Supplementary Material

Fueling a green future: Unlocking the environmental potential of CO_2-derived power-to-X liquid fuels via life cycle assessment

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SI. Functional units

For the LCA of the integrated fuel production process, the system produces 1230.1 kg/h of liquid fuel from 3000 kg/h of methanol feedstock. Methanol is synthesized from captured CO_2 and green hydrogen (H_2), requiring 4338 kg/h of CO_2 and 624 kg/h of H_2, respectively. To standardize all upstream flows to a common basis, the system was normalized to a functional unit of 1 ton (1000 kg) of fuel produced. The corresponding upstream input requirements, scaled accordingly, are presented below.

Table SI. Scaled Input requirements per 1 t functional unit

Process step	**Input material**	**Scaled quantity (t/t)**
Methanol synthesis	MeOH	2.44
CO_2 capture	CO_2	3.53
H_2 production	H_2	0.51

All values were derived using a proportional scaling factor of 0.8126, based on the liquid fuels output of 1230.1 kg/h. This normalization allows for consistent comparison across subsystems and supports the allocation of environmental impacts per ton of final fuel product.

Table SII. Process contributions of sub-processes of the integrated MTO-MOGD

Scenario	**S1**	**S2**	**S3**	**S4**
Global warming potential (kg CO_2 eq./t)				
Carbon capture	1.6	0.62	17.2	15.9
Water electrolysis	65.7	65.7	65.7	65.7
MeOH synthesis	12.6	12.6	12.6	12.6
MTO-MOGD	2.4	2.4	2.4	2.4
Total	82.3	83.1	97.9	96.6
Ozone formation, human health (kg NOx eq./t)				
Carbon capture	0.005	0.002	0.05	0.03
Water electrolysis	0.21	0.21	0.21	0.21
MeOH synthesis	0.04	0.04	0.04	0.04
MTO-MOGD	0.01	0.01	0.01	0.01
Total	0.26	0.26	0.30	0.28
Freshwater eutrophication (kg P eq./t)				
Carbon capture	0.002	0.001	0.010	0.005
Water electrolysis	0.065	0.065	0.065	0.065
MeOH synthesis	0.013	0.013	0.013	0.013
MTO-MOGD	0.002	0.002	0.002	0.002
Total	0.081	0.082	0.089	0.085
Marine eutrophication (kg N eq./t)				
Carbon capture	0.005	0.0001	0.001	0.010
Water electrolysis	0.004	0.004	0.004	0.004
MeOH synthesis	0.001	0.001	0.001	0.001
MTO-MOGD	0.000	0.000	0.000	0.000
Total	0.010	0.010	0.006	0.015
Land use (m^2a crop/t)				
Carbon capture	0.09	0.04	0.58	0.32
Water electrolysis	4.00	4.00	4.00	4.00
MeOH synthesis	0.78	0.78	0.78	0.78
MTO-MOGD	0.15	0.15	0.15	0.15
Total	5.01	5.06	5.50	5.24
Fossil resource scarcity (kg oil eq./t)				
Carbon capture	0.41	0.15	4.47	5.96
Water electrolysis	15.69	15.69	15.69	15.69
MeOH synthesis	3.00	3.00	3.00	3.00
MTO-MOGD	0.57	0.57	0.57	0.57
Total	19.68	19.87	23.74	25.23
Water consumption (m^3/t)				
Carbon capture	0.35	0.01	0.18	0.18
Water electrolysis	5.81	5.81	5.81	5.81
MeOH synthesis	0.14	0.14	0.14	0.14
MTO-MOGD	0.03	0.03	0.03	0.03
Total	6.32	6.37	6.16	6.16

SII. Calculations of excess heat and household heating potential from P2X plant

For the calculation of excess het demand to supply household in Finland, an average annual household heating demand of 15,471 kWh/year is used [1]. A typical plant continuous operation of 7,884 h/yr, which correspond to 90% availability was assumed [2]. The annual revenue from the sale of excess heat is calculated using Equation 1.

$$R = \frac{P.H.E.n_{use}}{C_1.C_2}.S, \quad (1)$$

where:

P = production rate (t/h)

H = annual operating hours (h/yr)

E = excess heat generated (MJ/t)

$n_{use} = (1-r).(1-l)$: combined usable heat efficiency

r = fractional heat recovery loss

d = fractional distribution loss

C_1 = conversion factor (MJ to kWh)

