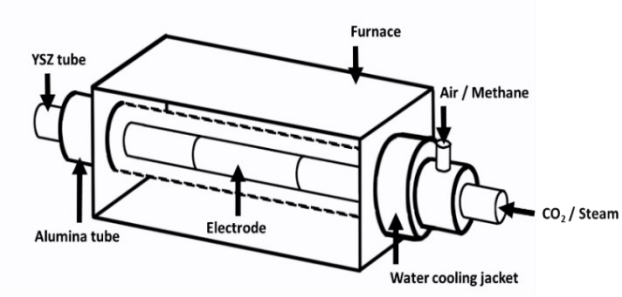
Electronic Supplementary Material (ESI) for Sustainable Energy & Fuels.

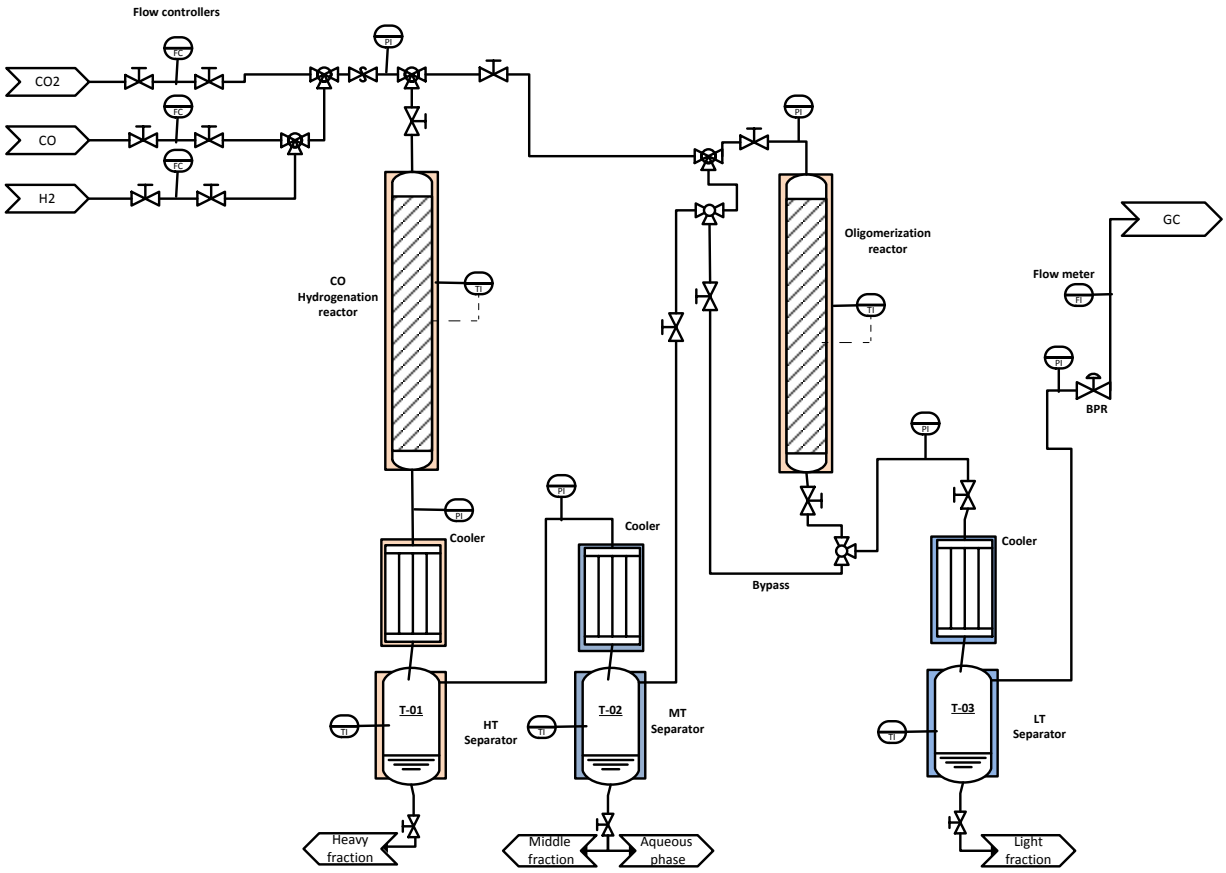
Supplementary Information:

Techno-Economic Analysis of a Sustainable Process for Converting CO_2 and H_2O to Feedstock for Fuels and Chemicals

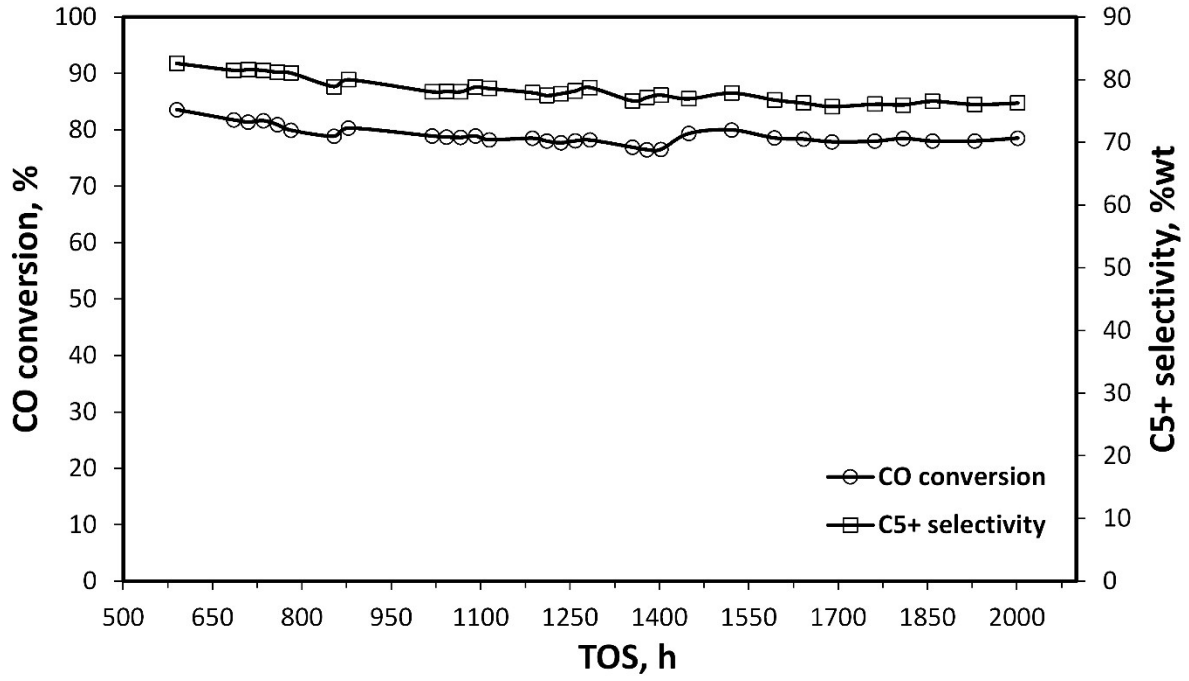
Ani Kulkarni*, Tomy Hos, Miron V. Landau, Daniel Fini, Sarbjit Giddey and Moti Herskowitz*



