Future environmental impacts of hydrogen production and its use in container shipping

Wei, S.

Supporting information

S1 Supporting information for chapter 2

S1.1 Unit process data of nine H_2 technologies

The unit process data of nine H_2 technologies are shown in below. Inputs, which are supplied from own processes, i.e. processes not already contained in the premise pLCI database, are marked with an asterisk (*).

Table S1.1. Life cycle inventory of gaseous H_2 production (1 kg, 30 bar, 99.8% purity) by CG.

Exchanges	Amount	Unit	Data source
Economic flows			
market for chemical factory, organics	7.00E-10	unit	[71]
market for hard coal	8.51	kilogram	[70]
market for lime, packed	1.68E-01	kilogram	[71]
market for liquid storage tank, chemicals, organics	3.97E-09	unit	[71]
market group for transport, freight train	1.14	ton kilometer	[71]
market for water, deionised	11.28	kilogram	[70]
market group for transport, freight, inland waterways, barge	4.24E-01	ton kilometer	[71]
market (group) for electricity, low voltage	-3.18	kilowatt hour	[70]
treatment of hard coal ash, residual material landfill	-5.05E-01	kilogram	[71]
treatment of waste gypsum, inert material landfill	-2.28E-01	kilogram	[71]
Environmental flows			
Ammonia (to air)	6.93E-03	kilogram	[71]
Carbon dioxide, fossil (to air)	21.42	kilogram	[70]
Hydrogen chloride (to air)	1.04E-02	kilogram	[71]

Table S1.2. Life cycle inventory of gaseous H_2 production (1 kg, 30 bar, 99.8% purity) by CG CCS.

Exchanges	Amount	Unit	Data source
Economic flows			
CO_2 storage/at H_2 production plant, pre, pipeline 400km, storage 3000m	20.39	kilogram	[73]
market for chemical factory, organics	7.00E-10	unit	[71]
market for hard coal	9.7	kilogram	[73]
market for lime, packed	1.68E-01	kilogram	[71]
market for liquid storage tank, chemicals, organics	3.97E-09	unit	[71]
market group for transport, freight train	1.14	ton kilometer	[71]
market for water, deionised	38.08	kilogram	[73]
market (group) for electricity, high voltage	1.36	kilowatt hour	[73]
market group for transport, freight, inland waterways, barge	4.24E-01	ton kilometer	[71]
treatment of hard coal ash, residual material landfill	-5.05E-01	kilogram	[71]
treatment of waste gypsum, inert material landfill	-2.28E-01	kilogram	[71]
Selexol (Dimethylether of polyethylene glycol)[a]*	1.43E-04	kilogram	[37]
market for heat pump, heat and power co-generation unit, 160kW electrical[a]	2.01E-07	unit	[37]
market for absorption chiller, 100kW[a]	4.02E-07	unit	[37]
market for gas turbine, 10MW electrical[a]	2.01E-07	unit	[37]
market for liquid storage tank, chemicals, organics[a]	5.57E-08	unit	[37]

market for pump, 40W[a]	2.01E-07	unit	[37]
treatment of spent solvent mixture, hazardous waste incineration[a]	-1.43E-04	kilogram	[37]
Environmental flows			
Water, cooling, unspecified natural origin (natural resource, in water)[a]	1.70E+00	cubic meter	[37]
Ammonia (to air)	6.93E-03	kilogram	[71]
Carbon dioxide, fossil (to air)	2.27	kilogram	[73]
Hydrogen chloride (to air)	1.04E-02	kilogram	[71]

a. These processes are used for CO_2 capture. The values are corresponding to capturing 20.39 kg CO_2.

Table S1.3. Life cycle inventory of Selexol (1 kg).

Exchanges	Amount	Unit
Economic flows		
market for dimethyl sulfate	0.96	kilogram
market for methanol	0.16	kilogram
market for transport, freight train	0.6	ton kilometer
market for transport, freight, lorry, unspecified	0.05	ton kilometer
market for triethylene glycol	0.62	kilogram

Source: Volkart, Bauer, and Boulet[37]

Table S1.4. Life cycle inventory of gaseous H_2 production (1 kg, 25 bar, 99.97% purity) by NG SMR.

Exchanges	Amount	Unit
Economic flows		
market for chemical factory, organics	5.35E-10	unit
market for aluminium oxide, metallurgical	5.33E-04	kilogram
market for chromium oxide, flakes	3.60E-05	kilogram
market for copper oxide	3.62E-04	kilogram
market for liquid storage tank, chemicals, organics	2.55E-09	unit
market for magnesium oxide	2.80E-05	kilogram
market for molybdenum trioxide	1.67E-05	kilogram
market for nickel, class 1	2.03E-04	kilogram
market for portafer	3.12E-04	kilogram
market for quicklime, milled, packed	4.80E-05	kilogram
market for silica sand	1.16E-05	kilogram
market for water, deionised	7.54E+00	kilogram
market for zeolite, powder	8.83E-04	kilogram
market for zinc oxide	3.71E-04	kilogram
market (group) for electricity, high voltage	-1.23331	kilowatt hour
market for natural gas, high pressure	3.919176	cubic meter
Environmental flows		
Acetaldehyde (to air)	3.07E-08	kilogram
Acetic acid (to air)	4.6E-06	kilogram
Benzene (to air)	1.23E-05	kilogram
Benzo(a)pyrene (to air)	3.07E-10	kilogram
Butane (to air)	2.15E-05	kilogram
Carbon dioxide, fossil (to air)	8.922294	kilogram
Carbon monoxide, fossil (to air)	6.44E-05	kilogram
Dinitrogen monoxide (to air)	3.07E-06	kilogram
Formaldehyde (to air)	3.07E-06	kilogram

Mercury (to air)	9.2E-10	kilogram
Methane, fossil (to air)	6.14E-05	kilogram
Nitrogen oxides (to air)	5.49E-04	kilogram
PAH, polycyclic aromatic hydrocarbons (to air)	3.07E-07	kilogram
Particulates, < 2.5 um (to air)	6.14E-06	kilogram
Pentane (to air)	3.68E-05	kilogram
Propane (to air)	6.14E-06	kilogram
Propionic acid (to air)	6.14E-07	kilogram
Sulfur dioxide (to air)	1.69E-05	kilogram
Toluene (to air)	6.14E-06	kilogram
Water, cooling, unspecified natural origin (natural resource, in water)	3.80E-01	cubic meter

Source: Antonini et al.[38]

Table S1.5. Life cycle inventory of gaseous H_2 production (1 kg, 25 bar, 99.97% purity) by NG SMR CCS.

Exchanges	Amount	Unit
Economic flows		
CO_2 storage/at H_2 production plant, pre, pipeline 400km, storage 3000m	5.664958	kilogram
market for chemical factory, organics	5.35E-10	unit
market for aluminium oxide, metallurgical	5.33E-04	kilogram
market for chromium oxide, flakes	3.60E-05	kilogram
market for copper oxide	3.62E-04	kilogram
market for diethanolamine	1.93E-04	kilogram
market for liquid storage tank, chemicals, organics	2.55E-09	unit
market for magnesium oxide	2.80E-05	kilogram
market for molybdenum trioxide	1.67E-05	kilogram
market for nickel, class 1	2.03E-04	kilogram
market for portafer	3.12E-04	kilogram
market for quicklime, milled, packed	4.80E-05	kilogram
market for silica sand	1.16E-05	kilogram
market for water, deionised	7.54E+00	kilogram
market for zeolite, powder	8.83E-04	kilogram
market for zinc oxide	3.71E-04	kilogram
market (group) for electricity, high voltage	-2.00E-01	kilowatt hour
market for natural gas, high pressure	3.856157	cubic meter
Environmental flows		
Acetaldehyde (to air)	2.82E-08	kilogram
Acetic acid (to air)	4.23E-06	kilogram
Benzene (to air)	1.13E-05	kilogram
Benzo(a)pyrene (to air)	2.82E-10	kilogram
Butane (to air)	1.97E-05	kilogram
Carbon dioxide, fossil (to air)	3.119275	kilogram
Carbon monoxide, fossil (to air)	5.92E-05	kilogram
Dinitrogen monoxide (to air)	2.82E-06	kilogram
Formaldehyde (to air)	2.82E-06	kilogram
Mercury (to air)	8.45E-10	kilogram
Methane, fossil (to air)	5.63E-05	kilogram
Nitrogen oxides (to air)	5.04E-04	kilogram
PAH, polycyclic aromatic hydrocarbons (to air)	2.82E-07	kilogram

Particulates, < 2.5 um (to air)	5.63E-06	kilogram
Pentane (to air)	3.38E-05	kilogram
Propane (to air)	5.63E-06	kilogram
Propionic acid (to air)	5.63E-07	kilogram
Sulfur dioxide (to air)	1.55E-05	kilogram
Toluene (to air)	5.63E-06	kilogram
Water, cooling, unspecified natural origin (natural resource, in water)	3.80E-01	cubic meter

Source: Antonini et al.[38]

Table S1.6. Life cycle inventory of gaseous H_2 production (1 kg, 26 bar, 99.97% purity) by BG.

Exchanges	Amount	Unit
Economic flows		
market for liquid storage tank, chemicals, organics	2.55E-09	unit
market for water, deionised	15.90552	kilogram
market for wood chips, wet, measured as dry mass	11.6966	kilogram
market (group) for electricity, low voltage	1.368832	kilowatt hour
synthetic gas factory construction	5.35E-10	unit
treatment of wastewater, average, capacity 1E9l/year	-1.24E-02	cubic meter
Environmental flows		
Carbon dioxide, non-fossil (to air)	21.19664	kilogram

Source: Antonini et al.[39]

Table S1.7. Life cycle inventory of gaseous H_2 production (1 kg, 26 bar, 99.97% purity) by BG CCS.

Exchanges	Amount	Unit	Data source
Economic flows			
CO_2 storage/at H_2 production plant, pre, pipeline 400km, storage 3000m	18.02775	kilogram	[39]
market for liquid storage tank, chemicals, organics	2.55E-09	unit	[39]
market for water, deionised[a]	16.3391	kilogram	[39, 85]
market for wood chips, wet, measured as dry mass	11.6966	kilogram	[39]
market (group) for electricity, low voltage	4.756841	kilowatt hour	[39]
market for diethanolamine	1.76E-04	kilogram	[85]
synthetic gas factory construction	5.35E-10	unit	[39]
treatment of wastewater, average, capacity 1E9l/year[a]	-1.29E-02	cubic meter	[39, 85]
Environmental flows			
Water, cooling, unspecified natural origin (from natural resource)[a]	1.496476	cubic meter	[85]
Carbon dioxide, non-fossil (to air)	3.168898	kilogram	[39]

a. The added amounts compared with the BG process are corresponding to capturing 18.02775 CO_2.

Table S1.8. Life cycle inventory of gaseous H_2 production (1 kg, 30 bar, 99.99% purity) by AE powered by grid electricity.

Exchanges	Amount	Unit	Data source
Economic flows			
electrolyzer, AE, Balance of Plant*	2.99E-07	unit	Calculation
electrolyzer, AE, Stack*	8.97E-07	unit	Calculation
market for potassium hydroxide	3.70E-03	kilogram	[40]
market (group) for electricity, low voltage[a]	49.75	kilowatt hour	Calculation
market for water, deionised	12	kilogram	[99]
Environmental flows			
Water, cooling, unspecified natural origin (natural resource, in water)	0.0881	cubic meter	[40]

Oxygen (to air)	8	kilogram	[40]

a. In the sensitivity analysis, for solar PV, onshore wind and hydro power, the processes of power generation "electricity production, photovoltaic, 570kWp open ground installation, multi-Si", "electricity production, wind, 1-3MW turbine, onshore" and "electricity production, hydro, reservoir, tropical region (alpine region)" are used. If the process of hydro power from reservoir is not available in specific region, the process of "electricity production, hydro, run-of-river" is used.

Table S1.9. Life cycle inventory of AE's BoP production (1 MW).

Exchanges	Amount	Unit	Data source
Economic flows			
market for cast iron	716.1	kilogram	[40]
market for concrete, 35MPa	7.7	cubic meter	[40]
market for electronics, for control units	100	kilogram	[40]
market for ethylene glycol	7	kilogram	[40]
market for extrusion, plastic pipes	464.6	kilogram	[40]
market for glass fibre	464.6	kilogram	[40]
market for injection moulding	3	kilogram	[40]
market for aluminium, wrought alloy	160	kilogram	[40]
market for copper, cathode	616.7	kilogram	[40]
market for polyethylene, low density, granulate	467.4	kilogram	[40]
market for reinforcing steel	5134.4	kilogram	[40]
market for sheet rolling, aluminium	100	kilogram	[40]
market for sheet rolling, chromium steel	6697.8	kilogram	[40]
market for sheet rolling, steel	10130	kilogram	[40]
market for steel, chromium steel 18/8, hot rolled	6697.8	kilogram	[40]
market for steel, low-alloyed, hot rolled	6075.6	kilogram	[40]
market for tube insulation, elastomere	207.9	kilogram	[40]
market for welding, arc, steel	29	meter	[40]
market for wire drawing, copper	616.7	kilogram	[40]
market (group) for electricity, low voltage	37113.5	kilowatt hour	[40]
Environmental flows			
Transformation, from industrial area (natural resource, land)	135	square meter	[97]
Transformation, to industrial area (natural resource, land)	135	square meter	[97]
Occupation, industrial area (natural resource, land)	2700	square meter-year	[97]

Source: Gerloff[40]

Table S1.10. Life cycle inventory of AE's stack production (1 MW).

Exchanges	Amount	Unit
Economic flows		
market for sheet rolling, chromium steel	20194.4	kilogram
market for steel, chromium steel 18/8, hot rolled	20194.4	kilogram
market for nickel, class 1	2884.9	kilogram
market for tetrafluoroethylene	144.2	kilogram
market for polysulfone	48.8	kilogram
market for zirconium oxide	73	kilogram
market (group) for electricity, low voltage	95553.3	kilowatt hour

Source: Gerloff[40]

Table S1.11. Life cycle inventory of gaseous H_2 production (1 kg, 30 bar, 99.99% purity) by PEM powered by grid electricity.

Exchanges	Amount	Unit	Data source
Economic flows			
electrolyzer, PEM, Balance of Plant*	3.45E-07	unit	Calculation
electrolyzer, PEM, Stack*	1.04E-06	unit	Calculation
market (group) for electricity, low voltage	57.47	kilowatt hour	Calculation
market for water, deionised	12	kilogram	[99]
Environmental flows			
Water, cooling, unspecified natural origin (natural resource, in water)	0.0881	cubic meter	[40]
Oxygen	8	kilogram	[40]

Table S1.12. Life cycle inventory of PEM's BoP production (1 MW).

Exchanges	Amount	Unit	Data source
Economic flows			
market for aluminium, wrought alloy	260	kilogram	[40]
market for cast iron	600	kilogram	[40]
market for copper, anode	345	kilogram	[40]
market for electronics, for control units	100	kilogram	[40]
market for ethylene glycol	7	kilogram	[40]
market for extrusion, plastic pipes	464.6	kilogram	[40]
market for injection moulding	300	kilogram	[40]
market for lubricating oil	100	kilogram	[40]
market for polyethylene, low density, granulate	464.6	kilogram	[40]
market for polypropylene, granulate	300	kilogram	[40]
market for reinforcing steel	3312.3	kilogram	[40]
market for sheet rolling, aluminium	200	kilogram	[40]
market for sheet rolling, chromium steel	4327	kilogram	[40]
market for sheet rolling, copper	100	kilogram	[40]
market for sheet rolling, steel	5382.3	kilogram	[40]
market for steel, chromium steel 18/8, hot rolled	4327	kilogram	[40]
market for steel, low-alloyed	3150	kilogram	[40]
market for tube insulation, elastomere	115	kilogram	[40]
market for welding, arc, steel	29	meter	[40]
market for wire drawing, copper	245	kilogram	[40]
market for zeolite, powder	100	kilogram	[40]
market for concrete, 35MPa	2.3	cubic meter	[40]
market (group) for electricity, low voltage	50000	kilowatt hour	[40]
Environmental flows			
Transformation, from industrial area (natural resource, land)	105	square meter	[97]
Transformation, to industrial area (natural resource, land)	105	square meter	[97]
Occupation, industrial area (natural resource, land)	2100	square meter-year	[97]

Table S1.13. Life cycle inventory of PEM's stack production (1 MW).

Exchanges	Amount	Unit	Data source
Economic flows			
market for titanium	528	kilogram	[41]
market for aluminium, wrought alloy	27	kilogram	[41]
market for sheet rolling, aluminium	27	kilogram	[41]

market for steel, chromium steel 18/8, hot rolled	100	kilogram	[41]
market for sheet rolling, chromium steel	100	kilogram	[41]
market for copper, anode	4.5	kilogram	[41]
market for sheet rolling, copper	4.5	kilogram	[41]
market for activated carbon, granular	9	kilogram	[41]
market for tetrafluoroethylene	9.184	kilogram	[41, 96]
market for sulfuric acid	6.816	kilogram	[41, 96]
market for platinum	0.075	kilogram	[41]
market for synthetic rubber	4.8	kilogram	[40]
market for iridium*	0.75	kilogram	[41]
market (group) for electricity, low voltage	103890.8	kilowatt hour	[40]

Table S1.14. Life cycle inventory of market for iridium (1 kg).

Exchanges	Amount	Unit
Economic flows		
market for electricity, low voltage	54212.21	kilowatt hour
Environmental flows		
Iridium, in ground (natural resource, in ground)	1	kilogram
Occupation, arable land, unspecified use (natural resource, land)	41.7465	square meter-year
Occupation, forest, unspecified (natural resource, land)	41.7465	square meter-year
Occupation, mineral extraction site (natural resource, land)	635.274	square meter-year
Transformation, from mineral extraction site (natural resource, land)	4.882	square meter
Transformation, to mineral extraction site (natural resource, land)	4.882	square meter
Water, unspecified natural origin (natural resource, in ground)	199.7499	cubic meter
Ethane, 1,1,1-trichloro-, HCFC-140 (to air)	8.02E-10	kilogram
Ethane, 1,2-dichloro- (to air)	4.56E-04	kilogram
Arsenic (to air)	3.38E-03	kilogram
Benzo(a)pyrene (to air)	3.03E-02	kilogram
Benzene (to air)	3.03E-02	kilogram
Lead (to air)	1.81E-02	kilogram
Cadmium (to air)	1.43E-04	kilogram
Methane, trichlorofluoro-, CFC-11 (to air)	1.44E-04	kilogram
Methane, non-fossil (to air)	7.81E-02	kilogram
Methane, fossil (to air)	19.13	kilogram
Hydrocarbons, chlorinated (to air)	8.10E-04	kilogram
Chromium (to air)	6.93E-03	kilogram
Carbon monoxide, fossil (to air)	7.159	kilogram
Carbon dioxide, fossil (to air)	11146.62	kilogram
Carbon dioxide, non-fossil (to air)	412.196	kilogram
Methane, dichloro-, HCC-30 (to air)	8.76E-08	kilogram
Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin (to air)	5.73E-09	kilogram
Ethane (to air)	5.56E-03	kilogram
Particulates, > 2.5 um, and < 10um (to air)	36.7	kilogram
Formaldehyde (to air)	4.86E-02	kilogram
Hydrogen sulfide (to air)	1.91E-02	kilogram
Hydrochloric acid (to air)	4.99E-01	kilogram
Benzene, hexachloro- (to air)	4.70E-09	kilogram
Hydrogen fluoride (to air)	4.87E-02	kilogram

Ethane, 1,1,1,2-tetrafluoro-, HFC-134a (to air)	2.10E-07	kilogram
Copper (to air)	2.56E-02	kilogram
Dinitrogen monoxide (to air)	1.06	kilogram
Ammonia (to air)	3.52E-01	kilogram
Nickel (to air)	2.69E-02	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air)	26.859	kilogram
Nitrogen oxides (to air)	30.635	kilogram
Polychlorinated biphenyls (to air)	9.52E-10	kilogram
Phenol, pentachloro- (to air)	2.46E-06	kilogram
Perfluoropentane (to air)	3.43E-06	kilogram
PAH, polycyclic aromatic hydrocarbons (to air)	1.50E-03	kilogram
Mercury (to air)	2.62E-04	kilogram
Sulfur hexafluoride (to air)	4.43E-05	kilogram
Sulfur dioxide (to air)	2172.255	kilogram
Methane, tetrachloro-, R-10 (to air)	1.02E-04	kilogram
Zinc (to air)	6.79E-02	kilogram
Arsenic, ion (to water)	2.75E-01	kilogram
Lead (to water)	2.67E-01	kilogram
Cadmium, ion (to water)	2.97E-02	kilogram
Chloride (to water)	34.494	kilogram
Chromium, ion (to water)	5.73E-02	kilogram
Cyanide (to water)	6.65E-01	kilogram
Fluoride (to water)	5.93E-01	kilogram
AOX, Adsorbable Organic Halogen as Cl (to water)	4.48E-05	kilogram
Copper, ion (to water)	8.41E-01	kilogram
Ammonium, ion (to water)	6.54E-02	kilogram
Nickel (to water)	4.51	kilogram
Nitrate (to water)	6.80E-02	kilogram
Tin, ion (to water)	1.50E-05	kilogram
TOC, Total Organic Carbon (to water)	10.576	kilogram
Phenol (to water)	2.00E-03	kilogram
PAH, polycyclic aromatic hydrocarbons (to water)	1.50E-04	kilogram
Mercury (to water)	3.53E-03	kilogram
Suspended solids, unspecified (to water)	6.86E-01	kilogram
Sulfate (to water)	272.715	kilogram
Phosphorus (to water)	1.73E-01	kilogram
Nitrogen (to water)	2.656	kilogram
Zinc, ion (to water)	7.043	kilogram

Source: ProBas[300]

Table S1.15. Life cycle inventory of gaseous H_2 production (1 kg, 30 bar, 99.9% purity) by SOEC powered by grid electricity.

Exchanges	Amount	Unit	Data source
Economic flows			
electrolyzer, SOEC, Balance of Plant*	2.57E-07	unit	Calculation
electrolyzer, SOEC, Stack*	2.31E-06	unit	Calculation
market (group) for electricity, low voltage	42.73	kilowatt hour	Calculation
market for heat, district or industrial, other than natural gas	18.864	megajoule	[40]
market for water, deionised	12	kilogram	[99]

Environmental flows			
Water, cooling, unspecified natural origin (natural resource, in water)	0.6447	cubic meter	[40]
Oxygen (to air)	8	kilogram	[40]

Table S1.16. Life cycle inventory of SOEC's BoP production (1 MW).

Exchanges	Amount	Unit	Data source
Economic flows			
market for cast iron	3000	kilogram	[40]
market for acrylonitrile-butadiene-styrene copolymer	1.4	kilogram	[40]
market for concrete, 35MPa	2.3	cubic meter	[40]
market for electronics, for control units	100	kilogram	[40]
market for ethylene glycol	35	kilogram	[40]
market for extrusion, plastic pipes	534	kilogram	[40]
market for injection moulding	1.4	kilogram	[40]
market for aluminium, wrought alloy	401	kilogram	[40]
market for copper, cathode	428.5	kilogram	[40]
market for polyethylene, low density, granulate	534	kilogram	[40]
market for reinforcing steel	13730.6	kilogram	[40]
market for sheet rolling, aluminium	100	kilogram	[40]
market for sheet rolling, chromium steel	16621.4	kilogram	[40]
market for sheet rolling, steel	12081.2	kilogram	[40]
market for steel, chromium steel 18/8, hot rolled	16621.4	kilogram	[40]
market for steel, low-alloyed, hot rolled	2250	kilogram	[40]
market for steel, low-alloyed	1503.6	kilogram	[40]
market for tube insulation, elastomere	176.6	kilogram	[40]
market for welding, arc, steel	33.3	meter	[40]
market for wire drawing, copper	428.5	kilogram	[40]
market (group) for electricity, low voltage	76420.2	kilowatt hour	[40]
Environmental flows			
Transformation, from industrial area (natural resource, land)	55	square meter	[98]
Transformation, to industrial area (natural resource, land)	55	square meter	[98]
Occupation, industrial area (natural resource, land)	1100	square meter-year	[98]

Table S1.17. Life cycle inventory of SOEC's stack production (1 MW).

Exchanges	Amount	Unit
Economic flows		
market for aluminium oxide, metallurgical	6.4	kilogram
market for barium oxide	6.4	kilogram
market for boric oxide	6.4	kilogram
Lanthanum strontium manganite (LSM)*	2.1	kilogram
market for cerium oxide	91.5	kilogram
market for nickel, class 1	144.1	kilogram
market for praseodymium oxide	9	kilogram
market for samarium-europium-gadolinium oxide	37.7	kilogram
market for sheet rolling, chromium steel	8976.1	kilogram
market for silicone product	6.4	kilogram
market for steel, chromium steel 18/8, hot rolled	8976.1	kilogram
market for zirconium oxide	170.7	kilogram

market (group) for electricity, low voltage	122224.4	kilowatt hour

Source: Gerloff [40]

Table S1.18. Life cycle inventory of LSM production (1 kg).

Exchanges	Amount	Unit
Economic flows		
market for lanthanum oxide	5.04E-01	kilogram
market for manganese	8.62E-02	kilogram
market for strontium carbonate	5.51E-01	kilogram
market for nitric acid, without water, in 50% solution state	1.3181	kilogram
market for chloroacetic acid	1.667388	kilogram
market for ammonia, anhydrous, liquid	3.00E-01	kilogram
market for water, deionised	8.833922	kilogram
market group for electricity, low voltage	15.68021	kilowatt hour

Source: Staffell et al.[301]

For the delivery purity and pressure of the H_2 from water electrolysis, only the information about PEM (industry grade N5.0-99.999% and 30 bar) can be available from the refence Bareiß et al.[41] that we directly used. We further checked other references to clarify these information about AE and SOEC and made a comparison to ensure the value used in our paper is reasonable. The H_2 produced by AE is delivered at 99.999% purity and 30 bar pressure with the system electrical efficiency of 53-70%, as mentioned in the Table5-1 in the report of Smolinka et al.[302] This electrical efficiency was cited in the research of Zhang et al.,[303] which is the main source reference of the AE's stack and BoP in the Gerloff.[40] Purity requirements vary significantly from different applications.[304] Although 99.999% purity of H_2 produced by AE and PEM can be achieved based on the electrical efficiency used in this paper, the mid-range value of 99.99% (N4.0) purity from manufacturer (between 99.9%-N3.0 and 99.999%) [305-308] was used as the target purity due to lack of specific users. Gerloff[40] used Häfele et al.[309]'s LCI of SOEC's stack, whose operating pressure is 1 bar, and added H_2 compressors in SOEC's BoP. In other references using the similar SOEC system, the generated H_2 (99.9% purity) is generally compressed from 1 bar to 30 bar, with the system electrical efficiency of SOEC between 75% and 88%.[310-313] The target delivery purity and pressure of the H_2 produced by water electrolysis are shown in Table S1.19.

Table S1.19. The system electrical efficiency of the target H_2 product of the water electrolysis.

Parameters	AE	PEM	SOEC
Electrical efficiency used in this paper (%)	67	58	78
Delivery pressure of H_2 (bar)	30	30	30
Delivery purity of H_2 (%)	99.99	99.99	99.9
Electrical efficiency for the target H_2 product (%)	53-70	50-70	75-88

Table S1.20. LCI of 1 MW PEM stack production in the Middle East and the USA in 2030 and 2050 broken down into technology improvements (likely material reductions), regional variations (where the regional electricity mix is used), and other inputs that do not change over time and region.

Economic flows	Unit	Location	Amount in 2030	Amount in 2050
Technology improvements				

market for titanium	kg	GLO	213.69	35
market for steel, chromium steel 18/8, hot rolled	kg	GLO	73.68	40
market for sheet rolling, chromium steel	kg	GLO	73.68	40
market for activated carbon, granular	kg	GLO	7.14	4.5
market for tetrafluoroethylene (Nafion)	kg	GLO	4.59	1.148
market for sulfuric acid (Nafion)	kg	RoW	3.41	0.852
market for platinum	kg	GLO	0.05	0.02
market for iridium	kg	GLO	0.26	0.03
Regional variations				
market for electricity, low voltage	kWh	MEA/USA	103890.8	103890.8
Others				
market for aluminium, wrought alloy	kg	GLO	27	27
market for sheet rolling, aluminium	Kg	GLO	27	27
market for copper, anode	kg	GLO	4.5	4.5
market for sheet rolling, copper	kg	GLO	4.5	4.5
market for synthetic rubber	kg	GLO	4.8	4.8

S1.2 Global H_2 markets across regions

Current H_2 production across regions (2020)

For the IEA's regions where no data of H_2 production by CG and NG SMR in 2020 was available, the following assumptions were made:

Coal is used as the feedstock of H_2 production in limited regions including China, India, Japan, Southeast Asia, Africa and Rest of Asia Pacific.[314] For Southeast Asia, Africa and Rest of Asia Pacific, where there is no data of H_2 production amount of CG, their values are generated by multiplying the remaining global total H_2 production amount by CG excluding the known amount of China, India and Japan, by the ratios of their respective coal supply amount in 2020.[67]

Australia's hydrogen production was around 0.65 Mt and virtually all of this H_2 is made using NG SMR.[315] For the 1.8 Mt H_2 produced and used in Korea in 2020, 40% was produced from NG SMR, with the remaining 60% obtained as by-product from various sources.[61] The NG SMR proportion in the H_2 market of Rest of Asia Pacific was set as the same as the weighted average value for Australia and Korea, which are dominated by H_2 producing countries in this region. Russia has no official statistics of its H_2 market,[316] but what can be confirmed is that there is practically no government or industry program for producing H_2 from coal.[317] Thus, the H_2 market of Russia is assumed to consist of only NG SMR technology excluding the by-product H_2. The Rest of Eurasia has a similar situation. So the global remaining H_2 production amount of NG SMR excluding other 13 regions were proportionally assigned to Russia and the Rest of Eurasia according their respective total H_2 production amount.

Future H_2 production across regions (until 2050)

The future regional dedicated H_2 production volumes in the IEA's STEPS, APS and NZE scenarios were derived via the following steps. For the H_2 production volumes from 2020 to 2050 in the STEPS and APS, the IEA provides global total H_2 production volumes and specific values of CG CCS, NG SMR CCS, water electrolysis and bioenergy (lacking CG and NG SMR), as well as the total production volumes including by-product H_2 of 15 regions.[67] At first, the fraction of the global H_2 production volumes of CG and NG SMR in 2020 was used to distinguish between CG and NG SMR in the residual production volumes (excluding by-product H_2, which was considered unchanged in the future). After getting the production volumes of different H_2 technologies at the global level, we can then assign these values to 15 regions.

Our further assumption is that the regional fractions in CG and NG SMR after 2020 will change with the same trend of their total H_2 production volumes[67] (The regional fractions are shown in Table S20-S23). Thus, the production volume of CG and NG SMR after 2020 in each region can be obtained by multiplying the global total production volume of CG and NG SMR with regional fractions. Above fractions were also used for assigning the production volume of CG CCS and NG SMR CCS. For bioenergy-based H_2 technology, the regional fraction of the total H_2 production volume was used to assign it due to lack of starting values in 2020 and reference basis. At last, the production volume of water electrolysis in each region over time can be obtained by subtracting the above known amount and by-product H_2 from the regional total H_2 production volume. Water electrolysis includes AE, PEM and SOEC. If there is no clear classification for one region in 2020, the global average proportion, 61%, 31% and 8% for AE, PEM and SOEC would be adopted as the alternative.[61] PEM is currently one of the two commercially available electrolyzer technologies together with AE.[318] On the one hand, the share of AE in the total installed capacity of announced projects remains at around 60% for the next five years, but decreases afterwards, so that by 2030 the total capacity could be equally split between AE and PEM electrolyzers.[104] On the other hand, Schmidt et al.[101] found that experts believed PEM would be the dominant electrolysis technology by as early as 2030. Moreover, PEM has a simpler balance of plant and produces H_2 at a higher pressure than AE, which means lower energy requirements for compression.[97] Studies also show that PEM might be more future-proof than AE; for example, PEM electrolyzers exhibit a higher power-density per footprint ratio compared to AE electrolyzers, making the overall system footprint less space-consuming,[23] and PEM is shown to exhibit higher flexibility and can be installed with variable power (solar photovoltaic and wind) without impacting the electrolyzer performance.[16] Thus, a conservative market share of 60% for PEM in water electrolysis in 2050 is assumed. The SOEC is simply assumed to increase 1% every 5 years from 2020 to 2050. At the same time, the remaining proportion is AE's market share.

For the NZE scenario, only the global H_2 production volume by fossil fuel, CCS, bioenergy, water electrolysis and by-product is available and there is no regional data.[59] Thus, the source of coal and natural gas in fossil fuel and CCS were distinguished by the fractions

used in the APS scenario. At the same time, the reginal fractions of the global H_2 production from 2020 to 2050 of the APS scenario were used to get the regional total production volumes in the NZE scenario. Other steps were also consistent with the APS scenario. BG CCS was only adopted in the NZE scenario from 2040 with a fraction of 1% in bioenergy-based H_2 production volume and can achieve no more than 5% by 2050.[67] The annual H_2 production volumes by various technologies in 15 regions between 2020 and 2050 under three scenarios are shown in Figure S1.1.

Table S1.21. The regional fraction of CG and CG CCS between 2020 and 2050 in the STEPS scenario.

Regions	2020	2025	2030	2035	2040	2045	2050
Africa	1.7%	1.9%	2.0%	2.2%	2.4%	2.5%	2.7%
China	84.7%	84.3%	83.9%	82.6%	81.3%	80.1%	79.1%
India	7.2%	7.5%	7.8%	8.6%	9.4%	10.1%	10.7%
Japan	0.5%	0.5%	0.5%	0.5%	0.5%	0.6%	0.6%
Southeast Asia	2.9%	3.0%	3.0%	3.2%	3.4%	3.5%	3.7%
Rest of Asia Pacific	3.0%	2.9%	2.7%	2.9%	3.0%	3.2%	3.3%

Table S1.22. The regional fraction of CG and CG CCS between 2020 and 2050 in the APS and NZE scenario.

