Electronic Supplementary Material (ESI) for Green Chemistry.

Global transportation of green hydrogen via liquid carriers: Economic and environmental sustainability analysis, policy implications, and future directions

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1. Process flow diagrams of different liquid carriers

To calculate mass and energy balances for various carriers synthesis (except LH_2 and SNG paths) and dehydrogenation (H_2 retrieval and SNG decomposition), process simulations were performed in Aspen Plus V12.2. The mass and energy balance for SNG and LH_2 was obtained from published studies.[1,2] Appropriate thermodynamic property packages were selected to accurately calculate mass and energy balances. For example, when processing units are operating above 10 bar or dealing with gas phases, Peng Robinson equation of state was used. Likewise, when processing units are operating below 10 bar or dealing with liquid phases, non-random two liquid (NRTL) activity coefficient model was used. The mass storage density of different carriers and operating condition and reactions used in hydrogenation and dehydrogenation of carriers are reported in Table S1.

Table S1 Mass storage density of different carriers and operating condition and reactions used in hydrogenation and dehydrogenation of carriers, including ammonia, methanol, DBT, and MCH.

Carrier	Process	H_2 storage density (wt.%)	Operating conditions	Reaction
NH_3	Hydrogenation	17.8%	450°C and 150 bar	$N_2 + 3H_2 \rightarrow 2NH_3$ ΔH = –92.4KJmol^{-1}
NH_3	Dehydrogenation	–	250°C and 50 bar	$2NH_3 \rightarrow N_2 + 3H_2$ ΔH = 92.4KJmol^{-1}
CH_3OH	Hydrogenation	12.6%	250°C and 50 bar	$CO_2 + H_2 \rightleftharpoons CO + H_2O$ $\Delta H = -90.77\ KJ/mol$ $CO + 2H_2 \rightleftharpoons CH_3OH$ $\Delta H = +41.21\ KJ/mol$ $CO_2 + 3H_2 \rightleftharpoons CH_3OH + H_2O$ $\Delta H = -49.16\ KJ/mol$
CH_3OH	Dehydrogenation	–	250°C and 1 bar	Phase and chemical equilibrium conversions are estimated using Aspen
DBT	Hydrogenation	6.2%	150°C and 50 bar	$H0.DBT + 9H_2 \rightarrow H18.DBT$
DBT	Dehydrogenation	–	310°C and 1 bar	$H18.DBT + 9H_2 \rightarrow H0.DBT$
MCH	Hydrogenation	6.1%	200°C and 20 bar	$3H_2 + C_7H_8 \rightarrow C_7H_{14}$
MCH	Dehydrogenation	–	320°C and 1 bar	$C_7H_{14}\ 3H_2 \rightarrow C_7H_8$

1.1 Ammonia synthesis

Haber–Bosch process was used to model the NH_3 production process. NH_3 is produced as a result of the reaction between N_2 and H_2 at a high temperature of 450°C and a pressure of 150 bar in the presence of a catalyst, typically iron oxide.[3]

Nitrogen is mainly obtained using a cryogenic air separation unit, in which air is compressed from 1 to 7 bar in a multistage compressor (C1) and liquefied, followed by fractional distillation with two columns, high-pressure (HP) and low-pressure (LP) columns.[3,4] Nitrogen gas with a purity of 99.9% is separated at the top of the LP column, and oxygen is collected from the bottom. Pure H_2 gas is available from the water electrolysis plant. Pure nitrogen and H_2 are then mixed in mixer 1 (M1) and introduced into the NH_3 synthesis loop, where they are compressed in a multistage compressor (C2) at a pressure of 150 bar and heated in a heater (HX2) to achieve the required temperature of 450°C. The mixture is then fed to the reactor (R1), where NH_3 is produced and separated in high pressure (HPF) and low-pressure flash (LPF) columns.