Supplementary Figure 1. Schematic of test setup used for measurement of solid oxide electrolysis cell

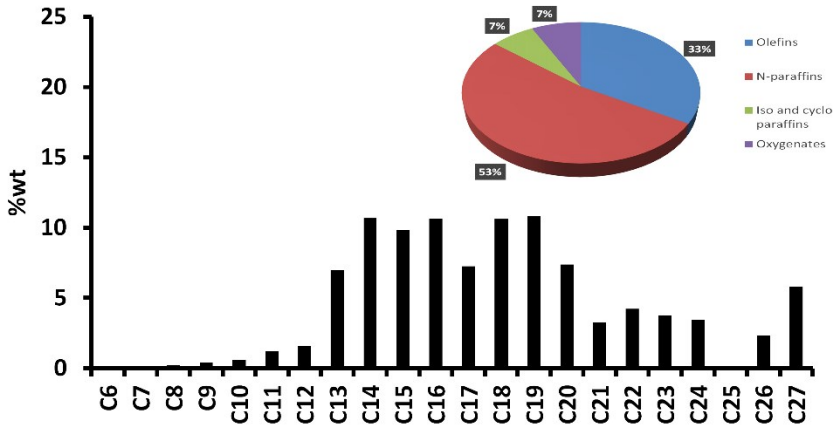


Supplementary Figure 2. Schematic drawing of CO conversion experimental rig

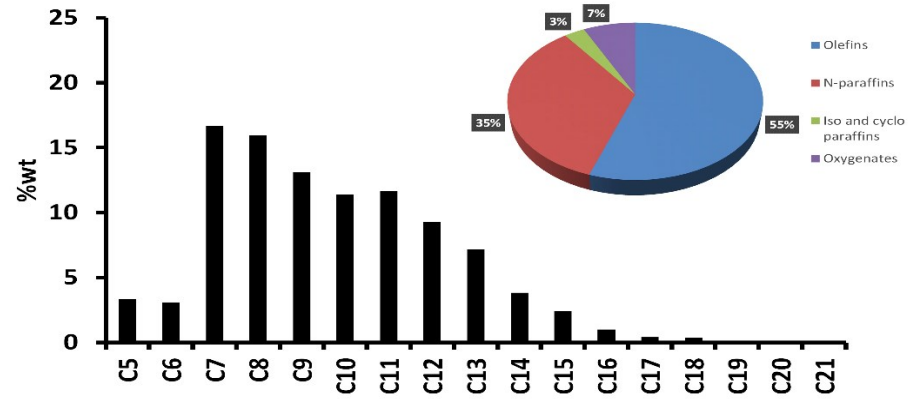


Supplementary Figure 3. 2,000h life test in mini-pilot unit at 50 bar, $WHSV_{CO}$=1.1 g CO h^{-1} $gcat^{-1}$, molar H_2/CO of 0.7 and CO_2 content of 6 v/v%.

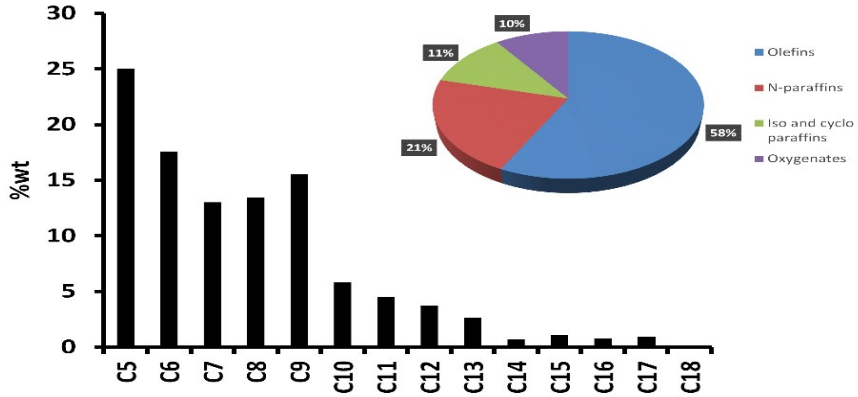
a)



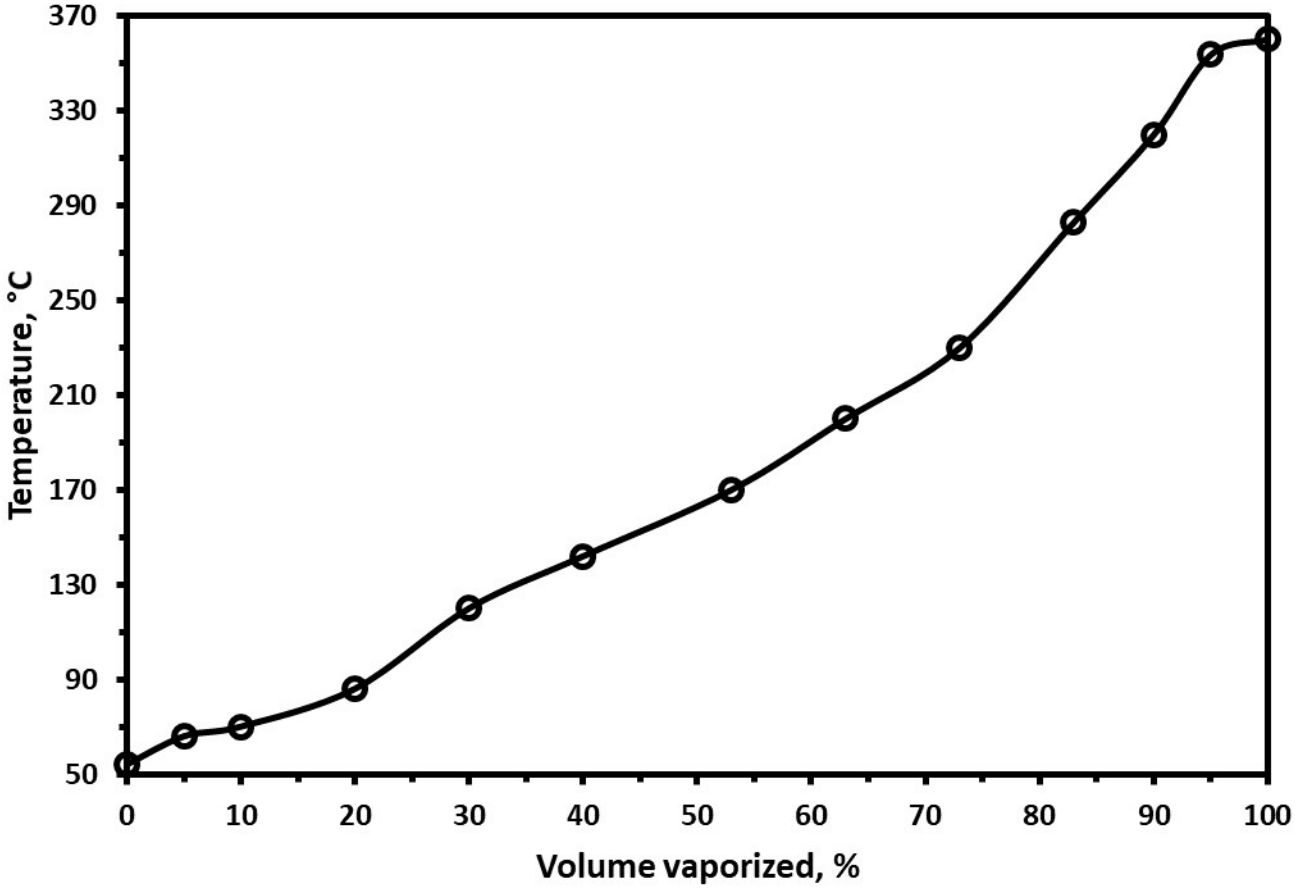
b)



