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Communication

China's growing methanol economy and its implications for energy and the environment

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ABSTRACT

For more than a decade, Nobel laureate George Olah and coworkers have advocated the Methanol Economy – replacing petroleum-based fuels and chemicals with methanol and methanol-derivatives – as a path to sustainable development. A first step to this vision appears to be occurring in China. In the past five years, China has quickly built an industry of coal-based methanol and dimethyl ether (DME) that is competitive in price with petroleum-based fuels. Methanol fuels offer many advantages, including a high octane rating and cleaner-burning properties than gasoline. Methanol also has some disadvantages. A coal-based Methanol Economy could enhance water shortages in China, increase net carbon dioxide emissions, and add volatility to regional and global coal prices. China's rapidly expanding Methanol Economy provides an interesting experiment for what could happen elsewhere if methanol is widely adopted, as proposed by Olah and researchers before him.

1. Introduction

China has abundant coal resources but scarce oil and natural gas. Adapting to such limitations, it has developed a chemical industry that relies primarily on coal as a feedstock (Fig. 1; An, 2010; Xie et al., 2010). In recent years, the industry has experienced rapid growth, most notably in the production of both methanol (Fig. 2; Xiao, 2010) and dimethyl ether (DME) (Fig. 3; CPN, 2010). In 2009, $>75\%$ of methanol in China was made from coal, with the rest coming from natural gas (Peng, 2011). Methanol is commonly used to produce formaldehyde, methyl tertiary butyl ether (MTBE), acetic acid, DME, esters, olefins, and a potentially long list of other petrochemical products. It and its derivatives are used for fuels, pesticides, medicines, and various industrial purposes.

This paper emphasizes methanol's applications in fuels. In China, the recent growth in methanol demand is being driven by direct blending with gasoline (Kong, 2011; Li et al., 2009). DME, a derivative of methanol, is also blended into liquefied petroleum gas (LPG) and sold as a fuel for residential uses (Zhang, 2011).

The rapid expansion of methanol and DME as fuels in China appears to fit Nobel Laureate George Olah's vision of a Methanol Economy (Olah et al., 2009), recognizing that earlier researchers promoted the use of methanol as a fuel (e.g., Reed and Lerner, 1973; Phillips and Takahashi, 1990). As Olah suggested, methanol and DME fit well within most existing energy infrastructure. Methanol can be used in today's internal combustion engines, and DME can be burned in common household stoves and water heaters. The transition from oil and gas to methanol would also likely be easier than a transition to the Hydrogen Economy or to electric vehicles. The Methanol Economy could therefore, in principle, be a relatively feasible and affordable path towards replacing oil. As the world's largest methanol consumer and producer, accounting for $>20\%$ of global methanol output (Fig. 4; Chemical Week, 2009), China could play a leading role in a transition to the Methanol Economy.

2. Methanol policy in China

The Sino-American Scientific Collaboration initiated the first methanol pilot project for vehicles in China in 1995. Ford Motor Company donated a methanol engine and assisted in developing the first methanol automobile in China (Kostka and Hobbs, 2010). The Chinese government then promoted methanol fuels for automobiles from 1998 to 2008. However, political support for methanol fuels nationally waned after 2008 (Kostka and Hobbs, 2010). National subsidies for engine conversion to methanol fuels were discontinued, and methanol pilot projects for cars were downgraded from national programs to provincial initiatives.

Despite the announcement of a national standard for M85 (85% methanol) gasoline in 2009, the Chinese government has delayed the approval of a M15 (15% methanol) national standard. Because M85 gasoline requires an engine conversion, it therefore has limited market acceptance. By delaying the M15 standard, the Chinese government appears to be deterring the legalization of

