Electronic Supplementary Information:

CO_2 utilization framework for liquid fuels and chemicals: Techno-economic and environmental analysis

Thai Ngan Do[*], *Chanhee You*[*], *and Jiyong Kim*[1]

School of Chemical Engineering, Sungkyungkwan University, 16419, Republic of Korea

[1] Corresponding Author: E-mail address: jiyongkim@skku.edu (J. Kim).
* Authors contributed equally to the manuscript

S1. Potential of CO_2 utilization for energy-based product (CCU4E)

Table S1.1. The current and potential of supply and demand of CO_2

	Supply	Mtpa	Demand*	Mtpa
Current	Natural geological CO_2 reservoirs	55	EOR	80
	Industrial by-products	55	Food industry	7
			Beverage carbonation	7
			Fabrication of metal	5
			Other applications	10
Future	Current supply (2019)	110	Growth of existing demand	200
	Growth of existing supply to (2030)	90	EGS	5 – 30
	Bulk CO_2 (low cost)	500	ECBM	30 – 300
	Bulk CO_2 (medium cost)	2,000	EOR & EGR	30 – 300
	Bulk CO_2 (high cost)	18,000	Polymer processing	5 – 30
			Bauxite treatment	5 – 30
			Carbonate aggregates	30 – 300
			CO_2 cement curing	60 – 600
			Surplus to energy-based product	>910

* The estimation do not consider the use of CO_2 in the urea manufacturing [1].

The potential supply and future demand for CO_2 production are not readily available, which is provided of the order of magnitude, as reviewed by Global CCS Institute [1] and where else [2,3]. The global consumption of CO_2 is currently estimated to be 110 Mtpa (2020) in which the large volume of CO_2 onsite-generated and directly consumed in urea manufacturing is excluded [2]. About 80 Mtpa CO_2 is consumed for enhanced oil recovery (EOR) whereas the remain is supplied for the food and beverage industry, fabrication of metal, and others.

Since a small portion of CO_2 has been industrially utilized, the huge potential emission sources at the different concentrated levels corresponded to the CO_2 captured cost was reported by IPCC [4]. The potential supply of CO_2 from large point sources is estimated at 500 Mtpa of low-cost of high-concentrated CO_2, 2,000 Mtpa of medium cost, and 18,000 Mtpa of high-cost of CO_2 [1]. With the consideration of using only the low- and medium-cost of captured CO_2, there is still very large unbalance between CO_2 demand and supply. The current use of CO_2 is estimated to 2030 at roughly 200 Mtpa [2]. Several existed and emerging technology have been considered for the large potential use of CO_2 as sequestrated underground or utilized for materials, chemicals, and fuels. Eventually, the high scenarios of the use of CO_2 for sequestration and CO_2-based materials were estimated, there is still a large surplus of CO_2 for chemical and fuel that have vast demand. That has driven effort to develop technology of CO_2 utilization into chemical and fuel production that have vast demand. The potential fuel production of CO_2 utilization was reviewed and estimated based on the current market size considered the annual growth rate to 2030 [5].

While a number of fuels and chemicals can be produced through different technological combinations, we selected eight different products and representative 72 pathways based on several considerations such as commercialization, fully accessible information, technology maturity, especially potential market size of these products in future. The potential market size of CO_2-based fuels was estimated followed the methodology of Reference [5], and presented in Table S1.2.

Table S1.2. The potential market size of liquid fuels from CO2 utilization

Product	Potential production of CO_2 utilization in 2030 (Mt/y)
Methanol	204[a]
Ethanol	163[b]
Olefin	7[c]
Gasoline	2154[d] (to Infinite)
Fischer-Tropsch fuel	163[e]
Bio-diesel	176[f]
Dimethyl ether	41[e]
Formic acid	10[g]

[a] Estimated in high scenario for methanol as a chemical feedstock and fuel, based on Ref [5]
[b] The annual growth of ethanol is assumed at 6%, and 85% of market share in 2030 [5,6]
[c] Estimated in high scenario for olefin (mainly ethylene and propylene), based on Ref [5]
[d] Estimated based on global oil demand (105.4 million barrel per day in 2030) [7]
[e] Estimated in high scenario based on Ref [7]
[f] Estimated from 115 Mt in 2018 with the growth of 3.6% per year [8]
[g] Taken from Ref [9]

S2. Process simulation and modeling

S2.1. Simulation of each technology

Based on the generated superstructure, summarized in Fig. S2.1, the unit technologies were firstly simulated using Aspen Plus software, subsequent full CO_2-to-fuel pathways. Here, each technology consists of various equipment for its operation purpose (e.g., reaction kinetic expressions, temperature, pressure, etc.) that was detailed described in Table S2.1.

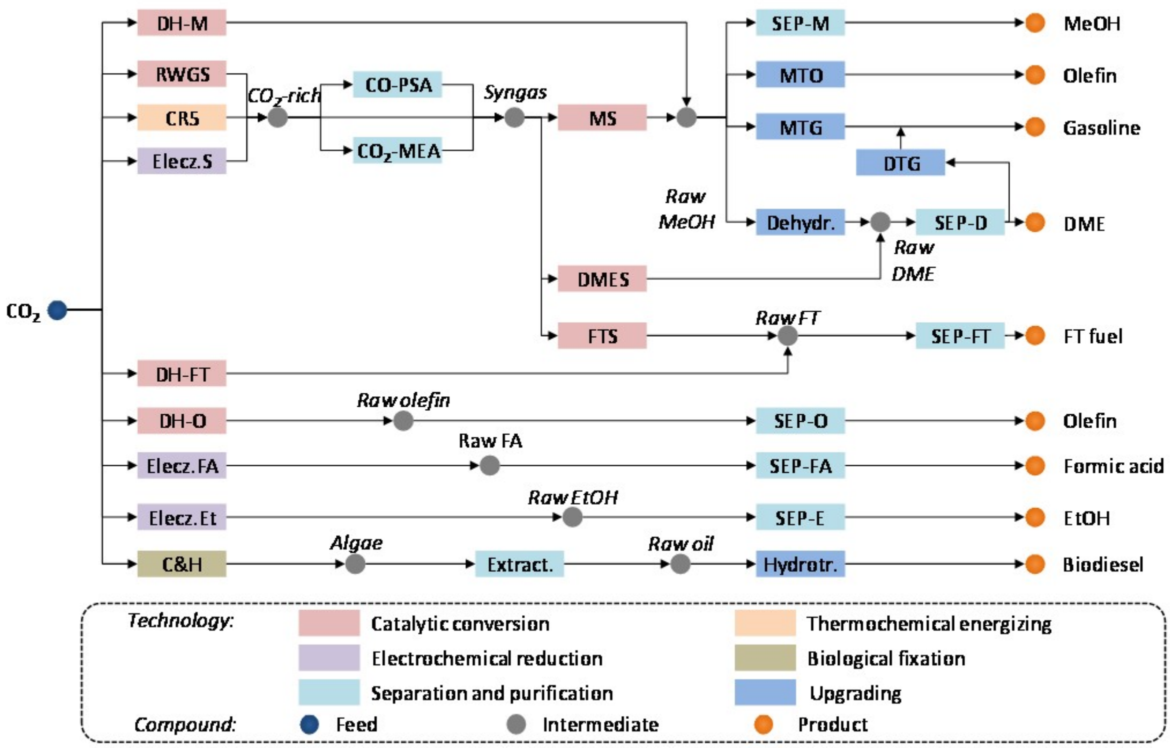
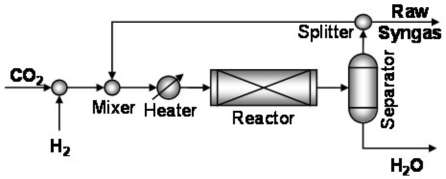
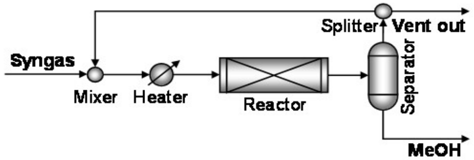
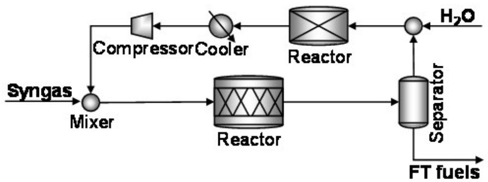
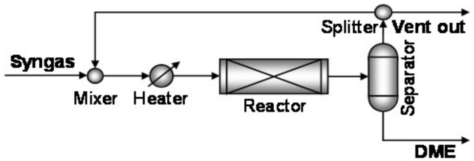
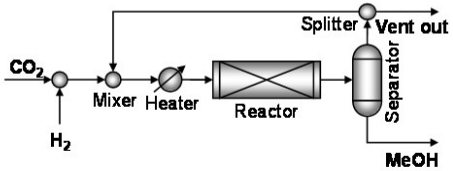
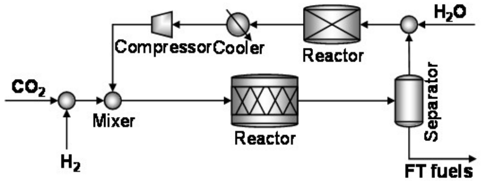
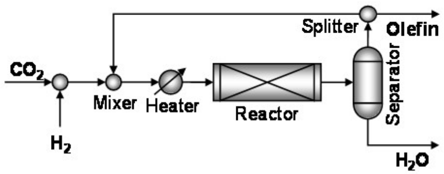
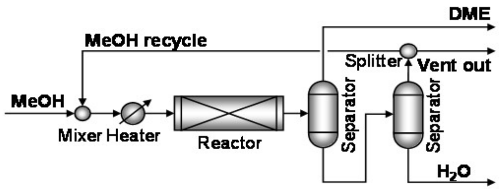
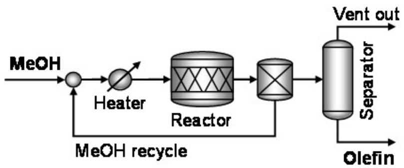
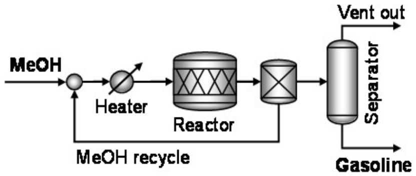
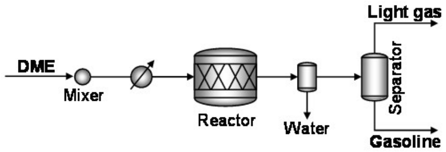
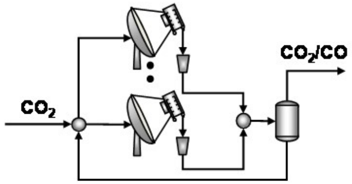
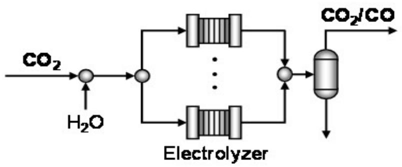
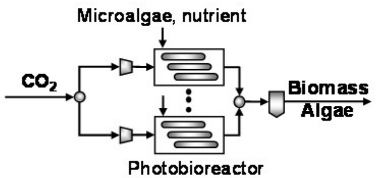


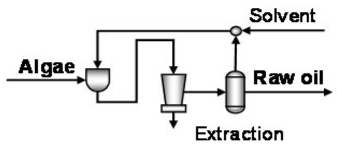
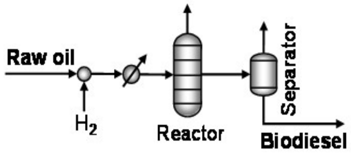
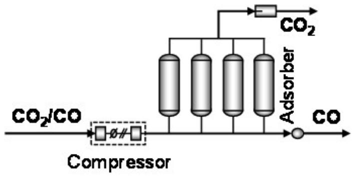
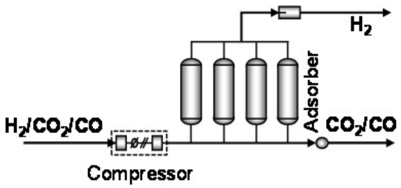
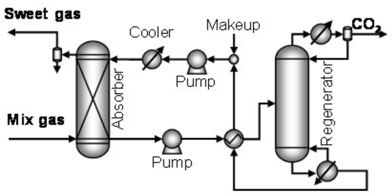
Fig. S2.1. The CCU4E superstructure. Abbreviation: RWGS: Reverse water-gas shift, DH-M: Direct hydrogenation to methanol, DH-FT: Direct hydrogenation to Fischer-Tropsch, DH-O: Direct hydrogenation to olefin, CR5: Counter-Rotating-Ring/Receiver/Reactor/Recuperator, Elecz.S: Electrochemical reduction to syngas, Elecz.FA: Electrochemical reduction to formic acid, Elecz.EtOH: Electrochemical reduction to ethanol, MS: Methanol synthesis, FTS: Fischer-Tropsch synthesis, DMES: Dimethyl ether synthesis, C&H: cultivation and harvesting, Extract.: Oil extraction, Hydrotr.: Hydrotreating, Dehydro.: Dehydration, MTO: methanol-to-olefin, MTG: Methanol-to-gasoline, DTG: dimethyl ether-to-gasoline, CO-PSA: CO Pressure Swing Adsorption, CO_2-MEA: CO_2 Absorption by monoethanolamine, SEP-M, SEP-D, SEP-FT, SEP-O, SEP FA, SEP-E: Separation and purification for methanol, dimethyl ether, FT fuel, olefin, formic acid, ethanol.

Table S2.1. Unit process specification and parameters for simulation

Process	Simplified PFD	Operating conditions		
		T (°C)	P (bar)	Description
Reverse water gas shift (RWGS)		400-1,200	1-20	$r_1 = \frac{k_2 P_{CO_2}(1 - P_{H_2O}P_{CO} / k_{e,2}P_{H_2}P_{CO_2})}{(1 + K_1 P_{H_2}^{0.5} + K_2 P_{H_2O} + K_3 P_{H_2O} / P_{H_2})}$ [10,11]
Methanol synthesis (MS)		150-300	50-75	$r_2 = \frac{k_2 P_{CO_2}(1 - P_{H_2O}P_{CO} / k_{e,2}P_{H_2}P_{CO_2})}{(1 + K_1 P_{H_2}^{0.5} + K_2 P_{H_2O} + K_3 P_{H_2O} / P_{H_2})}$, $r_3 = \frac{k_1 P_{CO_2}P_{H_2}(1 - P_{H_2O}P_{MeOH} / k_{e,1}P_{H_2}^3 P_{CO_2})}{(1 + K_1 P_{H_2}^{0.5} + K_2 P_{H_2O} + K_3 P_{H_2O} / P_{H_2})^3}$ [10]
Fischer-Tropsch synthesis (FTS)		200-250	25-60	$r_1 = \frac{a e^{-b/RT} K_7^{0.5} P_{H_2}^{d}}{(1 + K_7^{0.5}(2 + 1/K_4) P_{H_2}^{0.5} + \frac{K_7^{0.5}}{K_3 P_4 P_{H_2}^{-0.5}} + \frac{K_7^{0.5} P_{H_2O}}{K_2 K_3 K_4 P_{H_2}^{1.5}})}$ [12]
Dimethyl ether synthesis (DMES)		200-400	20-60	$r_1 = \frac{k_1 f_{CO} f_{H_2}^2 \left[1 - f_{MeOH} / (K_1 f_{CO} f_{H_2}^2)\right]}{(1 + K_{CO} f_{CO} + K_{CO_2} f_{CO_2} + K_{H_2} f_{H_2})^3}$, $r_2 = \frac{k_2 f_{CO_2} f_{H_2}^3 \left[1 - f_{MeOH} f_{H_2O} / (K_2 f_{CO_2} f_{H_2}^3)\right]}{(1 + K_{CO} f_{CO} + K_{CO_2} f_{CO_2} + K_{H_2} f_{H_2})^4}$ $r_3 = \frac{k_3 f_{H_2O} \left[1 - f_{CO_2} f_{H_2} / (K_3 f_{CO} f_{H_2O})\right]}{1 + K_{CO} f_{CO} + K_{CO_2} f_{CO_2} + \sqrt{K_{H_2} f_{H_2}}}$, $r_4 = \frac{k_4 f_{MeOH} \left[1 - f_{DME} f_{H_2O} / (K_4 f_{MeOH}^2)\right]}{\left(1 + \sqrt{K_{MeOH} f_{MeOH}}\right)^2}$, [13,14]

