aramco

METHANOL INSTITUTE

Accelerating the Net-zero Transition:

Assessing Potentials of E-fuels in China's Road Transport

Foreword

Methanol as a road transportation fuel is not new. China, in particular, boasts more than three decades of experience using methanol in cars, trucks and buses. Today, and around the world, methanol is gaining extensive attention as a key enabler of the global sustainability transition. As the simplest alcohol molecule with the highest hydrogen-to-carbon ratio of any liquid fuel at ambient temperature, methanol can be used directly as a fuel, fuel additive, or converted into gasoline or jet fuel as a drop-in carbon neutral fuel for hard-to-abate sectors like transportation and shipping; and methanol can be sustainably produced from numerous renewable feedstocks. Carbon-based e-methanol and e-gasoline integrate renewable power with water electrolysis (for green hydrogen) and a chemical reaction, resulting in an overall improvement in greenhouse gas (GHG) emission performance.

This report - a 3E (Environment, Economy and Efficiency) study - makes the case for e-fuels (e-hydrogen, e-methanol, and e-gasoline via methanol to gasoline (MTG) technology) to accelerate the transition of the Chinese road transport sector. The authors compare the latest development of e-fuels in advanced powertrains (methanol- and gasoline-powered hybrid electric vehicles, HEVs) with its counterparts of conventional ICEV, battery electric vehicles (BEV) charged with Chinese grid electricity now and in the future, along with fuel cells electric vehicles (FCEV) powered by e-hydrogen. Taking one more conversion step from methanol to gasoline, the drop-in, liquid e-fuels also show promising results in overall environmental performance, providing an effective solution to mitigate lifecycle GHG emissions for both new vehicles and existing fleet in China.

While the current production cost of e-fuels presents challenges, at approximately 2 - 3 times more than their fossil-based counterparts, China envisions overcoming this barrier by leveraging its abundant renewable sources, advanced manufacturing capabilities, and its mature energy and chemical value chains, to achieve economies for scale and competitiveness. Anticipated advancements suggest the potential for halving e-fuels' production costs by 2030 – making e-methanol for example, only 30% higher compared to China's coal-based methanol. The confluence of electrified powertrains and e-fuels, positions China on an accelerated trajectory toward sustainable, low-carbon mobility.

With that, I would like to thank the many contributors to this study, As Lao Tzu noted, "The journey of a thousand miles begins with one step" and we hope this report is an important step forward in China's and the world's recognition of the role e-fuels can play in the transition to cleaner road transport.

Greg Dolan
CEO of the Methanol Institute

Citation: Frank T. Hong, Victor Gordillo Zavaleta, Xingyu Xue, Kai Zhao. Methanol Institute 2024. Accelerating the Net-zero Transition: Assessing Potentials of E-fuels in China's Road Transport

Acknowledgement

This report is collaboratively prepared with experts from Aramco Strategic Transportation Analysis Team, by Frank T. Hong (Asia), Victor Gordillo Zavaleta (Europe), Xingyu Xue (Asia).

The authors are grateful for valuable comments and feedback from experts of Geely Auto Group, OCI Global and Company representatives in Road and Aviation Committee of Methanol Institute, and Transport Technologies R&D Division of Saudi Aramco.

Comments and questions are welcome and can be addressed to Beijing Representative Office of the Methanol Institute, Kai Zhao at: **kzhao@methanol.org**

Disclaimer

Preface

The journey towards a low-carbon society is one of the greatest challenges of our time, and road transport plays a pivotal role in this transition by contributing over 15% of global greenhouse gas (GHG) emissions. China, as the world's largest vehicle market, bears the responsibility of contributing approximately one third of global vehicle production, and the road transport sector accounts for about 10% of the country's GHG emissions. Consequently, decarbonizing the road transport sector becomes imperative to fulfill China's ambitious climate targets to peak carbon emissions by 2030 and achieve carbon neutrality by 2060 , as stated by President Xi Jinping in the 75th United Nations General Assembly, 2020.

To tackle this challenge, integrating renewable energy into road transport is vital. Plug-in electric vehicles offer the opportunity to transfer the progress in renewable electricity development to the automotive sector. In parallel, low-carbon synthetic fuels (i.e., e-fuels) could facilitate renewable energy uptake through "fuel electrification", which combines hydrogen produced using renewable electricity and CO_2 captured either directly from air or from industrial exhausts. E-fuels can tap into low-cost, large-scale renewable energies, while circumventing electricity curtailment often occurring in the power grid. The resulting energy-dense liquid fuels can be designed to be fully compatible with the fuel distribution network and combustion engines in the market today, enabling them as a drop-in solution to reduce GHG emissions immediately. Despite their potential, e-fuels development in China is at its early stages, with a lack of comprehensive understanding of their application in the road transport.

Methanol Institute has commissioned this study with its members to assess the GHG emissions, energy efficiency, and economics of e-fuels produced in Northwest China, an area abundant in both wind and solar resources, and their application in passenger vehicles. We further select a fast-growing e-fuels path in China, e-methanol, to reveal its cost-competitiveness for relevant technical options, such as fuel synthesis, carbon sources and renewable energies, with cost reduction potential by 2030 projected.

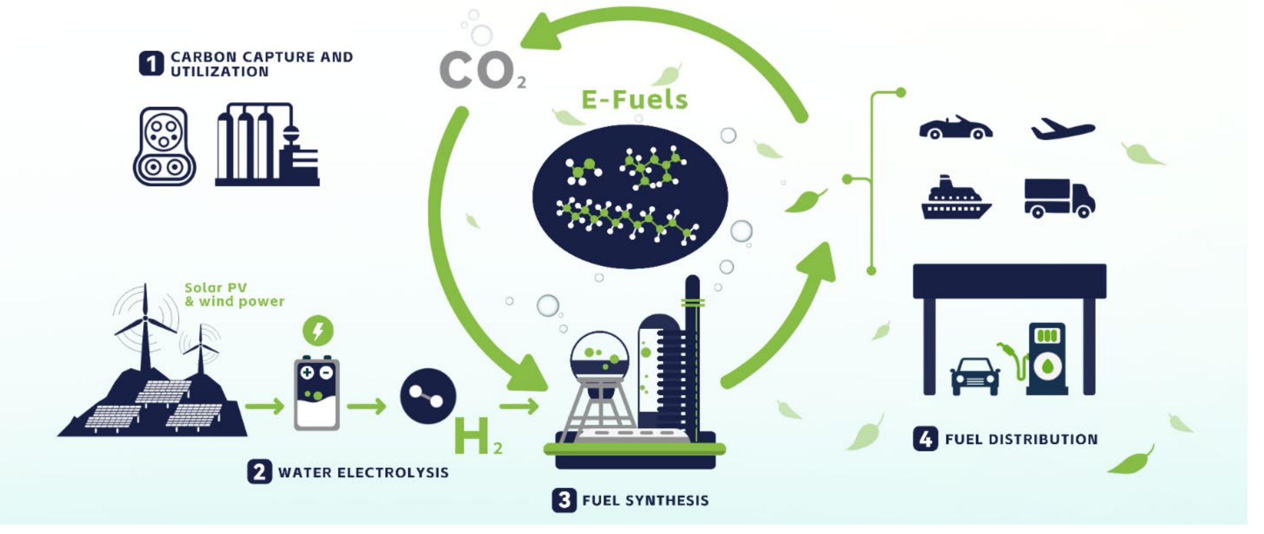
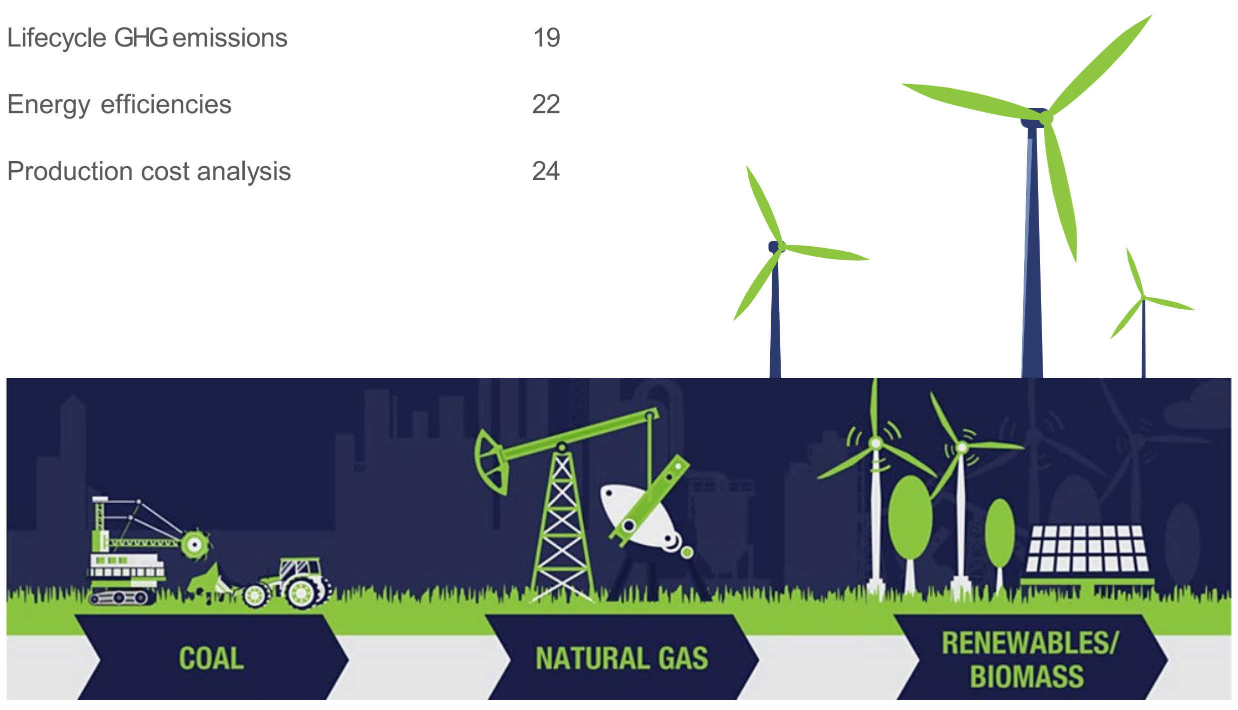


Table of Contents



List of Figures

List of Tables

Key Findings

E-fuels, such as e-hydrogen, e-methanol, and e-gasoline, exhibit 70% to 90% lower GHG emissions than their fossil-based counterparts. When HEVs (hybrid electric vehicles) and FCEVs (fuel cell electric vehicles) are powered by e-fuels, their lifecycle GHG emissions can decrease to the level comparable to that of BEVs (battery electric vehicles) charged with renewable electricity produced from solar photovoltaic (PV) or wind power.

E-gasoline, produced through the conversion of e-methanol, can serve as a "drop-in" solution, allowing for its GHG mitigation potential to be realized without being hindered by uncertain vehicle turnovers. Using 47% and 85% e-gasoline blends in efficient HEV could bring lifecycle GHG emissions down to the levels of BEV charged by China's low-carbon grid projected in 2035 and in 2050, respectively.

E-fuels production process is inherently inefficient and subject to multiple conversion losses. However, e-fuels could enable 31% to 104% more renewable electricity uptake as compared to direct renewable electricity supply to grids (from solar PV or wind farms). Taking the electricity uptake into account, the overall efficiency of e-fuels could be narrowed to roughly half of direct renewable electricity supply to BEVs.

Producing e-fuels costs 2 to 3 times higher than fossil fuel counterparts today. Taking e-methanol as an example, up to 53% cost reduction can be achieved by 2030 through a combination of cheaper renewable electricity, and lower carbon capture costs, along with optimized electrolyzer operation. Achieving these reductions hinges on collaborative efforts from government and industries to commercialize e-fuels.

China has abundant coal reserves and the world's largest methanol value chain. Capitalizing on this value chain could position local energy and chemical industries to play a proactive role in responding to the nation's climate goals. Methanol synthesis from underutilized coke oven gas, for instance, could be a bridging technology to achieve cost levels comparable to a coal-based methanol production pathway, but with 70% lower GHG emissions.