c)



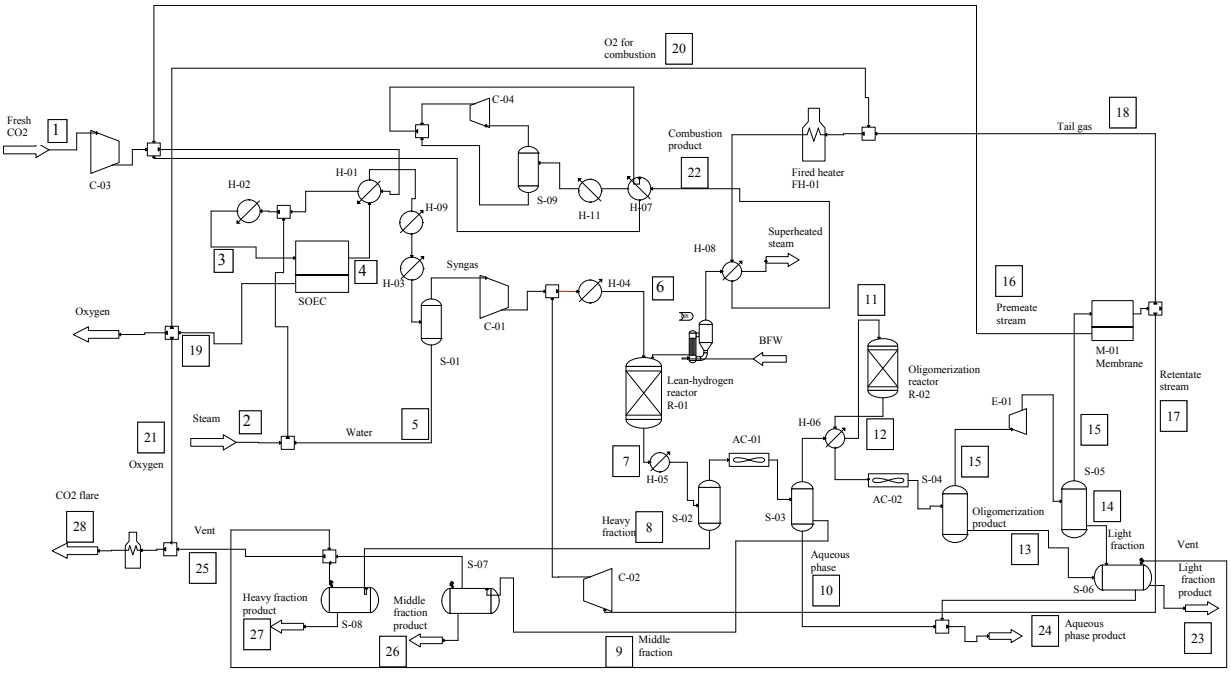
Supplementary Figure 4. Carbon number distribution and composition after 2,000h on stream in mini-pilot unit. a) Effluent from high-temperature separator (25%wt of total product). b) low-temperature separator (55%wt of total product). c) low-temperature separator after oligomerization (20%wt of total product).



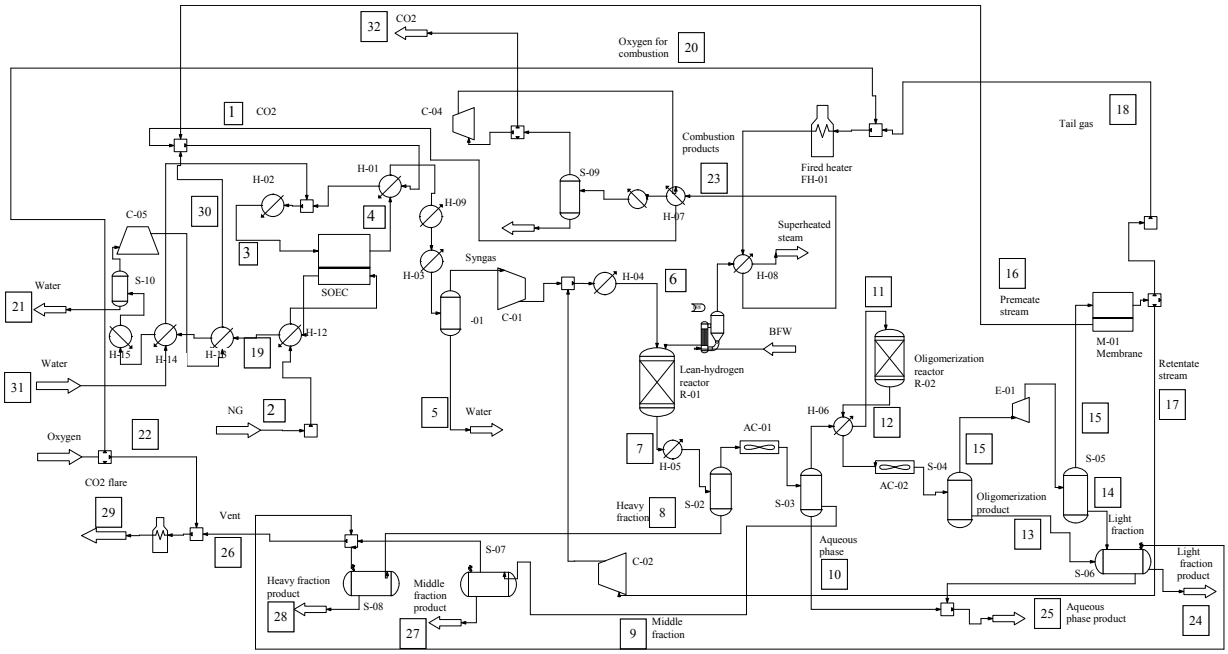
Supplementary Figure 5. Distillation curve of organic liquid product obtained by using the ASTM D86 method.

