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Review

Methanol Vehicles in China: A Review from a Policy Perspective

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Abstract: Mature methanol vehicle technology with low exhaust emissions and economic benefits are a viable way to mitigate oil dependency and reduce greenhouse gas emissions. As a result, pilot projects for methanol vehicles have been carried out in 10 different cities in China over the last decade. They positively affect the economy and the environment, as shown by the acceptance results. This study chronologically reviewed the previous development and adopted pertinent policies determine the feasibility of deploying methanol vehicles from national to provincial levels. Based on the analysis and evaluations, the local government is suggested to make the following dynamic policy recommendations: (a) Before reaching the "carbon peak", development strategies should be formulated according to the resource situation of each region. Priority should be given to the deployment of coal-to-methanol vehicles and bio-methanol vehicles to maximize the economy, so as to promote the construction of transmission and distribution systems, advance the manufacturing process of methanol fuel, and prepare the technology for the next stage. (b) In the second stage, the advancement of CO_2-to-methanol technology should be promoted, focusing on the development of green methanol vehicles to better contribute to the "carbon neutrality".

Keywords: methanol vehicles; green methanol; policy initiatives; China

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1. Introduction

China's vehicle fleet reached 408 million by 2022, and therefore has to import massive amounts of petroleum to meet the increasing energy demands [1–3]. In 2021, China imported 513 million tons of petroleum, which accounted for more than 70% of its total petrol consumption [4]. Similarly, 168.7 billion m^3 of natural gas was bought from overseas, which made the foreign-gas-dependency ratio higher than 45% [5]. In the last decade, China was the world's largest oil and gas importer, which made it highly vulnerable to external oil and gas supply shocks [6–9]. The increase in conventional vehicle ownership in China has also resulted in severe environmental problems. Vehicular exhaust emission has become a major source of local air pollutants, such as particulate matter (PM), causing heavy smog in urban areas of many cities [10–13].

To improve energy security and reduce emissions from traditional vehicles, China has accelerated the deployment of AEVs such as electric, gas, ethanol, and methanol vehicles since the 2000s, with varying degrees of success [14,15]. After years of pilot project testing, China is now the largest producer and consumer of methanol, a widely used clean alternative fuel [16].

Methanol can be produced from a variety of carbonaceous feedstocks (coal, natural gas, biomass, carbon dioxide, etc.) and is therefore capable of being produced at scale [17–19]. It has already been extensively trialed as an alternative fuel in various attempts to reduce dependency on gasoline and diesel [20–23]. However, methanol, as a convenient liquid fuel for range-extending fuel cells, may also play a role in improving EV performance [16]. The technological route of methanol application in vehicles is to directly inject liquid methanol into vehicles. Figure 1 shows the structural components of a methanol vehicle. However, due to the increase in the heating rate of the power battery packs, the charging/discharging efficiencies, service life and safety of the EV battery packs will be affected, and thermal runaway accidents will occur in some extreme cases [24–27]. In addition, EVs have a significantly shorter range due to the battery performance degradation in winter [28,29]. According to the China Automotive Consumer Research and Testing Center, the range of EVs decreases by roughly 39% in winter, while the range of methanol vehicles is unaffected. Therefore, methanol vehicles can be an effective supplement to the electrification of passenger vehicles.

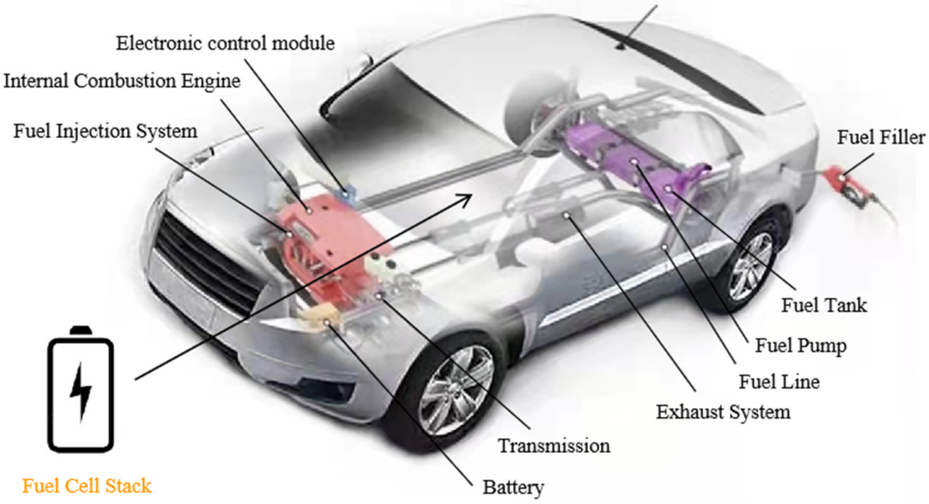

Figure 1. Vehicular structure of methanol vehicles.

Methanol has a molecular weight of 32.04, contains 50% oxygen, and is liquid at standard temperature and pressure. Compared with traditional gasoline, methanol has only half the energy density of gasoline, but the octane number is about 20% higher than 92# gasoline. In addition, its carbon content is low and does not contain nitrogen, while the oxygen content is nearly two times higher than that of gasoline, making it a recognized clean fuel. It is therefore easier for it to achieve complete combustion than it is for conventional fuels. Thus, the disadvantages of methanol's lower energy density are partially offset by its reduced exhaust pollutants and improved fuel efficiency [23]. In practice, methanol fuel can be applied as dedicated methanol (M100) or methanol-gasoline mixtures, blended in high (M85: 85% methanol mixed with 15% gasoline), mid (M50), or low (M30, M15, M5) proportions [30]. Methanol vehicles equipped with conventional spark-ignition ICEs have a limited technological barrier, but a higher compression ratio without knocking [31–34]. In operation, methanol vehicles emit fewer polluting tailpipe emissions than conventional vehicles [35,36]. From a life-cycle perspective, China's coal-to-methanol capacity accounts for more than 78% of the total capacity, and coal-to-methanol has high carbon emissions during the fuel production phase, which has led to the limited contribution of methanol vehicle deployment to carbon neutrality. Green methanol production technology can effectively solve this problem. Compared with coal-to-methanol, green methanol has significantly lower carbon emissions during the fuel production phase [37–39]. At present, the manufacture of green methanol mainly focuses on two technical routes: one is CO_2-to-methanol, the other is bio-methanol [19]. At present, the development of the two routes in China and worldwide has matured. For example, Gansu took the lead in launching the world's first kiloton-class CO_2-to-methanol demonstration project [40]. In addition, biomethanol plants are under construction in Shanxi and Henan provinces [41]. Canada's Enerkem uses municipal solid waste as a raw material to produce green methanol. The

Icelandic company Carbon Recycling International produces green methanol by combining the carbon dioxide captured in geothermal power generation with renewable hydrogen [19].

The research on methanol vehicles has lasted for more than 40 years. The U.S. took the lead in conducting research to deal with the oil crisis [42–44]. In the late 1980s, the state government of California led a pilot project using a methanol vehicle to address heavy photochemical smog in the Greater Los Angeles area. The project peaked with over 15,000 vehicles on the road, ranging from passenger vehicles to heavy vehicles [45,46]. The achievements indicated that methanol vehicle technology made a breakthrough at that time, and vehicular emissions were significantly decreased compared to conventional vehicles [47]. However, research on methanol vehicles temporarily stalled in the 2000s because of improvements in price and technology for conventional vehicles. However, the initial exploration proved that methanol is a usable alternative energy source, and a possible option for some countries. For example, Israel established a national M15 standard in 2016 [48]. The Indian government also aims to reduce oil imports and fuel costs by rolling out methanol as fuel for vehicles [44].