Part A:

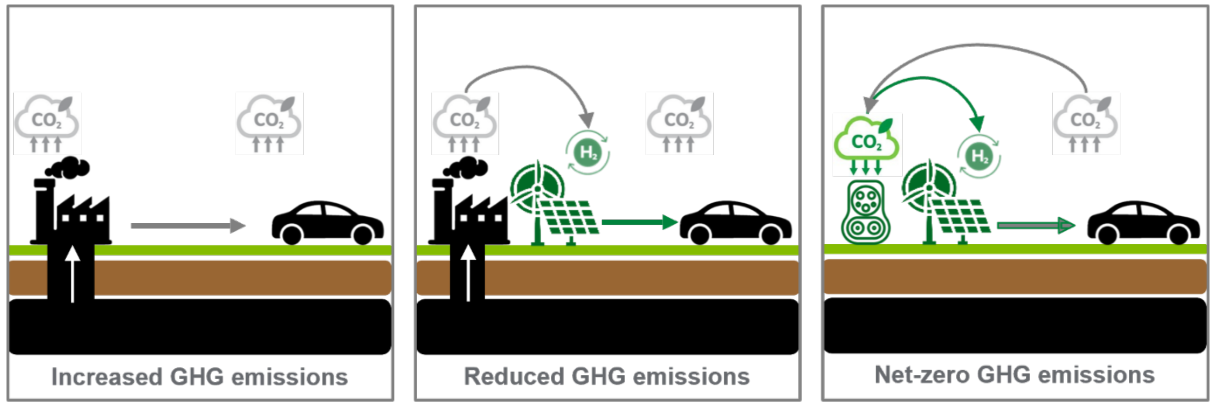
OVERVIEW & CONTEXT

Background

China's ambitious net-zero targets require the deployment of scalable, sustainable, and low-carbon technologies. In the context of road transportation, where passenger vehicles alone contribute to about 6% of the country's GHG emissions in 2020 [1], a targeted approach is imperative. Electrified powertrains are regarded as one effective means to mitigate GHG emissions by ensuring efficient energy conversion and end use. Along with local grids increasingly loaded with renewable electricity, plug-in electric vehicles have made significant strides in curbing GHG emissions for passenger vehicles. However, the pursuit of decarbonization does not halt at electrifying powertrains. Vehicles relying on internal combustion engines could chart a course toward effective GHG mitigation through the utilization of renewable fuels such as biofuels or low-carbon synthetic fuels, also known as e-fuels.

E-fuels production hinges on three fundamental components: renewable electricity, recycled CO_2, and fuel synthesis. The process begins by tapping into renewable electricity sources for electrolysis, which separates water into hydrogen and oxygen. This approach holds the promise to leverage the increasing deployment of solar PV and wind power plants in China, while also utilizing a large amount of electricity potentially curtailed by the grid [2]. Next, the produced hydrogen could be combined with recycled CO_2, using a catalyst to enable the fuel synthesis. The incorporation of recycled CO_2 from point sources (e.g., power plants, steel industries, refineries, etc.) or from direct air capture for e-fuel synthesis could facilitate reduced GHG emissions or even potential carbon neutrality. These processes based on recycled CO_2 distinguish e-fuels from other synthetic fuels such as coal-to-liquids or gas-to-liquids, which rely on fossil-based resources contributing to increased GHG emissions to the atmosphere.

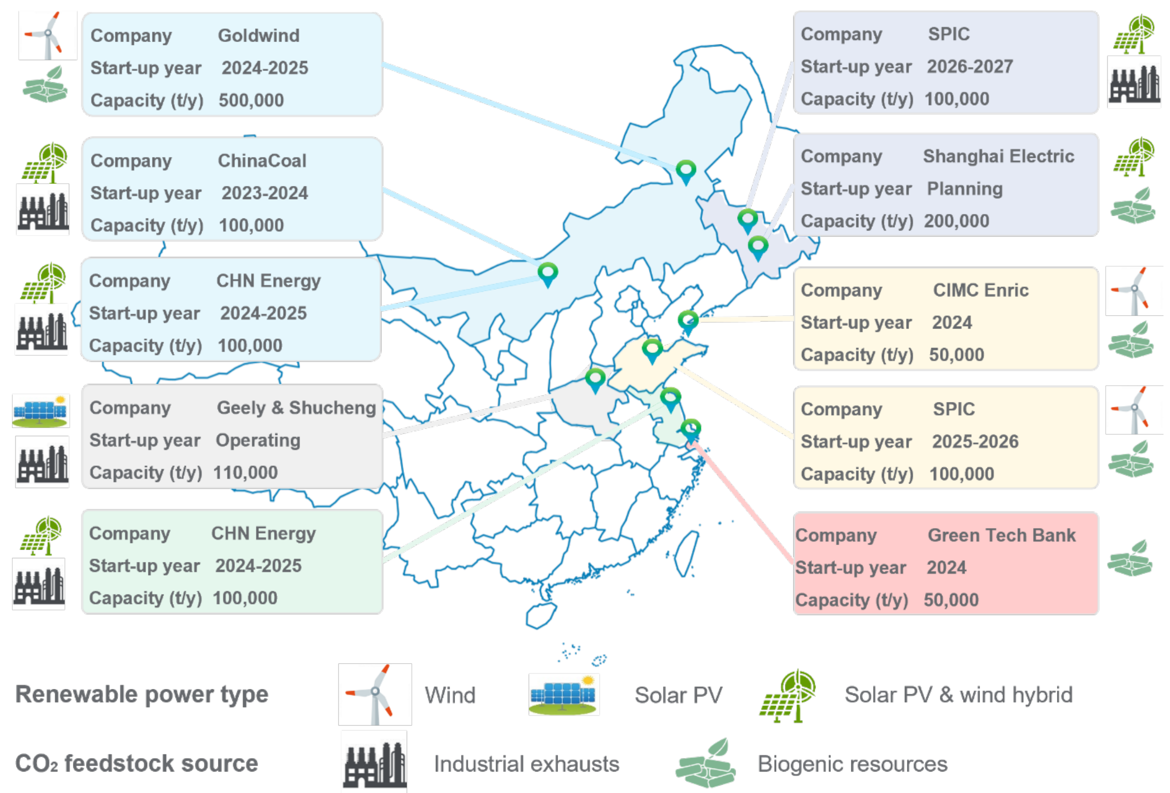
Figure 1 | Role of e-fuels to enable net-zero transitions in road transport



In 2011, the world witnessed a significant milestone with the establishment of the George Olah Renewable Methanol plant by Carbon Recycling International (CRI) in Iceland, marking the first industrial-scale e-fuels production facility. Pioneering the use of renewable geothermal power, this facility harnessed hydrogen and recycled CO_2 to produce 4,000 tonnes of e-methanol per year. Since then, the momentum for e-fuels has grown rapidly, with more than 18 projects being announced or operated across the world as of now, including Europe, the Middle East, Australia, North and South America [3], and recently in China [4]. In 2022, a plant in Chile, South America started delivering e-gasoline (converting from e-methanol) for vehicle applications [5]. The resulting energy-dense liquids demonstrate the feasibility of seamlessly integrating renewable energies into today's road transport system without changing the fuel distribution network nor the vehicle fleet.

Renewable methanol production is being rapidly scaled in China in response to the stated national climate goals.

Figure 2 | Map of renewable methanol plants currently planned in China



Note: map only shows annual production capacity greater than 100,000 tonnes.

Leading energy and chemical companies in China have been advancing renewable methanol production as a pivotal strategy to enable current net-zero transitions. As of 2023, a total of ten commercial-scale renewable methanol production plants have been planned, with an expected annual production capacity of approximately 1.7 million tonnes by 2030, and with e-methanol accounting for about 60% of this capacity (see Figure 2). Within this context, the preference for e-methanol production by local industries stems from several compelling factors. Abundant renewable energy resources within China provide a solid foundation for its production. Local industries could effectively reduce GHG emissions associated with the coal-based methanol platform for its application in chemicals and fuels, such as olefins (MTO), aromatics (MTA), and gasoline (MTG) [6]. Leveraging the world's largest methanol value chain in China allows for efficient e-methanol scaling, with seamless transition enabled by established production technologies such as coal-to-methanol process [6] and efficient synthesis developed by the Dalian Institute of Chemical Physics, Chinese Academy of Sciences [7].

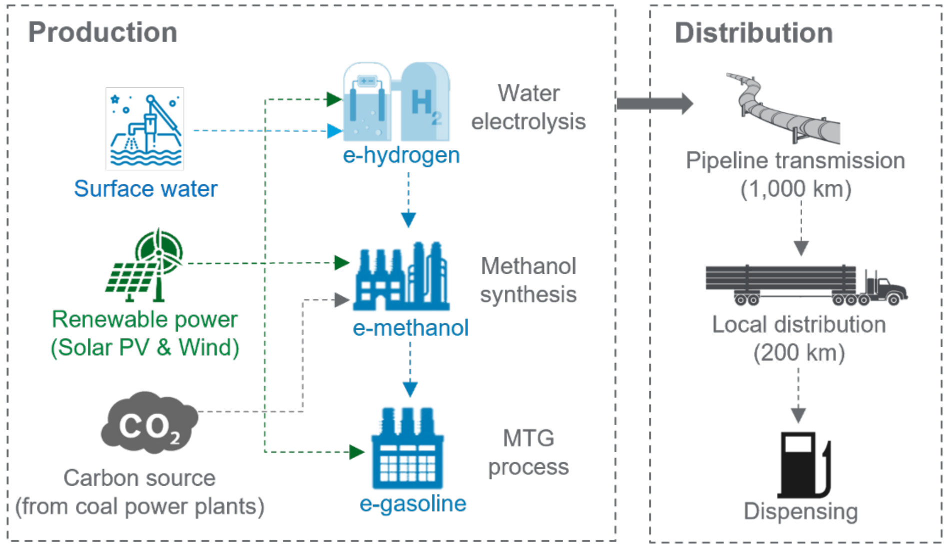
China also takes the lead in the development of methanol-based transport systems by implementing policies, standards, and cross-industry initiatives. The central government issued multiple standards supporting methanol uses as a road transport fuel (Tables A.1 and A.2). Successful methanol-fueled pilot programs in passenger vehicles in selected provinces (e.g., Shaanxi, Guizhou, and Shanxi) led to the adoption of a national policy for the standardization and promotion of methanol-powered ICEVs (internal combustion engine vehicles) as passenger vehicles in 2019 [8]. Leading automotive and shipping companies such as Geely Auto [9], China State Shipbuilding Corporation [10], and China Ocean Shipping Company are also proactively developing, promoting, and utilizing methanol-powered energy systems for road and marine transport [11]. Methanol-fueled powertrains, along with other low-carbon powertrains, have become a critical component in supporting China's climate goals, while their potentials of curbing GHG emissions with emerging e-methanol fuel in the context of road transport remain to be explored.

In this report, we aim to provide a comprehensive assessment of e-fuels paths in China. Specifically, we investigate the fast-growing e-methanol route along with other e-fuels for passenger vehicle application such as e-hydrogen and e-gasoline. The environmental impacts and energy efficiency of passenger vehicles powered by fossil fuels and e-fuels are measured. An economic analysis of producing e-fuels and their cost outlook towards 2030 are also provided. Finally, we conclude our analysis results with recommendations to maximize e-fuels potentials in road transport, considering both short- and long-term perspectives.

Setting base-case e-fuels production

The assessment of e-fuels production is set by a stand-alone plant that could produce three types of e-fuels, namely, e-hydrogen, e-methanol, and e-gasoline. Overall, the evaluation of e-fuels production has three main components, renewable electricity, carbon feedstock, and fuel synthesis. All e-fuels synthesis is powered by renewable electricity from solar PV and wind turbine. Solar PV units assume a 20% system loss, use 2-axis tracking, and employ 35% tilt with a 180% azimuth. Wind power is generated using the GW109 2500 model at a 100 m hub height. Capacity factors are based on Inner Mongolia data from the 2019 MERRA-2 dataset on the renewables.ninja website (see Table A.3). Solar PV and wind power match a 100,000-tonne annual e-methanol production, with buffer storage including battery and hydrogen tank to maintain a 20% minimum load. The objective function minimizes the levelized cost of e-fuels by optimizing electricity supply with minimal capital investment in solar PV and wind power units. Additionally, excess electricity may be sold to local grids. The carbon feedstock considers carbon capture from external coal power plants without further constructing carbon capture units in our stand-alone e-fuels plant.