Supplementary Table 1. Input parameters for the process simulation

Parameter	Value
SOEC Operating conditions	800°C and 9 Bar
Lean hydrogen operating conditions	270-275°C, 60Bar and $WHSV_{CO}$=1 gCO h^{-1} $gcat^{-1}$
Oligomerization operating conditions	230-255°C, 59Bar and WHSV=0.8 h^{-}
SOEC Performance	X_{CO_2}, X_{H_2O}=0.81
Lean hydrogen reactor Performance	X_{CO}=0.80, X_{H_2}=0.73, S_{C5+}=78%.
Oligomerization reactor Performance	$X_{olefins}$=0.78, S_{C5+}=88%.
Methane assisted SOEC Performance	X_{CH_4}=0.89, $S_{Partial\ combustion}$=58%.
Condensation conditions of light product fraction	5°C, 20Bar
Ratio of recycle syngas stream ($Q_{syngas\ recycle}/Q_{Tail\ gas}$)	1.5
SOEC powered by RE productivity	64.0Wh/mol syngas
Methane-assisted SOEC productivity	10.7Wh/mol syngas
Lean Hydrogen productivity	0.17kg liquid product/kg CO



Supplementary Figure 6. Process flow sheet of the integrated process powered by RE



Supplementary Figure 7. Process flow sheet of the integrated process powered by NG

Supplementary Table 2. Detailed mass balance for integrated process powered by RE

Stream no.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Stream name	**Fresh CO2**	**Fresh Water**	**SOEC Inlet**	**SOEC Outlet**	**Water condens.**	**Lean-hydrogen Inlet**	**Lean-hydrogen outlet**	**Heavy fraction product**	**Middle fraction product**	**First aqueues phase**
Temperature, °C	**40**	**40**	**800**	**800**	**40**	**270**	**275**	**200**	**55**	**55**
Pressure, Bar	**1.1**	**1.1**	**9.0**	**8.7**	**8.5**	**60**	**59.7**	**59.5**	**59.4**	**59.4**
Mass Flow rate, kg/h										
CO			760	13,903		15,272	3,053	1	4	
CO_2	8,757		25,494	4,844		7,237	16,312	11	109	
H_2			103	710		771	206	0		
H_2O		4,175	6,702	1,273	1,088	186	543	0		390
CH_4			58	58		369	582	0	2	
C_2H_6						176	302	0	3	
C_2H_4						33	201	0	2	
C_3H_8						124	203	0	6	
C_3H_6						15	268	0	5	
C_4H_{10}						106	211	1	11	
C_4H_8						17	219	1	10	
Oxygenates						6	197			41
C_{5+} (Org. liquid)						90	2,106	528	1,065	
O_2										
Total	**8,757**	**4,175**	**33,117**	**20,788**	**1,088**	**24,402**	**24,402**	**542**	**1,217**	**431**

Stream no.	11	12	13	14	15	16	17	18	19	20
Stream name	**Oligomer. inlet**	**Oligomer. outlet**	**Oligomer. product**	**Oligomer. light product**	**Membrane feed**	**Permeate side**	**Retentate side**	**Tail gas**	**Oxygen**	**Oxygen for Tail gas combustion**
Temperature, °C	**235**	**260**	**97**	**5**	**35**	**35**	**35**	**35**	**800**	**800**
Pressure, Bar	**59.3**	**59.1**	**59.0**	**20.0**	**19.5**	**9.2**	**19.3**	**19.3**	**1.0**	**1.0**
Mass Flow rate, kg/h										
CO	3,047	3,047	5	2	3,040	760	1,368	912		
CO_2	16,191	16,191	121	112	15,958	11,968	2,394	1,596		
H_2	205	205	0		205	103	62	40		
H_2O	152	152	99	51	2	2	0	0		
CH_4	580	580	2	1	577	58	312	208		
C_2H_6	299	299	3	3	293		176	117		
C_2H_4	200	55	0	0	54		33	22		
C_3H_8	197	229	7	8	214		124	90		
C_3H_6	262	26	1	1	24		15	10		
C_4H_{10}	199	223	14	27	182		106	76		
C_4H_8	209	35	2	5	28		17	11		
Oxygenates	158	158	43	107	9		6	3		
C_{5+} (Org. liquid)	513	1,012	594	268	150		90	60		
O_2									12,328	3,063
Total	**22,212**	**22,212**	**891**	**585**	**20,736**	**12,891**	**4,703**	**3,145**	**12,328**	**3,063**

Stream no.	21	22	23	24	25	26	27	28
Stream name	**Oxygen for purge**	**Combustion product**	**Light fraction product**	**Aqueous phase**	**Vent**	**Middle fraction product**	**Heavy fraction product**	**CO2 flare**
Temperature, °C	**800**	**294**	**30**	**25**	**25**	**25**	**60**	**30**
Pressure, Bar	**1.0**	**1.0**	**2.0**	**2.0**	**1.0**	**2.0**	**1.0**	**1.0**
Mass Flow rate, kg/h								
CO					12			
CO_2		4,769			353			503
H_2								
H_2O		1,439		540				73
CH_4					5			
C_2H_6					9			
C_2H_4					2			
C_3H_8					21			
C_3H_6					7			
C_4H_{10}			41			11	1	
C_4H_8			7			10	1	
Oxygenates				191		0	0	
C_{5+} (Org. liquid)			862			1,065	528	
O_2	168					0	0	
Total	**168**	**6,208**	**910**	**731**	**409**	**1,086**	**530**	**576**

Supplementary Table 3. Detailed mass balance for integrated process powered by NG