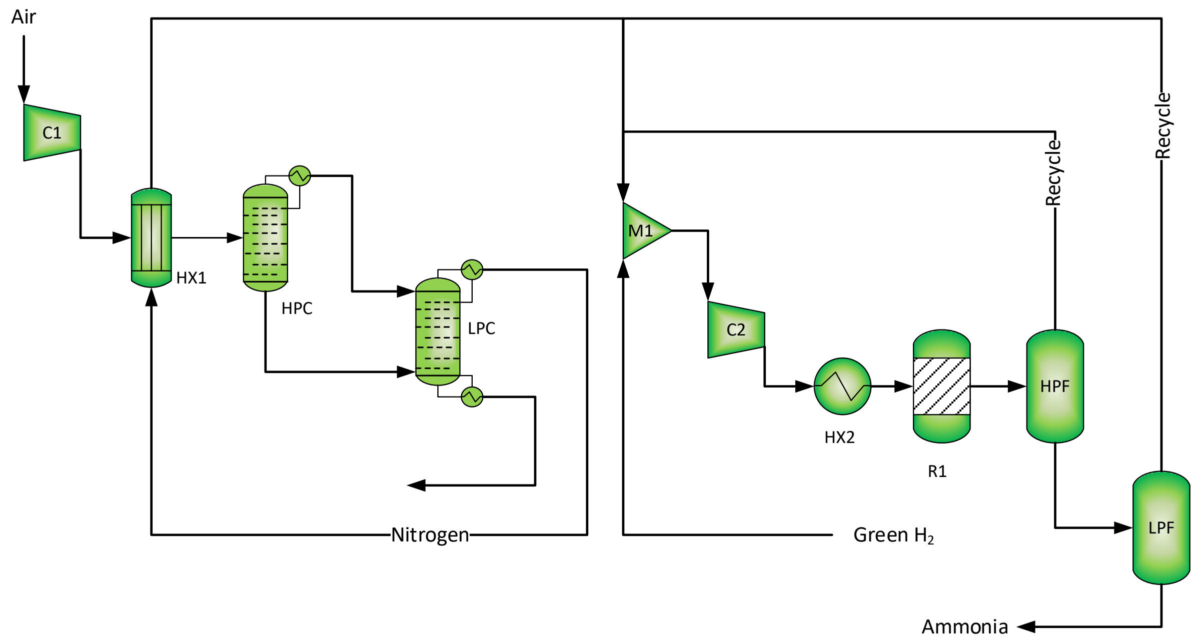

Figure S1 Simplified process flow diagram of ammonia synthesis.

1.2 Ammonia dehydrogenation

NH_3 decomposition is an endothermic reaction and is favorable at a high temperature and in the presence of a catalyst. Reaction conditions are set at 450°C and 1.01 bar, and ruthenium (Ru)-based catalysts [Ru/La(x)-Al_2O_3] are selected because the conversion performance of the decomposition reaction for Ru-based catalysts [Ru/La(x)-Al_2O_3] is greater than 95%.[5] Liquid ammonia is passed through heat exchangers (HX1 and HX2) to attain the required reaction temperature and then passes to the reactor for the decomposition process. Heat integration is performed to improve the energy efficiency of the process. The outlet stream is then compressed to increase the pressure from 1.01 bar to 40 bar and then passed to two-stage pressure swing adsorption columns for further purification. The purified hydrogen is collected from the top and a part of it is recycled back for further purification and removal of traces of ammonia and nitrogen.

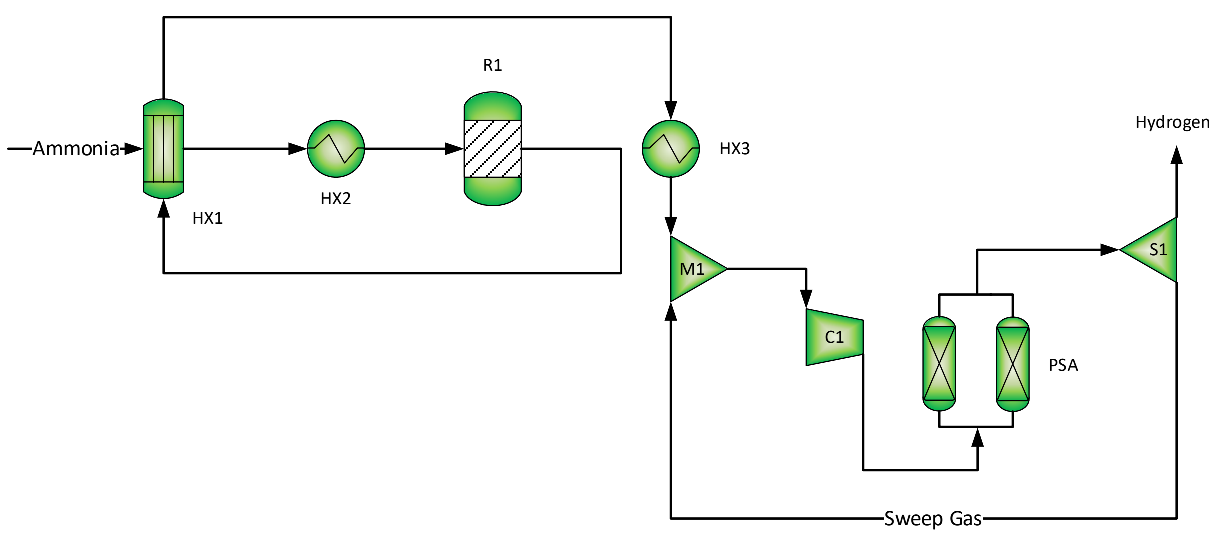

Figure S2 Simplified process flow diagram of ammonia dehydrogenation.

2.1 Methanol synthesis

Methanol is produced via direct CO_2 hydrogenation at 50 bar and 250 °C in the presence of $Cu/ZnO/Al_2O_3$ catalyst.[6] The H_2:CO_2 molar ratio of 3:1 is considered. The CO_2 captured from flue gases and H_2 produced by water electrolysis is mixed in the mixer (M1), which is then compressed (C1) and heated (HX1 and HX2) to reaction conditions. The mixture is finally fed to reactor R1 to produce methanol. The energy of the reactor's effluent (hot stream) is exchanged (HX1) with the reactor's inlet (cold stream) to minimize utility load. The partially cooled reactor effluent from HX1 is further cooled in HX3 and unreacted gases are recovered in two flash columns (HP and LP) and recycled to the mixer (M1). The bottom of LP mainly consisting of water and methanol is fed to the distillation column (DC1) to get pure methanol in the distillate, while the water recovered in bottom and is used to heat (HX4) inlet of distillation columns before discarding it.