Figure 3 | Production and distribution of e-hydrogen, e-methanol, and e-gasoline



E-hydrogen is produced through the widely adopted alkaline water electrolysis (AWE) process [4], with water sourced from ground surface and powered by the installed solar PV and wind power plant using an optimal ratio (see Table A.4). As for the e-methanol synthesis, e-hydrogen is coupled with carbon source supplied from coal power plants and undergoes a two-step conversion process already practiced by local industries [2,3].

The synthesis includes: 1) reverse water-gas shift reaction (endothermic) and 2) CO/CO_2 hydrogenation (exothermic), outlined below:

$$CO_2 + H_2 \leftrightarrow CO + H_2O,\ \Delta H_{298} = 41.20\ kJ/mol$$

$$2CO + 4H_2 \leftrightarrow 2CH_3OH + H_2O,\ \Delta H_{298} = -49.43\ kJ/mol$$

$$2CO_2 + 5H_2 \leftrightarrow 2CH_3OH + H_2O,\ \Delta H_{298} = -90.80\ kJ/mol$$

E-gasoline can be efficiently produced through an additional conversion step known as the methanol-to-gasoline (MTG) process. This technology is well-established and has been successfully scaled within local industries [12]. The MTG process typically comprises a series of reactions, including methanol-to-olefins and olefin oligomerization.

This report sets the e-fuels transportation and dispensing scenarios that would need to be scaled towards 2030, according to the plan announced by the Chinese government for integrating the delivery of hydrogen into today's crude oils and natural gas transmission network [13]. The transportation of e-fuels here therefore considers a long-distance distribution (e.g., from the Western to the Central region by 1,000 km), using pipeline transmissions and local delivery (200 km) through trailers. Dispensing e-methanol and e-gasoline at refueling stations follows the established procedures for methanol and gasoline fuels today, while e-hydrogen considers compression to 875 bar required by the FCEV model (Toyota Mirai) investigated in this report. It should be noted that China's hydrogen distribution today is limited to 20 MPa tube trailers only and dispensing at 45 MPa, but it is currently evolving to the technical standards investigated in this report.

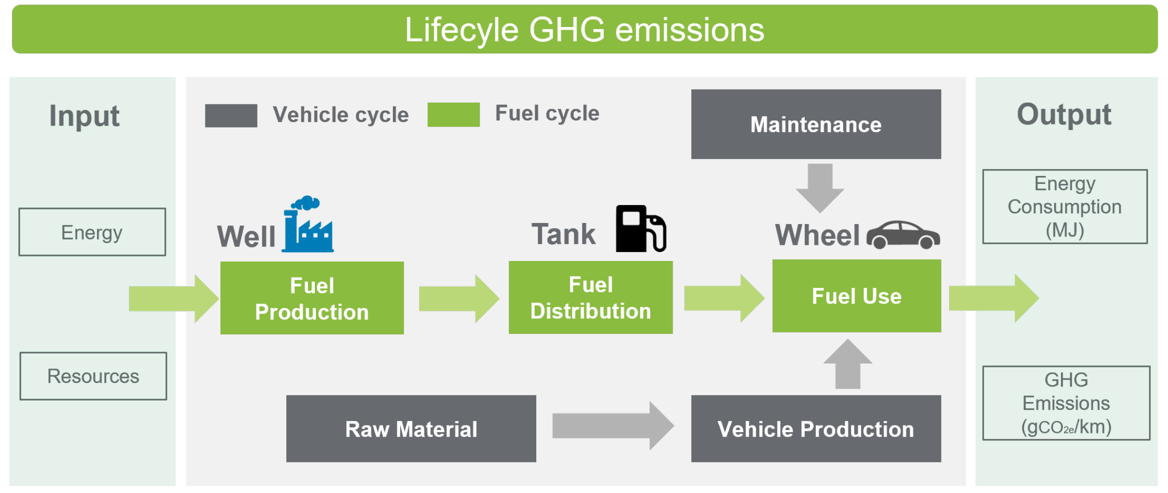
Technical and economic parameters taken for studying e-fuels production and distribution can be found in Tables A.5 to A.8. Assessment results in this report are based on our surveys to industries or estimated using the LCA for Experts (formerly "GaBi") software platform (Sphera CN 2021 database). The presentation, therefore, does not indicate performances of any specific plants, but illustrate the best practices possibly adopted by local industries towards 2030 or beyond. Also, e-fuels production here does not consider recycling waste heat for e-fuels synthesis yet; further investigation to improve its conversion efficiencies can be referred to in other studies [14].

Assessment framework

Our life-cycle assessment (LCA) measures GHG emissions of produced e-fuels (i.e,. e-hydrogen, e-methanol, and e-gasoline) and their application in corresponding vehicles (see Figure 4). The GHG emissions are measured through the global warming potential matrix defined in the IPCC fifth assessment report, in g CO2 equivalent (g CO_{2e}). GHG emissions factors are provided in Table A.9.

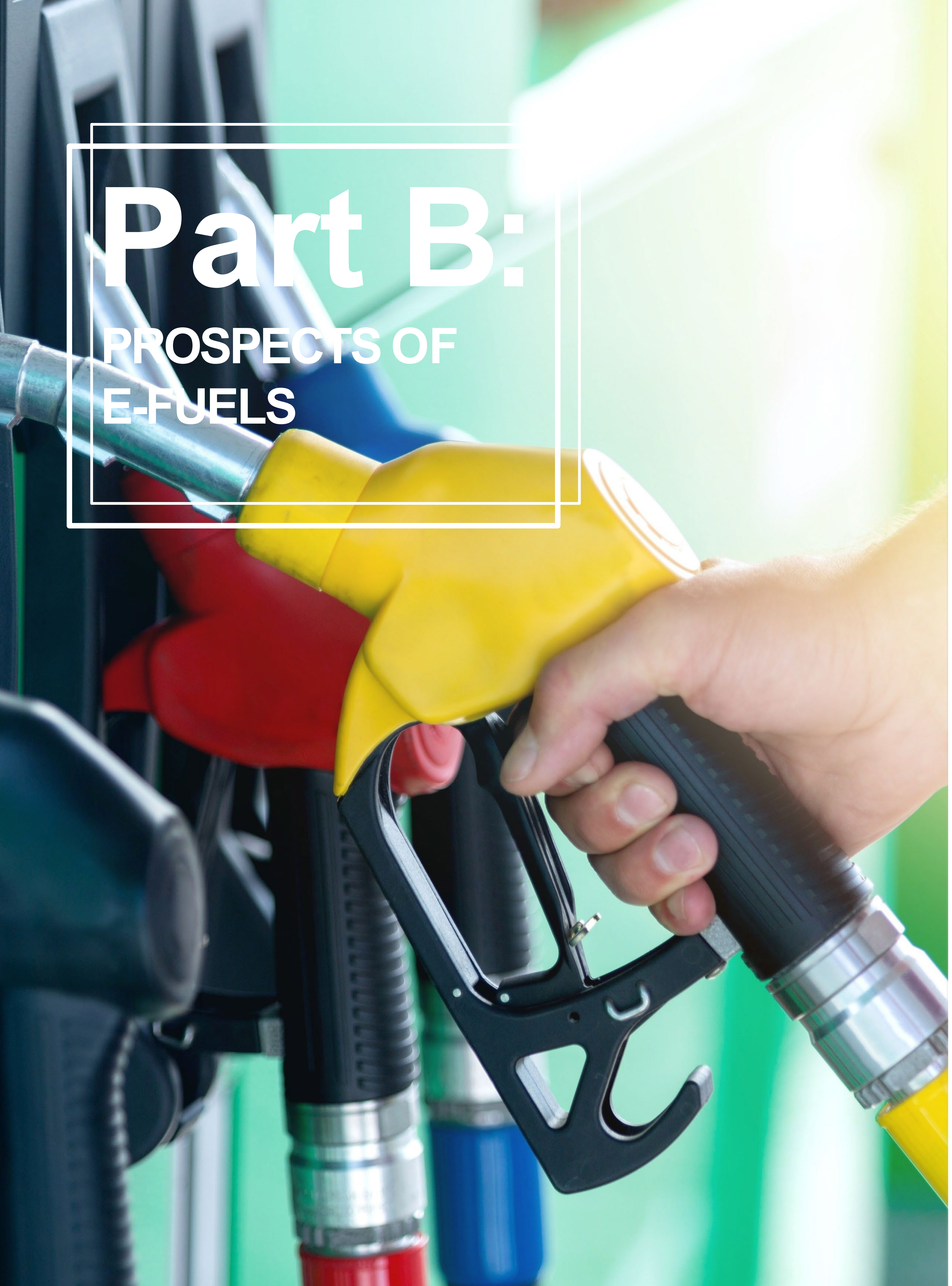
The LCA scope covers: (1) fuel cycle (including production, distribution, and usage in corresponding powertrains) and (2) vehicle cycle (including raw materials, vehicle manufacturing, and maintenance). The methodology in this report is in consistence with China Automotive Technology and Research Center's publication in 2021 [1]. The 2020 sales weighted average vehicle characteristics for each powertrain type are adopted as the reference models in this study, including ICEV (internal combustion engine vehicle), HEV (hybrid electric vehicle), and BEV (battery electric vehicle). Vehicle production data are sourced from China Automobile Low Carbon Action Plan Research Report 2021 [1], while data of methanol-powered vehicles (e.g., M100 ICEV and M100 HEV) is sourced from published literatures (see details in Table A.10).Note that the introduction of China's new dual-credit scheme [15], which incentivizes long-range BEVs, could accelerate the adoption of larger battery capacities in the long term. The 70 kWh battery capacity is therefore considered for BEVs to be charged with renewable or lower-carbon electricity beyond 2030. This choice also aligns with the average battery size 75±5 kWh by 2035 projected by International Energy Agency [16].

Figure 4 I System boundary of environmental impact assessments



Energy efficiencies are determined by measuring each conversion step from renewable energy to electricity or e-fuels, and finally to wheel in corresponding powertrains. The reference capacity of 1 MW solar PV, wind, and renewable hybrid is set for evaluating electricity uptake and overall efficiencies via direct electricity supply to BEV and e-fuels-powered FCEV and HEVs. The efficiency of each conversion step is measured as the ratio of output energy to input energy, expressed as percentages. Note that the energy efficiency assessment is limited to the fuel cycle only. Energy required by vehicle cycles (e.g., vehicle manufacturing and assembly) and building infrastructures for e-fuels production are not included here.

Economic competitiveness investigates costs of producing e-fuels, including e-hydrogen, e-methanol, and e-gasoline. E-methanol, as a fast-growing e-fuels path in China (refer to Figure 2), is further taken as the reference point to chart e-fuels production cost landscape towards 2030. Parameters such as renewable power settings, CO_2 supply costs, and fuel synthesis pathways are investigated. The renewable electricity costs considered are based on three cases: 1) solar PV only, 2) solar PV and wind hybrid, and 3) selling excess electricity. The CO_2 supply costs consider CO_2 captured from: 1) coal gasification units, 2) coal power plants, 3) natural gas power plants, and 4) direct air capture. The alternative fuel synthesis pathways include: 1) state-of-art direct process (developed by CAS DICP [7]), and 2) CO/CO_2 hydrogenation from recycled coke oven gas (scaled by CRI [9]). Based on our sensitivity analysis results and review on potential technology improvements, we put forward our projection of China's e-methanol production cost by 2030.

