Task 64 – E-fuels and end-use perspectives

Insights into e-fuel demonstration plants and pilot-scale e-fuel production routes in China

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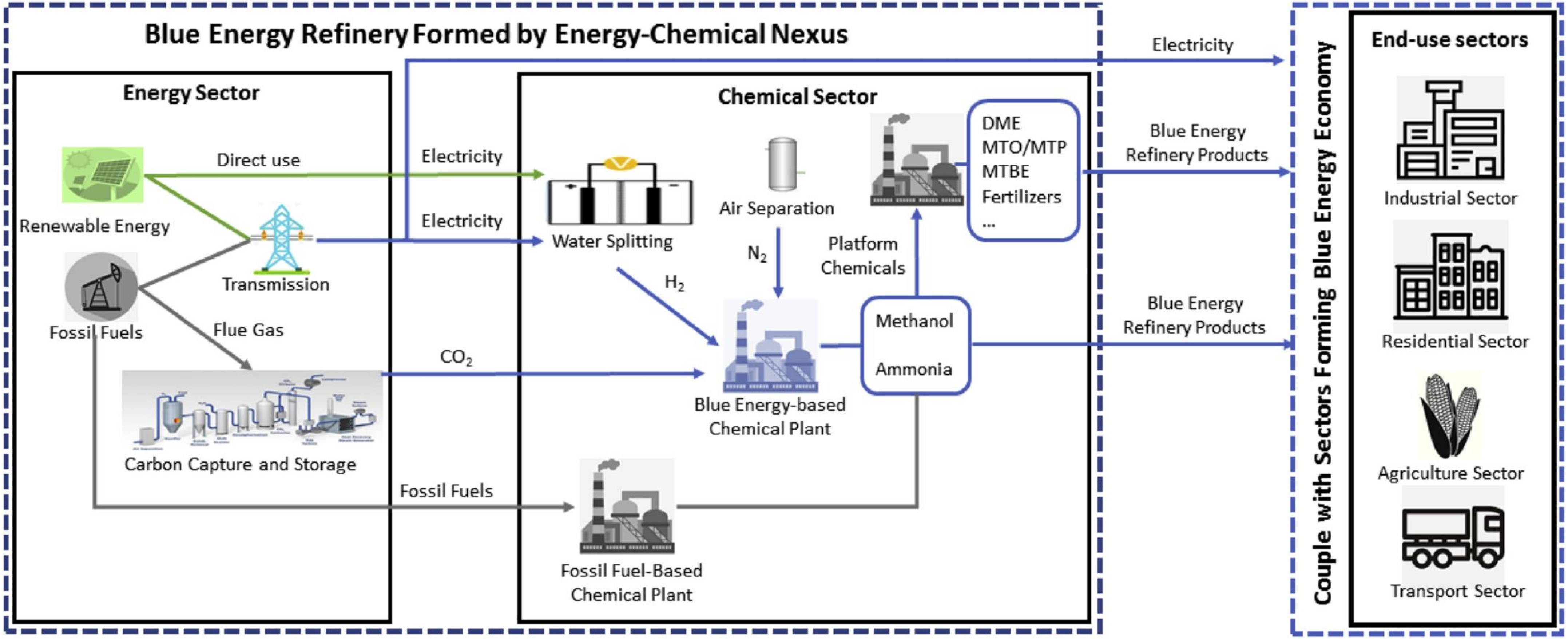
Outline

- Background and overview of e-fuel projects in China
- Technical details of selected e-fuel projects
- Stakeholders, regulations and cost competiveness
- Summary

China's carbon neutrality target and the role of e-fuels

- E-fuel is considered to play a critical role in forming the **zero-carbon energy-carbon industrial nexus** and decarbonizing the transportation modes with **high energy density demand (e.g., aviation jet fuels)**.



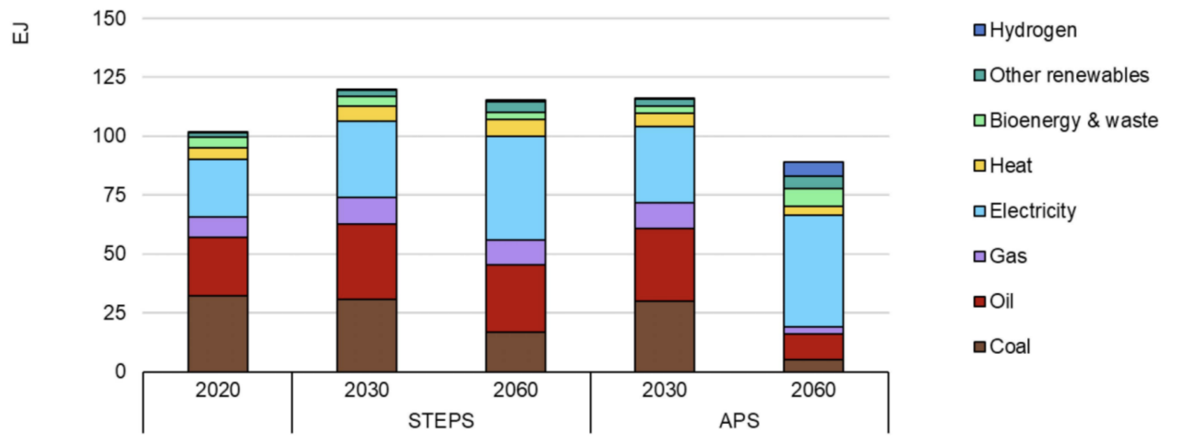
Blue energy denotes the concept of converting renewable and fossil-based (plus CCS) fuels into methanol and ammonia as energy carriers.

Li et al., 2021. A quantitative roadmap for China towards carbon neutrality in 2060 using methanol and ammonia as energy carriers.

China's carbon neutrality target and the role of e-fuels

- IEA's report "An Energy Sector Roadmap to Carbon Neutrality in China" estimates H_2 and e-fuels will contribute to 3% of cumulative emissions savings by 2060 (including ~26% of total aviation fuel demand).
- This report also notes the role of sustainable biofuels that could contribute to 7% of cumulative emission savings. Hydrogen-derived fuels will compete with biofuels in future energy transition.