	2020	2025	2030	2035	2040	2045	2050
Africa	1.7%	1.8%	1.9%	2.1%	2.3%	2.4%	2.5%
China	84.7%	84.6%	84.4%	81.7%	79.9%	78.6%	77.7%
India	7.2%	7.2%	7.1%	8.1%	8.8%	9.2%	9.5%
Japan	0.5%	0.6%	0.6%	0.8%	0.9%	0.9%	1.0%
Southeast Asia	2.9%	2.9%	2.9%	3.2%	3.4%	3.5%	3.6%
Rest of Asia Pacific	3.0%	3.0%	3.0%	4.1%	4.8%	5.3%	5.7%

Table S1.23. The regional fraction of NG SMR and NG SMR CCS between 2020 and 2050 in the STEPS scenario.

	2020	2025	2030	2035	2040	2045	2050
United States	17.9%	17.4%	16.9%	16.7%	16.5%	16.4%	16.2%
Rest of North America	4.7%	4.4%	4.2%	4.1%	4.0%	3.9%	3.9%
Brazil	0.3%	0.5%	0.6%	0.7%	0.8%	0.9%	1.0%
Rest of Central and South America	4.2%	4.3%	4.4%	4.8%	5.1%	5.3%	5.6%
European Union	8.8%	7.7%	6.9%	6.4%	6.0%	5.7%	5.4%
Rest of Europe	2.4%	2.4%	2.3%	2.3%	2.3%	2.3%	2.3%
Africa	4.7%	5.1%	5.5%	5.8%	6.1%	6.4%	6.6%
Middle East	18.3%	20.0%	21.3%	20.9%	20.6%	20.3%	20.0%
Russia	5.2%	4.5%	4.0%	3.8%	3.6%	3.5%	3.3%
Rest of Eurasia	0.4%	0.4%	0.4%	0.4%	0.3%	0.3%	0.3%
China	11.4%	11.3%	11.2%	10.6%	10.2%	9.8%	9.4%
India	11.5%	12.1%	12.4%	13.3%	14.1%	14.7%	15.3%
Japan	1.7%	1.6%	1.5%	1.5%	1.6%	1.6%	1.6%
Southeast Asia	4.0%	4.1%	4.2%	4.3%	4.4%	4.5%	4.5%
Rest of Asia Pacific	4.7%	4.4%	4.2%	4.3%	4.4%	4.5%	4.5%

Table S1.24. The regional fraction of NG SMR and NG SMR CCS between 2020 and 2050 in the APS and NZE scenario.

	2020	2025	2030	2035	2040	2045	2050
United States	17.9%	19.4%	20.4%	21.6%	22.3%	22.8%	23.2%
Rest of North America	4.7%	4.3%	4.0%	3.5%	3.2%	3.0%	2.8%
Brazil	0.3%	0.6%	0.8%	1.1%	1.3%	1.4%	1.5%

Rest of Central and South America	4.2%	4.6%	4.9%	4.9%	5.0%	5.0%	5.0%
European Union	8.8%	9.2%	9.6%	9.3%	9.1%	9.0%	8.9%
Rest of Europe	2.4%	2.9%	3.2%	3.3%	3.3%	3.3%	3.4%
Africa	4.7%	4.8%	4.8%	5.1%	5.4%	5.5%	5.6%
Middle East	18.3%	18.4%	18.4%	15.8%	14.3%	13.2%	12.5%
Russia	5.2%	3.9%	3.1%	2.4%	1.9%	1.7%	1.4%
Rest of Eurasia	0.4%	0.4%	0.3%	0.3%	0.2%	0.2%	0.2%
China	11.4%	10.8%	10.3%	9.6%	9.1%	8.8%	8.6%
India	11.5%	10.9%	10.5%	11.5%	12.0%	12.4%	12.7%
Japan	1.7%	1.8%	1.9%	2.2%	2.4%	2.5%	2.6%
Southeast Asia	4.0%	3.8%	3.6%	3.8%	4.0%	4.1%	4.1%
Rest of Asia Pacific	4.7%	4.4%	4.3%	5.6%	6.4%	7.0%	7.3%

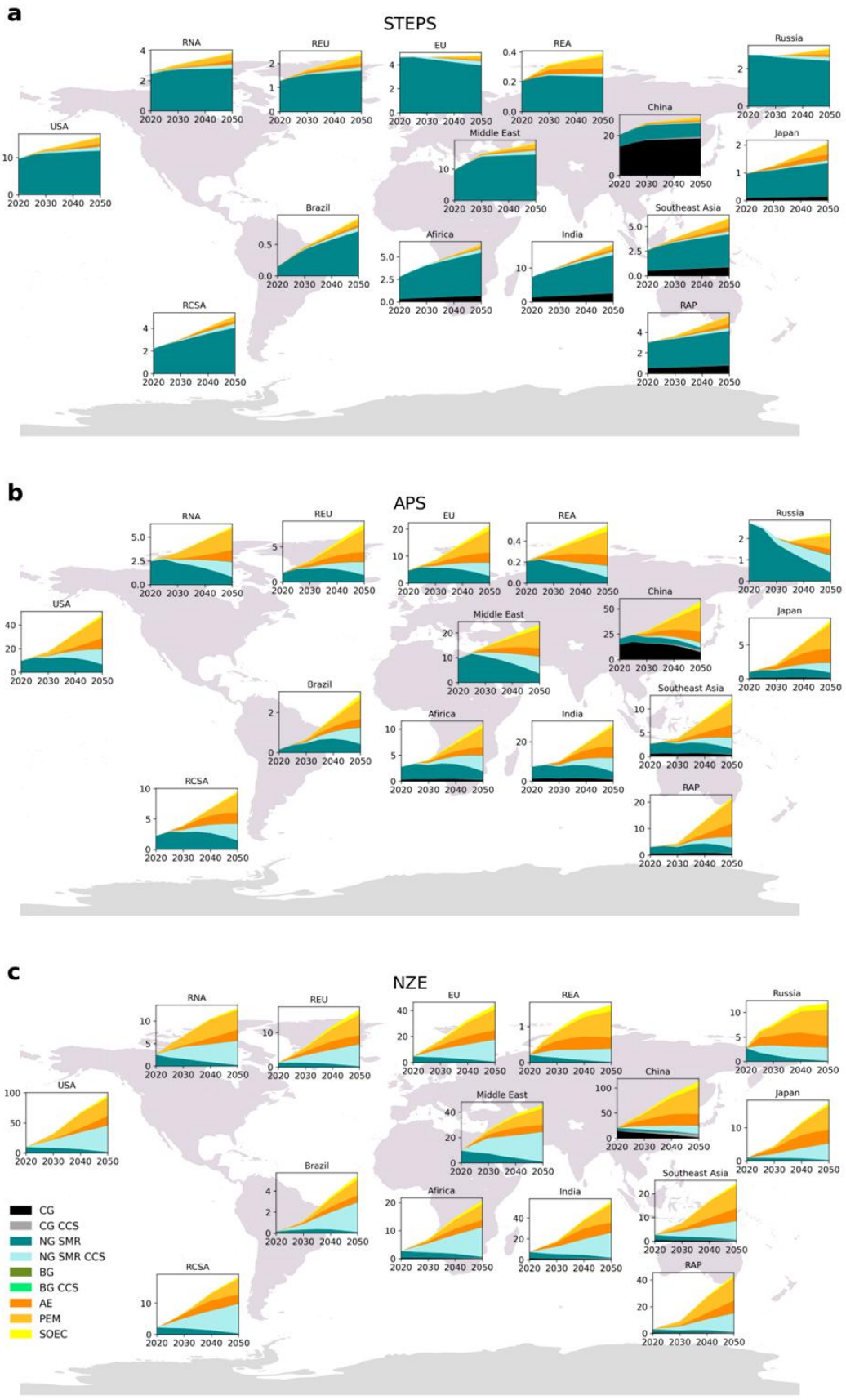

Figure S1.1. H_2 production volumes in 15 regions from 2020 to 2050 in the STEPS, APS and NZE scenarios. In the figure, RNA= Rest of North America, REU= Rest of Europe, REA= Rest of Eurasia, RCSA= Rest of Central and South America and RAP= Rest of Asia Pacific. The unit of the stacked area charts is Mt per year.

S1.3 Regional scope

Table S1.25. The region matching between IEA and REMIND models.

No.	IEA regions	REMIND regions
1	Brazil	LAM
2	Rest of Central and South America	LAM
3	Southeast Asia	OAS
4	Rest of Asia Pacific	OAS
5	Africa	SSA
6	European Union (EU)	EUR
7	Rest of Europe	NEU
8	Middle East	MEA
9	Russia	REF
10	Rest of Eurasia	REF
11	Rest of North America	CAZ
12	China	CHA
13	India	IND
14	Japan	JPN
15	USA	USA

Table S1.26. IEA regions and countries (ISO alpha-3 code).

No.	IEA Regions	ISO code of countries belonging to this region
1	Brazil	BRA
2	Rest of Central and South America	ABW, AIA, ARG, ATG, BES, BHS, BLM, BLZ, BMU, BOL, BRB, BVT, CHL, COL, CRI, CUB, CUW, CYM, DMA, DOM, ECU, FLK, GLP, GRD, GTM, GUF, GUY, HND, HTI, JAM, KNA, LCA, MAF, MSR, MTQ, NIC, PAN, PER, PRI, PRY, SGS, SLV, SUR, SXM, TCA, TTO, URY, VCT, VEN, VGB and VIR
3	Southeast Asia	BRN, IDN, KHM, LAO, MMR, MYS, PHL, SGP, THA and VNM
4	Rest of Asia Pacific	AFG, ASM, ATF, AUS, BGD,BTN, CCK, COK, CXR, FJI, FSM, GUM, HMD, IOT, KIR, KOR, LKA, MDV, MHL, MNG, MNP, NCL, NFK, NIU, NPL, NRU, NZL, PAK, PCN, PLW, PNG, PRK, PYF, SLB, TKL, TLS, TON, TUV, TWN, UMI, VUT, WLF, WSM and MAC
5	Africa	AGO, BDI, BEN, BFA, BWA, CAF, CIV, CMR, COD, COG, COM, CPV, DJI, DZA, EGY, ERI, ESH, ETH, GAB, GHA, GIN, GMB, GNB, GNQ, KEN, LBR, LBY, LSO, MAR, MDG, MLI, MOZ, MRT, MUS, MWI, MYT, NAM, NER, NGA, REU, RWA, SDN, SEN, SHN, SLE, SOM, SSD, STP, SWZ, SYC, TCD, TGO, TUN, TZA, UGA, ZAF, ZMB and ZWE
6	EU	AUT, BEL, BGR, CYP, CZE, DEU, DNK, ESP, EST, FIN, FRA, GRC, HRV, HUN, IRL, ITA, LTU, LUX, LVA, MLT, NLD, POL, PRT, ROU, SVK, SVN and SWE
7	Rest of Europe	ALA, ALB, AND, BIH, BLR, CHE, FRO, GBR, GGY, GIB, GRL, IMN, ISL, LIE, JEY, MCO, MDA, MKD, MNE, NOR, SJM, SMR, SRB, TUR, UKR, VAT, ISR and PSE,
8	Middle East	ARE, BHR, IRN, IRQ, JOR, KWT, LBN, OMN, QAT, SAU, SYR and YEM
9	Russia	RUS
10	Rest of Eurasia	ARM, AZE, GEO, KAZ, KGZ, TJK, TKM and UZB
11	Rest of North America	CAN, SPM and MEX
12	China	CHN and HKG
13	India	IND
14	Japan	JPN
15	USA	USA

Source: IEA[103]

Table S1.27. REMIND regions and countries (ISO alpha-3 code).

No.	REMIND regions	ISO code of countries belonging to this region
1	LAM	ABW, AIA, ARG, ATA, ATG ,BES, BHS, BLM, BLZ, BMU, BOL, BRA, BRB, BVT, CHL, COL, CRI, CUB, CUW, CYM, DMA, DOM, ECU, FLK, GLP, GRD, GTM, GUF, GUY, HND, HTI,

		JAM, KNA, LCA, MAF, MEX, MSR, MTQ, NIC, PAN, PER, PRI, PRY, SGS, SLV, SUR, SXM, TCA, TTO, URY, VCT, VEN, VGB, and VIR
2	OAS	AFG, ASM, ATF, BGD, BRN, BTN, CCK, COK, CXR, FJI, FSM, GUM, IDN, IOT, KHM, KIR, KOR, LAO, LKA, MDV, MHL, MMR, MNG, MNP, MYS, NCL, NFK, NIU, NPL, NRU, PAK, PCN, PHL, PLW, PNG, PRK, PYF, SGP, SLB, THA, TKL, TLS, TON, TUV, UMI, VNM, VUT, WLF, and WSM
3	SSA	AGO, BDI, BEN, BFA, BWA, CAF, CIV, CMR, COD, COG, COM, CPV, DJI, ERI, ETH, GAB, GHA, GIN, GMB, GNB, GNQ, KEN, LBR, LSO, MDG, MLI, MOZ, MRT, MUS, MWI, MYT, NAM, NER, NGA, REU, RWA, SEN, SHN, SLE, SOM, SSD, STP, SWZ, SYC, TCD, TGO, TZA, UGA, ZAF, ZMB, and ZWE
4	EUR	ALA, AUT, BEL, BGR, CYP, CZE, DEU, DNK, ESP ,EST, FIN, FRA, FRO, GBR, GGY, GIB, GRC, HRV, HUN, IMN, IRL, ITA, JEY, LTU, LUX, LVA, MLT, NLD, POL, PRT, ROU, SVK, SVN, and SWE
5	NEU	ALB, AND, BIH, CHE, GRL, ISL, LIE, MCO, MKD, MNE, NOR, SJM, SMR, SRB, TUR, and VAT
6	MEA	ARE, BHR, DZA, EGY, ESH, IRN, IRQ, ISR, JOR, KWT, LBN, LBY, MAR, OMN, PSE, QAT, SAU, SDN, SYR, TUN, and YEM
7	REF	ARM, AZE, BLR, GEO, KAZ, KGZ, MDA, RUS, TJK, TKM, UKR, and UZB
8	CAZ	AUS, CAN, HMD, NZL, and SPM
9	CHA	CHN, HKG, MAC, and TWN
10	IND	IND
11	JPN	JPN
12	USA	USA

Source: Baumstark et al.[66]

S1.4 Supplementary results

Prospective environmental impacts of H_2 production

Table S1.28. The contribution of various drivers to GHG emissions reduction from 2020 to 2050 of per kg H_2 produced by grid-powered water electrolysis.

Scenario	Region	Technology	Electricity decarbonization (%)	Efficiency improvement (%)	Material demand decrease (%)	Lifespan extension (%)
STEPS	China	AE-Grid	99.57	0.27	0.08	0.09
		PEM-Grid	99.45	0.48	0.05	0.02
		SOEC-Grid	99.62	0.13	0.10	0.14
	USA	AE-Grid	99.42	0.27	0.14	0.16
		PEM-Grid	99.36	0.52	0.09	0.03
		SOEC-Grid	99.45	0.09	0.19	0.26
	EU	AE-Grid	98.69	0.87	0.21	0.24
		PEM-Grid	98.26	1.56	0.13	0.05
		SOEC-Grid	98.87	0.46	0.27	0.40
APS	China	AE-Grid	99.60	0.24	0.07	0.09
		PEM-Grid	99.50	0.44	0.05	0.02
		SOEC-Grid	99.65	0.12	0.10	0.14
	USA	AE-Grid	99.40	0.30	0.14	0.16
		PEM-Grid	99.32	0.56	0.09	0.03
		SOEC-Grid	99.44	0.11	0.19	0.26
	EU	AE-Grid	98.73	0.84	0.20	0.23
		PEM-Grid	98.32	1.50	0.13	0.05
		SOEC-Grid	98.91	0.44	0.27	0.39

NZE	China	AE-Grid	99.62	0.21	0.08	0.09
		PEM-Grid	99.54	0.39	0.05	0.02
		SOEC-Grid	99.66	0.10	0.10	0.14
	USA	AE-Grid	99.92	-0.23	0.14	0.16
		PEM-Grid	100.22	-0.34	0.09	0.03
		SOEC-Grid	99.81	-0.23	0.19	0.24
	EU	AE-Grid	99.22	0.35	0.20	0.23
		PEM-Grid	99.16	0.67	0.12	0.05
		SOEC-Grid	99.26	0.11	0.26	0.36

Table S1.29. Environmental impacts of per kg H_2 in the global H_2 market in three scenarios.

Environmental impact categories (unit)	STEPS			APS		NZE	
	2020	2030	2050	2030	2050	2030	2050
Acidification (mol H+-eq $\times 10^{-2}$)	1.3	1.6	1.6	2.3	1.4	2.8	1.3
Ecotoxicity: freshwater (CTUe)	171.9	187.2	177.2	208.2	135.4	196.6	123.7
Resource use: energy carriers (MJ, net calorific value)	157.4	163.7	148.4	170.5	86.7	171.2	90.4
Eutrophication: aquatic freshwater (kg PO_4-eq $\times 10^{-3}$)	1.0	1.3	1.2	2.0	0.8	1.9	0.7
Eutrophication: aquatic marine (kg N-eq $\times 10^{-3}$)	1.7	2.3	2.2	3.5	1.9	4.1	1.9
Eutrophication: terrestrial (mol N-eq $\times 10^{-2}$)	3.8	4.3	3.9	5.0	2.3	4.9	2.2
Human toxicity: cancer effects (CTUh $\times 10^{-9}$)	1.5	1.8	2.2	2.9	4.7	4.1	4.6
Human toxicity: non- cancer effects (CTUh $\times 10^{-9}$)	3.2	4.3	5.1	7.3	9.6	9.8	9.2
Ionising radiation: human health (kBq U^{235}-eq)	0.4	0.5	0.6	1.2	1.6	2.2	1.8
Land use (dimensionless)	11.8	15.4	26.6	28.8	84.6	44.2	81.8
Resource use: minerals and metals (kg Sb-eq $\times 10^{-5}$)	2.2	2.8	4.6	5.7	14.4	9.7	13.8
Ozone depletion (kg CFC-11-eq $\times 10^{-7}$)	6.9	6.7	6.1	6.9	4.2	7.1	4.5
Particulate matter (disease incidence $\times 10^{-7}$)	3.7	4.0	3.5	4.0	1.8	3.1	1.5
Photochemical ozone formation (kg NMVOC-eq $\times 10^{-2}$)	1.3	1.5	1.3	1.7	0.9	1.9	0.9
Water use (m^3 world eq. deprived)	0.2	0.6	1.0	1.9	2.9	3.2	3.2
Climage change (kg CO_2-eq)	13.6	13.8	12.0	12.9	3.7	9.4	2.3

Table S1.30. Environmental impacts of per kg H_2 in the H_2 market of China in three scenarios.

Environmental impact categories (unit)	STEPS			APS		NZE	
	2020	2030	2050	2030	2050	2030	2050
Acidification (mol H+-eq $\times 10^{-2}$)	2.5	2.9	1.9	3.2	1.9	3.7	1.7
Ecotoxicity: freshwater (CTUe)	394.5	427.7	212.9	437.9	212.9	370.0	175.2
Resource use: energy carriers (MJ, net calorific value)	156.0	168.1	101.8	173.6	101.8	166.9	91.6
Eutrophication: aquatic freshwater (kg PO_4-eq $\times 10^{-3}$)	2.4	2.7	1.3	2.8	1.3	2.9	1.1
Eutrophication: aquatic marine (kg N-eq $\times 10^{-3}$)	2.4	3.3	2.4	4.2	2.4	5.4	2.1
Eutrophication: terrestrial (mol N-eq $\times 10^{-2}$)	8.3	9.0	3.6	9.0	3.6	7.6	2.7
Human toxicity: cancer effects (CTUh $\times 10^{-9}$)	1.5	1.9	5.5	3.1	5.5	5.6	5.8
Human toxicity: non- cancer effects (CTUh $\times 10^{-7}$)	0.4	0.6	1.2	1.0	1.2	1.5	1.3
Ionising radiation: human health (kBq U^{235}-eq)	-0.07	0.03	2.7	0.6	2.7	1.7	2.9
Land use (dimensionless)	27.6	30.9	121.5	48.1	121.5	86.0	125.2
Resource use: minerals and metals (kg Sb-eq $\times 10^{-4}$)	0.2	0.2	1.8	0.6	1.8	1.4	1.9
Ozone depletion (kg CFC-11-eq $\times 10^{-7}$)	2.5	2.6	2.5	2.8	2.5	3.8	2.6

Particulate matter (disease incidence ×10^{-6})	1.1	1.2	0.4	1.2	0.4	0.8	0.3
Photochemical ozone formation (kg NMVOC-eq ×10^{-2})	0.7	1.0	0.7	1.2	0.7	1.6	0.7
Water use (m^3 world eq. deprived)	0.6	0.8	1.4	1.1	1.4	1.6	1.5
Climage change (kg CO_2-eq)	19.1	20.0	5.2	19.1	5.2	13.5	2.4

Table S1.31. Environmental impacts of per kg H_2 in the H_2 market of USA in three scenarios.

Environmental impact categories (unit)	STEPS			APS		NZE	
	2020	2030	2050	2030	2050	2030	2050
Acidification (mol H+-eq ×10^{-2})	1.3	1.4	1.3	1.9	1.3	1.6	1.4
Ecotoxicity: freshwater (CTUe)	114.4	114.3	117.8	139.8	117.8	133.7	119.8
Resource use: energy carriers (MJ, net calorific value)	147.1	150.4	69.6	162.8	69.6	156.3	84.3
Eutrophication: aquatic freshwater (kg PO_4-eq ×10^{-3})	-0.1	0.2	0.5	1.9	0.5	0.4	0.5
Eutrophication: aquatic marine (kg N-eq ×10^{-3})	1.8	2.0	1.6	3.0	1.6	2.4	1.7
Eutrophication: terrestrial (mol N-eq ×10^{-2})	2.1	2.1	1.7	2.9	1.7	2.6	1.9
Human toxicity: cancer effects (CTUh ×10^{-9})	2.4	2.7	4.5	3.5	4.5	3.8	4.3
Human toxicity: non- cancer effects (CTUh ×10^{-8})	2.4	3.1	8.0	5.6	8.0	5.7	7.2
Ionising radiation: human health (kBq U^{235}-eq)	0.8	1.2	0.7	1.9	0.7	2.6	1.0
Land use (dimensionless)	3.3	7.5	75.5	20.5	75.5	29.3	69.3
Resource use: minerals and metals (kg Sb-eq ×10^{-4})	0.3	0.3	1.2	0.6	1.2	0.8	1.1
Ozone depletion (kg CFC-11-eq ×10^{-7})	5.8	5.8	3.4	5.6	3.4	5.4	3.8
Particulate matter (disease incidence ×10^{-7})	0.9	1.0	1.1	1.3	1.1	1.2	1.1
Photochemical ozone formation (kg NMVOC-eq ×10^{-2})	1.8	1.9	1.0	2.0	1.0	1.8	1.2
Water use (m^3 world eq. deprived)	0.2	0.3	0.8	0.8	0.8	1.1	1.0
Climage change (kg CO_2-eq)	10.4	10.4	3.4	10.1	3.4	6.6	2.4

Table S1.32. Environmental impacts of per kg H_2 in the H_2 market of EU in three scenarios.

Environmental impact categories (unit)	STEPS			APS		NZE	
	2020	2030	2050	2030	2050	2030	2050
Acidification (mol H+-eq ×10^{-2})	0.7	0.6	1.2	1.1	1.2	1.3	1.2
Ecotoxicity: freshwater (CTUe)	59.0	57.0	106.8	93.4	106.8	110.4	106.0
Resource use: energy carriers (MJ, net calorific value)	170.7	168.6	75.1	169.9	75.1	161.3	81.4
Eutrophication: aquatic freshwater (kg PO_4-eq ×10^{-4})	3.3	1.7	5.8	3.6	5.8	4.6	5.4
Eutrophication: aquatic marine (kg N-eq ×10^{-3})	2.0	1.9	2.1	2.8	2.1	3.1	2.2
Eutrophication: terrestrial (mol N-eq ×10^{-2})	2.2	2.1	2.3	3.1	2.3	3.4	2.5
Human toxicity: cancer effects (CTUh ×10^{-9})	1.7	1.7	5.1	3.3	5.1	4.1	4.9
Human toxicity: non- cancer effects (CTUh ×10^{-8})	2.5	2.3	9.2	5.6	9.2	7.4	8.7
Ionising radiation: human health (kBq U^{235}-eq)	1.1	1.1	0.8	2.7	0.8	3.5	0.9
Land use (dimensionless)	3.4	3.9	50.4	22.8	50.4	34.4	54.0
Resource use: minerals and metals (kg Sb-eq ×10^{-4})	0.3	0.3	1.4	0.7	1.4	1.0	1.3
Ozone depletion (kg CFC-11-eq ×10^{-6})	1.9	1.9	0.8	1.6	0.8	1.3	0.9
Particulate matter (disease incidence ×10^{-7})	0.5	0.5	1.1	1.0	1.1	1.2	1.1
Photochemical ozone formation (kg NMVOC-eq ×10^{-2})	1.6	1.6	1.0	1.6	1.0	1.5	1.1
Water use (m^3 world eq. deprived)	0.3	0.3	1.4	1.4	1.4	1.9	1.6
Climage change (kg CO_2-eq)	11.4	11.2	3.6	8.8	3.6	5.5	2.7

Table S1.33. Environmental impacts of per kg H_2 in the H_2 market of Brazil in three scenarios.

Environmental impact categories (unit)	STEPS			APS		NZE	
	2020	2030	2050	2030	2050	2030	2050
Acidification (mol H+-eq $\times 10^{-2}$)	0.4	0.6	1.0	0.9	1.0	1.0	1.0
Ecotoxicity: freshwater (CTUe)	35.8	45.0	88.9	61.1	88.9	66.9	79.4
Resource use: energy carriers (MJ, net calorific value)	161.9	155.6	78.9	138.0	78.9	129.8	92.8
Eutrophication: aquatic freshwater (kg PO_4-eq $\times 10^{-4}$)	0.1	1.6	4.9	2.5	4.9	3.5	4.1
Eutrophication: aquatic marine (kg N-eq $\times 10^{-3}$)	1.3	1.5	1.6	1.8	1.6	1.9	1.6
Eutrophication: terrestrial (mol N-eq $\times 10^{-2}$)	1.4	1.7	1.7	2.0	1.7	2.1	1.9
Human toxicity: cancer effects (CTUh $\times 10^{-9}$)	0.9	1.3	3.8	2.1	3.8	2.4	3.3
Human toxicity: non- cancer effects (CTUh $\times 10^{-8}$)	1.8	2.6	7.7	4.1	7.7	4.6	6.5
Ionising radiation: human health (kBq U^{235}-eq)	0.03	0.1	0.2	0.2	0.2	0.3	0.2
Land use (dimensionless)	4.3	11.6	87.3	28.7	87.3	29.8	76.3
Resource use: minerals and metals (kg Sb-eq $\times 10^{-4}$)	0.2	0.3	1.2	0.6	1.2	0.7	1.0
Ozone depletion (kg CFC-11-eq $\times 10^{-6}$)	2.0	1.9	1.0	1.6	1.0	1.5	1.1
Particulate matter (disease incidence $\times 10^{-8}$)	1.6	3.6	9.5	6.3	9.5	7.2	8.9
Photochemical ozone formation (kg NMVOC-eq $\times 10^{-3}$)	6.3	7.0	6.2	7.5	6.2	7.6	6.5
Water use (m^3 world eq. deprived)	-0.8	1.6	7.1	6.1	7.1	8.2	8.5
Climage change (kg CO_2-eq)	10.1	9.5	3.6	7.9	3.6	5.3	2.5

Table S1.34. Environmental impacts of per kg H_2 in the H_2 market of Rest of Central and South America in three scenarios.

Environmental impact categories (unit)	STEPS			APS		NZE	
	2020	2030	2050	2030	2050	2030	2050
Acidification (mol H+-eq $\times 10^{-3}$)	4.1	5.5	9.7	8.1	9.7	9.4	9.2
Ecotoxicity: freshwater (CTUe)	36.2	40.1	85.6	57.1	85.6	65.4	77.4
Resource use: energy carriers (MJ, net calorific value)	161.9	160.6	79.6	141.7	79.6	130.8	92.2
Eutrophication: aquatic freshwater (kg PO_4-eq $\times 10^{-4}$)	0.2	1.2	4.7	2.3	4.7	3.3	3.9
Eutrophication: aquatic marine (kg N-eq $\times 10^{-3}$)	1.3	1.5	1.5	1.7	1.5	1.8	1.5
Eutrophication: terrestrial (mol N-eq $\times 10^{-2}$)	1.4	1.6	1.6	1.9	1.6	2.0	1.8
Human toxicity: cancer effects (CTUh $\times 10^{-9}$)	0.9	1.0	3.8	2.0	3.8	2.4	3.3
Human toxicity: non- cancer effects (CTUh $\times 10^{-8}$)	1.9	2.2	7.5	3.8	7.5	4.5	6.5
Ionising radiation: human health (kBq U^{235}-eq)	0.03	0.06	0.2	0.2	0.2	0.3	0.2
Land use (dimensionless)	4.3	6.3	86.5	25.1	86.5	28.9	76.4
Resource use: minerals and metals (kg Sb-eq $\times 10^{-4}$)	0.2	0.3	1.2	0.5	1.2	0.7	1.0
Ozone depletion (kg CFC-11-eq $\times 10^{-6}$)	2.0	1.9	1.0	1.7	1.0	1.6	1.1
Particulate matter (disease incidence $\times 10^{-8}$)	1.7	2.7	8.0	5.3	8.0	6.4	7.8
Photochemical ozone formation (kg NMVOC-eq $\times 10^{-3}$)	6.4	6.8	6.0	7.3	6.0	7.5	6.3
Water use (m^3 world eq. deprived)	-0.7	0.3	7.0	5.2	7.0	8.0	8.6
Climage change (kg CO_2-eq)	10.1	9.8	3.5	8.1	3.5	5.3	2.4

Table S1.35. Environmental impacts of per kg H_2 in the H_2 market of Rest of North America in three scenarios.

Environmental impact categories (unit)	STEPS			APS		NZE	
	2020	2030	2050	2030	2050	2030	2050
Acidification (mol H+-eq $\times 10^{-2}$)	1.8	1.8	1.2	1.7	1.2	1.6	1.3
Ecotoxicity: freshwater (CTUe)	31.2	38.5	61.0	50.4	61.0	62.6	60.7
Resource use: energy carriers (MJ, net calorific value)	139.2	136.5	67.2	130.1	67.2	119.6	76.9

Eutrophication: aquatic freshwater (kg PO_4-eq $\times 10^{-4}$)	-3.7	1.5	2.6	1.6	2.6	3.2	2.2
Eutrophication: aquatic marine (kg N-eq $\times 10^{-3}$)	2.3	2.5	1.7	2.4	1.7	2.3	1.7
Eutrophication: terrestrial (mol N-eq $\times 10^{-2}$)	2.6	2.7	1.8	2.6	1.8	2.4	1.9
Human toxicity: cancer effects (CTUh $\times 10^{-9}$)	1.9	2.0	3.0	2.3	3.0	2.5	2.7
Human toxicity: non- cancer effects (CTUh $\times 10^{-8}$)	1.7	2.2	4.0	2.7	4.0	3.1	3.5
Ionising radiation: human health (kBq U^{235}-eq)	-0.1	0.4	0.6	1.1	0.6	2.1	1.0
Land use (dimensionless)	6.5	9.2	36.2	8.1	36.2	5.6	32.7
Resource use: minerals and metals (kg Sb-eq $\times 10^{-5}$)	2.2	2.6	5.5	3.2	5.5	3.8	4.6
Ozone depletion (kg CFC-11-eq $\times 10^{-6}$)	1.4	1.3	0.7	1.1	0.7	1.0	0.7
Particulate matter (disease incidence $\times 10^{-7}$)	1.0	1.0	0.9	1.0	0.9	1.0	0.9
Photochemical ozone formation (kg NMVOC-eq $\times 10^{-2}$)	1.0	1.0	0.7	1.0	0.7	0.9	0.7
Water use (m^3 world eq. deprived)	-0.5	2.1	10.5	6.5	10.5	12.0	14.9
Climage change (kg CO_2-eq)	9.3	8.9	2.9	7.5	2.9	4.3	2.1

Table S1.36. Environmental impacts of per kg H_2 in the H_2 market of Rest of Europe in three scenarios.

Environmental impact categories (unit)	STEPS			APS		NZE	
	2020	2030	2050	2030	2050	2030	2050
Acidification (mol H+-eq $\times 10^{-2}$)	0.6	1.2	0.9	0.7	0.9	4.3	0.9
Ecotoxicity: freshwater (CTUe)	26.8	35.9	92.9	64.7	92.9	81.2	84.2
Resource use: energy carriers (MJ, net calorific value)	161.0	152.9	60.3	122.0	60.3	134.5	69.6
Eutrophication: aquatic freshwater (kg PO_4-eq $\times 10^{-3}$)	0.3	1.0	0.5	0.3	0.5	4.6	0.5
Eutrophication: aquatic marine (kg N-eq $\times 10^{-3}$)	1.2	1.5	1.2	1.3	1.2	3.0	1.2
Eutrophication: terrestrial (mol N-eq $\times 10^{-2}$)	1.3	1.4	1.3	1.4	1.3	2.3	1.3
Human toxicity: cancer effects (CTUh $\times 10^{-9}$)	1.0	1.5	3.8	2.4	3.8	3.4	3.6
Human toxicity: non- cancer effects (CTUh $\times 10^{-8}$)	1.8	3.0	8.5	4.7	8.5	8.1	7.8
Ionising radiation: human health (kBq U^{235}-eq)	0.9	0.9	0.4	0.9	0.4	1.2	0.5
Land use (dimensionless)	1.9	2.6	8.3	3.6	8.3	3.8	9.0
Resource use: minerals and metals (kg Sb-eq $\times 10^{-4}$)	0.2	0.4	1.4	0.7	1.4	0.9	1.3
Ozone depletion (kg CFC-11-eq $\times 10^{-6}$)	1.2	1.1	0.5	1.0	0.5	0.9	0.6
Particulate matter (disease incidence $\times 10^{-8}$)	2.5	3.6	6.1	4.5	6.1	9.0	5.8
Photochemical ozone formation (kg NMVOC-eq $\times 10^{-3}$)	4.0	4.7	4.2	4.3	4.2	8.9	4.2
Water use (m^3 world eq. deprived)	0.3	3.0	11.6	10.5	11.6	13.3	11.4
Climage change (kg CO_2-eq)	9.8	9.2	2.6	6.8	2.6	6.0	2.0

Table S1.37. Environmental impacts of per kg H_2 in the H_2 market of Africa in three scenarios.