Stream no.	1	2	3	4	5	6	7	8	9	10
Stream name	**Recycled CO2**	**Fresh Methane**	**SOEC Inlet**	**Cathode side Outlet**	**Water condens.**	**Lean-hydrogen Inlet**	**Lean-hydrogen outlet**	**Heavy fraction product**	**Middle fraction product**	**First aqueous phase**
Temperature, °C	**150**	**40**	**800**	**800**	**40**	**270**	**275**	**200**	**55**	**55**
Pressure, Bar	**9.0**	**9.0**	**9.0**	**8.7**	**8.5**	**60**	**59.7**	**59.5**	**59.4**	**59.4**
Mass Flow rate, kg/h										
CO			3,903	13,900		15,267	3,049	1	6	
CO_2	5,015		19,390	3,684		5,858	14,829	11	166	
H_2			539	701		753	173			
H_2O			1,793	341	320	21	459			401
CH_4		3,375	544	544		1,418	1,633	1	7	
C_2H_6						177	304		5	
C_2H_4						33	203		3	
C_3H_8						108	189		7	
C_3H_6						15	270		10	
C_4H_{10}						96	201	1	17	
C_4H_8						17	222	1	19	
Oxygenates						5	201			89
C_{5+} (Org. liquid)						66	2,101	579	1,166	
O_2										
Total	**5,015**	**3,375**	**26,169**	**19,170**	**320**	**23,834**	**23,834**	**594**	**1,406**	**490**

Stream no.	11	12	13	14	15	16	17	18	19	20	21
Stream name	**Oligomer. inlet**	**Oligomer. outlet**	**Oligomer. product**	**Oligomer. light product**	**Membrane feed**	**Permeate side**	**Retentate side**	**Tail gas**	**Anode side outlet**	**Oxygen for Tail gas combustion**	**Water**
Temperature, °C	**235**	**260**	**97**	**5**	**35**	**35**	**35**	**35**	**800**	**25**	**40**
Pressure, Bar	**59.3**	**59.1**	**59.0**	**20.0**	**19.5**	**9.2**	**19.3**	**19.3**	**5.0**	**1.0**	**5.0**
Mass Flow rate, kg/h											
CO	3,041	3,041	3	2	3,036	759	1,366	911	3,144		
CO_2	14,652	14,652	74	83	14,495	10,871	2,174	1,450	3,517		13
H_2	173	170			170	87	52	31	453		
H_2O	58	58	4	51	3	2		1	2,879		2,854
CH_4	1,625	1,625	3	2	1,620	162	875	583	382		
C_2H_6	299	299	2	3	294		177	117			
C_2H_4	201	56			56		33	23			
C_3H_8	182	202	4	7	191		108	83			
C_3H_6	260	26		1	25		15	10			
C_4H_{10}	183	206	12	28	166		96	70			
C_4H_8	202	34	1	4	29		17	12			
Oxygenates	112	112	13	89	10		5	5			
C_{5+} (Org. liquid)	356	863	446	307	110		66	44			
O_2										4,395	
Total	**21,344**	**21,344**	**562**	**577**	**20,205**	**11,881**	**4,984**	**3,340**	**10,375**	**4,395**	**2,867**

Stream no.	22	23	24	25	26	27	28	29	30	31	32
Stream name	**Oxygen for vent stream**	**Combustion product**	**Light fraction product**	**Aqueous phase**	**Vent**	**Middle fraction product**	**Heavy fraction product**	**CO_2 flare**	**Anode recycle stream**	**Water feed SOEC**	**CO_2 Purge**
Temperature, °C	**25**	**294**	**30**	**25**	**25**	**25**	**60**	**30**	**800**	**25**	**30**
Pressure, Bar	**1.0**	**1.0**	**2.0**	**2.0**	**1.0**	**2.0**	**1.0**	**1.0**	**9.0**	**1.0**	**1.0**
Mass Flow rate, kg/h											
CO					12				3,144		
CO_2		5,569			334			516	3,504		554
H_2									453		
H_2O		2,166		456				95	26	1,767	
CH_4					13				382		
C_2H_6					10						
C_2H_4					3						
C_3H_8					18						
C_3H_6					11						
C_4H_{10}			40			17	1				
C_4H_8			5			19	1				
Oxygenates				191			0				
C_{5+} (Org. liquid)			753			1,166	579				
O_2	210		0								
Total	**210**	**7,735**	**798**	**647**	**401**	**1,202**	**581**	**611**	**7,509**	**1,767**	**554**

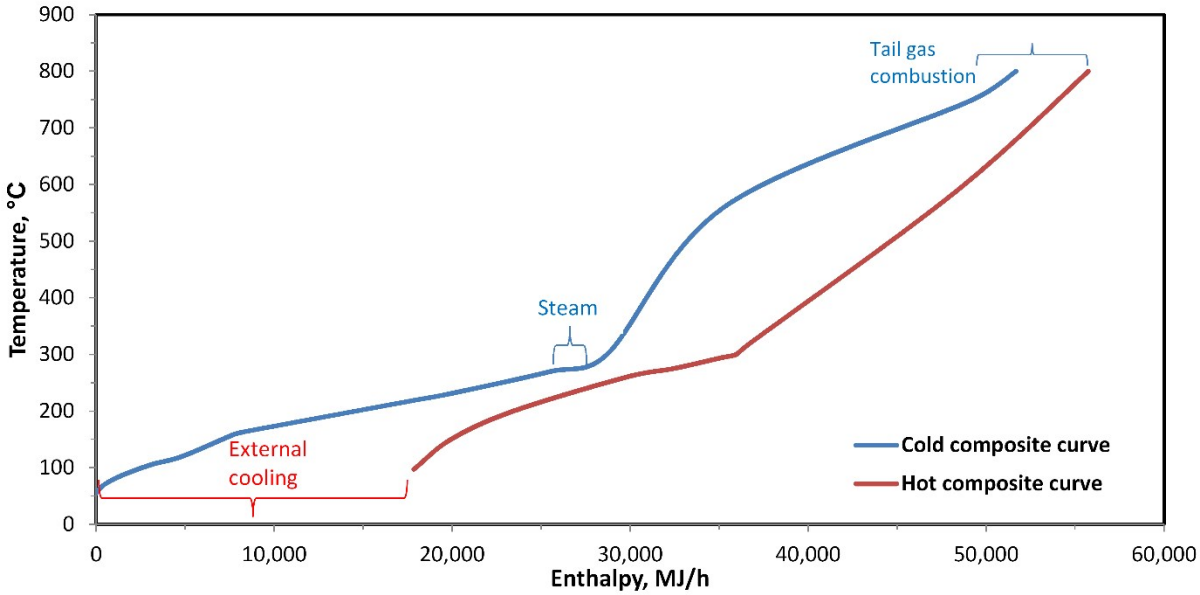
Supplementary Table 4. Energy balance for the established heat exchanger network