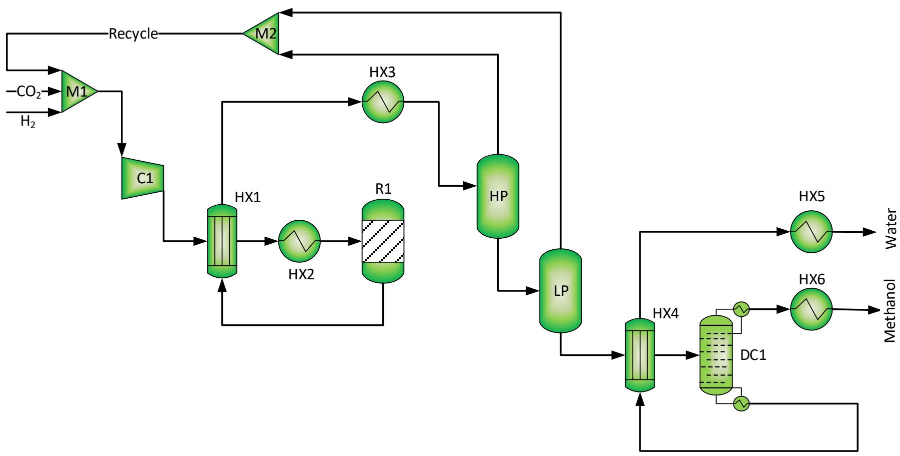

Figure S3 Simplified process flow diagram of methanol synthesis. HP = High pressure and LP = Low pressure.

2.2 Methanol dehydrogenation

Hydrogen is retrieved from methanol through methanol steam reforming (~100% conversion) at 420 °C and 1.01 bar at a molar ratio of 1.5 (water/methanol).[7,8] As shown in Figure S4, methanol and water are mixed in (M1) and passed through the heat exchanger (HX1), and finally heated to 420 °C in heater (HX2). The heated mixture is fed to the reactor (R1) and effluents are separated in a flash drum (F1) after heat integration (HX1). The top stream (mainly CO_2 and hydrogen gases) of F1 is compressed (C1) and fed to pressure swing adsorption (PSA) to recover the pure hydrogen stream. The part of pure recovered hydrogen is recycled to M2 as a sweep gas. Whereas the CO_2 recovered from PSA is discharged to the environment.

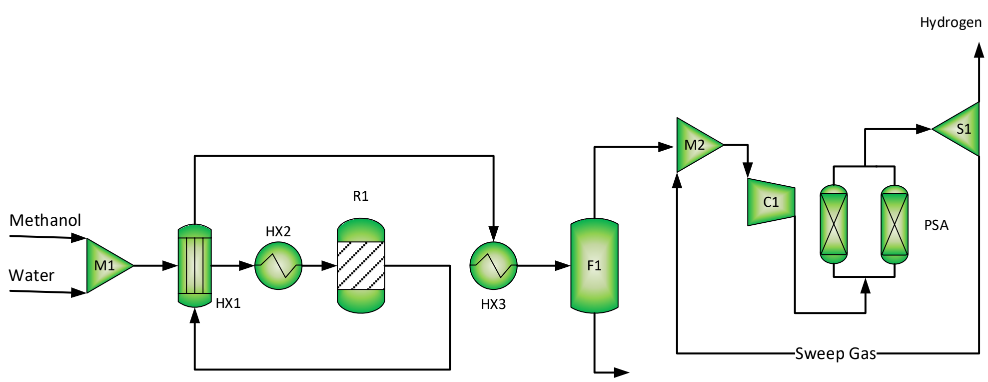

Figure S4 Simplified process flow diagram of methanol dehydrogenation.

3.1 DBT/Toluene hydrogenation

Processing pathways for both DBT and toluene are similar. Toluene/DBT is pumped at 20/50 bar and 200/150 °C. The reactor's effluents are cooled via heat exchanger (HX1) and cooler (HX2) and sent to flash column. The recovered vapors are recycled and liquid products mainly containing hydrogenated products (MCH/H18-DBT) are recovered in bottom streams and cooled before their international transportation.

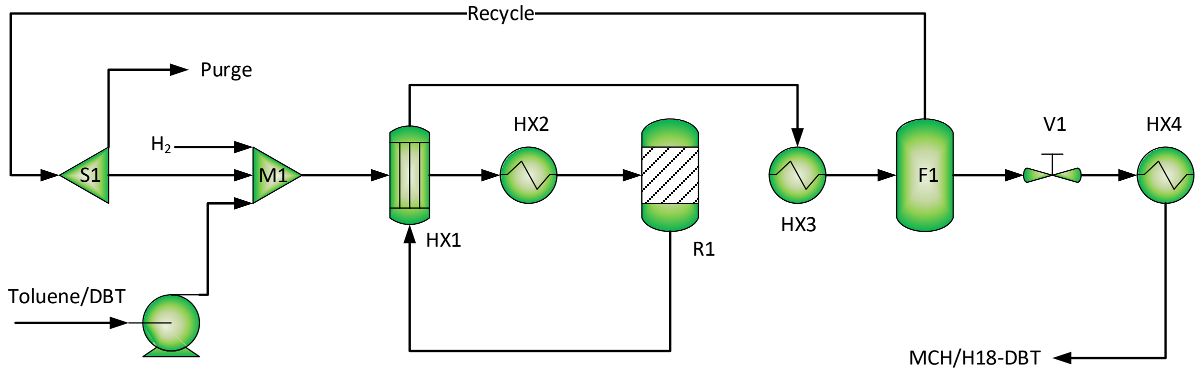

Figure S5 Simplified process flow diagram of MCH and H18-DBT synthesis.

