

Supplementary Information

Techno-Economic Analysis and Carbon Footprint Assessment of Gasification based Green Methanol Production from Diverse Biomass Residues in China

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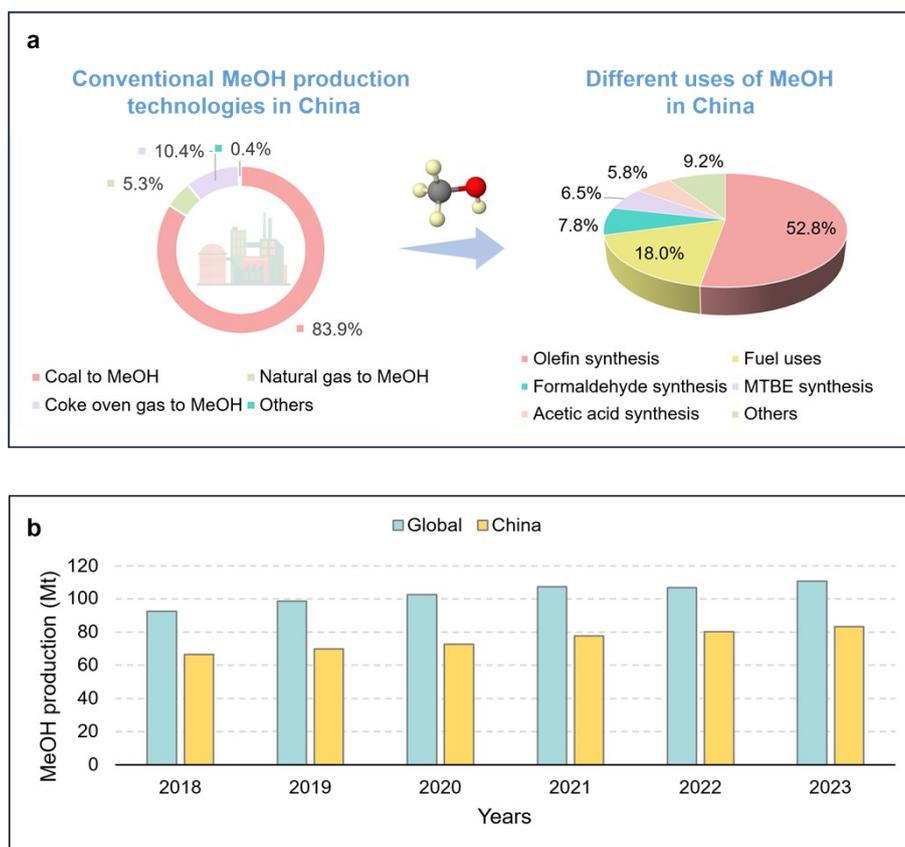
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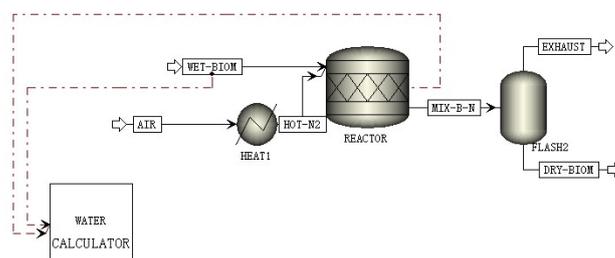
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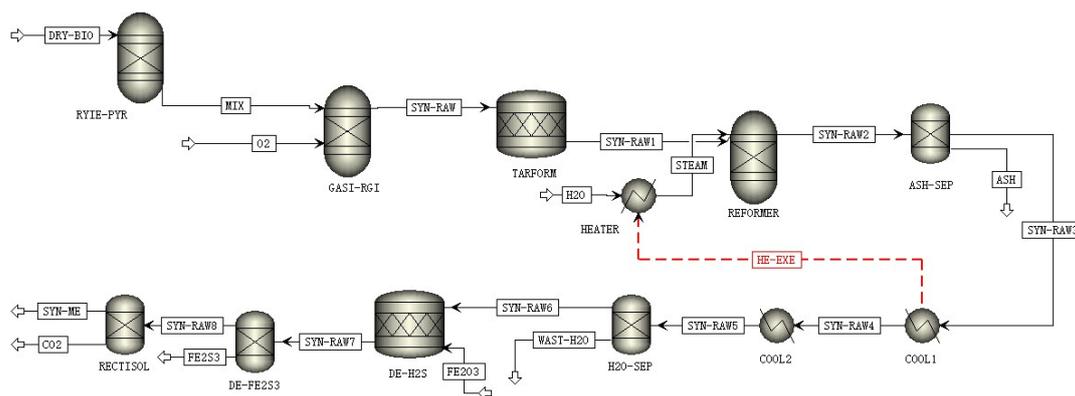
Section S1. Supplementary Figures



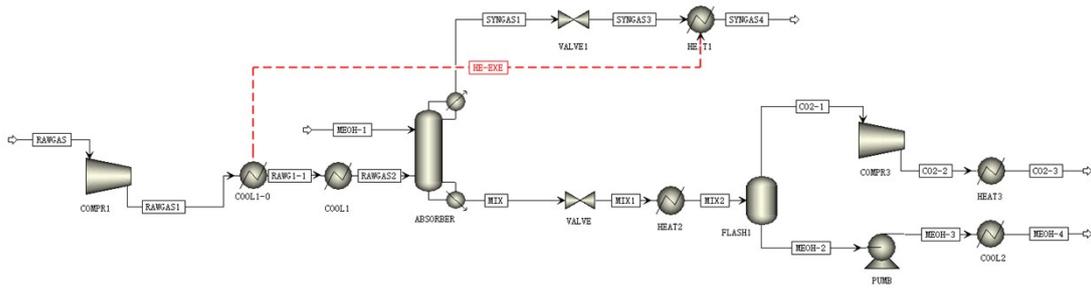
Supplementary Figure 1. Overview of the production and uses of methanol (MeOH). (a) Conventional production technologies and uses of MeOH in China in 2023. (b) MeOH production in China and the world. Data source: market investigation.¹



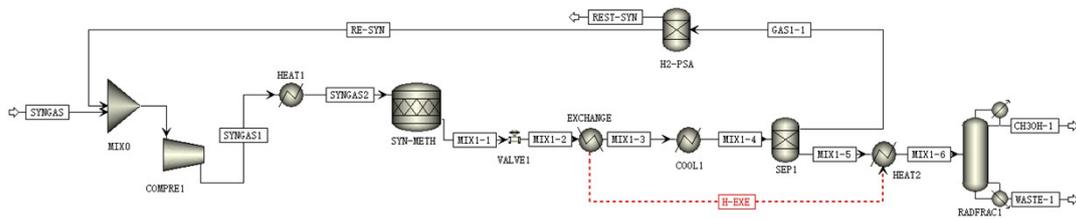
Supplementary Figure 2 | Process flowsheet of drying process of biomass feedstocks on the Aspen Plus (This process applies to all cases). The drying process is adapted from the coal drying example.² Here, biomass is defined as ‘nonconventional solid (NC)’ in the drying model, and the ultimate & proximate analysis data of agricultural crop straws, wood residues, bamboo residues, and MSW are summarized in **Supplementary Table 4**, respectively. The moisture of the biomass feedstock during the drying process is controlled by the ‘WATER’ calculator in the Aspen model.



Supplementary Figure 3 | Process flowsheet of oxygen gasification of biomass feedstocks on the Aspen Plus (This process applies to cases using oxygen as the gasification agent). Firstly, the dried biomass feedstocks, which are defined as ‘nonconventional solids (NC)’, are taken into a yield reactor ‘RYIE-PYR’ to produce conventional components, including H_2O , H_2 , C , S , N_2 , and O_2 . The yields of these components are set based on the ultimate and proximate analysis data of associated dried biomass feedstocks. Secondly, these conventional components are going through the gasification process in a RGibbs reactor ‘GASI-RGI’. The oxygen used for the gasification of biomass is produced from air separation. The energy consumption of producing per cubic meter of oxygen is set to 0.56 kWh/m^3 according to the industry standard for oxygen production from air separation in China.³ Tar, which may lead to damage of the gasification system, is also formed during the gasification, and it is represented by C_6H_6 , C_7H_8 and C_{10}H_8 in the model (‘TARFORM’). Besides CO and H_2 , raw syngas usually contains $\text{H}_2\text{O}(\text{g})$, HCl , H_2S , NH_3 , CH_4 , and CO_2 . To meet the requirements of MeOH production, it is necessary to adjust H_2/CO ratio to about 2.4 by increasing the H_2 formation through the water-gas shift reaction in the presence of steam and Mo_2C catalysts (in ‘REFORMER’) (see **Supplementary Figure 15**).⁴ Tar and CH_4 can also be reformed by the steam (in ‘REFORMER’). Besides, NH_3 is decomposed into N_2 and H_2 catalyzed by dolomite (in ‘REFORMER’); Ash is removed through the “ASH-SEP”; $\text{H}_2\text{O}(\text{g})$ is removed via condensation into $\text{H}_2\text{O}(\text{l})$ (H2O-SEP), and $\text{HCl}(\text{g})$ can dissolve in the $\text{H}_2\text{O}(\text{l})$; H_2S is removed by $\text{Fe}_2\text{O}_3 \cdot \text{H}_2\text{O}$ (in ‘DE-H2S’), which is an efficient desulfurizing agent; CO_2 is captured by a Rectisol®-based acid gas removal system (RECTISOL). Here, the CO_2 removal process is simplified and conducted in module “RECTISOL”, and a more specific process about the CO_2 removal can be found in **Supplementary Figure 5**.

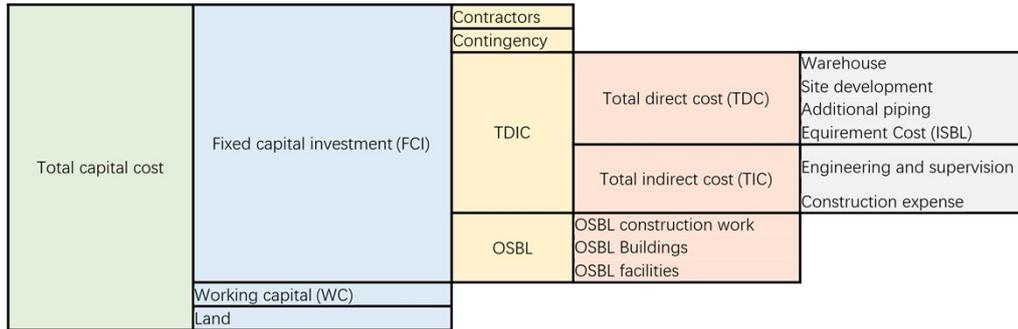


Supplementary Figure 6 | Process flowsheet of CO₂ capture and compression in the CCS process on the Aspen Plus (This process applies to “With CCS” cases). The captured CO₂ (flow ‘CO2-1’) needs to be pressurized to a high pressure (8 MPa) before the storage, while the captured CO₂ in the CO₂ removal process in **Supplementary Figure 5** can be released into the air at a normal pressure. Therefore, more electricity and equipment cost are required to capture the CO₂ in the CCS process than the CO₂ removal process.