China launched a series of pilot projects to verify the technical maturity, environmental benefits, and competitive economic advantages of methanol vehicles [49–51]. A series of policies were issued by relevant units from national to provincial levels to ensure the promotion and development of methanol vehicles [30]. This paper reviews four decades of methanol vehicle policies in China to further explore the rationale for methanol vehicle deployment in China, while also identifying the challenges of developing methanol vehicles in China. In the end, policy implications for the further deployment of methanol vehicles are provided accordingly.

2. Rationale for Deploying Methanol Vehicles in China

This section discusses the rationale for deploying methanol vehicles from the perspectives of energy security, economic benefit, environmental impact and vehicle technology.

2.1. Energy Security

Compared to limited oil and gas reserves, China is rich in coal [52]. Therefore, coal is crucial for the supply of energy for development, and the maintenance of energy security [53–55]. To lessen its reliance on oil and gas, China has developed a coal-based chemical industry over the years [56,57]. In 2020, China's coal consumption was 2.829 billion tons, accounting for 56.8% of China's total energy consumption (Figure 2), and 54.33% of global coal consumption [58,59]. With abundant coal resources, more than 78% of the methanol consumed in China was produced from coal, based on gasification and synthesis processes (Figure 2). Thus, with such a large volume of coal and methanol production, China could minimize its dependency on oil by expanding the use of coal-based methanol to fuel vehicles [32,56]. According to the "Strategic Energy Action Plan" [60], the application of methanol made from coal (especially low-quality coal) to vehicle fuel could reform the coal industry by reducing overcapacity and increasing efficiency [14,61–63].

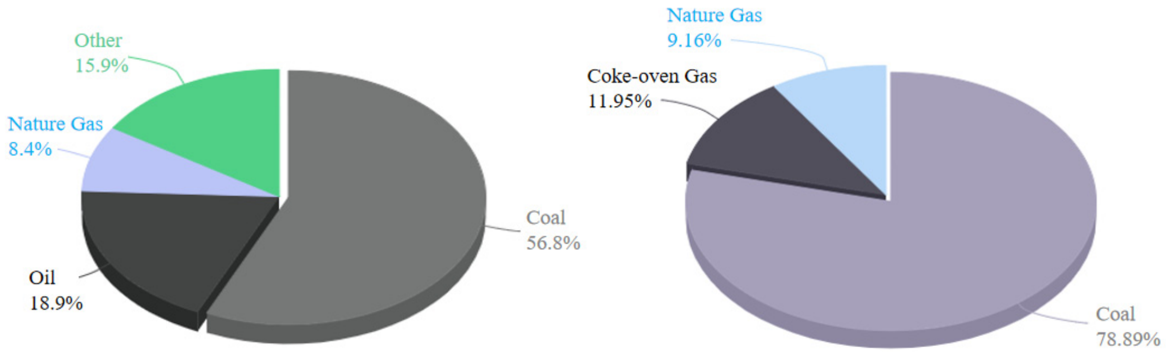

Figure 2. Energy consumption (**left**) and methanol feedstocks in China (**right**) (Source from: National Bureau of Statistics, 2019).

2.2. Economic Benefit

The quantity and price advantages of coal makes coal-to-methanol a competitive fuel in China [32]. Figure 3 compares the price of different vehicle fuels in China. According to the results of a methanol vehicle pilot project, compared to gasoline and compressed natural gas, taxis using dedicated methanol reduced their fuel costs by 37.5% and 10.6%, respectively [51]. The cost of fuel additives was around 10 USD per ton, no more than roughly 5% of the total cost of the methanol fuel [64,65].

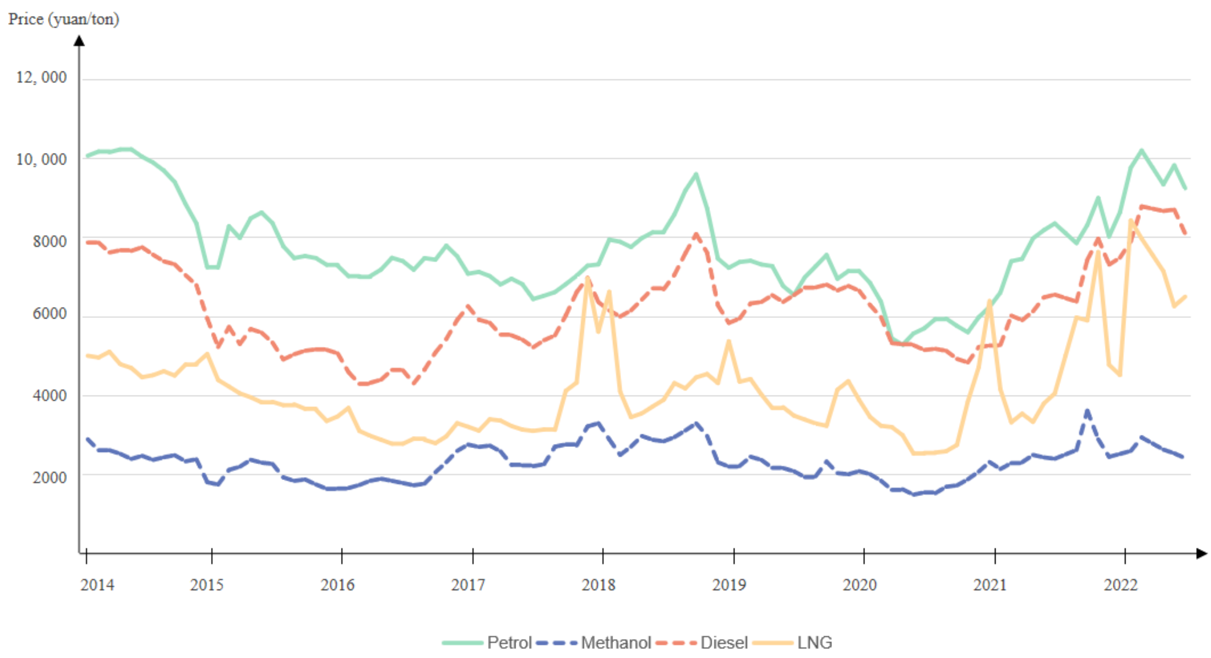

Figure 3. The comparison of different types of vehicle fuels in China (Source from: National Bureau of Statistics, 2022).

A comprehensive evaluation model was also used to compare green methanol vehicles and other typical vehicles from energy, environmental and economic (3E) perspectives [66]. The evaluation result shows that bio-methanol vehicles rank first; CO_2-to-methanol vehicles have limited potential due to their high cost and energy consumption [67].

In terms of vehicle cost, most vehicles can be "methanolized" with little to no engine modifications, which reduces the manufacturing cost compared to other AEVs, especially electric vehicles [46,68]. Moreover, as the current fuelling infrastructure is compatible with methanol, limited modification is required for the existing systems to transport, distribute and operate methanol [14,30]. Compared with other alternative energy vehicles, methanol vehicles are competitive in terms of fuel price, vehicle price and infrastructure cost [30,69].

2.3. Environmental Impact

From an environmental perspective, methanol is soluble in water, which means it has a limited impact on the environment as it can be rapidly broken down in aerobic and anaerobic conditions [17]. As methanol is an oxygenated hydrocarbon, methanol vehicles generate less CO, HC, and benzene than conventional vehicles [31,70–72]. According to the results of the pilot project in Shanxi province, emissions from tested methanol vehicles, including CO, HC, and PM, were lower than those from conventional vehicles [73]. However, when using different materials to produce methanol, the life-cycle CO_2 emissions of methanol vehicles differ (Figure 4). Regarding the number of produced benzenes, aldehydes, and ketones, methanol vehicles had clear advantages over conventional vehicles [74]. Although methanol vehicles can generate additional emissions in the form of formaldehyde, the actual amount (1.3 mg/km) is less than 10% of the required national standard [51]. While methanol is toxic to humans, it is manageable when methanol is properly handled. According to the physical examination results of drivers, service personnel and fuelling station employees in the Shanxi pilot project, no human health issues were observed. The risk of potential methanol leaks during distribution was avoided [75].