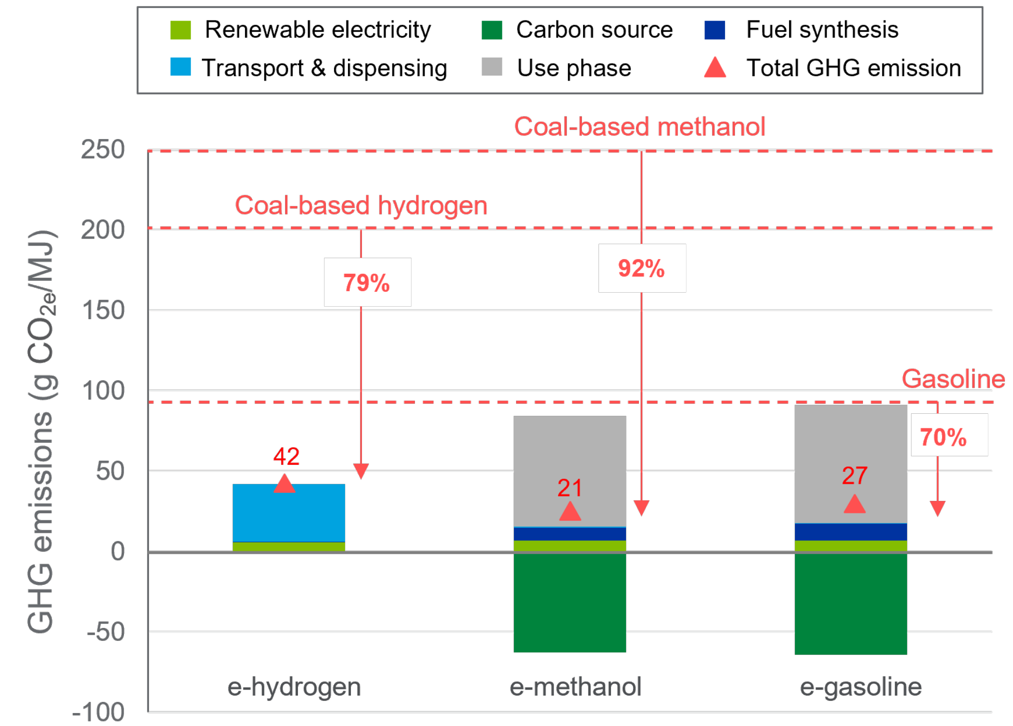


Part B:

PROSPECTS OF E-FUELS

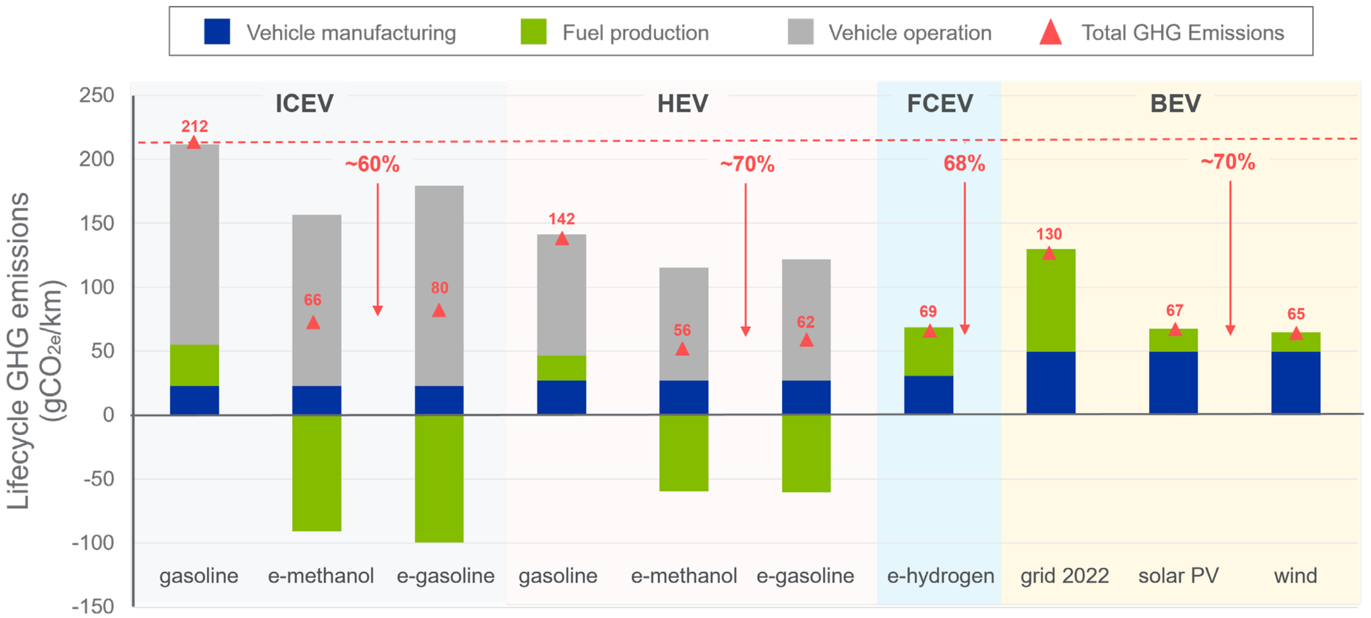
Lifecycle GHG emissions

Figure 5 I GHG emissions of e-hydrogen, e-methanol, and e-gasoline



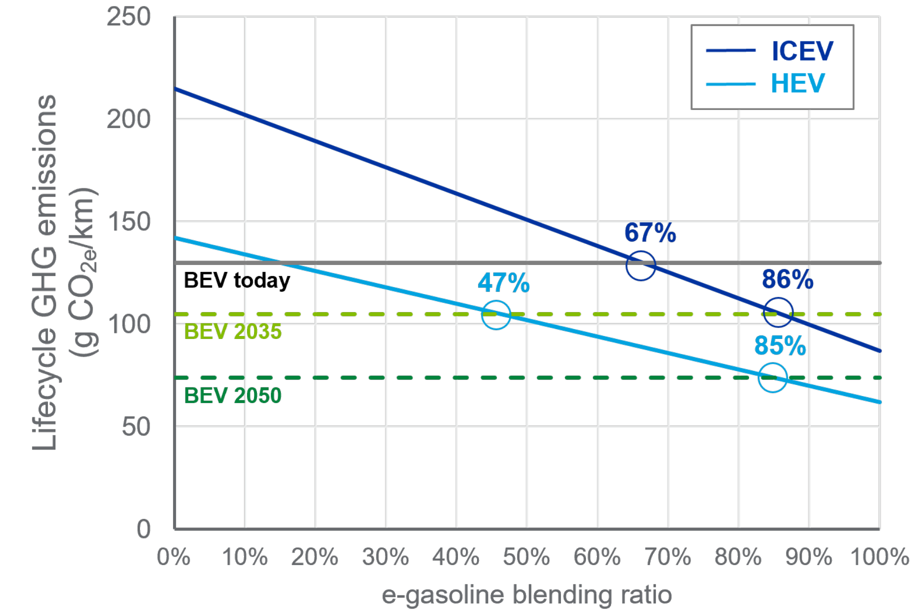
E-fuels exhibit 70% to 90% lower GHG emissions compared to their fossil-based counterparts. These reductions can be attributed to the clean e-fuels production relying on renewable energies and recycled CO_2. While e-fuels GHG emissions are overall low, transportation and dispensing of e-hydrogen could be relatively carbon-intensive as compared to e-methanol and e-gasoline. This is because long-distance distribution of e-hydrogen could involve energy-intensive processes as well as fossil-based energy consumption (see the contribution of transport & dispensing in Figure 5). Compression, which is typically grid-powered at the demand sites, and road transportation, which relies heavily on diesel, could emit substantial GHG emissions. E-hydrogen today are thereby limited to applications within a few pilot cities in China, awaiting efficient pipeline transmission networks for scaling [13]. Alternatively, converting e-hydrogen into liquids such as e-methanol and e-gasoline could facilitate efficient distribution or use across the country today, both locally and to the demand sites in the East. Their compatibility with existing vehicles makes e-methanol and e-gasoline an attractive GHG mitigation measure, which will be discussed in Figures 6 and 7.

Figure 6 | Lifecycle GHG emissions of vehicles powered by renewable energies



Various powertrains can capitalize on e-fuels to mitigate their lifecycle GHG emissions (Figure 6). Methanol- or gasoline-powered ICEVs, if fully loaded with corresponding e-fuels, could enable about 60% lower lifecycle GHG emission than the ICEV powered by gasoline. Combining e-fuels uses in advanced HEVs results in about 70% lower lifecycle GHG emission compared to gasoline-powered ICEV – placing it on par with BEVs powered by solar PV and wind electricity. FCEV can also achieve low lifecycle GHG emissions with e-hydrogen, although it would require pipeline transmission to ensure delivery efficiency across the country [13] and improve its GHG emission performance. In brief, e-fuels can significantly curb lifecycle GHG emissions of ICEVs, HEVs, and FCEVs, and bring the GHG emissions of HEVs and FCEVs to a comparable level to those of BEVs fully powered by renewable electricity.

Figure 7 | Lifecycle GHG emissions of ICEV and HEV using e-gasoline blends

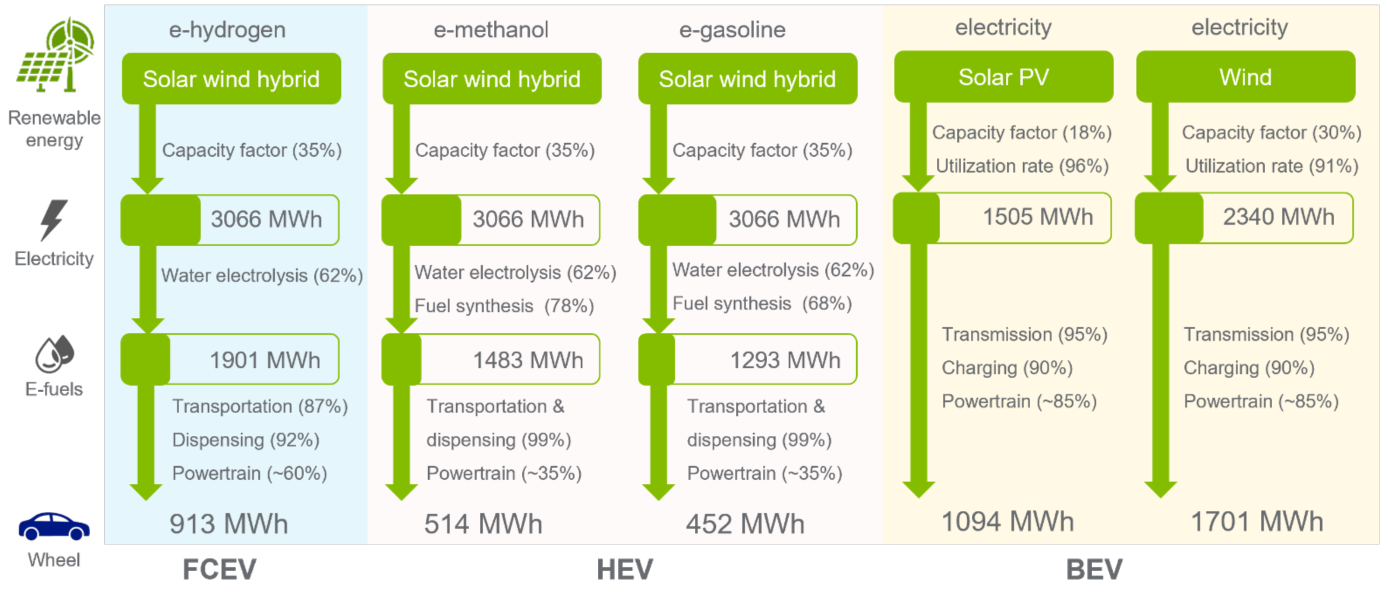


Our analysis in Figure 7 confirms that as conventional gasoline is progressively phased out in favor of e-gasoline, both ICEV and HEV could achieve lifecycle GHG emissions comparable to BEVs powered by low-carbon grids. For example, an ICEV using gasoline blends containing 67% and 86% e-gasoline would emit the same amount of lifecycle GHG emissions of a BEV powered by grid electricity today (541 g CO_{2e}/kWh) and in 2035 (278 g CO_{2e}/kWh) respectively. Furthermore, an advanced HEV would need a gasoline blend with only 47% e-gasoline to reach the level of GHG emissions of a BEV in 2035 (278 g CO_{2e}/kWh), and it could even reach the level of emissions of a BEV in 2050 (73 g CO_{2e}/kWh) with an 85% e-gasoline blend. The “drop-in” e-gasoline showcases its effectiveness to reduce GHG emissions across a range of blending ratios, overcoming potential compatibility issues and uncertainty in vehicle turnovers.