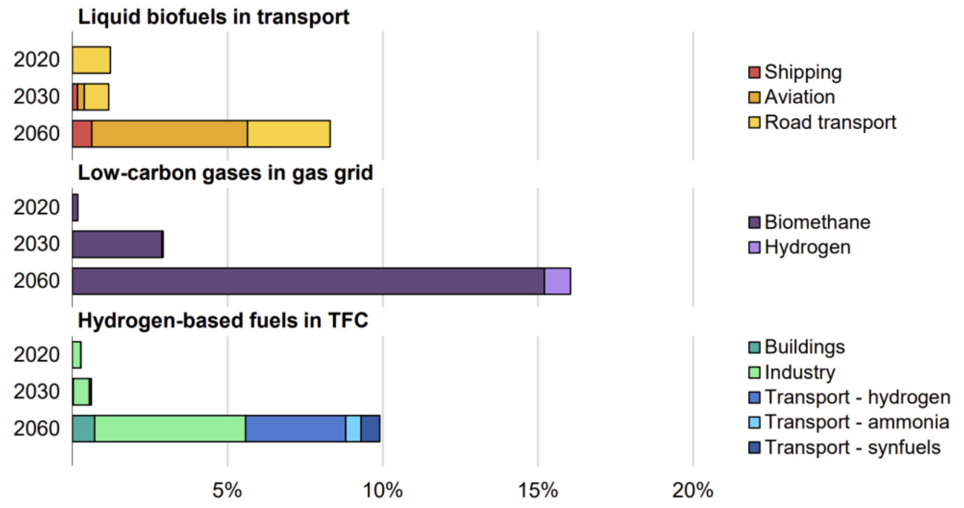
Figure 2.6 Final energy demand by fuel and sector in China by scenario



IEA, 2021.

Notes: APS = Announced Pledges Scenario; STEPS = Stated Policies Scenario. Hydrogen includes low-carbon hydrogen and hydrogen-derived fuels (ammonia and synthetic hydrocarbon fuels).

Figure 3.7 Supply of low-emissions fuel by sector and fuel in China in the APS



IEA, 2021.

Notes: TFC = total final consumption. Hydrogen-based fuels refer to the fuel use of hydrogen, synthetic hydrocarbon fuels (synfuels) produced from hydrogen and CO_2, and ammonia, and includes also onsite hydrogen production in the industry sector.

The share of low-emissions fuels in final energy demand jumps from less than 1% in 2020 to more than 1% in 2030 and almost 10% in 2060, led by industry and transport

IEA et al., 2021. An Energy Sector Roadmap to Carbon Neutrality in China

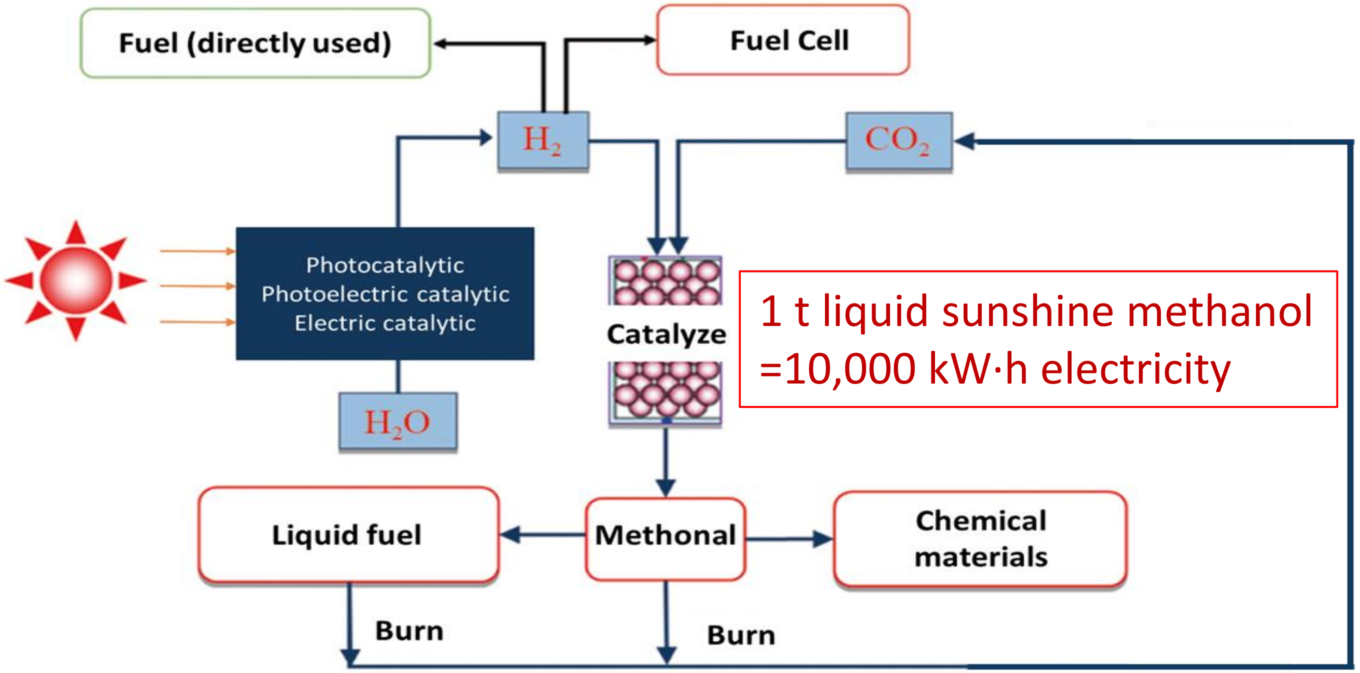
Overview of demonstration and pilot-scale e-fuel projects

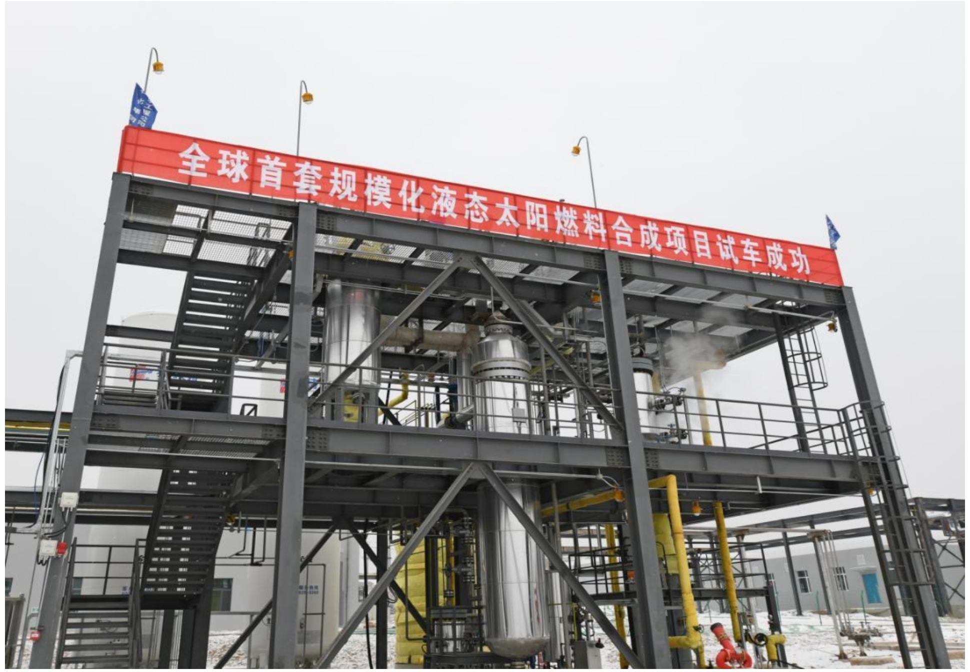
- Demonstration and pilot-scale e-fuel projects have been developed and announced since 2018.
- The amount of e-fuel projects is still limited. We currently gather the information from limited public sources.
- Products from existing e-fuel projects: **methanol, gasoline and aviation jet fuel**.
- The direct feedstocks are **CO_2 and H_2**, but their sources differ across various projects.