Environmental impact categories (unit)	STEPS			APS		NZE	
	2020	2030	2050	2030	2050	2030	2050
Acidification (mol H+-eq $\times 10^{-2}$)	1.1	1.0	1.3	2.8	1.3	1.4	1.2
Ecotoxicity: freshwater (CTUe)	116.9	115.6	120.7	172.6	120.7	122.6	109.8
Resource use: energy carriers (MJ, net calorific value)	152.6	151.6	73.9	159.1	73.9	135.5	85.3
Eutrophication: aquatic freshwater (kg PO_4-eq $\times 10^{-3}$)	1.3	1.3	0.9	2.4	0.9	0.9	0.6
Eutrophication: aquatic marine (kg N-eq $\times 10^{-3}$)	1.6	1.6	1.6	3.0	1.6	1.9	1.5
Eutrophication: terrestrial (mol N-eq $\times 10^{-2}$)	2.5	2.4	1.9	3.7	1.9	2.3	1.8
Human toxicity: cancer effects (CTUh $\times 10^{-9}$)	1.0	1.0	4.7	2.4	4.7	2.4	4.0
Human toxicity: non- cancer effects (CTUh $\times 10^{-8}$)	3.3	3.3	9.2	8.4	9.2	6.0	8.1

Ionising radiation: human health (kBq U^{235}-eq)	0.09	0.08	0.08	0.2	0.09	0.2	0.1
Land use (dimensionless)	7.7	8.5	92.8	21.2	92.8	24.8	77.1
Resource use: minerals and metals (kg Sb-eq $\times 10^{-4}$)	0.2	0.2	1.3	0.5	1.3	0.7	1.1
Ozone depletion (kg CFC-11-eq $\times 10^{-7}$)	6.7	6.7	4.2	6.5	4.2	6.7	4.7
Particulate matter (disease incidence $\times 10^{-7}$)	0.6	0.5	1.2	1.0	1.2	0.9	1.0
Photochemical ozone formation (kg NMVOC-eq $\times 10^{-2}$)	0.7	0.7	0.7	1.1	0.7	0.9	0.7
Water use (m^3 world eq. deprived)	0.1	0.1	3.3	3.3	3.3	5.3	3.8
Climage change (kg CO_2-eq)	11.4	11.1	3.9	11.2	3.9	7.0	2.8

Table S1.38. Environmental impacts of per kg H_2 in the H_2 market of India in three scenarios.

Environmental impact categories (unit)	STEPS			APS		NZE	
	2020	2030	2050	2030	2050	2030	2050
Acidification (mol H+-eq $\times 10^{-2}$)	-0.2	1.4	1.5	4.9	1.5	6.1	1.3
Ecotoxicity: freshwater (CTUe)	103.9	150.3	143.7	249.4	143.7	268.1	129.2
Resource use: energy carriers (MJ, net calorific value)	135.9	152.4	130.0	187.3	130.0	201.8	130.1
Eutrophication: aquatic freshwater (kg PO_4-eq $\times 10^{-3}$)	0.6	1.5	1.0	3.3	1.0	3.6	0.7
Eutrophication: aquatic marine (kg N-eq $\times 10^{-3}$)	-0.2	1.9	2.1	6.3	2.1	7.8	1.8
Eutrophication: terrestrial (mol N-eq $\times 10^{-2}$)	1.2	3.3	2.2	7.7	2.2	8.7	1.9
Human toxicity: cancer effects (CTUh $\times 10^{-9}$)	0.8	1.3	4.4	2.9	4.4	4.0	4.1
Human toxicity: non- cancer effects (CTUh $\times 10^{-7}$)	0.2	0.5	1.1	1.1	1.1	1.4	1.0
Ionising radiation: human health (kBq U^{235}-eq)	-0.03	0.08	5.3	1.3	5.3	3.1	5.0
Land use (dimensionless)	6.7	10.3	21.4	17.8	21.4	18.2	19.5
Resource use: minerals and metals (kg Sb-eq $\times 10^{-4}$)	0.2	0.3	1.6	0.6	1.6	0.9	1.4
Ozone depletion (kg CFC-11-eq $\times 10^{-7}$)	6.2	6.2	4.3	6.1	4.3	6.3	4.5
Particulate matter (disease incidence $\times 10^{-7}$)	0.4	0.7	1.3	1.4	1.3	1.7	1.1
Photochemical ozone formation (kg NMVOC-eq $\times 10^{-2}$)	0.2	0.8	0.7	2.0	0.7	2.5	0.7
Water use (m^3 world eq. deprived)	-0.2	0.1	6.7	2.2	6.7	5.0	6.7
Climage change (kg CO_2-eq)	10.8	11.8	3.8	12.9	3.8	10.0	2.6

Table S1.39. Environmental impacts of per kg H_2 in the H_2 market of Japan in three scenarios.

Environmental impact categories (unit)	STEPS			APS		NZE	
	2020	2030	2050	2030	2050	2030	2050
Acidification (mol H+-eq $\times 10^{-2}$)	2.4	2.7	1.9	3.9	1.9	3.2	1.8
Ecotoxicity: freshwater (CTUe)	137.9	150.1	132.3	191.9	132.3	178.5	131.9
Resource use: energy carriers (MJ, net calorific value)	177.1	184.2	90.4	210.6	90.4	211.8	91.4
Eutrophication: aquatic freshwater (kg PO_4-eq $\times 10^{-3}$)	1.1	1.3	0.8	2.4	0.8	1.3	0.6
Eutrophication: aquatic marine (kg N-eq $\times 10^{-3}$)	3.8	4.5	3.2	6.6	3.2	5.6	3.0
Eutrophication: terrestrial (mol N-eq $\times 10^{-2}$)	4.8	5.4	3.9	7.6	3.9	6.2	3.9
Human toxicity: cancer effects (CTUh $\times 10^{-9}$)	2.5	3.0	5.6	4.4	5.6	5.0	5.4
Human toxicity: non- cancer effects (CTUh $\times 10^{-7}$)	0.6	0.7	1.0	1.1	1.0	1.1	1.0
Ionising radiation: human health (kBq U^{235}-eq)	0.1	1.1	2.6	3.3	2.6	5.6	2.7
Land use (dimensionless)	17.8	27.3	79.0	50.3	79.0	39.1	82.6
Resource use: minerals and metals (kg Sb-eq $\times 10^{-4}$)	0.3	0.5	1.5	0.9	1.5	1.2	1.4
Ozone depletion (kg CFC-11-eq $\times 10^{-7}$)	1.8	2.1	2.1	3.1	2.1	3.6	2.0
Particulate matter (disease incidence $\times 10^{-7}$)	1.1	1.3	1.6	1.9	1.6	1.9	1.6

Photochemical ozone formation (kg NMVOC-eq ×10^{-2})	1.6	1.7	1.1	2.2	1.1	1.9	1.0
Water use (m^3 world eq. deprived)	0.3	0.7	1.9	1.7	1.9	2.4	2.1
Climage change (kg CO_2-eq)	13.1	12.4	0.9	11.4	0.9	7.3	-1.0

Table S1.40. Environmental impacts of per kg H_2 in the H_2 market of Southeast Asia in three scenarios.

Environmental impact categories (unit)	STEPS			APS		NZE	
	2020	2030	2050	2030	2050	2030	2050
Acidification (mol H+-eq ×10^{-2})	1.2	1.6	1.3	2.2	1.3	2.3	1.2
Ecotoxicity: freshwater (CTUe)	91.8	111.8	119.3	138.0	119.3	156.7	114.8
Resource use: energy carriers (MJ, net calorific value)	153.5	159.6	65.9	167.5	65.9	167.3	70.0
Eutrophication: aquatic freshwater (kg PO_4-eq ×10^{-3})	1.9	3.1	0.9	4.7	0.9	4.1	0.7
Eutrophication: aquatic marine (kg N-eq ×10^{-3})	1.6	2.6	1.6	3.8	1.6	4.1	1.5
Eutrophication: terrestrial (mol N-eq ×10^{-2})	3.0	3.6	1.9	4.4	1.9	4.2	1.6
Human toxicity: cancer effects (CTUh ×10^{-9})	1.0	1.7	4.6	2.6	4.6	3.7	4.4
Human toxicity: non- cancer effects (CTUh ×10^{-7})	0.4	0.6	1.0	0.8	1.0	1.0	0.9
Ionising radiation: human health (kBq U^{235}-eq)	0.1	0.3	0.5	0.7	0.5	1.5	0.8
Land use (dimensionless)	11.6	23.4	121.4	39.4	121.4	63.1	113.7
Resource use: minerals and metals (kg Sb-eq ×10^{-4})	0.2	0.4	1.5	0.6	1.5	1.0	1.4
Ozone depletion (kg CFC-11-eq ×10^{-7})	6.1	6.1	3.6	6.1	3.6	6.4	3.7
Particulate matter (disease incidence ×10^{-7})	0.7	1.1	1.1	1.6	1.1	1.8	1.0
Photochemical ozone formation (kg NMVOC-eq ×10^{-2})	0.7	0.9	0.6	1.1	0.6	1.3	0.6
Water use (m^3 world eq. deprived)	0.2	1.2	2.7	2.5	2.7	4.9	3.2
Climage change (kg CO_2-eq)	12.4	12.4	3.4	12.3	3.4	9.0	2.1

Table S1.41. Environmental impacts of per kg H_2 in the H_2 market of Rest of Asia Pacific in three scenarios.

Environmental impact categories (unit)	STEPS			APS		NZE	
	2020	2030	2050	2030	2050	2030	2050
Acidification (mol H+-eq ×10^{-2})	1.1	1.4	1.3	2.2	1.3	2.4	1.2
Ecotoxicity: freshwater (CTUe)	90.3	101.3	117.3	138.0	117.3	156.8	114.7
Resource use: energy carriers (MJ, net calorific value)	152.9	156.0	65.1	167.6	65.1	167.4	69.7
Eutrophication: aquatic freshwater (kg PO_4-eq ×10^{-3})	1.7	2.4	0.9	4.6	0.9	4.1	0.7
Eutrophication: aquatic marine (kg N-eq ×10^{-3})	1.6	2.1	1.6	3.8	1.6	4.1	1.4
Eutrophication: terrestrial (mol N-eq ×10^{-2})	2.9	3.2	1.9	4.4	1.9	4.1	1.6
Human toxicity: cancer effects (CTUh ×10^{-9})	1.0	1.4	4.6	2.6	4.6	3.7	4.5
Human toxicity: non- cancer effects (CTUh ×10^{-7})	0.4	0.5	1.0	0.8	1.0	1.0	0.9
Ionising radiation: human health (kBq U^{235}-eq)	0.1	0.2	0.5	0.7	0.5	1.6	0.8
Land use (dimensionless)	11.0	18.3	122.3	39.6	122.3	63.5	113.9
Resource use: minerals and metals (kg Sb-eq ×10^{-4})	0.2	0.3	1.5	0.5	1.5	1.0	1.4
Ozone depletion (kg CFC-11-eq ×10^{-7})	6.2	6.2	3.7	6.2	3.7	6.4	3.7
Particulate matter (disease incidence ×10^{-7})	0.6	0.9	1.0	1.6	1.0	1.8	1.0
Photochemical ozone formation (kg NMVOC-eq ×10^{-2})	0.7	0.8	0.6	1.1	0.6	1.3	0.6
Water use (m^3 world eq. deprived)	0.2	0.8	2.7	2.6	2.7	5.0	3.2
Climage change (kg CO_2-eq)	12.2	12.1	3.3	12.2	3.3	9.0	2.1

Table S1.42. Environmental impacts of per kg H_2 in the H_2 market of Middle East in three scenarios.

Environmental impact categories (unit)	STEPS			APS		NZE	
	2020	2030	2050	2030	2050	2030	2050
Acidification (mol H+-eq $\times 10^{-2}$)	0.5	0.6	1.0	0.9	1.0	1.2	1.0
Ecotoxicity: freshwater (CTUe)	39.7	44.4	89.4	64.4	89.4	74.1	80.9
Resource use: energy carriers (MJ, net calorific value)	177.1	178.7	90.1	184.0	90.1	177.3	99.7
Eutrophication: aquatic freshwater (kg PO_4-eq $\times 10^{-4}$)	1.9	2.1	5.4	2.4	5.4	3.5	4.7
Eutrophication: aquatic marine (kg N-eq $\times 10^{-3}$)	1.4	1.5	1.6	2.0	1.6	2.3	1.6
Eutrophication: terrestrial (mol N-eq $\times 10^{-2}$)	1.5	1.6	1.7	2.2	1.7	2.5	1.9
Human toxicity: cancer effects (CTUh $\times 10^{-9}$)	1.3	1.5	3.9	2.1	3.9	2.5	3.7
Human toxicity: non- cancer effects (CTUh $\times 10^{-8}$)	2.7	3.1	8.5	4.6	8.5	5.5	7.5
Ionising radiation: human health (kBq U^{235}-eq)	1.1	1.1	0.7	1.1	0.7	1.0	0.7
Land use (dimensionless)	2.6	5.8	110.7	19.4	110.7	31.1	102.9
Resource use: minerals and metals (kg Sb-eq $\times 10^{-4}$)	0.2	0.3	1.3	0.5	1.3	0.7	1.1
Ozone depletion (kg CFC-11-eq $\times 10^{-7}$)	4.7	5.0	3.2	6.2	3.2	6.5	3.3
Particulate matter (disease incidence $\times 10^{-7}$)	0.7	0.7	1.1	0.9	1.1	1.0	1.1
Photochemical ozone formation (kg NMVOC-eq $\times 10^{-2}$)	3.2	3.2	1.8	3.0	1.8	2.9	2.0
Water use (m^3 world eq. deprived)	0.2	0.3	0.7	0.6	0.7	0.8	0.7
Climage change (kg CO_2-eq)	12.3	12.2	4.6	11.9	4.6	9.3	3.1

Table S1.43. Environmental impacts of per kg H_2 in the H_2 market of Russia in three scenarios.

Environmental impact categories (unit)	STEPS			APS		NZE	
	2020	2030	2050	2030	2050	2030	2050
Acidification (mol H+-eq $\times 10^{-2}$)	0.9	0.8	1.3	0.8	1.3	7.1	1.8
Ecotoxicity: freshwater (CTUe)	110.2	108.7	133.9	108.4	133.9	247.4	154.4
Resource use: energy carriers (MJ, net calorific value)	185.2	183.7	132.2	183.1	132.2	315.8	106.7
Eutrophication: aquatic freshwater (kg PO_4-eq $\times 10^{-4}$)	3.2	2.3	5.5	2.3	5.5	3.6	7.
Eutrophication: aquatic marine (kg N-eq $\times 10^{-3}$)	2.3	2.2	2.7	2.2	2.7	8.1	3.4
Eutrophication: terrestrial (mol N-eq $\times 10^{-2}$)	2.	2.4	2.8	2.4	2.8	8.0	3.9
Human toxicity: cancer effects (CTUh $\times 10^{-9}$)	2.6	2.6	4.8	2.6	4.8	6.4	6.5
Human toxicity: non- cancer effects (CTUh $\times 10^{-7}$)	0.3	0.3	0.9	0.3	0.9	1.4	1.2
Ionising radiation: human health (kBq U^{235}-eq)	1.3	1.2	2.0	1.2	2.0	6.7	3.5
Land use (dimensionless)	5.2	6.8	23.2	9.1	23.2	15.5	80.9
Resource use: minerals and metals (kg Sb-eq $\times 10^{-4}$)	0.3	0.3	1.2	0.3	1.2	1.3	1.8
Ozone depletion (kg CFC-11-eq $\times 10^{-6}$)	1.4	1.4	0.9	1.4	0.9	1.6	0.5
Particulate matter (disease incidence $\times 10^{-7}$)	0.8	0.8	1.6	0.8	1.6	3.2	2.6
Photochemical ozone formation (kg NMVOC-eq $\times 10^{-2}$)	2.7	2.7	2.0	2.7	2.0	4.4	1.5
Water use (m^3 world eq. deprived)	0.4	0.3	1.6	0.3	1.6	4.0	2.9
Climage change (kg CO_2-eq)	12.6	12.3	5.9	11.7	5.9	15.7	-0.1

Table S1.44. Environmental impacts of per kg H_2 in the H_2 market of Rest of Eurasia in three scenarios.

Environmental impact categories (unit)	STEPS			APS		NZE	
	2020	2030	2050	2030	2050	2030	2050
Acidification (mol H+-eq $\times 10^{-2}$)	0.9	5.2	1.5	7.8	1.5	7.5	1.8
Ecotoxicity: freshwater (CTUe)	110.2	175.5	148.5	213.1	148.5	255.8	154.3
Resource use: energy carriers (MJ, net calorific value)	185.2	233.3	108.4	259.0	108.4	323.8	106.8

Eutrophication: aquatic freshwater (kg PO_4-eq $\times 10^{-3}$)	0.3	2.7	0.7	4.3	0.7	3.8	0.8
Eutrophication: aquatic marine (kg N-eq $\times 10^{-3}$)	2.3	5.3	2.9	7.0	2.9	8.5	3.4
Eutrophication: terrestrial (mol N-eq $\times 10^{-2}$)	2.5	5.3	3.0	6.8	3.0	8.4	3.9
Human toxicity: cancer effects (CTUh $\times 10^{-9}$)	2.6	4.0	6.0	4.8	6.0	6.6	6.5
Human toxicity: non- cancer effects (CTUh $\times 10^{-7}$)	0.3	0.8	1.2	1.1	1.2	1.4	1.2
Ionising radiation: human health (kBq U^{235}-eq)	1.3	2.7	2.4	3.7	2.4	7.0	3.5
Land use (dimensionless)	5.2	10.7	23.3	14.8	23.3	16.0	80.8
Resource use: minerals and metals (kg Sb-eq $\times 10^{-4}$)	0.3	0.6	1.7	0.8	1.7	1.3	1.8
Ozone depletion (kg CFC-11-eq $\times 10^{-6}$)	1.4	1.5	0.7	1.4	0.7	1.6	0.5
Particulate matter (disease incidence $\times 10^{-7}$)	0.8	2.0	2.1	2.5	2.1	3.3	2.6
Photochemical ozone formation (kg NMVOC-eq $\times 10^{-2}$)	2.7	3.5	1.6	3.9	1.6	4.5	1.5
Water use (m^3 world eq. deprived)	0.4	1.7	2.2	2.5	2.2	4.2	2.8
Climage change (kg CO_2-eq)	12.6	15.4	4.6	16.6	4.6	16.1	-0.1

Cumulative GHG emissions of H2 production

As shown in Figure S1.2, in the STESP, APS and NZE scenarios, China emits 16 Gt CO_2-eq, 14 Gt CO_2-eq, and 15 Gt CO_2-eq GHG emissions from 2020 to 2050. Although China will produce four times more H_2 in 2050 in the NZE scenario compared to the STEPS scenario, the cumulative GHG emissions between 2020 and 2050 in the NZE can be lower than that in the STEPS due to the large-scale use of water electrolysis. In the USA, these cumulative emissions in these scenarios will be 3.9 Gt CO_2-eq, 5.2 Gt CO_2-eq, and 6.1 Gt CO_2-eq. The H_2 demand in the USA in 2050 in the NZE scenario is close to that in China. However, since the US has a lower emission intensity of electricity, the cumulative GHG emissions are lower than China.

Contrary to the decreasing trend of H_2 production in the STEPS scenario, the EU is expected to produce more H_2 in the APS and NZE scenarios. In the EU, the cumulative GHG emissions of H_2 production will be 1.6 Gt CO_2-eq, 2.4 Gt CO_2-eq, and 3.1 Gt CO_2-eq in three scenarios. The high increase of H_2 production in the APS and NZE scenarios makes the cumulative GHG emissions in these scenarios higher than those in the STEPS scenario. The overall H_2 production related GHG emissions of China, the USA and the EU in the NZE scenario could use 2.5-8.6%, 1.0-3.4% and 0.5-1.7% of the residual carbon budget between 2020 and 2050 to limit global warming to 1.5°C with 67% certainty.[142] Overall, in the NZE scenario, the cumulative GHG emissions of H_2 production in most regions will always be higher than in the STEPS scenario. Their H_2 production mixes in the NZE scenario need a more significant and faster transition to reverse this trend.

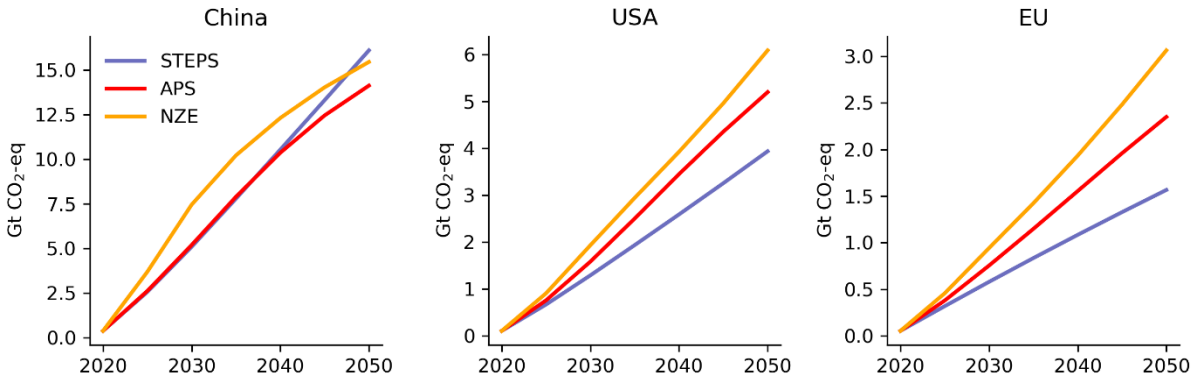

Figure S1.2. The cumulative GHG emissions of H_2 production in China, USA and EU in three scenarios.

Sensitivity analysis

This sensitivity analysis assumes the use of dedicated renewable electricity generation from solar photovoltaic (PV), on-shore wind, and hydropower, as currently planned and listed in IEA's H_2 production projects database.[69] We modeled these as the electricity source for water electrolysis. The proportion of H_2 production amount of water electrolysis powered by renewable electricity in water electrolysis is further assumed as 100% to quantify their impacts on the global and regional cumulative GHG emissions of H_2 production by 2050. In addition, NG SMR CCS is further assumed to be replaced by water electrolysis powered by 100% renewables to quantify the GHG emissions reduction potential of radically transitioning H_2 production to green H_2 technologies.

As shown in Figure S1.3, the 100% renewable electricity-powered water electrolysis and its substitution for NG SMR CCS have a limited impact on cumulative GHG emissions of H_2 production at regional and global levels in the STEPS scenario (declining 3.5% at the most). STEPS assumes a limited amount of H_2 production from water electrolysis and NG CCS. As water electrolysis plays a more critical role in the APS and NZE scenarios, the impact of the electricity source of water electrolysis on cumulative GHG emissions by 2050 becomes more significant. In the APS scenario, the global cumulative GHG emissions of H_2 production by 2050 can decrease by 5.4-10.9%, if 100% of electricity from renewable sources are used in water electrolysis. Using water electrolysis powered 100% renewables to further replace NG SMR CCS, the cumulative GHG emissions of H_2 production can be reduced by 10.8%-18.0%. In the NZE scenario, the global cumulative GHG emissions of H_2 production by 2050 can decrease by 9.8-21.9% and 30.7-49.8% corresponding to these two assumptions. Unlike in China and the USA, the scale-up of water electrolysis using dedicated electricity from solar PV will not cause a significant decrease in cumulative GHG emissions of H_2 production by 2050 in the EU. The EU will decarbonize its electricity production quicker than China and the USA. In the EU, only on-shore wind and hydropower can help water electrolysis to decarbonize further as its grid electricity will move relatively quickly to low carbon emissions. In the USA, the dedicated renewable has a very limited potential to help water electrolysis to decarbonize further due to the adoption of BECCS in its grid electricity.

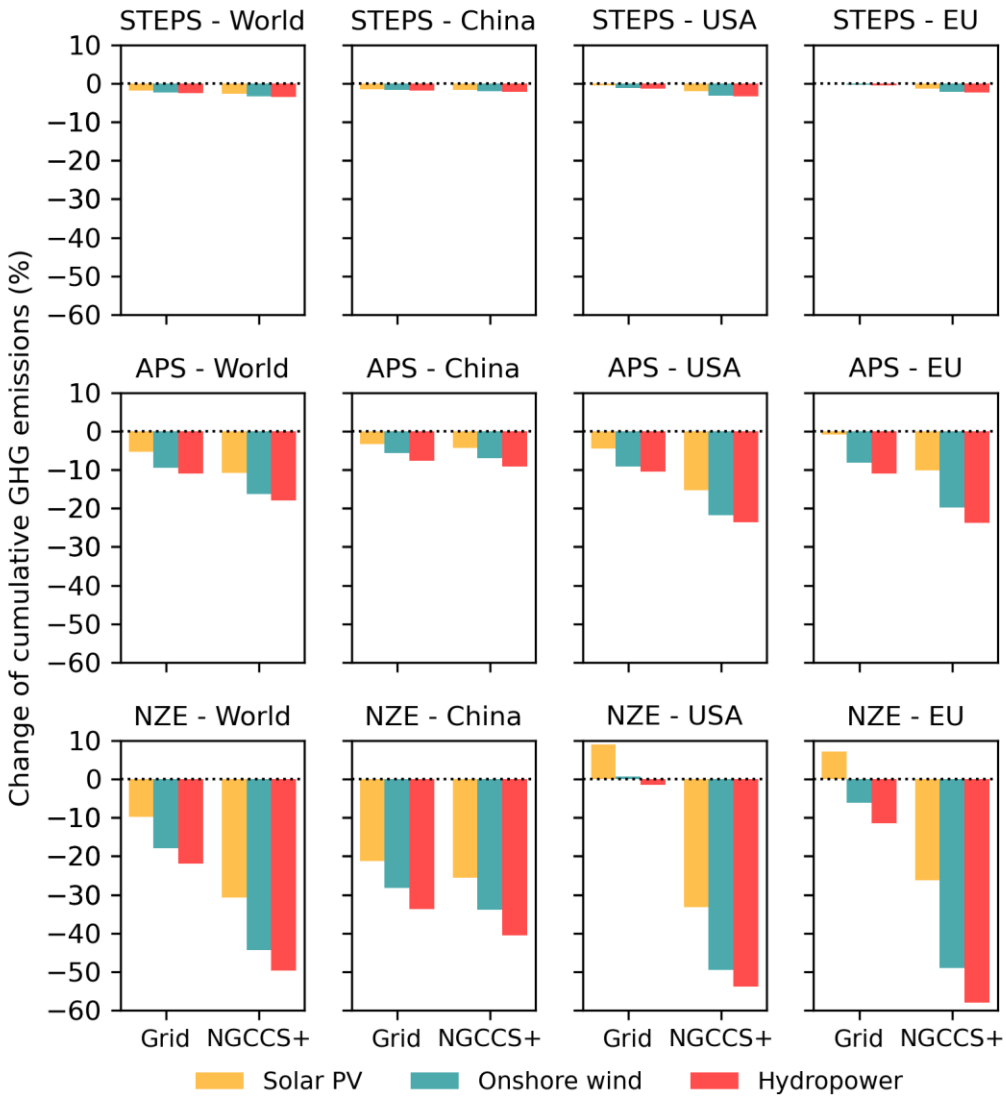

Figure S1.3. Sensitivity analysis. This figure shows the relative change of global and regional cumulative GHG emissions of H_2 production by 2050 caused by 100% renewable electricity-powered water electrolysis and its further substitution for NG SMR CCS. The "NGCCS+" refers to the grid-connected water electrolysis and NG SMR CCS.

S2 Supporting information for chapter 3

S2.1 Propulsion systems

Ship information

Table S2.1. Main information of the case ship Colombo Express.

Specification	Value
Overall Length	335 m
Beam	43 m
Deadweight tonnage (DWT)	103,800 t
Payload utilization rate	62%
Main Engine Power	2 stroke 68.64 MW
Propellers	1x Fixed pitch propeller
Boilers	1x Auxiliary boiler, composite
Generators	2*4.267 MW 1*2.454 MW 1*1.867 MW
Cargo gear	Gearless
Fuel Capacity	12,000 m^3
Maximum Speed	25.2 knots
Average Speed (SOA)	20 knots
Built year	2005

Propulsion system configuration

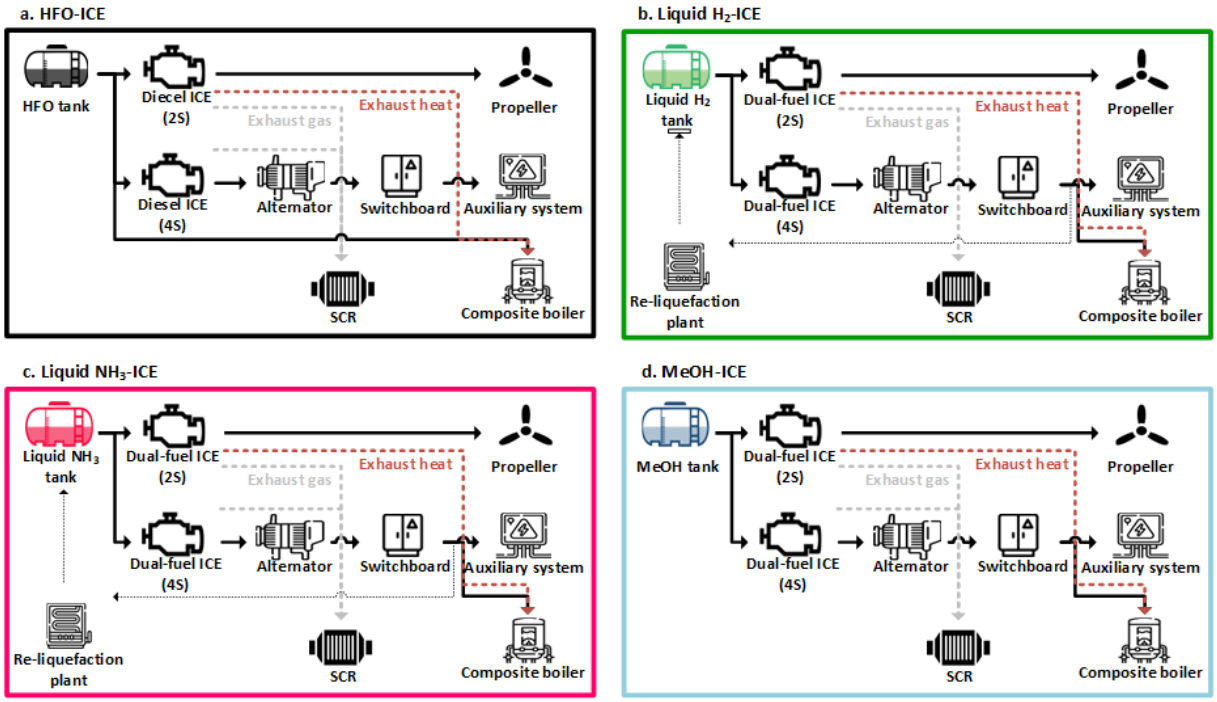

Figure S2.1. The component configuration of different propulsion systems.[h]

[h] The switchboard is created by Andreis Kirma from Noun Project. Ammonia cracker is designed by Eucalyp from Noun Project. Battery is designed by Adrien Coquet from Noun Project. The image of inverter is designed by Maurizio Fusillo from Noun Project. The SCR is designed by Thanga Vignesh from Noun Project. The image of fuel tank is from https://www.pikpng.com/pngvi/bRTRiw_fuel-tank-storage-tank-gasoline-clip-art-oil-tank-icon-png-transparent). Other images are from Flaction.com.

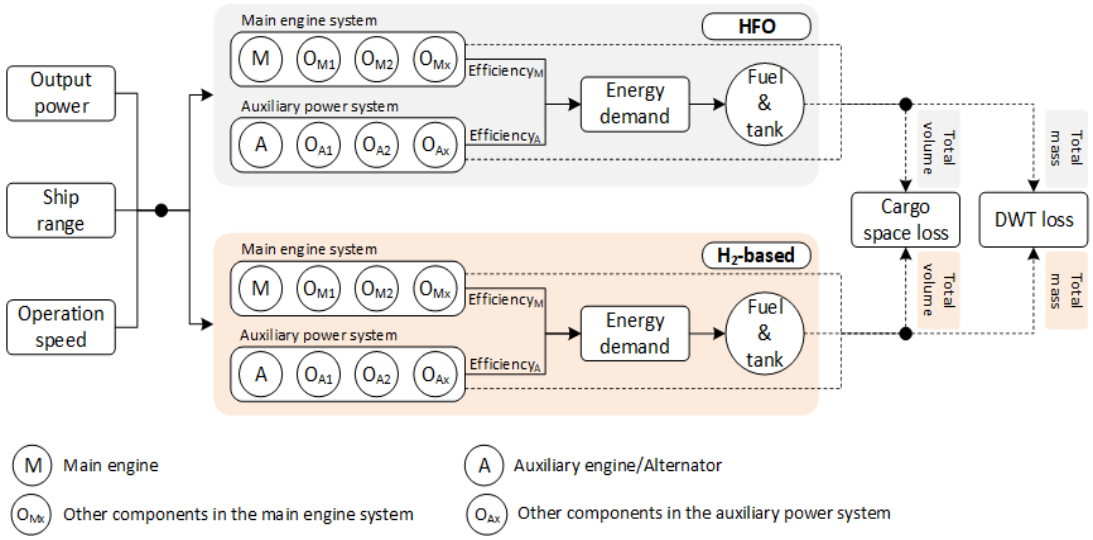

Figure S2.2. The schematic diagram of calculating the cargo space and weight loss of H_2-based fuel ship compared to the HFO ship.