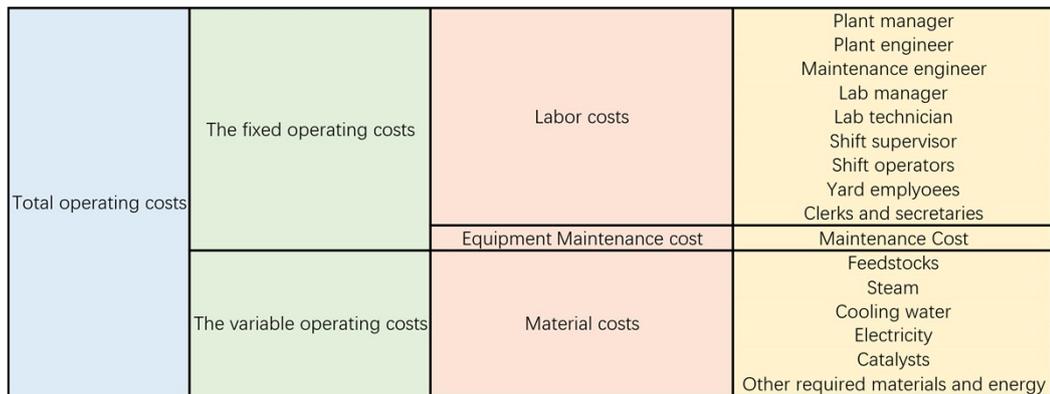


Supplementary Figure 7 | Process flowsheet of syngas to MeOH process on the Aspen Plus. The purified and adjusted syngas is taken into the reactor for MeOH synthesis (in ‘SYN-METH’). CO and CO₂ can be hydrogenated at conversion rates of approximately 35% and 17% respectively to form MeOH.⁶ These reactions are conducted at 220 °C, 54.3 atm, catalyzed by Cu/ZnO.⁶ The unconverted H₂, CO, and CO₂ should be recycled for MeOH production. However, in order to make the composition of the mixed syngas (‘SYNGAS’ + ‘RE-SYN’) meet the requirements of MeOH production, approximately 35% of the unconverted CO, 90% of the unconverted CO₂, and 38% of the unconverted H₂ need to be removed from the system. After the removal of CO₂ through the Rectisol wash process, the H₂ and the CO in ‘REST-SYN’ will be burned to provide heat for the generation of steam or electricity, as shown in **Supplementary Tables 8-12**.

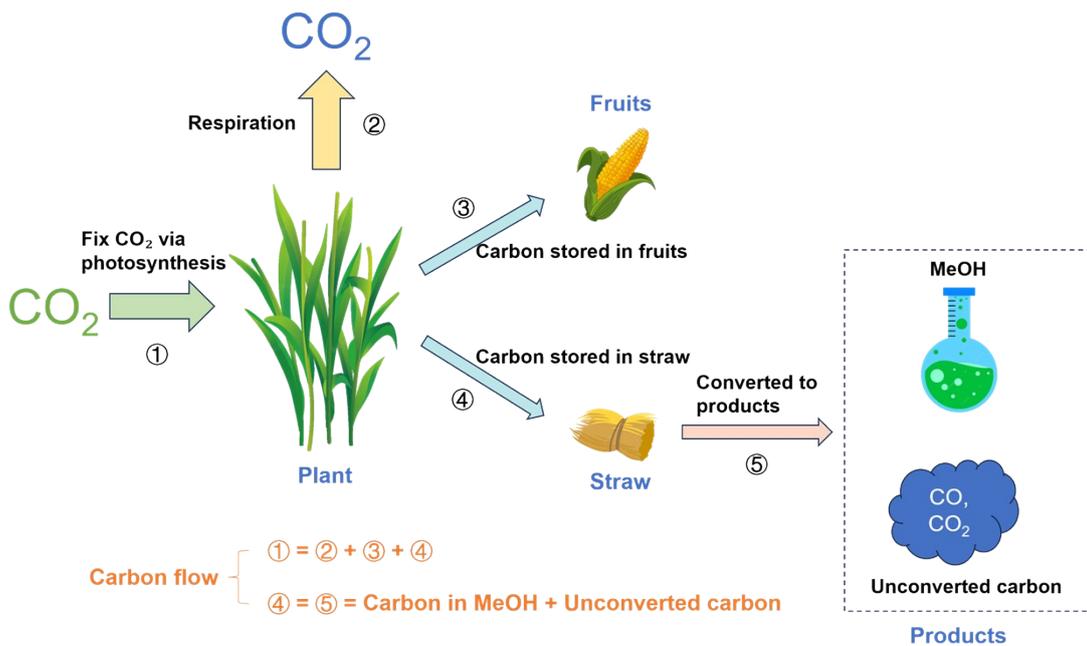
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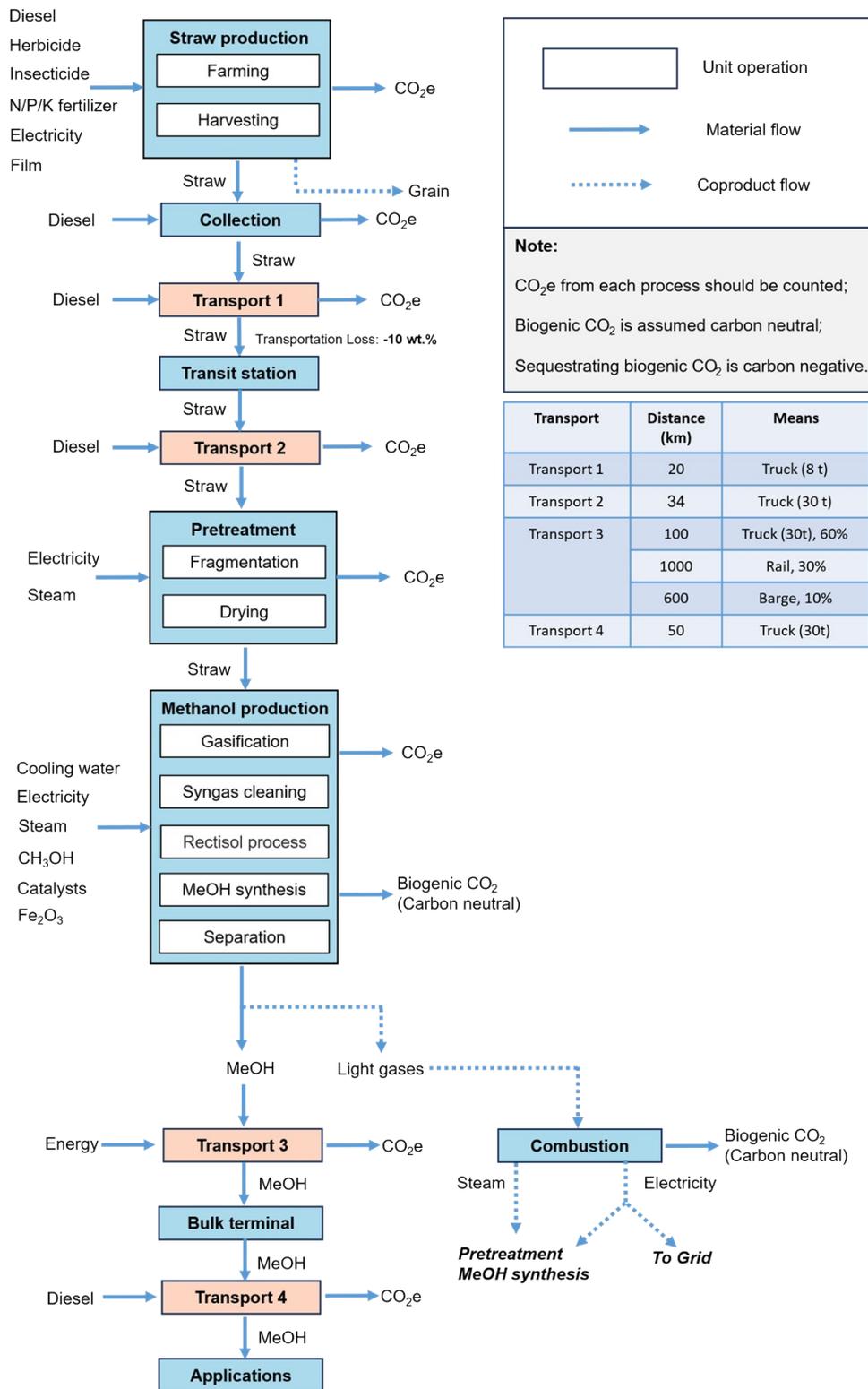
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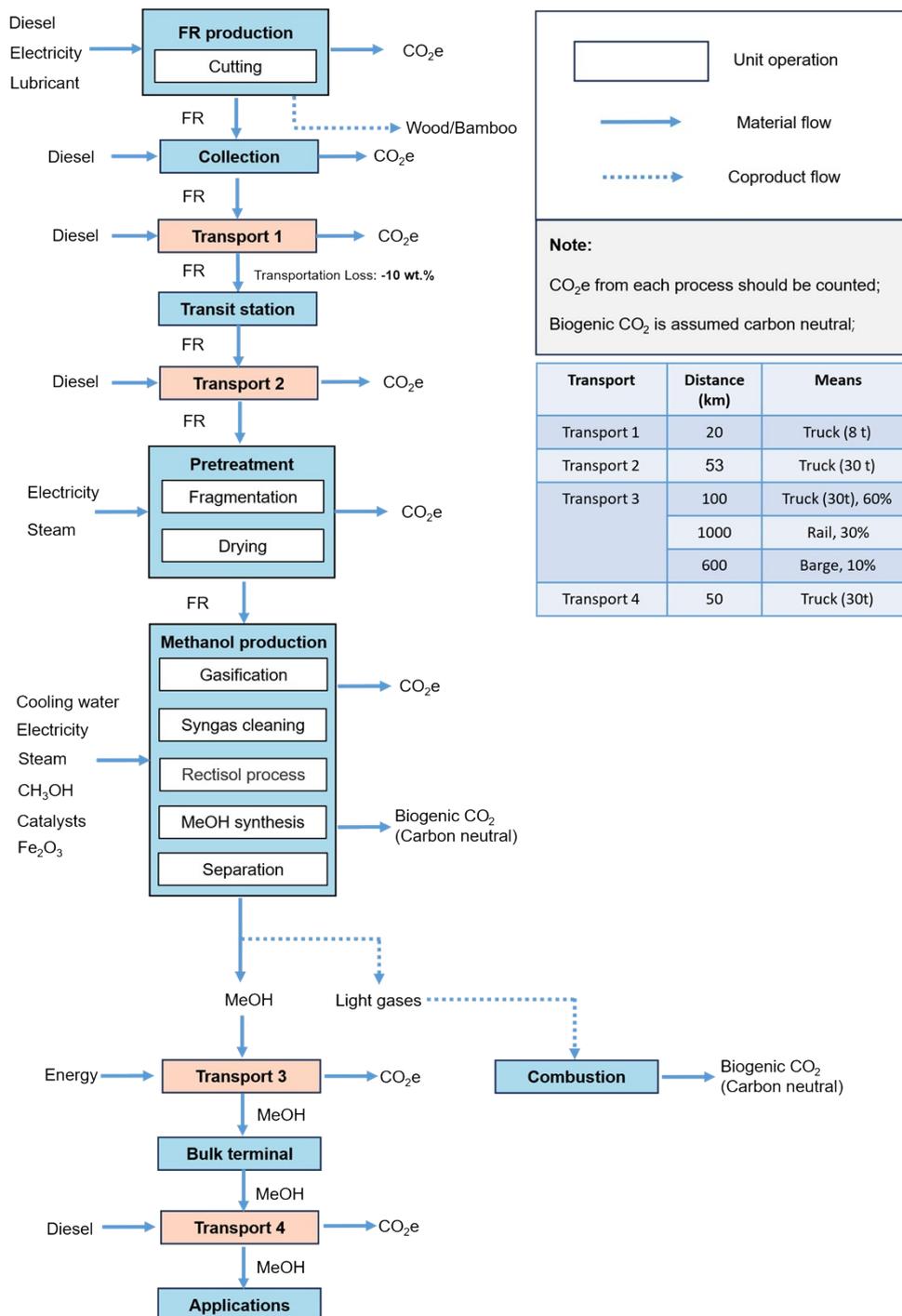
Supplementary Figure 8. TEA model based on the NPV method: (a) The structure of capital costs; (b) The structure of operating costs.