Project name and location	Feedstocks	Products	Year	Annual capability
Liquid Sunshine, Lanzhou, Gansu	CO_2, H_2 (solar)	Methanol	2018	1,000 t
Carbon Hydrogenated methanol Project, Fudao, Hainan	CO_2, H_2	Methanol	2020	5,000 t
Carbon Hydrogenated Gasoline Project, Zoucheng, Shandong	CO_2, H_2	Gasoline (C5-C11)	2020	1,000 t
Green Methanol Co-generated LNG, Anyang, Henan	CO_2, COG-H_2	Methanol, LNG	2022	110,000 t, 70,000t
CO_2AF^{TM} Project, Erdos, Inner Mongolia	CO_2, H_2 (solar)	Aviation fuel (C8-C15)	2022	1000 to 10,000 t
Methanol production project between Wuhuan and Clariant	-	Methanol	2022	Note: still under research

Liquid Sunshine Project, Lanzhou

- Liquid Sunshine Project: the world's first commercial-scale demonstration project of synthetic fuels using solar-based renewable hydrogen (led by Prof. Can Li, member of Chinese Academy of Science)
  - Located in the chemical industrial park of Lanzhou, Gansu (CO_2 sources from nearby factories)
  - Power generation from photovoltaic
  - Hydrogen production from electrolysis of water
  - Hydrogenation of CO_2 to methanol



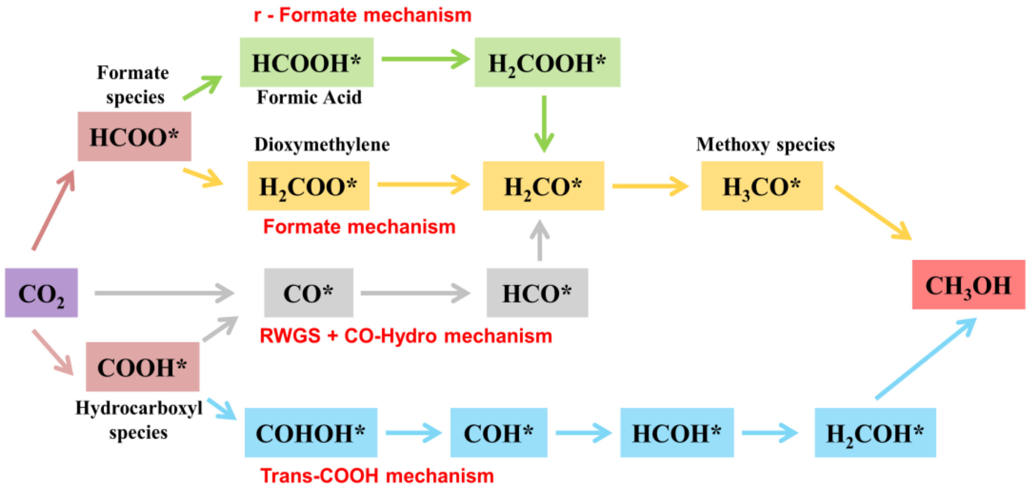


http://www.canli.dicp.ac.cn/info/1030/4875.htm

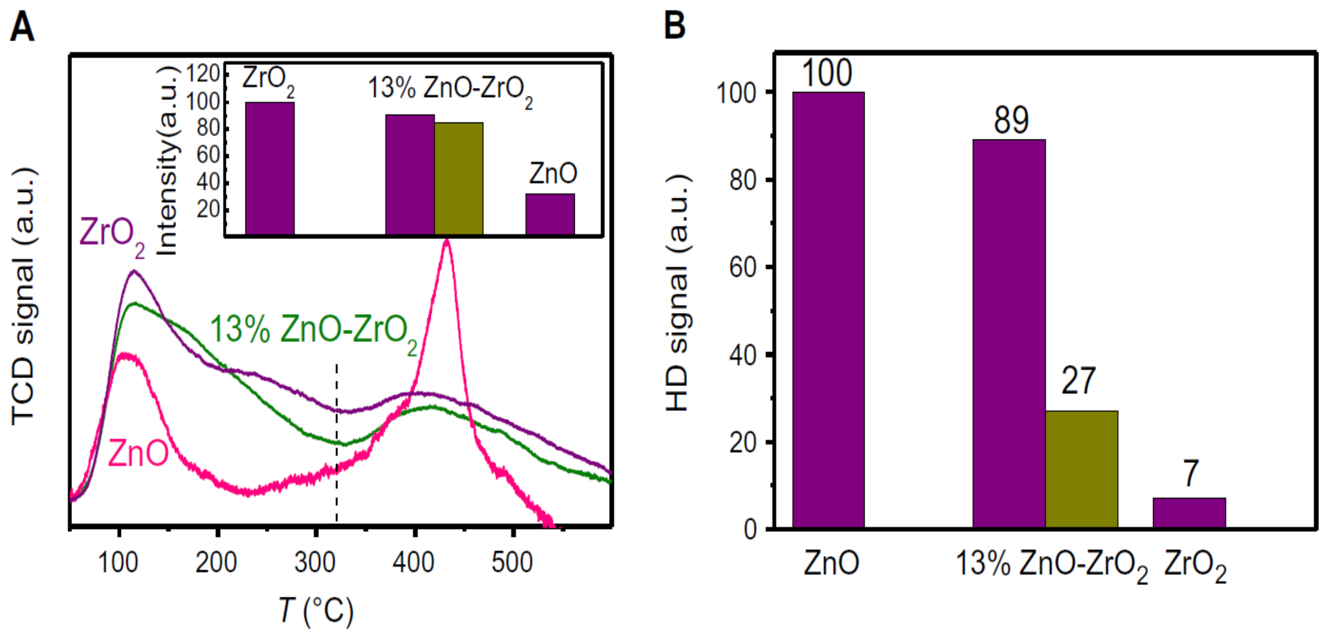
Liquid Sunshine Project, Lanzhou

- According to available publications, improving catalyst and chemical process is a major focus.
  - Active temp window and thermal stability: the reverse water–gas shift reaction generate products of CO and H_2O, which might would accelerate the sintering and deactivation of the catalyst
  - Selectivity: to improve the selectivity of methanol for CO_2 hydro-conversion. A bimetallic solid solution oxide catalyst **ZnO-ZrO$_2$** was invented, rising the selectivity of methanol from ~60% (Cu catalyst) to 90%.