3.2 MCH/H18-DBT dehydrogenation

The MCH/H18-DBT is heated to 320/310 °C and sent to the reactor (R1) at 1 atm after exchanging heat (HX1) with reactor's effluent. MCH/H18-DBT is dehydrogenated (95/97%) to toluene/DBT and hydrogen. Hydrogen is recovered in the top stream using two flash drums (F1 and F2). The bottom products of flash drums are heated and sent to the distillation column, where carriers are recovered in bottoms and unreacted MCH/H18-DBT is recycled.

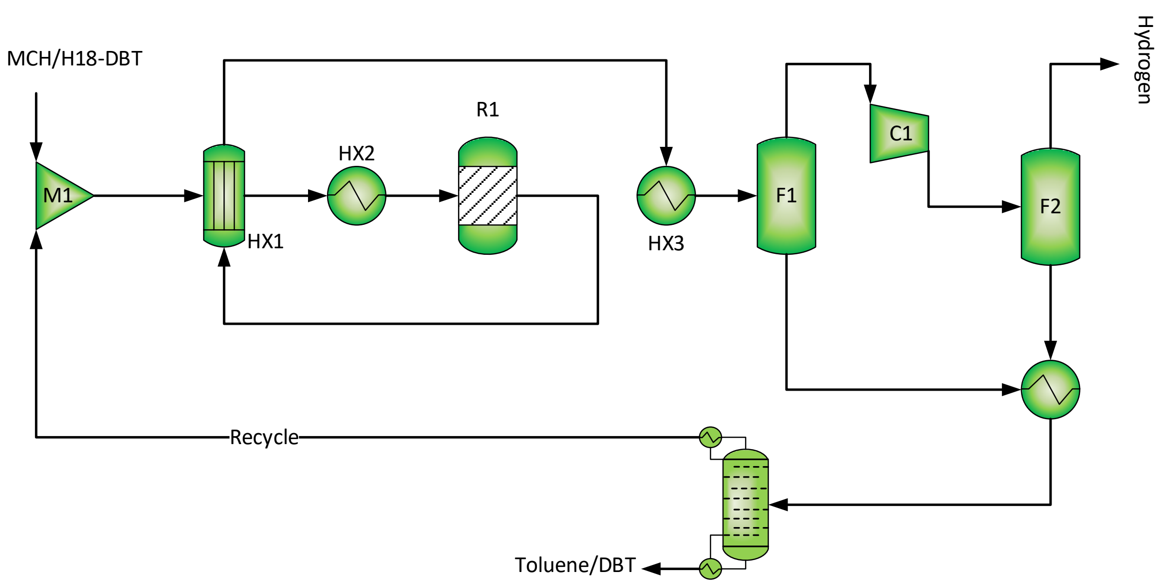

Figure S6 Simplified process flow diagram of MCH and DBT dehydrogenation.

Table S2 Raw material and utility costs.

Parameters	Value
Raw material[9]	
Hydrogen	4 USD/kg
Carbon dioxide	50 USD/ton
Toluene	82 USD/ton
DBT	400 USD/ton
Utilities[10]	
Steam	6.13 USD/GJ
Cooling water	0.28 USD/GJ
Electricity	0.07 USD/kWh
Chilled water	5 USD/GJ
Wastewater	0.041 USD/m^3

Table S3 Assumptions for hydrogen transportation via road.[11–14]

Parameters	LOHC-Truck	LH_2 or NH_3 Trucks
Maximum loading	28.5 t	50 m^3
Average speed	45 km/h	45 km/h
Fuel costs	0.89 $/L	0.89 $/L
Fuel consumption	0.35 L/km	0.35 L/km
Operating costs	4%	4%
Loading/unloading	1.5 h	3 h
Truck cost	206,400 $/unit	206,400 $/unit
Tank cost	103,200 $/unit	580,500 and 522,450 $/unit for LH_2 and NH_3, respectively
Truck depreciation	8 y	8 y
Tank depreciation	12 y	12 y
Truck daily use	18 h/d	18 h/d

†CAPEX and OPEX of LNG truck and tank was similar to that for LH_2.

Table S4 Assumptions for hydrogen transportation via ships.

Parameters	LOHC ship†	LH_2 ship	NH_3 ship	LNG ship
Maximum loading	52,560 t	173,400 m^3	20,600 m^3	145,700 m^3
Average speed	26.8 knots	33.3 knots	29.4 knots	22.9 knots
Fuel costs	412.8 $/t	412.8 $/t	412.8 $/t	412.8 $/t
OPEX	7,940 $/d	13,340 $/d	7,552 $/d	10,107 $/d
Operating costs	4%	4%	4%	4%
Loading/unloading	2 d	2 d	2 d	2 d
Ship costs	51.0 M$/unit	168.2 M$/unit	49.8 M$/unit	161.7 M$/unit
Ship depreciation	15 y	15 y	15 y	15 y
DWT	50,000 t	84,554 t	18,208	84,554
% of DWT for products	0.9	0.9	0.9	0.9
Ship weight	11,121 t	18,989 t	8,842 t	18,989