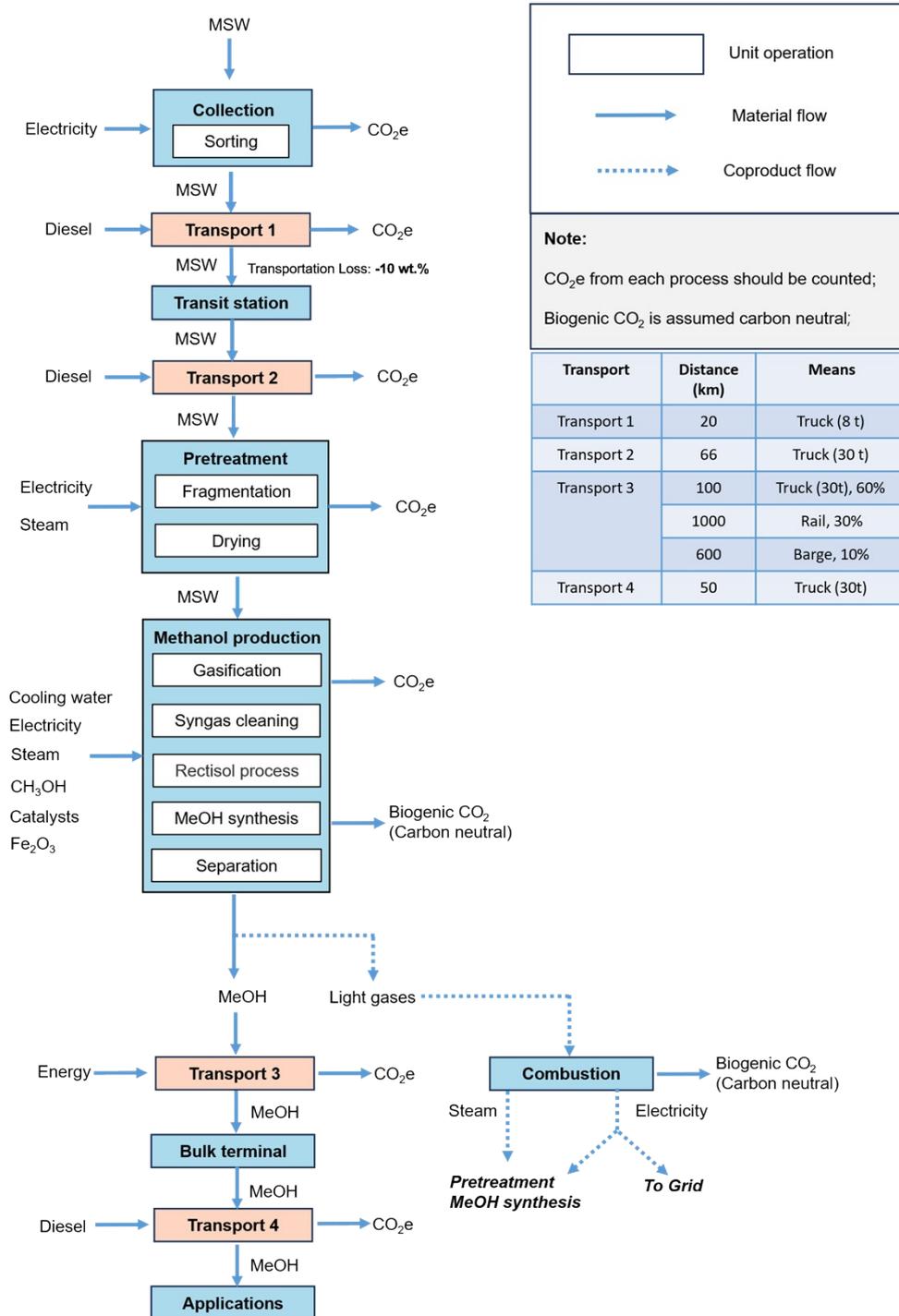
Supplementary Figure 9. Schematic of carbon flow and balance for biomass-derived methanol production.



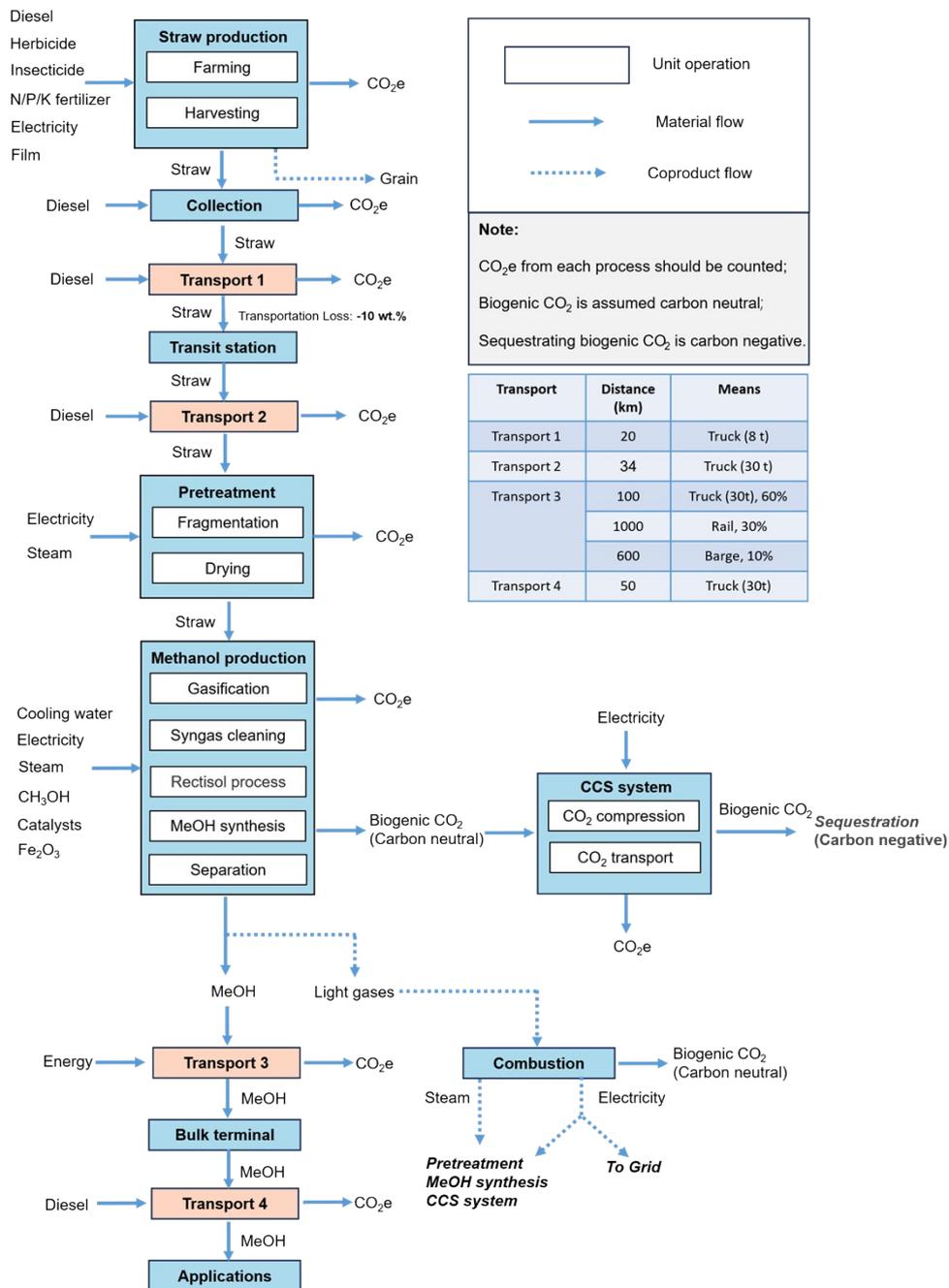
Supplementary Figure 10 | Well-to-Gate (WTG) LCA boundary of biomethanol from agricultural crop straws in “No CCS” scenario. This boundary applies to cases when using rice straw, wheat straw, maize straw, peanut straw, cotton straw, beans straw, sugarcane bagasse, rape straw as the feedstocks in “No CCS” scenario.