Reaction process



CO_2 adsorption and H_2 activation

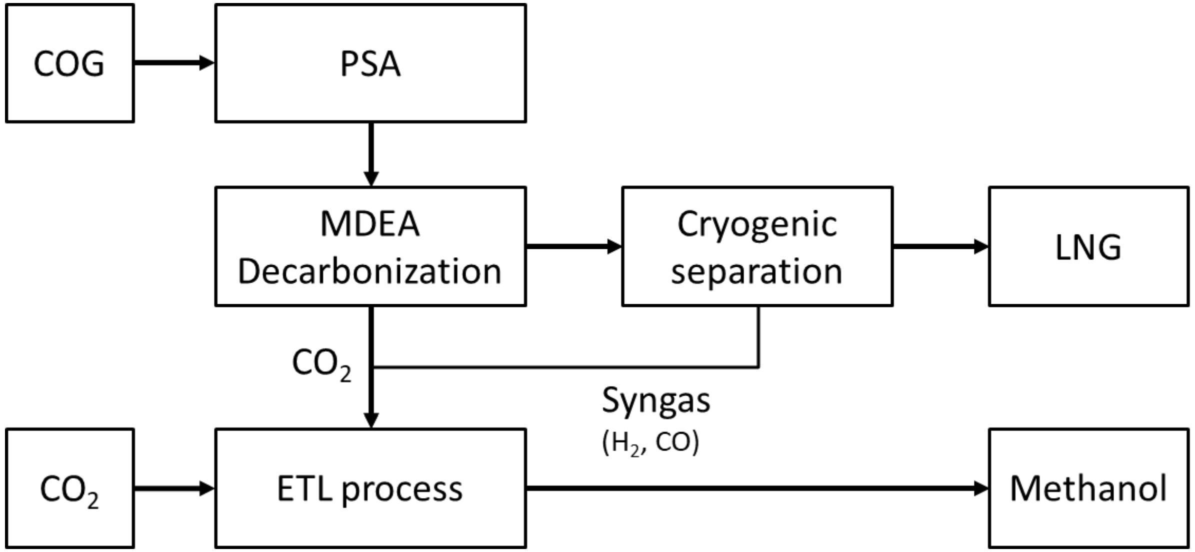


Wang, et al. 2017. A highly selective and stable ZnO-ZrO2 solid solution catalyst for CO2 hydrogenation to methanol. Science Advances.

Green Methanol Co-generated LNG Plant, Anyang

- This project uses the **ETL (emissions to liquids)** process invented by Iceland Carbon Recycle International (CRI) Corporation:
  - COG decarbonization, whose feedstock is **limekiln flue gas** from Henan Shuncheng Energy Technology Co. LTD., and devices is developed by Shanghai Electric Power Station Group
  - ETL process to produce methanol and cryogenic separation to produce LNG

Production process

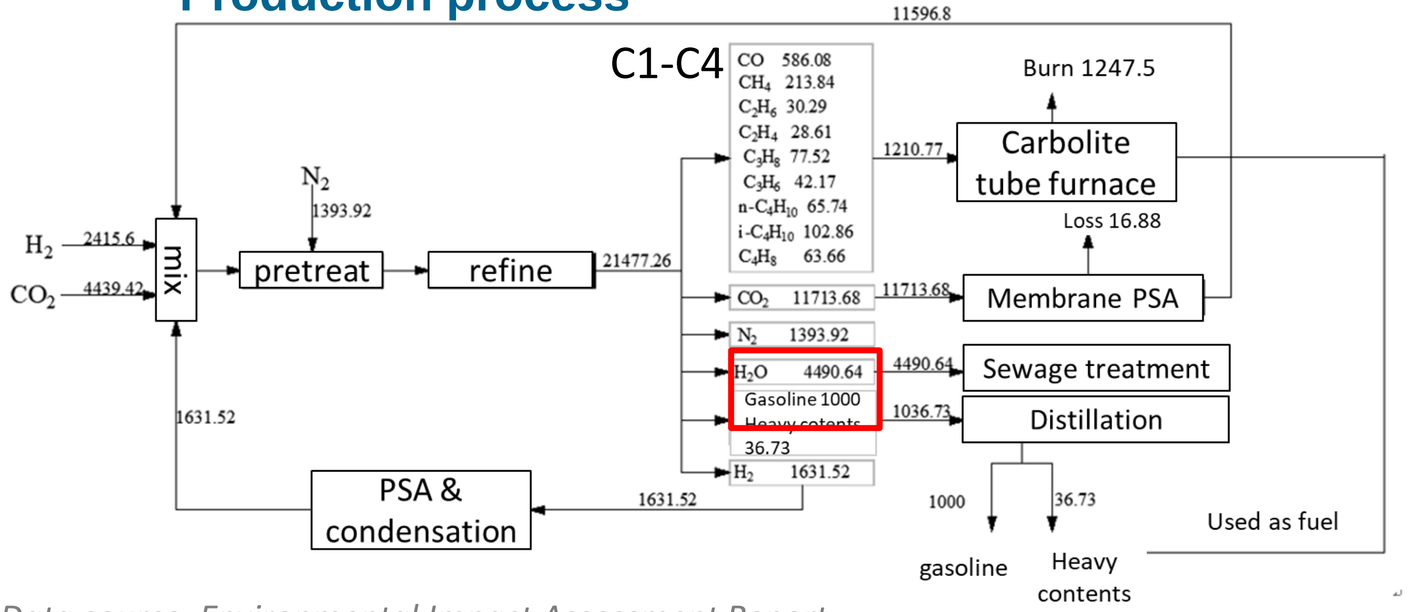


https://baijiahao.baidu.com/s?id=1746096513856676818&wfr=spider&for=pc
http://www.coalchem.org.cn/news/html/800201/189277.html

Carbon Hydrogenated Gasoline Project, Zoucheng

- This project is **the world's first plant** of hydrogenation of CO_2 to gasoline products (Led by Prof. Zhongmin Liu, member of Chinese Academy of Science).
  - The product quality is designed to meet the China 6 standard (i.e., specific requirements for density, RVP, olefins and aromatics.
  - H_2 source: coke oven gas-H_2 from Jining Bao steel Gas Co., LTD
  - CO_2 source: purchase externally from Jining and its surrounding areas
  - **Life-cycle emissions: 0.58 t CO_2/t e-gasoline** (18.4 t CO_2/t e-gasoline in the well-to-gate stage, minus 17.8 t CO_2/t e-gasoline purchased externally) and could reach zero emissions with cleaner grid and hydrogen.