<table>
<tr><td>Direct CO_2 hydrogenation to methanol (DH-M)</td><td>
</td><td>250-350</td><td>35-55</td><td>$$r_1 = k_1\left(K_{CO} f_{CO} f_{H_2}^{1.5} - \frac{K_{CO}}{K_A} f_{CH_3OH} f_{H_2}^{-0.5}\right) / ABS$$, [15]
$$r_2 = k_2\left(K_{CO_2} f_{CO_2} f_{H_2} - \frac{K_{CO_2}}{K_B} f_{H_2O} f_{CO}\right) / ABS$$,
$$r_3 = k_3\left(K_{CO_2} f_{CO_2} f_{H_2}^{1.5} - \frac{K_{CO_2}}{K_C} f_{H_2O} f_{CH_3OH} f_{H_2}^{-1.5}\right) / ABS,$$
$$ABS = f_{H_2}^{0.5} + \frac{K_{H_2O}}{K_H^{0.5}} f_{H_2O} + K_{CO} f_{CO} f_{H_2}^{0.5} + \frac{K_{CO} K_{H_2O}}{K_H^{0.5}} f_{CO} f_{H_2O} + K_{CO_2} f_{CO_2} f_{H_2}^{0.5} + \frac{K_{CO_2} K_{H_2O}}{K_H^{0.5}} f_{CO_2} f_{H_2O}$$</td></tr>
<tr><td>Direct CO_2 hydrogenation to FT fuel (DH-FT)</td><td>
</td><td>300</td><td>25</td><td>The FT synthesis considered hydrogenation of both CO_2 and CO, followed by reference [16]:
$$n\mathrm{CO_2} + 3n\mathrm{H_2} \rightarrow -(\mathrm{CH_2})n- + 2n\mathrm{H_2O},$$
$$n\mathrm{CO} + 2n\mathrm{H_2} \rightarrow -(\mathrm{CH_2})n- + n\mathrm{H_2O}$$</td></tr>
<tr><td>Direct CO_2 hydrogenation to olefin (DH-O)</td><td>
</td><td>290-360</td><td>10</td><td>$$r_1 = k_1 \frac{P_{CO_2} P_{H_2} - P_{CO} P_{H_2O} / K_{eq}}{P_{CO} + a_1 P_{H_2O} + b_1 P_{CO_2}}, \quad r_i = k_i \frac{P_{CO} P_{H_2}}{P_{CO} + a_i P_{H_2O} + b_i P_{CO_2}}$$, [17,18]</td></tr>
<tr><td>Dehydration of methanol to DME (Dehydr)</td><td>
</td><td>250-400</td><td>2-20</td><td>$$r = \frac{k_s K_{MeOH}^2 (C_{MeOH}^2 + C_{water} C_{DME} / K_{eq})}{(1 + 2\sqrt{K_{MeOH} C_{MeOH}} + K_{water} C_{water})^4}$$, [13]</td></tr>
<tr><td>`Methanol-to-olefin (MTO)</td><td>
</td><td>490</td><td>2.2</td><td>The black box model was adopted for the reactor.
Mass balance and energy balance was followed by reference [19].
$n\mathrm{CH_3OH} \rightarrow \mathrm{C_nH_{2n}} + n\mathrm{H_2O}$, n = 2, 3, 4</td></tr>
</table>

Methanol-to-gasoline (MTG)		300-400	10-20	The black box model was adopted for the reactor. Mass balance and energy balance was followed by reference [20,21] $\frac{n}{2}\left[2CH_3OH \Leftrightarrow CH_3OCH_3 + H_2O\right] \rightarrow C_nH_{2n} + nH_2O \rightarrow n\left[C_nH_{2n}\right] + nH_2O$
Dimethyl ether-to gasoline (DTG)		200-400	20-60	$r_1 = \frac{k_1 f_{CO} f_{H_2}^2 \left[1 - f_{MeOH} / (K_1 f_{CO} f_{H_2}^2)\right]}{(1 + K_{CO} f_{CO} + K_{CO_2} f_{CO_2} + K_{H_2} f_{H_2})^3}$, $r_2 = \frac{k_2 f_{CO_2} f_{H_2}^3 \left[1 - f_{MeOH} f_{H_2O} / (K_2 f_{CO_2} f_{H_2}^3)\right]}{(1 + K_{CO} f_{CO} + K_{CO_2} f_{CO_2} + K_{H_2} f_{H_2})^4}$, $r_3 = \frac{k_3 f_{H_2O} \left[1 - f_{CO_2} f_{H_2} / (K_3 f_{CO} f_{H_2O})\right]}{1 + K_{CO} f_{CO} + K_{CO_2} f_{CO_2} + \sqrt{K_{H_2} f_{H_2}}}$, $r_4 = \frac{k_4 f_{MeOH} \left[1 - f_{DME} f_{H_2O} / (K_4 f_{MeOH}^2)\right]}{\left(1 + \sqrt{K_{MeOH} f_{MeOH}}\right)^2}$, [22–24]
Counter-Rotating-Ring Receiver/Reactor/ Recuperator (CR5)		~1500	-	Collecting solar energy and converting CO_2 into CO. [25,26] Containing reactive materials such as YSZ-supported iron oxide or ceria Energy transfer efficiency from solar to chemical (stored in CO): 20% Efficiency of CO_2 to CO: 25%
Electrolyzer for CO_2 reduction (Elecz.)		-	1-30	Requiring significant energy input. Containing heterogeneous electrocatalysts for specific products (i.e., Ag for CO, Cu or Ag for ethanol, Sn for formic acid. [27–29]
Cultivation and Harvesting of Microalgae (C&H)		Ambient	Ambient	Algae growth in open pond system or closed photobioreactor (PBR) [30,31]. $[a]CO_2 + [b]\text{nutrients} + \text{sunlight} \rightarrow [c]O_2 + \text{biomass}$

Lipid extraction (Extract.)		-	-	Lipid extraction was assumed at 90% efficiency [30]. Oil/solvent phase was separated from water and biomass. Then, solvent was separated in stripper and recycled. The lipid was at 99.5% purity.
Hydrotreating for oil upgrading (Hydrotr.)		350	35	Hydrogen consumption 1.5%wt of feed [30]
CO Pressure Swing Adsorption (CO-PSA)		60	9	CO-PSA yield at 90%. Operating up to at 9 bar [32] Adsorbent: Cu-Cu^+/θ-Al_2O_3 Adsorbent rate: 16.4 ton/ton of feed. Adsorbent lifetime of 2 years.
H_2 Pressure Swing Adsorption (H_2-PSA)		30-35	15	H_2 PSA yield at 90%. Operating up to at 15 bar. [17,33] Adsorbent: zeolite 5A. Adsorbent requirement: 0.01 kmol/kg of feed.
CO_2 Absorption by monoethanolamine (CO_2-MEA)		25-120	1-15	CO_2-MEA for 90% of CO_2 recovery [17,34,35] Monoethanolamine(MEA): 23%

Reverse water-gas shift (RWGS): converts CO_2 and H_2 into CO and H_2O, using Cu/ZnO/Al_2O_3 catalyst in this study [10,11]. CO_2 and H_2 were mixed, heated, and compressed before entering into plug flow reactor (RPlug model). Since RWGS is equilibrium reaction, mixture gas of three components CO, CO_2, and H_2 required further gas component separation (e.g., CO_2 absorption) or mixed with outsourcing H_2 for optimal stoichiometric number, $SN=(H_2+CO_2)/(CO_2+CO)$, for specific further synthesis (e.g., methanol synthesis, Fischer-Tropsch synthesis, or dimethyl ether synthesis). The simplified process flow diagram and kinetic expression are presented in Table S2.1 – S2.2.

Methanol synthesis: MeOH is produced from syngas (mixture of CO and H_2). In methanol synthesis unit, feed gas was first mixed with the recycle gas from downstream, before pressed up and heated to reaction condition. The RPlug model was used for plug flow reactor, that operated at 150 °C, 50 bar and filled by Cu/ZnO/Al_2O_3 catalyst [25,36]. In methanol synthesis unit, SN at 2 was preferred for optimal methanol yield. The kinetic expression and parameters are described in Table S2.1 – S2.2. Cooler and simple flash tank were operated right after reactor to separate liquid of methanol/water from unreacted gas that was further recycled back to reactor. The methanol/water liquid was brough into distillation column for purifying methanol from water.

Table S2.2. Kinetics and adsorption parameters for MS and RWGS reactions [10]

Parameters	Value
k_1	1.07 exp(36,696 kJkmol^{-1}/RT)
k_2	1.22 exp(-94,765 kJkmol^{-1}/RT)
$K_{e,1}$	10^(3,066/T -10.592)
$K_{e,2}$	10^(-2073/T +2.029)
	6.62·10^{-11} exp(124,119 kJkmol^{-1}/RT)
	3,453.38

Fischer-Tropsch synthesis (FTS): is the most common technology to produces liquid hydrocarbon (e.g., gasoline, diesel, and aviation fuels) from synthetic gas. Firstly, syngas was mixed with recycle stream (unreacted syngas), then pressed up and heated up to 38 bar and 210 °C before fed into reactor. The reaction mechanism was assumed by a series of reaction steps as shown in Eqs. (1) – (7) [12]. The kinetic expression and parameters are described in Table S2.1 and S2.3. The reactor outlet were brought to the separator unit, in which main hydrocarbon products (i.e., FT fuels) flow out from the bottom while the light hydrocarbon gas, and unreacted gases are merged with steam and reformed before recycle [12].

$$CO + H-\sigma \rightarrow H-\sigma-CO,\ CO + CH_3-\sigma \rightarrow CH_3-\sigma-CO,\ CO + C_nH_{2n+1}-\sigma \rightarrow CnH_{2n+1}-\sigma-CO \quad (1)$$

$$H-\sigma-CO + H_2 \leftrightarrow H-\sigma-C + H_2O,\ CH_3-\sigma-CO + H_2 \leftrightarrow CH_3-\sigma-C + H_2O,$$

$$C_nH_{2n+1}-\sigma-CO + H_2 \leftrightarrow C_nH_{2n+1}-\sigma-C + H_2O \quad (2)$$

$$H-\sigma-CO + H_2 \leftrightarrow H-\sigma-C + H_2O,\ CH_3-\sigma-C + H_2 \leftrightarrow CH_3-\sigma-CH_2,$$

$$C_nH_{2n+1}-\sigma-C + H_2 \leftrightarrow C_nH_{2n+1}-\sigma-CH_2 \quad (3)$$

$$C_nH_{2n+1}-\sigma-CH_2 \leftrightarrow C_nH_{2n+1}CH_2-\sigma \quad (4)$$

$$CH_3-\sigma-H_2 \rightarrow CH_4 + H-\sigma,\ C_nH_{2n+1}-\sigma + H_2 \rightarrow C_nH_{2n} + H-\sigma \quad (5)$$

$$C_2H_5-\sigma \rightarrow C_2H_4 + H-\sigma,\ C_nH_{2n+1}-\sigma \rightarrow C_nH_{2n} + H-\sigma \quad (6)$$

$$H_2 + 2\sigma \leftrightarrow 2H-\sigma \quad (7)$$

Table S2.3. Kinetics and adsorption parameters for FT reactions [12]

Parameters	Value	Unit	Parameters	Value	Unit
A_1	1.83 x 10^9	kmol/kg_{cat}·h·bar	E_1	1.00 x 10^5	kJ/kmol
A_2	5.08	-	ΔH_2	8.68 x 10^3	kJ/kmol
A_3	2.44	1/bar	ΔH_3	9.44 x 10^3	kJ/kmol
A_4	2.90	-	ΔH_4	7.90 x 10^3	kJ/kmol
A_5	4.49 x 10^4	kmol/kg_{cat}·h·bar	E_5	7.24 x 10^4	kJ/kmol
A_{5M}	8.43 x 10^4	kmol/kg_{cat}·h·bar	E_{5M}	6.30 x 10^4	kJ/kmol
A_6	7.47 x 10^8	kmol/kg_{cat}·h·bar		9.72 x 10^4	kJ/kmol
A_{6E}	7.03 x 10^8	kmol/kg_{cat}·h		1.09 x 10^5	kJ/kmol
A_7	1.00 x 10^{-4}	1/bar	ΔH_7	-2.50 x 10^5	kJ/kmol
			ΔE	1.12 x 10^3	kJ/kmol(CH_2)

Dimethyl ether synthesis (DMES): produces DME from syngas which is preferred CO/H_2 ratio at 1. Mixture feed gas was pressed up, and heated to 260 °C, 50 bar before fed in reactor filled catalyst of $Cu/ZnO/Al_2O_3$ and γ-Al_2O_3 [13]. The outlet stream was brought into separation unit to separate DME from others (e.g., CO_2, MeOH), and recycle unreacted H_2/CO. In separation, chemical absorption using methanol for CO_2 absorption that results in liquid of DME/MeOH/CO_2-rich solvent, and mixture of H_2, CO (for recycling). The liquid stream then entered to two distillation columns for separating DME from CO_2, and MeOH solvent, respectively. The simplified process flow diagram, kinetic expressions, and parameters for DMES are described in Table S2.1 and S2.4. Here, Rplug model was used for DMES reactor.

Table S2.4. Kinetics and parameters for dimethyl ether synthesis (DMES) [13]

Parameters	Value
k_1	7,380 exp(-54,307/RT)
k_2	5,059 exp(-67,515/RT)
k_3	1,062 exp(-43,473/RT)
k_4	7.3976 exp(-20,436/RT)
K_{CO}	3.934 x10^{-6} exp(37,373/RT)
K_{CO2}	1.585 x 10^{-6} exp(53,795/RT)
K_{H2}	0.6716 exp(-6,476/RT)
K_{MeOH}	3.480 x 10^{-6} exp(54,689/RT)

Direct CO_2 hydrogenation to MeOH (DH-M): directly synthesizes MeOH from CO_2 and H_2 in a single conversion pot, in which the two-step process of RWGS to CO and subsequent CO hydrogenation is proceeded. Firstly, CO_2 and H_2 was mixed with recycling, then pressed up and heated to 50 bar and 250 °C. Plug flow reactor was modeled using RPlug, in which kinetic expression for the catalyst of fibrous Cu/Zn/Al/Zr was embed as followed Table S2.1 and S2.5. [15,37]. Then, flash tank was operated for separating MeOH/water liquid, leaving gas of CO_2, CO, H_2 for recycling. Finally, MeOH was separated and purified in distillation column.

Table S2.5. Kinetics and adsorption parameters for direct CO_2 hydrogenation to MeOH [15,37]

Parameters	Value	
k_1	4.0638 x 10^{-6} exp(-11,695/RT)	kmol/kg.s.Pa
k_2	2.3714 x 10^{-23} exp(-112,860/RT)	kmol/kg.s.Pa
K_B	281.1780 x exp(-43,939/RT)	-
K_C	6.6687 x 10^{-21} exp(54,499/RT)	Pa^{-2}
K_{CO}	8.3965 x 10^{-11} exp(118,270/RT)	Pa^{-1}
K_{CO2}	1.7214 x 10^{-10} exp(81,287/RT)	Pa^{-1}
$K_{H2O}/K_H^{0.5}$	4.3676 x 10^{-12} exp(956,775/RT)	-

Direct CO_2 hydrogenation to FT fuel (DH-FT): Similarly to DH-M, the two-step process of RWGS to CO and subsequent CO hydrogenation is proceeded in one reactor. CO_2 and H_2 was first mixed with recycling, then pressed up and heated to 25 bar and 300 °C. DH-FT reactor contains Fe-based catalyst (here, Rstoic reactor model was used) that promotes reactions as shown in Eqs. (8) – (16) [16]. The following separation stage is similar to that of FTS. The main product of FT fuels was separated and purified from water, light gas and unreacted gas. The gas from the top of column was further treated in reforming unit that convert by-product C_1-C_4 into syngas for recycling.

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \tag{8}$$

$$3CO_2 + 9H_2 \rightarrow C_3H_6 + 6H_2O \tag{9}$$

$$3CO_2 + 10H_2 \rightarrow C_3H_8 + 6H_2O \quad (10)$$

$$12CO_2 + 37H_2 \rightarrow C_{12}H_{26} + 24H_2O \quad (11)$$

$$CO + 3H_2 \rightarrow CH_4 + H_2O \quad (12)$$

$$3CO + 6H_2 \rightarrow C_3H_6 + 3H_2O \quad (13)$$

$$3CO + 7H_2 \rightarrow C_3H_8 + 3H_2O \quad (14)$$

$$12CO + 25H_2 \rightarrow C_{12}H_{26} + 12H_2O \quad (15)$$

$$CO_2 + H_2 \rightarrow CO + H_2O \quad (16)$$

Direct CO_2 hydrogenation to olefin (DH-O): produces olefin (C_2-C_4 hydrocarbon) from CO_2 and H_2 in one reactor filled by catalyst of Fe-K/γ-Al_2O_3 and operated at 300 °C, 10 bar. RPlug reactor model was used, which embed kinetic metrics as shown in Table S2.6. Following separation target to separated olefin from liquid hydrocarbon (naphtha) as by-product, unreacted gas (CO_2, H_2) for recycling, and undesired gas (CO, CH_4) for onsite heat and electricity generation. More description on DH-O can be found in Reference [17].

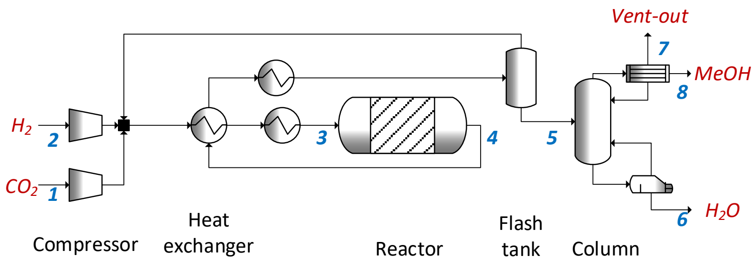
Table S2.6. Kinetics and parameters for direct CO_2 hydrogenation to olefin [17,18]

No	Reaction	a_i	b_i	K_{0i} (mol/(s.g.MPa))	E_i (kJ/mol)
1	$CO_2 + H_2 \leftrightarrow CO + H_2O$	53.4768	4.5679	0.619e8	136
2	$CO + 3H_2 \rightarrow CH_4 + H_2O$	43.048	3.4174	0.3817e8	135
3	$2CO + 4H_2 \rightarrow C_2H_4 + 2H_2O$	41.1777	3.1104	4.0918e8	146
4	$2CO + 5H_2 \rightarrow C_2H_6 + 2H_2O$	85.9319	2.3182	0.4931e8	141
5	$3CO + 6H_2 \rightarrow C_3H_6 + 3H_2O$	15.9468	4.0486	2.5451e8	147.1
6	$3CO + 7H_2 \rightarrow C_3H_8 + 3H_2O$	55.5611	3.1525	0.0142e8	127
7	$4CO + 8H_2 \rightarrow C_4H_8 + 4H_2O$	30.9118	4.9477	0.0014e8	111
8	$4CO + 9H_2 \rightarrow C_4H_{10} + 4H_2O$	87.9118	3.7471	84.4447	87
9	$nCO_2 + 3nH_2 \rightarrow (CH_2)_n + 2nH_2O$	74.347	62.0165	36.5745	150

S2.2. Simulation of CO_2-to-fuel pathway

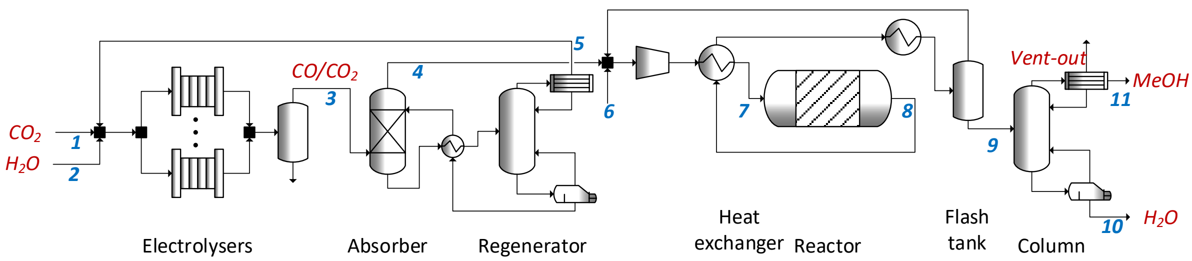
As proposed in CCU4E superstructure, there are 72 pathways for various fuel product from CO_2. The process simulation of each pathway was performed in Aspen Plus software. In this part, we would present the simplified process flow diagram with stream information of some CO_2-to-fuel pathways. Noted that the pathway number and integrated technologies for each was already presented in Table 1 in manuscript.