C_2 = conversion factor (kWh to MWh)

S = average selling price (€/MWh)

Table SIII. Data and Assumptions

Parameter	**Value**	**Source/Note**
Plant operating at 0.9 capacity factor (hr/yr)	7884	[2]
Production rate (t/hr)	1.2301	Plant design data
Annual production (t/yr)	9485.24	Total output per year
Average annual heating demand (kWh/yr)	15741	[1]
Conversion factor (MJ)	3.6	Standard conversion
Heat recovery losses (%)	5	[3]
Average heat distribution losses (%)	8.5	[4]
Average heat selling price (€/MWh)	96.26	[5]
Light fuel oil emission factor (kg CO_2/MWh)	266.7	[6]
Natural gas emission factor (kg CO_2/MWh)	199	[6]

Table SIV. Excess heat supply estimation

Scenario	Excess heat per batch (MJ/t)	Annual excess heat (MJ/yr)	Annual excess heat (kWh/yr)	Annual excess heat (GWh/yr)	No. of household supplied	Annual revenue (€)
S1	3,751.61	35,584,922.74	9,884,700.76	8.59	555	827092.50
S2	4,021.40	38,143,945.74	10,595,540.48	9.21	595	886571.31
S3	3,847.54	36,494,841.85	10,137,456.07	8.81	570	848241.55
S4	3,845.11	36,471,792.71	10,131,053.53	8.81	569	847705.82

Table SV. Annual CO_2 savings for utilization of excess heat in residential heating. Calculated using emission factors in Table SIII.

Scenario	Annual excess heat (MWh/year)	CO_2 savings (t/year)	
		Light fuel oil	Natural gas
S1	8592.3	2291.6	1709.86
S2	9210.2	2456.4	1832.82
S3	8812.0	2350.2	1753.58
S4	8806.4	2348.7	1752.48

Table SVI. Sensitivity ratio for global warming potential impact category of the analyzed scenarios.

	S1	S2	S3	S4
CO_2 capture				
Biogas	0.0	-	-	-
CO_2	-	0.0	0.0	0.0
Electricity	0.8	1.0	0.1	0.0
H_2O	0.1	-	-	0.0
MEA	0.1	0.0	-	0.9
NaOH	-	0.0	-	0.0
Zeolite	-	-	0.8	-
Activated carbon	-	-	-	0.0
Water electrolysis				
Water	0.03	0.03	0.03	0.03
Electricity	0.97	0.97	0.97	0.97
MeOH synthesis				
Electricity	1.0	1.0	1.0	1.0
MTO-MOGD				
Electricity	1.0	1.0	1.0	1.0

Table SVII. Sensitivity ratio for ozone formation, human health of the analyzed scenarios.

	S1	**S2**	**S3**	**S4**
CO_2 capture				
Biogas	0.0	-	-	-
CO_2	-	0.0	0.0	0.0
Electricity	0.9	1.0	0.1	0.0
H_2O	0.1	-	-	0.0
MEA	0.0	0.0	-	0.9
NaOH	-	0.0	-	0.0
Zeolite	-	-	0.8	-
Activated carbon	-	-	-	0.0
Water electrolysis				
Water	0.02	0.02	0.02	0.02
Electricity	0.98	0.98	0.98	0.98
MeOH synthesis				
Electricity	1.0	1.0	1.0	1.0
MTO-MOGD				
Electricity	1.0	1.0	1.0	1.0

Table SVIII. Sensitivity ratio for freshwater eutrophication impact category of the analyzed scenarios.

	S1	**S2**	**S3**	**S4**
CO_2 capture				
Biogas	0.0	-	-	-
CO_2	-	0.0	0.0	0.0
Electricity	0.9	1.0	0.2	0.0
H_2O	0.0	-	-	0.0
MEA	0.0	0.0	-	0.9
NaOH	-	0.0	-	0.0
Zeolite	-	-	0.7	-
Activated carbon	-	-	-	0.05
Water electrolysis				
Water	0.0	0.0	0.0	0.0
Electricity	0.98	0.98	0.98	0.98
MeOH synthesis				
Electricity	1.0	1.0	1.0	1.0
MTO-MOGD				
Electricity	1.0	1.0	1.0	1.0

Table SIX. Sensitivity ratio for marine eutrophication impact category of the analyzed scenarios.