†LOHC ships include methanol, DBT, MCH

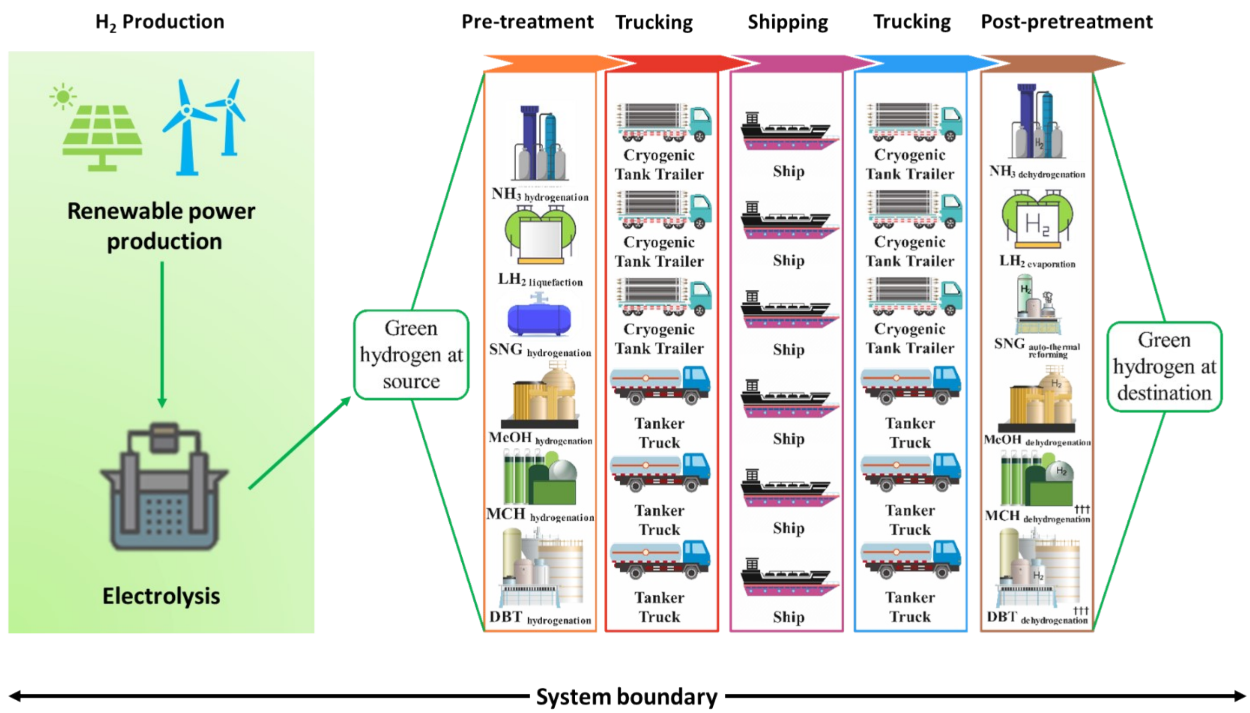

Figure S7 System boundary for life cycle assessment of process chain for international transport of renewable hydrogen via liquid organic hydrogen carriers and alternatives. Trucking at source and destination country is considered as one stage in LCA.

Table S5 Inventory data for the international transport of renewable hydrogen via liquid hydrogen carriers. Data is scaled based on one kg hydrogen.

Stages	Methanol	Ammonia	MCH	DBT	SNG	LH_2
Hydrogen production						
Electricity (kWh)	50.000	50.000	50.000	50.000	50.000	50.000
Water (kg)	10.000	10.000	10.000	10.000	10.000	10.000
Nitrogen (g)	0.290	0.290	0.290	0.290	0.290	0.290
Potassium hydroxide (g)	0.190	0.190	0.190	0.190	0.190	0.190
Steam (kg)	0.110	0.110	0.110	0.110	0.110	0.110
Pre-treatment						
Nitrogen (kg)	-	4.634	-	-	-	-
Carbon dioxide (kg)	7.300	-	-	-	5.500	-
Toluene (kg)	-	-	15.240	-	-	-
Dibenzenetoluene (kg)	-	-	-	15.013	-	-
Hydrogen Loss (kg)	0.001	0.001	0.001	0.001	0.001	0.030
Total energy demand (kWh)	7.300	4.600	13.400	11.100	0.950	6.800
Trucking						
Carrier Loss (kg)	-	0.004	-	-	0.002	0.004
Diesel (kg)	0.078	0.043	0.160	0.145	0.039	0.080
Shipping						
Carrier Loss (kg)	-	0.017	-	-	0.013	0.015
Diesel (kg)	0.161	0.204	0.222	0.256	0.088	0.288
Post-treatment						
Nitrogen (kg)	-	-	-	-	-	-
Carbon dioxide (kg)	-	-	-	-	-	-
Toluene (kg)	-	-	0.076	-	-	-
Dibenzenetoluene (kg)	-	-	-	0.015	-	-
Hydrogen Loss (kg)	0.001	0.001	0.001	0.001	0.001	0.030
Total energy demand (kWh)	7.700	14.300	18.000	11.700	15.310	0.600

Table S6 Databases selected for life cycle impact assessment of the international transport of renewable hydrogen via liquid hydrogen carriers.