S2.2.1. CO_2-to-MeOH



Steam No.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Temperature (°C)	30	30	250	250	30	107	35	35
Pressure (bar)	1.0	1.0	50.0	50.0	45.0	1.2	1.1	1.1
Mass Flows (kg/h)	388,254	51,861	7,460,394	7,460,394	433,088	152,099	10,591	270,399
Mole Flows (kmol/h)	8,822	25,726	595,373	578,507	17,121	8,430	261	8,430
H_2	0	25,726	443,742	418,438	4	0	4	0
CO	0	0	4,860	4,865	0	0	0	0
CO_2	8,822	0	144,677	136,239	248	0	196	52
H_2O	0	0	326	8,764	8,438	8,414	0	24
MeOH	0	0	1,768	10,201	8,431	16	60	8,354

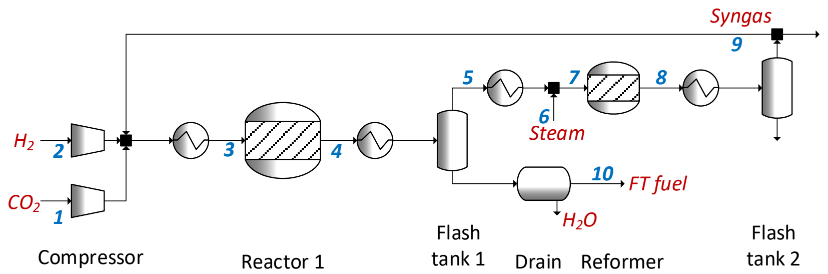
Fig. S2.2. Pathway #10 for methanol: Catalytic direct CO_2 hydrogenation to methanol



Steam No.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Temperature (°C)	35	35	40	40	40	30	250	250	40	83	30
Pressure (bar)	1.0	1.0	2.9	2.9	2.9	1.0	50.0	50.0	50.0	1.0	1.0
Mass Flows (kg/h)	388,254	3,153	575,601	259,233	316,369	31,151	794,774	794,774	290,934	7,537	263,906
Mole Flows (kmol/h)	8,997	175	16,150	8,961	7,189	15,453	69,190	52,583	9,106	364	8,245
H_2	0	0	175	175	0	15,453	48,096	31,132	24	0	0
CO	0	0	7,987	7,987	0	0	14,140	6,192	10	0	0
CO_2	8,822	0	7,987	799	7,189	0	6,605	6,249	413	0	48
H_2O	0	175	0	0	0	0	10	366	356	295	61
MeOH	0	0	0	0	0	0	339	8,643	8,302	69	8,136

Fig. S2.3. Pathway #9 for methanol: Electrochemical CO_2 reduction to CO → CO_2MEA → MeOH synthesis

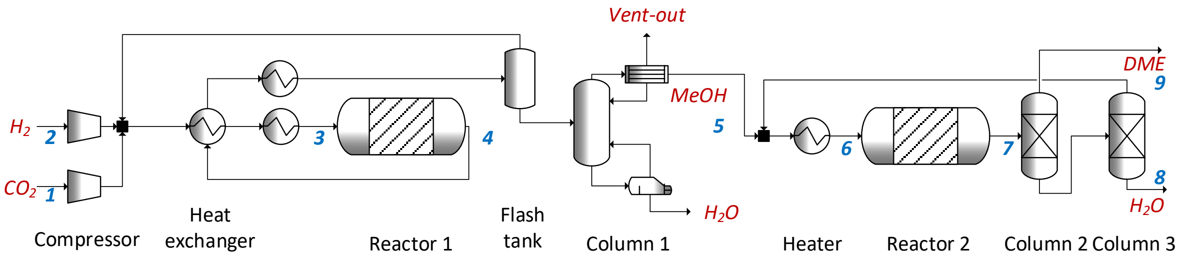
S2.2.2. CO_2-to-FT fuels



Steam No.	1	2	3	4	5	6	7	8	9	10
Temperature (°C)	30	30	483	500	303	947	624	1,123	589	303
Pressure (bar)	1	1	38	36	36	36	36	35	38	36
Mass Flows (kg/h)	388,254	54,565	3,786,517	3,786,517	3,290,039	207,053	3,497,092	3,497,092	2,136,064	119,212
Mole Flows (kmol/h)	8,822	27,283	520,410	496,113	474,340	11,503	485,843	512,872	507,153	814
H_2	0	27,283	436,518	401,624	401,610	0	401,610	422,862	422,862	15
CO	0	0	48,595	45,268	45,250	0	45,250	49,070	48,595	18
CO_2	8,822	0	35,288	26,466	26,453	0	26,453	26,468	26,466	13
H_2O	0	0	0	20,971	0	11,503	11,503	5,242	0	11
CH4	0	0	10	10	10	0	10		0	0
LIGHT GAS	0	0	0	838	821	0	821		0	17
GASOLINE	0	0	0	571	196	0	196		0	375
DIESEL	0	0	0	316	0	0	0		0	316
WAX	0	0	0	49	0	0	0		0	49

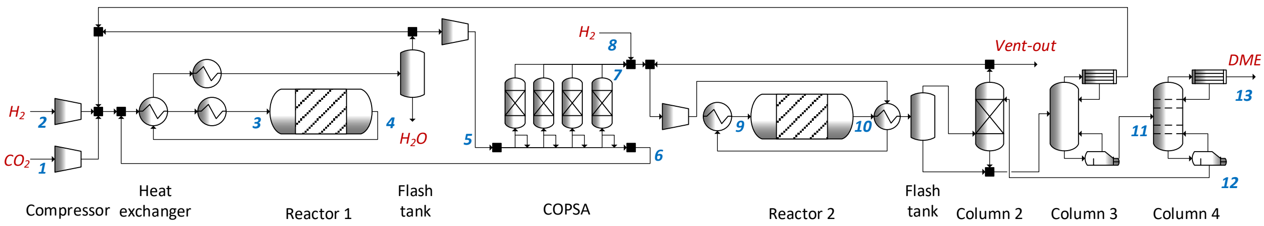
Fig. S2.4. Pathway #17 for FT fuels: Catalytic direct CO_2 hydrogenation to FT fuel

S2.2.3. CO_2-to-DME



Steam No.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Temperature (°C)	30	30	250	250	35	270	391	164	49
Pressure (bar)	1.0	1.0	50.0	50.0	1.1	12.0	12.0	12.0	12.0
Mass Flows (kg/h)	388,254	51,861	7,460,394	7,460,394	270,399	317,498	317,498	123,237	194,261
Mole Flows (kmol/h)	8,822	25,726	595,373	578,507	8,430	9,918	9,918	5,696	4,222
H_2	0	25,726	443,742	418,438	0	0	0	0	0
CO	0	0	4,860	4,865	0	0	0	0	0
CO_2	8,822	0	144,677	136,239	52	49	49	0	49
H_2O	0	0	326	8,764	24	63	4,230	4,226	4
MeOH	0	0	1,768	10,201	8,354	9,805	1,471	1,469	1
DME	0	0	0	0	0	0	4,168	0	4,167

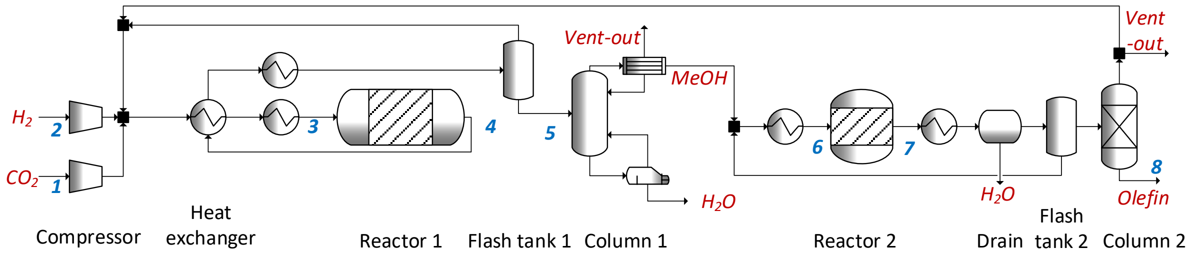
Fig. S2.5. Pathway #27 for dimethyl ether: Catalytic direct CO_2 hydrogenation to MeOH → Dehydration of MeOH to DME



Steam No.	1	2	3	4	5	6	7	8	9	10	11	12	13
Temperature (°C)	30	30	650	511	60	60	60	35	260	260	109	154	61
Pressure (bar)	1.0	1.0	5.0	5.0	9.0	9.0	9.0	1.0	50.0	50.0	21.0	15.0	15.0
Mass Flows (kg/h)	388,254	406,039	1,077,273	1,077,273	948,267	674,607	273,659	10,559	344,219	344,219	266,005	163,699	102,306
Mole Flows (kmol/h)	8,822	17,644	46,698	46,698	39,538	29,200	10,338	5,238	19,738	10,727	7,364	5,143	2,221
H_2	0	8,822	22,837	15,650	15,650	14,085	1,565	5,238	9,056	2,264	0	0	0
CO	0	0	794	7,981	7,981	798	7,183	0	8,966	2,242	0	0	0
CO_2	8,822	8,822	22,829	15,642	15,642	14,077	1,564	0	1,687	3,906	4	0	4
H_2O	0	0	238	7,425	266	240	27	0	27	27	77	77	0
MeOH	0	0	0	0	0	0	0	0	4	71	5,066	5,065	1
DME	0	0	0	0	0	0	0	0	0	2,219	2,217	0	2,217

Fig. S2.6. Pathway #28 for dimethyl ether: Catalytic RWGS → COPSA → DME synthesis → Separation

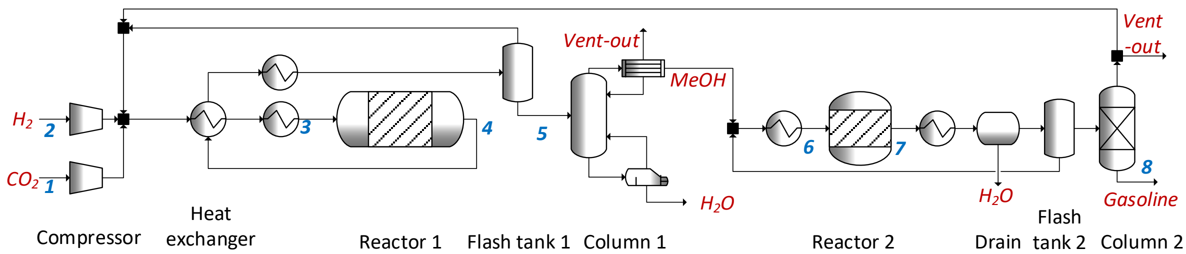
S2.2.4. CO_2-to-olefin



Steam No.	1	2	3	4	5	6	7	8
Temperature (°C)	30	30	250	250	35	490	490	60
Pressure (bar)	1.0	1.0	50.0	50.0	1.1	2.2	2.2	1.0
Mass Flows (kg/h)	388,254	51,861	7,460,394	7,460,394	433,088	433,088	433,088	164,367
Mole Flows (kmol/h)	8,822	25,726	595,373	578,507	17,121	17,121	20,864	5,935
H_2	0	25,726	443,742	418,438	248	248	248	248
CO	0	0	4,860	4,865	0	0	0	0
CO_2	8,822	0	144,677	136,239	4	4	4	4
H_2O	0	0	326	8,764	8,438	8,438	17,466	2,537
MeOH	0	0	1,768	10,201	8,431	8,431	0	0
C_2H_4	0	0	0	0	0	0	1,939	1,771
C_3H_6	0	0	0	0	0	0	1,124	1,124
C_4H_8	0	0	0	0	0	0	295	295

Fig. S2.7. Pathway #43 for olefin: Catalytic direct CO_2 hydrogenation to MeOH → Methanol-to-olefin

S2.2.4. CO_2-to-gasoline



Steam No.	1	2	3	4	5	6	7	8
Temperature (°C)	30	30	250	250	35	350	350	120
Pressure (bar)	1.0	1.0	50.0	50.0	50.0	20.0	20.0	2.0
Mass Flows (kg/h)	388,254	51,861	7,460,394	7,460,394	433,088	433,088	433,088	139,888
Mole Flows (kmol/h)	8,822	25,726	595,373	578,507	17,121	17,121	18,740	2,267
H_2	0	25,726	443,742	418,438	248	248	248	
CO	0	0	4,860	4,865	0	0	0	
CO_2	8,822	0	144,677	136,239	4	4	4	2
H_2O	0	0	326	8,764	8,438	8,438	17,345	1,147
MeOH	0	0	1,768	10,201	8,431	8,431	0	
LIGHT GAS	0	0	0	0	0	0	35	10
LIGHT GASOLINE	0	0	0	0	0	0	919	919
HEAVY GASOLINE	0	0	0	0	0	0	189	189

Fig. S2.8. Pathway #54 for gasoline: Catalytic direct CO_2 hydrogenation to MeOH → Methanol-to-gasoline

S3. Economic, unit cost and CO_{2eq} inventory assumptions

The economic parameters and cost of materials and utilities used in this study are presented in Table S3.1. Otherwise, The $CO_{2\text{-}eq}$ inventory of raw material, conventional utility, and conventional fuels are presented in Table S3.2. Noted that using different raw material and utility sources (e.g., conventional or renewable based utility and H_2 feedstock) results in different Operating Cost (TOC) and indirect CO_2 emission (ICE).

Table S3.1. Economic assumptions and parameters

	Value	Unit	Ref.
General parameters:			
Reference year	2018		
Economic plant life	20	years	
Interest rate	8	%	
Operability	8000	h/y	
Scaling exponent	0.67	-	
Capacity Charge Factor (CCF)	0.1019	-	
Total capital investment cost (TCI)	**373**	**% of PE**	38
Direct plan cost (DC)	247	% of PE	
Purchased equipment (PE)	100	% of PE	
Equipment setting	39	% of PE	
Instrumentation and control	26	% of PE	
Piping	31	% of PE	
Electrical installation	10	% of PE	
Land	12	% of PE	
Building and building services	29	% of PE	
Indirect plant cost (IDC)	126	% of PE	
Engineering	32	% of PE	
Construction expenses	34	% of PE	
Contractor's fee	23	% of PE	
Contingency	37	% of PE	
Fixed operating cost (FOC)	5.1	% of TCI	20
Materials and utilities:			
Raw material			
Captured CO_2	0.035	$/kg	26
Renewable/green H_2	4.415	$/kg	39
Conventional/black H_2	2.700	$/kg	40
Process water	0.001	$/kg	26
Solvent, other materials input			
Adsorbent for CO	50	$/kg	32
Adsorbent for H_2	6.11	$/kg	17
Conventional based utility			
Electricity	0.060	$/kWh	26
Low-pressure steam	0.014	$/kWh	26
High-pressure steam	0.019	$/kWh	26
Fired heat	0.029	$/kWh	16
Cooling water	0.030	$/ton	26
Refrigeration	0.063	$/kWh	41
Renewable based utility			
RES-Electricity	0.073	$/kWh	26
RES-Heat	0.050	$/kWh	26
RES-Refrigeration	0.066	$/kWh	41
Market prices:			
Fuel products			
Methanol	0.400	$/kg	5

Ethanol	1.003	\$/kg	42
Olefin	0.673	\$/kg	43
Gasoline	0.847[a]	\$/kg	44
Fischer-Tropsch fuel	1.173	\$/kg	5
Bio-diesel	1.000	\$/kg	45
Dimethyl ether	0.66	\$/kg	5
Formic acid	0.74	\$/kg	42
By-products			
Syngas (CO/H_2)	0.550 [b]	\$/kg	
Naphtha	0.250	\$/kg	46
Electricity	0.073 [c]	\$/kg	

[a] Assumed at 2.5 \$/gal of gasoline
[b] Estimated based on CO and H_2 price
[c] Assumed at the same price of renewable electricity

Table S3.2. The $CO_{2\text{-eq}}$ inventory of raw material, conventional utility, and conventional fuels

	Value	Unit	Ref
Maw material			
Captured CO_2	-1.00	kg/kg	
H_2[a]	3.5	kg/kg	40
Conventional utility			
Electricity	0.6235	kg/kg	47
Low-pressure steam	0.1875	kg/kg	48
High-pressure steam	0.1875	kg/kg	48
Fuel gas	0.3406	kg/kg	48
Refrigeration	1.4746	kg/kg	48
Fuel products			
Methanol	0.300	kg/kg	49
Ethanol	1.923	kg/kg	50
Olefin	2.797	kg/kg	48
Gasoline	3.102	kg/kg	50
Fischer-Tropsch fuel	3.137	kg/kg	50
Biodiesel	0.039	kg/kg	48
Dimethyl ether	1.000	kg/kg	48
Formic acid	2.510	kg/kg	49

[a] Assumed produced via steam methane reforming with carbon capture and storage facility (SMRwCCS).