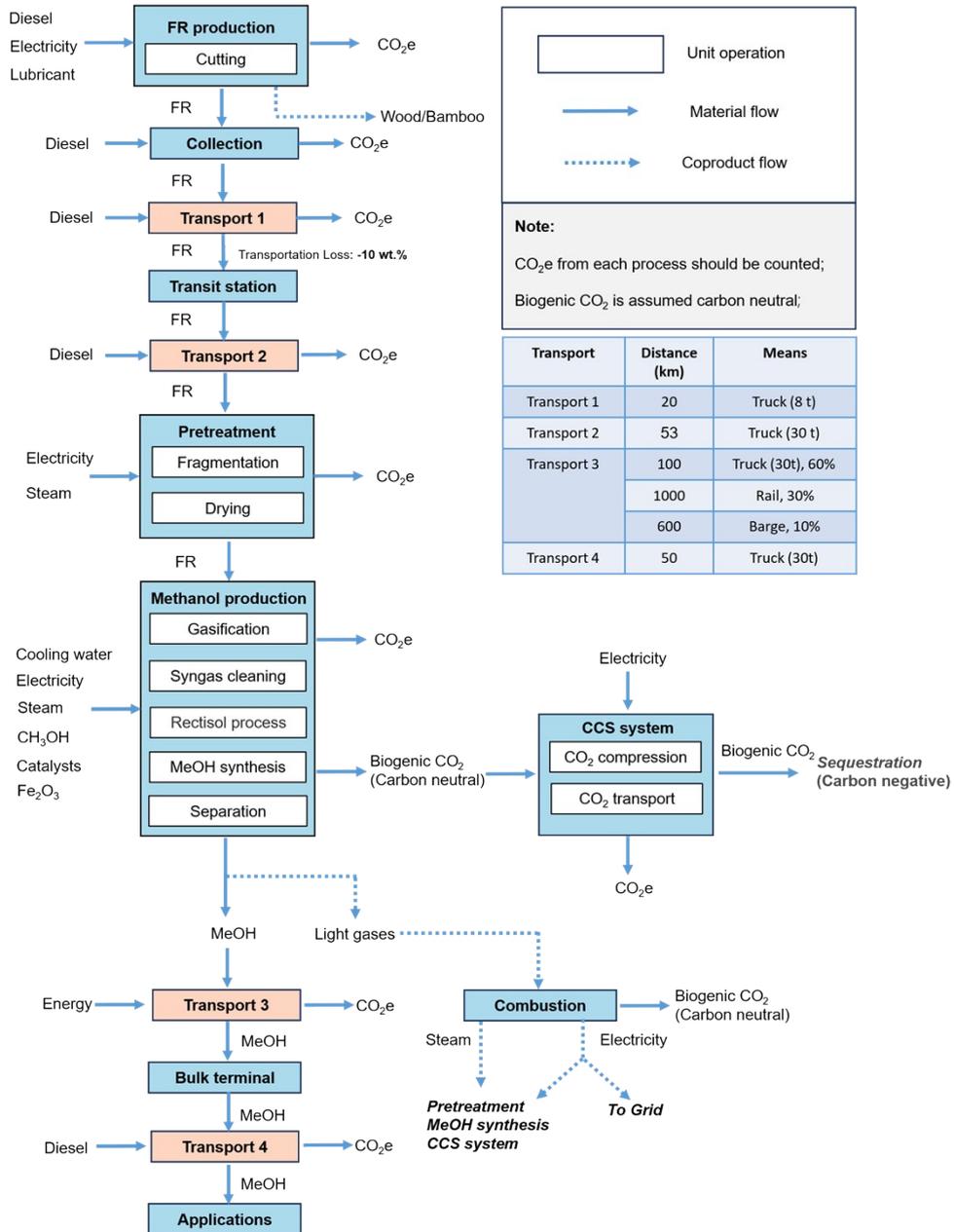
Supplementary Figure 11 | Well-to-Gate (WTG) LCA boundary of biomethanol from forest residues in “No CCS” scenario. This boundary applies to cases when using wood residues and bamboo residues as the feedstocks in “No CCS” scenario.



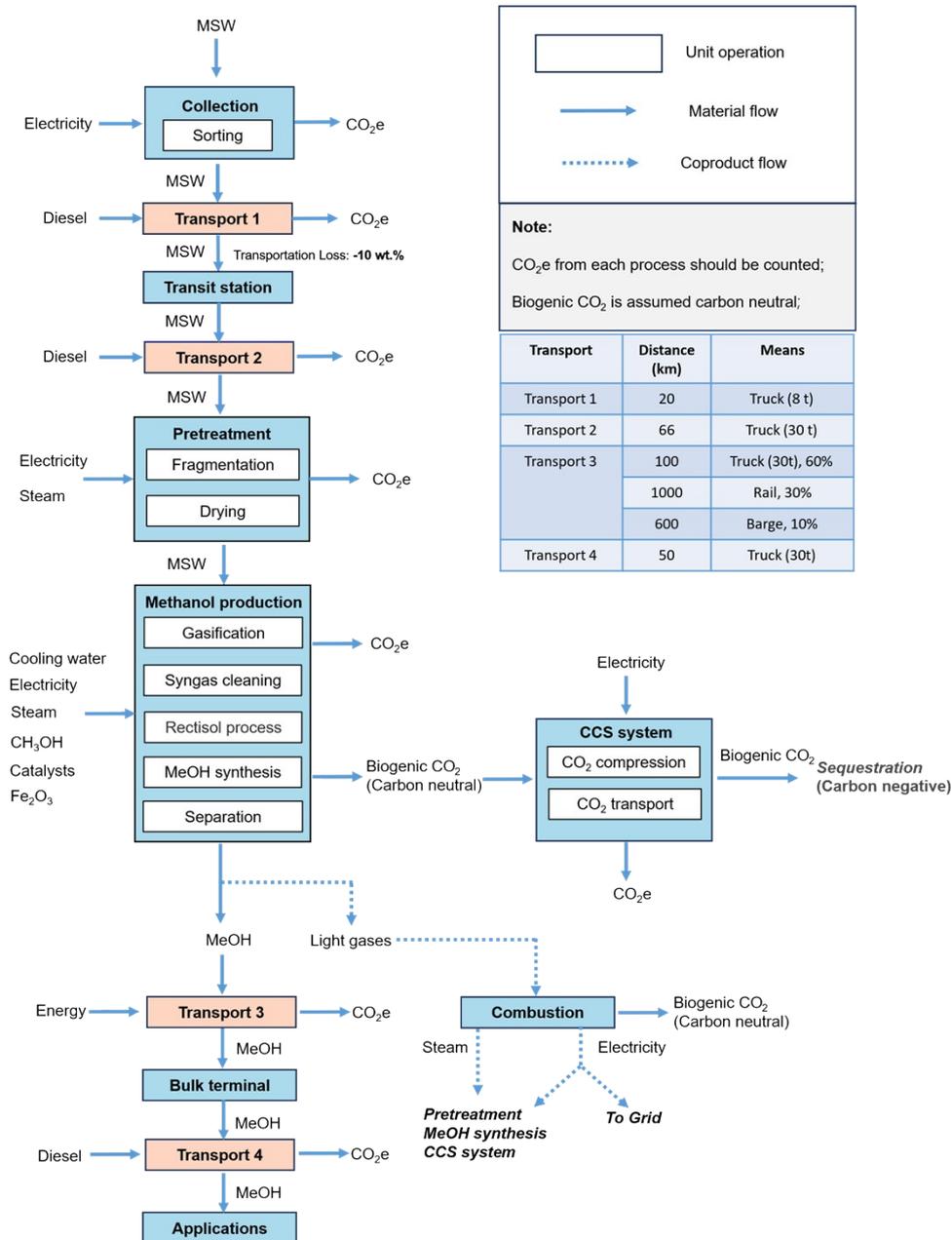
Supplementary Figure 12 | Well-to-Gate (WTG) LCA boundary of biomethanol from municipal solid wastes in “No CCS” scenario. This boundary applies to cases when using municipal solid wastes as the feedstocks in “No CCS” scenario.



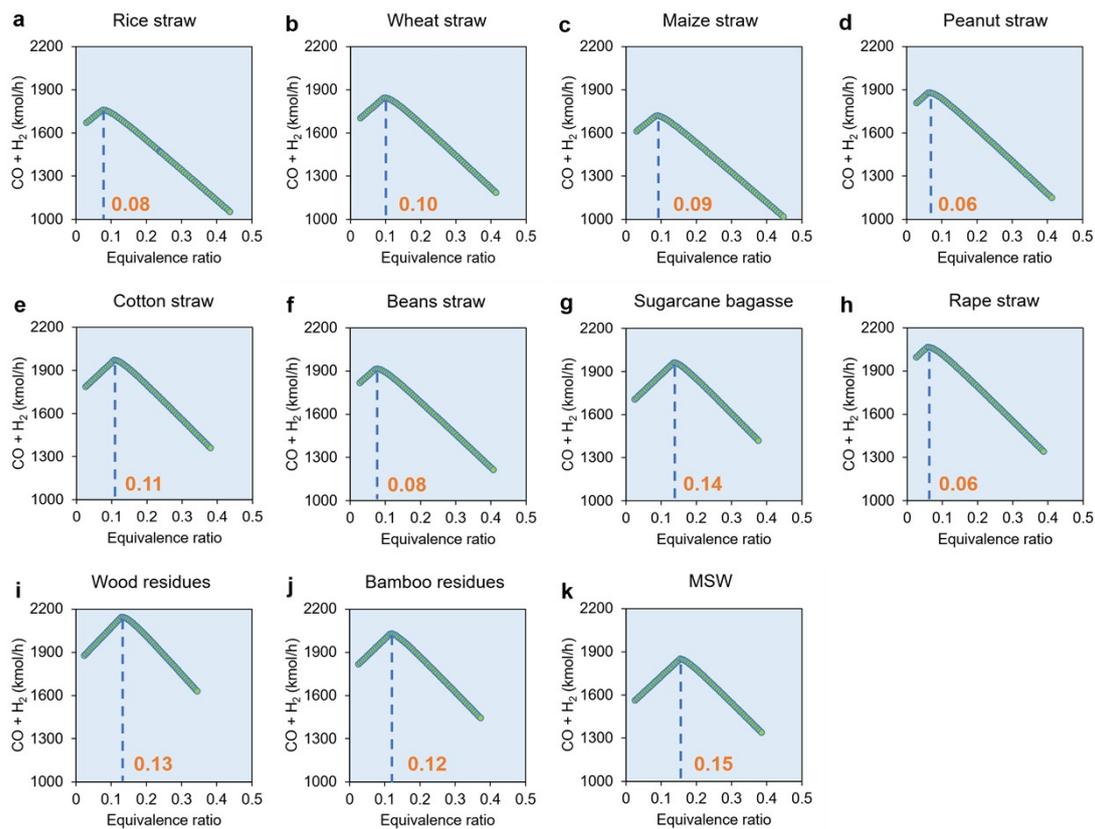
Supplementary Figure 13 | Well-to-Gate (WTG) LCA boundary of biomethanol from agricultural crop straws in “With CCS” scenario. This boundary applies to cases when using rice straw, wheat straw, maize straw, peanut straw, cotton straw, beans straw, sugarcane bagasse, rape straw as the feedstocks in “With CCS” scenario.