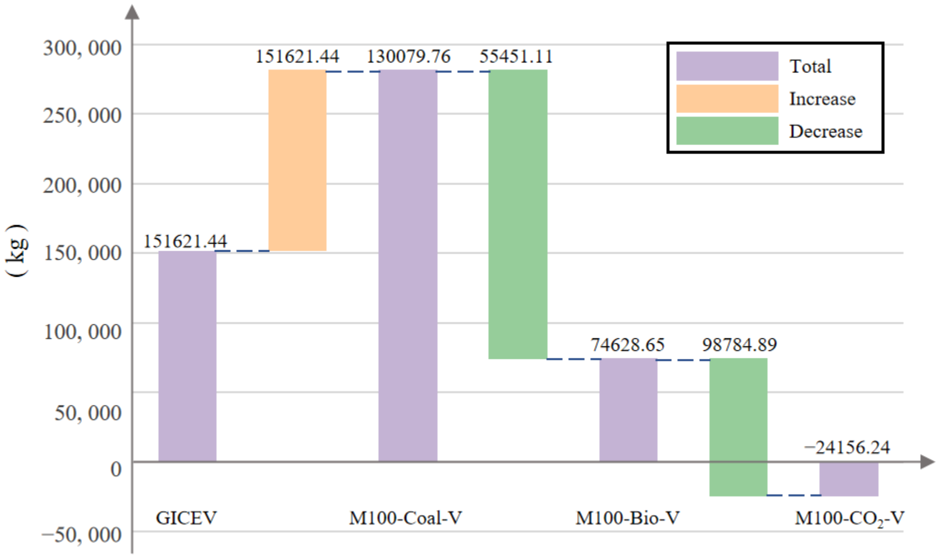

Figure 4. The life-cycle CO_2 emissions of different vehicles (Unit: kg).

2.4. Green Methanol Vehicle Technology

2.4.1. Fuel Technology

The advances in green methanol technology can resolve the hassle of excessive carbon emissions of coal-to-methanol fuel, and the production of green methanol is mainly based on two technical routes (Figure 5). One of the technologies is CO_2-to-methanol, which produces methanol by reacting the CO_2 captured from point sources (such as power plants) with the hydrogen (H_2) produced by electrolyzing water from renewable sources such as wind or solar energy, also known as "liquid sunlight" methanol technology [16,19,76,77]. CCUS is used to capture carbon dioxide to produce methanol, which also constitutes an artificial carbon cycle [78–80]. According to the simulation of three technologies considered for the conversion of CO_2 to methanol, the thermal efficiency of the conventional and tri-reforming processes is higher than the direct CO_2 hydrogenation process, while the dry reforming process has the lowest thermal efficiency [81].

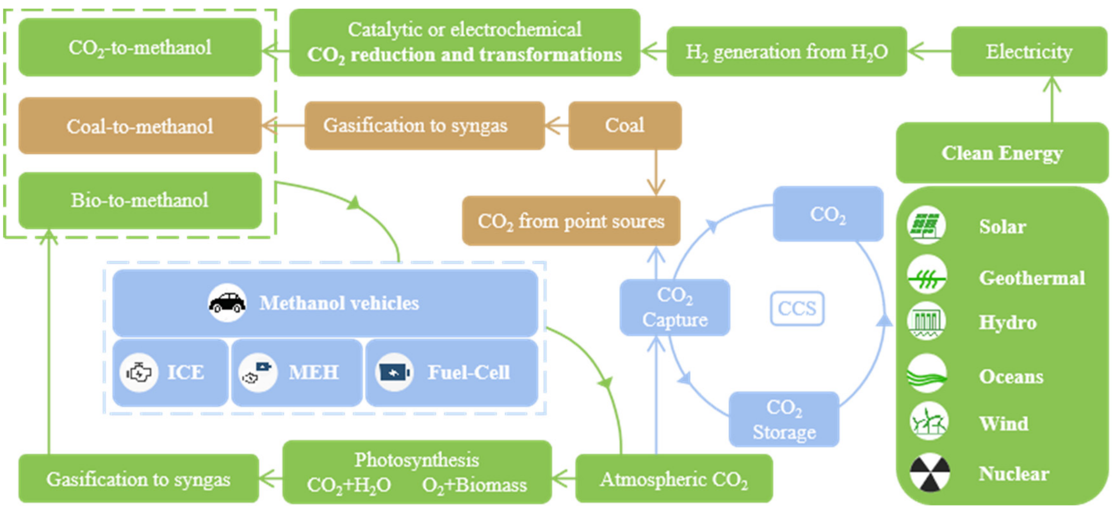

Figure 5. Technical routes of methanol and methanol vehicles.

The other technology is biomass-to-methanol, which produces methanol through biomass such as forest trees, crops and municipal solid waste. The use of these two technology routes to produce methanol can significantly reduce carbon emissions [19]. The replacement of coal by abundant biomass resources to produce methanol has been identified as a promising alternative to the environmental impact of coal mining. A simulation showed that, from a life cycle assessment perspective, the life cycle energy consumption of bio-methanol is lower than that of the coal-to-methanol process, offering significant advantages in terms of reducing greenhouse gas emissions [82].

Liquid solar technology uses renewable energy sources such as wind, photovoltaics, hydropower and other renewable energy to decompose water to produce hydrogen, while recovering carbon dioxide and achieving zero-carbon emissions. Liquid solar technology can solve the problems of hydrogen fuel storage, transportation, and safety. Compared with gas energy, liquid methanol has higher stability, is easy to store and transport, and is the most abundant hydrogen energy under normal temperature and pressure. Additionally, methanol is an ideal chemical hydrogen storage molecule that can help solve the storage and transportation problems faced by the current large-scale development of the hydrogen energy industry [83,84].

Although CO_2 methanol and bio-methanol vehicles consume a lot of energy in their fuel cycle compared with other vehicles, the problem can be solved by applying superior methods in CO_2 methanol production and bio-methanol production. A new cross-comparison method was recently used to assess the technical feasibility [81]. The results of its assessment indicate that if cost-reducing, technology-improving electrolysis pathways can be achieved and expanded in CO_2, then biomass gasification to methanol is a viable pathway [85].

2.4.2. Vehicle Technology

Methanol can corrode certain metals and seals in an engine [86]. As methanol needs more energy to evaporate in the cylinder, the intake temperature for the methanol engine would be lower, which may cause cold start problems [68]. With the advantage of the mature automobile industry, China has overcome these technical issues throughout the research and development stages [49]. In terms of vehicle compatibility, engine retrofit technology has been upgraded with alcohol-resistant materials and innovative lubricants, which minimize component corrosion problems [23]. Dual-fuel tanks and electronic control unit technology have been introduced for storing and switching dual fuel, which can minimize cold start issues and maximize the mileage of methanol vehicles. These leading technologies have ensured that methanol vehicles can run on methanol fuel with minimal modifications. Moreover, methanol can markedly improve vehicle performance and efficiency compared to conventional gasoline formulations. The high heat of vaporization, combined with the low stoichiometric air/fuel ratio, leads to high degrees of intake charge cooling as the fuel evaporates. This is especially true for engines with direct injection. The charge cooling not only leads to increased charge density and, thus, higher volumetric efficiency, but also considerably reduces the engine's propensity to knock [66]. To further test methanol vehicles, a pilot project was launched by a domestic automaker Geely Auto in Iceland in 2015 and no technical problems were found [49].