Energy efficiencies

E-fuels could enhance the integration of intermittent renewable energy sources and expand the application of renewables beyond direct electricity supply to BEVs.

Figure 8 | Energy efficiencies through e-fuels and direct electricity supply



Note: tank-to-wheel efficiency of powertrains estimated under NEDC cycle following this reference [17]; FCEV assumed a fuel cell efficiency of 63% and a drivetrain and transmission efficiency of 95%, giving an overall powertrain efficiency of ~60%

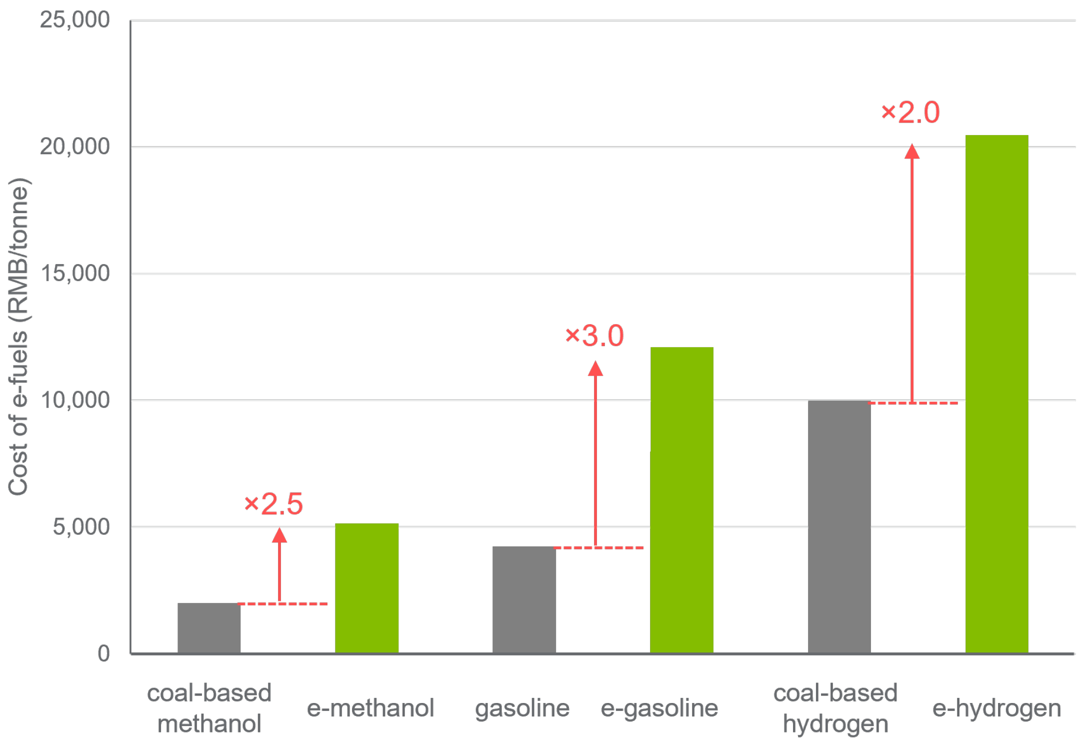
Figure 8 illustrates the efficiency gap between e-fuels and direct electrification. At the same operation scale of renewable power plant (1 MW), the standalone e-fuels production plants could harness 31% to 104% more renewable energy compared to direct grid supply. This advantage stems from the accommodation of optimized solar PV and wind power installations, avoiding curtailment caused by intermittent renewables and demand fluctuations [18]. Nonetheless, depending on the type of e-fuels synthesized, converting renewable electricity to e-fuels incurs an energy loss of 38% to 58%. At the wheels, e-fuels could deliver less than half the energy of direct electrification.

The electricity-to-useful-energy efficiencies of e-fuels are inherently low because of the several conversion steps involved. However, several benefits can be offered by e-fuels for utilizing renewable energy. First, renewable energies can be converted into e-fuels to circumvent curtailed electricity with increasing installation of solar PV and wind power plants [19]. Second, taking the renewable electricity uptake into account, the energy efficiency gap between direct electrification (to BEV) and e-fuels (to FCEVs and HEVs) could be only a factor of approximately 2 to 3 (see energy delivered to wheels presented in Figure 8), not as high as some have claimed [20]. Third, e-fuels can democratize access to renewable electricity application beyond BEVs, addressing regional disparities in vehicle markets and renewable electricity availability [21]. To summarize, e-fuels hold potentials to harness intermittent renewables and extend the use of renewable energies to hydrogen-, methanol-, and gasoline-powered vehicles, not limited to just BEV.

Production cost analysis

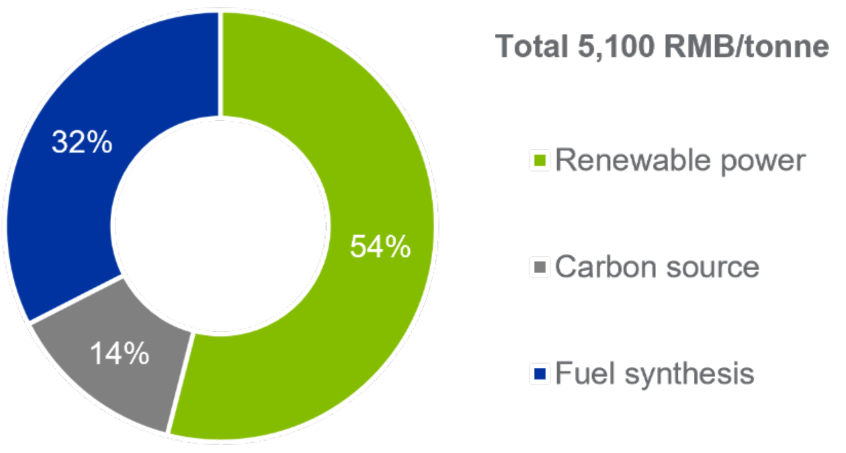
Figure 9 | Cost of producing e-hydrogen, e-methanol, and e-gasoline

Note: costs of producing fossil-based counterparts consider coal price at 800 RMB per tonne and crude oil price at 80 USD per barrel



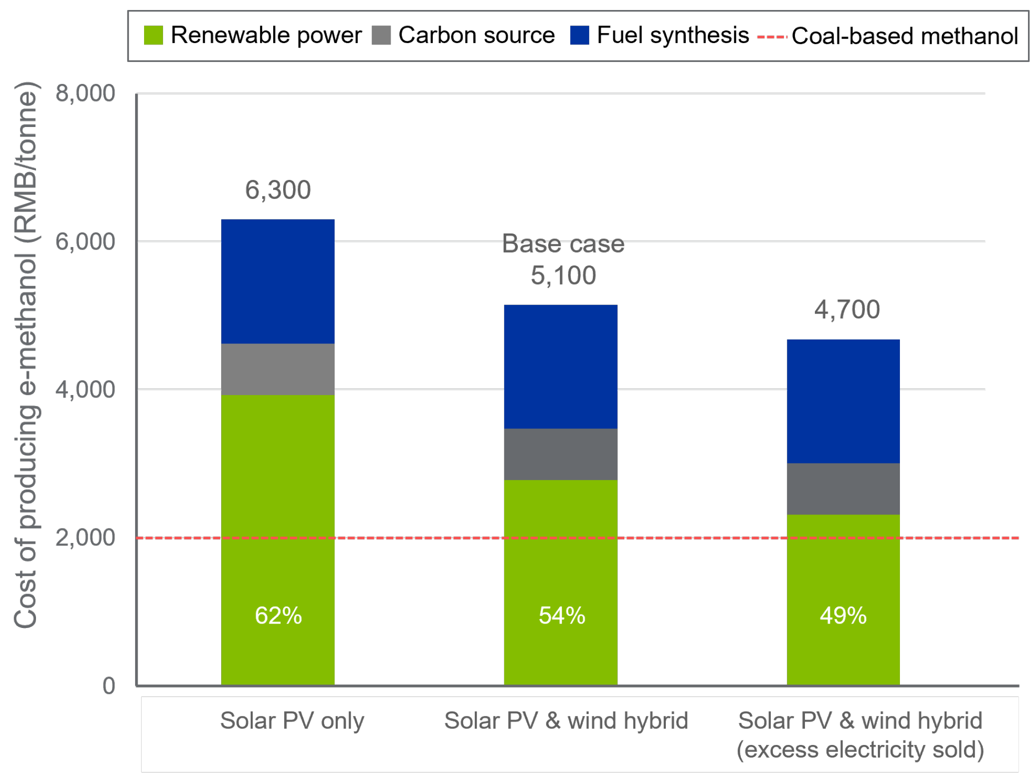
In the context of China's energy landscape, our analysis shows that producing e-fuels is approximately 2 to 3 times more costly than their fossil-based counterparts. E-hydrogen production costs twice the level of fossil-based one, while e-methanol and e-gasoline register cost differentials of 2.5 and 3 times, respectively, in comparison to their fossil-based counterparts. This cost variance in producing e-hydrogen, e-methanol, and e-gasoline arises from the inherent complexity of e-fuels synthesis. Producing e-methanol or e-gasoline involves an extra step of coupling CO_2 with hydrogen and necessitates buffer storage for intermittent electricity and hydrogen. This intermediary role positions e-methanol as a critical building block in the progression from hydrogen to higher hydrocarbons. Given this pivotal role, the subsequent sections delve into an in-depth analysis of e-methanol, showcasing its potential and contribution to the evolution of China's e-fuels landscape.

Figure 10 | Breakdown of e-methanol production cost



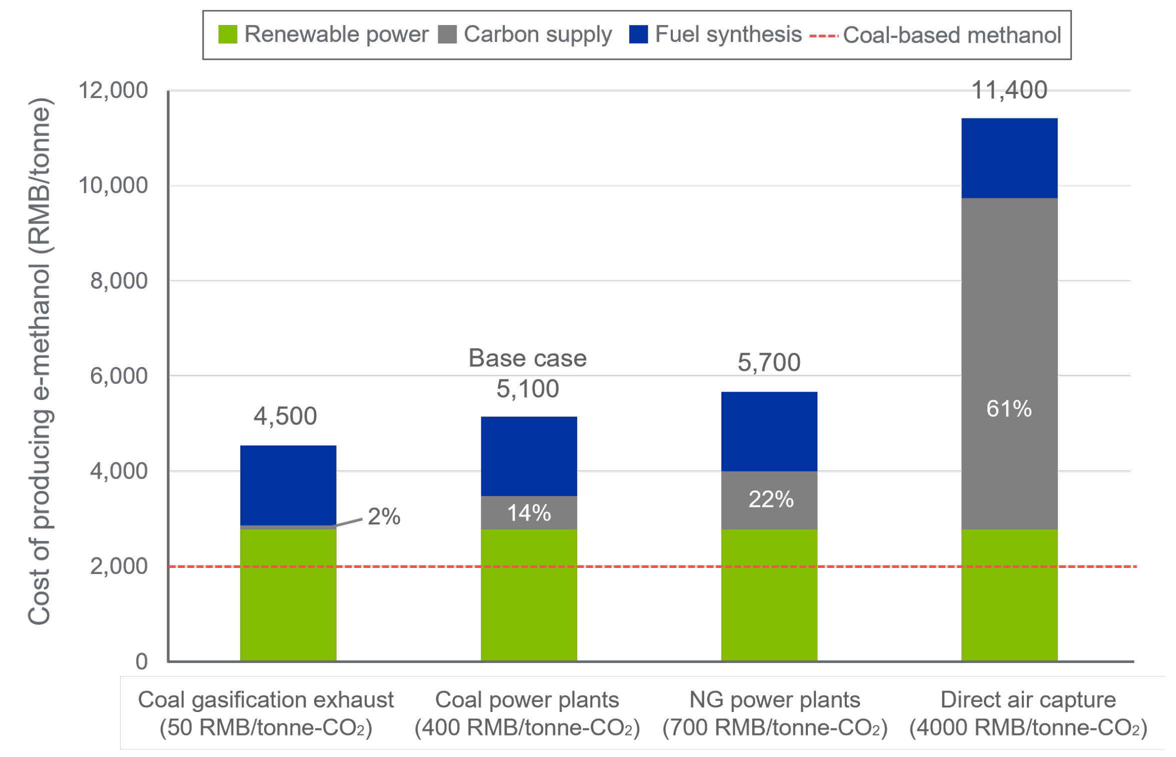
E-methanol production cost using our base-case settings is about 5,100 RMB per tonne, and can be divided into three main components: renewable power, carbon source, and fuel synthesis. About half of e-methanol production cost comes from the renewable power, and the other half from the carbon source and fuel synthesis. The upcoming sections offer sensitivity analyses that unveil the relationships between individual cost component and total production cost, as outlined in Figure 10. In Figure 11, we study the impact of different renewable power settings. Figure 12 illustrates the influence of carbon source supplied at different costs, that is, from various exhausts to direct air capture. Figure 13 investigates diverse methanol synthesis pathways per China's current industrial landscapes. Finally, we provide our projection of e-methanol production cost by 2030 in Figure 14.