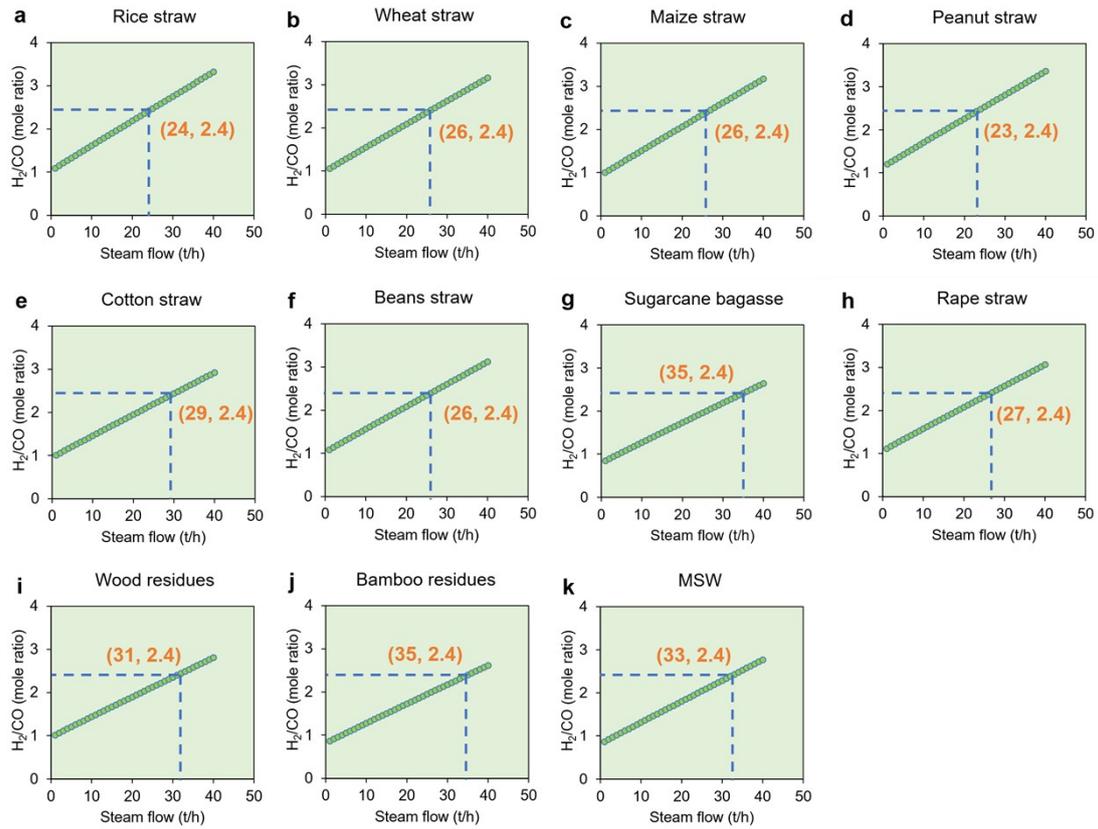
Supplementary Figure 14 | Well-to-Gate (WTG) LCA boundary of biomethanol from forest residues in “With CCS” scenario. This boundary applies to cases when using wood residues and bamboo residues as the feedstocks in “With CCS” scenario.



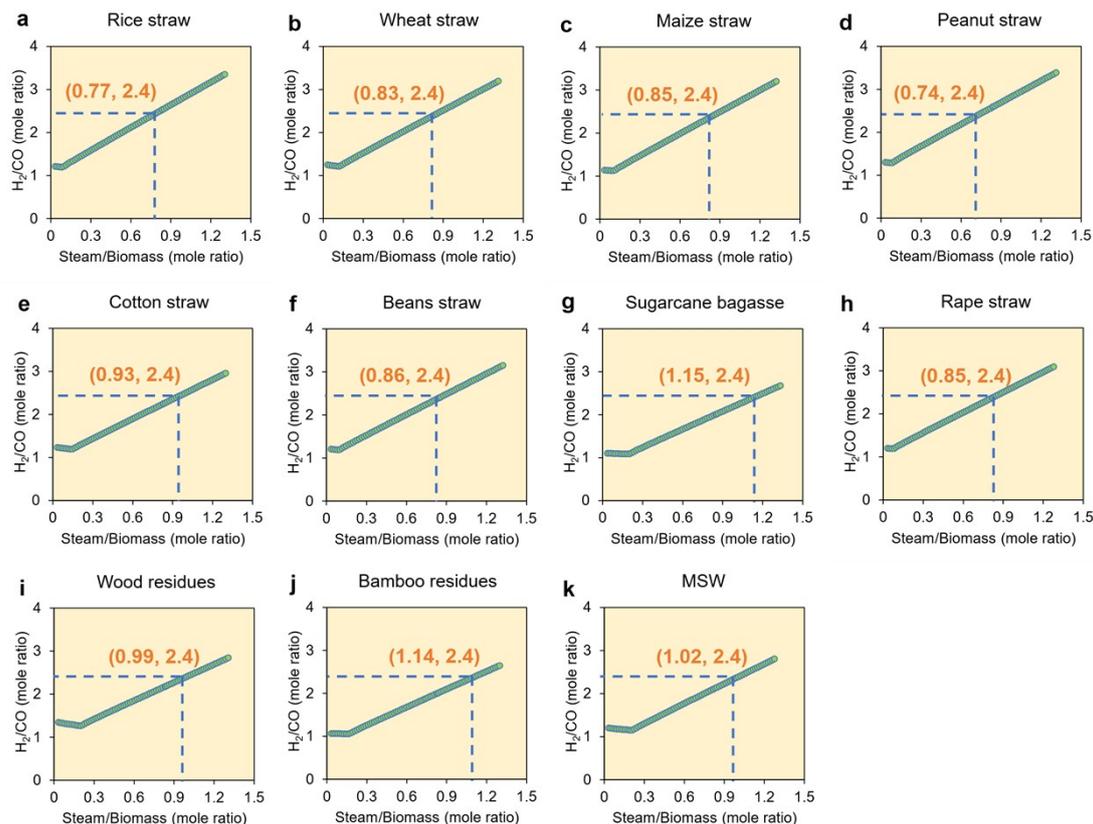
Supplementary Figure 15 | Well-to-Gate (WTG) LCA boundary of biomethanol from municipal solid wastes in “With CCS” scenario. This boundary applies to cases when using municipal solid wastes as the feedstocks in “With CCS” scenario.



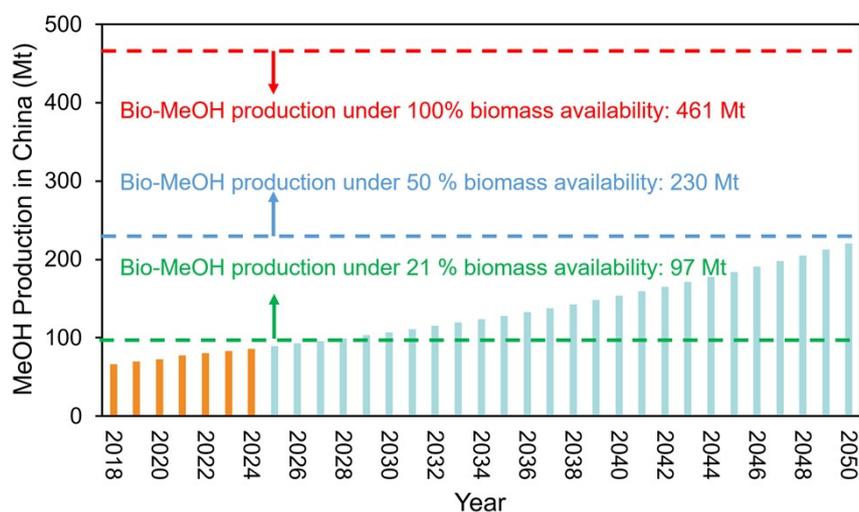
Supplementary Figure 16 | The optimal equivalence ratio in the oxygen gasification for biomethanol production by using (a) rice straw, (b) wheat straw, (c) maize straw, (d) peanut straw, (e) cotton straw, (f) beans straw, (g) sugarcane bagasse, (h) rape straw, (i) wood residues, (j) bamboo residues, (k) municipal solid wastes as the feedstocks.



Supplementary Figure 17 | Steam addition for adjusting the H_2/CO mole ratio to about 2.4 via the water-gas shift reaction after the oxygen-based gasification of (a) rice straw, (b) wheat straw, (c) maize straw, (d) peanut straw, (e) cotton straw, (f) beans straw, (g) sugarcane bagasse, (h) rape straw, (i) wood residues, (j) bamboo residues, (k) municipal solid wastes.



Supplementary Figure 18 | The optimal steam/biomass mole ratio in the steam gasification for biomethanol production by using (a) rice straw, (b) wheat straw, (c) maize straw, (d) peanut straw, (e) cotton straw, (f) beans straw, (g) sugarcane bagasse, (h) rape straw, (i) wood residues, (j) bamboo residues, (k) municipal solid wastes as the feedstocks.



Supplementary Figure 19 | MeOH production in China from 2018-2050. The orange columns represent historical data and the green columns represent predicted data. The average annual growth rate of MeOH production in China from 2018 to 2024 is approximately 3.6%, and thus future MeOH production is predicted based on the same growth rate (3.6%).

Section S2. Supplementary Tables

Supplementary Table 1 | Biomass-to-methanol projects in China.

Company Name	Province	Capacity (10k tons/year)	Biomass Feedstock Type	Current Project Status
Shanghai Electric Green Energy (Jilin)	Jilin	25 (Total plan)	Agricultural and forestry waste	Under Construction
Mingyang Smart Energy	Jilin	60 (Total plan)	Corn Straw	Under Construction
CIMC Green Energy Low-Carbon Tech	Guangdong	5 (Phase I)	Agricultural and forestry waste	Under Construction
China Energy Engineering Group (CEEC)	Heilongjiang	20	Crop straw	Preparation
China Coal Group	Inner Mongolia	20	Cattle manure	Preparation
Debo Energy	Jiangxi	15	Agricultural and forestry waste	Under Construction
CNOOC Chemical	Hubei	15	Agricultural and forestry waste	Under Construction
CGN	Jiangxi	20	Agricultural and forestry waste	Preparation
Xuchang Longji Bioenergy	Henan	12	Crop straw, forestry residues	Preparation
Sinochem Yueda	Jiangsu	100 (Total plan)	Agricultural waste	Preparation
Shanghai Huayi Group	Shanghai	10	MSW, animal manure	Under Construction
Yicheng Green Hydrogen Ammonia Energy	Hubei	20	Agricultural waste	Preparation
Inner Mongolia Xiugang Green Energy	Inner Mongolia	20	Agricultural waste	Preparation
Yuanhuang Energy	Inner Mongolia	70	Agricultural waste	Under Construction
Daan Chengyang Green Hydrogen Energy	Jilin	20	Agricultural and forestry waste	Preparation
KTAI (Shanghai) Chemical Engineering	Anhui	20	Agricultural and forestry waste	Preparation

Note: these projects are summarized from publicly available information, such as web pages and news reports.^{7, 8} There may be some undisclosed or unsearchable biomethanol projects which are not in the table.