S4. Techno-economic and environmental performance results (green H_2)

S.4.1. Mass, energy, and economic data of each technology

Based on process simulation, the mass balance, energy balance, and economic data was obtained for each technology as shown in Table S4.1 – S4.2. Then, the metrics for full CO_2-to-fuel pathways, which is integration of technologies, were also estimated and obtained (shown in Table 1 of manuscript)

Table S4.1. Technical, economic and environment data of each technology obtained from simulation

Tech.	Group	Technology	Input	Output	Yield	CAP (kg/h)	TCI (M$)	ER (kWh)	DCE (kg/h)
1	Catalytic conversion	RWGS_1	CO2, H2	CO2-rich_1	0.887	360,159	157.65	115,922	9
2		RWGS_2	CO2, H2	CO2-rich_4	0.682	277,032	257.76	298,149	39
3		RWGS_3	CO2, H2	CO2-rich_7	0.769	312,275	164.01	335,541	33
4		MS_1	CO2-rich_1	Raw MeOH_1	0.948	371,459	478.92	411,221	11,357
5		MS_2	CO2-rich_2	Raw MeOH_2	0.979	389,584	545.62	408,428	6,359
6		MS_3	CO2-rich_3	Raw MeOH_3	0.982	352,009	457.31	334,527	4,692
7		MS_4	Syngas_4	Raw MeOH_4	0.987	301,726	362.69	220,013	2,293
8		MS_5	Syngas_5	Raw MeOH_5	0.987	308,531	364.81	238,724	2,731
9		MS_6	Syngas_6	Raw MeOH_6	0.991	290,793	347.96	187,319	1,284
10		MS_7	Syngas_7	Raw MeOH_7	0.985	324,201	449.88	287,269	3,617
11		MS_8	Syngas_8	Raw MeOH_8	0.987	308,648	412.82	250,647	2,732
12		MS_9	Syngas_9	Raw MeOH_9	0.991	290,934	390.84	250,647	1,284
13		DHCO2-MeOH_1	CO2, H2	Raw MeOH_10	0.984	433,088	721.69	175,478	5,985
14		DMES_1	Syngas_4	Raw DME_11	0.999	283,924	293.09	75,996	27
15		DMES_2	Syngas_5	Raw DME_12	0.999	289,229	292.70	77,471	26
16		DMES_3	Syngas_6	Raw DME_13	1.00	273,684	298.83	83,888	30
17		DMES_4	Syngas_7	Raw DME_14	1.00	302,288	208.71	79,921	21
18		DMES_5	Syngas_8	Raw DME_15	1.00	289,342	292.75	77,515	26
19		DMES_6	Syngas_9	Raw DME_16	1.00	273,786	298.86	83,911	31
20		FTS_1	Syngas_4	FT fuel_1	0.27	82,312	798.27	900,087	3,211
21		FTS_2	Syngas_5	FT fuel_2	0.26	81,670	795.61	907,666	3,485
22		FTS_3	Syngas_6	FT fuel_3	0.28	83,605	782.62	859,714	2,912
23		FTS_4	Syngas_7	FT fuel_4	0.24	79,920	819.31	969,527	3,798
24		FTS_5	Syngas_8	FT fuel_5	0.26	81,706	795.72	908,017	3,486
25		FTS_6	Syngas_9	FT fuel_6	0.28	83,648	782.79	860,222	2,915
26		DHCO2-FT_1	CO2, H2	FT fuel_7	0.27	119,212	880.48	437,800	145,858
27		DHCO2-O_1	CO2, H2	Raw olefin_1	0.40	176,191	1,186.43	354,912	14,396
28	Thermochemical energizing	CR5_1	CO2	CO2-rich_2	0.91	352,968	10,356.30	26,370	

29		CR5_2	CO2	CO2-rich_5	0.72	280,796	31,403.34	114,700	
30		CR5_3	CO2	CO2-rich_8	0.72	280,796	31,403.34	111,481	
31	Electrochemical reduction	Elecz-S_1	CO2	CO2-rich_3	0.81	318,034	2,754.12	434,017	
32		Elecz-S_2	CO2	CO2-rich_6	0.67	260,815	4,986.99	785,906	
33		Elecz-S_3	CO2	CO2-rich_9	0.66	259,233	4,986.99	805,328	
34		Elecz-FA_1	CO2	Raw FA_1	0.67	361,486	15,640.50	1,676,735	1,885
35		Elecz-FA	CO2	Raw EtOH_1	0.32	199,296	25,037.57	3,148,615	1,820
36	Separation	CO-PSA_1	CO2-rich_4	Syngas_4	0.98	273,659	2,991.53	18,601	3,098
37		CO-PSA_2	CO2-rich_5	Syngas_5	0.98	276,701	3,444.78	9,801	3,990
38		CO-PSA_3	CO2-rich_6	Syngas_6	0.99	259,093	1,930.97	45,231	1,582
39		CO2-MEA_1	CO2-rich_7	Syngas_7	0.95	298,114	32.41	841,185	6,001
40		CO2-MEA_2	CO2-rich_8	Syngas_8	0.99	276,806	30.19	756,388	3,990
41		CO2-MEA_3	CO2-rich_9	Syngas_9	1.00	259,233	28.61	698,303	1,582
42		SEP-MeOH_1	Raw MeOH_1	MeOH_1	0.67	249,861	27.75	231,946	25,372
43		SEP-MeOH_2	Raw MeOH_2	MeOH_2	0.65	253,538	32.28	243,792	26,479
44		SEP-MeOH_3	Raw MeOH_3	MeOH_3	0.73	255,491	31.25	221,899	25,680
45		SEP-MeOH_4	Raw MeOH_4	MeOH_4	0.86	259,415	26.76	170,773	21,073
46		SEP-MeOH_5	Raw MeOH_5	MeOH_5	0.83	256,482	27.59	203,507	22,470
47		SEP-MeOH_6	Raw MeOH_6	MeOH_6	0.91	264,255	24.82	150,303	15,911
48		SEP-MeOH_7	Raw MeOH_7	MeOH_7	0.78	253,149	45.47	235,083	24,186
49		SEP-MeOH_8	Raw MeOH_8	MeOH_8	0.83	256,594	27.59	203,566	22,477
50		SEP-MeOH_9	Raw MeOH_9	MeOH_9	0.91	263,906	23.82	118,289	16,073
51		SEP-MeOH_10	Raw MeOH_10	MeOH_10	0.62	270,399	11.90	207,718	8,643
52		SEP-DME_1	Raw DME_1	DME_1	0.72	179,506	38.93	150,381	
53		SEP-DME_2	Raw DME_2	DME_2	0.72	182,147	39.32	152,594	
54		SEP-DME_3	Raw DME_3	DME_3	0.72	183,550	39.52	153,769	
55		SEP-DME_4	Raw DME_4	DME_4	0.72	186,369	39.92	156,131	
56		SEP-DME_5	Raw DME_5	DME_5	0.72	184,262	39.62	154,366	
57		SEP-DME_6	Raw DME_6	DME_6	0.72	189,847	40.42	159,044	
58		SEP-DME_7	Raw DME_7	DME_7	0.72	181,868	39.27	152,360	
59		SEP-DME_8	Raw DME_8	DME_8	0.72	184,343	39.63	154,434	
60		SEP-DME_9	Raw DME_9	DME_9	0.72	189,596	40.39	158,834	
61		SEP-DME_10	Raw DME_10	DME_10	0.72	194,261	41.05	162,742	
62		SEP-DME_11	Raw DME_11	DME_11	0.36	102,306	30.45	118,378	178,987
63		SEP-DME_12	Raw DME_12	DME_12	0.33	95,613	29.58	113,076	179,711
64		SEP-DME_13	Raw DME_13	DME_13	0.42	113,816	33.45	125,712	157,457
65		SEP-DME_14	Raw DME_14	DME_14	0.27	80,462	28.58	98,047	209,859
66		SEP-DME_15	Raw DME_15	DME_15	0.33	95,667	44.23	103,671	191,668
67		SEP-DME_16	Raw DME_16	DME_16	0.42	113,886	33.45	125,699	157,493
68		SEP-O_1	Raw olefin_1	Olefin_11	0.39	68,270	1,213.90	133,589	24,791
69		SEP-FA_1	Raw FA_1	FA_1	0.99	359,366	63.29	11	42
70		SEP-EtOH_1	Raw EtOH_1	EtOH_1	0.24	47,900	203.04	22,254	

71	Upgrading	Dehydration_1	MeOH_1	Raw DME_1	1.00	249,858	547.00	82,171	
72		Dehydration_2	MeOH_2	Raw DME_2	1.00	253,535	552.38	83,380	
73		Dehydration_3	MeOH_3	Raw DME_3	1.00	255,488	555.23	84,022	
74		Dehydration_4	MeOH_4	Raw DME_4	1.00	259,412	560.93	85,313	
75		Dehydration_5	MeOH_5	Raw DME_5	1.00	256,479	556.67	84,348	
76		Dehydration_6	MeOH_6	Raw DME_6	1.00	264,252	567.92	86,904	
77		Dehydration_7	MeOH_7	Raw DME_7	1.00	253,146	551.82	83,252	
78		Dehydration_8	MeOH_8	Raw DME_8	1.00	256,591	556.84	84,385	
79		Dehydration_9	MeOH_9	Raw DME_9	1.00	263,903	567.42	86,789	
80		Dehydration_10	MeOH_10	Raw DME_10	1.00	270,396	576.73	88,925	
81		MTO_1	Raw MeOH_1	Olefin_1	0.38	140,552	4.03	0	
82		MTO_2	Raw MeOH_2	Olefin_2	0.38	147,410	4.23	0	
83		MTO_3	Raw MeOH_3	Olefin_3	0.38	133,193	3.82	0	
84		MTO_4	Raw MeOH_4	Olefin_4	0.38	114,167	3.28	0	
85		MTO_5	Raw MeOH_5	Olefin_5	0.38	116,741	3.35	0	
86		MTO_6	Raw MeOH_6	Olefin_6	0.38	110,030	3.16	0	
87		MTO_7	Raw MeOH_7	Olefin_7	0.38	122,671	3.52	0	
88		MTO_8	Raw MeOH_8	Olefin_8	0.38	116,786	3.35	0	
89		MTO_9	Raw MeOH_9	Olefin_9	0.38	110,083	3.16	0	
90		MTO_10	Raw MeOH_10	Olefin_10	0.38	163,871	4.70	0	
91		MTG_1	Raw MeOH_1	Gasoline_1	0.32	119,981	883.49	79	
92		MTG_2	Raw MeOH_2	Gasoline_2	0.32	125,836	912.15	83	
93		MTG_3	Raw MeOH_3	Gasoline_3	0.32	113,699	852.22	75	
94		MTG_4	Raw MeOH_4	Gasoline_4	0.32	97,458	768.61	65	
95		MTG_5	Raw MeOH_5	Gasoline_5	0.32	99,655	780.18	66	
96		MTG_6	Raw MeOH_6	Gasoline_6	0.32	93,926	749.83	62	
97		MTG_7	Raw MeOH_7	Gasoline_7	0.32	104,717	806.51	69	
98		MTG_8	Raw MeOH_8	Gasoline_8	0.32	99,693	780.37	66	
99		MTG_9	Raw MeOH_9	Gasoline_9	0.32	93,972	750.07	62	
100		MTG_10	Raw MeOH_10	Gasoline_10	0.32	139,888	979.19	93	
101		DTG_1	Raw DME_1	Gasoline_11	0.47	84,685	25.74	13,692	
102		DTG_2	Raw DME_2	Gasoline_12	0.47	85,931	25.99	13,894	
103		DTG_3	Raw DME_3	Gasoline_13	0.47	86,593	26.13	14,001	
104		DTG_4	Raw DME_4	Gasoline_14	0.47	87,923	26.39	14,216	
105		DTG_5	Raw DME_5	Gasoline_15	0.47	86,929	26.19	14,055	
106		DTG_6	Raw DME_6	Gasoline_16	0.47	89,563	26.72	14,481	
107		DTG_7	Raw DME_7	Gasoline_17	0.47	85,799	25.97	13,872	
108		DTG_8	Raw DME_8	Gasoline_18	0.47	86,967	26.20	14,061	
109		DTG_9	Raw DME_9	Gasoline_19	0.47	89,445	26.70	14,462	
110		DTG_10	Raw DME_10	Gasoline_20	0.47	91,646	27.14	14,818	
111		DTG_11	DME_11	Gasoline_21	0.47	48,265	17.66	7,804	
112		DTG_12	DME_12	Gasoline_22	0.47	45,107	16.88	7,293	

113		DTG_13	DME_13	Gasoline_23	0.47	53,694	18.97	8,682	
114		DTG_14	DME_14	Gasoline_24	0.47	37,959	15.04	6,137	
115		DTG_15	DME_15	Gasoline_25	0.47	45,133	16.88	7,297	
116		DTG_16	DME_16	Gasoline_26	0.47	53,728	18.98	8,687	

Table S4.2. Obtained input mass and energy, and by-product of each technology from process simulation

	Input materials											Input energy						By-product			
Tech.	CO_2 (kg/h)	H_2 (kg/h)	H_2O (kg/h)	CO_2-rich (kg/h)	Raw MeOH (kg/h)	MeOH (kg/h)	Raw DME (kg/h)	Raw olefin (kg/h)	Raw FA (kg/h)	Ads_CO (kg/h)	Ads_H_2 (kg/h)	LP (kWh)	HP (kWh)	FH (kWh)	Elec (kWh)	CW (ton/h)	REF (kWh)	Syngas (kg/h)	Light gas (kg/h)	Naphtha (kg/h)	Electricity (kg/h)
1	388,254	17,784												100,339	15,583	114,433					
2	388,254	17,784												272,916	25,233	53,262					
3	388,254	17,784												319,933	15,608	56,565					
4		31,834		360,159									290,025		121,196	88,583					
5		45,005		352,968									321,357		87,071	100,765					
6		40,313		318,034									252,302		82,225	83,200					
7		32,095		273,659									158,794		61,219	57,347					
8		35,894		276,701									175,763		62,961	61,804					
9		34,205		259,093									125,932		61,387	50,929					
10		31,151		298,114									208,395		78,874	70,998					
11		35,908		276,806									175,807		74,840	63,626					
12		34,207		259,233									175,807		74,840	63,626					
13	388,254	51,861												28,472	147,006	58,875					
14		10,559		273,659										21,619	41,928	11,061	12,449				
15		12,815		276,701										21,033	43,732	11,171	12,706				
16		14,928		259,093										22,703	48,804	12,323	12,381				
17		4,389		298,114										19,394	47,457	8,202	13,069				
18		12,823		276,806										21,044	43,756	11,178	12,715				
19		14,919		259,233										22,716	48,807	12,326	12,389				
20		36,451		273,659										780,859	119,228	118,337					
21		40,102		276,701										785,529	122,137	119,163					
22		37,618		259,093										742,448	117,266	112,331					
23		36,187		298,114										846,158	123,369	128,550					
24		40,118		276,806										785,831	122,186	119,208					
25		37,623		259,233										742,904	117,318	112,401					
26	388,254	54,565												273,443	164,358	67,850					
27	388,254	47,106									28		211,818		143,094	81,191				60,111	
28	388,254														26,370	5,864					
29	388,254														114,700	575,864					
30	388,254														111,481	19,428					

31	388,254		3,150												434,017						
32	388,254		3,153												785,906						
33	388,254		3,153												805,328						
34	388,254		154,729												1,676,735						
35	388,254		233,103												3,148,615						
36				277,032						971					18,601	1,397					
37				280,796						1,122					9,801	19,445					
38				260,815						618					45,231	10,670					
39				312,275								840,870			315	117,873					
40				280,796								756,105			283	105,991					
41				259,233								698,042			261	97,852					
42					371,459							231,946				39,307					
43					389,584							243,792				41,196					
44					352,009							221,899				37,870					
45					301,726							170,773				29,604					
46					308,531							203,507				35,111					
47					290,793							150,303				26,248					
48					324,201							235,083				40,339					
49					308,648							203,566				35,122					
50					290,934							118,289				20,549					
51					433,088							207,718				33,148					
52							249,858						150,381		0	24,667					
53							253,535						152,594		0	25,030					
54							255,488						153,769		0	25,222					
55							259,412						156,131		0	25,610					
56							256,479						154,366		0	25,320					
57							264,252						159,044		0	26,088					
58							253,146						152,360		0	24,991					
59							256,591						154,433		0	25,331					
60							263,903						158,834		0	26,053					
61							270,396						162,742		0	26,694					
62							283,924					61,238			921	4,126	56,219				
63							289,229					58,677			869	4,651	53,531				
64							273,684					64,648			1,010	5,152	60,054				
65							302,288					53,150			736	7,860	44,161				
66							289,342					64,645			870	3,859	38,156				
67							273,786					64,645			1,011	5,154	60,044				
68								176,191				7,775	44,829	0	61,078	57,341	19,907				
69									361,486						11	18,350					
70									199,296						4,305	3,657	17,948	149,576			
71						249,861							0	82,057	114	13,841					
72						253,538							0	83,264	115	14,044					

73						255,491							0	83,906	116	14,153					
74						259,415							0	85,194	118	14,370					
75						256,482							0	84,231	117	14,207					
76						264,255							0	86,784	120	14,638					
77						253,149							0	83,136	115	14,023					
78						256,594							0	84,268	117	14,214					
79						263,906								86,669	120	14,619					
80						270,399							0	88,802	123	14,978					
81					371,459								0		0						
82					389,584								0		0						
83					352,009								0		0						
84					301,726								0		0						
85					308,531								0		0						
86					290,793								0		0						
87					324,201								0		0						
88					308,648								0		0						
89					290,934								0		0						
90					433,088								0		0						
91					371,459										79						
92					389,584										83						
93					352,009										75						
94					301,726										65						
95					308,531										66						
96					290,793										62						
97					324,201										69						
98					308,648										66						
99					290,934										62						
100					433,088										93						
101							179,506					0	9	9,824	200	10,034	3,659		24,045		
102							182,147					0	9	9,969	203	10,181	3,713		24,399		
103							183,550					0	9	10,045	205	10,260	3,741		24,587		
104							186,369					0	9	10,200	208	10,417	3,799		24,965		
105							184,262					0	9	10,084	206	10,300	3,756		24,682		
106							189,847					0	9	10,390	212	10,612	3,870		25,430		
107							181,868					0	9	9,953	203	10,166	3,707		24,361		
108							184,343					0	9	10,089	206	10,304	3,758		24,693		
109							189,596					0	9	10,376	211	10,598	3,865		25,397		
110							194,261					0	10	10,632	217	10,859	3,960		26,022		
111							102,306					0	5	5,599	114	5,719	2,085		13,704		
112							95,613					0	5	5,233	107	5,344	1,949		12,808		
113							113,816					0	6	6,229	127	6,362	2,320		15,246		
114							80,462					0	4	4,404	90	4,498	1,640		10,778		

115							95,667					0	5	5,236	107	5,348	1,950		12,815		
116							113,886					0	6	6,233	127	6,366	2,321		15,255		

S4.2. Techno-economic and environmental performance of full CO_2-to-fuel pathways in CCU4E

Table S4.3 presents not only the integration of technologies involved each CO_2-to-fuel pathway (from CO_2 feedstock to final fuel products), but also the estimated sizing and costing data for the techno-economic and environmental analysis.