Figure 11 | Sensitivity analysis of renewable power settings



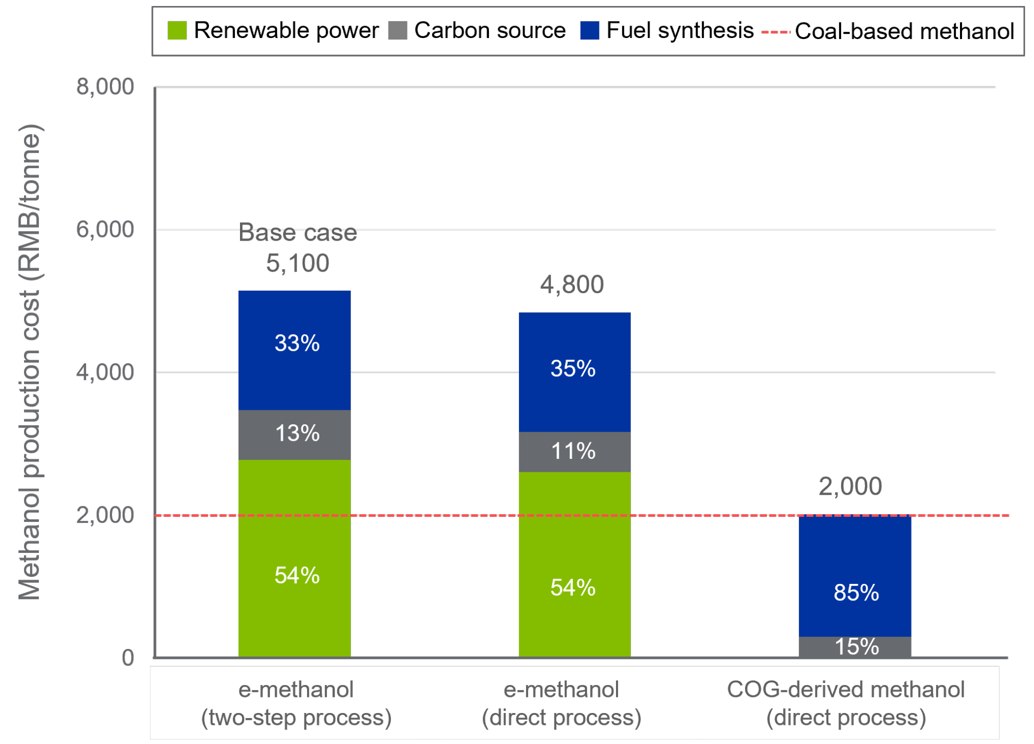
E-methanol production costs today could vary from 4,700 to 6,300 RMB per tonne depending on the renewable power settings, which is about 2.5 to 3 times more costly than today's coal-based methanol. Hybridizing solar PV with wind power can significantly reduce e-methanol production cost, decreasing it to 5,100 RMB per tonne – compared to using only solar PV with production cost 6,300 RMB per tonne. This cost saving through renewable hybridization can be attributed to the reduced installation scale of both renewable power and hydrogen storage. Under the optimal hybrid setting, selling excess electricity could further reduce e-methanol production costs to 4,700 RMB per tonne. This strategy capitalizes on the opportunities of both e-fuels and renewable electricity sales, contributing to the increase of overall economic competitiveness.

Figure 12 | Sensitivity analysis of carbon supply costs



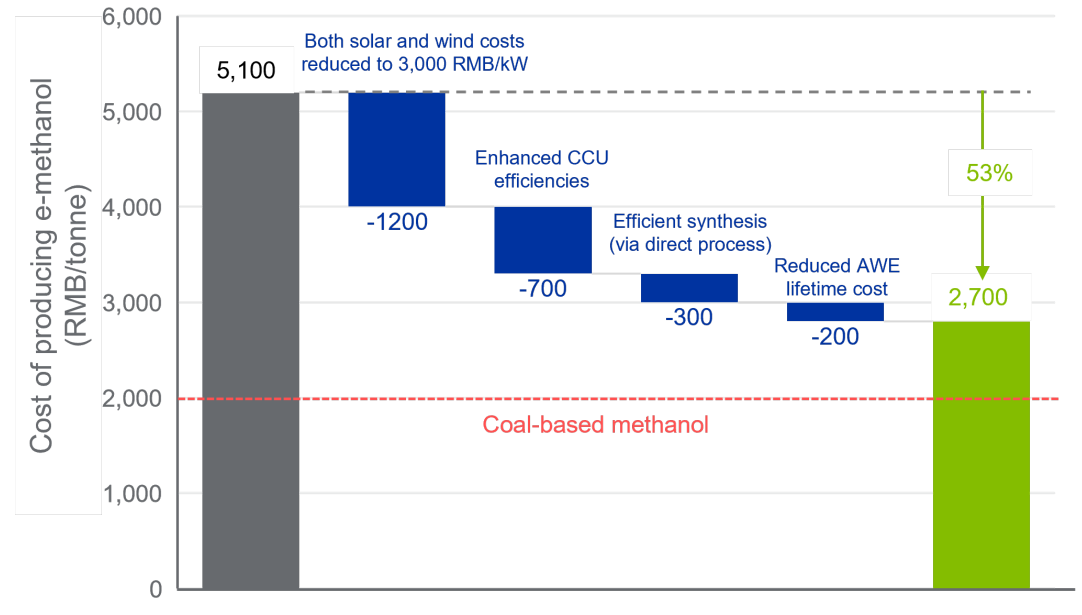
Supply costs of carbon source rise with decreasing CO_2 concentrations, and thereby impacting the e-methanol production cost. At present, sourcing CO_2 from concentrated industrial exhausts could be the most cost-competitive pathway for e-fuels synthesis considering their large availability, low energy-intensive capture, and economic efficiencies. For instance, utilizing CO_2 from coal gasification exhausts could account for as little as 2% of the total e-methanol production cost (see Figure 12). In the long term, where CO_2 point sources from power plants or industries will become scarce or restricted by regulations, e-fuels synthesis using the carbon source from direct air capture (DAC) will be needed. The use of atmospheric CO_2 could enable net-zero GHG emissions as illustrated in Figure 1, although significantly more costly today (DAC increases the e-methanol cost by more than 2 times the base case value). While large-scale DAC carbon source is not economically viable at present, it is projected to become available at approximately 700 RMB per tonne CO_2 by 2045 [22].

Figure 13 | Sensitivity analysis of fuel synthesis pathways



Several low-carbon, synthetic methanol production routes can be taken within local industries (see Figure 13). Compared to the two-step process, direct e-methanol synthesis could reduce the production cost from 5,100 to 4,800 RMB per tonne due to the efficient utilization of hydrogen and CO_2 in the synthesis process (see Table A.5). This technology is currently being scaled to annual production of 100,000 tonnes [7]. Alternatively, the coal industry in China generates about 80 million tonnes coke oven gas (COG) annually [23], and about 20% of the COG is directly discharged to the air [24]. This underutilized portion could be taken for producing methanol with 70% lower GHG emissions than the coal-based one at approximately 2,000 RMB/tonne, which has been proven at commercial scales [9]. The low production cost and carbon footprint are achieved by recycling COG and CO_2 for methanol synthesis, coproducing natural gas, and avoiding direct discharge of COG into the air (see Table A.11 to A.14).

Figure 14 | E-methanol production cost reduction by 2030



E-methanol production cost by 2030 could go down to 2,700 RMB per tonne. Renewable electricity from sources such as low-cost solar PV and wind power are anticipated to play a crucial role in this cost reduction, contributing to a decrease of 1,300 RMB per tonne towards 2030 [25]. Other potential cost reducing measures include efficient carbon capture and utilization (CCU) technologies [26], lifetime cost reduction with optimized alkaline water electrolysis operation [27], and direct CO_2 hydrogenation technologies [7,9], which could decrease the production cost by another 1,100 RMB/tonne in total. Translating the cost reduction potentials of e-methanol to the “drop-in” e-gasoline can result in a significant reduction in its current production from 12,100 to 6,800 RMB per tonne by 2030. This cost reduction encompasses a decrease in the renewable power cost component from 6,400 to 3,600 RMB per tonne, a reduction in carbon source cost component from 1,600 to 200 RMB per tonne, and a decrease in the fuel synthesis cost component from 4,100 to 3,000 RMB per tonne. With collaborative efforts between government and industries, e-fuels could evolve into an affordable, credible, and sustainable solution to support the nation’s climate goals within the context of road transport.

Part C:
CONCLUSION & RECOMMENDATIONS

Conclusion

This report assesses the potential of e-fuels in driving the transition towards a low-carbon and sustainable future for passenger vehicle application. E-fuels, such as e-hydrogen, e-methanol and e-gasoline emerge as powerful contenders, demonstrating remarkable GHG emission reductions ranging from 70% to 90% when compared to their fossil-based counterparts in China (Figure 5). The combination of electrified powertrains (e.g., HEVs and FCEVs) with e-fuels presents a compelling proposition, as it can achieve lifecycle GHG emissions comparable to BEV fully powered by solar PV and wind electricity (Figure 6).

In the near term, the e-fuels GHG mitigation potential could be enabled by the “drop-in” e-gasoline that can be easily blended into conventional gasoline. The ICEV using the 67% and 86% e-gasoline blends can meet lifecycle GHG emissions of BEV powered by grid electricity today and in 2035. On the other hand, with e-gasoline blend ratios from 47% to 85%, an efficient HEV could achieve GHG emissions equivalent to the BEV charged by low-carbon grid electricity in 2035 and 2050 (Figure 7). This approach effectively lowers the lifecycle GHG emissions of passenger vehicles, free from the constraint of uncertain vehicle turnovers.

Despite challenges related to e-fuels production processes, such as inefficiencies and conversion losses, the e-fuels pathway facilitates the incorporation of renewable energy into various powertrains powered by hydrogen, methanol, and gasoline fuels, alongside direct renewable electricity supply to BEV. The optimized solar and wind hybridization system promises to increase renewable electricity uptake by stabilizing the electricity supply and avoiding curtailment. The overall energy efficiencies of e-fuels-powered FCEVs and HEVs can be narrowed to about half of BEV powered by the renewable electricity from solar PV or wind (Figure 8).

While producing e-fuels costs about 2 to 3 times more than fossil fuels in China (Figures 9 and 10), we identify paths towards cost optimization through renewable power, carbon source, and fuel synthesis settings (Figures 11, 12 and 13). By 2030, e-methanol production costs could be halved to a value only 30% higher than the cost of coal-derived methanol (Figure 14). This significant cost reduction could be achieved by leveraging cheaper solar PV and wind power installment, lowering carbon capture costs, developing efficient fuel synthesis, and optimizing electrolyzer operation.

The uniqueness of China's abundant coal reserves merits attention. Leveraging these reserves and established value chains, e-methanol synthesis presents a strategic avenue for coal-based local industries to play a proactive role in responding to the nation's climate goals through the established production technologies and the integration with renewable energies and recycled CO_2. By capitalizing underutilized byproducts or exhausts, these industries could generate additional revenue streams while contribute to reduced GHG emissions in road transport, either by direct fuel use in methanol-powered vehicles, or by deriving into e-gasoline for today's vast vehicle fleet.