Methanol vehicle technology is also constantly evolving; in early 2022, the Geely Group released the 4th generation of Emgrand methanol/electric hybrid vehicles. Compared with Emgrand methanol vehicles, over 100 km, fuel consumption was reduced from 14 L to 9.2 L, which is more energy-saving. The relevant parameters are shown in Table 1. The differences in maximum power are due to the additional batteries in the hybrid vehicles [87].

Table 1. Maximum power and fuel consumption of vehicles *.

	Geely Emgrand Methanol Vehicle	Geely Emgrand Methanol/Electric Hybrid Vehicle	Geely Emgrand Conventional Vehicle
Maximum power (KW)	95	97	93
Methanol consumption (L/100 km)	14	9.2	/
Gasoline consumption (L/100 km)	/	/	5.82

* Fuel consumption: about 1.7 L methanol = 1 L gasoline (source: Geely Auto).

3. Policy Review for Deploying Methanol Vehicles in China

China started research on methanol vehicles in the 1980s and accelerated the research in the late 2000s to promote economic development and environmental friendliness [30]. According to the summarized policies (Table A1), the deployment of methanol vehicles in China can be divided into three stages (Figure 6). After a long preparation stage, the central government launched methanol pilot projects in five provinces from 2012 to 2017. With more than 25,000 taxis and heavy-duty vehicles using M100 as fuel in ten provinces, China has become a world leader in the application of methanol vehicles [30]. With the completed pilot projects demonstrating the technical maturity of methanol vehicles and their competitive economic advantages, the government aimed to continue developing methanol vehicles in coal-resource-endowed provinces [50,51]. This section reviews three stages of policies adopted for methanol vehicles' deployment and their implementation from national to provincial levels.

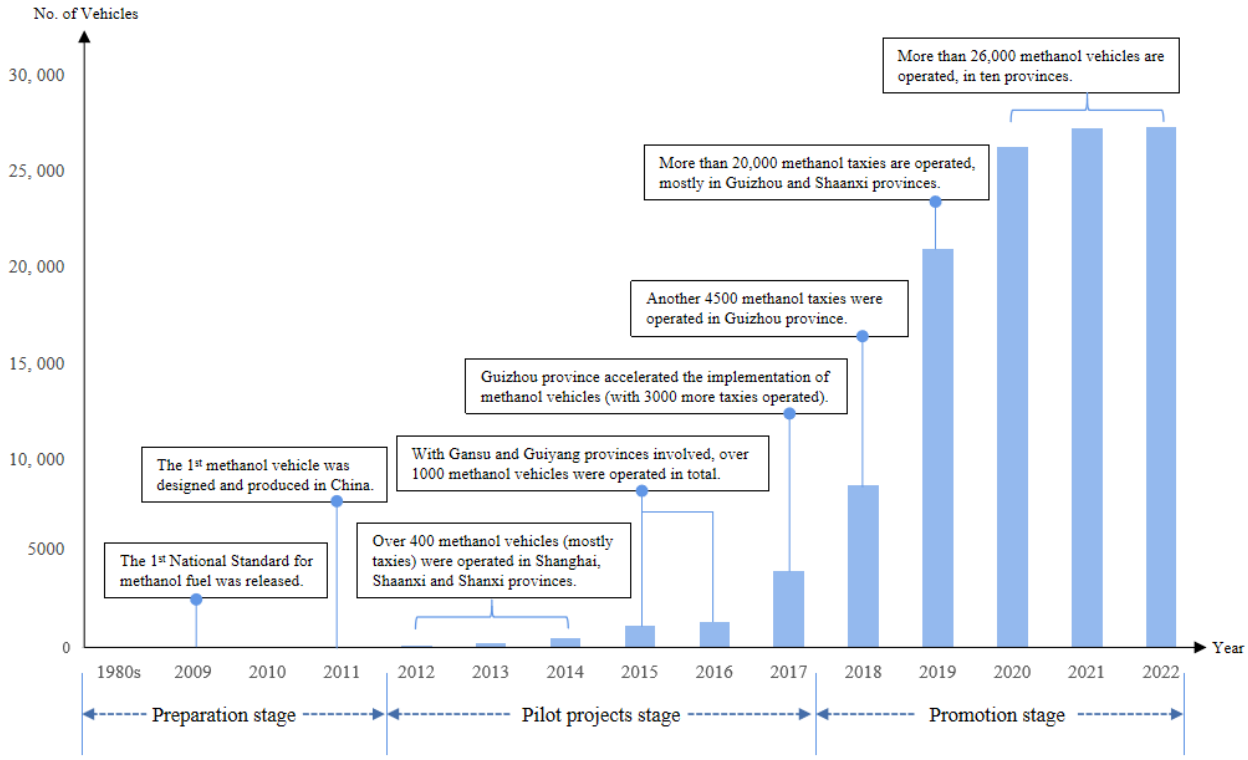

Figure 6. Three stages of deploying methanol vehicles in China.

3.1. The Preparation Stage (1980s–2011)

3.1.1. National Level

The oil crisis of the 1970s had a profound impact on energy policies in different countries [46]. Since then, China has conducted research on alternative fuels. During the "6th five-year plan" (1981–1985), the SSTC conducted the first study on methanol fuel in Shanxi province and operated 475 methanol vehicles using M15 [75].

The National Science and Technology Commission also organized transportation, engine, environmental protection, health and other departments to tackle the key problems of M15 blending burning technology, and to study the toxicity, power and emission of M15. But then, the "National Science and Technology Commission" was abolished due to institutional reform, so methanol research was put on hold again. During the "7th and 8th five-year plans" (1986–1995), the Chinese Academy of Sciences led the research on methanol engines. The performance of 10 M100 Santana methanol vehicles was tested. During the "8th five-year plan" (1991–1995), China and Germany launched research on the M100 methanol engine. The application of a low proportion of M30 and M50 methanol fuel was included in the national key research plan. During the "9th five-year plan" (1996–2000), SSTC studied coal-based methanol fuel based on the "energy, economy, and environment" lifecycle assessment, and studied the feasibility of developing methanol vehicles in coal-rich regions [88]. As a result, SETC released the "Methanol Vehicle (M85) Project" and tested 55 methanol minibuses in 1998 [75].

Due to institutional reforms, the development of methanol vehicles was delayed. Due to this, the national specifications for high-proportion methanol fuel (M85) and specialized methanol fuel (M100) were not made public until 2009 [89,90]. The deployment of methanol vehicles then moved from the national to the provincial level as a result of China's promotion of electric vehicles [91].

3.1.2. Provincial Level

Shanxi, the "coal capital" of China, was the primary province that officially implemented methanol vehicles during the preparation stage.

In order to maximize the use of coal-based methanol as fuel, the Shanxi provincial government accelerated the industrialization of methanol vehicles from 2001. For example, the government organized local governments and enterprises to build fuelling stations and operate methanol buses in 2003 [75]. The Shanxi provincial government announced the extension of dedicated methanol vehicles and M15 fuel in the province in 2005. The government planned to operate 620 methanol passenger vehicles and modify 600 conventional vehicles to use M15 fuel [92].

This early promotion of methanol vehicles in these provinces provided the country with valuable experience.

3.2. The Pilot Project Stage (2012–2018)

3.2.1. National Level

During a long period of preparation, China accumulated technology development experience and progressed the implementation of methanol vehicles into the project stage. In 2012, MIIT released the initial policy launched pilot programs for methanol vehicles [93].

The pilot was published by the Notice on Carrying out the Pilot Work of Methanol Vehicles (MIIT Energy Saving (2012) No. 42) issued by the MIIT in January 2012 [94]. The notice includes the main objectives, technical standards and phases of the pilot project.