Table S4.3. Techno-economic parameters of 72 CO_2-to-fuel pathways

Pathway No.	Technology	Technology	Product	Yield	CAP (ton/h)	CAP (GGE/h)	ER (MWh)	DCE (ton/h)	TCI (M$)	ACC (M$)	FOC (M$)	Credit (M$)	Input materials			Input energy/utilities					
													CO_2 (ton/h)	H_2 (ton/h)	H_2O (ton/h)	LPS (MWh)	HPS (MWh)	FH (MWh)	Elec (MWh)	CW (Mton/h)	Refri. (MWh)
1	Catalytic.	RWGS-MS-SEP	MeOH	0.57	249.9	47,376.8	759.1	36.7	664.3	67.7	33.9	0.0	388.3	49.6	0.0	231.9	290.0	100.3	136.8	0.2	0.0
2	Thermo.	CR5-MS-SEP	MeOH	0.59	253.5	48,074.0	678.6	32.8	10,934.2	1,113.7	557.6	0.0	388.3	45.0	0.0	243.8	321.4	0.0	113.4	0.1	0.0
3	Electro.	ELECZCO-MS-SEP	MeOH	0.59	255.5	48,444.3	990.4	30.4	3,242.7	330.3	165.4	0.0	388.3	40.3	3.2	221.9	252.3	0.0	516.2	0.1	0.0
4	Catalytic.	RWGS-COPSA-MS-SEP	MeOH	0.59	259.4	49,188.3	707.5	26.5	3,638.7	370.6	185.6	0.0	388.3	49.9	0.0	170.8	158.8	272.9	105.1	0.1	0.0
5	Thermo.	CR5-COPSA-MS-SEP	MeOH	0.60	256.5	48,632.2	566.7	29.2	35,240.5	3,589.3	1,797.3	0.0	388.3	35.9	0.0	203.5	175.8	0.0	187.5	0.7	0.0
6	Electro.	ELECZCO-COPSA-MS-SEP	MeOH	0.62	264.3	50,106.1	1,168.8	18.8	7,290.7	742.6	371.8	0.0	388.3	34.2	3.2	150.3	125.9	0.0	892.5	0.1	0.0
7	Catalytic.	RWGS-CO_2MEA-MS-SEP	MeOH	0.58	253.1	48,000.2	1,699.1	33.8	691.8	70.5	35.3	0.0	388.3	48.9	0.0	1,076.0	208.4	319.9	94.8	0.3	0.0
8	Thermo.	CR5-CO_2MEA-MS-SEP	MeOH	0.60	256.6	48,653.4	1,322.1	29.2	31,873.9	3,246.4	1,625.6	0.0	388.3	35.9	0.0	959.7	175.8	0.0	186.6	0.2	0.0
9	Electro.	ELECZCO-CO_2MEA-MS-SEP	MeOH	0.62	263.9	50,039.9	1,872.6	18.9	5,430.3	553.1	276.9	0.0	388.3	34.2	3.2	816.3	175.8	0.0	880.4	0.2	0.0
10	Catalytic.	DHM-SEP	MeOH	0.61	270.4	51,271.0	383.2	14.6	733.6	74.7	37.4	0.0	388.3	51.9	0.0	207.7	0.0	28.5	147.0	0.1	0.0
11	Catalytic.	RWGS-COPSA-FTS-SEP	FT fuel	0.19	82.3	30,875.5	1,216.8	6.3	4,047.6	412.3	206.4	0.0	388.3	54.2	0.0	0.0	0.0	1,053.8	163.1	0.2	0.0
12	Thermo.	CR5-COPSA-FTS-SEP	FT fuel	0.19	81.7	30,634.7	1,032.2	7.5	35,643.7	3,630.4	1,817.8	0.0	388.3	40.1	0.0	0.0	0.0	785.5	246.6	0.7	0.0
13	Electro.	ELECZCO-COPSA-FTS-SEP	FT fuel	0.19	83.6	31,360.5	1,690.9	4.5	7,700.6	784.3	392.7	0.0	388.3	37.6	3.2	0.0	0.0	742.4	948.4	0.1	0.0
14	Catalytic.	RWGS-CO_2MEA-FTS-SEP	FT fuel	0.18	79.9	29,978.2	2,146.3	9.8	1,015.7	103.5	51.8	0.0	388.3	54.0	0.0	840.9	0.0	1,166.1	139.3	0.3	0.0
15	Thermo.	CR5-CO_2MEA-FTS-SEP	FT fuel	0.19	81.7	30,648.2	1,775.9	7.5	32,229.2	3,282.6	1,643.7	0.0	388.3	40.1	0.0	756.1	0.0	785.8	234.0	0.2	0.0
16	Electro.	ELECZCO-CO2MEA-FTS-SEP	FT fuel	0.19	83.6	31,376.6	2,363.9	4.5	5,798.4	590.6	295.7	0.0	388.3	37.6	3.2	698.0	0.0	742.9	922.9	0.2	0.0
17	Catalytic.	DHFT-SEP	FT fuel	0.27	119.2	44,716.8	437.8	145.9	880.5	89.7	44.9	0.0	388.3	54.6	0.0	0.0	0.0	273.4	164.4	0.1	0.0
18	Catalytic.	RWGS-MS-DEHYDR-SEP	DME	0.41	179.5	46,911.3	991.6	36.7	1,250.3	127.3	63.8	0.0	388.3	49.6	0.0	231.9	440.4	182.4	136.9	0.3	0.0
19	Thermo.	CR5-MS-DEHYDR-SEP	DME	0.42	182.1	47,601.5	914.6	32.8	11,525.9	1,173.9	587.8	0.0	388.3	45.0	0.0	243.8	474.0	83.3	113.6	0.2	0.0
20	Electro.	ELECZCO-MS-DEHYDR-SEP	DME	0.43	183.6	47,968.1	1,228.2	30.4	3,837.4	390.8	195.7	0.0	388.3	40.3	3.2	221.9	406.1	83.9	516.4	0.2	0.0
21	Catalytic.	RWGS-COPSA-MS-DEHYDR-SEP	DME	0.43	186.4	48,704.8	949.0	26.5	4,239.6	431.8	216.2	0.0	388.3	49.9	0.0	170.8	314.9	358.1	105.2	0.2	0.0
22	Thermo.	CR5-COPSA-MS-DEHYDR-SEP	DME	0.43	184.3	48,154.2	805.4	29.2	35,836.8	3,650.1	1,827.7	0.0	388.3	35.9	0.0	203.5	330.1	84.2	187.6	0.7	0.0
23	Electro.	ELECZCO-COPSA-MS-DEHYDR-SEP	DME	0.45	189.8	49,613.8	1,414.7	18.8	7,899.1	804.5	402.9	0.0	388.3	34.2	3.2	150.3	285.0	86.8	892.6	0.1	0.0
24	Catalytic.	RWGS-CO_2MEA-MS-DEHYDR-SEP	DME	0.42	181.9	47,528.6	1,934.7	33.8	1,282.9	130.7	65.4	0.0	388.3	48.9	0.0	1,076.0	360.8	403.1	94.9	0.3	0.0
25	Thermo.	CR5-CO_2MEA-MS-DEHYDR-SEP	DME	0.43	184.3	48,175.4	1,560.9	29.2	32,470.4	3,307.2	1,656.0	0.0	388.3	35.9	0.0	959.7	330.2	84.3	186.7	0.3	0.0
26	Electro.	ELECZCO-CO_2MEA-MS-DEHYDR-SEP	DME	0.45	189.6	49,548.2	2,118.2	18.9	6,038.1	615.0	307.9	0.0	388.3	34.2	3.2	816.3	334.6	86.7	880.5	0.2	0.0
27	Catalytic.	DHM-DEHYDR-SEP	DME	0.44	194.3	50,767.3	634.9	14.6	1,351.4	137.6	68.9	0.0	388.3	51.9	0.0	207.7	162.7	117.3	147.1	0.1	0.0
28	Catalytic.	RWGS-COPSA-DMES-SEP	DME	0.43	179.5	46,911.3	511.1	182.2	3,572.8	363.9	182.2	0.0	388.3	28.3	0.0	61.2	0.0	294.5	86.7	0.1	68.7
29	Thermo.	CR5-COPSA-DMES-SEP	DME	0.45	182.1	47,601.5	315.0	183.7	35,170.4	3,582.2	1,793.7	0.0	388.3	12.8	0.0	58.7	0.0	21.0	169.1	0.6	66.2
30	Electro.	ELECZCO-COPSA-DMES-SEP	DME	0.28	113.8	29,744.2	1,040.7	159.1	7,250.2	738.5	369.8	0.0	388.3	14.9	3.2	64.6	0.0	22.7	881.0	0.0	72.4
31	Catalytic.	RWGS-CO_2MEA-DMES-SEP	DME	0.20	80.5	21,027.6	1,354.7	215.9	433.7	44.2	22.1	0.0	388.3	22.2	0.0	894.0	0.0	339.3	64.1	0.2	57.2
32	Thermo.	CR5-CO_2MEA-DMES-SEP	DME	0.24	95.7	25,001.2	1,049.1	195.7	31,770.5	3,235.9	1,620.3	0.0	388.3	12.8	0.0	820.8	0.0	21.0	156.4	0.1	50.9
33	Electro.	ELECZCO-CO_2MEA-DMES-SEP	DME	0.28	113.9	29,762.5	1,713.2	159.1	5,347.9	544.7	272.7	0.0	388.3	14.9	3.2	762.7	0.0	22.7	855.4	0.1	72.4
34	Catalytic.	RWGS-MS-MTO	Olefin	0.32	140.6	53,648.5	527.1	11.4	640.6	65.2	32.7	0.0	388.3	49.6	0.0	0.0	290.0	100.3	136.8	0.2	0.0
35	Thermo.	CR5-MS-MTO	Olefin	0.34	147.4	56,266.1	541.4	6.4	10,906.2	1,110.8	556.2	0.0	388.3	45.0	0.0	321.4	0.0	113.4	106.6	0.0	0.0

36	Electro.	ELECZCO-MS-MTO	Olefin	0.31	133.2	50,839.5	768.5	4.7	3,215.3	327.5	164.0	0.0	388.3	40.3	3.2	0.0	252.3	0.0	516.2	0.1	0.0
37	Catalytic.	RWGS-COPSA-MS-MTO	Olefin	0.26	114.2	43,577.3	536.8	5.4	3,615.3	368.2	184.4	0.0	388.3	49.9	0.0	0.0	158.8	272.9	105.1	0.1	0.0
38	Thermo.	CR5-COPSA-MS-MTO	Olefin	0.28	116.7	44,559.8	363.2	6.7	35,216.3	3,586.9	1,796.0	0.0	388.3	35.9	0.0	0.0	175.8	0.0	187.5	0.7	0.0
39	Electro.	ELECZCO-COPSA-MS-MTO	Olefin	0.26	110.0	41,998.3	1,018.5	2.9	7,269.1	740.4	370.7	0.0	388.3	34.2	3.2	0.0	125.9	0.0	892.5	0.1	0.0
40	Catalytic.	RWGS-CO_2MEA-MS-MTO	Olefin	0.29	122.7	46,823.3	1,018.5	2.9	7,269.4	740.4	370.7	0.0	388.3	34.2	3.2	0.0	125.9	0.0	892.5	0.1	0.0
41	Thermo.	CR5-CO_2MEA-MS-MTO	Olefin	0.28	116.8	44,577.0	1,118.5	6.7	31,849.7	3,244.0	1,624.3	0.0	388.3	35.9	0.0	756.1	175.8	0.0	186.6	0.2	0.0
42	Electro.	ELECZCO-CO_2MEA-MS-MTO	Olefin	0.26	110.1	42,018.5	1,754.3	2.9	5,409.6	551.0	275.9	0.0	388.3	34.2	3.2	698.0	175.8	0.0	880.4	0.2	0.0
43	Catalytic.	DHM-MTO	Olefin	0.37	163.9	62,549.3	175.5	6.0	726.4	74.0	37.0	0.0	388.3	51.9	0.0	0.0	0.0	28.5	147.0	0.1	0.0
44	Catalytic.	DHO-SEP	Olefin	0.16	68.3	26,058.5	488.5	39.2	2,400.3	244.5	122.4	120.2	388.3	47.1	0.0	7.8	256.6	0.0	204.2	0.1	19.9
45	Catalytic.	RWGS-MS-MTG	Gasoline	0.27	120.0	45,895.5	527.2	11.4	1,520.1	154.8	77.5	0.0	388.3	49.6	0.0	0.0	290.0	100.3	136.9	0.2	0.0
46	Thermo.	CR5-MS-MTG	Gasoline	0.29	125.8	48,135.1	434.9	6.4	11,814.1	1,203.3	602.5	0.0	388.3	45.0	0.0	0.0	321.4	0.0	113.5	0.1	0.0
47	Electro.	ELECZCO-MS-MTG	Gasoline	0.26	113.7	43,492.4	768.6	4.7	4,063.7	413.9	207.2	0.0	388.3	40.3	3.2	0.0	252.3	0.0	516.3	0.1	0.0
48	Catalytic.	RWGS-COPSA-MS-MTG	Gasoline	0.22	97.5	37,279.9	536.8	5.4	4,380.6	446.2	223.4	0.0	388.3	49.9	0.0	0.0	158.8	272.9	105.1	0.1	0.0
49	Thermo.	CR5-COPSA-MS-MTG	Gasoline	0.23	99.7	38,120.3	363.3	6.7	35,993.1	3,666.0	1,835.6	0.0	388.3	35.9	0.0	0.0	175.8	0.0	187.5	0.7	0.0
50	Electro.	ELECZCO-COPSA-MS-MTG	Gasoline	0.22	93.9	35,928.8	1,018.5	2.9	8,015.8	816.4	408.8	0.0	388.3	34.2	3.2	0.0	125.9	0.0	892.6	0.1	0.0
51	Catalytic.	RWGS-CO_2MEA-MS-MTG	Gasoline	0.24	104.7	40,056.6	1,464.1	9.7	1,452.8	148.0	74.1	0.0	388.3	48.9	0.0	840.9	208.4	319.9	94.9	0.2	0.0
52	Thermo.	CR5-CO_2MEA-MS-MTG	Gasoline	0.24	99.7	38,134.8	1,118.6	6.7	32,626.7	3,323.1	1,664.0	0.0	388.3	35.9	0.0	756.1	175.8	0.0	186.7	0.2	0.0
53	Electro.	ELECZCO-CO_2MEA-MS-MTG	Gasoline	0.22	94.0	35,946.4	1,754.3	2.9	6,156.5	627.1	314.0	0.0	388.3	34.2	3.2	698.0	175.8	0.0	880.5	0.2	0.0
54	Catalytic.	DHM-MTG	Gasoline	0.32	139.9	53,510.3	175.6	6.0	1,700.9	173.2	86.7	0.0	388.3	51.9	0.0	0.0	0.0	28.5	147.1	0.1	0.0
55	Catalytic.	RWGS-MS-DEHYDR-SEP-DTG	Gasoline	0.19	84.7	32,393.9	1,005.3	36.7	1,276.0	130.0	65.1	48.1	388.3	49.6	0.0	231.9	440.4	192.2	137.1	0.3	3.7
56	Thermo.	CR5-MS-DEHYDR-SEP-DTG	Gasoline	0.20	85.9	32,870.6	928.5	32.8	11,551.9	1,176.6	589.1	48.8	388.3	45.0	0.0	243.8	474.0	93.2	113.8	0.2	3.7
57	Electro.	ELECZCO-MS-DEHYDR-SEP-DTG	Gasoline	0.20	86.6	33,123.7	1,242.2	30.4	3,863.5	393.5	197.0	49.2	388.3	40.3	3.2	221.9	406.1	94.0	516.6	0.2	3.7
58	Catalytic.	RWGS-COPSA-MS-DEHYDR-SEP-DTG	Gasoline	0.20	87.9	33,632.5	963.2	26.5	4,266.0	434.5	217.6	49.9	388.3	49.9	0.0	170.8	314.9	368.3	105.4	0.2	3.8
59	Thermo.	CR5-COPSA-MS-DEHYDR-SEP-DTG	Gasoline	0.20	86.9	33,252.2	819.5	29.2	35,863.0	3,652.7	1,829.0	49.4	388.3	35.9	0.0	203.5	330.1	94.3	187.8	0.7	3.8
60	Electro.	ELECZCO-COPSA-MS-DEHYDR-SEP-DTG	Gasoline	0.21	89.6	34,260.0	1,429.2	18.8	7,925.8	807.3	404.2	50.9	388.3	34.2	3.2	150.3	285.0	97.2	892.9	0.1	3.9
61	Catalytic.	RWGS-CO_2MEA-MS-DEHYDR-SEP-DTG	Gasoline	0.20	85.8	32,820.1	1,948.6	33.8	1,308.8	133.3	66.8	48.7	388.3	48.9	0.0	1,076.0	360.8	413.0	95.1	0.3	3.7
62	Thermo.	CR5-CO_2MEA-MS-DEHYDR-SEP-DTG	Gasoline	0.21	87.0	33,266.8	1,575.0	29.2	32,496.6	3,309.9	1,657.3	49.4	388.3	35.9	0.0	959.7	330.2	94.4	186.9	0.3	3.8
63	Electro.	ELECZCO-CO_2MEA-MS-DEHYDR-SEP-DTG	Gasoline	0.21	89.4	34,214.7	2,132.7	18.9	6,064.8	617.7	309.3	50.8	388.3	34.2	3.2	816.3	334.7	97.0	880.8	0.2	3.9
64	Catalytic.	DHCO_2MEOH-DEHYDR-SEP-DTG	Gasoline	0.21	91.6	35,056.5	649.7	14.6	1,378.5	140.4	70.3	52.0	388.3	51.9	0.0	207.7	162.8	127.9	147.3	0.1	4.0
65	Catalytic.	RWGS-COPSA-DMES-SEP-DTG	Gasoline	0.12	48.3	18,462.3	518.9	182.2	3,590.5	365.7	183.1	27.4	388.3	28.3	0.0	61.2	0.0	300.1	86.8	0.1	70.8
66	Thermo.	CR5-COPSA-DMES-SEP-DTG	Gasoline	0.11	45.1	17,254.4	322.3	183.7	35,187.3	3,583.9	1,794.6	25.6	388.3	12.8	0.0	58.7	0.0	26.3	169.2	0.6	68.2
67	Electro.	ELECZCO-COPSA-DMES-SEP-DTG	Gasoline	0.13	53.7	20,539.3	1,049.4	159.1	7,269.2	740.4	370.7	30.5	388.3	14.9	3.2	64.6	0.0	28.9	881.1	0.0	74.8
68	Catalytic.	RWGS-CO_2MEA-DMES-SEP-DTG	Gasoline	0.09	38.0	14,520.3	1,360.8	215.9	448.8	45.7	22.9	21.6	388.3	22.2	0.0	894.0	0.0	343.7	64.2	0.2	58.9
69	Thermo.	CR5-CO_2MEA-DMES-SEP-DTG	Gasoline	0.11	45.1	17,264.3	1,056.4	195.7	31,787.4	3,237.6	1,621.2	25.6	388.3	12.8	0.0	820.8	0.0	26.3	156.5	0.1	52.8
70	Electro.	ELECZCO-CO_2MEA-DMES-SEP-DTG	Gasoline	0.13	53.7	20,552.0	1,721.9	159.1	5,366.9	546.6	273.7	30.5	388.3	14.9	3.2	762.7	0.0	28.9	855.5	0.1	74.8
71	Electro.	ELECZFA-SEP	FA	0.66	359.4	15,701.9	1,676.7	1.9	15,703.8	1,599.5	800.9	0.0	388.3	0.0	154.7	0.0	0.0	0.0	1,676.7	0.0	0.0
72	Electro.	ELECZETOH-SEP	EtOH	0.08	47.9	11,728.2	3,170.9	1.8	25,240.6	2,570.8	1,287.3	658.1	388.3	0.0	233.1	0.0	0.0	0.0	3,152.9	0.0	17.9