Production process



Data source: Environmental Impact Assessment Report.

Carbon Hydrogenated Gasoline Project, Zoucheng

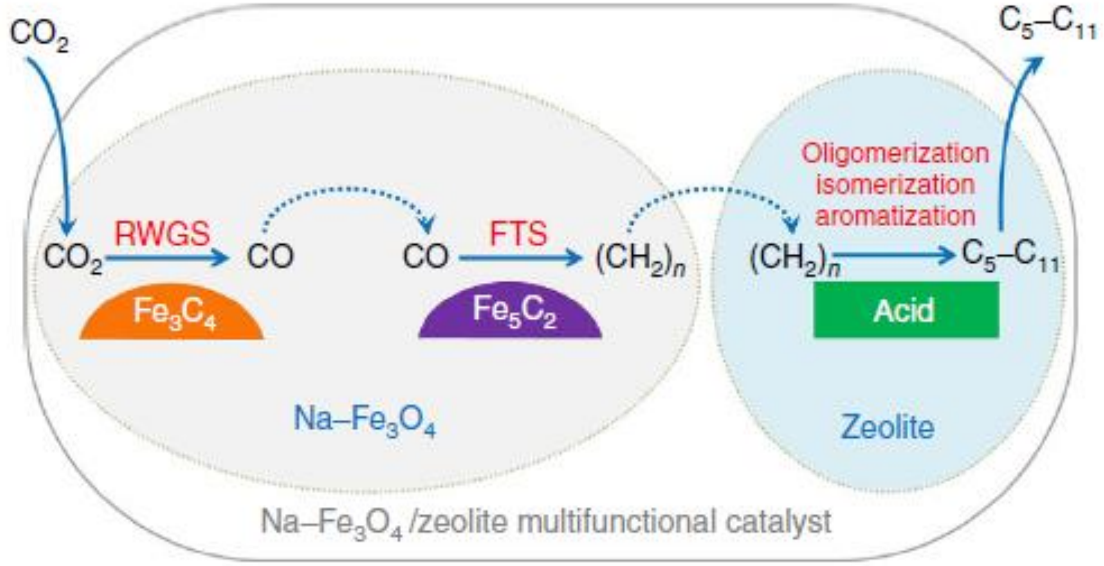


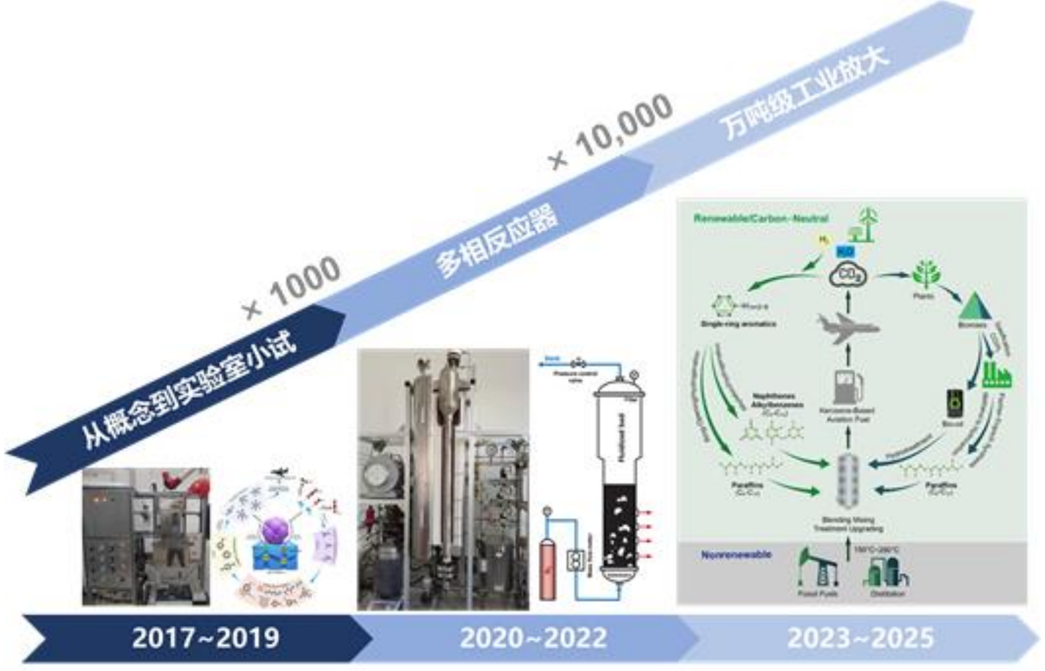
Figure 3 | Reaction scheme for CO_2 hydrogenation to gasoline-range hydrocarbons. The CO_2 hydrogenation reaction over Na-Fe_3O_4/Zeolite multifunctional catalyst takes place in three steps: (1) an initially reduced to CO intermediate via RWGS, (2) a subsequent hydrogenation of CO to α-olefins intermediate via FTS and (3) the formation of gasoline-range hydrocarbons via the acid-catalysed oligomerization, isomerization and aromatization reactions.