In addition, the government released a document explained the data collection procedures, requirements for engines, emissions, impacts on human health, and fuelling stations [95]. In 2013, the State Council issued the Opinions on Strengthening Energy Conservation and Emission Reduction in the Internal Combustion Engine Industry, in which methanol fuel and engines were listed as one of the important alternative fuels [96]. From 2015 to 2017, the state will grant marketing subsidies to new energy vehicle manufacturers listed in the announcement directory of Vehicle Manufacturers and Products according to their sales.

According to the above policies, from 2013 to 2017, several cities in the provinces of Shanxi, Shaanxi, Gansu, and Guizhou, as well as the municipality of Shanghai, started methanol vehicle pilot projects (Table 2). As part of these pilot projects, the central government released a policyto emphasize the importance of safety [97]. In 2017, the MIIT issued the Notice on Preparing for the Acceptance of Methanol Automobile Pilot, requiring methanol automobile pilot areas to organize experts to carry out on-site acceptance of the pilot work, and review and evaluate the overall work of the pilot.

Table 2. Methanol vehicle pilot projects in different provinces (Source from: MIIT, 2019).

Province	City	Start Year	Inspect Year	No. of Vehicle	No. Station	Mile (1000 km)
Shanxi	Jinzhong	2013	2016	300	6	21,290
	Changzhi	2014	2017	96	1	24,100
Shaanxi	Yulin	2014	2017	5	1	415
	Xi'an	2014	2017	20	1	-
	Baoji	2013	2017	215	2	-
	Hanzhong	2015	2018	20	1	287
Gansu	Lanzhou	2015	2017	150	1	-
	Pingliang	2015	2017	50	2	24,432
Guizhou	Guiyang	2015	2017	300	7	72,090
Shanghai	Shanghai	2013	2017	56	1	5572

3.2.2. Provincial Level

Although the pilot projects were initiated by the central government, the provincial governments played a vital role in deploying methanol vehicles during the pilot projects. Under the guidance and supervision of the central government, some provincial governments issued policies, including standards and subsidies, for methanol vehicles [30].

Shanxi province, which already had methanol vehicle development experience, was the first to launch several pilot projects and issue policies to strengthen the implementation of methanol vehicles [98]. The Shanxi provincial government, for the first time, classified methanol vehicles as new energy vehicles (NEVs) [99,100]. The provincial government provided incentives for purchasing methanol vehicles in 2015: approximately 710 USD per passenger vehicle and 1420 USD per heavy-duty vehicle [100]. Further, the provincial government recommended that the central government define methanol vehicles as NEVs and provide subsidies at the national level [75]. The document also proposed the development of "methanolized" conventional vehicles and the application of methanol-blended gasoline (M5, M15, and M30). The Shanxi provincial government issued provincial standards for M5, M15 and M30 to diversify methanol fuels [88].

Shaanxi is another coal-rich province with abundant methanol and mature methanol production technologies. It has an advanced automobile industry [30,49]. As a result, four cities were selected for pilot projects. In addition to the passenger vehicles produced by Geely Auto, the Shaanxi provincial government tested heavy-duty vehicles. These vehicles were produced by local manufacturers such as the Shaanxi Automobile Group [49].

In 2012, Shaanxi Province issued the document "Proposal for the Comprehensive Promotion of the Use of Methanol Fuel", suggesting that the promotion of methanol gasoline is accelerated in the province [101]. In the same year, a special meeting was held on "issues related to accelerating the promotion of methanol fuel and methanol vehicle pilot". At the same time, Shaanxi DIIT urged the five cities listed as Xi'an, Baoji, Xianyang, Yulin and Hanzhong to develop pilot operation programs.

Guizhou province, which is capable of producing vast coal-based methanol, has been deploying methanol fuels and methanol taxis since 2010 [102]. Consequently, Guizhou was selected to start a pilot project in 2015 [103]. Although the pilot project started late, Guizhou operated more than 2000 methanol taxis, accounting for 70% of China's total. In addition, the Guizhou provincial government appointed enterprises to develop manufacturing bases and fuelling stations [104].

Another province, Gansu, which also produces large volumes of methanol, operated methanol taxis in two cities. Shanghai, which has advanced methanol and automobile industries, also launched a pilot project [104].

3.3. The Promotion Stage (2018 Onward)

3.3.1. National Level

The completed projects were inspected by the central government in 2018, and the results satisfied the government that methanol vehicles were economical, green, safe and reliable [30]. With these positive results, the central government decided to further develop methanol vehicles. In a landmark development, eight central departments jointly issued the policy "Guidance of Developing Methanol Vehicles Applications in Some Parts of China" ("Guidance") in March 2019 [51]. The "Guidance" is the first official policy that outlines the approach that the nationwide rollout of methanol vehicles is expected to take, according to the central government.

The six sub-strategies of the "Guidance" are analyzed as follows:

- Technology development is a priority for the application of methanol vehicles. In addition to methanol vehicles, the government also encourages the development of methanol fuel-cell electric vehicles in response to the further deployment of electric vehicles.
- Regarding methanol fuel and fuelling stations, the "Guidance" encourages the production of methanol through multiple pathways and the expansion of fuelling stations; it also emphasizes the importance of meeting national standards and local energy conditions.
- The central government aims to regulate the methanol automotive industry by standardizing methanol fuels, methanol vehicles, and fuelling stations.
- Considering local conditions and safety issues, the implementation of methanol vehicles is encouraged in pilot provinces, not nationwide, at present. Subsidies are mentioned for the first time, although the amount is not clarified.
- The regulations for methanol vehicles and vehicular emissions are strict.
- The provincial governments have the right to formulate additional policies for methanol vehicles. However, as the "Guidance" prohibits the use of low-proportion methanol and "methanolized" conventional vehicles, only dedicated methanol vehicles (M100) are encouraged.

The "Guidance" describes the continued use of methanol cars from a technical, social, environmental, and policy perspective, according to the evaluation of the pilot projects. This illustrates that, for the time being, the deployment of methanol vehicles in China is still mostly dependent on the province governments, much as the "Guidance" suggests the implementation of methanol vehicles in "certain regions" rather than nationwide.

In 2020, the Ministry of Ecology and Environment issued the Measurement Method for the Emission of Non-conventional Pollutants from Methanol-Fueled Vehicles, aiming to further prevent and control air pollution, protect and improve the ecological environment, and ensure human health, which also provides further specifications for the development of methanol-fueled vehicles [105].

In 2021, the MIIT promulgated the "14th Five-Year Plan for Industrial Green Development", which included "promoting the promotion of alternative fuel vehicles such as methanol vehicles" into the "Green Products and Energy-saving and Environmental Protection Equipment Supply Project" and included "carbon dioxide coupling methanol" in the "Green Low-carbon Technology Promotion and Application Project". This shows that the country is gradually attaching importance to the development of green methanol, but the current policy regarding green methanol is a national macro-policy, and there is a lack of detailed policies for the specific implementation at the provincial level [106,107].

Driven by the pilot demonstration, the application and promotion of methanol vehicles in China have achieved positive results. As of April 2022, the market stock of methanol vehicles in China is close to 30,000, with a total mileage of nearly 10 billion kilometers.

In 2022, China's 20th National Congress proposed that, in the future, China will continue to promote carbon peaking and carbon neutrality, strengthen the clean and efficient use of coal, and accelerate the planning and construction of a new energy system [108]. This is undoubtedly a positive signal for the future development of methanol vehicles.