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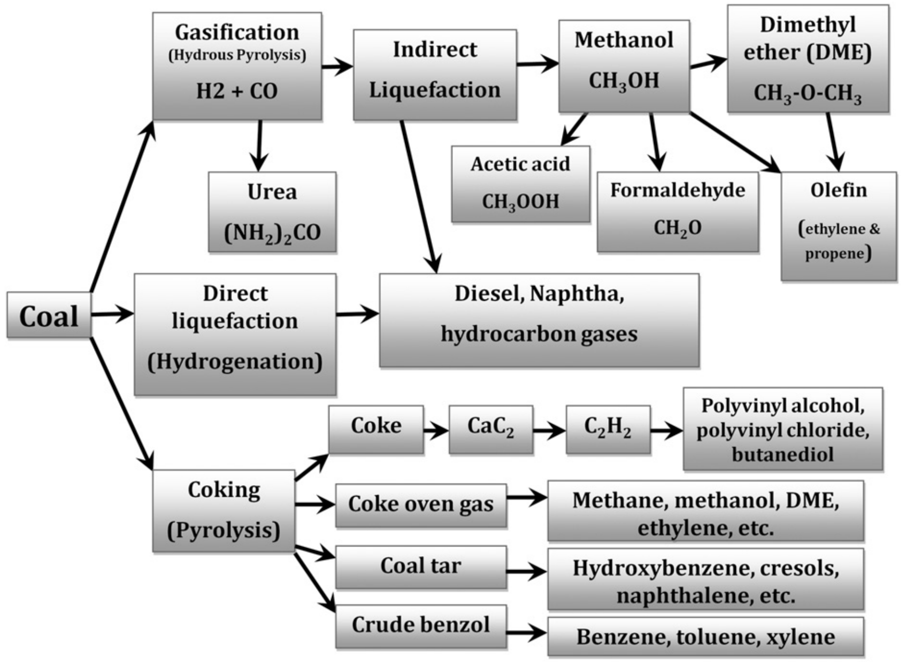

Fig. 1. A schematic representation of China's coal-based chemical industry.

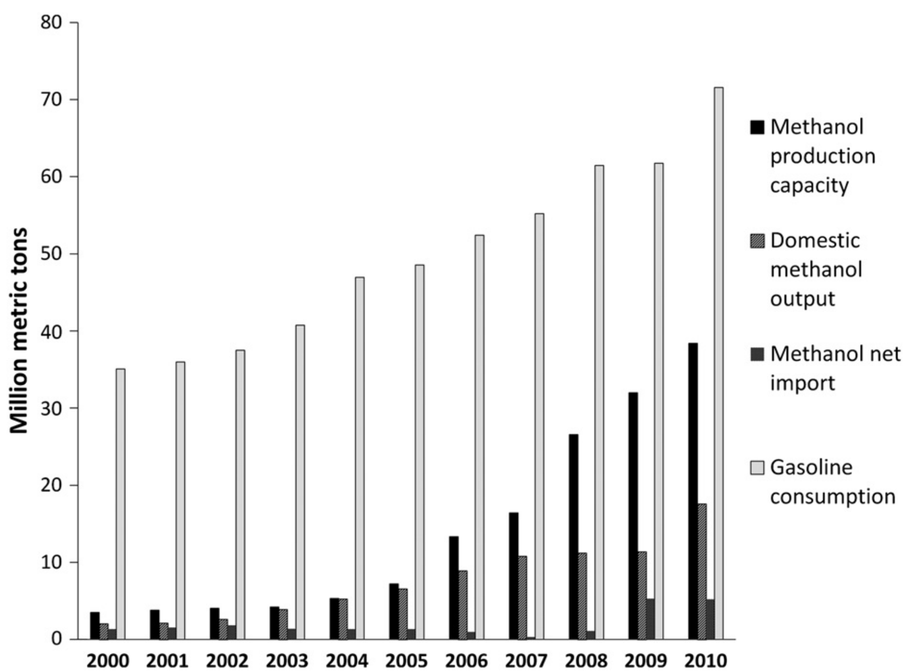

Fig. 2. Growth of methanol production and demand in China from 2000 to 2010.

nation-wide methanol blending. Nevertheless, methanol fuels have proven to be commercially viable, and several provincial governments continue to support methanol development and have legalized methanol gasoline standards locally.

In spite of the de-emphasis of methanol nationally, methanol-based industries continue to expand rapidly in China through local or provincial supports. Private gasoline stations often blend methanol in gasoline without consumers' knowledge, and LPG distributors similarly add DME to LPG (Luo, 2009; Wang, 2010a). In fact, its illegal status makes methanol blending more profitable than it would be with legal standards. Illegally blended methanol content is sold at the same price as gasoline. If legalized, standard methanol gasoline would be required to be properly labeled and sold at a lower price than regular gasoline because of its reduced energy content. Such unannounced blending is now common in China (Wang, 2010b). A Chinese business magazine has described methanol automotive fuels as a bottom–up revolution (Luo, 2009). Some estimates suggest that about 3–5 million metric tons of methanol were blended into gasoline in 2009, approximately 3.5–5.8% of China's gasoline consumption that year (Peng, 2011; Wang, 2010).