Processes	Databases
Process water, ion exchange, production mix, at plant, from groundwater RER S	ELCD
Nitrogen, liquid {RoW}| air separation, cryogenic | APOS, S	Ecoinvent 3.8
Potassium hydroxide {RoW}| production | APOS, S	Ecoinvent 3.8
Steam, in chemical industry {RoW}| market for steam, in chemical industry | APOS, S	Ecoinvent 3.8
Electricity, low voltage {RoW}| electricity production, photovoltaic, 570kWp open ground installation, multi-Si | APOS, S	Ecoinvent 3.8
Electricity, medium voltage {GLO}| market group for | APOS, S	Ecoinvent 3.8
Electricity, high voltage {RoW}| electricity production, wind, 1-3MW turbine, onshore | APOS, S	Ecoinvent 3.8
Toluene, at plant/kg/RNA	USLCI
Carbon dioxide, in chemical industry {GLO}| market for carbon dioxide, in chemical industry | APOS, S	Ecoinvent 3.8
Diesel {RoW}| market for | APOS, S	Ecoinvent 3.8
Chlorine, gaseous {RoW}| sodium chloride electrolysis | APOS, U	Ecoinvent 3.8
Heat, central or small-scale, other than natural gas {AU}| heat and power co-generation, biogas, gas engine | APOS, S	Ecoinvent 3.8

Table S7 Analyzed environmental impact categories.

Impact Category	Abbreviation	Unit
Abiotic Depletion Potential	ADP	kg Sb eq
Abiotic Depletion Potential Fossil Fuels	ADPFF	MJ
Global Warming Potential	GWP	kg CO_2 eq
Ozone Layer Depletion Potential	ODP	kg CFC-11 eq
Human Toxicity Potential	HTP	kg 1,4-DB eq
Fresh Water Aquatic Ecotoxicity Potential	FWETP	kg 1,4-DB eq
Marine Aquatic Ecotoxicity Potential	MAETP	kg 1,4-DB eq
Terrestrial Ecotoxicity Potential	TETP	kg 1,4-DB eq
Photochemical Oxidation Potential	PCOP	kg C_2H_4 eq
Acidification Potential	ACP	kg SO_2 eq
Eutrophication Potential	EP	kg PO_4 eq

Table S8 Simplified material balance, energy balance, and capital cost data.

Parameters	Methanol	Ammonia	MCH	DBT	SNG[15]	LH_2[1,2]
Hydrogenation						
CAPEX ($)	685,594	1,626,559	375,046	611,540	5,319,123	18,801,100
Capacity (kg/h)	100	100	100	100	100	100
Scaling exponent	0.6	0.6	0.6	0.6	0.67	0.66
Loss	0.1%	0.1%	0.1%	0.1%	0.1%	1.65%
Total energy demand (kWh/kg)	7.3	4.6	13.4	11.1	0.95	6.8
Dehydrogenation						
CAPEX ($)	23,946,473	2,482,013	303,381	673,650	2,926,912	16,627
Capacity (kg/h)	100	100	100	100	100	100
Scaling exponent	0.6	0.6	0.6	0.6	1	1
Loss	0.1%	0.1%	0.1%	0.1%	0.1%	1.65%
Total energy demand (kWh/kg)	7.7	14.3	18	11.7	15.31	0.6

Table S9 Life cycle indicator results of the international transport of renewable hydrogen via liquid hydrogen carriers.

Impact categories	LH_2	Methanol	Ammonia	SNG	DBT	MCH
ADP (kg Sb eq.)	1.84E-05	2.62E-05	3.70E-05	1.70E-05	7.19E-05	5.13E-05
AFFDP (MJ)	2.78E+01	7.54E+01	1.27E+02	1.24E+02	1.07E+03	1.01E+03
GWP100 (kg CO_2 eq.)	1.0266364	5.8736505	10.498176	10.768718	26.696209	27.582419
ODP (kg CFC-11 eq.)	3.16E-07	3.79E-07	5.31E-07	4.31E-07	7.12E-07	7.16E-07
HTP (kg 1,4-DB eq.)	3.55E-01	1.11E+00	1.85E+00	1.71E+00	1.29E+01	1.20E+01
FWAETP (kg 1,4-DB eq.)	1.47E-02	4.31E-02	7.22E-02	6.88E-02	3.54E+00	3.22E+00
MAETP (kg 1,4-DB eq.)	6.80E+02	4.48E+03	8.11E+03	8.28E+03	2.31E+04	2.43E+04
TEP (kg 1,4-DB eq.)	2.09E-03	1.12E-02	1.99E-02	2.01E-02	2.67E-02	2.89E-02
PCOP (kg C_2H_4 eq.)	2.70E-04	1.08E-03	1.88E-03	1.86E-03	1.32E-02	6.08E-02
AP (kg SO_2 eq.)	5.76E-03	2.59E-02	7.91E-02	4.58E-02	1.57E-01	1.55E-01
EP (kg PO_4 eq.)	6.32E-04	2.95E-03	1.26E-02	5.24E-03	1.66E-02	1.61E-02

Table S10 Stagewise breakdown of life cycle indicator results of the international transport of renewable hydrogen via methanol carrier.