3.3.2. Provincial Level

There are differences between the pilot provinces in their development of methanol vehicles. Without specific incentives from the central government, Shanghai municipality and the Gansu provinces have slowed their development activities. By contrast, the provincial governments of Guizhou, Shaanxi and Shanxi further introduced relevant policies to promote the development of methanol vehicles. The "Policies for deploying methanol vehicles in Xi'an" were published by the city government of Xi'an in 2018 [109].

Similarly, the General Office of the People's Government of Guizhou Province issued the Notice on the Establishment of the Leading Group for the Development of the Methanol Automobile Industry in Guizhou Province in 2018, aiming to further promote the promotion and application of methanol automobiles in the province [110]. In 2022, the Guizhou Provincial Development and Reform Commission issued the "Several Policy Measures to Support the Promotion and Application of Methanol Vehicles in the Province", proposing a series of specific measures and expected goals for promoting methanol vehicles (Figure 7) [111]. Guiyang's (capital of Guizhou province) municipal government also provided subsidies for methanol taxis [112]. With the release of incentives, these two provinces are leading the country in the deployment of methanol vehicles.

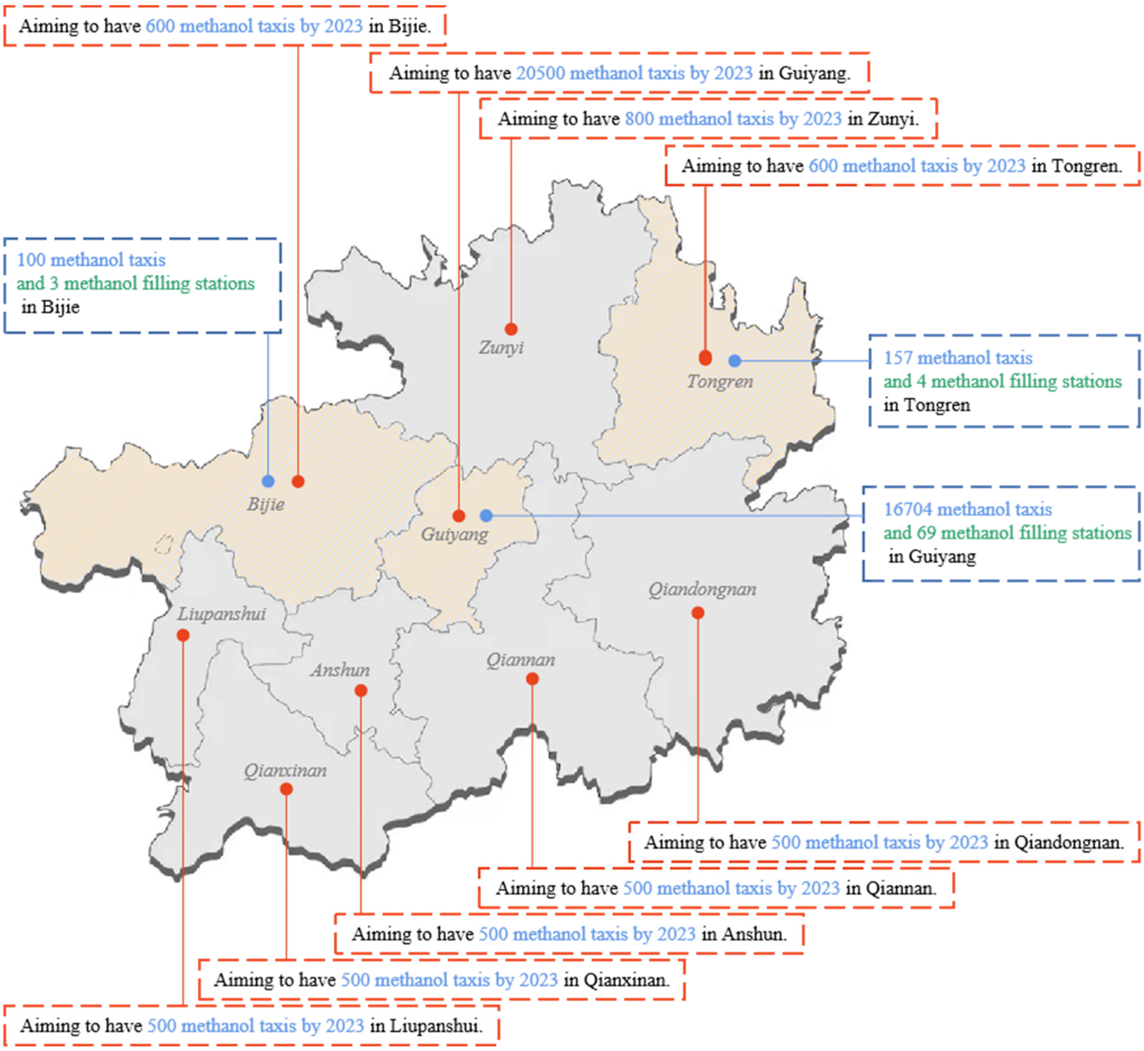

Figure 7. Distribution of methanol vehicles in Guizhou Province (2022) and targets for 2023.

In 2020, 12 departments and bureaus of Shanxi Province jointly issued the Implementation Plan for Accelerating the Development of the Methanol Vehicle Industry and the Promotion and Application of Methanol Vehicles, which demonstrates the strength and determination of Shanxi to promote the development of the methanol automobile industry [113]. To implement the above plan, Jinzhong Municipal People's Government then released a work plan, which aims to further accelerate the promotion and application of methanol vehicles [114].

In addition, the MIIT also pointed out, in its reply to the proposal of the 13th National People's Congress, that it should continuously support the development of the methanol vehicle industry [115], promote the technical innovation capacity of methanol vehicles, improve the level of technical equipment, update the supporting standards, and improve the technical capacity of the whole industrial chain of methanol vehicles.

4. Challenges of Further Deploying Methanol Vehicles in China

With the policies issued from local to central governments, the implementation of methanol vehicles has been accelerated. However, there are other obstacles in the way of China's continued use of methanol vehicles.

According to the latest national policy "Guidance" [51], coal-rich provinces are a priority in the development of methanol vehicles. However, some other regions are also suitable for the deployment of methanol vehicles. For example, Xinjiang and Inner Mongolia, which also have abundant coal reserves, have the potential to develop methanol vehicles, especially heavy-duty vehicles, to reduce fuel costs for long-distance road transportation within the province. Note that there is no overall policy for methanol vehicle deployment in China, which creates a real challenge in promoting methanol vehicles in an extensive area.

In coal-rich regions, the deployment of methanol vehicles relies on the coal chemical industry. To drive the sustainable development of the coal chemical industry in China, the central government issued policy initiatives on the clean and efficient utilization of coal [116]. A steady environment for the development of methanol cars has been created by the implementation of such policies. Although coal-based methanol is economical, expanding the deployment of methanol vehicles in coal-rich regions may destabilize the price of coal-based methanol. Therefore, integrating the development of both coal chemical and methanol industries from a policy perspective is also a challenge.

Compared to conventional vehicles, methanol vehicles emit fewer pollutants that cause smog. However, the process of making coal-based methanol itself emits more CO_2 than gasoline [56,117–119]. Table 3 compares different life-cycle vehicular emissions [120]. Due to the complex purification process of coal-based methanol, the use of low-purity methanol is still common. This leads to an increase in emissions such as formaldehyde [32,121]. Therefore, there is a need for policies related to the entire lifecycle of greenhouse gas (GHG) emissions of methanol vehicles. In addition to the above challenges, while the emerging green methanol fuel technology could dramatically reduce CO_2 emissions, how to reduce the total cost of such technology is still uncertain [120]. Another challenge is wastewater, which is a by-product of coal-based methanol production [56].

Table 3. Processed data for the vehicles' life-cycle emissions (unit: kg).