In China's most recent five-year plan (2011–2015), the national government aims to cap methanol production capacity at 50 million metric tons per year by 2015. The main reasons for containing the expansion of a coal-based chemical industry appear to include

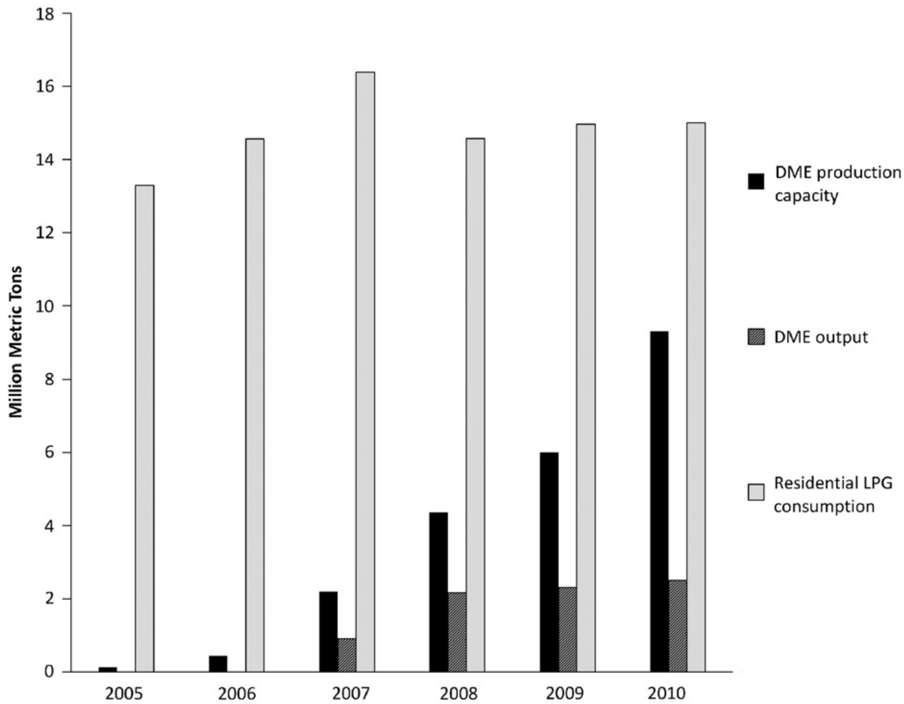

Fig. 3. Growth of the dimethyl ether (DME) industry in China from 2005 to 2010.

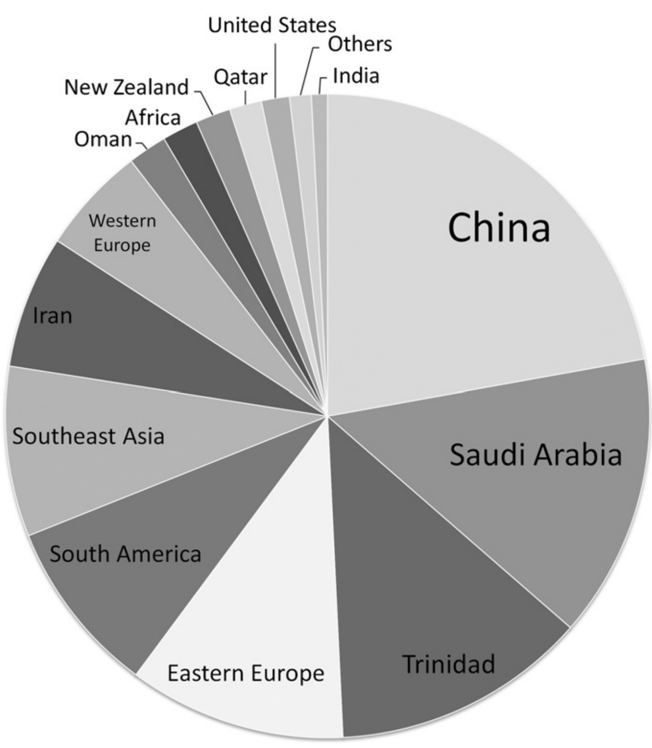

Fig. 4. Global methanol production in 2009.

concern for overcapacity, potential water resource shortages, and competition with the power industry for coal resources. How seriously the government will in fact pursue the methanol cap is unclear. Even if the cap is successful, at full capacity the coal-based methanol industry would be still able to substitute more than half of China's gasoline supply by 2015.