Supplementary Table 2 | CO₂-to-methanol projects (e-methanol) in China.

Company	Province	Design Capacity (10k tons/year)	Power Source	Current Status
CRI & China Tianying Group	Jilin	17	Wind + Solar	Under construction
Shenghong Petrochemical	Jiangsu	10	Industrial grid (CO ₂ from ethanol plants)	Operational (since September 2023)
Jinfeng Green Energy	Inner Mongolia	50	Biomass + Wind/Solar	Preparation
Mingyang Green Chemical	Inner Mongolia	100 Phase I (60 tons)	Wind + Solar	under construction
Yuanheng Energy	Inner Mongolia	70	Wind/Solar + Biomass CO ₂	Preparation
Vision Energy	Shaanxi	30	Wind + Solar	Preparation
China General Nuclear Power Group	Inner Mongolia	100	Wind + Solar	Preparation
Zhejiang Energy & Dalian Shipbuilding	Liaoning	1	Wind	Pilot project operational (2024)

Note: these projects are summarized from publicly available information, such as web pages and news reports.^{9, 10} There may be some undisclosed or unsearchable CO₂-to-methanol projects which are not in the table.

feedstocks.

Author	Country	Feedstock	Gasification agent	Assessment		
				Process simulation	TEA	LCA
Liu et al. ¹¹	China	Cotton stalk	Oxygen	✓		✓
Biswas et al. ¹²	India	Municipal solid waste	Oxygen		✓	✓
Giorgia et al. ¹³	Italy	Residual forestry	Oxygen steam	✓	✓	
Wang et al. ¹⁴	China	Corn straw	Oxygen	✓	✓	✓
Zhang et al. ¹⁵	China	Corn straw	Oxygen	✓	✓	✓
Im-orb et al. ¹⁶	Thailand	Oil palm trunk	Oxygen	✓	✓	
Makepa et al. ¹⁷	Zimbabwe	Jatropha curcas	Oxygen	✓	✓	✓
Cerqueira et al. ¹⁸	Brazil	Municipal solid waste	unspecified			✓
AlNouss et al. ¹⁹	Qatar	Palm wastes	Steam	✓	✓	✓
Nugroho et al. ²⁰	Ireland	Rice straws	Steam	✓	✓	
Wang et al. ²¹	China	Rice straw	Oxygen	✓		✓
This study	China	11 types of biomass residues	Oxygen steam	✓	✓	✓

Supplementary Table 4 | Compositions of biomass feedstocks in this research (before drying process). These data are summarized from the literature. ²²⁻²⁶

Composition (wt.%)		Rice straw	Wheat straw	Corn straw	Peanut straw	Cotton straw	Beans straw	Sugarcane bagasse	Rape straw	Wood residues	Bamboo residues	Municipal solid waste
Proximate analysis	Moisture	8.11	8.63	9.31	8.56	7.66	9.34	10.00	6.15	8.19	7.6	6.06
	FC	16.91	16.37	16.35	17.12	20.11	17.23	16.20	18.39	17.41	19.52	14.17
	VM	66.49	70.00	69.18	72.90	72.95	76.06	80.50	77.77	78.45	80.15	71.07
	Ash	16.60	13.63	14.47	9.97	6.94	6.71	3.30	3.84	4.14	0.33	14.77
Ultimate analysis	C	37.81	40.37	39.35	39.28	43.91	41.93	48.10	42.46	47.27	48.00	43.46
	H	6.02	6.26	5.68	7.00	6.52	6.70	5.90	7.07	7.16	6.04	5.43
	N	0.68	0.56	0.91	2.01	1.04	0.92	0.15	0.23	0.33	0.15	0.70
	Cl	0.05	0.05	0.05	0.05	0.05	0.05	0.00	0.00	0.05	0.00	0.00
	S	0.28	0.31	0.19	0.27	0.25	0.19	0.00	0.27	0.12	0.05	0.58
	O	38.56	38.83	39.35	41.42	41.29	43.49	42.55	46.14	40.93	45.42	35.06

Supplementary Table 5 | Assumed economic parameters in the TEA model

Basic Economic Index	Value
Construction period	3 years (2020-2022)
Production period	28 years (2023-2050)
Plant financing	50% equity, 50% loan
Loan rate	0.0365 (Ref. ⁴⁹)
Loan term	10 years (Ref. ⁵³)
Income tax rate	0.15 (Ref. ⁵⁰)
Inflation	0.02 (Ref. ⁵¹)
Operation days/year	329 (90% uptime)
Discount Rate	0.1 (Ref. ⁵²)
Depreciation schedule	7 years (Ref. ⁵³)
Annual salary increase rate	10%
Working capital	10% of FCI (Ref. ⁵⁴)
USD/RMB exchange rate	7.2 (2024 base)

Supplementary Table 6 | Prices of biomass feedstocks, associated materials and energy in this model

Type	Item	Price		References/Sources
		Value	Unit	
Biomass feedstock	Rice straw	107.5	\$/t	Market investigation ⁵⁵
	Wheat straw	98.4	\$/t	Market investigation ⁵⁵
	Corn straw	79.5	\$/t	Market investigation ⁵⁵
	Peanut straw	161.3	\$/t	Market investigation ⁵⁵
	Cotton straw	55.6	\$/t	Market investigation ⁵⁵
	Beans straw	120.6	\$/t	Market investigation ⁵⁵
	Sugarcane bagasse	52.2	\$/t	Market investigation ⁵⁵
	Rape straw	57.8	\$/t	Market investigation ⁵⁵
	Wood residues	42.6	\$/t	It is evaluated by analyzing the collection (\$20.4/t) ⁵⁶ , transportation (\$20/t) ⁵⁷ , and storage cost (\$2.1/t) ⁵⁶ .
	Bamboo residues	42.6	\$/t	It is evaluated by analyzing the collection (\$20.4/t) ⁵⁶ , transportation (\$20/t) ⁵⁷ , and storage cost (\$2.1/t) ⁵⁶ .
Materials/energy	MSW	28.3	\$/t	It is evaluated by analyzing the transportation (\$20/t) ⁵⁷ , storage (\$2.1/t) ⁵⁶ , and pretreatment cost (\$6.2/t) ⁵⁶ .
	Hydrogen	4615	\$/t	Market investigation ⁵⁸
	Cooling water	0.55	\$/t	Market investigation ⁵⁹
	Electricity	0.077	\$/kWh	Market investigation ⁶⁰
	Propane	0.021	\$/kW	Market investigation ⁶¹
	Natural gas	0.42	\$/Nm ³	Market investigation ⁶¹
	MP steam	37.8	\$/t	Market investigation ⁶²
	Fe ₂ O ₃	166.7	\$/t	Market investigation ⁶¹
	CH ₃ OH (fossil derived)	347.2	\$/t	Market investigation ⁶¹
	Wastewater treatment	0.21	\$/t	Market investigation ⁶³
Cu/ZnO Catalyst	41.1	\$/kg	Market investigation ⁶⁴	
Mo ₂ C	1597	\$/kg	Market investigation ⁶⁵	

Supplementary Table 7 | The compositions of original MSW in China. Metal, glass, dust & bricks, and other hazardous mixtures should be removed when using MSW as the feedstocks for bio-MeOH production.

Region	MSW (10 ⁴ t)	KW (%)	Paper (%)	Textiles (%)	Metal (%)	Glass (%)	Plastic & rubber (%)	Wood (%)	Dust & bricks (%)	Other mixtures (%)
Beijing	740.6	42.8	9.2	2.1	1.2	2.9	8	5.9	26.3	1.6
Tianjin	309.1	42.8	9.2	2.1	1.2	2.9	8	5.9	26.3	1.6
Hebei	749.0	42.8	9.2	2.1	1.2	2.9	8	5.9	26.3	1.6
Shanxi	466.7	42.8	9.2	2.1	1.2	2.9	8	5.9	26.3	1.6
Inner Mongolia	348.6	42.8	9.2	2.1	1.2	2.9	8	5.9	26.3	1.6
Liaoning	994.4	43.1	4	1.9	1.7	2.3	6.7	2.2	37.9	0.3
Jilin	435.7	43.1	4	1.9	1.7	2.3	6.7	2.2	37.9	0.3
Heilongjiang	507.9	43.1	4	1.9	1.7	2.3	6.7	2.2	37.9	0.3
Shanghai	890.1	53.3	10	3	1.3	3.1	10.9	4.1	15.2	0.3
Jiangsu	1958.7	53.3	10	3	1.3	3.1	10.9	4.1	15.2	0.3
Zhejiang	1553.5	53.3	10	3	1.3	3.1	10.9	4.1	15.2	0.3
Anhui	745.4	53.3	10	3	1.3	3.1	10.9	4.1	15.2	0.3
Fujian	874.5	53.3	10	3	1.3	3.1	10.9	4.1	15.2	0.3
Jiangxi	527.7	53.3	10	3	1.3	3.1	10.9	4.1	15.2	0.3
Shandong	1724.0	53.3	10	3	1.3	3.1	10.9	4.1	15.2	0.3
Henan	1087.9	50.8	6.6	2.2	1.1	1.9	7.9	1.2	28.7	0.3
Hubei	1032.6	50.8	6.6	2.2	1.1	1.9	7.9	1.2	28.7	0.3
Hunan	860.8	50.8	6.6	2.2	1.1	1.9	7.9	1.2	28.7	0.3
Guangdong	3280.6	48.8	11.6	4.2	0.8	3.5	13.7	3	9.4	5.0
Guangxi	601.4	48.8	11.6	4.2	0.8	3.5	13.7	3	9.4	5.0
Hainan	264.8	48.8	11.6	4.2	0.8	3.5	13.7	3	9.4	5.0
Chongqing	678.8	43.6	10.6	3.4	1.4	3	11.3	3	18.7	5.1
Sichuan	1259.2	43.6	10.6	3.4	1.4	3	11.3	3	18.7	5.1
Guizhou	415.9	43.6	10.6	3.4	1.4	3	11.3	3	18.7	5.1
Yunnan	538.1	43.6	10.6	3.4	1.4	3	11.3	3	18.7	5.1
Tibet	62.2	43.6	10.6	3.4	1.4	3	11.3	3	18.7	5.1
Shaanxi	654.9	42.9	5.6	3.1	0.5	3.1	7.7	3.2	31.8	2.4
Gansu	266.3	42.9	5.6	3.1	0.5	3.1	7.7	3.2	31.8	2.4
Qinghai	117.7	42.9	5.6	3.1	0.5	3.1	7.7	3.2	31.8	2.4
Ningxia	117.2	42.9	5.6	3.1	0.5	3.1	7.7	3.2	31.8	2.4
Xinjiang	380.4	42.9	5.6	3.1	0.5	3.1	7.7	3.2	31.8	2.4