Vehicle Type	VOC	CO	NO_x	SO_x	CH_4	Dust	CO_2
M100-Coal-V	85.20	631.9	115.1	124.3	69.07	74.82	281,700
M100-CO_2-V	83.40	631.6	140.0	105.5	29.23	40.45	−24,160
M100-Bio-V	84.45	633.6	69.80	100.9	45.19	31.71	74,630
GICEV	125.5	1128	177.2	130.2	214.6	36.35	151,600

For coal-to-methanol production, the fuel production phase produces more CO_2 than green methanol and gasoline, but the price is low and economical. The fuel production stage of green methanol has obvious advantages in terms of environmental emissions and low carbon emissions, but the cost of green methanol production is higher. Therefore, how to maximize the advantages of coal-to-methanol and green methanol and rationally plan the production of coal-to-methanol and green methanol in areas with different resource endowments in the country is a challenge. In addition, according to China's carbon target, combined with the advantages and disadvantages of coal-to-methanol and green methanol, formulating a dynamic development plan is another challenge.

According to the "Guidance", only dedicated methanol (M100) can be used. To control the fuel market and guarantee the safety of methanol vehicles, the central government has outlawed the unauthorized modification of ordinary vehicles for methanol use [51]. Although the "Guidance" provides overall information on subsidies for methanol fuel and vehicles, there is no clear subsidy scheme that addresses the financial implications. As a result, the number of automakers engaged in the manufacture of methanol vehicles is still limited [30,122].

The implementation of methanol vehicles in each of the five provinces differed according to their local conditions, manufacturers' participation, and policy priorities. Taking Guiyang city of Guizhou province as an example, by April 2022, there were 69 methanol fuel stations, which can cover more than 20,000 methanol taxis' daily operation [120]. However, as can be seen from Figure 8, as methanol vehicles are still developing in other pilot cities, it is impossible to realize the cross-province operation of methanol vehicles. Therefore, how to build a mature and wide network of methanol fuel stations and vehicle applications is the main challenge at the current stage.

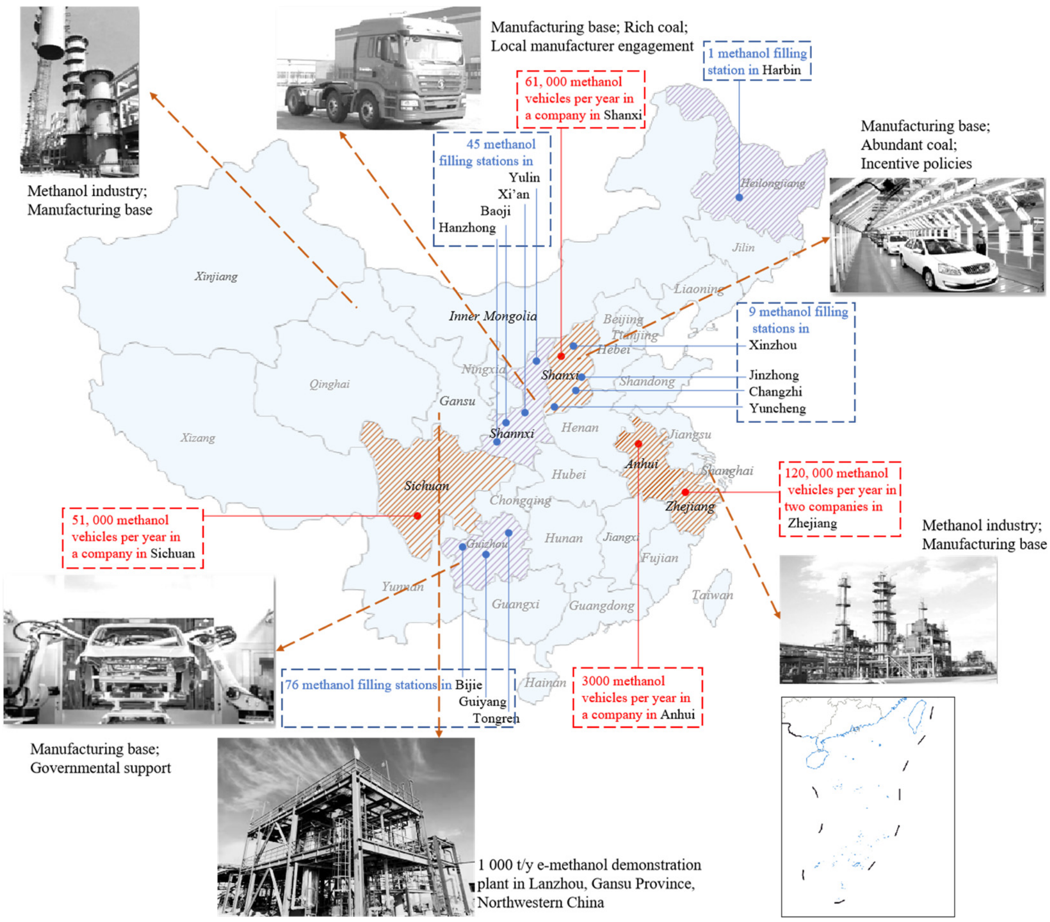

Figure 8. Methanol vehicle production, distribution and local conditions in the pilot provinces in China. (Source from: Geely Auto, April 2022).

5. Conclusions and Policy Implications

A series of methanol vehicle-related policies issued by Chinese authorities at all levels have been effective in improving energy security, lowering fuel costs and reducing air pollution. After a long preparation period, the deployment of domestic methanol vehicles has progressed from the pilot project stage to a wider deployment stage, with an increasing number of methanol vehicles in use. Currently, the promotion of methanol vehicles in China is concentrated in areas with rich coal resources, but this is a problem to be overcome for the further development of methanol vehicles. There are no effective solutions for the promotion of methanol vehicles in oil-poor regions. In addition, the lifecycle emissions of methanol vehicles should be reduced, and stricter emission standards should be introduced to accelerate the transformation of the coal industry. These measures could make methanol vehicles more environmentally friendly.

- Green methanol fuel has environmental and economic advantages and can respond to the call of the national "carbon neutral" policy, so it is recommended to further promote its use.
- Different measures are taken depending on the region. For economically developed regions with high carbon emissions, pilot projects for green methanol taxi fleets could be led by the government, thus opening up new research areas to promote the conversion of CO_2 to methanol or biomass to methanol vehicle fuel.
- Improve the economy of methanol vehicles. It suggested that the government can introduce relevant policies to subsidize the preparation of methanol fuel and the production of methanol vehicles, to reduce the cost of methanol vehicles and thus further encourage related industrial fields to innovate the key core technologies.
- Support research on key processes and equipment technologies for capturing carbon dioxide to prepare methanol. Carry out basic research on the application of methanol fuel power and thermal combustion engineering.
- For regions with large straw production and abundant biomass resources reserves, bio-methanol fuel can be further developed, thus expanding the scale of bio-methanol vehicles. In this way, the production cost can be effectively reduced according to the regional situation, and the economic advantages of methanol vehicles can be fully utilized.
- Incorporating the carbon-capture portion of the fuel cycle into carbon trading for CO_2-to-methanol vehicles to reduce the cost of preparing CO_2-to-methanol, such as by allowing companies to purchase or provide subsidies.
- In coal-rich regions, make full use of regional advantages to continue to develop and promote coal-to-methanol vehicles. Thus, the benefits will be maximized, and the economy of coal-to-methanol vehicles will be further improved.
- Combine the planning of the coal chemical industry and other related industries in coal-rich areas, make full use of the existing and proposed methanol storage, as well as the fuel transfer infrastructure, build a methanol fuel transmission and distribution system with coal-rich areas as the core and radiating to surrounding cities, and expand the deployment area of existing coal-to-methanol vehicles.
- Advance the construction of methanol fuel stations. Relying on the planning and layout of existing gas stations, form a supply system with a reasonable layout to meet demand and encourage existing gas stations to increase the filling function of methanol fuel for vehicles through transformation.
- China is a vast country and can diversify into methanol vehicles. For example, in coal-rich areas, coal-based methanol vehicles should be developed vigorously; in natural gas-rich areas, natural gas-based methanol vehicles should be developed; and for areas with developed coal chemical infrastructure, the preparation of coal-based methanol fuel can be increased.
- Strengthen publicity and promotion. Popularize the knowledge of methanol fuel and methanol vehicles, publicize, and promote the importance of the application of methanol vehicles for energy conservation and emission reduction, and improve the public's awareness and acceptance of methanol vehicles.
- Establish a methanol vehicle data industry platform, and improve the service system of methanol vehicle financing, insurance, leasing, logistics, after-sales service, second-hand car-trading. Promote the innovation of various methanol vehicle business