Continued overcapacity is notable in China's coal-based chemical industry. The National Development and Reform Commission in China concluded that the reason for the overcapacity was the incentive for "Quan Di" or "enclosure" of coal resources (NDRC, 2009; Mo, 2010). Specifically, in China all mineral resources are public properties, and local governments generally allocate coal mineral rights. In recent years, coal-rich provinces and local governments have expanded conventional development by coupling assignment of their mineral rights to developers' investment in local value-added processing of coal. As a result, coal mining companies build new processing facilities, such as coal-to-methanol and coal-to-DME plants, to acquire the mineral rights, even if market demand may not justify the additional capacity.

3. Implications

The development of a Methanol Economy in China has profound economic and environmental implications. Coal-based methanol production could provide China with a domestic alternative to imported oil and reduce conventional automotive emissions. However, the expansion of coal-based methanol could exacerbate water shortages in coal-rich but arid regions, increase greenhouse gas emissions, jeopardize consumer safety, and add possible volatility to coal prices in China and worldwide.

3.1. Water resources

The availability of water resources presents a serious constraint to China's Methanol Economy. China's coal resources are concentrated in a few severely water-limited provinces, namely Shanxi, Inner Mongolia, Shaanxi, and Xinjiang, and the coal-based chemical industry is a water-intensive one. Producing one ton of methanol from coal requires about 20 m^3 of fresh water and discharges significant amounts of wastewater (Chen et al., 2008). In addition, coal mining consumes substantial water resources (Qiu, 2010). China's national government considers water shortages as a major rationale for restricting the expansion of the Methanol Economy in the coal-rich provinces (Xiao et al., 2011). Local governments have taken a different view, however.

The scarcity of water has not deterred them from developing coal-based chemical industries. If the Methanol Economy continues to expand in coal-rich, water-scarce regions, it may lead to unsustainable withdrawals of surface and ground water and harm surrounding ecosystems. If coal-based chemical developments cause substantial water shortages, the Chinese government may strengthen its restrictive policy.

Several options exist for reducing at least some of these limitations but are unlikely to be a solution in the short term. One option is to transport coal to wherever water resources are available. However, coal-transport railways and highways in China are already in high demand; the expansion of coal transport capacity is unlikely to catch up with the rapid expansion of coal-fired power, and maintaining a stable electric power supply is a higher priority to the Chinese government than developing the Methanol Economy. Another option is to transport water from wetter regions to the drier, coal-containing provinces. China is currently implementing south-to-north water diversion projects with three designated routes. The eastern and middle routes currently under construction are designed to supplement urban water supplies. The western route, which would potentially increase water supply to the coal-rich region, is still being planned and will not be completed for at least a decade. The availability of water is therefore likely to continue to be a severe constraint in the near future.

3.2. Energy security for fuels

A buildup in methanol and DME production capacities would provide China with a readily available alternative to petroleum-based fuels and chemicals in post-peak-oil scenario or as an emergency reserve in a temporary oil crisis (Deffeyes, 2001). However, the availability of excess capacity alone cannot provide a sufficient safeguard against disruption of oil supplies unless the capacities for coal mining and transport expand accordingly.

Supplementing petroleum-based fuels with coal-based methanol is not only technically feasible but apparently affordable. Methanol's heat content is about half of gasoline's, but methanol burns more efficiently than gasoline in an internal combustion engine (Olah et al., 2009). Roughly 1.4 t of methanol can replace one ton of gasoline (Li, 2008). Because methanol is usually priced at one third to one quarter the price of gasoline (Table 1), blending methanol in gasoline in China is currently profitable, even if illegal in some places.

Natural-gas-based methanol is also an alternative to petroleum-based products. Outside of China, methanol is primarily made from natural gas. In the United States, increased supply of shale gas and other unconventional sources is expected to keep gas prices relatively low (Ridley, 2011). Increasing methanol imports (Fig. 2) could therefore be an alternative to domestic coal-based methanol.

3.3. Carbon dioxide emissions

As a transportation fuel, coal-based methanol has a larger CO_2 footprint than gasoline. The lifecycle CO_2 emissions for a coal-based methanol fuel are $\sim$5.3 t CO_2 per ton of methanol burned (Zhu et al., 2010). In contrast, the lifecycle CO_2 emissions are $\sim$4.03 t CO_2 per ton of gasoline, with 3.14 t CO_2 per ton of gasoline at the end of the car's exhaust pipe (USEPA, 2005) and a further 22% of CO_2 emissions from upstream processing (Brandt and Farrell, 2007).

Replacing a ton of gasoline requires $\sim$1.4 t of coal-based methanol, which has lifecycle CO_2 emissions of $\sim$7.42 t. This value is 84% higher than the lifecycle CO_2 emissions (4.03 t) from 1 t of gasoline. Without a plan to transition to more sustainable methanol production, such as a potential biomass-based process, a coal-based Methanol Economy would be far worse than a petroleum-based economy in its contribution to global warming.