In conclusion, this report highlights the transformative potential of deploying e-fuels in the road transport to mitigate lifecycle GHG emissions. As governments and industries work collaboratively to drive technological advancements, both e-fuels and electrified powertrains are poised to accelerate the transition towards a low-carbon, sustainable road transportation.

Recommendations

The GHG mitigation potential of e-fuels for road transport applications could be maximized both in the short and long terms as follows:

Short-term by scaling up from existing value chains

- Encourage collaboration across upstream and downstream industries to integrate e-fuels into the road transport such as combining their uses with efficient powertrains such as HEV and FCEV.
- Enable the GHG mitigation potential of e-fuels by the "drop-in" e-gasoline that is fully compatible with existing fuel distribution network and combustion engines
- Recycle CO_2 from concentrated industrial exhausts for e-fuels synthesis to ensure conversion efficiency and on the other hand, help to avoid further exploitation of fossil-based resources.
- Explore opportunities from China's coal-based value chains to produce cost-competitive, low-carbon fuels
- Establish the LCA-based policy and certification to measure decarbonization efforts from both upstream (e.g. energy supply) and downstream (e.g. automotive manufactures, fuel consumption rate improvements) industries. Adopting lifecycle thinking and practice is the key to ensure transitions to carbon neutrality [28].

Long-term by enabling carbon neutrality

- Develop circular carbon value chains based on biogenic resources, such as waste, biomass, or direct air capture. Cases such as collection of scattered biogenic resources, exploiting virgin natural resources, or converting food crops into fuels should be avoided.

Part D:

ANNEXES

Abbreviations

AWE	Alkaline water electrolysis
BEV	Battery electric vehicle
CAPEX	Capital expenditures
CDG	Coke dry quenching
COG	Coke oven gas
CWQ	Coke wet quenching
FCEV	Fuel cell electric vehicle
GHG	Greenhouse gas
HEV	Hybrid electric vehicle
ICEV	Internal combustion engine vehicle
IPCC	Intergovernmental Panel on Climate Change
LCA	Lifecycle assessment
LHV	Lower heating values
MeOH	Methanol
MTA	Methanol-to-aromatics
MTO	Methanol-to-olefins
MTG	Methanol-to-gasoline
NG	Natural gas
OPEX	Operating expenditures
Solar PV	Solar Photovoltaics

References

1. China Automotive Technology and Research Center, 2021, China Automobile Low Carbon Action Plan Research Report 2021
2. Chinese Academy of Sciences, 2018, *Joule,* vol.2, page 1925-1949
3. eFuel Alliance | E-fuels Production Map 2023 (website)
4. Methanol Institute | Current and Upcoming Renewable Methanol Project across Countries (website)
5. Porsche | 2022, e-Fuels pilot plant in Chile officially opened (website)
6. Shenhua Group - National Institute of Clean and Low Carbon Energy, 2017, Catalysis Today , vol. 298, page 61-68
7. Chinese Academy of Sciences - Dalian Institute of Chemical & Physics, 2020, "Liquid Sunshine Enlightens New Way of Green Energy" (news)
8. Methanol Institute, 2019, A Brief Review of China's Methanol Vehicle Pilot and Policy
9. Geely Auto & Henan Shunchen, 2022, The Shunli CO2-To-Methanol Plant: Commercial Scale Production in China (news)
10. China State Shipbuilding Corporation, 2022, "Methanol Dual Fuel Powered Ship Delivered" (news)
11. China Ocean Shipping Company (COSCO), 2023, "COSCO proactively responds to sustainable, low-carbon initiatives for building green fleets" (news)
12. Chinese Academy of Sciences – Institute of Coal Chemistry | 2016, Methanol-to-gasoline process using a fixed bed adiabatic reactor (website)
13. National Energy Administration, 2023, Country's Oil and Gas Network Construction Plan
14. Concawe & Aramco, 2022, report no.17/22, "E-Fuels: A techno-economic assessment of European domestic production and imports towards 2050"
15. Ministry of Industry and Information Technology, 2017, Passenger Cars Corporate Average Fuel Consumption and New Energy Vehicle Credit Regulation (in Chinese)
16. International Energy Agency, 2021, Global EV Outlook 2021
17. ETH Zurich., 2012, 2013, Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering.vol.227, page 78-86

18. National Energy Administration, 2022, Notice on the 2021 Results on Monitoring and Evaluation of National Renewable Energy Development
19. National Development and Reform Commission, 2022, Plan on the Development of Hydrogen Energy for the 2021-2035 Period (in Chinese)
20. International Council on Clean Transportation | 2020, "E-fuels won't save the internal combustion engine" (website)
21. Argonne National Laboratory, 2021, Environmental Science & Technology, vol. 55, page 6944-6956
22. Global CCS Institute, 2022, Economics of Direct Air Carbon Capture and Storage
23. National Bureau of Statistics of China, 2021, China Energy Statistical Yearbook 2021 (in Chinese)
24. Shanxi Coking Group, 2021, *China Chemical Trade – Technical Process*, pages 46-48
25. National Development and Reform Commission | 1) Prospects of China's Photovoltaic Development 2) Prospects of China's Wind Power Development toward 2050 (in Chinese)
26. Global CCS Institute, 2023, CCS Progress in China – A Status Report
27. World Economic Forum, 2023, Green Hydrogen in China: A Roadmap for Progress
28. Aramco Asia & China Automotive Technology and Research Center, 2023, *Transportation Research Part D: Transport and Environment*, vol.118, 103725
29. China Renewable Energy Engineering Institute, 2023, China Renewable Energy Development Report 2022 (in Chinese)
30. Chinese Academy of Sciences – Dalian Institute of Chemical & Physics, 2022, Chemical Industry and Engineering Progress, vol. 41(3), page1309-1317
31. China Electricity Council, 2023, 2023 annual report of China's power industry (in Chinese)
32. Global Energy Interconnection Development and Cooperation Organization, 2020, "14th-five" Electricity Development Pathway Study (in Chinese)
33. State Key Laboratory of Pollution Control and Resource Reuse, Nanjing University, 2016, *Journal of Cleaner Production* vol. 112, page 1292-1301

Appendix

Table A.1 | National policy supports for methanol applications in road and marine transport sectors

Time	Departments	Government Notice or Policy	Content & Implications
2013.02	General Office of the State Council	Opinions on strengthening energy conservation and emission reduction in the internal combustion engine industry	Starts the application of methanol-based dual fuel supply systems in passenger vehicles, commercial vehicles, and vessels
2018.03	1. Ministry of Industry and Information Technology, 2. National Development and Reform Commission, 3. Ministry of Science and Technology	Report on the pilot test work of methanol vehicles	Prove reliability, cost-effectiveness, and environmental impacts of methanol-fueled vehicles through 1,024 methanol-fueled vehicles and 20 constructed methanol refueling stations
2019.03	1. National Development and Reform Commission 2. National Health Commission 3. Ministry of Science and Technology 4. Ministry of Industry and Information Technology 5. Ministry of Public Security 6. Ministry of Ecology and Environment 7. State Administration for Market Regulation 8. Ministry of Transport	Guidance on the development of methanol automotive applications in selected regions	Enable national energy security by establishing methanol production, distribution, and downstream application value chains in the road transport sector
2020.11	Ministry Of Ecology and Environment	n.a.	Discloses environmental information of methanol-fueled vehicles to the public
2020.12	Ministry of Industry and Information Technology	Notice on adjusting requirements for methanol automotive product	Includes methanol-fueled vehicles into the national management system
2021.11	Ministry of Industry and Information Technology	"14th Five-Year Plan" industrial green development plan	Highlights the development of efficient methanol synthesis and promotes alternative low-carbon powertrains, such as methanol-fueled vehicles
2022.04	1. Ministry of Transport 2. Ministry of Science and Technology	"14th Five-Year Plan" for scientific and technological innovations in the field of transportation	List methanol with renewable electricity, hydrogen, ammonia, natural gas, and biomass as clean energy pathways to meet China's dual carbon targets
2022.06	1. Ministry of Industry and Information Technology, 2. National Development and Reform Commission	Industrial Energy Efficiency Improvement Action Plan	Encourage the development of efficient energy storage technologies or hydrogen carriers such as methanol)
2022.06	Ministry of Transport	Opinions on the complete, accurate and effective implementation of 30/60 carbon targets	Fosters the development of alternative low-carbon synthetic fuels and efficient powertrain applications in road and marine transport sectors.
2022.09	1. Ministry of Industry and Information Technology, 2. National Development and Reform Commission, 3. Ministry of Finance, 4. Ministry of Ecology and Environment, 5. Ministry of Transport	Implementation opinions on accelerating the green and intelligent development of inland waterways	Promote the development and commercialization of methanol-powered vessels in the marine transport sector including internal combustion engines and fuel cell electric powertrains.
2023.08	1. National Development and Reform Commission 2. Ministry of Science and Technology 3. Ministry of Industry and Information Technology 4. Ministry of Finance 5. Ministry of Ecology and Environment 6. Ministry of Housing and Urban-Rural Development 7. Ministry of Transport 8. State-owned Assets Supervision and Administration Commission of the State Council 9. National Energy Administration 10. Civil Aviation Administration of China	Notice on deploying demonstration projects featuring advanced green and low-carbon technologies	Deploy several low-carbon synthetic fuel demonstration projects for marine and aviation transport applications by central enterprises by 2025. Examples of low-carbon synthetic fuels could be liquid fuels produced from recycled CO_2 through the syngas and methanol pathways.

Table A.2 | Standards related to methanol-fueled vehicles in China

Code	Name of Standards
GB/T 23510-2009	Methanol fuel for motor vehicles
GB 338-2011	Methanol for uses in the industry
GB/T 31776-2015	Determination method of methanol content in methanol gasoline for motor vehicles
GB/T 34548-2017	The additive of methanol gasoline for methanol-fueled vehicles
HJ1137-2020	Measurement methods for unconventional pollutant emissions by methanol-fueled vehicles
GB/T 23799-2021	Methanol gasoline blend (M85) for methanol-fueled vehicles
QC/T 1130-2021	Methanol vehicle fuel consumption test method
QC/T 1150-2021	Technical specifications of fuel systems in methanol-fueled vehicles
QC/T 1151-2021	Technical specifications of methanol-fueled vehicles
QC/T 1145-2021	Technical specifications of diesel/methanol dual fuel systems
QC/T 1146-2021	Technical specifications of powertrains in methanol-fueled vehicles
GB/T 41884-2022	Safety specification for operation of methanol fuel for vehicles
GB/ T42416-2023	M100 methanol fuel for motor vehicles
GB/T 42436-2023	Additives for vehicular M100 methanol fuel

Notes: standards issued by Standardization Administration of China (SAC), Ministry of Industry and Information Technology (MIIT), and Ministry of Ecology and Environment (MEE)

Table A.3 | Technical and economic parameters for renewable power generation and buffer storage of electricity and hydrogen tank [1]

Items	Unit	Wind	Solar PV	Battery	Hydrogen tank
Mean capacity factors	a.u.	37.6%	22.5%	-	-
CAPEX	RMB/kW	6,000	4,100	1,200	6,800
OPEX	RMB/kW/yr	300	250	12	6.8
Lifetime	a.u.	20	25	10	20

1 CAPEX and OPEX data are sourced from the report of China Renewable Energy Engineering Institute [29]

Table A.4 | Installed Solar PV and wind power capacities for the standalone e-fuels plant

Items	Unit	Solar PV	Solar PV & wind (Hybrid)
Wind installed capacity	MW	-	300
Solar PV installed capacity	MW	900	80
Annual electricity generation	GWh	1,780	1,150
Capacity factor [1]	a.u.	23%	35%
Excess electricity [2]	a.u.	46%	13%

1 Capacity factors are rated by annual electricity generation to the total installed capacity

2 Excess electricity assumed to be sold at 0.29 RMB/kWh according to the announcement by National Development and Reform Commission.