Yield: calculated based on the main fuel product and material input.
CAP (ton/h or GGE/h): the capacity or production rate of each process.
ER (MWh): energy requirement that is energy required for process.
DCE (ton/h): direct CO_{2eq} emission that was the CO_{2eq} flow emit to the environment via vent-out gas, purge gas (obtained from process simulation).
TCI (M$): total capital investment cost of plant.
ACC (M$/y): annualized capital investment cost.
FOC (M$/y): fixed operating cost (5.1 % of TCI).
Credit (M$/y): achieved credits by byproducts (e.g., naphtha, extra-electricity,…)
Consumed utilities included low-pressure steam (LPS), high-pressure steam (HPS), fired heat (FH), electricity (Elec), cooling water (CW), refrigeration (Refri.).

Technology abbreviations:

Catalytic.: Catalytic CO_2 conversion, Thermo.: Thermochemical CO_2 energizing, Electro.: Electrochemical CO_2 reduction. RWGS: Reverse water-gas shift, DHM: Direct CO_2 hydrogenation to methanol, DHFT: Direct CO_2 hydrogenation to Fischer–Tropsch fuel, DHO: Direct CO_2 hydrogenation to light olefin, CR5: Thermochemical splitting via Counter-Rotating-Ring Receiver/Reactor/ Recuperator, ELECZCO: Electrochemical reduction to CO, ELECZETOH: Electrochemical reduction to ethanol, ELECZEFA: Electrochemical reduction to formic acid, MS: Methanol synthesis, FTS: Fischer–Tropsch synthesis, DMES: dimethylether synthesis, DEHYDR.: Dehydration of methanol to dimethylether, MTO: methanol-to-olefin, MTG: methanol-to-gasoline, DTG: DME-to-gasoline synthesis, COPSA: CO pressure swing adsorption, CO_2MEA: CO_2 absorption by monoethanolamine, SEP: separation and purification.

Table S4.4. Energy flows in CO_2-to-fuel pathways and energy efficiency of processes

Pathway No.	Material input (kWh)	Utility (kWh)	Product (kWh)	Energy efficiency	Pathway No.	Material input (kWh)	Utility (kWh)	Product (kWh)	Energy efficiency
1	1,954,949	759,090	1,596,334	58.82%	37	1,965,233	536,763	1,468,314	58.69%
2	1,773,197	678,590	1,619,826	66.07%	38	1,414,224	363,225	1,501,419	84.47%
3	1,588,332	990,442	1,632,304	63.30%	39	1,347,677	1,018,456	1,415,108	59.81%
4	1,965,233	707,536	1,657,374	62.01%	40	1,347,677	1,018,456	1,577,685	66.68%
5	1,414,224	566,732	1,638,635	82.72%	41	1,414,775	1,118,516	1,501,998	59.29%
6	1,347,677	1,168,759	1,688,296	67.09%	42	1,347,756	1,754,278	1,415,790	45.64%
7	1,928,039	1,699,077	1,617,341	44.59%	43	2,043,323	175,478	2,107,563	94.99%
8	1,414,775	1,322,082	1,639,351	59.90%	44	1,855,976	488,501	878,028	37.45%
9	1,347,756	1,872,567	1,686,066	52.36%	45	1,954,949	527,223	1,546,422	62.30%
10	2,043,323	383,196	1,727,549	71.19%	46	1,773,197	434,881	1,621,886	73.45%
11	2,136,859	1,216,837	1,040,332	31.02%	47	1,588,332	768,619	1,465,454	62.18%
12	1,580,019	1,032,166	1,032,218	39.52%	48	1,965,233	536,828	1,256,125	50.20%
13	1,482,149	1,690,850	1,056,674	33.30%	49	1,414,224	363,291	1,284,442	72.26%
14	2,126,457	2,146,253	1,010,100	23.64%	50	1,347,677	1,018,518	1,210,602	51.16%
15	1,580,649	1,775,886	1,032,673	30.77%	51	1,928,039	1,464,064	1,349,686	39.79%
16	1,482,346	2,363,853	1,057,218	27.49%	52	1,414,775	1,118,582	1,284,932	50.72%
17	2,149,861	437,801	1,506,707	58.23%	53	1,347,756	1,754,340	1,211,195	39.04%
18	1,954,949	991,641	1,580,650	49.07%	54	2,043,323	175,571	1,803,001	81.26%
19	1,773,197	914,563	1,603,906	54.59%	55	1,954,949	1,005,333	1,091,494	36.87%
20	1,588,332	1,228,234	1,616,260	52.50%	56	1,773,197	928,457	1,107,556	41.00%
21	1,965,233	948,979	1,641,083	51.52%	57	1,588,332	1,242,235	1,116,086	39.43%
22	1,414,224	805,445	1,622,529	66.87%	58	1,965,233	963,195	1,133,229	38.70%
23	1,347,677	1,414,707	1,671,708	55.36%	59	1,414,224	819,500	1,120,416	50.16%
24	1,928,039	1,934,689	1,601,449	37.93%	60	1,347,677	1,429,188	1,154,373	41.57%
25	1,414,775	1,560,899	1,623,243	49.90%	61	1,928,039	1,948,561	1,105,854	28.53%
26	1,347,756	2,118,190	1,669,498	44.07%	62	1,414,775	1,574,960	1,120,906	37.49%
27	2,043,323	634,863	1,710,576	58.43%	63	1,347,756	2,132,652	1,152,846	33.12%
28	1,116,714	511,125	1,580,650	88.83%	64	2,043,323	649,681	1,181,211	43.86%
29	504,911	315,049	1,603,906	93.93%	65	1,116,714	518,929	622,078	38.03%
30	588,163	1,040,736	1,002,213	56.29%	66	504,911	322,342	581,379	70.28%
31	873,616	1,354,693	708,513	29.09%	67	588,163	1,049,418	692,062	42.26%
32	505,226	1,049,054	842,401	49.58%	68	873,616	1,360,830	489,255	21.90%
33	587,809	1,713,242	1,002,830	39.87%	69	505,226	1,056,351	581,711	37.25%
34	1,954,949	527,144	1,807,655	72.83%	70	587,809	1,721,929	692,488	29.98%
35	1,773,197	541,427	1,895,856	81.91%	71	0	1,676,745	529,067	31.55%
36	1,588,332	768,543	1,713,010	72.68%	72	0	3,170,868	395,175	12.46%

Carbon and energy efficiency present how much carbon and energy are captured and stored in the products, which are expressed as follow:

$$Carbon\ efficiency = \frac{Carbon\ in\ products}{Carbon\ in\ raw\ material}, (\%) \quad (17)$$

$$Enery\ efficiency = \frac{Heat\ of\ reaction\ of\ products}{Heat\ of\ reaction\ in\ raw\ material\ +\ Consumed\ energy\ as\ utility}, (\%) \quad (18)$$

Fig. S4.1. ranks CO_2-to-fuel pathways in terms of carbon efficiency, energy efficiency, unit production cost (UPC), and net CO_{2eq} emission (NCE), in which the order is from good performance to bad performance.

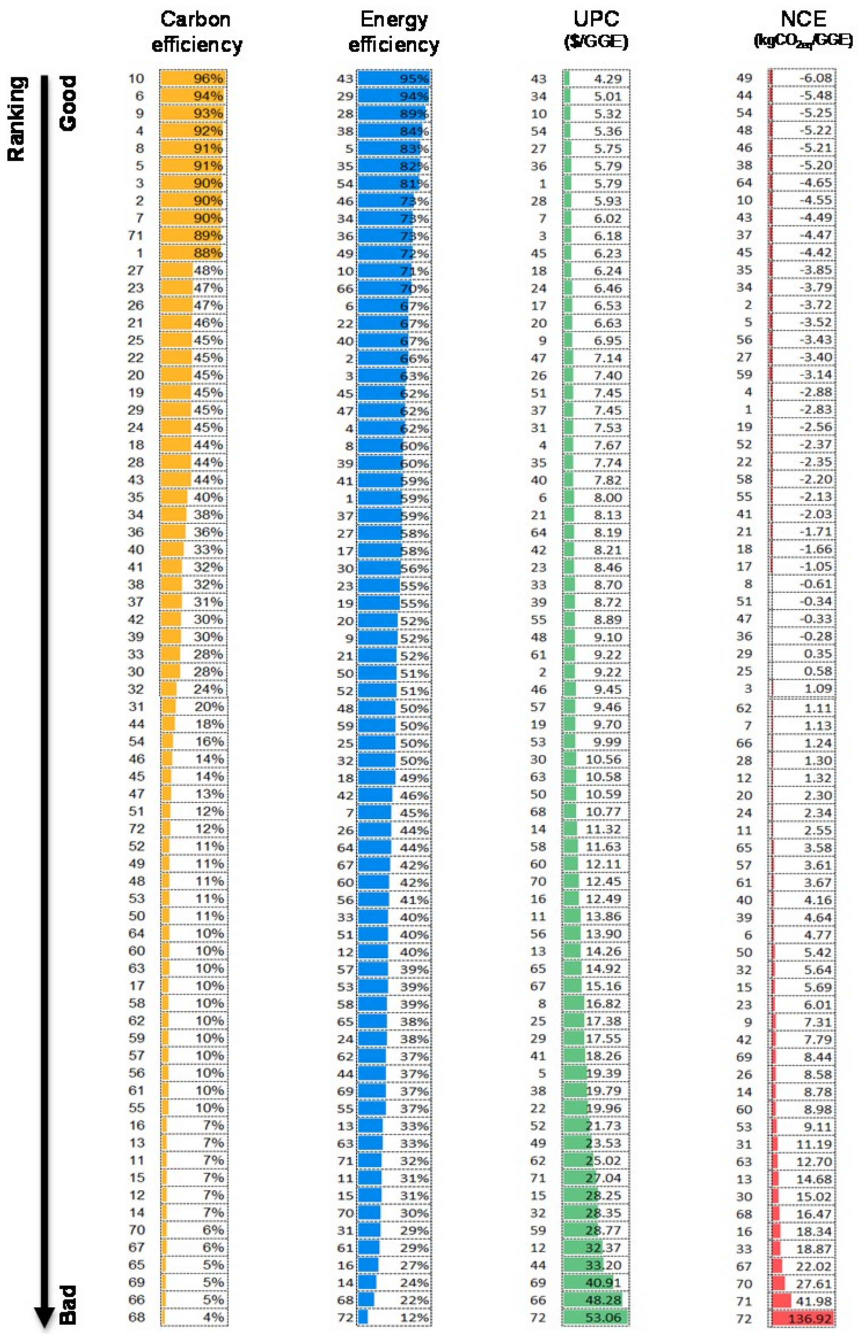


Fig. S4.1. Ranking CO_2-to-fuel pathways by technical, economic and environmental performance

Table S4.5. CO_2-based fuel's unit production cost and its breakdown (using green H_2).