Heat exchanger	Stream number	Type	Tin, C	Tout, C	Heat load, MJ/h
H-01	4	Hot	800	320	16,822
	1+16+22	Cold	86	750	
H-02[a]	3	Cold	492	800	14,800
H-03[b]	4	Hot	150	40	6,200
H-04	6	Cold	164	270	4,086
	Steam	Hot	300	260	
H-05	7	Hot	275	200	2,677
	BFW	Cold	159	217	
H-06	11	Cold	55	230	5,233
	12	Hot	260	97	
H-07	22	Cold	70	120	1,560
	22	Hot	294	80	
H-08	Steam	Cold	270	300	2,395
	22	Hot	588	294	
H-09	4	Hot	320	150	5,261
	BFW	Cold	105	270	
H-10[a]	BFW	Cold	217	270	2,538
H-11 [b]	22	Hot	80	40	3,345
AC-01[c]	11	Hot	200	55	6,506
AC-02[c]	12	Hot	97	55	1,672

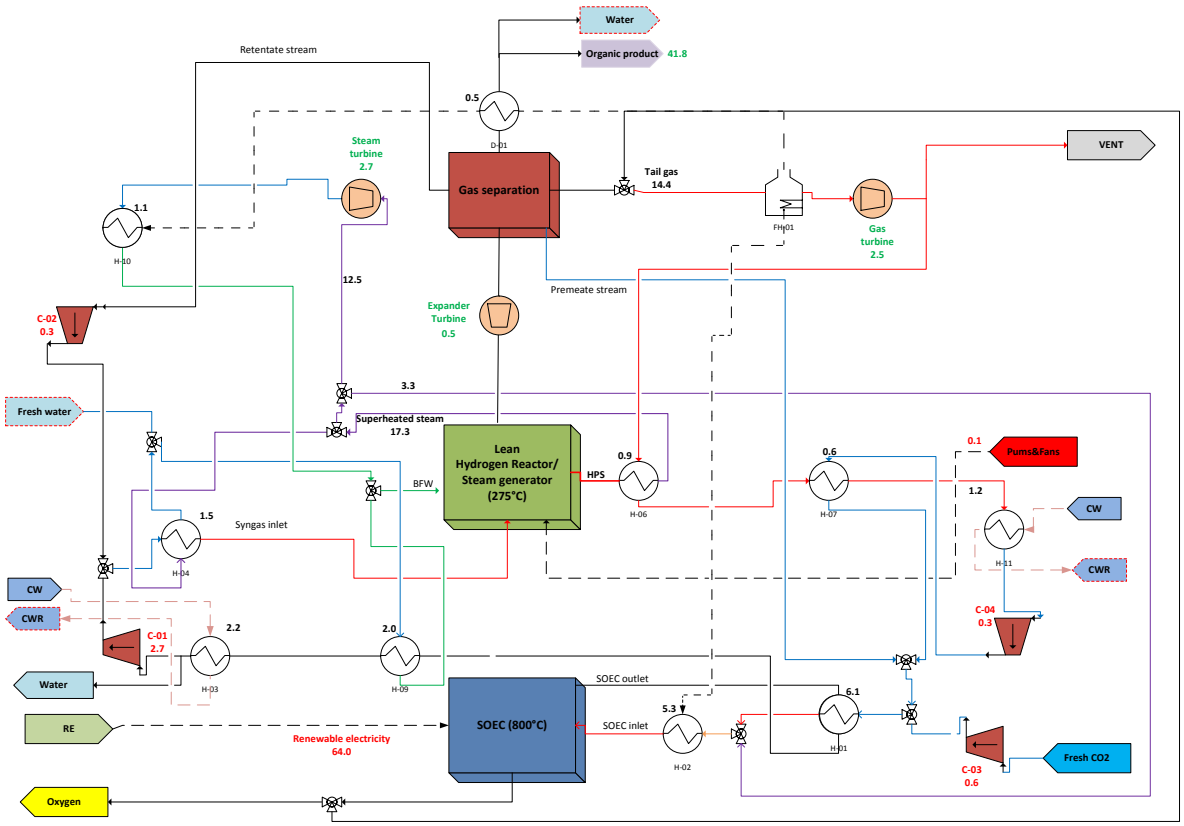
[a]Heating by tail gas combustion.

[b]Cooling by cold water.

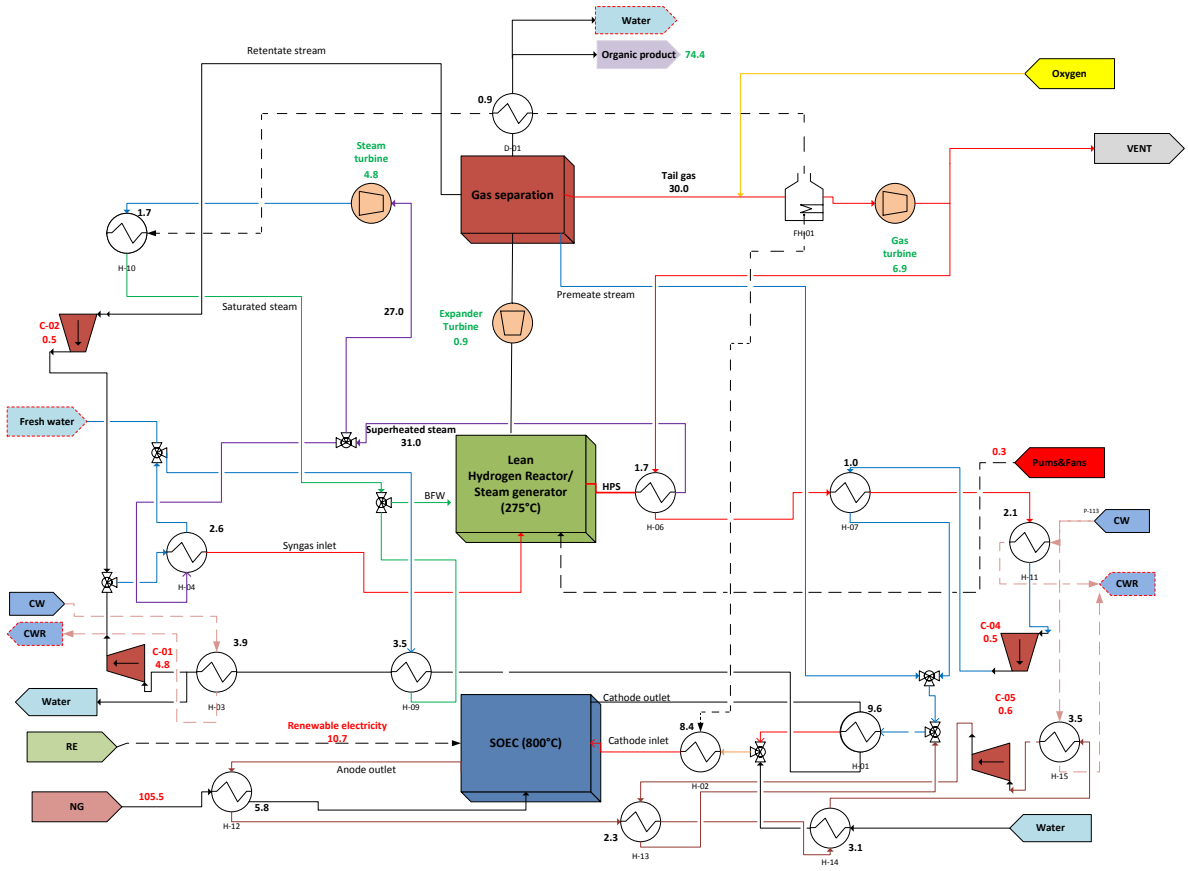
[c]Cooling by air cooler.