Note: The composition of MSW is complex, containing kitchen wastes, paper, textiles, metal, glass, plastic & rubber, wood, dust and bricks, and other hazardous mixtures. From the perspective of biorefining, metal, glass, dust & bricks, and other hazardous mixtures should be removed since they can't be used as the feedstocks for bio-MeOH production. The province-level distribution of MSW can be found in the latest *China Statistical Yearbook* (2023), and the compositions of MSW in different regions of China are from the literature²⁷ (see **Supplementary Table 6**). The resource potential of MSW (Res_{MSW}) can be calculated according to **equation (1)**, where M_i represents the amount of original MSW (not removing metal, glass, dust & bricks, and other hazardous materials) in province i ; $\beta_{k,i}$, $\beta_{p,i}$, $\beta_{t,i}$, $\beta_{p\&r,i}$, and $\beta_{w,i}$ respectively represent the mass ratio of kitchen wastes, paper, textiles, plastic & rubber, and wood in the MSW of province i . We assume that 1 t of waste cooking oil (WCO) can be obtained from 25 t of kitchen wastes (KW)^{28, 29}, and thereby the quality of WCO needs to be deducted after the processing of KW.

$$Res_{MSW} = \sum_{i=1}^{31} M_i \cdot (0.96 \cdot \beta_{k,i} + \beta_{p,i} + \beta_{t,i} + \beta_{p\&r,i} + \beta_{w,i}) \quad (1)$$

Importantly, compared with agricultural or forest residues, the carbons in the MSW are not 100% biogenic due to the existence of plastics and rubber. We present a rough estimation of fossil source carbon contents in the MSW, as shown below:

$$C_{total} = \sum_{i=1}^{31} M_i \cdot (0.96 \cdot \beta_{k,i} \cdot \tau_k + \beta_{p,i} \cdot \tau_p + \beta_{t,i} \cdot \tau_t + \beta_{p\&r,i} \cdot \tau_{pr} + \beta_{w,i} \cdot \tau_w) \quad (2)$$

where C_{total} is the total amount of carbons in MSW; τ_k , τ_p , τ_t , τ_{pr} , and τ_w are the carbon contents (wt.%) in KW (46%)³⁰, paper (44%)³¹, textiles (55%)³², plastic & rubber (63%)³³, and wood (49%)³⁴, respectively. The fossil derived carbons can be estimated as follows:

$$C_{fossil} = \sum_{i=1}^{31} M_i \cdot (\beta_{p,i} \cdot \tau_p \cdot \sigma_p + \beta_{t,i} \cdot \tau_t \cdot \sigma_t + \beta_{p\&r,i} \cdot \tau_{pr} \cdot \sigma_{pr}) \quad (3)$$

where σ_p , σ_t , and σ_{pr} are the fossil derived carbon contents (wt.%) in paper (1%)³⁵, textiles (40%)³⁵, and plastic & rubber (100%), respectively. Then the fossil source carbon contents in the MSW (wt.%) can be estimated as follows:

$$\sigma_{MSW} = \frac{C_{fossil}}{C_{total}} \cdot 100\% \quad (4)$$

In summary, we estimate that the fossil source carbon contents in the MSW is about 19.5 wt.%.

Supplementary Table 8 | Installed equipment cost in the techno-economic analysis

Process	Items	Installed Cost [USD]	Source
Biomass pretreatment	Crusher	109777.8	Market investigation
	FLASH	89331.67	Aspen
	HEATER	82367.64	Aspen
	Drying reactor	530393	literature investigation ⁶⁶
Biomass gasification	Gasifier	41834728	literature investigation ⁶⁶
	Tar reformer	19528540	literature investigation ⁶⁷
	HEATER	102745.1	Aspen
	H2O-SEP	58567.13	Aspen
	COOL2	207548.6	Aspen
	DE-FE2S3	66597.38	Aspen
	ASH-SEP	73173.75	Aspen
	DE-H2S	466190.8	literature investigation ⁶⁷
AGRS	AGRS system	6433362	Aspen
CCS	CCS system	14220531	Aspen
Syngas to methanol	SYN-METH	25943918	literature investigation ⁶⁶
	HEAT2	207480	Aspen
	H2-PSA	8906796	literature investigation ⁶⁷
	RADFRAC1	1156454	Aspen
	COOL1	71136	Aspen
	COMPRE1	3631394	Aspen
	VALVE1	61527.7	Aspen
	SEP 1 (FLASH)	70148	Aspen
	EXCHANGE	48165	Aspen
	HEAT1	118313	Aspen
	CO-PSA	4656715	literature investigation ⁶⁸
DAC O ₂ production	VPSA (O ₂ -PSA)	1212072	literature investigation ⁶⁸

Supplementary Table 9 | LCA datasets of the life-cycle inventory in this research.

Input	GHG intensity	Unit	Source
K ₂ O	0.660	kg CO ₂ e/kg	CPCD Database ³⁶
P ₂ O ₅	2.330	kg CO ₂ e/kg	CPCD Database ³⁶
Nitrogen	7.760	kg CO ₂ e/kg	CPCD Database ³⁶
Insecticides	13.500	kg CO ₂ e/kg	CLCD Database ³⁷
Electricity, mixed	0.570	kg CO ₂ e/kwh	CPCD Database ³⁶
Herbicides	18.902	kg CO ₂ e/kg	REET database ³⁸
Agricultural PE film	2.490	kg CO ₂ e/kg	CPCD Database ³⁶
Mo/γ-Al ₂ O ₃	9.397	kg CO ₂ e/kg	REET database ³⁸
MgO	1.889	kg CO ₂ e/kg	CPCD Database ³⁶
ZnO	2.010	kg CO ₂ e/kg	CPCD Database ³⁶
Na ₂ CO ₃	1.875	kg CO ₂ e/kg	CPCD Database ³⁶
Steam, from Natural gas	0.162	kg CO ₂ e/kg	CLCD Database ³⁷
Cooling water	0.820	kg CO ₂ e/m ³	CPCD Database ³⁶
H ₂ , from coal	21.780	kg CO ₂ e/kg	CPCD Database ³⁶
H ₂ , from natural gas	10.063	kg CO ₂ e/kg	CPCD Database ³⁶
H ₂ , from coke-oven gas	13.780	kg CO ₂ e/kg	CPCD Database ³⁶
H ₂ , from electrolysis of water	6.460	kg CO ₂ e/kg	CPCD Database ³⁶
H ₂ , Mixed	17.961	kg CO ₂ e/kg	CPCD Database ³⁶
Natural gas	2.688	kg CO ₂ e/kg	CPCD Database ³⁶
CH ₃ OH, from coal	3.470	kg CO ₂ e/kg	CPCD Database ³⁶
Wastewater treatment	0.520	kg CO ₂ e/t	CPCD Database ³⁶
Transportation by vehicles (loading capacity: 8t)	0.179	kg CO ₂ e/t*km	CPCD Database ³⁶
Transportation by vehicles (loading capacity: 30 t)	0.078	kg CO ₂ e/t*km	CPCD Database ³⁶
Diesel	3.797	kg CO ₂ e/kg	CPCD Database ³⁶
Transportation by pipe	0.075	kg CO ₂ e/t*km	CPCD Database ³⁶
Transportation by steamship	0.014	kg CO ₂ e/t*km	CPCD Database ³⁶
Transportation by train	0.007	kg CO ₂ e/t*km	CPCD Database ³⁶
Copper loaded catalysts	20.369	kg CO ₂ e/kg	CPCD Database ³⁶
Coal	2.400	kg CO ₂ e/kg	CPCD Database ³⁶
Dilute H ₂ SO ₄ solution	0.040	kg CO ₂ e/kg	CLCD database ³⁷
NaOH (s)	1.590	kg CO ₂ e/kg	CPCD Database ³⁶
NH ₄ Cl (s)	0.581	kg CO ₂ e/kg	CPCD Database ³⁶
NaCl (s)	0.222	kg CO ₂ e/kg	REET database ³⁸
Fe ₂ O ₃	1.64	kg CO ₂ e/kg	Kiyoshi et al. ³⁹
Dolomite	0.471	kg CO ₂ e/kg	CPCD Database ³⁶
MSW collection and	7.000	kg CO ₂ e/t	CPCD Database ³⁶

sorting			
Ni-based catalysts	34.377	kg CO ₂ e/kg	CPCD Database ³⁶
ZSM-5 catalysts	6.369	kg CO ₂ e/kg	GREET database ³⁸
Lubricating oil	5.260	kg CO ₂ e/kg	CPCD Database ³⁶
CO ₂ transport	10	kg CO ₂ e/t	CPCD Database ⁴⁰

Supplementary Table S10 | Required, produced, and outsourced steam/electricity in oxygen gasification-based methanol production under “No CCS” scenario.

The data is derived from our process modeling using Aspen Plus.

Feedstock	Gas (kg/hr)	LHV (MJ/kg)	Required steam (t/hr)	Required electricity (kW)	Produced steam (t/hr)	Produced electricity (kW)	Outsourced steam (t/hr)	Outsourced electricity (kW)
RS	7160.3	28.9	39.2	6056.1	39.2	12522.5	0.0	(6466.5) ^a
WS	7470.9	28.9	42.2	6411.7	42.2	12581.8	0.0	(6170.1)
MZ	7023.3	28.7	41.1	6417.7	41.1	11110.3	0.0	(4692.6)
PS	7832.5	29.1	46.2	6254.5	46.2	12632.2	0.0	(6377.7)
CS	8090.5	28.6	47.0	7263.4	47.0	12805.3	0.0	(5541.8)
BS	7834.4	28.7	43.1	6783.7	43.1	13410.6	0.0	(6626.8)
SCB	7892.3	28.9	53.0	8161.0	53.0	10215.5	0.0	(2054.5)
RS	8365.8	29.0	45.4	6882.2	45.4	14928.0	0.0	(8045.8)
WR	8709.6	28.7	50.6	7556.1	50.6	13936.4	0.0	(6380.3)
BR	8161.0	28.6	52.7	8214.7	52.7	11042.1	0.0	(2827.4)
MSW	7488.5	29.1	49.8	7883.9	49.8	10071.7	0.0	(2187.8)

^a: (value) means that the energy can be net output.

Supplementary Table S11 | Required, produced, and outsourced steam/electricity in oxygen gasification-based methanol production under “With CCS” scenario. The data is derived from our process modeling using Aspen Plus.