Unit: $/GGE

Pathway No.	Technology	Product	UPC	ACC	CO_2	H_2	Utility	FOC
1	RWGS-MS-SEP	MeOH	5.83	0.18	0.29	4.65	0.63	0.09
2	CR5-MS-SEP	MeOH	9.26	2.90	0.28	4.16	0.47	1.45
3	ELECZCO-MS-SEP	MeOH	6.22	0.85	0.28	3.69	0.96	0.43
4	RWGS-COPSA-MS-SEP	MeOH	7.71	0.94	0.28	4.50	1.52	0.47
5	CR5-COPSA-MS-SEP	MeOH	19.42	9.23	0.28	3.28	2.01	4.62
6	ELECZCO-COPSA-MS-SEP	MeOH	8.02	1.85	0.27	3.03	1.94	0.93
7	RWGS-CO$_2$MEA-MS-SEP	MeOH	6.06	0.18	0.28	4.53	0.97	0.09
8	CR5-CO$_2$MEA-MS-SEP	MeOH	16.85	8.34	0.28	3.28	0.78	4.18
9	ELECZCO-CO$_2$MEA-MS-SEP	MeOH	6.98	1.38	0.27	3.04	1.60	0.69
10	DHM-SEP	MeOH	5.36	0.18	0.27	4.49	0.33	0.09
11	RWGS-COPSA-FTS-SEP	FT fuel	13.93	1.67	0.44	7.80	3.19	0.84
12	CR5-COPSA-FTS-SEP	FT fuel	32.43	14.81	0.44	5.81	3.94	7.42
13	ELECZCO-COPSA-FTS-SEP	FT fuel	14.30	3.13	0.43	5.33	3.85	1.57
14	RWGS-CO$_2$MEA-FTS-SEP	FT fuel	11.40	0.43	0.45	7.99	2.30	0.22
15	CR5-CO$_2$MEA-FTS-SEP	FT fuel	28.30	13.39	0.44	5.81	1.96	6.70
16	ELECZCO-CO2MEA-FTS-SEP	FT fuel	12.53	2.35	0.43	5.32	3.25	1.18
17	DHFT-SEP	FT fuel	6.58	0.25	0.30	5.42	0.49	0.13
18	RWGS-MS-DEHYDR-SEP	DME	6.28	0.34	0.29	4.70	0.78	0.17
19	CR5-MS-DEHYDR-SEP	DME	9.74	3.08	0.29	4.20	0.63	1.54
20	ELECZCO-MS-DEHYDR-SEP	DME	6.66	1.02	0.28	3.73	1.12	0.51
21	RWGS-COPSA-MS-DEHYDR-SEP	DME	8.17	1.11	0.28	4.55	1.68	0.55
22	CR5-COPSA-MS-DEHYDR-SEP	DME	19.99	9.47	0.28	3.31	2.18	4.74
23	ELECZCO-COPSA-MS-DEHYDR-SEP	DME	8.49	2.03	0.27	3.06	2.11	1.01
24	RWGS-CO$_2$MEA-MS-DEHYDR-SEP	DME	6.50	0.34	0.29	4.57	1.13	0.17
25	CR5-CO$_2$MEA-MS-DEHYDR-SEP	DME	17.41	8.58	0.28	3.31	0.94	4.30
26	ELECZCO-CO$_2$MEA-MS-DEHYDR-SEP	DME	7.43	1.55	0.27	3.07	1.76	0.78
27	DHM-DEHYDR-SEP	DME	5.79	0.34	0.27	4.54	0.48	0.17
28	RWGS-COPSA-DMES-SEP	DME	5.95	0.97	0.29	2.68	1.53	0.49
29	CR5-COPSA-DMES-SEP	DME	17.56	9.41	0.29	1.20	1.96	4.71
30	ELECZCO-COPSA-DMES-SEP	DME	10.58	3.10	0.46	2.23	3.24	1.55
31	RWGS-CO$_2$MEA-DMES-SEP	DME	7.57	0.26	0.65	4.68	1.85	0.13
32	CR5-CO$_2$MEA-DMES-SEP	DME	28.37	16.18	0.54	2.28	1.27	8.10
33	ELECZCO-CO$_2$MEA-DMES-SEP	DME	8.72	2.29	0.46	2.23	2.60	1.15
34	RWGS-MS-MTO	Olefin	5.05	0.15	0.25	4.11	0.46	0.08
35	CR5-MS-MTO	Olefin	7.77	2.47	0.24	3.55	0.28	1.24
36	ELECZCO-MS-MTO	Olefin	5.82	0.81	0.27	3.52	0.82	0.40
37	RWGS-COPSA-MS-MTO	Olefin	7.50	1.06	0.31	5.08	0.52	0.53
38	CR5-COPSA-MS-MTO	Olefin	19.82	10.06	0.30	3.58	0.84	5.04
39	ELECZCO-COPSA-MS-MTO	Olefin	8.75	2.20	0.32	3.62	1.51	1.10
40	RWGS-CO$_2$MEA-MS-MTO	Olefin	7.85	1.98	0.29	3.24	1.35	0.99
41	CR5-CO$_2$MEA-MS-MTO	Olefin	18.29	9.10	0.30	3.58	0.76	4.55
42	ELECZCO-CO$_2$MEA-MS-MTO	Olefin	8.24	1.64	0.32	3.61	1.84	0.82
43	DHM-MTO	Olefin	4.32	0.15	0.22	3.68	0.20	0.07
44	DHO-SEP	Olefin	33.28	1.15	0.51	7.89	23.14	0.58
45	RWGS-MS-MTG	Gasoline	6.27	0.42	0.30	4.80	0.54	0.21
46	CR5-MS-MTG	Gasoline	9.49	3.12	0.28	4.15	0.37	1.56
47	ELECZCO-MS-MTG	Gasoline	7.18	1.19	0.31	4.12	0.96	0.60
48	RWGS-COPSA-MS-MTG	Gasoline	9.16	1.50	0.36	5.94	0.61	0.75
49	CR5-COPSA-MS-MTG	Gasoline	23.56	12.02	0.36	4.18	0.99	6.02
50	ELECZCO-COPSA-MS-MTG	Gasoline	10.63	2.84	0.38	4.23	1.76	1.42
51	RWGS-CO$_2$MEA-MS-MTG	Gasoline	7.50	0.46	0.34	5.42	1.04	0.23
52	CR5-CO$_2$MEA-MS-MTG	Gasoline	21.77	10.89	0.36	4.18	0.88	5.45
53	ELECZCO-CO$_2$MEA-MS-MTG	Gasoline	10.03	2.18	0.38	4.23	2.16	1.09
54	DHM-MTG	Gasoline	5.40	0.40	0.25	4.30	0.23	0.20
55	RWGS-MS-DEHYDR-SEP-DTG	Gasoline	8.95	0.49	0.41	6.66	1.14	0.25
56	CR5-MS-DEHYDR-SEP-DTG	Gasoline	13.96	4.42	0.41	6.00	0.92	2.21
57	ELECZCO-MS-DEHYDR-SEP-DTG	Gasoline	9.51	1.46	0.40	5.30	1.62	0.73
58	RWGS-COPSA-MS-DEHYDR-SEP-DTG	Gasoline	11.69	1.59	0.40	6.48	2.43	0.80
59	CR5-COPSA-MS-DEHYDR-SEP-DTG	Gasoline	28.81	13.64	0.41	4.76	3.17	6.83
60	ELECZCO-COPSA-MS-DEHYDR-SEP-DTG	Gasoline	12.15	2.90	0.39	4.37	3.04	1.45
61	RWGS-CO$_2$MEA-MS-DEHYDR-SEP-DTG	Gasoline	9.27	0.50	0.41	6.49	1.63	0.25
62	CR5-CO$_2$MEA-MS-DEHYDR-SEP-DTG	Gasoline	25.07	12.35	0.41	4.76	1.38	6.18

63	ELECZCO-CO_2MEA-MS-DEHYDR-SEP-DTG	Gasoline	10.62	2.22	0.39	4.36	2.54	1.11
64	DHCO_2MEOH-DEHYDR-SEP-DTG	Gasoline	8.24	0.49	0.38	6.42	0.71	0.25
65	RWGS-COPSA-DMES-SEP-DTG	Gasoline	14.99	2.45	0.73	6.73	3.86	1.22
66	CR5-COPSA-DMES-SEP-DTG	Gasoline	48.31	25.86	0.78	3.28	5.42	12.95
67	ELECZCO-COPSA-DMES-SEP-DTG	Gasoline	15.19	4.45	0.65	3.19	4.66	2.23
68	RWGS-CO_2MEA-DMES-SEP-DTG	Gasoline	10.83	0.39	0.92	6.67	2.66	0.19
69	CR5-CO_2MEA-DMES-SEP-DTG	Gasoline	40.94	23.34	0.78	3.28	1.85	11.68
70	ELECZCO-CO_2MEA-DMES-SEP-DTG	Gasoline	12.48	3.28	0.65	3.18	3.74	1.64
71	ELECZFA-SEP	FA	27.04	12.73	0.87	0.00	7.05	6.38
72	ELECZETOH-SEP	EtOH	53.06	24.20	1.02	0.00	15.70	12.12

Abbreviation: UPC: unit production cost, ACC: annualized capital cost, CO_2, H_2, Utility: variable operating costs including CO_2 and H_2, utility cost, FOC: fixed operating cost.

Table S4.6. Net CO_{2eq} emission (NCE) and its components (using green H_2).

Unit: $kgCO_{2eq}$/GGE

Pathway No.	Technology	Product	NCE	CO_2 feed	Direct emission	Indirect emission
1	RWGS-MS-SEP	MeOH	-2.83	-8.20	0.78	4.59
2	CR5-MS-SEP	MeOH	-3.72	-8.08	0.68	3.68
3	ELECZCO-MS-SEP	MeOH	1.09	-8.01	0.63	8.48
4	RWGS-COPSA-MS-SEP	MeOH	-2.88	-7.89	0.54	4.48
5	CR5-COPSA-MS-SEP	MeOH	-3.52	-7.98	0.60	3.87
6	ELECZCO-COPSA-MS-SEP	MeOH	4.77	-7.75	0.37	12.14
7	RWGS-CO_2MEA-MS-SEP	MeOH	1.13	-8.09	0.70	8.52
8	CR5-CO_2MEA-MS-SEP	MeOH	-0.61	-7.98	0.60	6.77
9	ELECZCO-CO_2MEA-MS-SEP	MeOH	7.31	-7.76	0.38	14.69
10	DHM-SEP	MeOH	-4.55	-7.57	0.29	2.74
11	RWGS-COPSA-FTS-SEP	FT fuel	2.55	-12.57	0.21	14.92
12	CR5-COPSA-FTS-SEP	FT fuel	1.32	-12.67	0.24	13.75
13	ELECZCO-COPSA-FTS-SEP	FT fuel	14.68	-12.38	0.14	26.92
14	RWGS-CO_2MEA-FTS-SEP	FT fuel	8.78	-12.95	0.33	21.40
15	CR5-CO_2MEA-FTS-SEP	FT fuel	5.69	-12.67	0.24	18.12
16	ELECZCO-CO2MEA-FTS-SEP	FT fuel	18.34	-12.37	0.14	30.57
17	DHFT-SEP	FT fuel	-1.05	-8.68	3.26	4.37
18	RWGS-MS-DEHYDR-SEP	DME	-1.66	-8.28	0.78	5.83
19	CR5-MS-DEHYDR-SEP	DME	-2.56	-8.16	0.69	4.91
20	ELECZCO-MS-DEHYDR-SEP	DME	2.30	-8.09	0.63	9.76
21	RWGS-COPSA-MS-DEHYDR-SEP	DME	-1.71	-7.97	0.54	5.72
22	CR5-COPSA-MS-DEHYDR-SEP	DME	-2.35	-8.06	0.61	5.10
23	ELECZCO-COPSA-MS-DEHYDR-SEP	DME	6.01	-7.83	0.38	13.46
24	RWGS-CO_2MEA-MS-DEHYDR-SEP	DME	2.34	-8.17	0.71	9.80
25	CR5-CO_2MEA-MS-DEHYDR-SEP	DME	0.58	-8.06	0.61	8.03
26	ELECZCO-CO_2MEA-MS-DEHYDR-SEP	DME	8.58	-7.84	0.38	16.03
27	DHM-DEHYDR-SEP	DME	-3.40	-7.65	0.29	3.96
28	RWGS-COPSA-DMES-SEP	DME	1.30	-8.28	3.88	5.69
29	CR5-COPSA-DMES-SEP	DME	0.35	-8.16	3.86	4.65
30	ELECZCO-COPSA-DMES-SEP	DME	15.02	-13.05	5.35	22.73
31	RWGS-CO_2MEA-DMES-SEP	DME	11.19	-18.46	10.27	19.38
32	CR5-CO_2MEA-DMES-SEP	DME	5.64	-15.53	7.83	13.34
33	ELECZCO-CO_2MEA-DMES-SEP	DME	18.87	-13.05	5.35	26.57
34	RWGS-MS-MTO	Olefin	-3.79	-7.24	0.21	3.24
35	CR5-MS-MTO	Olefin	-3.85	-6.90	0.11	2.94
36	ELECZCO-MS-MTO	Olefin	-0.28	-7.64	0.09	7.26
37	RWGS-COPSA-MS-MTO	Olefin	-4.47	-8.91	0.12	4.32
38	CR5-COPSA-MS-MTO	Olefin	-5.20	-8.71	0.15	3.36
39	ELECZCO-COPSA-MS-MTO	Olefin	4.64	-9.24	0.07	13.81
40	RWGS-CO_2MEA-MS-MTO	Olefin	4.16	-8.29	0.06	12.39
41	CR5-CO_2MEA-MS-MTO	Olefin	-2.03	-8.71	0.15	6.53
42	ELECZCO-CO_2MEA-MS-MTO	Olefin	7.79	-9.24	0.07	16.96
43	DHM-MTO	Olefin	-4.49	-6.21	0.10	1.62
44	DHO-SEP	Olefin	-5.48	-14.90	1.50	7.91
45	RWGS-MS-MTG	Gasoline	-4.42	-8.46	0.25	3.79
46	CR5-MS-MTG	Gasoline	-5.21	-8.07	0.13	2.72
47	ELECZCO-MS-MTG	Gasoline	-0.33	-8.93	0.11	8.49

48	RWGS-COPSA-MS-MTG	Gasoline	-5.22	-10.41	0.15	5.05
49	CR5-COPSA-MS-MTG	Gasoline	-6.08	-10.18	0.18	3.93
50	ELECZCO-COPSA-MS-MTG	Gasoline	5.42	-10.81	0.08	16.15
51	RWGS-CO_2MEA-MS-MTG	Gasoline	-0.34	-9.69	0.24	9.11
52	CR5-CO_2MEA-MS-MTG	Gasoline	-2.37	-10.18	0.18	7.63
53	ELECZCO-CO_2MEA-MS-MTG	Gasoline	9.11	-10.80	0.08	19.83
54	DHM-MTG	Gasoline	-5.25	-7.26	0.11	1.90
55	RWGS-MS-DEHYDR-SEP-DTG	Gasoline	-2.13	-11.99	1.13	8.72
56	CR5-MS-DEHYDR-SEP-DTG	Gasoline	-3.43	-11.81	1.00	7.38
57	ELECZCO-MS-DEHYDR-SEP-DTG	Gasoline	3.61	-11.72	0.92	14.41
58	RWGS-COPSA-MS-DEHYDR-SEP-DTG	Gasoline	-2.20	-11.54	0.79	8.56
59	CR5-COPSA-MS-DEHYDR-SEP-DTG	Gasoline	-3.14	-11.68	0.88	7.66
60	ELECZCO-COPSA-MS-DEHYDR-SEP-DTG	Gasoline	8.98	-11.33	0.55	19.76
61	RWGS-CO_2MEA-MS-DEHYDR-SEP-DTG	Gasoline	3.67	-11.83	1.03	14.47
62	CR5-CO_2MEA-MS-DEHYDR-SEP-DTG	Gasoline	1.11	-11.67	0.88	11.90
63	ELECZCO-CO_2MEA-MS-DEHYDR-SEP-DTG	Gasoline	12.70	-11.35	0.55	23.49
64	DHCO_2MEOH-DEHYDR-SEP-DTG	Gasoline	-4.65	-11.08	0.42	6.01
65	RWGS-COPSA-DMES-SEP-DTG	Gasoline	3.58	-21.03	9.87	14.74
66	CR5-COPSA-DMES-SEP-DTG	Gasoline	1.24	-22.50	10.65	13.10
67	ELECZCO-COPSA-DMES-SEP-DTG	Gasoline	22.02	-18.90	7.74	33.18
68	RWGS-CO_2MEA-DMES-SEP-DTG	Gasoline	16.47	-26.74	14.87	28.34
69	CR5-CO_2MEA-DMES-SEP-DTG	Gasoline	8.44	-22.49	11.33	19.59
70	ELECZCO-CO_2MEA-DMES-SEP-DTG	Gasoline	27.61	-18.89	7.74	38.75
71	ELECZFA-SEP	FA	41.98	-24.73	0.12	66.58
72	ELECZETOH-SEP	EtOH	136.92	-33.10	0.16	169.87

S5. Optimization model for optimal pathway identification

To identify the optimal CO_2-to-fuel pathway from an economic perspective, we developed a network optimization model using a mixed integer linear programming (MILP) technique based on the generated CCU4E superstructure along with associated parameters that was obtained through a process simulation.

Objective function: The object function identifies the optimal CO_2-to-fuel pathway for each CO_2-based fuel types, which produce fuel at minimum UPC among several pathways. This objective function is calculated by annual capital cost, operating cost, and annual production rate.

$$MinUPC_s = \sum_j X_{js} \left(\frac{\sum_j \alpha_j + \sum_j \psi_j + \sum_{i \in I^U} \varpi_i \gamma_{ij} + \sum_{i \in I^F} \xi_i F_{ij} - \sum_{i \in I^B} \pi_{ij} S_{ij}}{\sum_{i \in I^P} S_{ij}} \right) \tag{17}$$

where X_{js} is the binary variable for the selection of pathway j in each fuel s, α_j is the total capital investment cost of pathway j, ψ_j is the fixed operating cost factor of pathway j. γ_{ij} and F_{ij} is the amount of utilities and feestock, respectively. ϖ_i and ξ_i are the unit costs for utilities $i \in I^U$ and feedstock $i \in I^F$, respectively. S_i is the annual production rate of final product $i \in I^P$ and π_i is assumed unit price by-product $i \in I^B$.

Constraints:

Logistic constraints: Only one pathway (the optimal one with the minimum UPC) should be selected toward each fuel s.

$$\sum_{j_1}^{j_n} X_{js} = 1$$

Compound material balance: the amount of feedstock and the production of a compound should be equal to the amount of product, by-product, and the consumption of compounds in pathway (a series of technologies):

$$F_i + \sum_{j \in J_i^+} \eta_{ij} Y_j = S_i - \sum_{j \in J_i^-} \eta_{ij} Y_j \quad \forall i \tag{18}$$

where F_i is the amount of feedstock $i \in I^F$, η_{ij} is the yield of compound i in technology j ($\eta_{ij} < 0$ for inputs and $\eta_{ij} > 0$ for outputs), Y_j is the production level of technology j, and S_i is the amount of product $i \in I^P$, by-product $i \in I^B$.

Capacity limits: the total amount of the production each technology should be bounded by its capacity and the number of facilities:

$$Y_j \leq N_j \beta_j \tag{19}$$

where N_j is the number of technology j, β_j is the capacity of technology j.

Feed availability: the amount of CO_2 $i \in I^{F'}$ for CO_2 utilization should be equal to its availability:

$$\sum_{i \in I^{F'}} F_i = \rho \tag{20}$$

where ρ is the availability of CO_2.

S6. Analysis of CCU4E in different local scenarios

Table S6.1. Top country's share of CO_2 emissions [51]

	% in 2018	This study (Mt/y)
Global	100	1000
China	29	290
US	16	160
Europe	11	110
India	7	110
Japan	4	40
Korea	2	20
Rest of the world	31	270

Table S6.2. The unit price of black H_2 (estimated based on natural gas market) [47,52–54]

	Natural gas ($/MMBTU)	Natural gas ($/GJ)	Black H_2* ($/kg)
Global	4.38	4.15	2.7
USA	3.15	2.99	2.3
Europe	7.68	7.28	4.1
China	8.1	7.68	4.3
India	8.1	7.68	4.3
Japan	8.1	7.68	4.3
Korea	8.1	7.68	4.3

* H_2 is assumed to produce via steam methane reforming integrated with CO_2 capture and storage [40].