Key parameters

Table S2.2. The key technical parameters of components in propulsion systems and their data sources. In this table, the mass and volume factors are multiplied by the component sizes to calculate the mass and volume of the respective propulsion systems.

Component	Efficiency (%)	Lifespan (years)	Mass factor (t/MW)	Volume factor (m^3/MW)	Parameters source	LCI source
Diesel ICE (Main)	50	25	29.2	27.5	26, 207	25, 26
Dual-fuel ICE H_2/MeOH (Main)	48	25	29.2	27.5	42, 207	26
Dual-fuel ICE NH_3 (Main)	46	25	29.2	27.5	42, 207	26
Diesel ICE (Auxiliary)	48	25	29.2	27.5	26, 207	26
Dual-fuel ICE H_2/MeOH (Auxiliary)	46	25	29.2	27.5	42, 207	26
Dual-fuel ICE NH_3 (Auxiliary)	44	25	29.2	27.5	42, 207	26
Alternator	96	25	2.5	5.0	26, 207	109
Shafting	99	25	-	-	208, 209	168
Switchboard	99.8	11	0.7	1.4	226-228	109, 168
SCR[a]	-	25	0.9	5.0	210, 211	25

a. The SCR is equipped to reduce nitrogen oxide emissions to meet the IMO Tier III regulations. For the HFO, H_2 and MeOH engines, urea is used as the reducing agent to convert nitrogen oxides to diatomic nitrogen and water. For the NH_3 engine, the unburned NH_3 acts as the reducing agent.[25]

Table S2.3. The key technical parameters and data source of fuels and their storage. In this table, the gravimetric and volumetric energy density, including tank, can be multiplied by the energy demand in different scenarios to determine the total mass and volume of the fuel and tank.

Fuel	Lower heating value (MWh/t)	Gravimetric energy density including tank (MWh/t)	Volumetric energy density including tank (MWh/m^3)	Data source	LCI of fuels	LCI of tanks
HFO	11.2	9.7	11.1	233	109	234
MGO	11.9	10.1	10.1	233, 277	109	234
Liquid H_2	33.3	5.6	1.3	233	53, 175, 176	235
Liquid NH_3	5.2	4.2	2.9	233, 236	53, 54	237, 238, 319
MeOH	5.6	4.6	4.4	233	53, 177, 178	109, 234, 278

Table S2.4. Emissions of different propulsion systems.

Propulsion systems	HFO-ICE[42, 239-241]	H_2-ICE[25, 42, 239-241]	NH_3-ICE[25, 42, 239-241]	MeOH-ICE[42, 239-241, 279]

ICE type	Diecel ICE		Dual-fuel ICE		Dual-fuel ICE		Dual-fuel ICE	
Engine	Main	Aux	Main	Aux	Main	Aux	Main	Aux
Specific fuel consumption (g/kWh)	178.6	186.0	59.4	62.0	397.2	415.2	353.4	368.8
Pilot fuel (g/kWh)	-	-	8.8	9.1	9.1	9.5	8.8	9.1
Urea/NH_3 (g/kWh)	14.4	9.6	14.4	-	8.2	6.6	14.4	3.7
CH_4 (g/kWh)	0.009	0.009	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004
CO (g/kWh)	0.9	1.0	0.2	0.2	0.2	0.2	4.1	4.3
CO_2 (g/kWh)	585	605	38	29	29	30	536	551
NO_x (g/kWh)	3.4	2.6	3.4	0.7	3.4	2.6	3.4	2.6
N_2O (g/kWh)	0.029	0.030	0.001	0.002	0.013	0.014	0.001	0.002
NH_3 (g/kWh)	0.026	0.026	0.024	0.0001	0.037	0.038	0.024	0.024
NMVOC (g/kWh)	0.424	0.441	0.024	0.025	0.025	0.026	0.021	0.022
PM_{10} (g/kWh)	0.051	0.053	0.003	0.003	0.003	0.003	0.011	0.011
$PM_{2.5}$	0.581	0.605	0.029	0.031	0.031	0.032	0.123	0.128
SO_2 (g/kWh)	1.795	1.869	0.086	0.090	0.090	0.094	0.086	0.090
Formaldehyde (g/kWh)	-	-	-	-	-	-	0.192	0.200

S2.2 Unit process data

The unit process data used in this study are shown below. For process data not directly available from the premise pLCA database, corresponding life cycle inventories were developed and are marked with an asterisk (*).

Ship operation

Table S2. 5. Life cycle inventory of transport, container ship, HFO-ICE, scenario R-A-N (1 t-nm).

Exchanges	amount	unit
Economic flows		
container ship production, HFO-ICE*	4.96E-12	unit
fuel tank, heavy fuel oil*	8.77E-06	kilogram
market for maintenance, container ship	1.20E-11	unit
heavy fuel oil, very low-sulphur*	5.79E-03	kilogram
urea solution, 40 wt%*	1.10E-03	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	2.78E-07	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	3.02E-05	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	1.89E-02	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	1.05E-04	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	9.28E-07	kilogram
Ammonia (to air, non-urban air or from high stacks)	8.40E-07	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	1.37E-05	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	1.63E-06	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	5.80E-05	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	0	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	1.88E-05	kilogram

Table S2.6. Life cycle inventory of transport, container ship, liquid H2-DFICE, scenario R-A-N (1 t-nm).

Exchanges	amount	unit
Economic flows		
container ship production, liquid H_2-DFICE*	5.77E-12	unit
fuel tank, heavy fuel oil*	4.93E-07	kilogram

fuel tank, cryogenic, liquid hydrogen*	9.62E-05	kilogram
Reliquefaction plant, 1 kg/h capacity*	3.14E-09	unit
market for maintenance, container ship	1.39E-11	unit
liquid hydrogen production*	2.29E-03	kilogram
marine gas oil, very low-sulphur*	3.39E-04	kilogram
urea solution, 40 wt%*	1.14E-03	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	1.59E-08	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	6.23E-06	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	1.40E-03	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	1.12E-04	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	5.63E-08	kilogram
Ammonia (to air, non-urban air or from high stacks)	7.61E-07	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	9.24E-07	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	9.83E-08	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	3.32E-06	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	0	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	1.13E-06	kilogram

Table S2.7. Life cycle inventory of transport, container ship, liquid NH_3-DFICE, scenario R-A-N (1 t-nm).

Exchanges	amount	unit
Economic flows		
container ship production, liquid NH_3-DFICE*	6.64E-12	unit
fuel tank, heavy fuel oil*	5.79E-07	kilogram
fuel tank, cryogenic, liquid ammonia*	3.50E-05	kilogram
Reliquefaction plant, 1 kg/h capacity*	2.41E-09	unit
market for maintenance, container ship	1.60E-11	unit
ammonia production, liquid*	1.73E-02	kilogram
marine gas oil, very low-sulphur*	3.97E-04	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	1.86E-08	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	7.30E-06	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	1.25E-03	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	1.41E-04	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	5.80E-07	kilogram
Ammonia (to air, non-urban air or from high stacks)	1.59E-06	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	1.08E-06	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	1.15E-07	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	3.89E-06	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	0	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	1.32E-06	kilogram

Table S2.8. Life cycle inventory of transport, container ship, MeOH-DFICE, scenario R-A-N (1 t-nm).

Exchanges	amount	unit
Economic flows		
container ship production, MeOH-DFICE*	6.14E-12	unit
fuel tank, heavy fuel oil*	5.13E-07	kilogram

fuel tank, methanol*	2.41E-05	kilogram
market for maintenance, container ship	1.48E-11	unit
methanol production, CO_2 from DAC*	1.42E-02	kilogram
marine gas oil, very low-sulphur*	3.51E-04	kilogram
urea solution, 40 wt%*	1.27E-03	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	1.65E-08	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	1.66E-04	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	2.14E-02	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	1.30E-04	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	5.83E-08	kilogram
Ammonia (to air, non-urban air or from high stacks)	9.58E-07	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	8.53E-07	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	4.28E-07	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	3.44E-06	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	7.69E-06	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	4.93E-06	kilogram

Table S2.9. Life cycle inventory of transport, container ship, HFO-ICE, scenario R-L-N (1 t-nm).

Exchanges	amount	unit
Economic flows		
container ship production, HFO-ICE*	6.20E-12	unit
fuel tank, heavy fuel oil*	1.10E-05	kilogram
market for maintenance, container ship	1.50E-11	unit
heavy fuel oil, very low-sulphur*	4.42E-03	kilogram
urea solution, 40 wt%*	8.05E-04	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	2.13E-07	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	2.31E-05	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	1.44E-02	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	7.81E-05	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	7.09E-07	kilogram
Ammonia (to air, non-urban air or from high stacks)	6.40E-07	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	1.05E-05	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	1.25E-06	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	4.43E-05	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	0	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	1.44E-05	kilogram

Table S2.10. Life cycle inventory of transport, container ship, liquid H_2-DFICE, scenario R-L-N (1 t-nm).

Exchanges	amount	unit
Economic flows		
container ship production, liquid H_2-DFICE*	6.90E-12	unit
fuel tank, heavy fuel oil*	4.53E-07	kilogram
fuel tank, cryogenic, liquid hydrogen*	8.85E-05	kilogram
Reliquefaction plant, 1 kg/h capacity*	2.87E-09	unit
market for maintenance, container ship	1.67E-11	unit

liquid hydrogen production*	1.69E-03	kilogram
marine gas oil, very low-sulphur*	2.50E-04	kilogram
urea solution, 40 wt%*	7.30E-04	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	1.17E-08	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	4.59E-06	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	1.00E-03	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	7.44E-05	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	4.15E-08	kilogram
Ammonia (to air, non-urban air or from high stacks)	4.89E-07	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	6.81E-07	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	7.24E-08	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	2.45E-06	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	0	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	8.33E-07	kilogram

Table S2.11. Life cycle inventory of transport, container ship, liquid NH_3-DFICE, scenario R-L-N (1 t-nm).

Exchanges	amount	unit
Economic flows		
container ship production, liquid NH_3-DFICE*	7.63E-12	unit
fuel tank, heavy fuel oil*	5.09E-07	kilogram
fuel tank, cryogenic, liquid ammonia*	3.08E-05	kilogram
Reliquefaction plant, 1 kg/h capacity*	2.12E-09	unit
market for maintenance, container ship	1.84E-11	unit
ammonia production, liquid*	1.22E-02	kilogram
marine gas oil, very low-sulphur*	2.79E-04	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	1.31E-08	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	5.13E-06	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	8.79E-04	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	9.62E-05	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	4.08E-07	kilogram
Ammonia (to air, non-urban air or from high stacks)	1.12E-06	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	7.60E-07	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	8.09E-08	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	2.73E-06	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	0	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	9.31E-07	kilogram

Table S2.12. Life cycle inventory of transport, container ship, MeOH-DFICE, scenario R-L-N (1 t-nm).

Exchanges	amount	unit
Economic flows		
container ship production, MeOH-DFICE*	7.21E-12	unit
fuel tank, heavy fuel oil*	4.60E-07	kilogram
fuel tank, methanol*	2.16E-05	kilogram
market for maintenance, container ship	1.74E-11	unit
methanol production, CO_2 from DAC*	1.02E-02	kilogram

marine gas oil, very low-sulphur*	2.52E-04	kilogram
urea solution, 40 wt%*	8.30E-04	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	1.18E-08	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	1.19E-04	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	1.53E-02	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	9.09E-05	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	4.19E-08	kilogram
Ammonia (to air, non-urban air or from high stacks)	6.86E-07	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	6.12E-07	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	3.08E-07	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	2.47E-06	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	5.52E-06	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	3.54E-06	kilogram

Table S2.13. Life cycle inventory of transport, container ship, HFO-ICE, scenario S-A-N (1 t-nm).

Exchanges	amount	unit
Economic flows		
container ship production, HFO-ICE*	4.96E-12	unit
fuel tank, heavy fuel oil*	8.77E-06	kilogram
market for maintenance, container ship	1.20E-11	unit
heavy fuel oil, very low-sulphur*	6.02E-03	kilogram
urea solution, 40 wt%*	1.14E-03	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	2.90E-07	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	3.14E-05	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	1.97E-02	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	1.10E-04	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	9.66E-07	kilogram
Ammonia (to air, non-urban air or from high stacks)	8.75E-07	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	1.42E-05	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	1.70E-06	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	6.04E-05	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	0	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	1.95E-05	kilogram

Table S2.14. Life cycle inventory of transport, container ship, liquid H_2-DFICE, scenario S-A-N (1 t-nm).

Exchanges	amount	unit
Economic flows		
container ship production, liquid H_2-DFICE*	5.26E-12	unit
fuel tank, heavy fuel oil*	2.31E-07	kilogram
fuel tank, cryogenic, liquid hydrogen*	4.52E-05	kilogram
Reliquefaction plant, 1 kg/h capacity*	1.49E-09	unit
market for maintenance, container ship	1.27E-11	unit
liquid hydrogen production*	2.15E-03	kilogram
marine gas oil, very low-sulphur*	3.18E-04	kilogram
urea solution, 40 wt%*	1.09E-03	kilogram

Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	1.49E-08	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	5.84E-06	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	1.32E-03	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	1.07E-04	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	5.28E-08	kilogram
Ammonia (to air, non-urban air or from high stacks)	7.28E-07	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	8.66E-07	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	9.21E-08	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	3.11E-06	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	0	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	1.06E-06	kilogram

Table S2.15. Life cycle inventory of transport, container ship, liquid NH_3-DFICE, scenario S-A-N (1 t-nm).

Exchanges	amount	unit
Economic flows		
container ship production, liquid NH3-DFICE*	5.63E-12	unit
fuel tank, heavy fuel oil*	2.55E-07	kilogram
fuel tank, cryogenic, liquid ammonia*	1.54E-05	kilogram
Reliquefaction plant, 1 kg/h capacity*	1.06E-09	unit
market for maintenance, container ship	1.36E-11	unit
ammonia production, liquid*	1.53E-02	kilogram
marine gas oil, very low-sulphur*	3.50E-04	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	1.64E-08	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	6.43E-06	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	1.10E-03	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	1.24E-04	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	5.11E-07	kilogram
Ammonia (to air, non-urban air or from high stacks)	1.40E-06	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	9.54E-07	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	1.01E-07	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	3.43E-06	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	0	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	1.17E-06	kilogram

Table S2.16. Life cycle inventory of transport, container ship, MeOH-DFICE, scenario S-A-N (1 t-nm).

Exchanges	amount	unit
Economic flows		
container ship production, MeOH-DFICE*	5.43E-12	unit
fuel tank, heavy fuel oil*	2.36E-07	kilogram
fuel tank, methanol*	1.11E-05	kilogram
market for maintenance, container ship	1.31E-11	unit
methanol production, CO_2 from DAC*	1.31E-02	kilogram
marine gas oil, very low-sulphur*	3.24E-04	kilogram
urea solution, 40 wt%*	1.17E-03	kilogram
Environmental flows		

Methane, fossil (to air, non-urban air or from high stacks)	1.51E-08	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	1.53E-04	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	1.97E-02	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	1.20E-04	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	5.37E-08	kilogram
Ammonia (to air, non-urban air or from high stacks)	8.83E-07	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	7.85E-07	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	3.94E-07	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	3.17E-06	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	7.08E-06	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	4.54E-06	kilogram

Table S2.17. Life cycle inventory of transport, container ship, HFO-ICE, scenario S-L-N (1 t-nm).

Exchanges	amount	unit
Economic flows		
container ship production, HFO-ICE*	6.20E-12	unit
fuel tank, heavy fuel oil*	1.10E-05	kilogram
market for maintenance, container ship	1.50E-11	unit
heavy fuel oil, very low-sulphur*	4.42E-03	kilogram
urea solution, 40 wt%*	8.05E-04	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	2.13E-07	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	2.31E-05	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	1.44E-02	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	7.81E-05	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	7.09E-07	kilogram
Ammonia (to air, non-urban air or from high stacks)	6.40E-07	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	1.05E-05	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	1.25E-06	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	4.43E-05	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	0	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	1.44E-05	kilogram

Table S2.18. Life cycle inventory of transport, container ship, liquid H_2-DFICE, scenario S-L-N (1 t-nm).

Exchanges	amount	unit
Economic flows		
container ship production, liquid H_2-DFICE*	6.43E-12	unit
fuel tank, heavy fuel oil*	2.08E-07	kilogram
fuel tank, cryogenic, liquid hydrogen*	4.06E-05	kilogram
Reliquefaction plant, 1 kg/h capacity*	1.34E-09	unit
market for maintenance, container ship	1.55E-11	unit
liquid hydrogen production*	1.55E-03	kilogram
marine gas oil, very low-sulphur*	2.29E-04	kilogram
urea solution, 40 wt%*	6.79E-04	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	1.07E-08	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	4.20E-06	kilogram

Carbon dioxide, fossil (to air, non-urban air or from high stacks)	9.20E-04	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	6.90E-05	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	3.80E-08	kilogram
Ammonia (to air, non-urban air or from high stacks)	4.56E-07	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	6.23E-07	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	6.63E-08	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	2.24E-06	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	0	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	7.63E-07	kilogram

Table S2.19. Life cycle inventory of transport, container ship, liquid NH_3-DFICE, scenario S-L-N (1 t-nm).

Exchanges	amount	unit
Economic flows		
container ship production, liquid NH_3-DFICE*	6.74E-12	unit
fuel tank, heavy fuel oil*	2.25E-07	kilogram
fuel tank, cryogenic, liquid ammonia*	1.36E-05	kilogram
Reliquefaction plant, 1 kg/h capacity*	9.37E-10	unit
market for maintenance, container ship	1.63E-11	unit
ammonia production, liquid*	1.07E-02	kilogram
marine gas oil, very low-sulphur*	2.46E-04	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	1.15E-08	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	4.53E-06	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	7.76E-04	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	8.49E-05	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	3.60E-07	kilogram
Ammonia (to air, non-urban air or from high stacks)	9.85E-07	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	6.71E-07	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	7.14E-08	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	2.41E-06	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	0	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	8.21E-07	kilogram

Table S2.20. Life cycle inventory of transport, container ship, MeOH-DFICE, scenario S-L-N (1 t-nm).

Exchanges	amount	unit
Economic flows		
container ship production, MeOH-DFICE*	6.57E-12	unit
fuel tank, heavy fuel oil*	2.10E-07	kilogram
fuel tank, methanol*	9.85E-06	kilogram
market for maintenance, container ship	1.59E-11	unit
methanol production, CO_2 from DAC*	9.28E-03	kilogram
marine gas oil, very low-sulphur*	2.30E-04	kilogram
urea solution, 40 wt%*	7.56E-04	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	1.08E-08	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	1.09E-04	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	1.40E-02	kilogram

Nitrogen oxides (to air, non-urban air or from high stacks)	8.28E-05	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	3.82E-08	kilogram
Ammonia (to air, non-urban air or from high stacks)	6.25E-07	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	5.58E-07	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	2.80E-07	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	2.25E-06	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	5.03E-06	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	3.22E-06	kilogram

Table S2.21. Life cycle inventory of transport, container ship, HFO-ICE, scenario S-A-I (1 t-nm).

Exchanges	amount	unit
Economic flows		
container ship production, HFO-ICE*	4.96E-12	unit
fuel tank, heavy fuel oil*	8.77E-06	kilogram
market for maintenance, container ship	1.20E-11	unit
heavy fuel oil, very low-sulphur*	6.02E-03	kilogram
urea solution, 40 wt%*	1.14E-03	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	2.90E-07	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	3.14E-05	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	1.97E-02	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	1.10E-04	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	9.66E-07	kilogram
Ammonia (to air, non-urban air or from high stacks)	8.75E-07	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	1.42E-05	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	1.70E-06	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	6.04E-05	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	0	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	1.95E-05	kilogram

Table S2.22. Life cycle inventory of transport, container ship, liquid H_2-DFICE, scenario S-A-I (1 t-nm).

Exchanges	amount	unit
Economic flows		
container ship production, liquid H_2-DFICE*	5.03E-12	unit
fuel tank, heavy fuel oil*	1.10E-07	kilogram
fuel tank, cryogenic, liquid hydrogen*	2.15E-05	kilogram
Reliquefaction plant, 1 kg/h capacity*	7.13E-10	unit
market for maintenance, container ship	1.22E-11	unit
liquid hydrogen production*	2.04E-03	kilogram
marine gas oil, very low-sulphur*	3.02E-04	kilogram
urea solution, 40 wt%*	1.04E-03	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	1.41E-08	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	5.55E-06	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	1.26E-03	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	1.02E-04	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	5.01E-08	kilogram

Ammonia (to air, non-urban air or from high stacks)	6.96E-07	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	8.23E-07	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	8.75E-08	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	2.96E-06	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	0	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	1.01E-06	kilogram

Table S2.23. Life cycle inventory of transport, container ship, liquid NH_3-DFICE, scenario S-A-I (1 t-nm).

Exchanges	amount	unit
Economic flows		
container ship production, liquid NH_3-DFICE*	5.20E-12	unit
fuel tank, heavy fuel oil*	1.18E-07	kilogram
fuel tank, cryogenic, liquid ammonia*	7.13E-06	kilogram
Reliquefaction plant, 1 kg/h capacity*	4.92E-10	unit
market for maintenance, container ship	1.25E-11	unit
ammonia production, liquid*	1.41E-02	kilogram
marine gas oil, very low-sulphur*	3.23E-04	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	1.51E-08	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	5.94E-06	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	1.02E-03	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	1.15E-04	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	4.72E-07	kilogram
Ammonia (to air, non-urban air or from high stacks)	1.29E-06	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	8.81E-07	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	9.37E-08	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	3.16E-06	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	0	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	1.08E-06	kilogram

Table S2.24. Life cycle inventory of transport, container ship, MeOH-DFICE, scenario S-A-I (1 t-nm).

Exchanges	amount	unit
Economic flows		
container ship production, MeOH-DFICE*	5.11E-12	unit
fuel tank, heavy fuel oil*	1.11E-07	kilogram
fuel tank, methanol*	5.22E-06	kilogram
market for maintenance, container ship	1.23E-11	unit
methanol production, CO_2 from DAC*	1.23E-02	kilogram
marine gas oil, very low-sulphur*	3.05E-04	kilogram
urea solution, 40 wt%*	1.10E-03	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	1.43E-08	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	1.44E-04	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	1.85E-02	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	1.13E-04	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	5.05E-08	kilogram
Ammonia (to air, non-urban air or from high stacks)	8.31E-07	kilogram

NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	7.39E-07	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	3.71E-07	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	2.98E-06	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	6.66E-06	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	4.27E-06	kilogram

Table S2.25. Life cycle inventory of transport, container ship, HFO-ICE, scenario S-L-I (1 t-nm).

Exchanges	amount	unit
Economic flows		
container ship production, HFO-ICE*	6.20E-12	unit
fuel tank, heavy fuel oil*	1.10E-05	kilogram
market for maintenance, container ship	1.50E-11	unit
heavy fuel oil, very low-sulphur*	4.42E-03	kilogram
urea solution, 40 wt%*	8.05E-04	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	2.13E-07	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	2.31E-05	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	1.44E-02	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	7.81E-05	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	7.09E-07	kilogram
Ammonia (to air, non-urban air or from high stacks)	6.40E-07	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	1.05E-05	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	1.25E-06	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	4.43E-05	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	0	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	1.44E-05	kilogram

Table S2.26. Life cycle inventory of transport, container ship, liquid H_2-DFICE, scenario S-L-I (1 t-nm).

Exchanges	amount	unit
Economic flows		
container ship production, liquid H_2-DFICE*	6.22E-12	unit
fuel tank, heavy fuel oil*	1.00E-07	kilogram
fuel tank, cryogenic, liquid hydrogen*	1.95E-05	kilogram
Reliquefaction plant, 1 kg/h capacity*	6.47E-10	unit
market for maintenance, container ship	1.50E-11	unit
liquid hydrogen production*	1.48E-03	kilogram
marine gas oil, very low-sulphur*	2.20E-04	kilogram
urea solution, 40 wt%*	6.58E-04	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	1.03E-08	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	4.04E-06	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	8.85E-04	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	6.66E-05	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	3.65E-08	kilogram
Ammonia (to air, non-urban air or from high stacks)	4.41E-07	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	5.98E-07	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	6.36E-08	kilogram

Sulfur dioxide (to air, non-urban air or from high stacks)	2.15E-06	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	0	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	7.32E-07	kilogram

Table S2.27. Life cycle inventory of transport, container ship, liquid NH_3-DFICE, scenario S-L-I (1 t-nm).

Exchanges	amount	unit
Economic flows		
container ship production, liquid NH_3-DFICE*	6.37E-12	unit
fuel tank, heavy fuel oil*	1.06E-07	kilogram
fuel tank, cryogenic, liquid ammonia*	6.42E-06	kilogram
Reliquefaction plant, 1 kg/h capacity*	4.43E-10	unit
market for maintenance, container ship	1.54E-11	unit
ammonia production, liquid*	1.02E-02	kilogram
marine gas oil, very low-sulphur*	2.33E-04	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	1.09E-08	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	4.28E-06	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	7.33E-04	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	8.02E-05	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	3.40E-07	kilogram
Ammonia (to air, non-urban air or from high stacks)	9.30E-07	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	6.34E-07	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	6.75E-08	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	2.28E-06	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	0	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	7.76E-07	kilogram

Table S2.28. Life cycle inventory of transport, container ship, MeOH-DFICE, scenario S-L-I (1 t-nm).

Exchanges	amount	unit
Economic flows		
container ship production, MeOH-DFICE*	6.29E-12	unit
fuel tank, heavy fuel oil*	1.00E-07	kilogram
fuel tank, methanol*	4.72E-06	kilogram
market for maintenance, container ship	1.52E-11	unit
methanol production, CO_2 from DAC*	8.89E-03	kilogram
marine gas oil, very low-sulphur*	2.20E-04	kilogram
urea solution, 40 wt%*	7.24E-04	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	1.03E-08	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	1.04E-04	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	1.34E-02	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	7.93E-05	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	3.66E-08	kilogram
Ammonia (to air, non-urban air or from high stacks)	5.98E-07	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	5.34E-07	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	2.68E-07	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	2.16E-06	kilogram

Formaldehyde (to air, non-urban air or from high stacks)	4.82E-06	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	3.09E-06	kilogram

Ship production

Table S2.29. Life cycle inventory of container ship production, HFO-ICE (1 unit).

Exchanges	amount	unit
Economic flows		
hull production, container ship, for DWT 103800*	1	unit
propulsion system, HFO-ICE*	1	unit

Table S2.30. Life cycle inventory of hull production, container ship, for DWT 103800 (1 unit).

Exchanges	amount	unit	source
Economic flows			
market for reinforcing steel	4.49E+07	kilogram	[167]
market for copper, cathode	7.12E+04	kilogram	[167]
market for bronze	6.67E+04	kilogram	[167]
market for zinc	3.11E+05	kilogram	[167]
market for aluminium, wrought alloy	2.22E+04	kilogram	[167]
market for cast iron	1.74E+06	kilogram	[167]
market for electronic component machinery, unspecified	2.22E+02	unit	[167]
market for glass wool mat	3.78E+05	kilogram	[167, 168]
market for asbestos, crysotile type	3.78E+05	kilogram	[167, 168]
market for sanitary ceramics	3.78E+05	kilogram	[167, 168]
market for polypropylene, granulate	1.07E+05	kilogram	[167, 168]
market for polyethylene, high density, granulate	1.07E+05	kilogram	[167, 168]
market for polystyrene, expandable	1.07E+05	kilogram	[167, 168]
market for polyvinylidenchloride, granulate	1.07E+05	kilogram	[167, 168]
market for polyurethane, flexible foam	1.07E+05	kilogram	[167, 168]
market for glued laminated timber, average glue mix	9.25E+02	cubic meter	[167, 168]
market for alkyd paint, white, without solvent, in 60% solution state	2.22E+05	kilogram	[167]
market for welding, arc, steel	2.79E+07	meter	[168]
market for welding, gas, steel	1.77E+08	meter	[168]
market group for electricity, medium voltage	1.48E+07	kilowatt hour	[168]
market group for heat, district or industrial, other than natural gas	1.70E+07	megajoule	[168]
market for inert waste, for final disposal	-3.78E+05	kilogram	[168]
market for scrap aluminium	-2.22E+04	kilogram	[168]
market for scrap copper	-7.12E+04	kilogram	[168]
market for scrap steel	-4.49E+07	kilogram	[168]
market for waste electric and electronic equipment	-5.56E+05	kilogram	[168]
market for waste emulsion paint	-2.14E+05	kilogram	[168]
market for waste mineral wool	-7.56E+05	kilogram	[168]
market for waste plastic, mixture	-5.34E+05	kilogram	[168]
bronze scrap, post-consumer, Recycled Content cut-off	-6.67E+04	kilogram	[168]
iron scrap, unsorted, Recycled Content cut-off	-1.74E+06	kilogram	[168]
zinc scrap, post-consumer, Recycled Content cut-off	-3.11E+05	kilogram	[168]
Environmental flows			
NMVOC, non-methane volatile organic compounds,	1.82E+05	kilogram	[168]

unspecified origin (to air)			
Hydrocarbons, unspecified (to water)	4.00E+03	kilogram	[168]
Hydrocarbons, unspecified (to soil)	4.00E+03	kilogram	[168]

Table S2.31. Life cycle inventory of propulsion system, HFO-ICE (1 unit).

Exchanges	amount	unit
Economic flows		
marine engine, CI, ICE*	68.64	MW
market for generator, 200kW electrical	64.3	unit
marine engine, CI, ICE*	12.86	MW
market for control cabinet, heat and power co-generation unit, 160kW electrical	231.375	unit
SCR*	81.5	MW
market for oil boiler, 100kW	6.2	unit

Table S2.32. Life cycle inventory of marine engine, CI, ICE (1 MW).

Exchanges	amount	unit
Economic flows		
market for steel, chromium steel 18/8	11674.07	kilogram
market for cast iron	13425.19	kilogram
market for aluminium, primary, ingot	2334.81	kilogram
market for zinc	58.37	kilogram
market for wire drawing, copper	29.19	kilogram
market for lead	29.19	kilogram
market for nylon 6	262.67	kilogram
market for silicone product	262.67	kilogram
market for alkyd paint, white, without solvent, in 60% solution state	262.67	kilogram
market for lubricating oil	875.56	kilogram
market group for electricity, medium voltage	10800	kilowatt hour

Source: Kanchiralla et al.[25]

Table S2.33. Life cycle inventory of SCR (1 MW).

Exchanges	amount	unit
Economic flows		
market for steel, chromium steel 18/8	942.08	kilogram
market for titanium dioxide	4.72	kilogram

Source: Kanchiralla et al.[25]

Table S2.34. Life cycle inventory of fuel tank, heavy fuel oil (1 kg).

Exchanges	amount	unit
Economic flows		
market for steel, unalloyed	1.16	kilogram
market for sheet rolling, steel	1.16	kilogram
market for scrap steel	-0.278	kilogram
market for epoxy resin, liquid	0.118	kilogram
market group for electricity, low voltage	0.47	kilowatt hour

Source: Dlamini et al.[234]

Table S2.35. Life cycle inventory of container ship production, liquid H_2-DFICE (1 unit).

Exchanges	amount	unit

Economic flows		
hull production, container ship, for DWT 103800*	1	unit
propulsion system, liquid H_2-DFICE *	1	unit

Table S2.36. Life cycle inventory of propulsion system, liquid H_2-DFICE (1 unit).

Exchanges	amount	unit
Economic flows		
marine engine, CI, ICE*	68.64	MW
market for generator, 200kW electrical	64.3	unit
marine engine, CI, ICE*	12.86	MW
market for control cabinet, heat and power co-generation unit, 160kW electrical	231.375	unit
SCR*	68.64	MW
electric boiler, 100kW*	6.2	unit

Table S2.37. Life cycle inventory of electric boiler, 100kW (1 unit).

Exchanges	amount	unit
Economic flows		
market group for electricity, medium voltage	749.59	kilowatt hour
market for heat, district or industrial, other than natural gas	1264.04	megajoule
market for glass fibre	3.15	kilogram
market for stone wool	1.92	kilogram
market for sanitary ceramics	4.79	kilogram
market for expanded vermiculite	11.64	kilogram
market for brass	15.89	kilogram
market for cast iron	53.97	kilogram
market for steel, low-alloyed, hot rolled	93.62	kilogram
market for zinc coat, coils	69.59	square meter
market for steel, chromium steel 18/8	62.33	kilogram
market for steel, low-alloyed	87.67	kilogram
market for steel, unalloyed	62.60	kilogram
market for cable, unspecified	44.52	kilogram
market for electric connector, wire clamp	4.25	kilogram
market for electronics, for control units	3.29	kilogram
market for printed wiring board, surface mounted, unspecified, Pb free	6.30	kilogram
market for resistor, wirewound, through-hole mounting	10.14	kilogram
market for nylon 6-6	0.92	kilogram
market for polyvinylchloride, bulk polymerised	0.33	kilogram
market for polyethylene, low density, granulate	0.66	kilogram
market for silicone product	0.49	kilogram
market for alkyd paint, white, without solvent, in 60% solution state	3.42	kilogram
market for coating powder	0.89	kilogram
market for inert waste, for final disposal	-44.20	kilogram
iron scrap, unsorted, Recycled Content cut-off	-185.07	kilogram
market for scrap steel	-185.07	kilogram
market for electronics scrap from control units	-0.76	kilogram
market for used cable	-30.27	kilogram
market for waste electric wiring	-0.34	kilogram
market for waste polyethylene	0.00	kilogram

market for waste polyvinylchloride	-0.25	kilogram
market for waste plastic, mixture	-1.41	kilogram
market for waste paint on metal	-4.32	kilogram

Source: Abbas[232]

Table S2.38. Life cycle inventory of fuel tank, cryogenic, liquid hydrogen (1 kg).