Supplementary Figure 8. Composite curve of the integrated process. A minimum pinch point of 10°C was defined for heat exchangers network.



Supplementary Figure 9. Energy flow diagram of overall process powered by RE. The numbers indicate the energy content or power requirement of each stream in W-h per mol syngas produced in the SOEC.



Supplementary Figure 10. Energy flow diagram for Methane-assisted SOEC process. The numbers indicate the energy content or power requirement of each stream in W-h per mol syngas produced in the cathode side.

Tag No	Description	Size	Purchase cost, $M	Ref.
R-01	Lean hydrogen reactor	No. of tubes:1,830, D=0.038m, H=12m	3.00	Manufacturer
C-01	Backpressure steam turbine compressor	M_{steam}=5.8kg/sec, P=2.1MW	1.60	Manufacturer
C-02	Lean hydrogen Recycle compressor	P=0.2MW	0.51	
C-03&E-01	CO_2 Turbo expander-compressor	P=0.4MW	1.25	Manufacturer
C-04	Tail gas Recycle compressor	P=0.2MW	0.51	
R-02	Oligomerization reactor	V=25m^3	0.13	[1]
H-01	Heat exchanger	A=300m^2	0.15	
H-02	Heat exchanger	A=110m^2	0.06	
H-03	Heat exchanger	A=130m^2	0.07	
H-04	Heat exchanger	A=75m^2	0.07	
H-05	Heat exchanger	A=180m^2	0.16	
H-06	Heat exchanger	A=300m^2	0.30	
H-07	Heat exchanger	A=30m^2	0.03	
H-08	Heat exchanger	A=95m^2	0.09	
H-09	Heat exchanger	A=300m^2	0.30	
H-10	Heat exchanger	A=15m^2	0.01	
H-11	Heat exchanger	A=100m^2	0.06	
A-01	Air cooler	A=11m^2	0.02	
A-02	Air cooler	A=6 m^2	0.01	
S-01	Gas liquid separator	V=3.5 m^3	0.07	
S-02	Gas liquid separator	V=1.5 m^3	0.09	
S-03	Gas liquid-liquid separator	V=2.0 m^3	0.12	
S-04	Gas liquid separator	V=0.7 m^3	0.06	
S-05	Gas liquid separator	V=1.5 m^3	0.06	
S-06	Gas liquid-liquid separator	V=1.8 m^3	0.06	
S-07	Gas liquid separator	V=1.0 m^3	0.04	
S-08	Gas liquid separator	V=0.5 m^3	0.03	
S-09	Gas liquid separator	V=0.7m^3	0.03	
C-01	Cooling tower&Pumps	Q=0.088 m^3/sec	0.12	[1]
P-01/02/03/04	Single-stage centrifugal pumps	Q=0.002 m^3/sec	0.03	[1]
M-01	Polymeric membrane	A=300m2	0.15	[3-4]
G-01	Gas Turbine	P=2.0MW	1.50	[5-6]

D-01	Distillation unit	D=0.4m, H=5m, Q=0.42MW	0.10	
	Total		**10.79**	

Supplementary Table 5. Summary of purchase cost for main equipment units[a]

[a] Cost data derived from CHAMCAD costing tool if not stated otherwise

Supplementary Table 6. Summary of additional main equipment units for MPE[a]

Tag No	Description	Size	Purchase cost, $M	Ref.
C-05	Anode Recycle compressor	P=0.3MW	0.72	
H-12	Heat exchanger	A=120m^2	0.07	
H-13	Heat exchanger	A=50m^2	0.04	
H-14	Heat exchanger	A=85m^2	0.06	
H-15	Heat exchanger	A=100m^2	0.06	
S-10	Gas liquid separator	V=0.9m^3	0.04	
H-01	Gas Turbine extension	P=3.0MW	0.60	[5-6]
C-01	Cooling tower extension	Q=0.123m^3/sec	0.02	[1]
P-05/06	Single-stage centrifugal pumps	Q=0.001m^3/sec	0.01	[1]
	Total		**1.62**	

[a] Equipment costs were obtained from CHEMCAD if not stated otherwise.

Supplementary Table 7. Cost of utilities and materials

Utility/Material	Cost, $/ton	Units	SOEC powered by RE		Methane-assisted SOEC		Ref.
			Quantity, ton/year	Cost M$/year	Quantity, ton/year	Cost M$/year	
Cooling water	0.03	$/ton	2,500,000	0.08	3,540,000	0.11	[1]
Process water	0.5	$/ton	33,400	0.02	-	-	[1]
CO_2 capture	22	$/ton	70,056	1.54	-	-	[7-8]
Oxygen	24	$/ton	-72,784	-1.75	36,832	0.88	[9]
Waste water treatment	2	$/ton	4,320	0.01	4,320	0.01	[1]
Fe catalyst	30,000[a]	$/ton	15[b]	0.45	15	0.45	
ZSM-5 catalyst	30,000[a]	$/ton	15[b]	0.45	15	0.45	
Natural gas[c]	195	$/ton			27,000	5.27	[10]

[a] Own assumption.

[b] Catalyst replacement every one year was assumed based on the exp. results.

[C] The cost was translated from 3.9$/MMBTU.

Supplementary Table 8. Annual operational expenses for production of 500bpd[1-2]

Fixed expenses	**SOEC powered by RE, $M**	**Methane-assisted SOEC, $M**
Maintenance[a]	2.87	3.21
Operating labour[b]	0.90	0.90
Laboratory costs[c]	0.23	0.23
Supervision[d]	0.23	0.23
Plant overheads[e]	0.45	0.45
Capital charges[f]	1.72	1.92
Local taxes[g]	1.15	1.28
Insurance[h]	1.15	1.28
Total fixed expenses	**8.69**	**9.49**
Variable expenses		
Raw materials[i]	1.56	0.88
Catalysts	0.90	0.90
Miscellaneous operating materials[j]	0.29	0.32
Utilities	0.08	0.11
Oxygen credit	-1.75	-
Total variable expenses	**1.08**	**2.22**
Indirect cost[k]	**1.47**	**1.76**
Energy expenses	**19.20**	**6.15**
Annual production expenses	**30.44**	**19.61**

[a] 5% of fixed capital. Includes: cost of maintenance labor and the materials needed for the maintenance; [b] 3 operators/shift*5 shifts*60,000$; [c] 25% of Operating labor; [d] 25% of operating labor; [e] 50% of operating labor. Includes: general management, general clerical staff and safety; [f] 3% of fixed capital. Interest payments due on any debt or loans used to finance the project; [g] 2% of fixed capital; [h] 2% of fixed capital; [i]Cost of CO_2 capture and process water; [j] 10% of

maintenance expenses. Includes: safety clothing, accessories; [k] 15% of fixed and variable costs. Includes: Sales expense, overheads and Contingency.