Impact category	H_2 Production	Pre-treatment	Trucking	Shipping	Post-Treatment	Total
ADP (kg Sb eq.)	3.15E-07	1.86E-05	4.92E-08	1.02E-07	7.14E-06	2.62E-05
AFFDP (MJ)	1.28E+00	3.78E+00	3.92E+00	8.09E+00	5.83E+01	7.54E+01
GWP100 (kg CO_2 eq.)	1.27E-01	3.32E-01	3.77E-02	7.78E-02	5.30E+00	5.87E+00
ODP (kg CFC-11 eq.)	2.70E-08	3.60E-08	5.15E-08	1.06E-07	1.59E-07	3.79E-07
HTP (kg 1,4-DB eq.)	2.03E-02	2.26E-01	1.27E-02	2.62E-02	8.26E-01	1.11E+00
FWAETP (kg 1,4-DB eq.)	8.20E-04	5.56E-03	1.30E-03	2.68E-03	3.28E-02	4.31E-02
MAETP (kg 1,4-DB eq.)	2.48E+01	3.06E+02	1.02E+01	2.11E+01	4.12E+03	4.48E+03
TEP (kg 1,4-DB eq.)	8.54E-05	9.69E-04	6.83E-05	1.41E-04	9.97E-03	1.12E-02
PCOP (kg C_2H_4 eq.)	2.83E-05	1.02E-04	1.63E-05	3.36E-05	9.02E-04	1.08E-03
AP (kg SO_2 eq.)	3.84E-04	1.83E-03	4.07E-04	8.40E-04	2.24E-02	2.59E-02
EP (kg PO_4 eq.)	3.94E-05	2.12E-04	4.13E-05	8.52E-05	2.57E-03	2.95E-03

Table S11 Stagewise breakdown of life cycle indicator results of the international transport of renewable hydrogen via ammonia carrier.

Impact category	H_2 Production	Pre-treatment	Trucking	Shipping	Post-Treatment	Total
ADP (kg Sb eq.)	3.15E-07	2.33E-05	2.71E-08	1.29E-07	1.33E-05	3.70E-05
AFFDP (MJ)	1.28E+00	4.67E+00	2.16E+00	1.02E+01	1.08E+02	1.27E+02
GWP100 (kg CO_2 eq.)	1.27E-01	4.10E-01	2.08E-02	9.86E-02	9.84E+00	1.05E+01
ODP (kg CFC-11 eq.)	2.70E-08	4.59E-08	2.84E-08	1.35E-07	2.95E-07	5.31E-07
HTP (kg 1,4-DB eq.)	2.03E-02	2.49E-01	7.41E-03	3.49E-02	1.53E+00	1.85E+00
FWAETP (kg 1,4-DB eq.)	8.20E-04	6.38E-03	7.15E-04	3.39E-03	6.09E-02	7.22E-02
MAETP (kg 1,4-DB eq.)	2.48E+01	3.97E+02	5.65E+00	2.68E+01	7.65E+03	8.11E+03
TEP (kg 1,4-DB eq.)	8.54E-05	1.13E-03	3.77E-05	1.79E-04	1.85E-02	1.99E-02
PCOP (kg C_2H_4 eq.)	2.83E-05	1.24E-04	8.97E-06	4.26E-05	1.68E-03	1.88E-03
AP (kg SO_2 eq.)	3.84E-04	2.28E-03	6.62E-03	2.83E-02	4.16E-02	7.91E-02
EP (kg PO_4 eq.)	3.94E-05	2.63E-04	1.42E-03	6.06E-03	4.77E-03	1.26E-02

Table S12 Stagewise breakdown of life cycle indicator results of the international transport of renewable hydrogen via MCH carrier.

Impact category	H_2 Production	Pre-treatment	Trucking	Shipping	Post-Treatment	Total
ADP (kg Sb eq.)	3.15E-07	3.41E-05	1.01E-07	1.40E-07	1.67E-05	5.13E-05
AFFDP (MJ)	1.28E+00	8.53E+02	8.04E+00	1.12E+01	1.36E+02	1.01E+03
GWP100 (kg CO_2 eq.)	1.27E-01	1.49E+01	7.73E-02	1.07E-01	1.24E+01	2.76E+01
ODP (kg CFC-11 eq.)	2.70E-08	6.65E-08	1.06E-07	1.47E-07	3.71E-07	7.16E-07
HTP (kg 1,4-DB eq.)	2.03E-02	9.94E+00	2.61E-02	3.62E-02	1.96E+00	1.20E+01
FWAETP (kg 1,4-DB eq.)	8.20E-04	3.14E+00	2.66E-03	3.69E-03	7.66E-02	3.22E+00
MAETP (kg 1,4-DB eq.)	2.48E+01	1.46E+04	2.10E+01	2.91E+01	9.63E+03	2.43E+04
TEP (kg 1,4-DB eq.)	8.54E-05	5.20E-03	1.40E-04	1.95E-04	2.33E-02	2.89E-02
PCOP (kg C_2H_4 eq.)	2.83E-05	1.02E-02	3.34E-05	4.63E-05	5.05E-02	6.08E-02
AP (kg SO_2 eq.)	3.84E-04	1.01E-01	8.35E-04	1.16E-03	5.24E-02	1.55E-01
EP (kg PO_4 eq.)	3.94E-05	9.85E-03	8.47E-05	1.18E-04	6.00E-03	1.61E-02

Table S13 Stagewise breakdown of life cycle indicator results of the international transport of renewable hydrogen via DBT carrier.