	S1	**S2**	**S3**	**S4**
CO_2 capture				
Biogas	0.00	-	-	-
CO_2	-	0.00	0.00	0.00
Electricity	0.02	0.77	0.13	0.00
H_2O	0.00	-	-	0.00
MEA	0.02	0.22	-	0.99
NaOH	-	0.01	-	0.00
Zeolite	-	-	0.81	-
Activated carbon	-	-	-	0.00
Water electrolysis				
Water	0.02	0.02	0.02	0.02
Electricity	0.98	0.98	0.98	0.98
MeOH synthesis				
Electricity	1.00	1.00	1.00	1.00
MTO-MOGD				
Electricity	1.00	1.00	1.00	1.00

Table SX. Sensitivity ratio for land use impact category of the analyzed scenarios.

Scenarios	**S1**	**S2**	**S3**	**S4**
CO_2 capture	-	-	-	-
Biogas	0.00	-	-	-
CO_2	-	0.00	0.00	0.00
Electricity	0.93	0.99	0.21	0.0
H_2O	0.0	-	-	0.00
MEA	0.0	0.0	-	0.9
NaOH	-	0.00		0.0
Zeolite	-	-	0.73	-
Activated carbon	-	-	-	0.03
Water electrolysis				
Water	0.0	0.0	0.0	0.0
Electricity	0.98	0.98	0.98	0.98
MeOH synthesis				
Electricity	1.0	1.0	1.0	1.0
MTO-MOGD				
Electricity	1.0	1.0	1.0	1.0

Table SXI. Sensitivity ratio for fossil resource scarcity impact category of the analyzed scenarios.

	S1	**S2**	**S3**	**S4**
CO_2 capture				
Biogas	0.00	-	-	-
CO_2	-	0.00	0.00	0.00
Electricity	0.80	0.95	0.09	0.01
H_2O	0.08	-	-	0.0
MEA	0.11	0.0	-	0.96
NaOH	-	0.00	-	0.01
Zeolite	-	-	0.85	-
Activated carbon	-	-	-	0.0
Water electrolysis				
Water	0.03	0.03	0.03	0.03
Electricity	0.97	0.97	0.97	0.97
MeOH synthesis				
Electricity	1.0	1.0	1.0	1.0
MTO-MOGD				
Electricity	1.0	1.0	1.0	1.0

Table SXII. Sensitivity ratio for water consumption impact category of the analyzed scenarios.

	S1	**S2**	**S3**	**S4**
CO_2 capture				
Biogas	0.00	-	-	-
CO_2		0.00	0.00	0.00
Electricity	0.04	0.96	0.11	0.01
H_2O	0.95	-	-	0.00
MEA	0.00	0.03		0.95
NaOH	-	0.01	-	0.0
Zeolite	-	-	0.84	-
Activated carbon	-	-	-	0.0
Water electrolysis				
Water	0.88	0.88	0.88	0.88
Electricity	0.12	0.12	0.12	0.12
MeOH synthesis				
Electricity	1.0	1.0	1.0	1.0
MTO-MOGD				
Electricity	1.0	1.0	1.0	1.0

References

[1] Statistics Finland. Energy consumption in households: Heating of residential buildings by building type, 2008-2023 2025. https://pxdata.stat.fi/PxWeb/pxweb/en/StatFin/StatFin__asen/statfin_asen_pxt_11zr.px/table/tableViewLayout1/ (accessed June 20, 2025).

[2] Sollai S, Porcu A, Tola V, Ferrara F, Pettinau A. Renewable methanol production from green hydrogen and captured CO2: A techno-economic assessment. J CO2 Util 2023;68:102345. https://doi.org/10.1016/j.jcou.2022.102345.

[3] IPIECA. Heat exchangers: Energy efficiency compendium. London: 2022.

[4] Finnish Energy. District heating statistics 2025. https://energia.fi/wp-content/uploads/2024/11/Vuositaulukot_23_ENG_updated20241212.xlsx (accessed July 5, 2025).

[5] Finnish Energy. District heating in Finland 2023. Helsinki: 2024.

[6] Statistics Finland. Greenhouse Gas Emissions in Finland 1990-2021: National Inventory Report under the UNFCCC and the Kyoto Protocol. Helsinki: 2023.