Table 1
Gasoline and methanol prices in China.

	Gasoline prices (Chinese Yuan/metric ton)	Methanol prices (Chinese Yuan/metric ton)
2009	6220–7900	1600–2800
2010	7900–8530	2200–3200

3.4. Risks of leakage and explosion

When used in automobiles, methanol can degrade some plastic or rubber components in the fuel systems of conventional gasoline or diesel vehicles. It can also corrode some metals, including aluminum, zinc, and magnesium (Olah et al., 2009). The degrading effects are usually relatively slow and only become apparent over long-term methanol use. Unfortunately, in China, considerable methanol blending in gasoline is done illegally. Over the long term, drivers are unable to attribute the cause of engine damage to any particular gasoline station. If the government cannot enforce fuel quality standards effectively, perhaps a more effective way to ensure safety is to require all vehicles be made or retrofitted to be safe for methanol. A legalized and formally regulated methanol gasoline standard can better protect consumers by requiring the blenders to add additives to neutralize the degrading and corrosive effects and to label properly (Wang, 2010).

DME can damage the rubber seals of LPG cylinders and cause leaks over time, and several accidents have occurred as a result. The Chinese government banned illegal blending of DME in LPG, but enforcement appears ineffective. The leakage problem could be resolved by replacing the rubber seal with a material that is safe for both DME and LPG (Zhang, 2011). Retrofitting the cylinders may also be more effective in ensuring safety than repeatedly reaffirming an ineffective ban on illegal DME blending that continues.

3.5. Urban air quality

Methanol–gasoline blends contribute to generally lower automotive emissions. The carbon monoxide (CO) and total hydrocarbon (THC) emissions from burning methanol–gasoline blends in a spark-ignition engine are significantly lower than for gasoline alone, whereas emissions of nitrogen oxides (NO_X) are comparable (Liu et al., 2007). However, a further breakdown of the hydrocarbon emissions (before catalytic conversion) reveals substantial increases in methanol and formaldehyde. The three-way catalytic converters in typical gasoline-powered cars can largely eliminate formaldehyde and reduce unburned methanol fairly effectively (Liu et al., 2007; Zhang et al., 2011). Nevertheless, the expanded use of methanol fuel may lead to an increase of methanol and formaldehyde in urban air.

Potential methanol leaks are another pathway for reducing urban air quality. A recent study by Clarisse et al. (2011) documented methanol concentrations over Beijing that were ten-times higher than predicted by biogenically based models. In fact methanol was the only pollutant that their model did not simulate well. The possibility of direct methanol leaks into the air over Beijing was not considered by the authors.

Finally, existing health studies on urban air quality typically only consider hydrocarbons as a group and rarely evaluate the effect of prevalent low-level methanol and formaldehyde. More research on methanol/formaldehyde pollution is needed in light of the recent developments in China's Methanol Economy.

3.6. Drinking water safety

Assessments of the potential impact of methanol fuel on drinking-water safety in China are currently lacking. Methanol is toxic and fully miscible in water. Methanol leaks during its distribution in trucking or in supply at gasoline stations could present a threat to human health and safety. If ingested, as little as 10 ml of pure methanol can cause permanent blindness and 30 ml can be fatal (Vale, 2007). Existing gasoline distribution systems are not designed to handle methanol. To ensure public safety, distribution networks need to be re-evaluated and retrofitted, if needed, to handle the effects of methanol. Methanol poses little long-term threat to ecosystems because it is biodegraded quickly in both aerobic and anaerobic conditions and therefore is unlikely to accumulate in the environment.

3.7. Global energy economy

Historically, coal prices have been more stable than oil and natural gas prices. In recent years, however, coal prices have been unusually volatile. The expansion of China's coal-based chemical industry may explain some of that volatility. In China, coal-based chemical products increasingly compete with petroleum products in the marketplace. A foreseeable consequence would be enhanced substitution between coal and oil, and hence, more similarity between coal and oil prices. In the past, the United States used to be the marginal supplier and price-setter in the global coal market, and coal prices were relatively uncorrelated with oil prices (Ellerman, 1995). The rapid rise of the Chinese economy has changed the balance of the world coal market and may be altering the dynamics of pricing.