Supplementary Table 9. Assumptions for economic model

Parameter	**Valve**
Economic plant life	30 years
Discount rate	10%
Construction time	2 years
1st year	66% of fixed capital
2nd year	34% of fixed capital+ Working capital+ 30% of fixed costs
3rd year	85% of design basis production rate
Fixed expenses growth rate	0.5%/year
Productivity degradation rate	0 %/year
Plant operation time	8,000h/year

Supplementary Table 10. Utilities requirements for different Carbon recycle ratios

Utility/Material	**Units**	**Carbon recycle ratios**		
		0	**0.5**	**0.95**
Cooling water	ton/year	2,127,500	2,327,500	2,500,000
Process water	ton/year	50,100	40,080	33,400
CO2 capture	ton/year	210,040	140,440	70,056
Oxygen	ton/year	-64,152	-68,152	-72,784
Waste water treatment	ton/year	3,542	3,974	4,320
Fe catalyst	ton/year	13	14	15
ZSM-5 catalyst	ton/year	13	14	15

Supplementary Table 11. Economic parameters for different Carbon recycle ratios

Carbon recycle ratio	**0**	**0.5**	**0.95**
Plant installed cost, $M	**40.5**	**43.39**	**44.59**
SOEC installed cost, $M	**12.82**	**12.82**	**12.82**
Total capital investment (TCI), $M	**55.98**	**59.02**	**60.28**
Annual expenses	$M		
Maintenance	2.67	2.81	2.87
Operating labour	0.9	0.9	0.9
Laboratory costs	0.23	0.23	0.23
Supervision	0.23	0.23	0.23
Plant overheads	0.45	0.45	0.45
Capital charges	1.6	1.69	1.72
Local taxes	1.07	1.12	1.15
Insurance	1.07	1.12	1.15
Total fixed expenses	**8.22**	**8.55**	**8.69**
Variable expenses			
Raw materials	4.65	3.11	1.56
Catalysts	0.81	0.84	0.9
Miscellaneous operating materials	0.27	0.28	0.29
Utilities	0.07	0.08	0.08
Oxygen credit	-1.54	-1.64	-1.75
Total variable expenses	**4.26**	**2.67**	**1.08**
Indirect cost	**1.87**	**1.68**	**1.47**
Energy expenses	**18.3**	**18.7**	**19.2**
Annual production expenses	**32.65**	**31.6**	**30.44**
LCOP, $/liter of liquid product	**1.62**	**1.43**	**1.29**

Supplementary Table 12. Economic parameters for different plant capacities.

Plant scale, bpd	**200**	**500**	**1,500**	**5,000**
Total capital investment (TCI), $M	**34.79**	**60.28**	**116.55**	**239.88**
Annual expenses		$M		
Maintenance	1.66	2.87	5.55	11.43
Operating labour	0.90	0.90	1.20	1.50
Laboratory costs	0.23	0.23	0.30	0.38
Supervision	0.23	0.23	0.30	0.38
Plant overheads	0.45	0.45	0.60	0.75
Capital charges	0.99	1.72	3.33	6.86
Local taxes	0.66	1.15	2.22	4.57
Insurance	0.66	1.15	2.22	4.57
Total fixed expenses	**5.78**	**8.69**	**15.72**	**30.43**
Variable expenses				
Raw materials	0.62	1.56	4.67	15.58
Catalysts	0.36	0.90	2.70	9.00
Miscellaneous operating materials	0.17	0.29	0.56	1.14
Utilities	0.03	0.08	0.25	0.84
Oxygen credit	-0.70	-1.75	-5.24	-17.47
Total variable expenses	**0.48**	**1.08**	**2.94**	**9.09**
Indirect cost	**0.94**	**1.47**	**2.80**	**5.93**
Energy expenses	**7.68**	**19.20**	**57.60**	**192.00**
Annual production expenses	**14.88**	**30.44**	**79.06**	**237.45**
LCOP, $/liter of liquid product	**1.64**	**1.29**	**1.06**	**0.91**

Supplementary Table 13. Economic and technical input parameters for battery storage[11-12]

Investment, $/kW	Variable cost, $/MWh	Fixed cost, $/kW	Lifetime, years	Efficiency, %	LCOE, $/MWh
160	2.1	7.2$/kW	15	95	140

Supplementary Table 14. Capex and Opex for plant operated by RE with large scale battery storage

Assumed availability factor	0.3
Total capital investment, $M	331.9
Annual production expenses, $M/year	53.86
LCOP, $/liter of liquid product	2.78

Supplementary References

1. G. Towler, R. Sinnott. *Chemical Engineering Design: Principles, Practice and Economics of Plant and Process Design*, Elsevier, 2012.
2. R. Sinnott. *Chemical Engineering Design*, *4th edition*, Elsevier, 2005.
3. R.W. Baker and K. Lokhandwala, *Industrial & Engineering Chemistry Research*, 2008, **47** 2109-2121.
4. T.C. Merkel, M. Zhou, and R.W. Baker, *Journal of membrane science*, 2012, **389** 441-450.
5. D. Pauschert. *Study of Equipment Prices in the Power Sector*, ESMAP Technical Paper, 2009.
6. EIA, *Capital Cost Estimates for Utility Scale Electricity Generating Plants*, 2016.
7. National Research Council. Climate Intervention: *Carbon Dioxide Removal and Reliable Sequestration*. The National Academies Press, Washington, DC, 2015.
8. L. Irlam, *Global Costs of Carbon Capture and Storage*. GLOBAL CCS INSTITUE, 2017.
9. F.G. Albrecht, D.H. König, N. Baucks, R.U. Dietrich, *Fuel*, 2017, **194** 511-526.
10. EIA, Natural gas prices, https://www.eia.gov/dnav/ng/ng_pri_sum_dcu_nus_a.htm, 2020.
11. IRENA, *Innovation landscape brief: Utility-scale batteries*, International Renewable Energy Agency, Abu Dhabi, 2019.
12. S. Morgenthaler, W. Kuckshinrichs, D. Witthaut, *Applied Energy*, 2020, **260** 114218.