Feedstock	Gas (kg/hr)	LHV (MJ/kg)	Required steam (t/hr)	Required electricity (kW)	Produced steam (t/hr)	Produced electricity (kW)	Outsourced steam (t/hr)	Outsourced electricity (kW)
RS	7160.3	28.9	39.2	7549.5	39.2	12522.5	0.0	(4973.0) ^a
WS	7470.9	28.9	42.2	8037.1	42.2	12581.8	0.0	(4544.6)
MZ	7023.3	28.7	41.1	8050.5	41.1	11110.3	0.0	(3059.9)
PS	7832.5	29.1	46.2	7666.4	46.2	12632.2	0.0	(4965.7)
CS	8090.5	28.6	47.0	9079.5	47.0	12805.3	0.0	(3725.7)
BS	7834.4	28.7	43.1	8411.2	43.1	13410.6	0.0	(4999.3)
SCB	7892.3	28.9	53.0	10345.6	53.0	10215.5	0.0	130.1
RS	8365.8	29.0	45.4	8549.2	45.4	14928.0	0.0	(6378.7)
WR	8709.6	28.7	50.6	9488.9	50.6	13936.4	0.0	(4447.5)
BR	8161.0	28.6	52.7	10421.6	52.7	11042.1	0.0	(620.5)
MSW	7488.5	29.1	49.8	9935.8	49.8	10071.7	0.0	(135.9)

^a: (value) means that the energy can be net output.

Supplementary Table S12 | Required, produced, and outsourced steam/electricity in steam gasification-based methanol production under “No CCS” scenario.
 The data is derived from our process modeling using Aspen Plus.

Feedstock	Gas (kg/hr)	LHV (MJ/kg)	Required steam (t/hr)	Required electricity (kW)	Produced steam (t/hr)	Produced electricity (kW)	Outsourced steam (t/hr)	Outsourced electricity (kW)
RS	7812.8	28.7	40.0	5891.5	40.0	14427.4	0.0	(8535.9) ^a
WS	8362.6	28.7	49.9	6056.2	49.9	12865.1	0.0	(6808.8)
MZ	7766.9	28.5	48.7	6183.3	48.7	10941.4	0.0	(4758.1)
PS	8388.7	28.8	46.8	5784.1	46.8	14224.8	0.0	(8440.7)
CS	9098.0	28.7	55.4	6833.6	55.4	13648.7	0.0	(6815.2)
BS	8530.2	28.5	44.0	6206.3	44.0	15479.6	0.0	(9273.3)
SCB	9244.8	28.5	61.1	7411.1	61.1	11807.0	0.0	(4395.9)
RS	8921.8	28.8	52.5	6416.6	52.5	14129.2	0.0	(7712.6)
WR	10081.9	28.6	59.3	6806.6	59.3	15751.2	0.0	(8944.6)
BR	9343.4	28.5	62.0	7621.7	62.0	11873.1	0.0	(4251.4)
MSW	8981.9	28.7	58.2	6650.5	58.2	12154.0	0.0	(5503.5)

^a: (value) means that the energy can be net output.

Supplementary Table S13 | Required, produced, and outsourced steam/electricity in steam gasification-based methanol production under “With CCS” scenario. The data is derived from our process modeling using Aspen Plus.

Feedstock	Gas (kg/hr)	LHV (MJ/kg)	Required steam (t/hr)	Required electricity (kW)	Produced steam (t/hr)	Produced electricity (kW)	Outsourced steam (t/hr)	Outsourced electricity (kW)
RS	7812.8	28.7	40.0	7172.2	40.0	14427.4	0.0	(7255.2) ^a
WS	8362.6	28.7	49.9	7394.7	49.9	12865.1	0.0	(5470.4)
MZ	7766.9	28.5	48.7	7576.9	48.7	10941.4	0.0	(3364.5)
PS	8388.7	28.8	46.8	7012.9	46.8	14224.8	0.0	(7211.9)
CS	9098.0	28.7	55.4	8336.6	55.4	13648.7	0.0	(5312.1)
BS	8530.2	28.5	44.0	7609.2	44.0	15479.6	0.0	(7870.4)
SCB	9244.8	28.5	61.1	9156.5	61.1	11807.0	0.0	(2650.5)
RS	8921.8	28.8	52.5	7901.0	52.5	14129.2	0.0	(6228.3)
WR	10081.9	28.6	59.3	8302.6	59.3	15751.2	0.0	(7448.6)
BR	9343.4	28.5	62.0	9451.3	62.0	11873.1	0.0	(2421.8)
MSW	8981.9	28.7	58.2	8220.4	58.2	12154.0	0.0	(3933.5)

^a: (value) means that the energy can be net output.

Supplementary Table S14 | Material and energy inputs for farming and harvesting. Compared with agricultural crops, plants in forestry relies on less artificial intervention, and thereby the input of pesticides, fertilizers, etc., can be ignored. For the agricultural residues, the emissions from the farming and harvesting process are allocated to grains and straws based on their market prices; The emissions from forest harvesting are also allocated to the wood/bamboo and residues based on their prices.

Material	Unit	Rice straw	Wheat straw	Corn straw	Peanut straw	Cotton straw	Beans straw	Sugarcane bagasse	Rape straw	Forest residues	Bamboo residues
Diesel	kg/ha	181.1	129	109.2	82	121.5	79.2	66.3	73.1	1.93	1.93
Electricity	kWh/ha	742.8	1766.3	948.3	776.9	4913.4	134.1	18.6	51.2	5.25	5.25
Nitrogen	kg/ha	144.6	177.3	158.5	108.8	247.4	43.3	346.1	103.1	0	0
Phosphorus	kg/ha	56.2	75.6	67.9	77.8	85.8	27.2	137.2	45.1	0	0
Potassium	kg/ha	45.3	47.4	44.6	45.2	62.6	21.2	130.6	24.8	0	0
Insecticide	kg/ha	4.543	2.006	1.475	3.54	6.136	1.416	5.251	1.416	0	0
Herbicide	kg/ha	3.157	1.394	1.025	2.46	4.264	0.984	3.649	0.984	0	0
Film (polyethylene)	kg/ha	2.5	0	2.5	4.9	23	0	4.2	0	0	0
Lubricant	kg/ha	0	0	0	0	0	0	0	0	0.008	0.008

Data source: for crop straws, from Chen et al.⁴⁶; for wood residues and bamboo residues, from Andrea et al.⁴⁷ and Sahoo et al.⁴⁸

Supplementary Table S15 | Biomass feedstocks collectable potential in China currently. The datasets for the estimation are from China Statistical Yearbook (2023) (Ref.⁴¹), the 9th national forest resource inventory in China,⁴² China Forestry Statistical Yearbook,⁴³ and associated literature;^{44, 45} the calculation methods are based on the studies from Gao et al.⁴⁴ and Fu et al.⁴⁵ (Unit: Mt/yr)

Region	Rice straw	Wheat straw	Maize straw	Peanut straw	Cotton straw	Beans straw	Sugarcane bagasse	Rape straw	Wood residues	Bamboo residues	MSW
Beijing	0.00	0.10	0.33	0.01	0.00	0.01	0.00	0.00	0.48	0.00	4.78
Tianjin	0.42	0.75	1.23	0.00	0.01	0.01	0.00	0.00	0.23	0.00	2.00
Hebei	0.39	15.14	20.74	1.15	0.60	0.26	0.00	0.10	4.40	0.00	4.84
Shanxi	0.01	2.52	10.11	0.02	0.00	0.22	0.00	0.05	3.12	0.00	3.01
Inner Mongolia	0.72	1.30	30.67	0.17	0.00	2.33	0.00	0.68	18.21	0.00	2.25
Liaoning	3.40	0.01	19.40	1.40	0.00	0.25	0.00	0.00	5.48	0.00	5.41
Jilin	5.44	0.02	32.25	0.99	0.00	0.72	0.00	0.00	6.88	0.00	2.37
Heilongjiang	21.72	0.09	39.98	0.15	0.00	8.66	0.00	0.00	14.20	0.00	2.77
Shanghai	0.66	0.11	0.01	0.00	0.00	0.00	0.00	0.00	0.07	0.00	6.86
Jiangsu	15.91	14.03	2.93	0.49	0.03	0.66	0.01	1.02	4.19	0.06	15.09
Zhejiang	3.70	0.57	0.24	0.06	0.02	0.27	0.09	0.50	5.27	2.10	11.97
Anhui	12.65	17.69	6.57	0.90	0.11	0.90	0.01	1.77	5.55	1.70	5.74
Fujian	3.15	0.00	0.15	0.28	0.00	0.11	0.07	0.02	10.29	8.79	6.74
Jiangxi	16.27	0.03	0.22	0.68	0.09	0.29	0.14	1.45	9.33	3.22	4.07
Shandong	0.72	27.13	26.04	3.36	0.62	0.53	0.00	0.04	4.13	0.00	13.28
Henan	3.83	39.16	22.52	7.66	0.06	0.79	0.02	0.90	4.31	0.02	7.03
Hubei	14.91	4.17	3.09	1.06	0.44	0.36	0.06	5.04	6.39	0.48	6.67
Hunan	21.09	0.08	2.23	0.39	0.35	0.39	0.08	4.48	9.38	4.15	5.56
Guangdong	8.86	0.00	0.63	1.44	0.00	0.11	2.98	0.01	12.84	8.03	25.39
Guangxi	8.21	0.01	2.78	0.89	0.00	0.24	16.40	0.07	31.85	4.10	4.65
Hainan	1.02	0.00	0.00	0.09	0.00	0.01	0.18	0.00	2.54	0.00	2.05
Chongqing	3.88	0.06	2.54	0.18	0.00	0.39	0.02	1.00	2.70	0.28	4.64
Sichuan	11.68	2.56	10.36	0.98	0.00	1.30	0.09	6.50	13.79	2.10	8.61

Guizhou	3.16	0.30	2.97	0.12	0.00	0.40	0.10	1.74	9.98	0.35	2.85
Yunnan	3.71	0.61	10.16	0.11	0.00	0.98	3.58	0.99	18.53	2.53	3.68
Tibet	0.00	0.19	0.03	0.00	0.00	0.01	0.00	0.09	9.78	0.00	0.43
Shaanxi	0.59	4.41	6.11	0.15	0.00	0.33	0.00	0.66	6.30	0.03	3.87
Gansu	0.01	3.05	6.58	0.00	0.17	0.34	0.00	0.67	4.16	0.00	1.57
Qinghai	0.00	0.38	0.15	0.00	0.00	0.03	0.00	0.57	2.83	0.00	0.70
Ningxia	0.19	0.28	2.74	0.00	0.00	0.03	0.00	0.01	0.54	0.00	0.69
Xinjiang	0.28	6.71	10.70	0.08	23.19	0.13	0.00	0.16	5.84	0.00	2.25
Taiwan	/	/	/	/	/	/	/	/	/	/	/
Hongkong		/	/	/	/	/	/	/	/	/	/
Macao		/	/	/	/	/	/	/	/	/	/
National	166.59	141.44	274.43	22.82	25.71	21.06	23.82	28.53	233.56	37.97	171.82

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