China used to be a net exporter of coal. Since the early 2000s, its exports have been shrinking and its imports growing (National Bureau of Statistics, 2010). In 2009 China became a net importer of coal for the first time, and it surged to be the world's second largest importer the following year (IEA, 2011; Kebede and Taylor, 2011). The sheer size of China's coal demand, with rapid growth and increasing reliance on imports, is likely to impact coal prices overseas (Oster and Davis, 2008). China now consumes three times as much coal as the United States does. With substantial consumption and excess capacity, the coal-based chemical industry is likely the marginal consumer of coal in China, and possibly a new price-setter or influence on the world coal market.

Fig. 5 shows the price movements of coal from China, Australia, South Africa, and the United State's central Appalachian region compared with Dubai oil (IMF, 2011; NACEC, 2011; Li, 2010; EIA, 2011). Coal prices appear to have moved largely in tandem with oil prices in recent years. As China's Methanol Economy grows, we may expect continued volatility of coal prices.

4. Discussion and future prospects

The development of China's Methanol Economy comes with both benefits and costs. It provides affordable alternative fuels using domestic resources and can help improve urban air quality. In contrast, it may also exacerbate water shortages, increase net greenhouse gas emissions, and jeopardize consumer safety, while possibly increasing coal price volatility.

China appears to lack a national consensus on whether the Methanol Economy should be promoted or restricted. The rapid expansion of coal-based chemical production in China suggests that a viable business model exists in spite of the national government's discontinued support. In the coming years, the national government's policy appears to be to contain rather than to promote the Methanol Economy. In contrast, local supports will likely continue.

Several unique features of the Chinese political economy have contributed to the rapid expansion of the coal-based chemical industry. The resource enclosure incentive for building coal processing facilities effectively bundles local production of coal chemicals with coal mineral rights. Higher coal prices in recent years have also provided mining companies with considerable

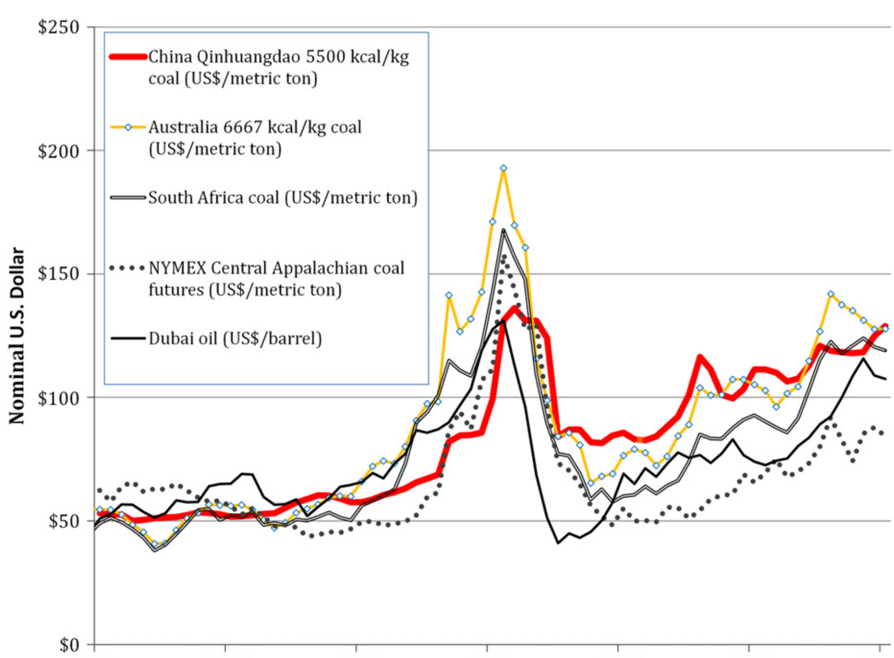

Fig. 5. Coal and oil prices from 2005 to 2011.

cash to invest in coal chemical facilities. The availability of excess coal chemical capacities, in turn, provides alternative markets for coal, thereby enhancing the coal industry's price-bargaining power and contributing to higher coal prices.

In March 2011, the National Development and Reform Commission issued a notice on the orderly development of the coal chemical industry. It stipulated the guiding principle of "Shan Da Ya Xiao"—continue to build big plants but suppress smaller projects, in order to achieve economy of scale and improve efficiency. Coal-based methanol or DME projects with capacities smaller than one million tonnes per year are now forbidden. However, the announced 50 million tonnes per year cap on methanol capacity for 2015 is not legally binding. It is unclear how seriously the Chinese government will pursue this target.