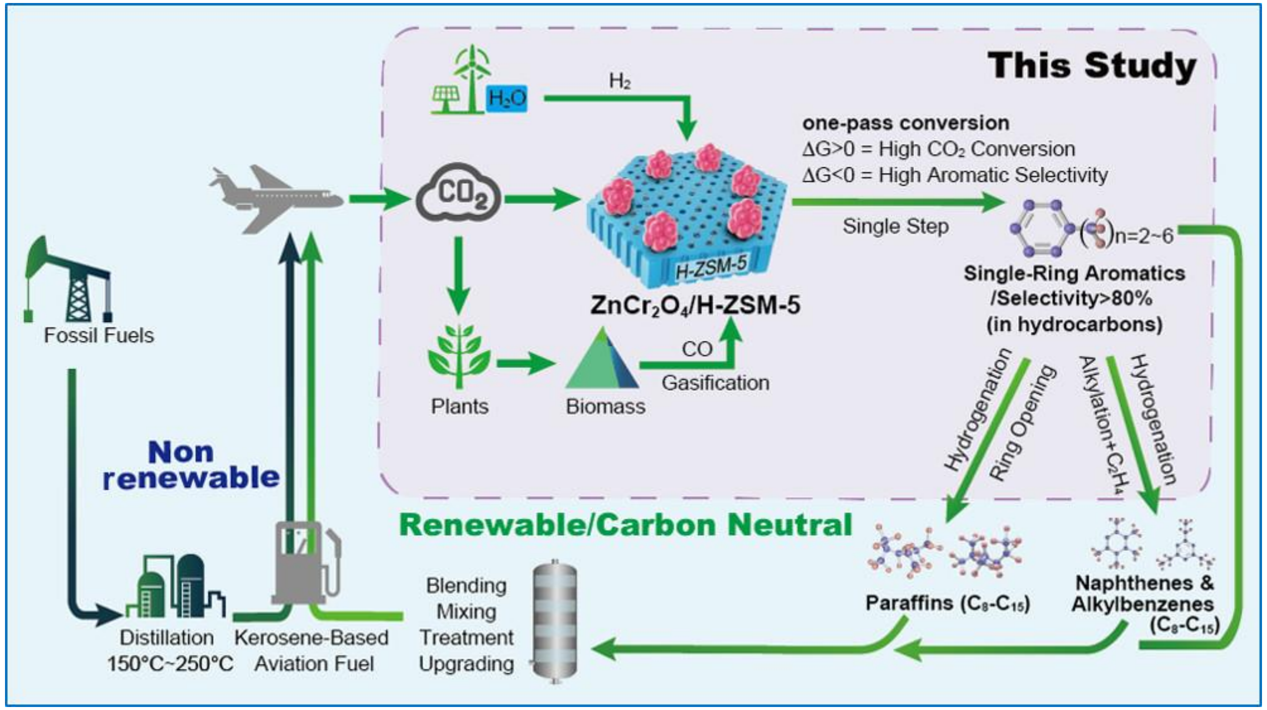
- A novel catalyst, Na-Fe_3O_4/HZSM-5, is developed to improve efficiency and reliability:
  - The catalyst achieves 95% conversion of CO_2 and H_2, and the selectivity of gasoline is higher than 85%, under quasi-industrial production conditions
  - The product can basically meet the China 6 standard on gasoline fuel quality
  - The catalyst has good stability and can be operated continuously for more than 1000 hours.

- Wei, J., *et al.* 2017. Directly converting CO_2 into a gasoline fuel. *Nature Communications.*

Tsinghua’s CO_2AF^{TM} Project, Erdos

- Profs. Fei WEI and Chenxi ZHANG from Tsinghua University’s Chemical Engineering are working on the proposed project to convert H_2 and CO_2 to kerosene-range aviation fuels
  - The next-step goal is to enlarge the scale up to over 10,000 tons per year
  - Feedstocks: **industrial CO_2 exhaust** and **H_2 from photovoltaic electrolysis**
  - **C8-C15 aromatic cyclic hydrocarbons** as product
- The CO_2 hydrogenation capacity is increased by 3 times while the directional conversion of over 80wt.% of ultra-high aromatic hydrocarbons is maintained.





https://www.tsinghua.edu.cn/info/1175/91107.htm

Municipal Solid Waste to H_2, and further to e-fuels

- Prof. Ming ZHAO from Tsinghua University's School of Environment is working on MSW-to-H_2 demonstration, and will extend the route to hydrocarbon products.

H_2 yield from wastes (pellet):

- Low NPV input (2500 kcal/kg): **30** kg-H_2/t-pellet
- High NPV input (4000 kcal/kg): **50** kg-H_2/t-pellet

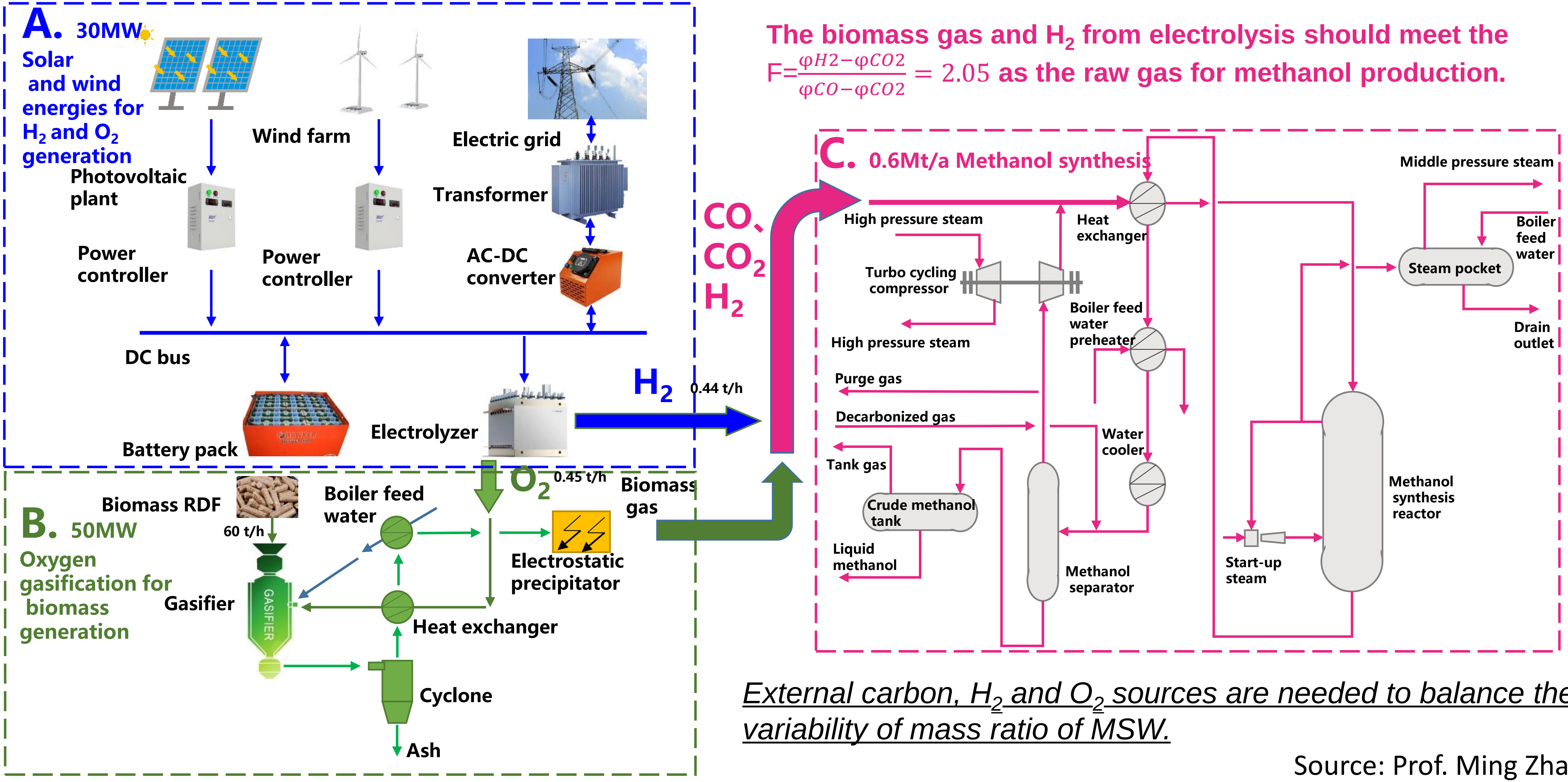
H_2 production cost from wastes:

- RMB **10-15**/kg-H_2

Composition of raw syngas	
CH_4(%)	2.91
O_2(%)	0.95
H_2(%)	26.39
CO_2(%)	20.58
CO(%)	45.95
C_nH_m(%)	2.22
CV kcal/Nm^3	3062

Municipal Solid Waste to H_2, and further to e-fuels

The biomass gas and H_2 from electrolysis should meet the $F=\frac{\varphi H2-\varphi CO2}{\varphi CO-\varphi CO2}=2.05$ as the raw gas for methanol production.