Impact category	H_2 Production	Pre-treatment	Trucking	Shipping	Post-Treatment	Total
ADP (kg Sb eq.)	3.15E-07	6.05E-05	9.14E-08	1.61E-07	1.09E-05	7.19E-05
AFFDP (MJ)	1.28E+00	9.64E+02	7.28E+00	1.29E+01	8.86E+01	1.07E+03
GWP100 (kg CO_2 eq.)	1.27E-01	1.83E+01	7.01E-02	1.24E-01	8.05E+00	2.67E+01
ODP (kg CFC-11 eq.)	2.70E-08	1.79E-07	9.57E-08	1.69E-07	2.41E-07	7.12E-07
HTP (kg 1,4-DB eq.)	2.03E-02	1.16E+01	2.36E-02	4.17E-02	1.26E+00	1.29E+01
FWAETP (kg 1,4-DB eq.)	8.20E-04	3.48E+00	2.41E-03	4.26E-03	4.98E-02	3.54E+00
MAETP (kg 1,4-DB eq.)	2.48E+01	1.68E+04	1.90E+01	3.36E+01	6.26E+03	2.31E+04
TEP (kg 1,4-DB eq.)	8.54E-05	1.11E-02	1.27E-04	2.24E-04	1.51E-02	2.67E-02
PCOP (kg C_2H_4 eq.)	2.83E-05	1.17E-02	3.03E-05	5.34E-05	1.37E-03	1.32E-02
AP (kg SO_2 eq.)	3.84E-04	1.20E-01	7.57E-04	1.34E-03	3.40E-02	1.57E-01
EP (kg PO_4 eq.)	3.94E-05	1.24E-02	7.67E-05	1.36E-04	3.90E-03	1.66E-02

Table S14 Stagewise breakdown of life cycle indicator results of the international transport of renewable hydrogen via SNG carrier.

Impact category	H_2 Production	Pre-treatment	Trucking	Shipping	Post-Treatment	Total
ADP (kg Sb eq.)	3.15E-07	2.42E-06	2.46E-08	5.55E-08	1.42E-05	1.70E-05
AFFDP (MJ)	1.28E+00	4.92E-01	1.96E+00	4.42E+00	1.16E+02	1.24E+02
GWP100 (kg CO_2 eq.)	1.27E-01	4.32E-02	1.88E-02	4.25E-02	1.05E+01	1.08E+01
ODP (kg CFC-11 eq.)	2.70E-08	4.68E-09	2.57E-08	5.81E-08	3.15E-07	4.31E-07
HTP (kg 1,4-DB eq.)	2.03E-02	2.94E-02	6.35E-03	1.43E-02	1.64E+00	1.71E+00
FWAETP (kg 1,4-DB eq.)	8.20E-04	7.23E-04	6.49E-04	1.46E-03	6.51E-02	6.88E-02
MAETP (kg 1,4-DB eq.)	2.48E+01	3.99E+01	5.12E+00	1.16E+01	8.19E+03	8.28E+03
TEP (kg 1,4-DB eq.)	8.54E-05	1.26E-04	3.42E-05	7.71E-05	1.98E-02	2.01E-02
PCOP (kg C_2H_4 eq.)	2.83E-05	1.33E-05	8.14E-06	1.84E-05	1.79E-03	1.86E-03
AP (kg SO_2 eq.)	3.84E-04	2.39E-04	2.03E-04	4.59E-04	4.45E-02	4.58E-02
EP (kg PO_4 eq.)	3.94E-05	2.76E-05	2.06E-05	4.66E-05	5.11E-03	5.24E-03

Table S15 Stagewise breakdown of life cycle indicator results of the international transport of renewable hydrogen via LH_2 carrier.

Impact category	H_2 Production	Pre-treatment	Trucking	Shipping	Post-Treatment	Total
ADP (kg Sb eq.)	3.15E-07	1.73E-05	5.04E-08	1.82E-07	5.57E-07	1.84E-05
AFFDP (MJ)	1.28E+00	3.52E+00	4.02E+00	1.45E+01	4.55E+00	2.78E+01
GWP100 (kg CO_2 eq.)	1.27E-01	3.09E-01	3.87E-02	1.39E-01	4.13E-01	1.03E+00
ODP (kg CFC-11 eq.)	2.70E-08	3.35E-08	5.28E-08	1.90E-07	1.24E-08	3.16E-07
HTP (kg 1,4-DB eq.)	2.03E-02	2.10E-01	1.30E-02	4.69E-02	6.44E-02	3.55E-01
FWAETP (kg 1,4-DB eq.)	8.20E-04	5.18E-03	1.33E-03	4.79E-03	2.55E-03	1.47E-02
MAETP (kg 1,4-DB eq.)	2.48E+01	2.85E+02	1.05E+01	3.78E+01	3.21E+02	6.80E+02
TEP (kg 1,4-DB eq.)	8.54E-05	9.03E-04	7.01E-05	2.52E-04	7.77E-04	2.09E-03
PCOP (kg C_2H_4 eq.)	2.83E-05	9.48E-05	1.67E-05	6.01E-05	7.03E-05	2.70E-04
AP (kg SO_2 eq.)	3.84E-04	1.71E-03	4.17E-04	1.50E-03	1.75E-03	5.76E-03
EP (kg PO_4 eq.)	3.94E-05	1.97E-04	4.23E-05	1.52E-04	2.00E-04	6.32E-04

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