Exchanges	amount	unit
Economic flows		
market for compressed air, 1000 kPa gauge	3.76E-04	cubic meter
market group for electricity, low voltage	5.98E-01	kilowatt hour
market for steel, chromium steel 18/8	9.74E-01	kilogram
market for aluminium alloy, AlMg3	2.59E-02	kilogram

Source: Abbas[235]

Table S2.39. Life cycle inventory of reliquefaction plant, 1 kg/h capacity (1 unit).

Exchanges	Amount	Unit
Economic flows		
market for steel, chromium steel 18/8	16.5	kilogram
market for cast iron	6	kilogram
market for steel, unalloyed	5.4	kilogram
market for aluminium, primary, ingot	2.1	kilogram
market for casting, steel, lost-wax	21.9	kilogram
market for casting, aluminium, lost-wax	2.1	kilogram
market group for electricity, medium voltage	11.34	kilowatt hour
market for scrap steel	-21.90	kilogram
market for scrap aluminium	-2.10	kilogram
market for iron scrap, unsorted	-6.00	kilogram
market for natural gas, liquefied	0.01	cubic meter
market for nitrogen, liquid	4.18	kilogram

Source: Park et al.[275]

Table S2.40. Life cycle inventory of container ship production, liquid NH_3-DFICE (1 unit).

Exchanges	Amount	Unit
Economic flows		
hull production, container ship, for DWT 103800	1	unit
propulsion system, liquid NH_3-DFICE	1	unit

Table S2.41. Life cycle inventory of propulsion system, liquid NH_3-DFICE (1 unit).

Exchanges	Amount	Unit
Economic flows		
marine engine, CI, ICE*	68.64	MW
market for generator, 200kW electrical	64.3	unit
marine engine, CI, ICE*	12.86	MW
market for control cabinet, heat and power co-generation unit, 160kW electrical	231.375	unit
SCR*	81.5	MW
electric boiler, 100kW*	6.2	unit

Table S2.42. Life cycle inventory of fuel tank, cryogenic, liquid ammonia (1 kg).

Exchanges	Amount	Unit

Economic flows		
market for steel, low-alloyed	0.55	kilogram
market for steel, unalloyed	0.56	kilogram
market for sheet rolling, steel	1.11	kilogram
market for scrap steel	-0.11	kilogram

Source: Ryste[237] and Cryocan[238]

Table S2.43. Life cycle inventory of container ship production, MeOH-DFICE (1 unit).

Exchanges	Amount	Unit
Economic flows		
hull production, container ship, for DWT 103800*	1	unit
propulsion system, MeOH-DFICE*	1	unit

Table S2.44. Life cycle inventory of propulsion system, MeOH-DFICE (1 unit).

Exchanges	Amount	Unit
Economic flows		
marine engine, CI, ICE*	68.64	MW
market for generator, 200kW electrical	64.3	unit
marine engine, CI, ICE*	12.86	MW
market for control cabinet, heat and power co-generation unit, 160kW electrical	231.375	unit
SCR*	81.5	MW
electric boiler, 100kW*	6.2	unit

Table S2.45. Life cycle inventory of fuel tank, methanol (1 kg).

Exchanges	Amount	Unit
Economic flows		
market for steel, unalloyed	1.16	kilogram
market for sheet rolling, steel	1.16	kilogram
market for scrap steel	-0.28	kilogram
market for epoxy resin, liquid	0.12	kilogram
market group for electricity, low voltage	0.47	kilowatt hour

Source: Dlamini et al.[234] and CGH[278]

Fuel supply

In the production processes of H_2-based fuels, the input of "market for hydrogen, gaseous, 25-30 bar" is from the databases established by.[53]

Table S2.46. Life cycle inventory of heavy fuel oil, very low-sulphur (1 kg).

Exchanges	Amount	Unit
Economic flows		
market for heavy fuel oil	1.00	kilogram
market group for electricity, low voltage	5.46E-03	kilowatt hour
market for petroleum coke	9.20E-05	kilogram
market for hydrogen, gaseous	8.92E-03	kilogram
Environmental flows		
Hydrogen sulfide (to air)	5.63E-03	kilogram

Source: Silva[174]

Table S2. 47. Life cycle inventory of marine gas oil, very low-sulphur (1 kg).

Exchanges	Amount	Unit
Economic flows		
market group for diesel, low-sulfur	1.00	kilogram
market group for electricity, low voltage	5.46E-03	kilowatt hour
market for petroleum coke	9.20E-05	kilogram
market for hydrogen, gaseous	8.92E-03	kilogram
Environmental flows		
Hydrogen sulfide (to air)	5.63E-03	kilogram

Source: Silva[174]

Table S2.48. Life cycle inventory of liquid hydrogen production (1 kg).

Exchanges	amount	unit	source
Economic flows			
market for hydrogen, gaseous, 25-30 bar*	1.0162	kilogram	[175]
hydrogen liquefaction plant construction*	3.43E-09	unit	[175]
market group for electricity, low voltage	10.5	kilowatt hour	[176]
Environmental flows			
Hydrogen (to air)	1.62E-02	kilogram	[175]

Table S2.49. Life cycle inventory of hydrogen liquefaction plant construction (1 unit).

Exchanges	amount	unit
Economic flows		
market for steel, chromium steel 18/8	5.95E+05	kilogram
market for reinforcing steel	3.80E+05	kilogram
market group for concrete, normal	2.03E+04	cubic meter
market for copper, cathode	1.50E+05	kilogram
market for aluminium alloy, AlMg3	1.40E+05	kilogram

Source: Wulf and Zapp[175]

Table S2.50. Life cycle inventory of ammonia production, liquid (1 kg).

Exchanges	amount	unit
Economic flows		
market for hydrogen, gaseous, 25-30 bar*	0.176	kilogram
nitrogen, gaseous, from cryogenic distillation, without compression*	0.815	kilogram
ammonia synthesis catalyst*	5.15E-05	kilogram
market for chemical factory, organics	3.29E-10	unit
market group for electricity, low voltage	1.440	kilowatt hour
treatment of inert waste, inert material landfill	-5.15E-05	kilogram
Environmental flows		
Water, cooling, unspecified natural origin (from natural resource)	0.149	cubic meter
Hydrogen (to air)	7.67E-04	kilogram
Ammonia (to air)	1.63E-03	kilogram
Nitrogen oxides (to air)	1.00E-03	kilogram
Water (to air)	4.76E-02	cubic meter
Water (to water)	1.01E-01	cubic meter

Source: D'Angelo et al.[54]

Table S2.51. Life cycle inventory of nitrogen, gaseous, from cryogenic distillation, without compression (1 kg).

Exchanges	amount	unit

Economic flows		
market for air separation facility	4.43E-10	unit
Environmental flows		
Water, cooling, unspecified natural origin (from natural resource)	4.00 E-03	cubic meter
Water (to water)	2.45E-03	cubic meter

Source: D'Angelo et al.[54]

Table S2.52. Life cycle inventory of ammonia synthesis catalyst (1 kg).

Exchanges	amount	unit
Economic flows		
market for magnetite	0.917	kilogram
market for lime	3.00E-02	kilogram
market for zeolite, powder	5.25E-02	kilogram
market group for electricity, low voltage	1.78	kilowatt hour

Source: D'Angelo et al.[54]

Table S2.53. Life cycle inventory of methanol production, CO_2 from DAC (1 kg).

Exchanges	amount	unit
Economic flows		
CO_2 from DAC*	1.51	kilogram
market for hydrogen, gaseous, 25-30 bar*	0.208	kilogram
market group for electricity, high voltage	0.272	kilowatt hour
market for steel, chromium steel 18/8	1.53E-04	kilogram
market for aluminium oxide, non-metallurgical	1.20E-05	kilogram
market for copper oxide	6.20E-05	kilogram
market for zinc oxide	2.90E-05	kilogram
market for heat, from steam, in chemical industry	-0.4397	megajoule
market for wastewater, average	-5.71E-04	cubic meter
Environmental flows		
Carbon dioxide, fossil (to air)	0.077	kilogram
Methanol (to air)	0.01	kilogram
Nitrogen oxides (to air)	1.78E-06	kilogram

Source: González-Garay et al.[177]

Table S2.54. Life cycle inventory of CO_2 from DAC (1 kg)

Exchanges	amount	unit
Economic flows		
market group for electricity, high voltage	0.366	kilowatt hour
market group for tap water	3.105	kilogram
market group for natural gas, high pressure	0.1895	cubic meter
market for calcium carbonate, precipitated	0.02	kilogram
Environmental flows		
Carbon dioxide, in air (from natural resource)	1	kilogram

Source: Keith et al.[178]

Others

Table S2.55. Life cycle inventory of urea solution, 40 wt% (kg).

Exchanges	Amount	Unit
Economic flows		

market for urea	0.4	kilogram
market for water, deionised	0.6	kilogram

Source: Brynolf et al.[262]

S2.3 Supplementary results

Prospective GHG emissions

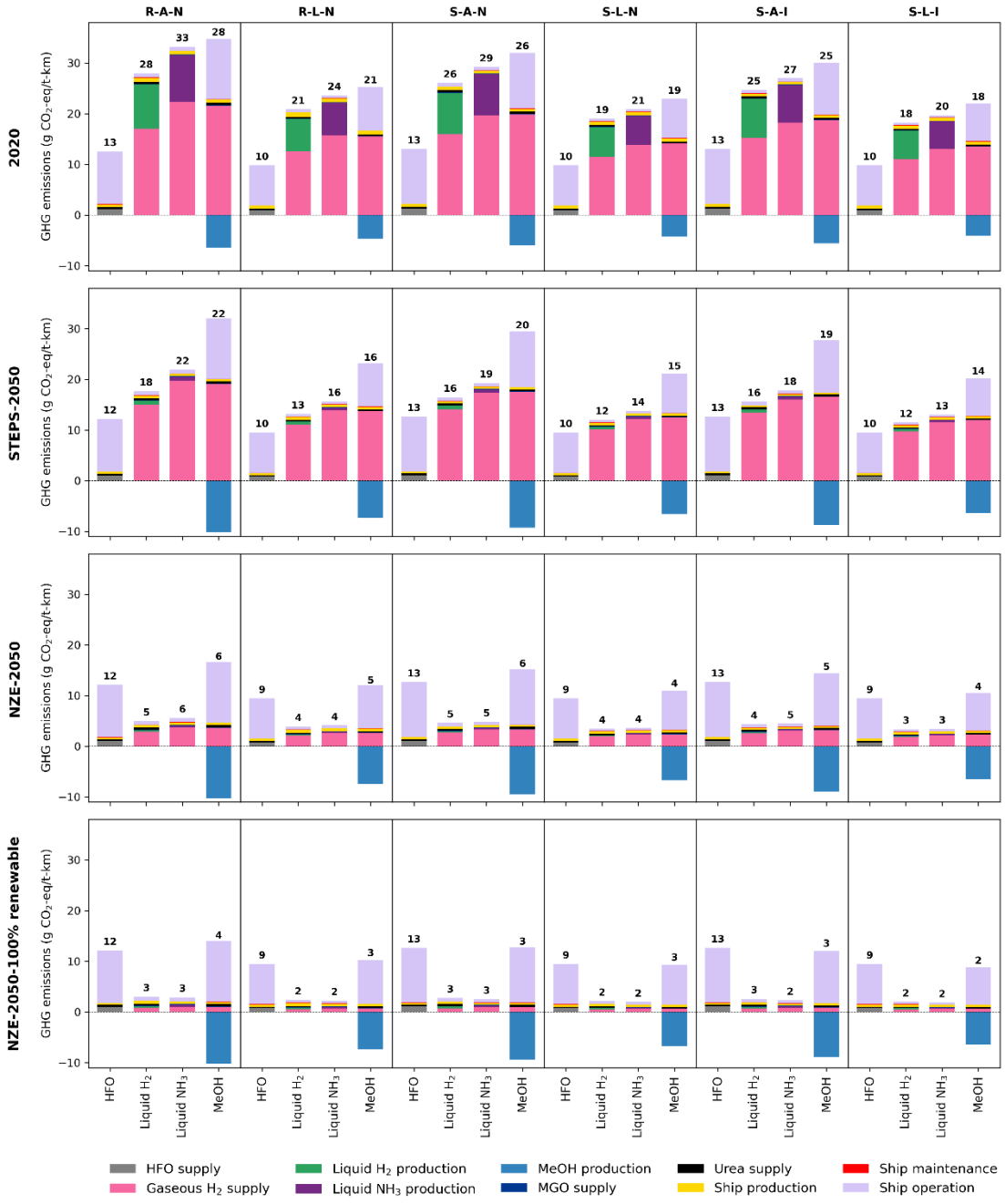

Figure S2.3. The process contribution to the GHG emissions (per t-km) of different ships in different scenarios. For the liquid H_2 production, liquid NH_3 production and MeOH production, the gaseous H_2 supply is a part of them and presented separately. In this figure, R-A-N=22000 nm-20 knots-Nonstop, R-L-N=22000 nm-16 knots-Nonstop, S-A-N=11000 nm-20 knots-Nonstop, S-L-N=11000 nm-16 knots-Nonstop, S-A-I=5500 nm-20 knots-1 refueling stop, and S-L-I=5500 nm-16 knots-1 refueling stop. For the MeOH-ICE case, the negative value is caused by the direct air capture.

GHG emissions from BOG treatment methods

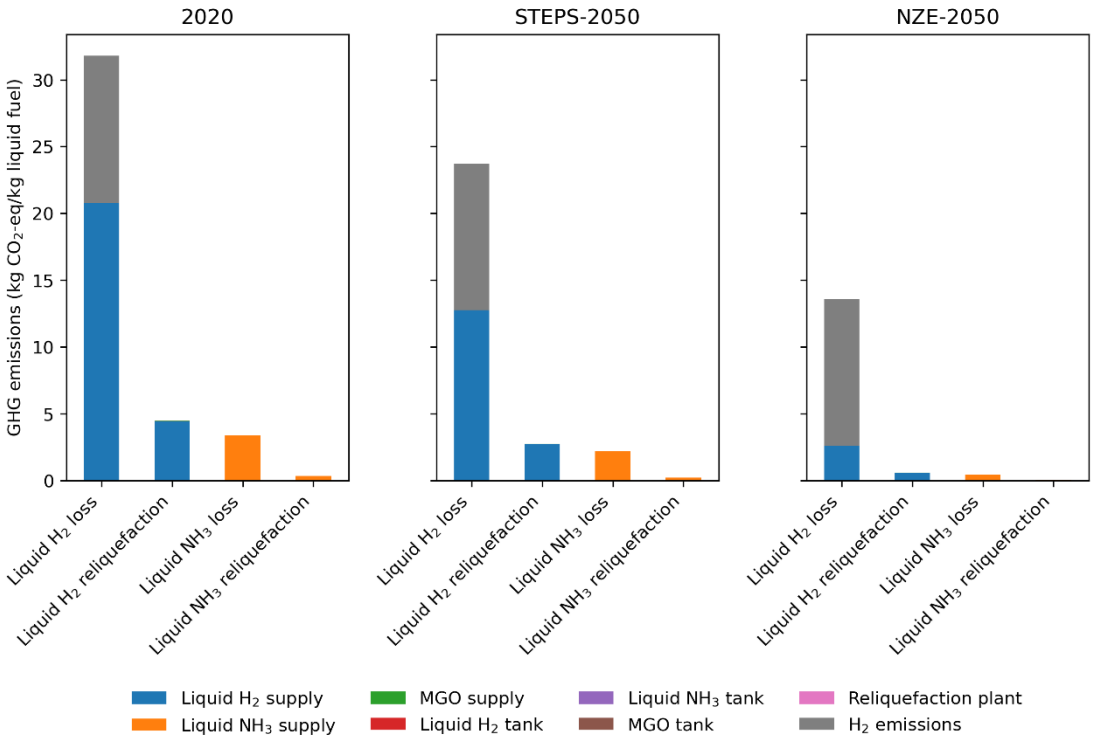

Figure S2.4. GHG emissions from different treatment methods of boil-off gas from liquid H_2 and NH_3 storage under the S-A-N (11000 nm-20 knots-Nonstop) scenario. In this figure, the MGO supply, the liquid NH_3 tank, the reliquefaction plant, the liquid H_2 tank, the MGO tank are related to liquid fuel reliquefaction, but their GHG emissions are negligible.

S3 Supporting information for chapter 4

S3.1 Unit process data

The unit process data used in this study are shown below. For process data not directly available from the Ecoinvent database, we created the corresponding life cycle inventories and marked them with an asterisk (*).

Ship operation

Table S3.1. Life cycle inventory of transport, container ship, HFO-ICE, scenario R-A-N (1 t-nm).

Exchanges	amount	unit
Economic flows		
container ship production, HFO-ICE*	4.96E-12	unit
fuel tank, heavy fuel oil*	8.77E-06	kilogram
market for maintenance, container ship	1.20E-11	unit
heavy fuel oil, very low-sulphur*	6.02E-03	kilogram
urea solution, 40 wt%*	1.14E-03	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	2.90E-07	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	3.14E-05	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	1.97E-02	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	1.10E-04	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	9.66E-07	kilogram
Ammonia (to air, non-urban air or from high stacks)	8.75E-07	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	1.42E-05	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	1.70E-06	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	6.04E-05	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	0	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	1.95E-05	kilogram

Table S3.2. Life cycle inventory of transport, container ship, liquid H_2-PEMFC, scenario R-A-N (1 t-nm).

Exchanges	amount	unit
Economic flows		
container ship production, liquid H_2-PEMFC*	5.54E-12	unit
fuel tank, cryogenic, liquid hydrogen*	9.37E-05	kilogram
Reliquefaction plant, 1 kg/h capacity*	3.06E-09	unit
market for maintenance, container ship	1.34E-11	unit
liquid hydrogen production*	2.23E-03	kilogram
market group for electricity, low voltage	2.38E-06	kilowatt hour

Table S3.3. Life cycle inventory of transport, container ship, liquid NH_3-SOFC, scenario R-A-N (1 t-nm).

Exchanges	amount	unit
Economic flows		
container ship production, liquid NH_3-SOFC*	6.43E-12	unit
fuel tank, cryogenic, liquid ammonia*	3.06E-05	kilogram
Reliquefaction plant, 1 kg/h capacity*	2.11E-09	unit
market for maintenance, container ship	1.55E-11	unit
ammonia production, liquid*	1.51E-02	kilogram

market group for electricity, low voltage	8.25E-06	kilowatt hour
Environmental flows		
Nitrogen oxides (to air, non-urban air or from high stacks)	1.45E-07	kilogram

Table S3.4. Life cycle inventory of transport, container ship, HFO-ICE, scenario R-L-N (1 t-nm).

Exchanges	amount	unit
Economic flows		
container ship production, HFO-ICE*	6.20E-12	unit
fuel tank, heavy fuel oil*	1.10E-05	kilogram
market for maintenance, container ship	1.50E-11	unit
heavy fuel oil, very low-sulphur*	4.42E-03	kilogram
urea solution, 40 wt%*	8.05E-04	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	2.13E-07	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	2.31E-05	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	1.44E-02	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	7.81E-05	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	7.09E-07	kilogram
Ammonia (to air, non-urban air or from high stacks)	6.40E-07	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	1.05E-05	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	1.25E-06	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	4.43E-05	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	0	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	1.44E-05	kilogram

Table S3.5. Life cycle inventory of transport, container ship, liquid H_2-PEMFC, scenario R-L-N (1 t-nm).

Exchanges	amount	unit
Economic flows		
container ship production, liquid H_2-PEMFC*	6.62E-12	unit
fuel tank, cryogenic, liquid hydrogen*	8.26E-05	kilogram
Reliquefaction plant, 1 kg/h capacity*	2.69E-09	unit
market for maintenance, container ship	1.60E-11	unit
liquid hydrogen production*	1.58E-03	kilogram
market group for electricity, low voltage	2.27E-06	kilowatt hour

Table S3.6. Life cycle inventory of transport, container ship, liquid NH_3-SOFC, scenario R-L-N (1 t-nm).

Exchanges	amount	unit
Economic flows		
container ship production, liquid NH_3-SOFC*	7.21E-12	unit
fuel tank, cryogenic, liquid ammonia*	2.26E-05	kilogram
Reliquefaction plant, 1 kg/h capacity*	1.55E-09	unit
market for maintenance, container ship	1.74E-11	unit
ammonia production, liquid*	8.92E-03	kilogram
market group for electricity, low voltage	7.41E-06	kilowatt hour
Environmental flows		
Nitrogen oxides (to air, non-urban air or from high stacks)	8.59E-08	kilogram

Table S3.7. Life cycle inventory of transport, container ship, HFO-ICE, scenario S-A-N (1 t-nm).

Exchanges	amount	unit
Economic flows		
container ship production, HFO-ICE*	4.96E-12	unit
fuel tank, heavy fuel oil*	8.77E-06	kilogram
market for maintenance, container ship	1.20E-11	unit
heavy fuel oil, very low-sulphur*	6.02E-03	kilogram
urea solution, 40 wt%*	1.14E-03	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	2.90E-07	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	3.14E-05	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	1.97E-02	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	1.10E-04	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	9.66E-07	kilogram
Ammonia (to air, non-urban air or from high stacks)	8.75E-07	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	1.42E-05	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	1.70E-06	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	6.04E-05	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	0	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	1.95E-05	kilogram

Table S3.8. Life cycle inventory of transport, container ship, liquid H_2-PEMFC, scenario S-A-N (1 t-nm).

Exchanges	amount	unit
Economic flows		
container ship production, liquid H_2-PEMFC*	5.09E-12	unit
fuel tank, cryogenic, liquid hydrogen*	4.26E-05	kilogram
Reliquefaction plant, 1 kg/h capacity*	1.41E-09	unit
market for maintenance, container ship	1.23E-11	unit
liquid hydrogen production*	2.02E-03	kilogram
market group for electricity, low voltage	4.36E-06	kilowatt hour

Table S3.9. Life cycle inventory of transport, container ship, liquid NH_3-SOFC, scenario S-A-N (1 t-nm).

Exchanges	amount	unit
Economic flows		
container ship production, liquid NH_3-SOFC*	5.62E-12	unit
fuel tank, cryogenic, liquid ammonia*	1.33E-05	kilogram
Reliquefaction plant, 1 kg/h capacity*	9.20E-10	unit
market for maintenance, container ship	1.36E-11	unit
ammonia production, liquid*	1.32E-02	kilogram
market group for electricity, low voltage	1.44E-05	kilowatt hour
Environmental flows		
Nitrogen oxides (to air, non-urban air or from high stacks)	1.27E-07	kilogram

Table S3.10. Life cycle inventory of transport, container ship, HFO-ICE, scenario S-L-N (1 t-nm).

Exchanges	amount	unit
Economic flows		
container ship production, HFO-ICE*	6.20E-12	unit
fuel tank, heavy fuel oil*	1.10E-05	kilogram
market for maintenance, container ship	1.50E-11	unit

heavy fuel oil, very low-sulphur*	4.42E-03	kilogram
urea solution, 40 wt%*	8.05E-04	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	2.13E-07	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	2.31E-05	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	1.44E-02	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	7.81E-05	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	7.09E-07	kilogram
Ammonia (to air, non-urban air or from high stacks)	6.40E-07	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	1.05E-05	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	1.25E-06	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	4.43E-05	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	0	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	1.44E-05	kilogram

Table S3.11. Life cycle inventory of transport, container ship, liquid H_2-PEMFC, scenario S-L-N (1 t-nm).

Exchanges	amount	unit
Economic flows		
container ship production, liquid H_2-PEMFC*	6.23E-12	unit
fuel tank, cryogenic, liquid hydrogen*	3.84E-05	kilogram
Reliquefaction plant, 1 kg/h capacity*	1.26E-09	unit
market for maintenance, container ship	1.50E-11	unit
liquid hydrogen production*	1.46E-03	kilogram
market group for electricity, low voltage	4.27E-06	kilowatt hour

Table S3.12. Life cycle inventory of transport, container ship, liquid NH_3-SOFC, scenario S-L-N (1 t-nm).

Exchanges	amount	unit
Economic flows		
container ship production, liquid NH_3-SOFC*	6.69E-12	unit
fuel tank, cryogenic, liquid ammonia*	1.05E-05	kilogram
Reliquefaction plant, 1 kg/h capacity*	7.21E-10	unit
market for maintenance, container ship	1.61E-11	unit
ammonia production, liquid*	8.27E-03	kilogram
market group for electricity, low voltage	1.37E-05	kilowatt hour
Environmental flows		
Nitrogen oxides (to air, non-urban air or from high stacks)	7.96E-08	kilogram

Table S3.13. Life cycle inventory of transport, container ship, HFO-ICE, scenario S-A-I (1 t-nm).

Exchanges	amount	unit
Economic flows		
container ship production, HFO-ICE*	4.96E-12	unit
fuel tank, heavy fuel oil*	8.77E-06	kilogram
market for maintenance, container ship	1.20E-11	unit
heavy fuel oil, very low-sulphur*	6.02E-03	kilogram
urea solution, 40 wt%*	1.14E-03	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	2.90E-07	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	3.14E-05	kilogram

Carbon dioxide, fossil (to air, non-urban air or from high stacks)	1.97E-02	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	1.10E-04	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	9.66E-07	kilogram
Ammonia (to air, non-urban air or from high stacks)	8.75E-07	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	1.42E-05	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	1.70E-06	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	6.04E-05	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	0	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	1.95E-05	kilogram

Table S3.14. Life cycle inventory of transport, container ship, liquid H_2-PEMFC, scenario S-A-I (1 t-nm).

Exchanges	amount	unit
Economic flows		
container ship production, liquid H_2-PEMFC*	4.89E-12	unit
fuel tank, cryogenic, liquid hydrogen*	2.04E-05	kilogram
Reliquefaction plant, 1 kg/h capacity*	6.76E-10	unit
market for maintenance, container ship	1.18E-11	unit
liquid hydrogen production*	1.94E-03	kilogram
market group for electricity, low voltage	8.39E-06	kilowatt hour

Table S3.15. Life cycle inventory of transport, container ship, liquid NH_3-SOFC, scenario S-A-I (1 t-nm).

Exchanges	amount	unit
Economic flows		
container ship production, liquid NH_3-SOFC*	5.28E-12	unit
fuel tank, cryogenic, liquid ammonia*	6.28E-06	kilogram
Reliquefaction plant, 1 kg/h capacity*	4.33E-10	unit
market for maintenance, container ship	1.28E-11	unit
ammonia production, liquid*	1.24E-02	kilogram
market group for electricity, low voltage	2.71E-05	kilowatt hour
Environmental flows		
Nitrogen oxides (to air, non-urban air or from high stacks)	1.19E-07	kilogram

Table S3.16. Life cycle inventory of transport, container ship, HFO-ICE, scenario S-L-I (1 t-nm).

Exchanges	amount	unit
Economic flows		
container ship production, HFO-ICE*	6.20E-12	unit
fuel tank, heavy fuel oil*	1.10E-05	kilogram
market for maintenance, container ship	1.50E-11	unit
heavy fuel oil, very low-sulphur*	4.42E-03	kilogram
urea solution, 40 wt%*	8.05E-04	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	2.13E-07	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	2.31E-05	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	1.44E-02	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	7.81E-05	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	7.09E-07	kilogram
Ammonia (to air, non-urban air or from high stacks)	6.40E-07	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	1.05E-05	kilogram

Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	1.25E-06	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	4.43E-05	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	0	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	1.44E-05	kilogram

Table S3.17. Life cycle inventory of transport, container ship, liquid H_2-PEMFC, scenario S-L-I (1 t-nm).

Exchanges	amount	unit
Economic flows		
container ship production, liquid H_2-PEMFC*	6.05E-12	unit
fuel tank, cryogenic, liquid hydrogen*	1.85E-05	kilogram
Reliquefaction plant, 1 kg/h capacity*	6.14E-10	unit
market for maintenance, container ship	1.46E-11	unit
liquid hydrogen production*	1.41E-03	kilogram
market group for electricity, low voltage	8.31E-06	kilowatt hour

Table S3.18. Life cycle inventory of transport, container ship, liquid NH_3-SOFC, scenario S-L-I (1 t-nm).

Exchanges	amount	unit
Economic flows		
container ship production, liquid NH_3-SOFC*	6.45E-12	unit
fuel tank, cryogenic, liquid ammonia*	5.04E-06	kilogram
Reliquefaction plant, 1 kg/h capacity*	3.48E-10	unit
market for maintenance, container ship	1.56E-11	unit
ammonia production, liquid*	7.98E-03	kilogram
market group for electricity, low voltage	2.65E-05	kilowatt hour
Environmental flows		
Nitrogen oxides (to air, non-urban air or from high stacks)	7.68E-08	kilogram

Ship production

Table S3.19. Life cycle inventory of container ship production, HFO-ICE (1 unit).

Exchanges	amount	unit
Economic flows		
hull production, container ship, for DWT 103800*	1	unit
propulsion system, HFO-ICE*	1	unit

Table S3.20. Life cycle inventory of hull production, container ship, for DWT 103800 (1 unit).

Exchanges	amount	unit	source
Economic flows			
market for reinforcing steel	4.49E+07	kilogram	[167]
market for copper, cathode	7.12E+04	kilogram	[167]
market for bronze	6.67E+04	kilogram	[167]
market for zinc	3.11E+05	kilogram	[167]
market for aluminium, wrought alloy	2.22E+04	kilogram	[167]
market for cast iron	1.74E+06	kilogram	[167]
market for electronic component machinery, unspecified	2.22E+02	unit	[167]
market for glass wool mat	3.78E+05	kilogram	[167, 168]
market for asbestos, crysotile type	3.78E+05	kilogram	[167, 168]
market for sanitary ceramics	3.78E+05	kilogram	[167, 168]
market for polypropylene, granulate	1.07E+05	kilogram	[167, 168]
market for polyethylene, high density, granulate	1.07E+05	kilogram	[167, 168]

market for polystyrene, expandable	1.07E+05	kilogram	[167], [168]
market for polyvinylidenchloride, granulate	1.07E+05	kilogram	[167], [168]
market for polyurethane, flexible foam	1.07E+05	kilogram	[167], [168]
market for glued laminated timber, average glue mix	9.25E+02	cubic meter	[167], [168]
market for alkyd paint, white, without solvent, in 60% solution state	2.22E+05	kilogram	[167]
market for welding, arc, steel	2.79E+07	meter	[168]
market for welding, gas, steel	1.77E+08	meter	[168]
market group for electricity, medium voltage	1.48E+07	kilowatt hour	[168]
market group for heat, district or industrial, other than natural gas	1.70E+07	megajoule	[168]
market for inert waste, for final disposal	-3.78E+05	kilogram	[168]
market for scrap aluminium	-2.22E+04	kilogram	[168]
market for scrap copper	-7.12E+04	kilogram	[168]
market for scrap steel	-4.49E+07	kilogram	[168]
market for waste electric and electronic equipment	-5.56E+05	kilogram	[168]
market for waste emulsion paint	-2.14E+05	kilogram	[168]
market for waste mineral wool	-7.56E+05	kilogram	[168]
market for waste plastic, mixture	-5.34E+05	kilogram	[168]
bronze scrap, post-consumer, Recycled Content cut-off	-6.67E+04	kilogram	[168]
iron scrap, unsorted, Recycled Content cut-off	-1.74E+06	kilogram	[168]
zinc scrap, post-consumer, Recycled Content cut-off	-3.11E+05	kilogram	[168]
Environmental flows			
NMVOC, non-methane volatile organic compounds, unspecified origin (to air)	1.82E+05	kilogram	[168]
Hydrocarbons, unspecified (to water)	4.00E+03	kilogram	[168]
Hydrocarbons, unspecified (to soil)	4.00E+03	kilogram	[168]

Table S3.21. Life cycle inventory of propulsion system, HFO-ICE (1 unit).

Exchanges	amount	unit
Economic flows		
marine engine, CI, ICE*	68.64	MW
market for generator, 200kW electrical	64.3	unit
marine engine, CI, ICE*	12.86	MW
market for control cabinet, heat and power co-generation unit, 160kW electrical	231.375	unit
SCR*	81.5	MW
market for oil boiler, 100kW	6.2	unit

Table S3.22. Life cycle inventory of marine engine, CI, ICE (1 MW).

Exchanges	amount	unit
Economic flows		
market for steel, chromium steel 18/8	11674.07	kilogram
market for cast iron	13425.19	kilogram
market for aluminium, primary, ingot	2334.81	kilogram
market for zinc	58.37	kilogram
market for wire drawing, copper	29.19	kilogram
market for lead	29.19	kilogram
market for nylon 6	262.67	kilogram
market for silicone product	262.67	kilogram

market for alkyd paint, white, without solvent, in 60% solution state	262.67	kilogram
market for lubricating oil	875.56	kilogram
market group for electricity, medium voltage	10800	kilowatt hour

Source: Kanchiralla et al.[25]

Table S3.23. Life cycle inventory of SCR (1 MW).

Exchanges	amount	unit
Economic flows		
market for steel, chromium steel 18/8	942.08	kilogram
market for titanium dioxide	4.72	kilogram

Source: Kanchiralla et al.[25]

Table S3.24. Life cycle inventory of fuel tank, heavy fuel oil (1 kg).

Exchanges	amount	unit
Economic flows		
market for steel, unalloyed	1.16	kilogram
market for sheet rolling, steel	1.16	kilogram
market for scrap steel	-0.278	kilogram
market for epoxy resin, liquid	0.118	kilogram
market group for electricity, low voltage	0.47	kilowatt hour

Source: Dlamini et al.[234]

Table S3.25. Life cycle inventory of container ship production, liquid H_2-PEMFC (1 unit).