Despite its leading market share in the global Methanol Economy, China's methanol policies have been erratic. The growth in methanol and DME production in recent years appears to be fortuitous, fostered by both the hidden incentives of resource enclosure and profit from illegal methanol blending in gasoline and DME in LPG. The slow progress in making national standards for methanol gasoline seriously lags the realities of the Chinese market. In the future, China's national methanol policy should be more proactive, including increased safety precautions and ideally a substantive plan for addressing the increased CO_2 emissions from methanol production.

According to Olah's vision, the Methanol Economy could contribute to a sustainable future where carbon-neutral methanol is produced from biomass and recycled carbon dioxide (CO_2). Turning biomass into methanol is a relatively mature technology and is likely cheaper and easier to produce than cellulosic ethanol (Wyman et al., 1993; Hamelinck et al., 2005). Although, biomass-based methanol in China could in principle reduce net greenhouse gas emissions and mitigate competition for coal between power generation and coal-based chemicals, to our knowledge there is no obvious plan to use biomass or other renewable sources of energy for producing methanol and its derivatives.

China's Methanol Economy is too big to ignore. Policymakers inside and outside of China should track its development, and policy responses in China and possibly elsewhere are needed to manage its impacts. In the 1980s and 1990s, California promoted methanol as an automotive fuel (Ward and Teague, 1996). In fact in the early 1990s, methanol was a more accepted automotive fuel than ethanol in the United States (Cushman et al., 1991), and the United States even helped initiate methanol fuel programs in China. Very little data are available on how and why methanol policy and programs ended in the United States. In light of recent developments in China, US policy researchers may re-examine the US experience and consider how China's growing methanol economy could affect coal and other raw material prices and whether methanol fuels might make a comeback in the United States.

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References

An, J., 2010. A survey of China's coal chemical industry. Gas Separation 4, 23–25 (in Chinese).

Brandt, A.R., Farrell, A.E., 2007. Scraping the bottom of the barrel: greenhouse gas emission consequences of a transition to low-quality and synthetic petroleum resources. Climatic Change 84, 241–263.

Chemical Week, June 29 2009. Product Focus: Methanol. pp. 31.

Chen, D., Zhu, B., Zhang, B., Ma, Y.-y., Hu, S.-y., Jin, Y., 2008. Analysis on perspective and problems of methanol-DME economy in China. Chemical Industry 26, 17–20 (in Chinese).

Clarisse, L., Fromm, M., Ngadi, Y., Emmons, L., Clerbaux, C., Hurtmans, D., Coheur, P.-F., 2011. Intercontinental transport of anthropogenic sulfur dioxide and other pollutants: an infrared remote sensing case study. Geophysical Research Letters 38, L19806.

CPN, 2010. China Polymer Net. A Synopsis of Dimethyl Ether Development in China (in Chinese). 〈http://www.polymer.cn/polymernews/2010-2-26/_2010226155914726.htm〉 (assessed July 20, 2011).

Cushman, J.H., Lynd, L.R., Nichols, R.J., Wyman, C.E., 1991. Fuel ethanol from cellulosic biomass. Science 251, 1318–1323.

Deffeyes, K.S., 2001. Hubbert's Peak: The Impending World Oil Shortage. Princeton University Press, Princeton, NJ.

EIA, 2011. NYMEX Coal Futures Near-Month Contract Final Settlement Price, Energy Information Administration. U.S. Department of Energy.

Ellerman, A.D., 1995. The world price of coal. Energy Policy 23, 499–506.

Hamelinck, C.N., Hooijdonk, G.v., Faaij, A.P.C., 2005. Ethanol from lignocellulosic biomass: techno-economic performance in short-, middle- and long-term. Biomass and Bioenergy 28, 384–410.

IEA, 2011. Coal Information 2011. International Energy Agency, Paris.

IMF, 2011. IMF Primary Commodity Prices. International Monetary Fund, Washington, DC.

Kebede, R., Taylor, M., 2011. China Coal Imports to Double in 2015, India Close Behind. Reuters May 30. Nusa Dua, Indonesia.

Kong, Q., 2011. Will M15 Substitution Trigger Market Disturbances?. China International Capital Corporation Limited (in Chinese).

Kostka, G., Hobbs, W., 2010. Embedded Interests and the Managerial Local State: Methanol Fuel-Switching in China. Frankfurt School of Finance & Management.

Li, S., 2008. Techno-economic analysis of coal-to-liquid technologies. Shaanxi Synthetic Economy 5, 16–19 (in Chinese).

Li, W.-Y., Li, Z., Xie, K.-C., 2009. The development of methanol industry and methanol fuel in China. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects 31, 1673–1679.

Li, Z.-X., 2010. China Coal Price Index and Its Application. China Coal Industry Publishing House, Beijing (in Chinese).