Table S6.3. UPC and NCE of CO_2-based fuels using black/green H_2 by country

		UPC ($/GGE)						NCE (kgCO_2/GGE)					
Product	Scenario	China	USA	Europe	India	Japan	Korea	China	USA	Europe	India	Japan	Korea
MeOH	Black H_2	5.37	3.15	5.14	5.33	5.31	5.34	0.00	-1.23	-0.11	0.19	-0.29	-0.26
	Green H_2	4.87	4.41	6.58	4.07	9.52	7.42	-0.67	-4.77	-0.78	-0.48	-0.29	-0.93
FT fuel	Black H_2	6.78	3.88	6.47	6.72	6.70	6.73	1.69	2.94	1.43	2.19	0.96	1.05
	Green H_2	6.17	5.40	8.21	5.20	11.78	9.25	0.09	-1.33	-0.17	0.59	0.96	-0.56
DME	Black H_2	5.86	3.55	5.62	5.81	5.80	5.83	0.31	-0.04	0.17	0.58	-0.09	-0.04
	Green H_2	5.36	4.82	6.86	4.54	8.64	7.39	-0.62	-3.62	-0.77	-0.35	-0.09	-0.98
Olefin	Black H_2	4.33	2.52	4.14	4.30	4.28	4.31	-0.29	-1.77	-0.46	0.03	-0.77	-0.71
	Green H_2	3.92	3.54	5.32	3.26	7.74	6.01	-1.40	-4.67	-1.57	-1.08	-0.77	-1.82
Gasoline	Black H_2	5.41	3.29	5.19	5.37	5.36	5.38	-0.34	-2.07	-0.54	0.04	-0.90	-0.84
	Green H_2	4.93	4.49	6.57	4.16	9.39	7.38	-1.64	-5.46	-1.84	-1.26	-0.90	-2.13

S7. Future estimation of black and green H_2

Basically, green H_2 price was estimated based on the price of green electricity type (e.g., solar-based, wind-based, bioenergy) and technology development of water electrolyzer (e.g., alkaline – ALK, proton exchange membrane – PEM, solid oxide electrolyzer cell – SOEC). The price of various renewable-based electricity was assumed and estimated from references [55–57], and presented in Table S7.1. Here, we also considered the potential development of electrolyzers with higher efficiency and lower capital cost, resulting in lower green H_2 price, in which the techno-economic characteristics was estimated and presented in Table S7. 2 – S7.4 [55,58–60]. Finally, green H_2 price was estimated and provided in Table S7.5.

Table S7.1. Estimated global renewable electricity price for 2020 – 2030

	Unit	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Solar Photovoltaic	$/kWh	0.085	0.082	0.078	0.075	0.071	0.068	0.064	0.061	0.057	0.054	0.050
Onshore wind	$/kWh	0.056	0.054	0.053	0.051	0.050	0.048	0.046	0.045	0.043	0.042	0.040
Offshore wind	$/kWh	0.127	0.120	0.114	0.107	0.101	0.094	0.088	0.081	0.074	0.068	0.061
Concentrated solar panel	$/kWh	0.185	0.177	0.168	0.160	0.151	0.143	0.134	0.126	0.117	0.109	0.100
Bioenergy	$/kWh	0.062	0.062	0.062	0.061	0.061	0.061	0.061	0.061	0.060	0.060	0.060
Hydropower	$/kWh	0.047	0.046	0.046	0.045	0.044	0.044	0.043	0.042	0.041	0.041	0.040
Geothermal	$/kWh	0.072	0.071	0.071	0.070	0.069	0.069	0.068	0.067	0.066	0.066	0.065
Assumed for solar&wind	$/kWh	0.071	0.068	0.065	0.063	0.060	0.058	0.055	0.053	0.050	0.048	0.045

Table S7.2. Assumption and estimated techno-economic characteristics for alkaline electrolyser (ALK) [58]

	Unit	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Efficiency (LHV)	%	67%	67%	67%	67%	67%	67%	67%	68%	68%	68%	68%
Efficiency	kWh/kgH_2	50	50	50	50	50	50	49	49	49	49	49
Stack lifetime	Operating hours	80000	81000	82000	83000	84000	85000	86000	87000	88000	89000	90000
CAPEX	$/kW	750	723	696	669	642	615	588	561	534	507	480
OPEX												
Stack replacement cost	$/kW	340	723	696	669	642	615	588	561	534	507	215
Stack replacement	% of stack	10%	10%	10%	10%	10%	9%	9%	9%	9%	9%	9%
OPEX-FC	% of CAPEX	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%
Capacity	kWh	20,000	20,000	20,000	20,000	20,000	20,000	20,000	20,000	20,000	20,000	20,000
Operability	h/y	8,000	8,000	8,000	8,000	8,000	8,000	8,000	8,000	8,000	8,000	8,000

Table S7.3. Assumption and estimated techno-economic characteristics for proton exchange membrane electrolyser (PEM) [58]

	Unit	**2020**	**2021**	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Efficiency (LHV)	%	58%	59%	60%	60%	61%	62%	63%	63%	64%	65%	66%
Efficiency	kWh/kgH_2	57	57	56	55	55	54	53	53	52	51	51
Stack lifetime	Operating hours	40000	43500	47000	50500	54000	57500	61000	64500	68000	71500	75000
CAPEX	$/kW	1,200	1,150	1,100	1,050	1,000	950	900	850	800	750	700
OPEX												
Stack replacement cost	$/kW	420	399	378	357	336	315	294	273	252	231	210
Stack replacement	% of stack	20%	18%	17%	16%	15%	14%	13%	12%	12%	11%	11%
OPEX-FC	% of CAPEX	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%
Capacity	kWh	20,000	20,000	20,000	20,000	20,000	20,000	20,000	20,000	20,000	20,000	20,000
Operability	h/y	8,000	8,000	8,000	8,000	8,000	8,000	8,000	8,000	8,000	8,000	8,000

Table S7.4. Assumption and estimated techno-economic characteristics for solid oxide electrolyzer cell (SOEC) [58]

	Unit	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Efficiency (LHV)	%	78%	78%	78%	78%	79%	79%	79%	80%	80%	80%	81%
Efficiency	kWh/kgH_2	43	43	43	42	42	42	42	42	42	42	41
Stack lifetime	Operating hours	20,000	22,000	24,000	26,000	28,000	30,000	32,000	34,000	36,000	38,000	40,000
CAPEX	$/kW	4,200	3,960	3,720	3,480	3,240	3,000	2,760	2,520	2,280	2,040	1,800
OPEX												
Stack replacement cost	$/kW	2,100	1,980	1,860	1,740	1,620	1,500	1,380	1,260	1,140	1,020	900
Stack replacement	% of stack	40%	36%	33%	31%	29%	27%	25%	24%	22%	21%	20%
OPEX-FC	% of CAPEX	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%	2%
Capacity	kWh	20,000	20,000	20,000	20,000	20,000	20,000	20,000	20,000	20,000	20,000	20,000
Operability	h/y	8,000	8,000	8,000	8,000	8,000	8,000	8,000	8,000	8,000	8,000	8,000

Table S7.5. Estimated of green hydrogen price in 2020 – 2030

Electrolyzer type	Energy source	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
ALK	SolarPV	5.041	5.068	4.840	4.613	4.388	4.164	3.942	3.722	3.502	3.284	2.924
	Onshore wind	3.589	3.714	3.584	3.454	3.326	3.199	3.073	2.948	2.823	2.700	2.434
	Offshore wind	7.144	7.013	6.627	6.243	5.862	5.483	5.106	4.731	4.358	3.987	3.474
	CSP	10.049	9.815	9.326	8.841	8.358	7.878	7.401	6.926	6.454	5.984	5.372
	Bioenergy	3.890	4.084	4.022	3.962	3.902	3.843	3.784	3.727	3.669	3.613	3.413
	Hydropower	3.138	3.309	3.225	3.141	3.058	2.976	2.895	2.815	2.735	2.656	2.434
	Geothermal	4.390	4.558	4.471	4.384	4.299	4.214	4.130	4.047	3.965	3.883	3.658
PEM	SolarPV	6.532	6.132	5.753	5.392	5.047	4.716	4.397	4.090	3.793	3.505	3.226
	Onshore wind	4.867	4.596	4.343	4.104	3.879	3.664	3.459	3.263	3.075	2.893	2.718
	Offshore wind	8.944	8.339	7.760	7.204	6.668	6.152	5.652	5.168	4.698	4.242	3.798
	CSP	12.274	11.517	10.790	10.090	9.414	8.760	8.127	7.512	6.914	6.334	5.768
	Bioenergy	5.212	5.016	4.835	4.668	4.512	4.365	4.227	4.095	3.970	3.850	3.735
	Hydropower	4.351	4.137	3.940	3.756	3.584	3.422	3.268	3.121	2.981	2.847	2.718
	Geothermal	5.786	5.554	5.339	5.138	4.949	4.770	4.600	4.437	4.282	4.133	3.989
SOEC	SolarPV	10.913	9.922	9.046	8.258	7.540	6.879	6.264	5.687	5.143	4.626	4.133
	Onshore wind	9.667	8.762	7.972	7.269	6.635	6.057	5.525	5.030	4.568	4.132	3.720
	Offshore wind	12.717	11.588	10.575	9.650	8.797	8.001	7.253	6.544	5.868	5.221	4.599
	CSP	15.209	13.988	12.883	11.869	10.925	10.040	9.203	8.406	7.643	6.910	6.202
	Bioenergy	9.924	9.079	8.347	7.702	7.126	6.605	6.129	5.691	5.284	4.904	4.547
	Hydropower	9.280	8.416	7.665	7.001	6.406	5.867	5.374	4.917	4.493	4.095	3.720
	Geothermal	10.354	9.486	8.731	8.063	7.464	6.921	6.423	5.963	5.534	5.133	4.754
ALK	SolarPV&wind-based	4.315	4.391	4.212	4.034	3.857	3.682	3.508	3.335	3.163	2.992	2.679

Also, black H_2 was assumed to be produced via steam methane reforming with carbon capture, in which H_2 price depends on natural gas price, as followed reference [61], extracted and shown in Fig. S7.1. Noted that future of natural gas price is unstable and not readily available, we estimated based on three big market of natural gas (USA, EU, and Asia) [52,53,62,63], as shown in Table S7.6.

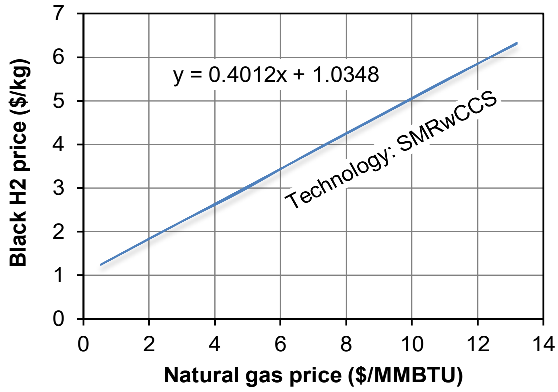


Fig. S7.1. Correlation of H_2 price and natural gas price via technology of steam methane reforming integrated with carbon capture process (SMRwCCS).

Table S7.6. Estimation for natural gas prices and black H_2 price

Natural gas price ($/MMBTU):														
Market	Assumption	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
USA	Pessimistic (World Bank)	3.15	2.50	2.70	2.81	2.92	3.04	3.16	3.29	3.42	3.56	3.70	3.85	4.00
Europe	Medium (World Bank)	7.68	4.50	4.50	4.70	4.92	5.14	5.37	5.61	5.87	6.13	6.41	6.70	7.00
Asia	Optimistic (World Bank)	8.10	8.10	8.11	8.15	8.19	8.23	8.27	8.31	8.35	8.39	8.43	8.47	8.51
USA	Pessimistic (WEO)	3.15	2.66	2.57	2.59	2.61	2.63	2.65	2.67	2.69	2.71	2.73	2.75	2.77
Europe	Medium (WEO)	7.68	4.77	5.96	5.89	5.81	5.74	5.67	5.60	5.53	5.46	5.39	5.33	5.26
Asia	Optimistic (WEO)	8.10	5.73	6.64	6.64	6.65	6.65	6.66	6.67	6.67	6.68	6.68	6.69	6.69
USA	Pessimistic (EIA)	3.15	3.29	3.43	3.58	3.74	3.91	4.08	4.26	4.45	4.64	4.85	5.06	5.28
Europe	Medium (EIA)	7.68	8.02	8.37	8.74	9.12	9.53	9.95	10.38	10.84	11.32	11.82	12.34	12.88
Asia	Optimistic (EIA)	8.10	8.46	8.83	9.22	9.62	10.05	10.49	10.95	11.43	11.94	12.46	13.01	13.58
Black H_2 price ($/kg):														
Market	Assumption	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
USA	Pessimistic (World Bank)	2.30	2.04	2.12	2.16	2.21	2.25	2.30	2.35	2.41	2.46	2.52	2.58	2.64
Europe	Medium (World Bank)	4.12	2.84	2.84	2.92	3.01	3.10	3.19	3.29	3.39	3.49	3.61	3.72	3.84
Asia	Optimistic (World Bank)	4.28	4.29	4.29	4.30	4.32	4.34	4.35	4.37	4.38	4.40	4.42	4.43	4.45
USA	Pessimistic (WEO)	2.30	2.10	2.07	2.07	2.08	2.09	2.10	2.11	2.11	2.12	2.13	2.14	2.15
Europe	Medium (WEO)	4.12	2.95	3.43	3.40	3.37	3.34	3.31	3.28	3.25	3.23	3.20	3.17	3.15
Asia	Optimistic (WEO)	4.28	3.33	3.70	3.70	3.70	3.70	3.71	3.71	3.71	3.71	3.71	3.72	3.72
USA	Pessimistic (EIA)	2.30	2.35	2.41	2.47	2.54	2.60	2.67	2.74	2.82	2.90	2.98	3.06	3.15
Europe	Medium (EIA)	4.12	4.25	4.39	4.54	4.70	4.86	5.02	5.20	5.38	5.58	5.78	5.98	6.20
Asia	Optimistic (EIA)	4.28	4.43	4.58	4.73	4.90	5.07	5.24	5.43	5.62	5.82	6.03	6.25	6.48

Table S7.7. Estimated CO_2-based fuel UPC in short-term future

	MeOH			FT			DME			Olefin			Gasoline		
	2020	2025	2030	2020	2025	2030	2020	2025	2030	2020	2025	2030	2020	2025	2030
Data	5.96	5.08	3.82	7.32	6.25	4.73	6.41	5.51	4.24	4.82	4.09	3.06	5.98	5.13	3.93
	4.50	4.10	3.33	5.55	5.07	4.00	4.92	4.52	3.74	3.61	3.29	3.00	4.57	4.20	3.45
	8.09	6.41	4.38	9.88	7.86	5.41	8.55	6.86	4.81	6.56	5.18	3.52	8.02	6.41	4.46
	11.03	8.83	6.30	13.43	10.78	7.72	11.52	9.30	6.74	8.97	7.17	5.09	10.83	8.73	6.30
	4.80	4.75	4.32	5.91	5.85	5.33	5.23	5.18	4.74	3.86	3.82	3.47	4.86	4.82	4.40
	4.04	3.88	3.33	5.00	4.80	4.14	4.46	4.30	3.74	3.24	3.11	2.66	4.14	3.98	3.45
	5.31	5.13	4.57	6.52	6.31	5.63	5.74	5.56	4.99	4.28	4.13	3.67	5.35	5.18	4.64
	7.47	5.64	4.13	9.14	6.92	5.10	7.93	6.07	4.55	6.06	4.55	3.31	7.43	5.67	4.22
	5.79	4.57	3.61	7.11	5.64	4.48	6.23	5.00	4.03	4.67	3.68	2.89	5.81	4.65	3.73
	9.91	7.09	4.71	12.08	8.67	5.80	10.39	7.54	5.14	8.05	5.74	3.79	9.76	7.06	4.78

	13.28	9.73	6.70	16.14	11.86	8.20	13.79	10.21	7.15	10.82	7.90	5.42	12.99	9.59	6.69
	6.14	5.28	4.64	7.53	6.49	5.72	6.58	5.72	5.07	4.96	4.26	3.74	6.15	5.33	4.71
	5.27	4.33	3.61	6.47	5.34	4.48	5.70	4.75	4.03	4.25	3.48	2.89	5.31	4.41	3.73
	7.00	5.69	4.90	8.00	6.99	6.03	7.00	6.13	5.33	5.00	4.59	3.95	7.00	5.72	4.96
	11.90	7.82	5.05	14.48	9.56	6.21	12.40	8.28	5.48	9.69	6.34	4.07	11.67	7.76	5.10
	10.64	6.99	4.63	12.96	8.56	5.70	11.13	7.44	5.06	8.65	5.66	3.72	10.46	6.97	4.70
	13.73	8.96	5.52	16.68	10.93	6.78	14.25	9.43	5.95	11.18	7.27	4.45	13.42	8.85	5.55
	16.25	11.02	7.14	19.73	13.42	8.73	16.79	11.51	7.59	13.25	8.96	5.78	15.84	10.83	7.11
	10.90	7.55	5.46	13.28	9.23	6.71	11.39	8.00	5.90	8.87	6.12	4.41	10.71	7.50	5.50
	10.25	6.80	4.63	12.49	8.33	5.70	10.74	7.25	5.06	8.33	5.50	3.72	10.09	6.78	4.70
	11.34	7.87	5.67	13.80	9.61	6.97	11.83	8.33	6.11	9.22	6.38	4.58	11.13	7.80	5.70
Mean	8.74	6.55	4.78	10.64	8.02	5.88	9.19	6.99	5.21	7.06	5.30	3.87	8.64	6.54	4.85

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