Exchanges	amount	unit
Economic flows		
hull production, container ship, for DWT 103800*	1	unit
propulsion system, liquid H_2-PEMFC*	1	unit

Table S3.26. Life cycle inventory of propulsion system, liquid H_2-PEMFC (1 unit).

Exchanges	amount	unit
Economic flows		
PEMFC*	432.95	MW
market for converter, for electric passenger car	4099.95	kilogram
market for inverter, 500kW	132.1	unit
market for battery, Li-ion, NMC111, rechargeable, prismatic	577.02	kilogram
motor drive*	71.48	MW
market for marine electric motor	187.218	unit
market for control cabinet, heat and power co-generation unit, 160kW electrical	1591.125	unit
electric boiler, 100kW*	6.2	unit

Table S3.27. Life cycle inventory of PEMFC (1 MW).

Exchanges	amount	unit
Economic flows		
market for pump, 40W	3000	unit
market for acrylonitrile	0.20787	kilogram
market for air filter, in exhaust air valve	13	unit
market for aluminium, cast alloy	268.25	kilogram
market for cable, three-conductor cable	16000	meter
market for carbon black	0.19171075	kilogram

market for steel, chromium steel 18/8	40	kilogram
market for cobalt oxide	0.0219	kilogram
market for wire drawing, copper	6	kilogram
market for electronics, for control units	34	kilogram
market for epoxy resin, liquid	70.2	kilogram
market for ethylene glycol	10	kilogram
market for extrusion of plastic sheets and thermoforming, inline	12.13	kilogram
market for formaldehyde	0.0111	kilogram
market for glass fibre	20	kilogram
market for polyethylene, high density, granulate	10.00952738	kilogram
market for hydrochloric acid, without water, in 30% solution state	0.0812	kilogram
market for steel, low-alloyed	83	kilogram
market for methanol	0.634	kilogram
market for methyl acrylate	0.0109265	kilogram
market for nitric acid, without water, in 50% solution state	0.187	kilogram
market for nylon 6	30	kilogram
market for permanent magnet, for electric motor	10	kilogram
market for extrusion, plastic pipes	30	kilogram
market for platinum	0.0181	kilogram
market for polyphenylene sulfide	10	kilogram
market for polypropylene, granulate	50	kilogram
market for polyurethane, rigid foam	19	kilogram
treatment of automobile catalyst	0.0543	kilogram
market for silicone product	30	kilogram
market for sodium hydroxide, without water, in 50% solution state	0.0148	kilogram
market for sodium nitrate	0.189	kilogram
market for spent solvent mixture	0.404	kilogram
market for sulfur trioxide	1.286	kilogram
market for tetrafluoroethylene	13.184	kilogram
market for titanium	240	kilogram
market for water, deionised	0.674	kilogram
market for heat, district or industrial, natural gas	765.3669	megajoule
market group for electricity, medium voltage	706.3249	kilowatt hour

Source: Usai et al.[213]

Table S3.28. Life cycle inventory of motor drive (1 MW).

Exchanges	amount	unit	source
Economic flows			
market for aluminium, primary, ingot	36.2	kilogram	[182]
market for copper, cathode	174.7	kilogram	[182]
market for kraft paper	0.3	kilogram	[182]
market for polyester-complexed starch biopolymer	73.45	kilogram	[182]
market for steel, low-alloyed	315.45	kilogram	[182]
market for brass	9.95	kilogram	[182]
market for sanitary ceramics	3.35	kilogram	[182]
market for chromium	0.05	kilogram	[182]
market for epoxy resin insulator, SiO2	3.8	kilogram	[182]
market for molybdenum	1.6	kilogram	[182]

market for nickel, class 1	0.1	kilogram	[182]
market for glass fibre reinforced plastic, polyester resin, hand lay-up	2.85	kilogram	[182]
market for glass fibre	0.1	kilogram	[182]
market for vegetable oil, refined	12.1	kilogram	[182]
market for pig iron	5.4	kilogram	[182]
market for silicone product	0.2	kilogram	[182]
market for silver	0.05	kilogram	[182]
market for solder, bar, Sn63Pb37, for electronics industry	0.85	kilogram	[182]
market for zinc	1.5	kilogram	[182]
market group for electricity, medium voltage	40	kilowatt hour	[183]

Table S3.29. Life cycle inventory of electric boiler, 100kW (1 unit).

Exchanges	amount	unit
Economic flows		
market group for electricity, medium voltage	749.59	kilowatt hour
market for heat, district or industrial, other than natural gas	1264.04	megajoule
market for glass fibre	3.15	kilogram
market for stone wool	1.92	kilogram
market for sanitary ceramics	4.79	kilogram
market for expanded vermiculite	11.64	kilogram
market for brass	15.89	kilogram
market for cast iron	53.97	kilogram
market for steel, low-alloyed, hot rolled	93.62	kilogram
market for zinc coat, coils	69.59	square meter
market for steel, chromium steel 18/8	62.33	kilogram
market for steel, low-alloyed	87.67	kilogram
market for steel, unalloyed	62.60	kilogram
market for cable, unspecified	44.52	kilogram
market for electric connector, wire clamp	4.25	kilogram
market for electronics, for control units	3.29	kilogram
market for printed wiring board, surface mounted, unspecified, Pb free	6.30	kilogram
market for resistor, wirewound, through-hole mounting	10.14	kilogram
market for nylon 6-6	0.92	kilogram
market for polyvinylchloride, bulk polymerised	0.33	kilogram
market for polyethylene, low density, granulate	0.66	kilogram
market for silicone product	0.49	kilogram
market for alkyd paint, white, without solvent, in 60% solution state	3.42	kilogram
market for coating powder	0.89	kilogram
market for inert waste, for final disposal	-44.20	kilogram
iron scrap, unsorted, Recycled Content cut-off	-185.07	kilogram
market for scrap steel	-185.07	kilogram
market for electronics scrap from control units	-0.76	kilogram
market for used cable	-30.27	kilogram
market for waste electric wiring	-0.34	kilogram
market for waste polyethylene	0.00	kilogram
market for waste polyvinylchloride	-0.25	kilogram
market for waste plastic, mixture	-1.41	kilogram
market for waste paint on metal	-4.32	kilogram

Source: Abbas.[232]

Table S3.30. Life cycle inventory of fuel tank, cryogenic, liquid hydrogen (1 kg).

Exchanges	amount	unit
Economic flows		
market for compressed air, 1000 kPa gauge	3.76E-04	cubic meter
market group for electricity, low voltage	5.98E-01	kilowatt hour
market for steel, chromium steel 18/8	9.74E-01	kilogram
market for aluminium alloy, AlMg3	2.59E-02	kilogram

Source: Abbas[235]

Table S3.31. Life cycle inventory of reliquefaction plant, 1 kg/h capacity (1 unit).

Exchanges	Amount	Unit
Economic flows		
market for steel, chromium steel 18/8	16.5	kilogram
market for cast iron	6	kilogram
market for steel, unalloyed	5.4	kilogram
market for aluminium, primary, ingot	2.1	kilogram
market for casting, steel, lost-wax	21.9	kilogram
market for casting, aluminium, lost-wax	2.1	kilogram
market group for electricity, medium voltage	11.34	kilowatt hour
market for scrap steel	-21.90	kilogram
market for scrap aluminium	-2.10	kilogram
market for iron scrap, unsorted	-6.00	kilogram
market for natural gas, liquefied	0.01	cubic meter
market for nitrogen, liquid	4.18	kilogram

Source: Park et al.[275]

Table S3.32. Life cycle inventory of container ship production, liquid NH_3-SOFC (1 unit).

Exchanges	amount	unit
Economic flows		
hull production, container ship, for DWT 103800*	1	unit
propulsion system, liquid NH3-SOFC*	1	unit

Table S3.33. Life cycle inventory of propulsion system, liquid NH_3-SOFC (1 unit).

Exchanges	amount	unit
Economic flows		
SOFC*	432.95	MW
market for converter, for electric passenger car	4505.4	kilogram
market for inverter, 500kW	132.1	unit
market for battery, Li-ion, NMC111, rechargeable, prismatic	1727.23	kilogram
motor drive*	71.48	MW
market for marine electric motor	187.218	unit
market for control cabinet, heat and power co-generation unit, 160kW electrical	1591.125	unit
electric boiler, 100kW*	6.2	unit

Table S3.34. Life cycle inventory of SOFC (1 MW).

Exchanges	amount	unit
Economic flows		

market for butyldiglycol acetate	50.52	kilogram
market for aluminium, primary, ingot	4000	kilogram
market for methyl methacrylate	135.1	kilogram
market for carbon black	87.6	kilogram
market for cobalt oxide	45.77007038	kilogram
market for wire drawing, copper	4000	kilogram
market for lanthanum oxide	45.18537089	kilogram
market for carboxymethyl cellulose, powder	89.04	kilogram
market for butyl acetate	404.95	kilogram
market for nickel, class 1	1136	kilogram
market for ethylene glycol	132	kilogram
market for strontium carbonate	7.044558724	kilogram
market for steel, chromium steel 18/8	31000	kilogram
market for yttrium oxide	53.43	kilogram
market for zirconium oxide	357.57	kilogram
market group for electricity, medium voltage	7577.777778	kilowatt hour
Environmental flows		
Carbon dioxide, fossil (to air)	432	kilogram

Source: Kanchiralla et al.[26]

Table S3.35. Life cycle inventory of fuel tank, pressurized, liquid ammonia (1 kg).

Exchanges	Amount	Unit
Economic flows		
market for steel, low-alloyed	0.55	kilogram
market for steel, unalloyed	0.56	kilogram
market for sheet rolling, steel	1.11	kilogram
market for scrap steel	-0.11	kilogram

Source: Ryste [237] and Cryocan[238]

Fuel supply

In the following processes, the input of "market for hydrogen, gaseous, 25-30 bar" is from the databases established by Wei et al.[53]

Table S3.36. Life cycle inventory of heavy fuel oil, very low-sulphur (1 kg).

Exchanges	Amount	Unit
Economic flows		
market for heavy fuel oil	1.00	kilogram
market group for electricity, low voltage	5.46E-03	kilowatt hour
market for petroleum coke	9.20E-05	kilogram
market for hydrogen, gaseous	8.92E-03	kilogram
Environmental flows		
Hydrogen sulfide (to air)	5.63E-03	kilogram

Source: Silva[174]

Table S3.37. Life cycle inventory of liquid hydrogen production (1 kg).

Exchanges	amount	unit	source
Economic flows			
market for hydrogen, gaseous, 25-30 bar*	1.0162	kilogram	[175]
hydrogen liquefaction plant construction*	3.43E-09	unit	[175]

market group for electricity, low voltage	10.5	kilowatt hour	[176]
Environmental flows			
Hydrogen (to air)	1.62E-02	kilogram	[175]

Table S3.38. Life cycle inventory of hydrogen liquefaction plant construction (1 unit).

Exchanges	amount	unit
Economic flows		
market for steel, chromium steel 18/8	5.95E+05	kilogram
market for reinforcing steel	3.80E+05	kilogram
market group for concrete, normal	2.03E+04	cubic meter
market for copper, cathode	1.50E+05	kilogram
market for aluminium alloy, AlMg3	1.40E+05	kilogram

Source: Wulf and Zapp[175]

Table S3.39. Life cycle inventory of ammonia production, liquid (1 kg).

Exchanges	amount	unit
Economic flows		
market for hydrogen, gaseous, 25-30 bar*	0.176	kilogram
nitrogen, gaseous, from cryogenic distillation, without compression*	0.815	kilogram
ammonia synthesis catalyst*	5.15E-05	kilogram
market for chemical factory, organics	3.29E-10	unit
market group for electricity, low voltage	1.440	kilowatt hour
treatment of inert waste, inert material landfill	-5.15E-05	kilogram
Environmental flows		
Water, cooling, unspecified natural origin (from natural resource)	0.149	cubic meter
Hydrogen (to air)	7.67E-04	kilogram
Ammonia (to air)	1.63E-03	kilogram
Nitrogen oxides (to air)	1.00E-03	kilogram
Water (to air)	4.76E-02	cubic meter
Water (to water)	1.01E-01	cubic meter

Source: D'Angelo[54]

Table S3.40. Life cycle inventory of nitrogen, gaseous, from cryogenic distillation, without compression (1 kg).

Exchanges	amount	unit
Economic flows		
market for air separation facility	4.43E-10	unit
Environmental flows		
Water, cooling, unspecified natural origin (from natural resource)	4.00 E-03	cubic meter
Water (to water)	2.45E-03	cubic meter

Source: D'Angelo[54]

Table S3.41. Life cycle inventory of ammonia synthesis catalyst (1 kg).

Exchanges	amount	unit
Economic flows		
market for magnetite	0.917	kilogram
market for lime	3.00E-02	kilogram
market for zeolite, powder	5.25E-02	kilogram
market group for electricity, low voltage	1.78	kilowatt hour

Source: D'Angelo[54]

Others

Table S3.42. Life cycle inventory of urea solution, 40 wt% (kg).

Exchanges	Amount	Unit
Economic flows		
market for urea	0.4	kilogram
market for water, deionised	0.6	kilogram

Source: Brynolf et al.[262]

S3.2 Supplementary results

Prospective GHG emissions

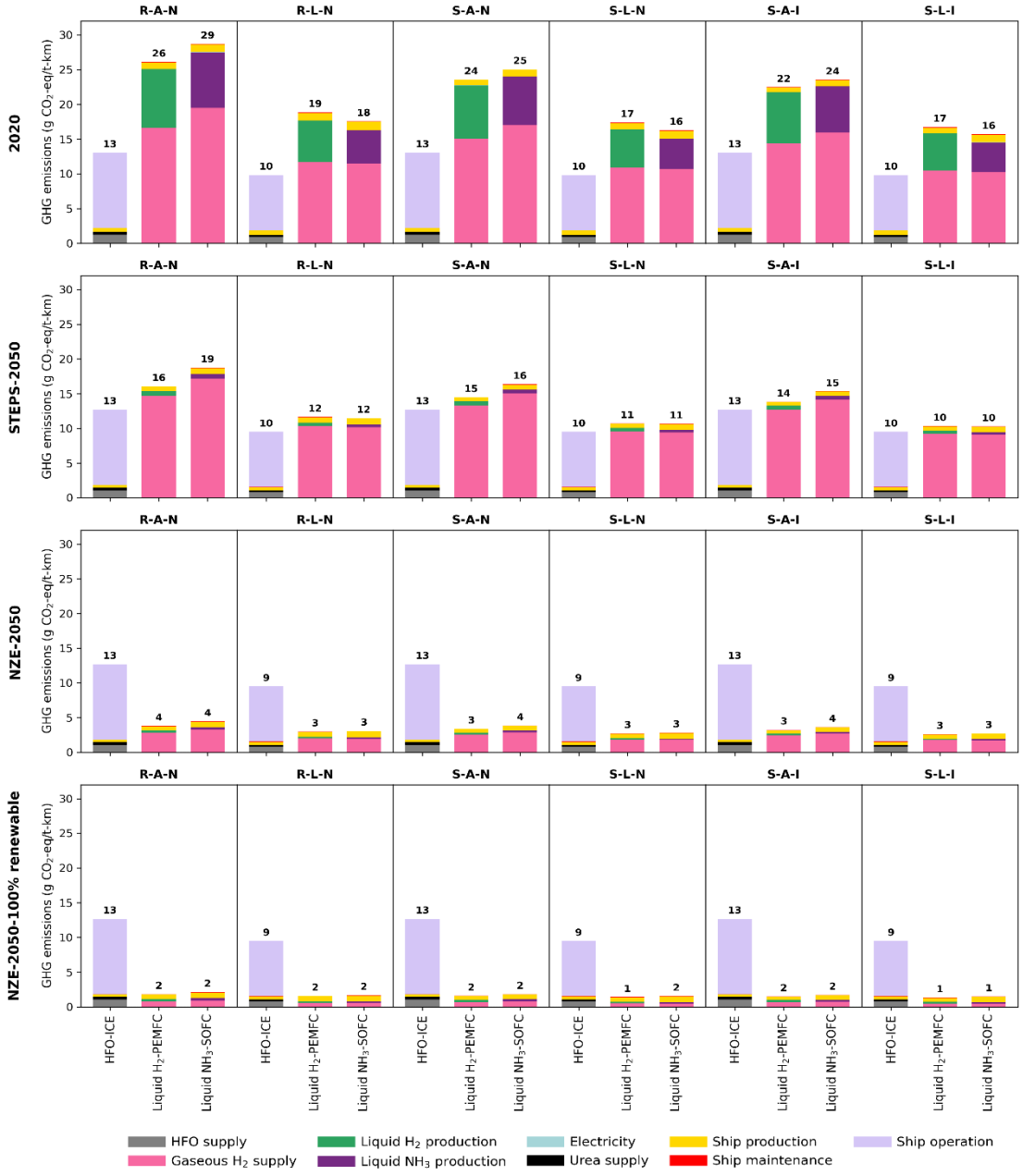

Figure S3.1. The process contribution to the GHG emissions (per t-km) of different ships in different scenarios. For the liquid H_2 production, and liquid NH_3 production, the gaseous H_2 supply is a part of them and presented separately. In this figure, R-A-N=22000 nm-20 knots-Nonstop, R-L-N=22000 nm-16 knots-Nonstop, S-A-N=11000 nm-20 knots-Nonstop, S-L-N=11000 nm-16 knots-Nonstop, S-A-I=5500 nm-20 knots-1 refueling stop, and S-L-I=5500 nm-16 knots-1 refueling stop.

Table S3.43. Comparison of fuel cell well-to-wake emissions under the NZE scenarios with IMO Net-Zero Framework targets (unit: g CO_2-eq/MJ). In this table, blue and red text indicate that fuel cell emissions meet the base and direct compliance targets, respectively.

	2030	2031	2032	2033	2034	2035	2040
Well-to-wake emissions of fuel cells							
Liquid H_2-PEMFC-market	97	88	78	69	59	50	32
Liquid NH_3-SOFC-market	105	95	85	75	65	54	35
Liquid H_2-PEMFC-100% renewable	9	9	8	8	8	8	8
Liquid NH_3-SOFC-100% renewable	10	9	9	9	9	9	8
Well-to-wake emissions regulated under the IMO Net-Zero Framework							
Tier 2: Base target	86	82	78	74	69	65	33
Tier 1: Direct compliance target	74	70	65	61	57	53	-

Table S3.44. Comparison of fuel cell well-to-wake emissions across different refueling regions under the NZE scenario with FuelEU Maritime requirements (unit: g CO_2-eq/MJ). In this table, blue text indicates that fuel cell emissions meet the FuelEU Maritime requirements. CG=coal gasification, NG SMR=steam methane reforming of natural, BG=biomass gasification, CCS=carbon capture and storage, AE=alkaline electrolyzer, PEM=proton exchange membrane electrolyzer and SOEC=solid oxide electrolysis cell.

	2020	2025	2030	2035	2040	2045	2050
Well-to-wake emissions of fuel cells							
Liquid H_2-PEMFC-China-market	244	254	136	61	41	28	22
Liquid H_2-PEMFC-China-CG	280	263	235	223	221	220	220
Liquid H_2-PEMFC-China-CG CCS	165	137	90	70	67	65	65
Liquid H_2-PEMFC-China-NG SMR	158	138	104	90	88	87	87
Liquid H_2-PEMFC-China-NG SMR CCS	118	95	57	41	39	38	38
Liquid H_2-PEMFC-China-BG	98	72	29	11	8	7	6
Liquid H_2-PEMFC-China-BG CCS	-23	-53	-108	-127	-126	-126	-122
Liquid H_2-PEMFC-China-AE	477	345	124	30	16	10	10
Liquid H_2-PEMFC-China-PEM	537	367	126	30	16	10	10
Liquid H_2-PEMFC-China-SOEC	441	320	125	44	32	27	26
Liquid H_2-PEMFC-Middle East-market	156	141	99	65	36	26	24
Liquid H_2-PEMFC-Middle East-CG	263	250	229	216	207	205	205
Liquid H_2-PEMFC-Middle East-CG CCS	115	100	75	60	50	47	47
Liquid H_2-PEMFC-Middle East-NG SMR	156	144	124	112	103	101	101
Liquid H_2-PEMFC-Middle East-NG SMR CCS	107	95	75	62	54	52	52
Liquid H_2-PEMFC-Middle East-BG	64	51	28	14	4	2	2
Liquid H_2-PEMFC-Middle East-BG CCS	-69	-82	-109	-123	-131	-132	-128
Liquid H_2-PEMFC-Middle East-AE	302	235	117	46	0	-11	-11
Liquid H_2-PEMFC-Middle East-PEM	339	249	120	48	-1	-13	-12
Liquid H_2-PEMFC-Middle East-SOEC	286	223	120	59	17	7	7
Liquid H_2-PEMFC-EU-market	129	92	51	34	29	26	24
Liquid H_2-PEMFC-EU-CG	239	222	209	205	205	204	204
Liquid H_2-PEMFC-EU-CG CCS	87	67	52	48	47	47	46
Liquid H_2-PEMFC-EU-NG SMR	129	113	100	97	97	97	97
Liquid H_2-PEMFC-EU-NG SMR CCS	80	63	51	48	48	48	48
Liquid H_2-PEMFC-EU-BG	40	22	9	5	5	5	5
Liquid H_2-PEMFC-EU-BG CCS	-100	-119	-135	-134	-130	-128	-124
Liquid H_2-PEMFC-EU-AE	185	94	25	9	8	7	7
Liquid H_2-PEMFC-EU-PEM	208	100	25	9	7	7	7

Liquid H_2-PEMFC-EU-SOEC	175	93	32	19	17	17	17
Liquid NH_3-SOFC-China-market	256	273	149	68	46	33	25
Liquid NH_3-SOFC-China-CG	296	282	259	249	248	247	247
Liquid NH_3-SOFC-China-CG CCS	168	141	97	78	75	74	74
Liquid NH_3-SOFC-China-NG SMR	161	143	113	101	99	98	98
Liquid NH_3-SOFC-China-NG SMR CCS	116	95	61	46	44	43	43
Liquid NH_3-SOFC-China-BG	93	69	29	12	9	8	8
Liquid NH_3-SOFC-China-BG CCS	-42	-71	-124	-142	-140	-140	-135
Liquid NH_3-SOFC-China-AE	516	374	135	34	19	13	12
Liquid NH_3-SOFC-China-PEM	584	399	138	34	19	12	12
Liquid NH_3-SOFC-China-SOEC	477	346	136	49	36	31	30
Liquid NH_3-SOFC-Middle East-market	165	150	108	72	42	32	29
Liquid NH_3-SOFC-Middle East-CG	284	272	253	241	233	231	231
Liquid NH_3-SOFC-Middle East-CG CCS	119	104	81	67	57	55	55
Liquid NH_3-SOFC-Middle East-NG SMR	165	154	135	124	117	115	115
Liquid NH_3-SOFC-Middle East-NG SMR CCS	110	99	80	69	62	60	60
Liquid NH_3-SOFC-Middle East-BG	62	49	28	15	6	4	4
Liquid NH_3-SOFC-Middle East-BG CCS	-87	-99	-125	-138	-145	-145	-141
Liquid NH_3-SOFC-Middle East-AE	328	255	128	51	2	-11	-10
Liquid NH_3-SOFC-Middle East-PEM	370	271	131	53	1	-12	-11
Liquid NH_3-SOFC-Middle East-SOEC	310	242	131	65	21	10	10
Liquid NH_3-SOFC-EU-market	139	102	58	40	33	30	28
Liquid NH_3-SOFC-EU-CG	262	246	234	230	230	230	229
Liquid NH_3-SOFC-EU-CG CCS	93	74	58	54	53	53	53
Liquid NH_3-SOFC-EU-NG SMR	139	124	113	110	110	110	110
Liquid NH_3-SOFC-EU-NG SMR CCS	84	69	58	55	54	54	54
Liquid NH_3-SOFC-EU-BG	40	23	10	7	7	6	6
Liquid NH_3-SOFC-EU-BG CCS	-117	-135	-150	-148	-144	-142	-137
Liquid NH_3-SOFC-EU-AE	202	104	28	11	10	9	9
Liquid NH_3-SOFC-EU-PEM	227	110	28	11	9	9	8
Liquid NH_3-SOFC-EU-SOEC	191	103	37	22	21	20	20
Well-to-wake emissions regulated under the FuelEU Maritime							
GHG intensity limit	91.16	89.34	85.69	77.94	62.9	34.64	18.23

Prospective regional environmental impacts

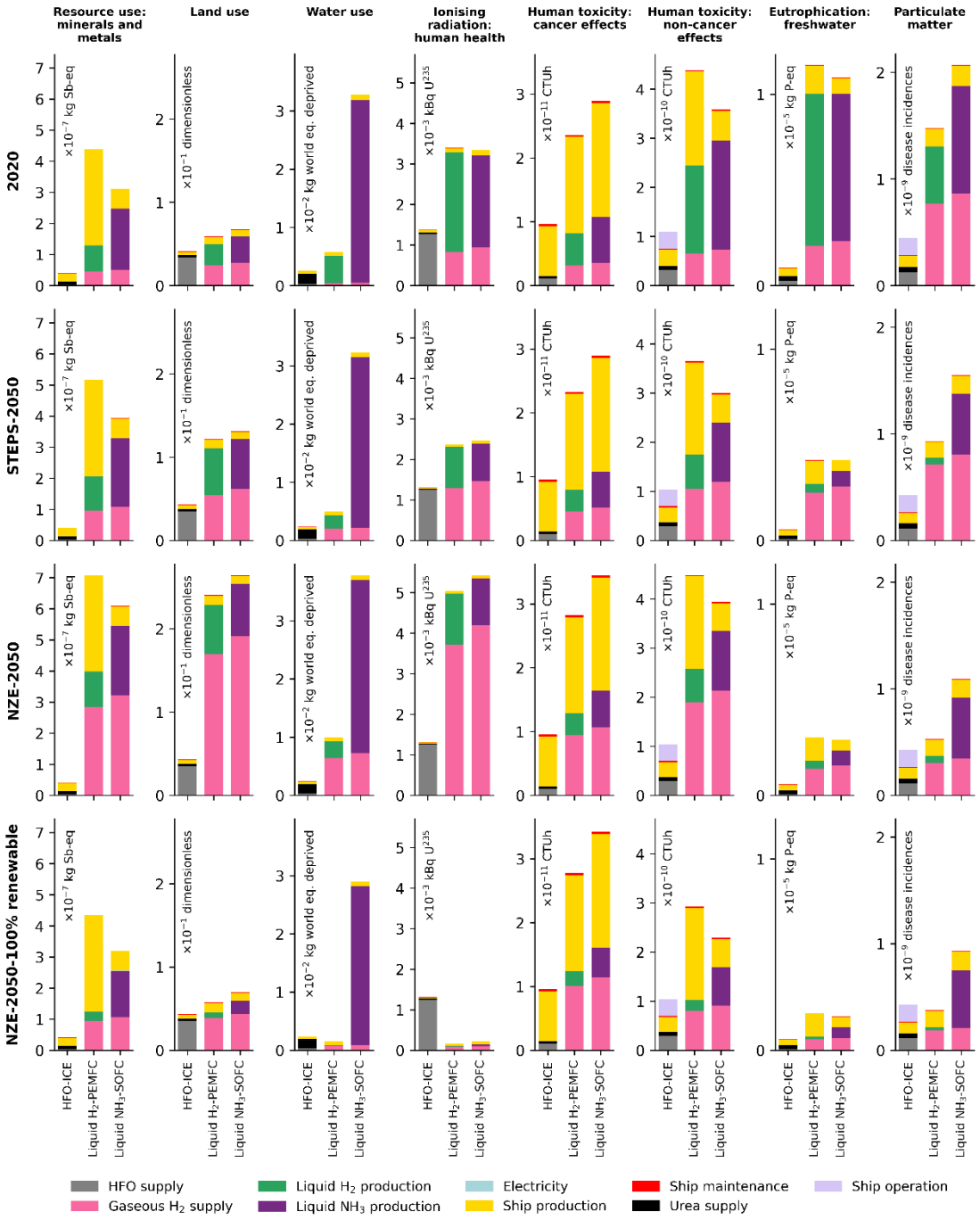

Figure S3.2. Contribution analysis of the main environmental trade-offs of using fuel cells compared to HFO from 2020 to 2050 under the S-A-N (11000 nm-20 knots-Nonstop) scenario.

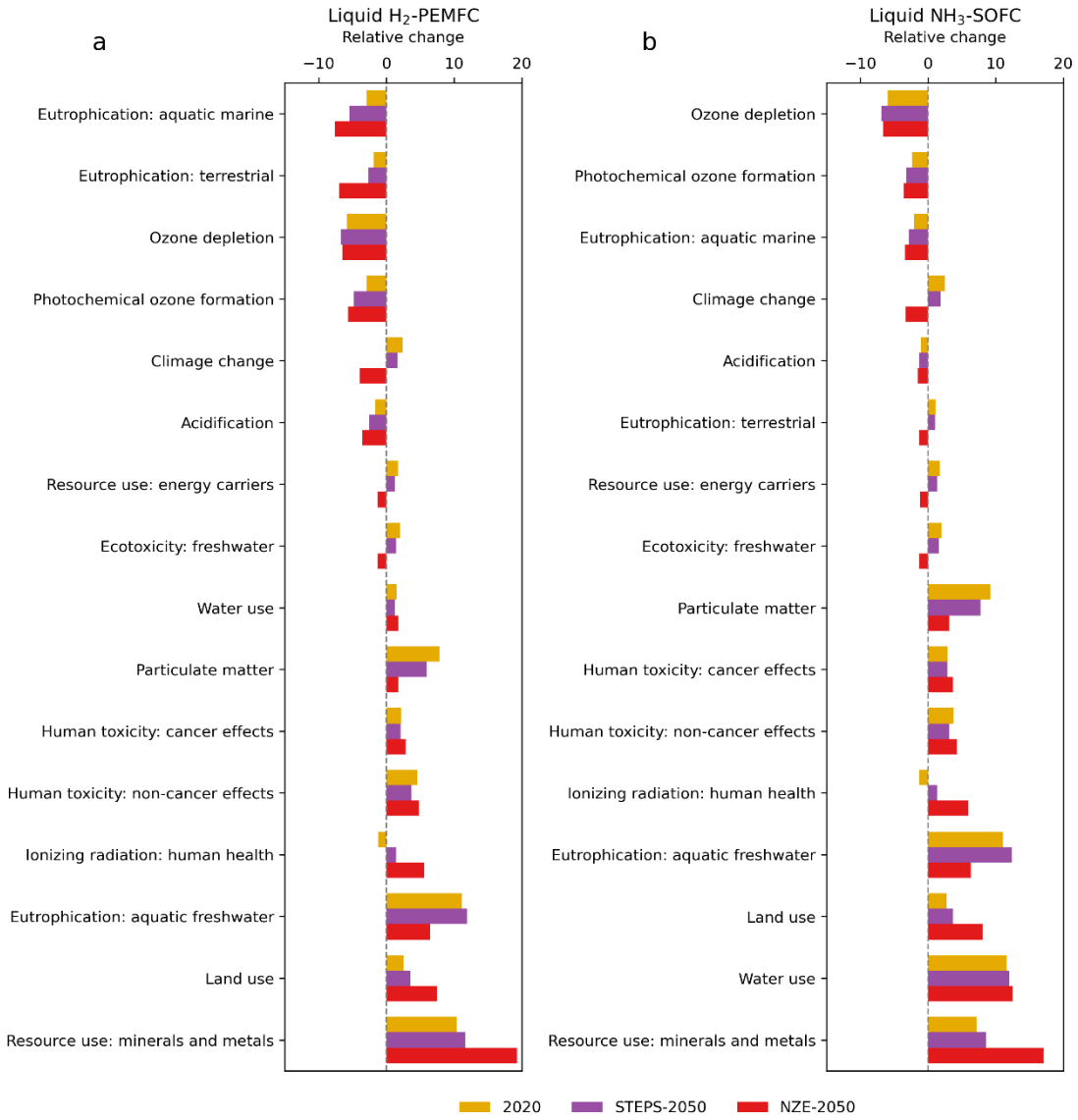

Figure S3.3. The relative environmental impacts of fuel cell systems compared to traditional ones from 2020 to 2050 under the S-A-I (5500 nm-20 knots-1 refueling stop) scenario in China. (a) Liquid H_2-PEMFC ship compared under the 2020, STEPS-2050, and NZE-2050 scenarios. (b) Liquid NH_3-SOFC ship compared with the HFO ship under the 2020, STEPS-2050, and NZE-2050 scenarios. The values indicate the factors of change in the environmental impact of fuel cell ships compared to HFO-powered ships.