Liu, S., Cuty Clemente, E.R., Hu, T., Wei, Y., 2007. Study of spark ignition engine fueled with methanol/gasoline fuel blends. Applied Thermal Engineering 27, 1904–1910.

Luo, Y., 2009. Methanol automobile standard: a bottom-up revolution. Fortune World 4, 46–49 (in Chinese).

Mo, X., 2010. Pursuing profit? Resource enclosure? Whither coal chemical industry?. China Petroleum Enterprise 10, 117 (in Chinese).

NACEC, 2011. Qinhuangdao Port Coal Prices. Northeast Asia Coal Exchange Center. 〈http://www.nacec.com.cn/data/jgsj/zzdpcj/qhd/〉 (assessed July 20, 2011).

National Bureau of Statistics, 2010. China Energy Statistics Yearbook. China Statistics Press, Beijing.

NDRC, December 30 2009. National Development and Reform Commission Press Release (on suppressing overcapacity in some industries and directing healthy industrial development) (in Chinese). 〈http://www.china.com.cn/zhibo/2009-12/30/content_19150082.htm〉 (assessed July 20, 2011).

Olah, G.A., Goeppert, A., Prakash, G.K.S., 2009. Beyond Oil and Gas: The Methanol Economy. second ed.. Wiley-VCH, Weinheim.

Oster, S., Davis, A., 2008. China spurs coal-price surge. The Wall Street Journal February 12, A1.

Peng, H.-B., 2011. 2010 review of China's methanol market. Market Economy & Price 1, 18–19 (in Chinese).

Phillips, V., Takahashi, P., 1990. Methanol from biomass. Environmental Science & Technology 24, 1136–1137.

Qiu, L., 2010. Prediction and analysis for influence of coal exploitation on water environment in northwestern China. Journal of Arid Land Resources and Environment, 148–153 (in Chinese).

Reed, T.B., Lerner, R.M., 1973. Methanol: a versatile fuel for immediate use. Science 182, 1299–1304.

Ridley, M., 2011. The Shale Gas Shock. The Global Warming Policy Foundation, London.

USEPA, 2005. Emission Facts: Average Carbon Dioxide Emissions Resulting from Gasoline and Diesel Fuel, EPA420-F-05-001. US Environmental Protection Agency.

Vale, A., 2007. Methanol. Medicine 35, 633–634.

Wang, X., 2010a. Alcohol and Ether Fuels: Better to Regulate Than to Restrict. China Energy News (in Chinese, section 03). China Institute of Energy Economics Research, Beijing.

Wang, Y., 2010b. The development of methanol gasoline. China High-tech Enterprises 166, 72–73 (in Chinese).

Ward, P.F., Teague, J.M., 1996. Fifteen Years of Fuel Methanol Distribution. California Energy Commission, Sacramento, CA.

Wyman, C.E., Bain, R.L., Hinman, N.D., Stevens, D.J., 1993. Ethanol and methanol from cellulosic biomass. In: Johansson, T.B., Kelly, H., Reddy, A.K.N., Williams, R.H., Burnham, L. (Eds.), Renewable Energy: Sources for Fuels and Electricity. Island Press, Washington DC, pp. 865–923.

Xiao, X., 2010. Analysis and outlook on China's methanol industry development since global financial crisis. Energy of China 32, 27–31 (in Chinese).

Xiao, X., Yang, C., Ci, Y., 2011. Restrictions of water resources on the development of coal-based liquid fuel in "Sanxi" region of China. Energy of China 33 (2), 26–30 (in Chinese).

Xie, K., Li, W., Zhao, W., 2010. Coal chemical industry and its sustainable development in China. Energy 35, 4349–4355.

Zhang, F., Wang, Z., Shuai, S.-J., Wang, J.-X., 2011. Experimental investigation of cold-start unregulated emissions and combustion characteristics of low-percent methanol-gasoline engine. Chinese Internal Combustion Engine Engineering 32, 235–241 (in Chinese).

Zhang, Z., 2011. The Puzzle of Dimethyl Ether, China Consumers' Magazine. China Consumers' Association, Beijing ⟨http://www.cca.org.cn/web/dzzz/newsShow.jsp?id=3361⟩ (assessed July 20, 2011). (in Chinese).

Zhu, B., Zhang, B., Zhou, W., Li, Q., Hu, S., 2010. Assessment of CO_2 emission in China's methanol industry. Journal of Tsinghua University (Science and Technology edition) 50, 686–690 (in Chinese).