External carbon, H_2 and O_2 sources are needed to balance the variability of mass ratio of MSW.

Source: Prof. Ming Zhao

Summary of Key Technical Information

Feedstocks	Catalyst	Products
● **CO_2 (large amount)** ✓ Carbon capture from industrial exhaust ✓ Purchase from factory ✓ COG ● **H_2 (large amount)** ✓ Electrolysis ✓ Photocatalytic ✓ Purchase from factory ✓ COG ● **CO (small amount)** ✓ COG ✓ Purchase from factory	● **Industrial application** □ Cu-based catalyst ✓ Diverse and easy to industrialize, but moderate efficiency (e.g., Clariant). □ Solid solution catalyst ✓ High heat stability, strong resistance to toxicity (e.g., *Liquid Solar Project)* ● **In research** □ Noble metal catalyst ✓ High catalytic performance, easy to activate H_2 but low CO_2 conversion □ In_2O_3 catalyst ✓ Double active site, improving methanol selectivity, but expensive	● **Methanol** ✓ Liquid fuel ✓ Chemical materials ● **Gasoline** ✓ Fuel ● **Aviation Fuel & Aromatics** ✓ Aviation fuel ✓ Chemical materials

Exhaust treatment	**Sewage** From reaction	**Exhaust** VOCs, CO, etc.	**Solid waste** Catalyst, etc.

Stakeholders Landscapes

CO_2 producer

Shanghai Electric Power Station Group
（上海电气电站集团）
Henan Shuncheng Group Energy Technology
（河南省顺成集团能源科技有限公司）
Jining Bao steel Gas Co., LTD.
（济宁宝钢气体有限公司）

H_2 production

Suzhou Jingli Hydrogen Productio Equipment
（苏州竞立制氢设备有限公司）

Chemical enterprise

Iceland Carbon Recycle International Corporation
（冰岛碳循环国际公司）
Clariant, Germany
（德国科莱恩）

Institution

Dalian Institute of Chemical Physics
（大连化物所）
Shanghai Institute of Advanced Science
（上海高等科学研究院）
Tsinghua University
（清华大学）

Production side

Several categories of stakeholders are involved in the e-fuel production chain for increasingly stringent regulatory measures under carbon neutrality.

Application side

Conventional Petrochemical

China National Offshore Oil Co., LTD
(中国海洋石油集团有限公司)
Jikuang Minsheng Coal Chemical Co., LTD
(山东济矿民生煤化有限公司)
Yankuang Klankemet Chemical Co., LTD
(兖矿科蓝凯美特化工有限公司)

Energy & environment related enterprises

Zhuhai Futian Energy Technology Co., LTD
(珠海市福沺能源科技有限公司)
Suzhou Komai New Energy Co., LTD
(苏州高迈新能源有限公司)
Anyang Shunli Environmental Protection Technology Co., LTD.
(安阳顺利环保科技有限公司)

Automotive enterprises

Zhejiang Geely Holding Group
(浙江吉利控股集团)

Regulations landscape

- No specific regulations on e-fuels. But there are **separate regulations** on various products.
  - Existing standards are ready for methanol used as industrial materials, pure or blended fuels (M85).
  - China 6 standards on gasoline fuel quality.
  - Appendix B of *Jet fuel Standard* regulates the non-fossil based syntenic fuel as a portion of jet fuel blending.

Mathanol

ICS 71.080.60
G 16
GB
中华人民共和国国家标准
GB/T 23510—2009
车用燃料甲醇
Fuel methanol for motor vehicles

ICS 71.080.60
G 16
GB
中华人民共和国国家标准
GB 338—2004
代替 GB 338—1992
工业用甲醇
Methanol for industrial use

ICS 75.160.20
E 31
GB
中华人民共和国国家标准
GB/T 23799—2009
车用甲醇汽油（M85）
Methanol gasoline (M85) for motor vehicles

Gasoline

ICS 75.160.20
E 31
GB
中华人民共和国国家标准
GB 17930—2016
代替 GB 17930—2013
车用汽油
Gasoline for motor vehicles

Emission values

	V	VI(A)	VI(B)
CO	1000	700	500
HC	68	68	35
NO_X	60	60	35
PM	4.5	4.5	3

Aviation Fuel

ICS 75.160.20
E 31
GB
中华人民共和国国家标准
GB 6537—2018
代替 GB 6537—2006
3 号喷气燃料
No.3 jet fuel

附 录 B
（规范性附录）
费托合成油改质工艺生产的煤油组分（FT-SPK）

Standard for F-T SPK

B.1 范围

本附录规定了来自于非石油基，采用 FT-SPK，作为 3 号喷气燃料调合组分使用时的技术要求和试验方法。

本附录所规定的合成烃调合组分不能单独供航空涡轮发动机使用，应与传统喷气燃料或传统喷气燃料调合组分进行调合后使用。

B.2 要求和试验方法

FT-SPK 应是全部由合成气和使用铁或钴催化剂的费托工艺生产的中间馏分，并进一步采用加氢精制、加氢裂化或加氢异构化和分馏，及结合其他传统炼油工艺处理而得到的产品。

产品的性能指标及试验方法应符合表 B.1 中所列的各项要求。

Production cost of e-fuels

- **Production cost will be a challenge facing e-fuel (methanol) in the near term.**
  - Prof. Can Li (Liquid Sunshine) compared the overall cost between coal-to-methanol and e-fuel methanol at an projected greater scale (600,000 t/yr, depreciation cycle of 10 years, carbon price of 50 CNY/t)
  - **Coal price and solar electricity generation cost** are tested: a price-parity could be achieved if the solar electricity generation cost could be reduced to 0.2 CNY/(kW·h) and coal price is over 1000 CNY/t