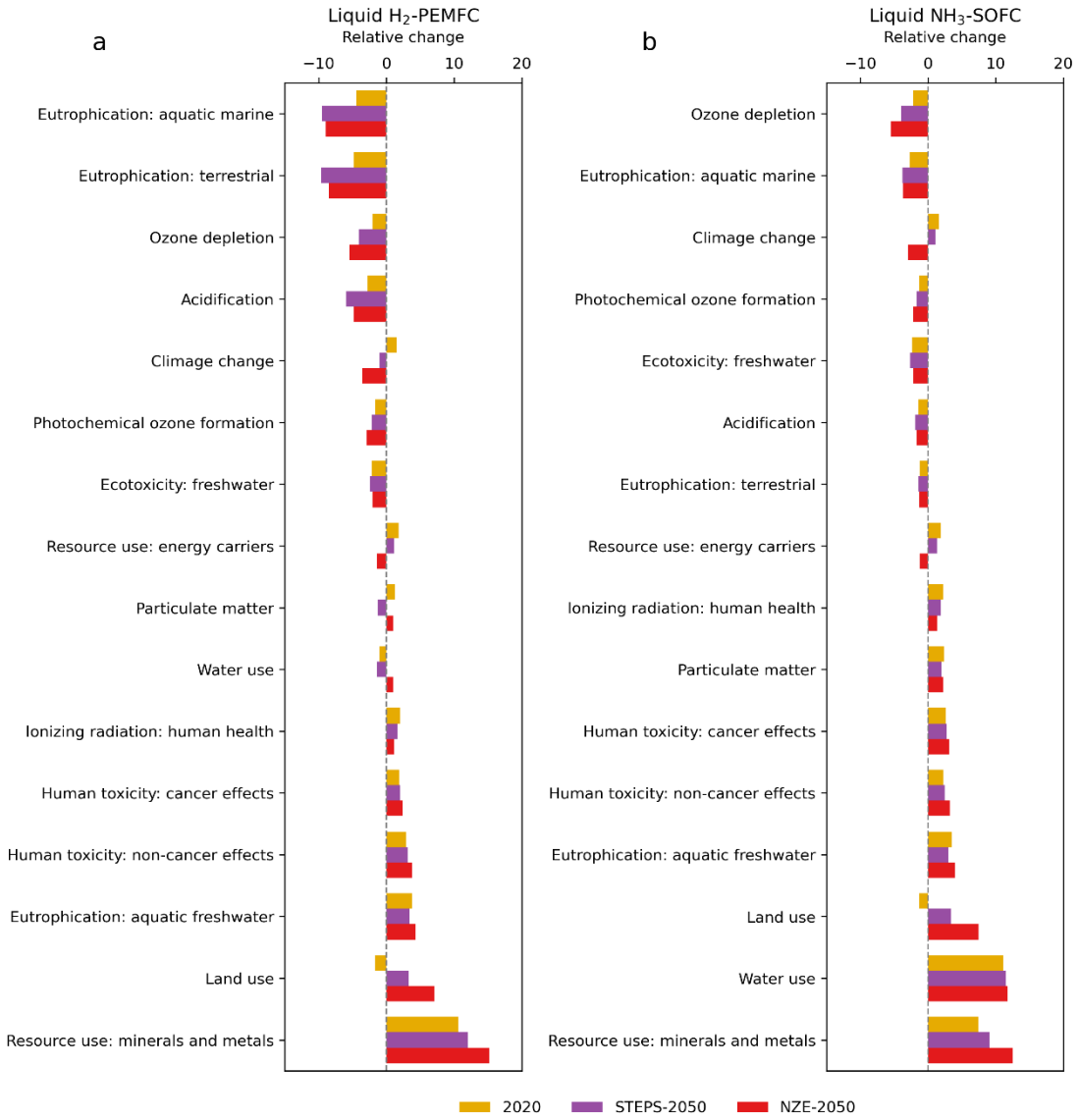

Figure S3.4. The relative environmental impacts of fuel cell systems compared to traditional ones from 2020 to 2050 under the S-A-I (5500 nm-20 knots-1 refueling stop) scenario in the Middle East. (a) Liquid H_2-PEMFC ship compared under the 2020, STEPS-2050, and NZE-2050 scenarios. (b) Liquid NH_3-SOFC ship compared with the HFO ship under the 2020, STEPS-2050, and NZE-2050 scenarios. The values indicate the factors of change in the environmental impact of fuel cell ships compared to HFO-powered ships.

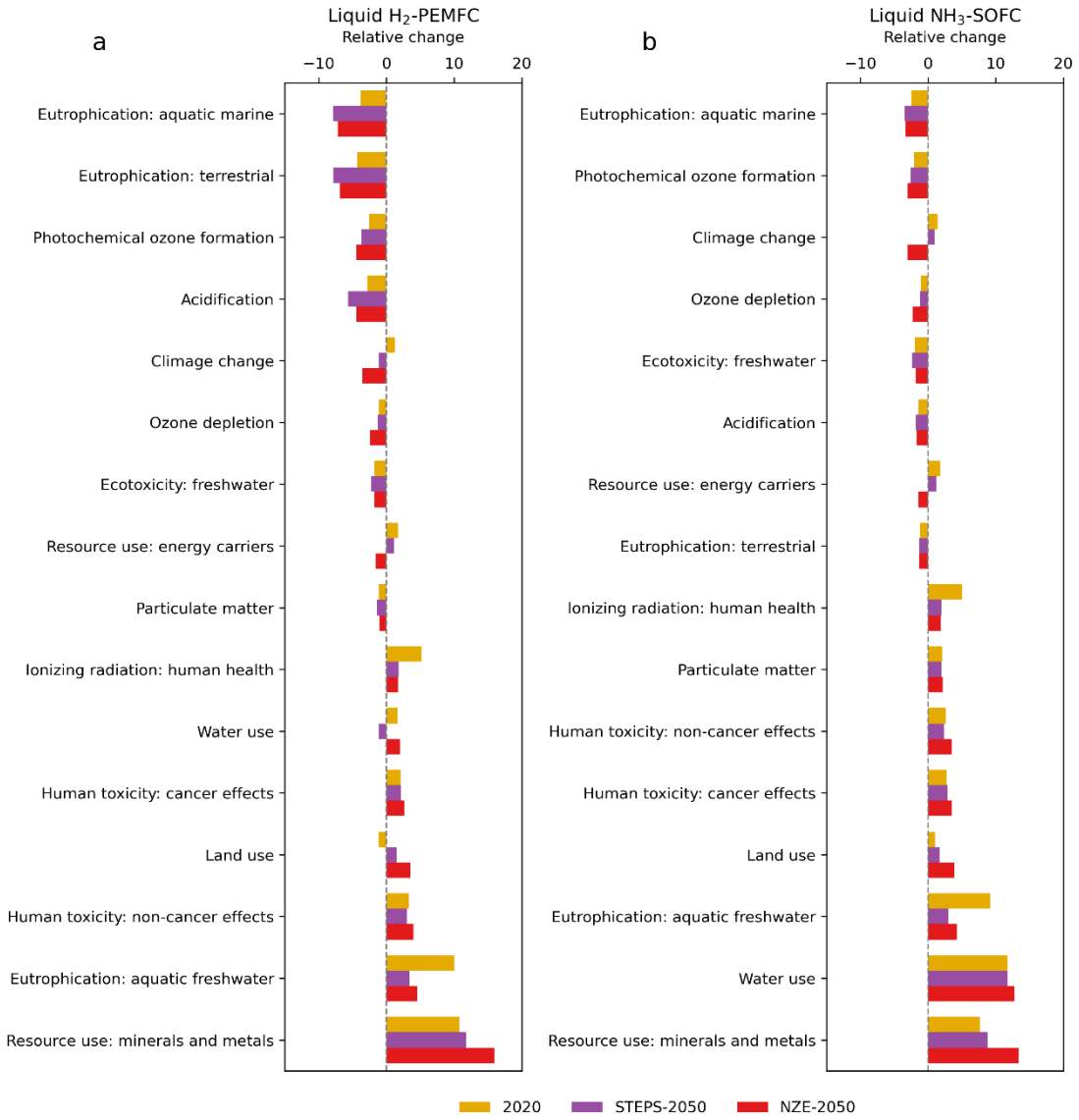

Figure S3.5. The relative environmental impacts of fuel cell systems compared to traditional ones from 2020 to 2050 under the S-A-I (5500 nm-20 knots-1 refueling stop) scenario in the European Union. (a) Liquid H_2-PEMFC ship compared under the 2020, STEPS-2050, and NZE-2050 scenarios. (b) Liquid NH_3-SOFC ship compared with the HFO ship under the 2020, STEPS-2050, and NZE-2050 scenarios. The values indicate the factors of change in the environmental impact of fuel cell ships compared to HFO-powered ships.

Sensitivity analysis

In this section, we conduct a sensitivity analysis to examine how changes in key parameter assumptions for fuel cell ships, potentially resulting from technological advancements, affect their environmental impacts. The efficiencies of PEMFC and SOFC, the lifespans of PEMFC and SOFC, and the lifespan of the battery are assumed to increase by 10%, while the BOG rates of liquid H_2 and liquid NH_3 are assumed to decrease by 10%. It should be noted that the replacement frequencies of fuel cells and the battery are not directly adjusted according to the percentage increase in lifespan. We first change the lifespans from the current assumptions to longer achievable values, for example from 5 to 10 years for PEMFC [320], from 6 to 11 years for SOFC [321], and from 11 to 15 years for the battery [322]. This means that the replacement frequencies of PEMFC, SOFC, and the

battery decrease from 5, 5, and 3 times to 3, 3, and 2 times, respectively, over a ship's 25-year lifespan. The resulting changes in environmental impacts are then allocated to the 10% lifespan increase. Therefore, the environmental impact changes related to the lifespans of the fuel cells and the battery should be interpreted as averaged values rather than the direct outcomes of a strict 10% increase in lifespan. In the decarbonization of water electrolysis, the decarbonization of electricity is the decisive factor, whereas improvements in electrolyzer efficiency make only a marginal contribution. As shown in our previous study, efficiency improvement contributes only about 0.5% to the decarbonization of electrolytic H_2 from 2020 to 2050 [53]. Therefore, we will not conduct further sensitivity analysis for this factor in this study.

As shown in Figure S3.6, among these main factors, fuel cell efficiency has the most significant influence on all environmental impacts because it directly affects fuel consumption. As the H_2-based fuel supply decarbonizes, these environmental impacts either increase or decrease, and their sensitivity to efficiency improvements changes accordingly. For instance, for climate change, the percentage decrease becomes smaller as the H_2-based fuel supply decarbonizes. In contrast, the percentage decreases for impacts such as ionizing radiation, land use, water use, human toxicity with cancer effects, and minerals and metals use become larger. At the same time, the sensitivity of certain environmental impacts to fuel cell efficiency differs between the two fuel cell propulsion systems. For example, human toxicity with non-cancer effects, and minerals and metals use decrease by around 6% and 5% when fuel cell efficiency increases by 10% for the liquid H_2-PEMFC ship, whereas these two impacts both decrease by around 9% for the liquid NH_3-SOFC ship. This is because PEMFC production is also an important contributor to these impacts for the liquid H_2-PEMFC ship, in addition to the fuel supply, as discussed in Section 3.4 of the main text. Furthermore, extending the lifespan of the PEMFC has a greater impact on human toxicity with non-cancer effects and minerals and metals use than on other environmental impacts, resulting in approximately a 2% decrease. Extending the lifespan of the SOFC induces a 1.5% decrease in human toxicity with cancer effects for the liquid NH_3-SOFC ship, while having negligible effects on the other environmental indicators. Changes in battery lifespan and in the BOG rates of liquid H_2 and liquid NH_3 have negligible effects on the results.

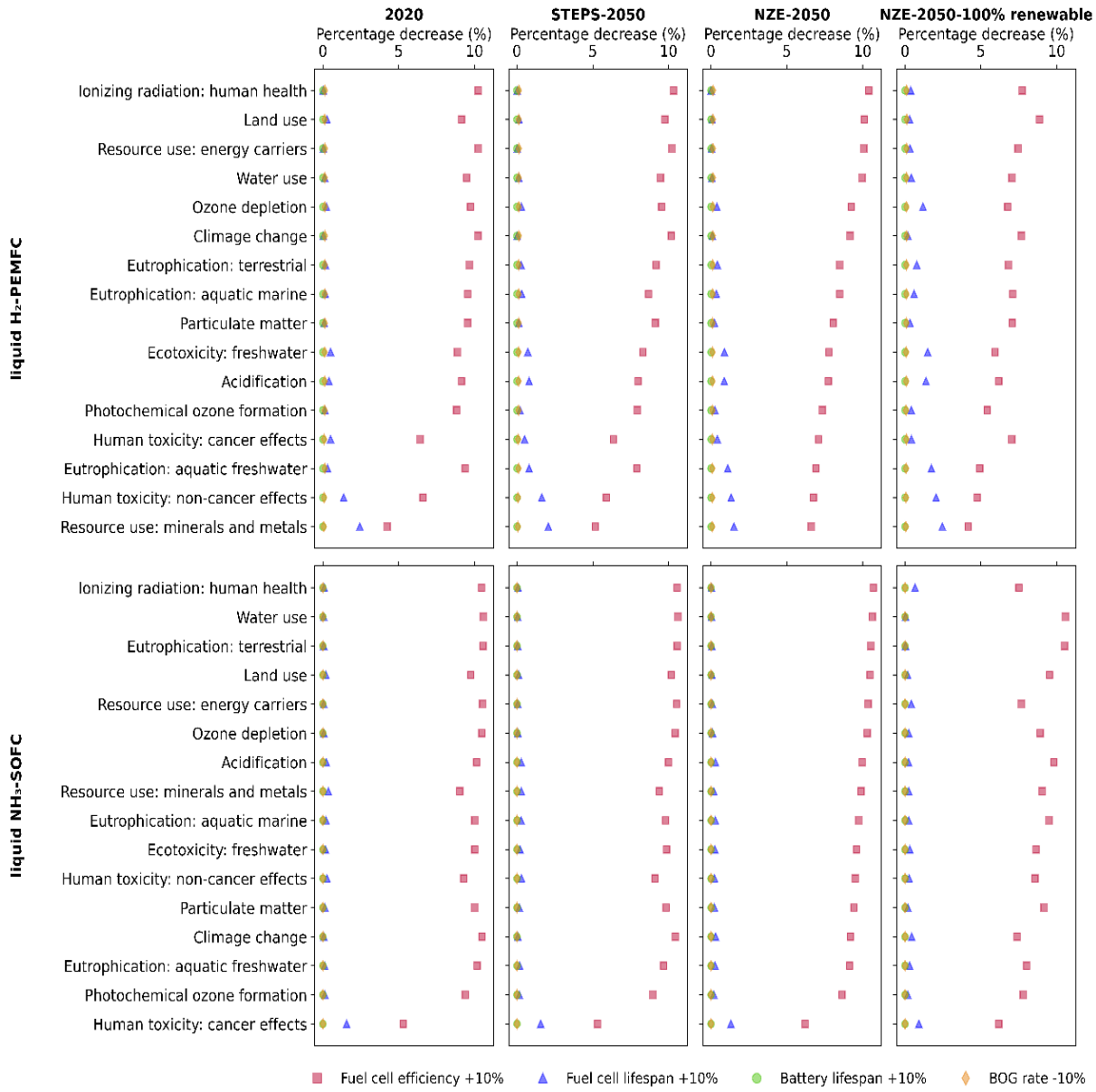

Figure S3.6. Sensitivity analysis of key parameter changes on environmental impacts of fuel cell ships under the S-A-N (11000 nm-20 knots-Nonstop) scenario. In this figure, Fuel cell efficiency +10% = a 10% improvement in fuel cell efficiency; Fuel cell lifespan +10% = a 10% extension in fuel cell lifespan; Battery lifespan +10% = a 10% extension in battery lifespan; BOG rate –10% = a 10% reduction in the boil-off gas (BOG) rate for onboard liquid hydrogen and ammonia storage.

S4 Supporting information for chapter 5

S4.1 Lifecycle inventory analysis

Representative ships

Table S4.1. The main information of representative ships for different ship sizes.[7, 258, 259]

Parameters	0-999	1,000-1,999	2,000-2,999	3,000-4,999	5,000-7,999	8,000-11,999	12,000-14,499	14,500-19,999	20,000+
Code	Ship 1	Ship 2	Ship 3	Ship 4	Ship 5	Ship 6	Ship 7	Ship 8	Ship 9
Representative ship	CANDELARIA B	Calisto	Evridiki G	CMA CGM AFRICA THREE	EVER STEADY	SEASPAN ZAMBEZI	ONE MILLAU	MSC NEW YORK	EVER GOLDEN
Ship capacity (TEU)	822	1574	2556	3718	7024	10100	13870	16652	20338
Ship DWT (t)	8627	20614	34654	51604	78664	115096	147443	186765	199692
Payload utilization rate (%)	66	63	59	61	62	62	65	66	65
Range (nm)	800	2500	5000	6500	7500	13000	14000	15500	17000
Installed main engine power (MW)	7.95	16.52	21.56	31.64	54.90	58.10	59.78	59.78	59.30
Installed auxiliary engine power (MW)	1	3.544	6.72	8.4	11.6	14.6	14.6	18	19.2
Installed auxiliary boiler power (MW)	0.25	0.34	0.46	0.48	0.59	0.62	0.63	0.63	0.7
HFO tank (m^3)	778	2412	3918	6948.99	9434.9	10584	10276.61	13067	15143.27
Average speed (kn)	13.2	12.5	13.7	14.3	15.8	15.1	14.2	15.5	15.8
Max speed (kn)	18.2	18.7	19.2	20.3	22.1	21.4	20.9	21.4	22.4
Average draught (m)	6.7	9.5	9	11.4	10.8	11.45	12.1	12.55	13.5
Max draught (m)	7.466	10.2	11.5	12.45	14.2	15.52	15.5	16.02	16
Weather correction factor	0.909	0.867	0.867	0.867	0.867	0.867	0.867	0.867	0.867
Fouling correction factor	0.917	0.917	0.917	0.917	0.917	0.917	0.917	0.917	0.917

Propulsion systems

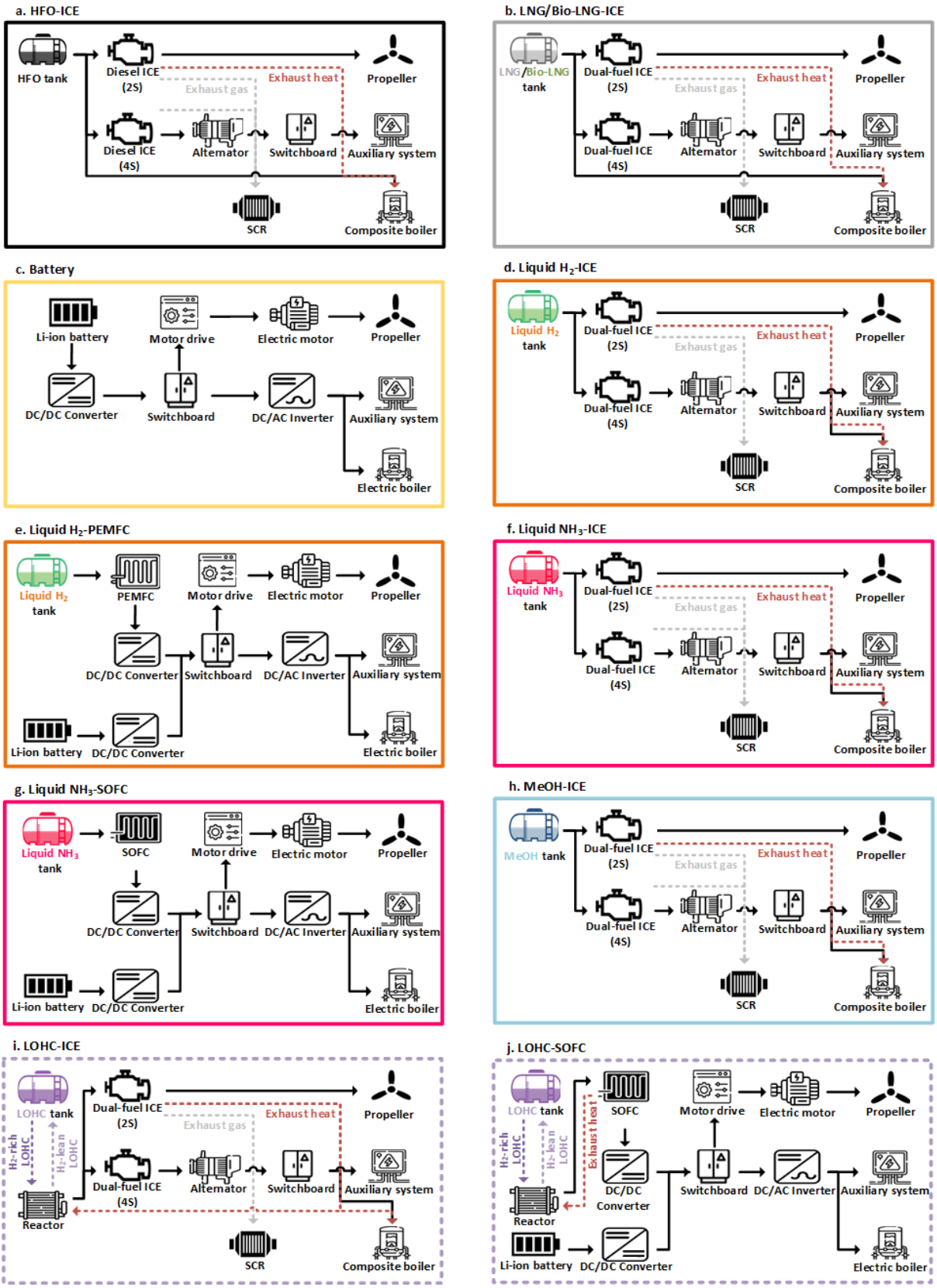

Figure S4.1. Components and workflow for different propulsion systems. For LNG/Bio-LNG-ICE, liquid H_2-ICE, liquid H_2-PEMFC, liquid NH_3-ICE, liquid NH_3-SOFC, the re-liquefaction plant is needed to deal with boil-off gas and consumes electricity. The liquid organic H_2 carrier (LOHC) systems are included for comparison with the liquid NH_3 systems.

Volumetric and gravimetric changes

Table S4.2. Total volume and weight of the fuel tank and propulsion system for different propulsion options, and the resulting cargo weight loss.

Ship	Propulsion System	Total Volume (m3)	Total Mass (t)	Cargo weight change (t)	Final cargo capacity (t)
Ship 1	HFO-ICE	1950	439	0	5694
Ship 1	LH_2-PEMFC	716	206	233	5927
Ship 1	LNH_3-SOFC	2220	633	-194	5500
Ship 1	Battery	2877	2506	-2067	3626
Ship 1	LH_2-DFICE	1611	377	62	5756
Ship 1	LNH_3-DFICE	1377	418	21	5715
Ship 1	MeOH-DFICE	1303	398	41	5735
Ship 1	LNG-DFICE	1352	341	98	5792
Ship 1	LOHC-SOFC	2995	914	-475	5219
Ship 1	LOHC-DFICE	2327	753	-314	5380
Ship 2	HFO-ICE	4903	1305	0	13076
Ship 2	LH_2-PEMFC	3473	889	416	13492
Ship 2	LNH_3-SOFC	5531	1836	-531	12545
Ship 2	LH_2-DFICE	5394	1300	5	13081
Ship 2	LNH_3-DFICE	3833	1562	-257	12819
Ship 2	MeOH-DFICE	3346	1430	-125	12951
Ship 2	LNG-DFICE	3688	1061	244	13320
Ship 2	LOHC-SOFC	7494	3081	-1775	11301
Ship 2	LOHC-DFICE	6361	3131	-1825	11251
Ship 3	HFO-ICE	7250	2382	0	20542
Ship 3	LH_2-PEMFC	8820	2156	226	20769
Ship 3	LNH_3-SOFC	9441	3751	-1369	19174
Ship 3	LH_2-DFICE	11473	2791	-409	20134
Ship 3	LNH_3-DFICE	7077	3511	-1129	19413
Ship 3	MeOH-DFICE	5716	3143	-761	19782
Ship 3	LNG-DFICE	6689	2118	264	20807
Ship 3	LOHC-SOFC	13854	7328	-4946	15597
Ship 3	LOHC-DFICE	12100	7541	-5159	15383
Ship 4	HFO-ICE	11781	3966	0	31451
Ship 4	LH_2-PEMFC	15772	3807	159	31610
Ship 4	LNH_3-SOFC	14135	5859	-1893	29558
Ship 4	Battery	88161	78526	-74560	-43109
Ship 4	LH_2-DFICE	19825	4762	-796	30655
Ship 4	LNH_3-DFICE	11707	6075	-2109	29342
Ship 4	MeOH-DFICE	9208	5398	-1432	30019
Ship 4	LNG-DFICE	11018	3522	444	31895
Ship 4	LOHC-SOFC	20853	11735	-7769	23682
Ship 4	LOHC-DFICE	20054	13325	-9360	22091
Ship 5	HFO-ICE	17702	6191	0	48558
Ship 5	LH_2-PEMFC	25470	6156	35	48593
Ship 5	LNH_3-SOFC	24036	10130	-3939	44619
Ship 5	LH_2-DFICE	32511	7746	-1554	47004
Ship 5	LNH_3-DFICE	19375	9863	-3671	44887
Ship 5	MeOH-DFICE	15337	8769	-2578	45980
Ship 5	LNG-DFICE	18273	5740	452	49010

Ship 5	LOHC-SOFC	35742	20515	-14323	34235
Ship 5	LOHC-DFICE	32621	21536	-15345	33213
Ship 6	HFO-ICE	19424	9082	0	71291
Ship 6	LH_2-PEMFC	47311	11208	-2126	69165
Ship 6	LNH_3-SOFC	33820	16365	-7283	64008
Ship 6	LH_2-DFICE	55663	13252	-4170	67120
Ship 6	LNH_3-DFICE	30116	17218	-8136	63155
Ship 6	MeOH-DFICE	22376	15118	-6036	65255
Ship 6	LNG-DFICE	28078	9342	-260	71031
Ship 6	LOHC-SOFC	52338	35673	-26591	44700
Ship 6	LOHC-DFICE	50659	38745	-29663	41628
Ship 7	HFO-ICE	19355	9649	0	95487
Ship 7	LH_2-PEMFC	52292	12361	-2712	92775
Ship 7	LNH_3-SOFC	35220	17175	-7525	87962
Ship 7	LH_2-DFICE	61022	14507	-4858	90629
Ship 7	LNH_3-DFICE	32621	18864	-9215	86272
Ship 7	MeOH-DFICE	24054	16538	-6889	88598
Ship 7	LNG-DFICE	30387	10155	-506	94981
Ship 7	LOHC-SOFC	54152	37492	-27843	67644
Ship 7	LOHC-DFICE	54518	42538	-32889	62598
Ship 8	HFO-ICE	22277	11559	0	123760
Ship 8	LH_2-PEMFC	64015	15072	-3513	120247
Ship 8	LNH_3-SOFC	40897	20823	-9265	114495
Ship 8	LH_2-DFICE	73481	17520	-5961	117799
Ship 8	LNH_3-DFICE	38331	22905	-11346	112414
Ship 8	MeOH-DFICE	27735	20027	-8469	115291
Ship 8	LNG-DFICE	35570	12133	-574	123186
Ship 8	LOHC-SOFC	64809	46560	-35001	88759
Ship 8	LOHC-DFICE	65316	52170	-40612	83148
Ship 9	HFO-ICE	24333	12375	0	128915
Ship 9	LH_2-PEMFC	68276	16055	-3681	125234
Ship 9	LNH_3-SOFC	41534	21196	-8821	120094
Ship 9	LH_2-DFICE	77874	18583	-6209	122706
Ship 9	LNH_3-DFICE	40266	24308	-11933	116982
Ship 9	MeOH-DFICE	28956	21235	-8860	120055
Ship 9	LNG-DFICE	37329	12816	-441	128474
Ship 9	LOHC-SOFC	65515	47379	-35004	93911
Ship 9	LOHC-DFICE	68529	55443	-43068	85847

Unit process data

The unit process data used in this study are shown in below. Inputs, which are supplied from own processes, i.e. processes not already contained in the premise pLCI database, are marked with an asterisk (*).

Table S4.3. Life cycle inventory of transport, container ship, HFO-ICE, size1 (t-nm)

Exchanges	Amount	Unit
Economic flows		
container ship production, HFO-ICE, size1*	1.13E-10	unit

fuel tank, heavy fuel oil*	1.30E-05	kilogram
market for maintenance, container ship	2.27E-11	unit
heavy fuel oil, very low-sulphur*	9.31E-03	kilogram
urea solution, 40 wt%*	1.78E-03	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	4.48E-07	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	4.85E-05	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	3.04E-02	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	1.70E-04	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	1.49E-06	kilogram
Ammonia (to air, non-urban air or from high stacks)	1.35E-06	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	2.20E-05	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	2.63E-06	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	9.33E-05	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	0	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	3.02E-05	kilogram

Table S4.4. Life cycle inventory of container ship production, HFO-ICE, size1 (unit)

Exchanges	Amount	Unit
Economic flows		
hull production, container ship, for DWT 103800*	8.31E-02	unit
propulsion system, HFO-ICE, size1*	1	unit

Table S4.5. Life cycle inventory of hull production, container ship, for DWT 103,800 (unit)

Exchanges	Amount	Unit
Economic flows		
market for reinforcing steel	4.49E+07	kilogram
market for copper, cathode	7.12E+04	kilogram
market for bronze	6.67E+04	kilogram
market for zinc	3.11E+05	kilogram
market for aluminium, wrought alloy	2.22E+04	kilogram
market for cast iron	1.74E+06	kilogram
market for electronic component machinery, unspecified	2.22E+02	unit
market for glass wool mat	3.78E+05	kilogram
market for asbestos, crysotile type	3.78E+05	kilogram
market for sanitary ceramics	3.78E+05	kilogram
market for polypropylene, granulate	1.07E+05	kilogram
market for polyethylene, high density, granulate	1.07E+05	kilogram
market for polystyrene, expandable	1.07E+05	kilogram
market for polyvinylidenchloride, granulate	1.07E+05	kilogram
market for polyurethane, flexible foam	1.07E+05	kilogram
market for glued laminated timber, average glue mix	9.25E+02	cubic meter
market for alkyd paint, white, without solvent, in 60% solution state	2.22E+05	kilogram
market for welding, arc, steel	2.79E+07	meter
market for welding, gas, steel	1.77E+08	meter
market group for electricity, medium voltage	1.48E+07	kilowatt hour
market group for heat, district or industrial, other than natural gas	1.70E+07	megajoule
market for inert waste, for final disposal	3.78E+05	kilogram

market for scrap aluminium	2.22E+04	kilogram
market for scrap copper	7.12E+04	kilogram
market for scrap steel	4.49E+07	kilogram
market for waste electric and electronic equipment	5.56E+05	kilogram
market for waste emulsion paint	2.14E+05	kilogram
market for waste mineral wool	7.56E+05	kilogram
market for waste plastic, mixture	5.34E+05	kilogram
bronze scrap, post-consumer, Recycled Content cut-off	6.67E+04	kilogram
iron scrap, unsorted, Recycled Content cut-off	1.74E+06	kilogram
zinc scrap, post-consumer, Recycled Content cut-off	3.11E+05	kilogram
Environmental flows		
NMVOC, non-methane volatile organic compounds, unspecified origin (to air)	1.82E+05	kilogram
Hydrocarbons, unspecified (to water)	4.00E+03	kilogram
Hydrocarbons, unspecified (to soil)	4.00E+03	kilogram

Data source: Jain et al.[167] and Notten et al.[168]

Table S4.6. Life cycle inventory of propulsion system, HFO-ICE, size1 (unit)

Exchanges	Amount	Unit
Economic flows		
marine engine, CI, ICE*	7.95	MW
market for generator, 200kW electrical	5	unit
marine engine, CI, ICE*	1	MW
market for control cabinet, heat and power co-generation unit, 160kW electrical	18	unit
SCR*	8.95	MW
market for oil boiler, 100kW	2.5	unit

Table S4.7. Life cycle inventory of marine engine, CI, ICE (MW)

Exchanges	Amount	Unit
Economic flows		
market for steel, chromium steel 18/8	1.17E+04	kilogram
market for cast iron	1.34E+04	kilogram
market for aluminium, primary, ingot	2.33E+03	kilogram
market for zinc	5.84E+01	kilogram
market for wire drawing, copper	2.92E+01	kilogram
market for lead	2.92E+01	kilogram
market for nylon 6	2.63E+02	kilogram
market for silicone product	2.63E+02	kilogram
market for alkyd paint, white, without solvent, in 60% solution state	2.63E+02	kilogram
market for lubricating oil	8.76E+02	kilogram
market group for electricity, medium voltage	1.08E+04	kilowatt hour

Data source: Kanchiralla et al.[26]

Table S4.8. Life cycle inventory of SCR (MW)

Exchanges	Amount	Unit
Economic flows		
market for steel, chromium steel 18/8	942.08	kilogram
market for titanium dioxide	4.72	kilogram

Data source: Kanchiralla et al.[25]

Table S4.9. Life cycle inventory of fuel tank, heavy fuel oil (kg)

Exchanges	Amount	Unit
Economic flows		
market for steel, unalloyed	1.16	kilogram
market for sheet rolling, steel	1.16	kilogram
market for scrap steel	-2.78E-01	kilogram
market for alkyd paint, white, without solvent, in 60% solution state	1.18E-01	kilogram
market group for electricity, low voltage	4.70E-01	kilowatt hour

Data source: Dlamini et al.[234]

Table S4.10. Life cycle inventory of marine gas oil, very low-sulphur (kg)

Exchanges	Amount	Unit
Economic flows		
market group for diesel, low-sulfur	1.00	kilogram
market group for electricity, low voltage	5.46E-03	kilowatt hour
market for petroleum coke	9.20E-05	kilogram
market for hydrogen, gaseous	8.92E-03	kilogram
Environmental flows		
Hydrogen sulfide (to air)	5.63E-03	kilogram

Data source: Silva[174]

Table S4.11. Life cycle inventory of heavy fuel oil, very low-sulphur (kg)

Exchanges	Amount	Unit
Economic flows		
market for heavy fuel oil	1.00	kilogram
market group for electricity, low voltage	5.46E-03	kilowatt hour
market for petroleum coke	9.20E-05	kilogram
market for hydrogen, gaseous	8.92E-03	kilogram
Environmental flows		
Hydrogen sulfide (to air)	5.63E-03	kilogram

Data source: Silva[174]

Table S4.12. Life cycle inventory of urea solution, 40 wt% (kg)

Exchanges	Amount	Unit
Economic flows		
market for urea	0.4	kilogram
market for water, deionised	0.6	kilogram

Data source: Brynolf et al.[262]

Table S4.13. Life cycle inventory of transport, container ship, liquid H_2-PEMFC, size1 (t-nm)

Exchanges	Amount	Unit
Economic flows		
container ship production, liquid H_2-PEMFC, size1*	1.09E-10	unit
fuel tank, cryogenic, liquid hydrogen*	9.43E-06	kilogram
market for maintenance, container ship	2.18E-11	unit
liquid hydrogen production*	3.05E-03	kilogram
market group for electricity, low voltage	7.14E-05	kilowatt hour