models such as financial leasing and methanol fuel-filling systems. Obtain feedback information to improve relevant technologies and scientifically adjust the output.

- The development of methanol vehicles should have a more comprehensive plan, while the implementation should be further increased to better contribute to the national goal of 'carbon neutrality'. Before reaching the carbon peak, priority should be given to the development of bio-methanol vehicles and coal-to-methanol vehicles from the economic and environmental perspectives, considering the resource situation of each Chinese province. In addition, a next step could also be to vigorously develop the core technology of green methanol fuel, thus promoting the development of CO_2-based methanol vehicles. However, this should also be comprehensively prepared to consider methanol fuel cell electric vehicles in the development scope according to the development situation and make reserves for other technical routes.

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Abbreviations

AEV	Alternative energy vehicles
DIIT	Department of Industry and Information Technology
EV	Electric Vehicle
GICEV	Gasoline Internal Combustion Engine Vehicle
ICE	Internal Combustion Engine
IRENA	International Renewable Energy Agency
M100-Bio-V	Methanol vehicle using neat biomass methanol as fuel
M100-CO_2-V	Methanol vehicle using neat CO_2-to-methanol as fuel
M100-Coal-V	Methanol vehicle using neat coal-to-methanol as fuel
MIIT	Ministry of Industry and Information Technology of China
NDRC	National Development and Reform Commission
SETC	China's State Economic and Trade Commission
SSTC	China's State Scientific and Technological Commission

Appendix A

Table A1. Policies and big events for China's methanol vehicle deployment.

Year	Policy and Big Event
2009	Before launching methanol vehicle pilot projects, MIIT entrusted Beijing Institute of Technology to test methanol vehicles' emissions, and the results were compared with gasoline vehicles.
	Fuel methanol (M100) and methanol-added gasoline for motor vehicles (M85) standards were established, the first standards for fuel methanol and methanol-added gasoline in China.

Table A1. *Cont.*

Year	Policy and Big Event
2010	A panel formed by MIIT evaluated alcohol ether fuel and methanol vehicles in the provinces of Shanxi, Shaanxi and Shanghai as the first stage of selecting potential pilot cities.
2012	The "Key Points of Industrial Energy Conservation and Integrated Utilization", which was issued by MIIT, proposed the development of methanol vehicle pilot projects in Shanxi, Shanghai and Shaanxi.
	MIIT released the "Notice on Methanol Vehicle Pilot Projects" and the "Technical Requirement for Methanol Vehicles" as standards for pilot projects in Shanxi, Shaanxi and Shanghai.
	Geely Holding Group designed and produced a model of methanol vehicle, which was the first methanol vehicle made by the Chinese automobile industry.
	The "Suggestions on Strengthening the Energy Saving and Emission Reduction of the Internal Combustion Engine Industry" was released by General Office of the State Council for promoting petrol/methanol dual fuel vehicles and diesel/methanol dual fuel load-carrying vehicles.
2013	The "Data Collection and Management for Methanol Vehicle Pilot Projects" was issued by MIIT. It describes data collection including data on methanol vehicle, engine, emissions, impacts on the environment and human health, fuel specification, and fuel stations.
	Methanol vehicle pilot projects in Shanxi and Shaanxi provinces (six cities in total) were officially launched. Over 400 methanol vehicles (taxies) were operated.
	Shanxi Automobile Holding Group designed and produced a model of a methanol/diesel dual-fuel truck.
2014	Provincial standards for methanol-added gasoline were applied in Zhejiang and other 13 provinces.
	Shanxi government released the "Policies for Accelerating New Energy Automobile Industry", which categorized electric, methanol and gas vehicles as new energy vehicles.
2015	The "Development of Methanol Fuel and Methanol Vehicles in China", which describes the advantages and barriers of implementing methanol fuel and vehicles in China, was provided.
	The "Regulation of Constructing Methanol Fuel Station" and the "Safely Using Methanol Fuel" were issued to guide and regulate the construction of methanol filling stations in pilot projects.
	Geely Holding Group launched a methanol vehicle test project in Iceland, which was organized and supported by Reykjavik Municipal Government.
2016	Methanol Vehicle Development Forum and Exhibition was held in Jiangsu province. International issues including the development of methanol vehicle technology, the construction of filling stations, environmental impact, methanol fuel and vehicle were discussed during the forum.
2017	MIIT, National Development and Reform Commission, Ministry of Science and Technology held a Panel Conference in Beijing to discuss the future of methanol vehicles in China. The panel suggested constantly promoting methanol vehicles in China.
2018	The 3rd methanol vehicle development conference was held in Kunshan. Stakeholders from methanol, automobile manufacturing and parts industry participated and displayed their products. Vehicle technology and development trends were discussed.
2019	The "Guidance of Developing Methanol Vehicles Applications in Some Parts of China" was released by the central government. Detailed regulations for the further implementation of methanol vehicles were listed.
2020	The Ministry of Ecology and Environment issued the Measurement Method of Non-conventional Pollutants from Methanol Vehicles (Draft for Comments), which strictly stipulates relevant emission parameters.
2020	The Ministry of Industry and Information Technology issued the "Notice on Adjusting the Requirements for the Access of Methanol Automobile Products".
2021	The Ministry of Ecology and Environment officially opened the declaration port for methanol vehicles, and methanol vehicles were included in the unified management of the national automobile industry.
2021	In the "14th Five Year" Industrial Green Development Plan, "promoting the promotion of alternative fuel vehicles such as methanol vehicles" was included in the "green product and energy-saving and environmental protection equipment supply project", and "carbon dioxide coupling methanol" was included in the "green low-carbon technology promotion and application project".

Table A1. *Cont.*

Year	Policy and Big Event
2021	According to the plan of the Department of Industry and Information Technology of Shanxi Province, by the end of 2021, Shanxi will have an annual production capacity of 150,000 methanol cars, promote 5000 M100 methanol cars in taxis, online car hailing and other fields in key cities such as Taiyuan, and build more than 100 methanol filling stations, strive to promote and apply more than 20,000 M100 methanol vehicles by the end of 2022, and build more than 200 methanol filling stations.
2022	The Fourteenth Five Year Plan for Scientific and Technological Innovation in the Transportation Field proposes promoting the application of new energy and clean energy, research and develop new energy transportation equipment.
2022	Guizhou Province issued Several Policies and Measures to Support the Promotion and Application of Methanol Vehicles in the Province (QFGY (2002) No. 172).

Source from: Ministry of Industry and Information Technology, 2009–2019. <http://www.miit.gov.cn/> (Accessed on 13 December 2021); National Development and Reform Commission, 2018. <http://en.ndrc.gov.cn/> (Accessed on 26 May 2019).

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