Cost comparison between coal-to-methanol and e-fuel methanol

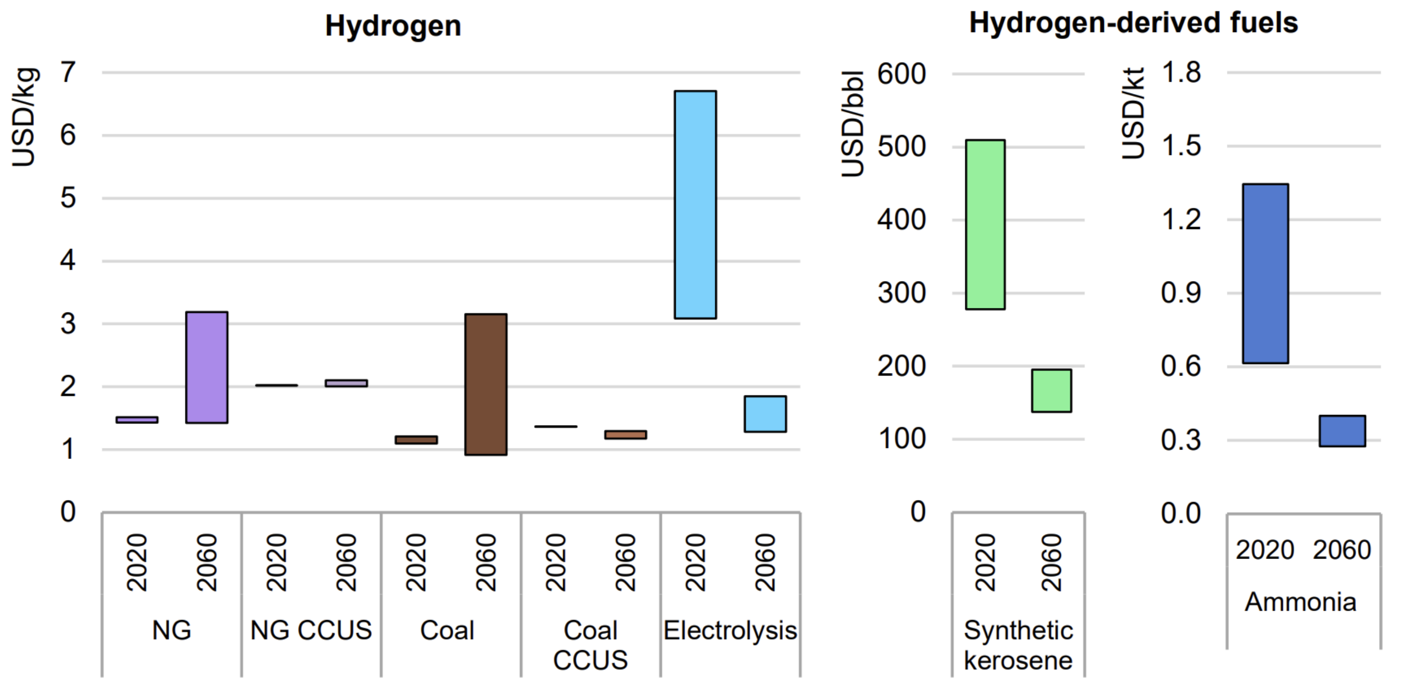
	Coal to methanol		E-fuel methanol	
	Coal	Methanol	Solar electricity	Methanol
Price CNY/t or CNY/(kW·h)	500	1800	0.1	1600
	1000	***2600***	***0.2***	***2600***
	1500	3300	0.3	3600
	2000	4100	0.4	4600

Key parameters:
Capability per electrolysis unit: 1500 m^3/h
Utilization hours of electrolysis: 8000 h
Electrolysis efficiency: 4.5kW·h/m^3-H_2
Annual coal demand: 900 thousand t
Annual H2 demand: 1.35 billion m^3

- 王集杰,韩哲,陈思宇,汤驰洲,沙峰,唐珊,姚婷婷,李灿.太阳燃料甲醇合成[J].化工进展,2022,41(03):1309-1317.DOI:10.16085/j.issn.1000-6613.2022-0244.

Production cost of e-fuels

Figure 3.10 Production costs of hydrogen and hydrogen-derived fuels by technology in China in the APS



IEA, 2021.

Notes: NG = natural gas reforming; Coal = coal gasification; CCUS = carbon capture, utilisation and storage. Electrolysis is based on dedicated renewables-based generation. Assumptions for technoeconomic parameters available from IEA (2021b). Fuel price assumptions: natural gas - 2020, USD 23.6/MWh (CNY 163/MWh) and, 2060 USD 23.4/MWh (CNY 162/MWh); coal – 2020, USD 10.7/MWh (CNY 74/MWh) and, 2060 USD 7.4/MWh (CNY 51/MWh); electricity – 2020, USD 25-99/MWh (CNY 172-683/MWh) and, 2060 USD 13-44/MWh (CNY 89-303/MWh). CO_2 price assumptions: 2020, USD 0-10/t CO_2 (CNY 0-69/t CO_2) and USD 0-200/t CO_2 (CNY 0-1 380/t CO_2).

Coal gasification is expected to remain cheaper than steam reforming of natural gas, but electrolysis emerges as a competitive option in the long term

Opportunities:

- E-fuels are expensive but often compatible with **existing infrastructure or end-use technologies** (as in the case of synthetic kerosene for aviation), lowering overall costs.
- **Low-cost renewables** in western regions in China is expected to drive down production costs.
- As a result, **a CO_2 price** of USD 200 to USD 345 (CNY 1380 to CNY 2380) per tonne is needed to make synthetic kerosene competitive with conventional jet kerosene.

IEA et al., 2021. An Energy Sector Roadmap to Carbon Neutrality in China

Summary remarks

- Demonstration and polit-scale e-fuel projects have been operated in China. However, first-hand operational data are rarely available for detailed sustainability and economic accounting.
- Methanol, gasoline and aviation fuels are seen as products in the e-fuel projects. Methanol is the most common product.
- Now, the sources of hydrogen and CO_2 are not necessarily in the context of green energy (i.e., renewable H_2 and CCUS-CO_2). For example, we see COG-H_2 as feedstock.
- From a technological perspective, many research efforts have been concentrated in the development of catalyst systems. For example, improving the selectivity of methanol of CO_2 hydro-conversion technology.
- Educational institutions, chemical and energy enterprises, and automotive companies have participated in the track of e-fuel demonstration as well as H_2 equipment and CO_2 producers.
- There is no standard set specifically for e-fuel in China, but there are clear regulations on the standards of various products contained in e-fuels.
- High cost of e-fuels is still a challenge faced by the hydrogenation of CO_2 to methanol. Appropriate carbon pricing and low renewable power cost are critical to enhance the economic competitiveness of e-fuels in China.

Thank you for listening!

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