Table A.5 | Inputs and outputs table of e-hydrogen, e-methanol, and e-gasoline synthesis

	Unit	e-hydrogen	e-methanol (Two-step process)	e-methanol (Direct process)	e-gasoline
Input					
Carbon dioxide	kg	-	1.74	1.40	-
Coke oven gas	kg	-	-	-	-
Hydrogen	kg	-	0.19	0.19	0.001
Methanol	kg	-	-	-	2.29
Cooling water	kg	-	4.49	4.49	-
Fresh water	kg	9.00	-	-	-
Electricity	kWh	72.43	0.45	0.28	0.71
Thermal energy	MJ	-	1.69	-	-
Output					
Hydrogen	kg	1.00	-	-	-
Methanol	kg	-	1.00	1.00	-
Gasoline	kg	-	-	-	1.00
Natural gas	kg	-	-	-	-
Water	Kg	-	0.93	0.59	1.29
Oxygen	kg	8.00	-	-	-
Heat production	MJ	-	1.19	-	1.30

Table A.6 | Technical and economic parameters for the e-methanol and e-gasoline synthesis

Cost components	Unit	Parameters
Inflation rate	a.u.	2%
Nominal discount rate	a.u.	8%
Operating hours	hour	8,000
e-methanol production plants [1]		
Lifetime	year	10
CAPEX	Million RMB	1,600
OPEX	Million RMB/yr	16
e-gasoline production plants [1]		
Lifetime	year	15
CAPEX	Million RMB	300
OPEX	Million RMB/yr	3

1 E-methanol and e-gasoline set to the annual production of 100,000 tonnes/yr, with economic parameters respectively taken from reference [30] and [12]; the carbon source supply for e-methanol and e-gasoline synthesis are taken out from OPEX for our cost breakdown analysis.

Table A.7 | Technical and economic parameters for the hydrogen production and storage unit

	Unit	Quantity
Technical parameters		
Nominal current density	A/cm^2	0.6
Cell voltage	V	1.8 - 2.2
System efficiency	%	60 - 65
Specific energy	kWh/ Nm3	4.5
Operating Pressure	bar	60
Operating Temperature	°C	60 - 80
Production Rate	Nm^3/h	1,000
Economic parameters		
Capital costs	RMB/kW	2,000 - 2,500
O&M costs	RMB/kW/yr	125
Lifetime	hours	80,000
Byproduct oxygen [1]	RMB/tonne	800

1 Oxygen sold as byproduct is included in the cost component of e-fuels production units.

Table A.8 | Technical and economic parameters for e-fuels distribution

	Unit	Quantity
Technical parameters		
Hydrogen transported by [1] pipeline transmission	MJ electricity per kg hydrogen per 100 km	0.086
Hydrogen transported by [2] 20 MPa tube trailer	kg-diesel per kg hydrogen per 100km	0.175
Hydrogen compression and [3] dispensing	MJ electricity per kg hydrogen	10
Methanol/gasoline [4] road distribution	kg-diesel per kg fuel per 100km	0.002
Economic parameters		
Diesel cost	RMB/liter	7.5
Electricity cost	RMB/kWh	0.8

1 The hydrogen transported by pipeline transmission assumes 392 kg/hour delivery, hydrogen loss 5E-07 kg/(kg*km), exit pressure 35 at bar, and 98% utilization over the entire year.

2 20 MPa tube trailers can load 360 kg hydrogen and operate at fuel economy of 25 liter-diesel per 100 km traveled on roads.

3 Hydrogen compression and dispensing considers pressurized to 875 bar for dispensing to 70 MPa storage tank.

4 Methanol and diesel are transported by trucks, with load capacity of 25 tonners per truck and being operated at fuel economy of 25 liter-diesel per 100 km traveled on roads.

Table A.9 | GHG emissions factors for different material and energy inputs

Inputs	GHG emission factor	Unit	Notes
Surface water	0.10	$kgCO_{2e}$/kg	GaBi Sphera CN 2021
Natural gas	76	gCO_{2e}/MJ	GaBi Sphera CN 2021
Carbon source from exhausts of coal power plants	-710	gCO_{2e}/kg	Carbon capture efficiency is sourced from this report [14]; calculation based on the conditions of China and database of GaBi Sphera CN 2021
Solar PV power	29	gCO_{2e}/kWh	GaBi Sphera CN 2021 (carbon intensity including GHG impacts of infrastructures)
Wind power	11	gCO_{2e}/kWh	GaBi Sphera CN 2021 (carbon intensity including GHG impacts of infrastructures)
Gasoline	89	gCO_{2e}/MJ	Data sourced from this public reported published by CATARC [1]
Methanol	250	gCO_{2e}/MJ	Calculated with the coal-based feedstock and energy inputs with data sourced from GaBi Sphera CN 2021
Grid electricity today	541	gCO_{2e}/kWh	China's grid electricity today is according to China Electricity Council [31]
Future grid electricity in 2035 and 2050	278 and 73	gCO_{2e}/kWh	Grid electricity in 2035 and 2050 are based on the renewable portion projected by China's (GEIDCO) Global Energy Interconnection Development and Cooperation Organization [32]

[1] The renewable portion of grid electricity assumed in 2035 and 2050 is respectively 71.4% and 82.3%.

Table A.10 | Technical parameters of ICEV, HEV, M100 ICEV, M100 HEV, FCEV, and BEV

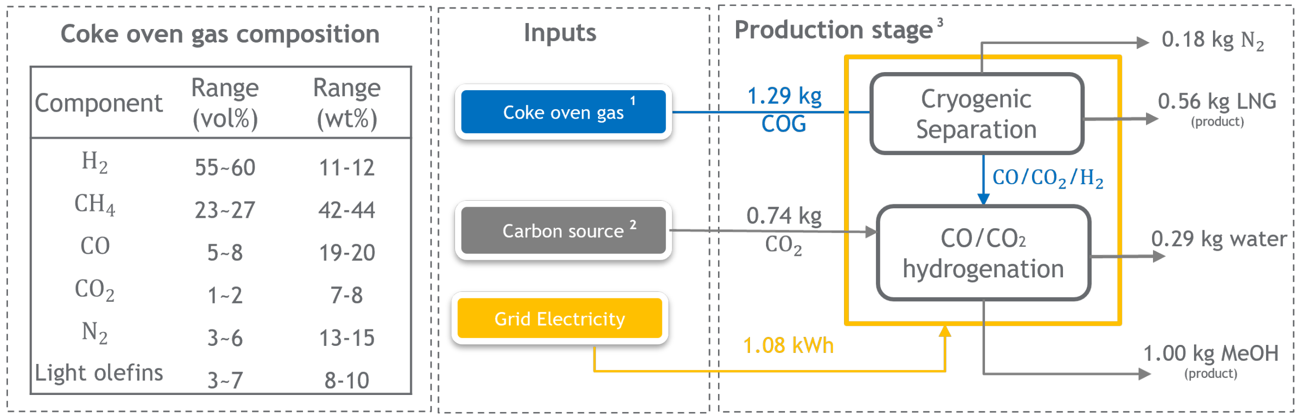
Technical parameters	Unit	M100 ICEV	M100 HEV	ICEV	HEV	FCEV [3]	BEV
Fuel types		Methanol	Methanol	Gasoline	Gasoline	Hydrogen	Electricity
Fuel consumption and emission profile							
Test condition [1]	a.u.	WLTP	WLTP	NEDC	NEDC	NEDC	NEDC
Fuel consumption rates	L/100km	14.0	9.2	6.6	4.0	0.8 kg-H_2	14.9 kWh
CO_2 emission [2]	g/km	134	88	156	95	-	-
Vehicle manufacturing and lifecycle							
Lifecycle mileage	km	150,000	150,000	150,000	150,000	150,000	150,000
Vehicle weight	kg	1240.0	1420.0	1487.0	1665.8	1947.0	1418.0
Body system weight	kg	702.9	725.6	738.4	684.4	841.2	542.5
Powertrain system weight	kg	224.1	351.1	213.6	343.0	142.8	48.8
Electric drive system weight	kg	-	59.4	-	59.4	135.9	133.2
Chassis system weight	kg	273.2	272.8	354.5	329.3	404.2	252.1
Tires	kg	74.4	37.2	37.1	40.9	37.1	42.9
Spare tire	kg	10.4	10.4	9.3	10.2	9.3	10.7
Lead-acid battery weight	kg	15.5	15.5	16.1	17.8	10.0	12.7
Lithium battery weight	kg	-	47.0	-	44.0	40.0	319.6
Lithium battery capacity	kwh	-	1.8	-	1.8	1.2	45.9

[1] WLTP fuel consumptions of methanol vehicles can be scaled to NEDC standards by dividing 1.15 [1].

[2] Under 99% fuel oxidation rates, 2.37 and 1.10 kg CO_2 are respectively released from burning each liter of gasoline and methanol.

[3] FCEV takes the Mirai model for calculation; data are sourced from Toyota public website.

Table A.11 I Illustration of co-producing methanol and natural gas from recycled coke oven gas



[1] The GHG emissions of each kg COG feedstock is 0.10 kg CO_{2e}, as measured by:

- **GHG emitted** (from well-to-gate) through the coal-to-coke process [33] as allocated by lower heating value of each product (in Table A.12), which is 2.60 kg CO_{2e} per kg COG;
- **GHG avoided** is 2.50 kg CO_{2e} for each kg COG, which addresses 20% COG today in China being directly discharge to the air (12.50 kg CO_{2e} per kg COG) [24].

[2] The evaluation for the GHG emissions of carbon source is according to this study [14], where GHG of carbon capture and purification processes are accounted. The overall electrical (local grid, 541 g CO_{2e}/kWh) and thermal (nature gas-based, 76 g CO_{2e} /MJ) energy demands for carbon capture and corresponding calculations can be referred to Table A.13.

[3] The well-to-gate GHG emissions for the co-production of methanol and natural gas from the described process is allocated by energy content of each product in Table A.14. The carbon intensity for producing 1 kg COG-derived methanol is 0.09 kg CO_{2e} (equal to 4.3 g CO_{2e}/MJ) and -0.18 kg CO_{2e} (equal to -8.5 g CO_{2e}/MJ), as powered by today's grid electricity (541 g CO_{2e}/kWh) and solar PV (29 g CO_{2e}/kWh) respectively. The well-to-wheel carbon intensities of COG-derived methanol using power from local grids and solar PV are respectively 76.4 and 63.6 g CO_{2e}/MJ, which further include GHG emissions from transportation (3.2 g CO_{2e}/MJ) and uses (68.9 g CO_{2e}/MJ).

[4] Economic parameters assumed here are: 1) methanol plant CAPEX and OPEX outlined in Table A.6, 2) COG feedstock cost for 1,200 RMB/tonne, 3) electricity cost for 0.6 RMB/kWh, 4) carbon source cost for 400 RMB/tonne-CO_2e, and 5) NG sold at 3,800 RMB per tonne.

Table A.12 | GHG emissions for producing 1 tonne metallurgical coke

Products	Total mass (kg)	Total energy content (MJ)	Allocation factor	Carbon intensity ($kgCO_{2e}$/kg-product)	
				CWQ process	CDQ process
Metallurgical coke	1,000.0	28,435	82.64%	1.57	1.67
Coke oven gas	93.3	4,195	12.19%	2.48	2.64
Tar	40.3	1,350	3.92%	1.85	1.97
Sulphur	10.0	420	1.22%	2.32	2.47
Crude benzene	1.2	11	0.03%	0.47	0.51

Note: total GHG emissions for producing 1,000 kg metallurgical coke is respectively 1,900 and 2,020 kg CO_{2e} through CWQ (coke wet quenching) and CDQ (coke dry quenching) process, respectively from the plant (well-to-gate) [33]

Table A.13 | GHG emissions of carbon source for COG-derived methanol synthesis

	Energy demand breakdowns (MJ/kg CO_2 supply)	GHG emission breakdowns (kg CO_{2e}/kg CO_2 supply)
Unavoidable CO_2 emissions	n.a.	-1.00
Electrical power demand	0.27	0.04
Thermal energy demand	3.00	0.23
Total	3.27	-0.71

Table A.14 | Allocation of GHG emissions for COG-derived methanol and natural gas

Product	Mass (kg)	Energy content (MJ, LHV)	Allocation by energy content	GHG emissions by different powers (kg CO_{2e} per kg product)	
				Local grid	Renewable
Natural gas	0.56	23.4	54%	0.10	-0.20
Methanol	1.00	19.9	46%	0.09	-0.17
Total	1.56	43.3	100%	0.19	-0.37