CTL plants when necessary, such as when oil price is lower than the threshold level. The subsidy helps to ensure full utilization of established capacities.

(5) The DME pathway offers the benefits of higher energy efficiency compared with the CTL pathway, lower vehicle emissions. The major disadvantage is its incompatibility with existing infrastructures. Besides, DME vehicle technology maturity is lower compared with other vehicle technologies. The demonstration of DME use as vehicle fuel is currently carried out in very small scale. The cost competitiveness of DME is lower than its competitor, LNG. The excise tax rate of

fuel DME is currently unclear. This could be a potential factor that further reduces the cost competitiveness of DME.

Based on such considerations, DME fuel and vehicle technologies are more likely to be developed as technology reserves rather than mainstream technologies. China should continue to promote the researches on DME fuel and vehicle technologies. Regional demonstration projects should be maintained to improve infrastructure and vehicle technology maturity. The national standards for DME distribution, storage, refueling infrastructures should be established.

DME is gaseous at normal temperature and pressure, which prevents its blend with other fuels. As an alternative to DME, Polyoxymethylene dimethyl ethers (DMMn) is liquid at normal temperature and pressure, which can be blended with diesel and used as low-level DMMn-diesel blend. The coal-derived DMMn production facility has been established and demonstrated, showing considerable market potential (Jin, 2015). The promotion of low-level DMMn-diesel blend faces similar challenges as LLB, which should be overcome through financial incentives and establishment of closed-operation regions.

7. Conclusions

In this review, the rationality of developing coal-derived alternative fuels in China is analyzed from the perspectives of resource abundance, environmental and economical constraints. The possible pathways of utilizing coal as vehicle fuel, including the methanol pathway, DME pathway, CTL pathway, electricity pathway, hydrogen pathway, are compared from the energy, environmental and economical dimensions. The policy initiatives to promote the development of coal-derived alternative fuels are summarized and evaluated. The market barriers and opportunities for coal-derived alternative fuels are further assessed.

This review contributes to (1) comprehensively summarizing China's experiences on developing coal-derived alternative fuels, which is of high relevance to countries with similar interests; (2) establishing a multi-dimension review framework for evaluating the rationality and feasibility of developing alternative fuels, which can be applied on the study of other alternative fuels.

As this study focuses on reviewing the development of coal-derived alternative fuels in China's context, international comparison would be a valuable further step. For example, the Sasol CTL project in South Africa can be a potential comparison to China's CTL projects. Through international comparison, the impacts of domestic energy policy, oil and coal prices, manufacturing cost, etc, can be more clearly identified. International comparison also helps to validate the rationality of regionally implemented policies, and evaluate their potentials to be promoted in other regions.

Another possible further step would be a more explicit projection on the vehicle fuel market, such as to quantitatively project the consumptions of methanol, DME and CTL over time and region. This can be realized by modeling the market competition among available fuel and vehicle technologies. The impacts from policy, technological and price factors can be modeled and quantified. This will be of high relevance to China's energy planning, especially in the transport sector.

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