Table S4.14. Life cycle inventory of container ship production, liquid H_2-PEMFC, size1 (unit)

Exchanges	Amount	Unit
Economic flows		

hull production, container ship, for DWT 103800*	0.083	unit
propulsion system, liquid H_2-PEMFC, size1*	1	unit

Table S4.15. Life cycle inventory of propulsion system, liquid H_2-PEMFC, size1 (unit)

Exchanges	Amount	Unit
Economic flows		
PEMFC*	48.65	MW
market for converter, for electric passenger car	460.80	kilogram
market for inverter, 500kW	12.40	unit
market for battery, Li-ion, NMC111, rechargeable, prismatic	65.11	kilogram
motor drive*	8.28	MW
market for marine electric motor	21.68	unit
market for control cabinet, heat and power co-generation unit, 160kW electrical	178.88	unit
electric boiler, 100kW*	2.50	unit
Reliquefaction plant, 1 kg/h capacity*	2.89	unit

Table S4.16. Life cycle inventory of PEMFC (MW)

Exchanges	Amount	Unit
Economic flows		
market for pump, 40W	3000	unit
market for acrylonitrile	0.21	kilogram
market for air filter, in exhaust air valve	13.00	unit
market for aluminium, cast alloy	268.25	kilogram
market for cable, three-conductor cable	16000	meter
market for carbon black	0.19	kilogram
market for steel, chromium steel 18/8	40	kilogram
market for cobalt oxide	0.02	kilogram
market for wire drawing, copper	6	kilogram
market for electronics, for control units	34	kilogram
market for epoxy resin, liquid	70.20	kilogram
market for ethylene glycol	10	kilogram
market for extrusion of plastic sheets and thermoforming, inline	12.13	kilogram
market for formaldehyde	0.01	kilogram
market for glass fibre	20	kilogram
market for polyethylene, high density, granulate	10.01	kilogram
market for hydrochloric acid, without water, in 30% solution state	0.08	kilogram
market for steel, low-alloyed	83	kilogram
market for methanol	0.63	kilogram
market for methyl acrylate	0.01	kilogram
market for nitric acid, without water, in 50% solution state	0.19	kilogram
market for nylon 6	30	kilogram
market for permanent magnet, for electric motor	10	kilogram
market for extrusion, plastic pipes	30	kilogram
market for platinum	0.02	kilogram
market for polyphenylene sulfide	10	kilogram
market for polypropylene, granulate	50	kilogram
market for polyurethane, rigid foam	19	kilogram
treatment of automobile catalyst	0.05	kilogram

market for silicone product	30	kilogram
market for sodium hydroxide, without water, in 50% solution state	0.01	kilogram
market for sodium nitrate	0.19	kilogram
market for spent solvent mixture	0.40	kilogram
market for sulfur trioxide	1.29	kilogram
market for tetrafluoroethylene	13.18	kilogram
market for titanium	240	kilogram
market for water, deionised	0.67	kilogram
market for heat, district or industrial, natural gas	765.37	megajoule
market group for electricity, medium voltage	706.32	kilowatt hour

Data source: Usai et al.[213]

Table S4.17. Life cycle inventory of motor drive (MW)

Exchanges	Amount	Unit
Economic flows		
market for aluminium, primary, ingot	36.2	kilogram
market for copper, cathode	174.7	kilogram
market for kraft paper	0.3	kilogram
market for polyester-complexed starch biopolymer	73.45	kilogram
market for steel, low-alloyed	315.45	kilogram
market for brass	9.95	kilogram
market for sanitary ceramics	3.35	kilogram
market for chromium	0.05	kilogram
market for epoxy resin insulator, SiO2	3.8	kilogram
market for molybdenum	1.6	kilogram
market for nickel, class 1	0.1	kilogram
market for glass fibre reinforced plastic, polyester resin, hand lay-up	2.85	kilogram
market for glass fibre	0.1	kilogram
market for vegetable oil, refined	12.1	kilogram
market for pig iron	5.4	kilogram
market for silicone product	0.2	kilogram
market for silver	0.05	kilogram
market for solder, bar, Sn63Pb37, for electronics industry	0.85	kilogram
market for zinc	1.5	kilogram
market group for electricity, medium voltage	40	kilowatt hour

Data source: Westberg[265] and ABB[183]

Table S4.18. Life cycle inventory of electric boiler, 100kW (unit)

Exchanges	Amount	Unit
Economic flows		
market group for electricity, medium voltage	7.50E+02	kilowatt hour
market for heat, district or industrial, other than natural gas	1.26E+03	megajoule
market for glass fibre	3.15	kilogram
market for stone wool	1.92	kilogram
market for sanitary ceramics	4.79	kilogram
market for expanded vermiculite	1.16E+01	kilogram
market for brass	1.59E+01	kilogram
market for cast iron	5.40E+01	kilogram
market for steel, low-alloyed, hot rolled	9.36E+01	kilogram

market for zinc coat, coils	6.96E+01	square meter
market for steel, chromium steel 18/8	6.23E+01	kilogram
market for steel, low-alloyed	8.77E+01	kilogram
market for steel, unalloyed	6.26E+01	kilogram
market for cable, unspecified	4.45E+01	kilogram
market for electric connector, wire clamp	4.25	kilogram
market for electronics, for control units	3.29	kilogram
market for printed wiring board, surface mounted, unspecified, Pb free	6.30	kilogram
market for resistor, wirewound, through-hole mounting	1.01E+01	kilogram
market for nylon 6-6	9.18E-01	kilogram
market for polyvinylchloride, bulk polymerised	3.29E-01	kilogram
market for polyethylene, low density, granulate	6.58E-01	kilogram
market for silicone product	4.93E-01	kilogram
market for alkyd paint, white, without solvent, in 60% solution state	3.42	kilogram
market for coating powder	8.90E-01	kilogram
market for inert waste, for final disposal	4.42E+01	kilogram
iron scrap, unsorted, Recycled Content cut-off	1.85E+02	kilogram
market for scrap steel	1.85E+02	kilogram
market for electronics scrap from control units	7.56E-01	kilogram
market for used cable	3.03E+01	kilogram
market for waste electric wiring	3.40E-01	kilogram
market for waste polyethylene	1.32E-03	kilogram
market for waste polyvinylchloride	2.50E-01	kilogram
market for waste plastic, mixture	1.41	kilogram
market for waste paint on metal	4.32	kilogram

Data source: Abbas[232]

Table S4.19. Life cycle inventory of reliquefaction plant, 1 kg/h capacity (unit)

Exchanges	Amount	Unit
Economic flows		
market for steel, chromium steel 18/8	16.5	kilogram
market for cast iron	6	kilogram
market for steel, unalloyed	5.4	kilogram
market for aluminium, primary, ingot	2.1	kilogram
market for casting, steel, lost-wax	21.9	kilogram
market for casting, aluminium, lost-wax	2.1	kilogram
market group for electricity, medium voltage	11.34	kilowatt hour
market for scrap steel	-21.90	kilogram
market for scrap aluminium	-2.10	kilogram
market for iron scrap, unsorted	-6.00	kilogram
market for natural gas, liquefied	0.01	cubic meter
market for nitrogen, liquid	4.18	kilogram

Data source: Park et al.[275]

Table S4.20. Life cycle inventory of fuel tank, cryogenic, liquid hydrogen (kg)

Exchanges	Amount	Unit
Economic flows		
market for compressed air, 1000 kPa gauge	3.76E-04	cubic meter
market group for electricity, low voltage	5.98E-01	kilowatt hour

market for steel, chromium steel 18/8	9.74E-01	kilogram
market for aluminium alloy, AlMg3	2.59E-02	kilogram

Data source: Abbas[235]

Table S4.21. Life cycle inventory of liquid hydrogen production (kg)

Exchanges	Amount	Unit
Economic flows		
market for hydrogen, gaseous, 25-30 bar	1.0162	kilogram
hydrogen liquefaction plant construction*	3.43E-09	unit
market group for electricity, low voltage	10.5	kilowatt hour
Environmental flows		
Hydrogen (to air)	0.0162	kilogram

Data source: Al Ghafri et al.[176] and Wulf and Zapp[175]

Table S4.22. Life cycle inventory of hydrogen liquefaction plant construction (unit)

Exchanges	Amount	Unit
Economic flows		
market for steel, chromium steel 18/8	5.95E+05	kilogram
market for reinforcing steel	3.80E+05	kilogram
market group for concrete, normal	2.03E+04	cubic meter
market for copper, cathode	1.50E+05	kilogram
market for aluminium alloy, AlMg3	1.40E+05	kilogram

Data source: Al Ghafri et al.[176]

Table S4.23. Life cycle inventory of transport, container ship, liquid NH_3-SOFC, size1 (t-nm)

Exchanges	Amount	Unit
Economic flows		
container ship production, liquid NH_3-SOFC, size1*	1.17E-10	unit
fuel tank, cryogenic, liquid ammonia*	2.57E-06	kilogram
market for maintenance, container ship	2.35E-11	unit
ammonia production, liquid*	1.73E-02	kilogram
market group for electricity, low voltage	2.30E-04	kilowatt hour
Environmental flows		
Nitrogen oxides (to air, non-urban air or from high stacks)	1.66E-07	kilogram

Table S4.24. Life cycle inventory of container ship production, liquid NH_3-SOFC, size1 (unit)

Exchanges	Amount	Unit
Economic flows		
hull production, container ship, for DWT 103800*	0.083	unit
propulsion system, liquid NH_3-SOFC, size1*	1	unit

Table S4.25. Life cycle inventory of propulsion system, liquid NH_3-SOFC, size1 (unit)

Exchanges	Amount	Unit
Economic flows		
SOFC*	48.65	MW
market for converter, for electric passenger car	506.25	kilogram
market for inverter, 500kW	12.40	unit
market for battery, Li-ion, NMC111, rechargeable, prismatic	194.04	kilogram
motor drive*	8.28	MW
market for marine electric motor	21.68	unit

market for control cabinet, heat and power co-generation unit, 160kW electrical	178.88	unit
electric boiler, 100kW*	2.50	unit
Reliquefaction plant, 1 kg/h capacity*	1.51	unit

Table S4.26. Life cycle inventory of SOFC (MW)

Exchanges	Amount	Unit
Economic flows		
market for butyldiglycol acetate	50.52	kilogram
market for aluminium, primary, ingot	4000	kilogram
market for methyl methacrylate	135.10	kilogram
market for carbon black	87.60	kilogram
market for cobalt oxide	45.77	kilogram
market for wire drawing, copper	4000	kilogram
market for lanthanum oxide	45.19	kilogram
market for carboxymethyl cellulose, powder	89.04	kilogram
market for butyl acetate	404.95	kilogram
market for nickel, class 1	1136	kilogram
market for ethylene glycol	132	kilogram
market for strontium carbonate	7.04	kilogram
market for steel, chromium steel 18/8	31000	kilogram
market for yttrium oxide	53.43	kilogram
market for zirconium oxide	357.57	kilogram
market group for electricity, medium voltage	7577.78	kilowatt hour
Environmental flows		
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	432	kilogram

Data source: Kanchiralla et al.[26]

Table S4.27. Life cycle inventory of fuel tank, cryogenic, liquid ammonia (kg)

Exchanges	Amount	Unit
Economic flows		
market for steel, low-alloyed	0.55	kilogram
market for steel, unalloyed	0.56	kilogram
market for sheet rolling, steel	1.11	kilogram
market for scrap steel	-0.11	kilogram

Data source: Ryste[237] and Cryocan[238]

Table S4.28. Life cycle inventory of ammonia production, liquid (kg)

Exchanges	Amount	Unit
Economic flows		
market for hydrogen, gaseous, 25-30 bar	1.76E-01	kilogram
nitrogen, gaseous, from cryogenic distillation, without compression*	8.15E-01	kilogram
ammonia synthesis catalyst*	5.15E-05	kilogram
market for chemical factory, organics	3.29E-10	unit
market group for electricity, low voltage	1.44	kilowatt hour
treatment of inert waste, inert material landfill	5.15E-05	kilogram
Environmental flows		
Water, cooling, unspecified natural origin (from natural resource)	1.49E-01	cubic meter
Hydrogen (to air)	7.67E-04	kilogram
Ammonia (to air)	1.63E-03	kilogram

Nitrogen oxides (to air)	1.00E-03	kilogram
Water (to air)	4.76E-02	cubic meter
Water (to water)	1.01E-01	cubic meter

Data source: D'Angelo et al.[54]

Table S4.29. Life cycle inventory of nitrogen, gaseous, from cryogenic distillation, without compression (kg)

Exchanges	Amount	Unit
Economic flows		
market for air separation facility	4.43E-10	unit
Environmental flows		
Water, cooling, unspecified natural origin (from natural resource)	4.00E-03	cubic meter
Water (to water)	2.45E-03	cubic meter

Data source: D'Angelo et al.[54]

Table S4.30. Life cycle inventory of ammonia synthesis catalyst (kg)

Exchanges	Amount	Unit
Economic flows		
market for magnetite	9.17E-01	kilogram
market for lime	3.00E-02	kilogram
market for zeolite, powder	5.25E-02	kilogram
market group for electricity, low voltage	1.78	kilowatt hour

Data source: D'Angelo et al.[54]

Table S4.31. Life cycle inventory of transport, container ship, battery, size1 (t-nm)

Exchanges	Amount	Unit
Economic flows		
container ship production, battery, size1*	1.78E-10	unit
market for maintenance, container ship	3.56E-11	unit
market group for electricity, low voltage	9.51E-02	kilowatt hour

Table S4.32. Life cycle inventory of container ship production, battery, size1 (unit)

Exchanges	Amount	Unit
Economic flows		
hull production, container ship, for DWT 103800*	8.31E-02	unit
propulsion system, battery, size1*	1	unit

Table S4.33. Life cycle inventory of propulsion system, battery, size1 (unit)

Exchanges	Amount	Unit
Economic flows		
market for converter, for electric passenger car	437.85	kilogram
market for inverter, 500kW	12.40	unit
market for battery, Li-ion, NMC111, rechargeable, prismatic	52814.04	kilogram
motor drive*	8.28	MW
market for marine electric motor	21.68	unit
market for control cabinet, heat and power co-generation unit, 160kW electrical	178.88	unit
electric boiler, 100kW	2.50	unit

Table S4.34. Life cycle inventory of transport, container ship, liquid H_2-DFICE, size1 (t-nm)

Exchanges	Amount	Unit
Economic flows		

container ship production, liquid H_2-DFICE, size1*	1.12E-10	unit
fuel tank, heavy fuel oil*	4.84E-08	kilogram
fuel tank, cryogenic, liquid hydrogen*	9.46E-06	kilogram
market for maintenance, container ship	2.25E-11	unit
liquid hydrogen production*	3.06E-03	kilogram
marine gas oil, very low-sulphur*	4.52E-04	kilogram
urea solution, 40 wt%	1.60E-03	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	2.12E-08	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	8.31E-06	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	1.90E-03	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	1.56E-04	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	7.51E-08	kilogram
Ammonia (to air, non-urban air or from high stacks)	1.08E-06	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	1.23E-06	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	1.31E-07	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	4.43E-06	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	0	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	1.51E-06	kilogram

Table S4.35. Life cycle inventory of propulsion system, liquid H_2-DFICE, size1 (unit)

Exchanges	Amount	Unit
Economic flows		
hull production, container ship, for DWT 103800*	8.31E-02	unit
propulsion system, liquid H_2-DFICE, size1*	1	unit

Table S4.36. Life cycle inventory of propulsion system, liquid H_2-DFICE, size1 (unit)

Exchanges	Amount	Unit
Economic flows		
marine engine, CI, ICE*	7.95	MW
market for generator, 200kW electrical	5	unit
marine engine, CI, ICE*	1	MW
market for control cabinet, heat and power co-generation unit, 160kW electrical	18	unit
SCR*	7.95	MW
electric boiler, 100kW*	2.5	unit
Reliquefaction plant, 1 kg/h capacity*	2.82	unit

Table S4.37. Life cycle inventory of transport, container ship, liquid NH_3-DFICE, size1 (t-nm)

Exchanges	Amount	Unit
Economic flows		
container ship production, liquid NH_3-DFICE, size1*	1.13E-10	unit
fuel tank, heavy fuel oil*	5.08E-08	kilogram
fuel tank, cryogenic, liquid ammonia*	3.07E-06	kilogram
market for maintenance, container ship	2.26E-11	unit
ammonia production, liquid*	2.07E-02	kilogram
marine gas oil, very low-sulphur*	4.75E-04	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	2.22E-08	kilogram

Carbon monoxide, fossil (to air, non-urban air or from high stacks)	8.73E-06	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	1.50E-03	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	1.70E-04	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	6.94E-07	kilogram
Ammonia (to air, non-urban air or from high stacks)	1.90E-06	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	1.29E-06	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	1.38E-07	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	4.65E-06	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	0	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	1.58E-06	kilogram

Table S4.38. Life cycle inventory of container ship production, liquid NH_3-DFICE, size1 (unit)

Exchanges	Amount	Unit
Economic flows		
hull production, container ship, for DWT 103800*	8.31E-02	unit
propulsion system, liquid NH_3-DFICE, size1*	1	unit

Table S4.39. Life cycle inventory of propulsion system, liquid NH_3-DFICE, size1 (unit)

Exchanges	Amount	Unit
Economic flows		
marine engine, CI, ICE*	7.95	MW
market for generator, 200kW electrical	5	unit
marine engine, CI, ICE*	1	MW
market for control cabinet, heat and power co-generation unit, 160kW electrical	18	unit
SCR*	8.95	MW
electric boiler, 100kW*	2.5	unit
Reliquefaction plant, 1 kg/h capacity*	1.88	unit

Table S4.40. Life cycle inventory of transport, container ship, MeOH-DFICE, size1 (t-nm)

Exchanges	Amount	Unit
Economic flows		
container ship production, MeOH-DFICE, size1*	1.12E-10	unit
fuel tank, heavy fuel oil*	4.85E-08	kilogram
fuel tank, methanol*	2.28E-06	kilogram
market for maintenance, container ship	2.25E-11	unit
methanol production, CO_2 from DAC*	1.83E-02	kilogram
marine gas oil, very low-sulphur*	4.53E-04	kilogram
urea solution, 40 wt%*	1.67E-03	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	2.12E-08	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	2.14E-04	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	2.76E-02	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	1.69E-04	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	7.52E-08	kilogram
Ammonia (to air, non-urban air or from high stacks)	1.24E-06	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	1.10E-06	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	5.53E-07	kilogram

Sulfur dioxide (to air, non-urban air or from high stacks)	4.44E-06	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	9.92E-06	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	6.36E-06	kilogram

Table S4.41. Life cycle inventory of container ship production, MeOH-DFICE, size1 (unit)

Exchanges	Amount	Unit
Economic flows		
hull production, container ship, for DWT 103800*	8.31E-02	unit
propulsion system, MeOH-DFICE, size1*	1	unit

Table S4.42. Life cycle inventory of propulsion system, MeOH-DFICE, size1 (unit)

Exchanges	Amount	Unit
Economic flows		
marine engine, CI, ICE*	7.95	MW
market for generator, 200kW electrical	5	unit
marine engine, CI, ICE*	1	MW
market for control cabinet, heat and power co-generation unit, 160kW electrical	18	unit
SCR*	8.95	MW
electric boiler, 100kW*	2.5	unit

Table S4.43. Life cycle inventory of fuel tank, methanol (kg)

Exchanges	Amount	Unit
Economic flows		
market for steel, unalloyed	1.16	kilogram
market for sheet rolling, steel	1.16	kilogram
market for scrap steel	-2.78E-01	kilogram
market for epoxy resin, liquid	1.18E-01	kilogram
market group for electricity, low voltage	4.70E-01	kilowatt hour

Data source: Dlamini et al.[234] and CGH[278]

Table S4.44. Life cycle inventory of methanol production, CO_2 from DAC (kg)

Exchanges	Amount	Unit
Economic flows		
CO_2 from DAC*	1.51	kilogram
market for hydrogen, gaseous, 25-30 bar	2.08E-01	kilogram
market group for electricity, high voltage	2.72E-01	kilowatt hour
market for steel, chromium steel 18/8	1.53E-04	kilogram
market for aluminium oxide, non-metallurgical	1.20E-05	kilogram
market for copper oxide	6.20E-05	kilogram
market for zinc oxide	2.90E-05	kilogram
market for heat, from steam, in chemical industry	4.40E-01	megajoule
market for wastewater, average	5.71E-04	cubic meter
Environmental flows		
Carbon dioxide, fossil (to air)	7.70E-02	kilogram
Methanol (to air)	1.00E-02	kilogram
Nitrogen oxides (to air)	1.78E-06	kilogram

Data source: González-Garay et al.[177]

Table S4.45. Life cycle inventory of CO_2 from DAC (kg)

Exchanges	Amount	Unit

Economic flows		
market group for electricity, high voltage	0.366	kilowatt hour
market group for tap water	3.105	kilogram
market group for natural gas, high pressure	0.1895	cubic meter
market for calcium carbonate, precipitated	0.02	kilogram
Environmental flows		
Carbon dioxide, in air	1	kilogram

Data source: Keith et al.[178]

Table S4.46. Life cycle inventory of transport, container ship, LNG-DFICE, size1 (unit)

Exchanges	Amount	Unit
Economic flows		
container ship production, LNG-DFICE, size1*	1.11E-10	unit
fuel tank, heavy fuel oil*	9.23E-09	kilogram
fuel tank, LNG*	2.91E-06	kilogram
market for maintenance, container ship	2.23E-11	unit
natural gas, liquid*	7.44E-03	kilogram
marine gas oil, very low-sulphur*	8.62E-05	kilogram
urea solution, 40 wt%*	1.59E-03	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	2.23E-04	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	5.88E-05	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	2.04E-02	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	1.55E-04	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	7.07E-07	kilogram
Ammonia (to air, non-urban air or from high stacks)	1.06E-06	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	2.28E-05	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	1.56E-07	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	8.44E-07	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	0	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	1.80E-06	kilogram

Table S4.47. Life cycle inventory of container ship production, LNG-DFICE, size1 (unit)

Exchanges	Amount	Unit
Economic flows		
hull production, container ship, for DWT 103800*	8.31E-02	unit
propulsion system, LNG-DFICE, size1*	1	unit

Table S4.48. Life cycle inventory of propulsion system, LNG-DFICE, size1 (unit)

Exchanges	Amount	Unit
Economic flows		
marine engine, CI, ICE*	7.95	MW
market for generator, 200kW electrical	5	unit
marine engine, CI, ICE*	1	MW
market for control cabinet, heat and power co-generation unit, 160kW electrical	18	unit
SCR*	7.95	MW
market for gas boiler	25	unit
Reliquefaction plant, 1 kg/h capacity*	2.24	unit

Table S4.49. Life cycle inventory of natural gas, liquid (kg)

Exchanges	Amount	Unit
Economic flows		
market for natural gas, liquefied	1.26	cubic meter

Table S4.50. Life cycle inventory of fuel tank, LNG (kg)

Exchanges	Amount	Unit
Economic flows		
market for steel, chromium steel 18/8	5.53E-01	kilogram
market for steel, low-alloyed	5.58E-01	kilogram
market for sheet rolling, steel	1.11	kilogram
market for scrap steel	-1.11E-01	kilogram

Data source: Ryste[237]

Table S4.51. Life cycle inventory of transport, container ship, BIO-LNG-DFICE, size1 (t-nm)

Exchanges	Amount	Unit
Economic flows		
container ship production, LNG-DFICE, size1*	1.11E-10	unit
fuel tank, heavy fuel oil*	9.23E-09	kilogram
fuel tank, LNG*	2.91E-06	kilogram
market for maintenance, container ship	2.23E-11	unit
natural gas, liquid, woody biomass*	7.44E-03	kilogram
marine gas oil, very low-sulphur*	8.62E-05	kilogram
urea solution, 40 wt%*	1.59E-03	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	2.23E-04	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	5.88E-05	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	2.04E-02	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	1.55E-04	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	7.07E-07	kilogram
Ammonia (to air, non-urban air or from high stacks)	1.06E-06	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	2.28E-05	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	1.56E-07	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	8.44E-07	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	0	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	1.80E-06	kilogram

Table S4.52. Life cycle inventory of natural gas, liquid, woody biomass (kg)

Exchanges	Amount	Unit
Economic flows		
biomethane production, high pressure from synthetic gas, wood, fluidised technology	1.33	cubic meter
market group for electricity, low voltage	1.33E-02	kilowatt hour

Data source: Gustafsson et al.[267]

Table S4.53. Life cycle inventory of transport, container ship, LOHC-SOFC, size1 (1 t-nm

Exchanges	Amount	Unit
Economic flows		
container ship production, LOHC-SOFC, size1*	1.23E-10	unit

fuel tank, heavy fuel oil	4.43E-06	kilogram
market for maintenance, container ship	2.48E-11	unit
dehydrogenation of perhydro-dibenzyltoluene (H18-DBT) for releasing hydrogen*	2.82E-03	kilogram
market group for electricity, low voltage	2.43E-04	kilowatt hour

Table S4.54. Life cycle inventory of container ship production, LOHC-SOFC, size1 (1 unit)

Exchanges	Amount	Unit
Economic flows		
hull production, container ship, for DWT 103800*	8.31E-02	unit
propulsion system, LOHC-SOFC, size1*	1	unit

Table S4.55. Life cycle inventory of propulsion system, LOHC-SOFC, size1 (1 unit)

Exchanges	Amount	Unit
Economic flows		
SOFC*	48.65	MW
market for converter, for electric passenger car	506.25	kilogram
market for inverter, 500kW	12.4	unit
market for battery, Li-ion, NMC111, rechargeable, prismatic	194.043	kilogram
motor drive*	8.28	MW
market for marine electric motor	21.681	unit
market for control cabinet, heat and power co-generation unit, 160kW electrical	178.875	unit
LOHC reactor*	6.49	MW H_2
electric boiler, 100kW*	2.5	unit

Table S4.56. Life cycle inventory of LOHC reactor (1 MW H_2)

Exchanges	Amount	Unit
Economic flows		
market for aluminium oxide, metallurgical	257.576	kilogram
market for copper oxide	1030.303	kilogram
market for zinc oxide	429.293	kilogram
market for steel, chromium steel 18/8	15282.828	kilogram

Data source: Adapted from the ammonia cracker in Kanchiralla et al.[25]

Table S4.57. Life cycle inventory of dehydrogenation of perhydro-dibenzyltoluene (H18-DBT) for releasing hydrogen (1 kg)

Exchanges	Amount	Unit
Economic flows		
hydrogenation of dibenzyltoluene (H0-DBT) for storing hydrogen*	1	kilogram
market for platinum	1.61E-07	kilogram
market for aluminium oxide, non-metallurgical	3.21E-05	kilogram

Data source: Wulf et al.[323]

Table S4.58. Life cycle inventory of hydrogenation of dibenzyltoluene (H0-DBT) for storing hydrogen (1 kg)

Exchanges	Amount	Unit
Economic flows		
dibenzyltoluene (H0-DBT) production*	1.51E-02	kilogram
market for hydrogen, gaseous, 25-30 bar*	1.01	kilogram
market for platinum	1.61E-07	kilogram
market for aluminium oxide, non-metallurgical	3.21E-05	kilogram
market for chemical factory	3.20E-04	kilogram

market group for electricity, low voltage	0.666	kilowatt hour
Environmental flows		
Hydrogen (to air)	0.01	kilogram
Heat, waste (to air)	2.42	megajoule

Data source: Wulf et al.[323]

Table S4.59. Life cycle inventory of dibenzyltoluene (H0-DBT) production (1 kg)

Exchanges	Amount	Unit
Economic flows		
market for water, decarbonised	1.20	kilogram
market for toluene, liquid	1.03	kilogram
market for chlorine, gaseous	0.26	kilogram
market for iron(III) chloride, without water, in 14% iron solution state	2.00E-06	kilogram
market group for electricity, low voltage	42.1	kilowatt hour
market for heat, from steam, in chemical industry	2.70	megajoule
market for transport, freight, lorry >32 metric ton, EURO6	0.20	ton kilometer

Data source: Wulf et al.[323]

Table S4.60. Life cycle inventory of transport, container ship, LOHC-DFICE, size1 (1 t-nm)

Exchanges	Amount	Unit
Economic flows		
container ship production, LOHC-DFICE, size1*	1.20E-10	unit
fuel tank, heavy fuel oil*	5.17E-08	kilogram
fuel tank, heavy fuel oil*	5.13E-06	kilogram
market for maintenance, container ship	2.40E-11	unit
dehydrogenation of perhydro-dibenzyltoluene (H18-DBT) for releasing hydrogen*	3.27E-03	kilogram
marine gas oil, very low-sulphur*	4.83E-04	kilogram
urea solution, 40 wt%*	1.72E-03	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	2.26E-08	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	8.88E-06	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	2.03E-03	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	1.67E-04	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	8.02E-08	kilogram
Ammonia (to air, non-urban air or from high stacks)	1.15E-06	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	1.32E-06	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	1.40E-07	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	4.73E-06	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	0	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	1.61E-06	kilogram

Table S4.61. Life cycle inventory of container ship production, LOHC-DFICE, size1 (1 unit)

Exchanges	Amount	Unit
Economic flows		
hull production, container ship, for DWT 103800*	8.31E-02	unit
propulsion system, LOHC-DFICE, size1*	1	unit

Table S4.62. Life cycle inventory of propulsion system, LOHC-DFICE, size1 (1 unit)

Exchanges	Amount	Unit

Economic flows		
marine engine, CI, ICE*	7.95	MW
market for generator, 200kW electrical	5	unit
marine engine, CI, ICE*	1	MW
market for control cabinet, heat and power co-generation unit, 160kW electrical	18	unit
LOHC reactor*	8.14	MW H_2
SCR*	7.95	MW
electric boiler, 100kW*	2.5	unit

Table S4.63. Life cycle inventory of transport, container ship, HFO-ICE, size2 (t-nm)

Exchanges	Amount	Unit
Economic flows		
container ship production, HFO-ICE, size2*	4.86E-11	unit
fuel tank, heavy fuel oil*	1.72E-05	kilogram
market for maintenance, container ship	2.33E-11	unit
heavy fuel oil, very low-sulphur*	8.51E-03	kilogram
urea solution, 40 wt%*	1.56E-03	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	4.09E-07	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	4.43E-05	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	2.77E-02	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	1.51E-04	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	1.36E-06	kilogram
Ammonia (to air, non-urban air or from high stacks)	1.23E-06	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	2.01E-05	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	2.40E-06	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	8.53E-05	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	0	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	2.76E-05	kilogram

Table S4.64. Life cycle inventory of container ship production, HFO-ICE, size2 (1 t-nm)

Exchanges	Amount	Unit
Economic flows		
hull production, container ship, for DWT 103800*	1.99E-01	unit
propulsion system, HFO-ICE, size2*	1	unit

Table S4.65. Life cycle inventory of propulsion system, HFO-ICE, size2 (1 unit)

Exchanges	Amount	Unit
Economic flows		
marine engine, CI, ICE*	16.52	MW
market for generator, 200kW electrical	17.72	unit
marine engine, CI, ICE*	3.54	MW
market for control cabinet, heat and power co-generation unit, 160kW electrical	63.94	unit
SCR*	20.06	MW
market for oil boiler, 100kW	3.4	unit

Table S4.66. Life cycle inventory of transport, container ship, liquid H_2-PEMFC, size2 (1 t-nm)

Exchanges	Amount	Unit

Economic flows		
container ship production, liquid H_2-PEMFC, size2*	4.71E-11	unit
fuel tank, cryogenic, liquid hydrogen*	2.61E-05	kilogram
market for maintenance, container ship	2.26E-11	unit
liquid hydrogen production*	2.74E-03	kilogram
market group for electricity, low voltage	2.22E-05	kilowatt hour

Table S4.67. Life cycle inventory of container ship production, liquid H_2-PEMFC, size2 (1 unit)

Exchanges	Amount	Unit
Economic flows		
hull production, container ship, for DWT 103800*	1.99E-01	unit
propulsion system, liquid H_2-PEMFC, size2*	1	unit

Table S4.68. Life cycle inventory of propulsion system, liquid H_2-PEMFC, size2 (1 unit)

Exchanges	Amount	Unit
Economic flows		
PEMFC	107.5	MW
market for converter, for electric passenger car	1017.9	kilogram
market for inverter, 500kW	38.2	unit
market for battery, Li-ion, NMC111, rechargeable, prismatic	142.98	kilogram
motor drive	17.2	MW
market for marine electric motor	45.036	unit
market for control cabinet, heat and power co-generation unit, 160kW electrical	394.875	unit
electric boiler, 100kW	3.4	unit
Reliquefaction plant, 1 kg/h capacity	18.42	unit

Table S4.69. Life cycle inventory of transport, container ship, liquid NH_3-SOFC, size2 (1 t-nm)

Exchanges	Amount	Unit
Economic flows		
container ship production, liquid NH_3-SOFC, size2*	5.06E-11	unit
fuel tank, cryogenic, liquid ammonia*	6.76E-06	kilogram
market for maintenance, container ship	2.43E-11	unit
ammonia production, liquid*	1.48E-02	kilogram
market group for electricity, low voltage	7.14E-05	kilowatt hour
Environmental flows		
Nitrogen oxides (to air, non-urban air or from high stacks)	1.42E-07	kilogram

Table S4.70. Life cycle inventory of container ship production, liquid NH_3-SOFC, size2 (1 unit)

Exchanges	Amount	Unit
Economic flows		
hull production, container ship, for DWT 103800	1.99E-01	unit
propulsion system, liquid NH_3-SOFC, size2	1	unit

Table S4.71. Life cycle inventory of propulsion system, liquid NH_3-SOFC, size2 (1 unit)

Exchanges	Amount	Unit
Economic flows		
SOFC*	107.5	MW
market for converter, for electric passenger car	1118.7	kilogram

market for inverter, 500kW	38.2	unit
market for battery, Li-ion, NMC111, rechargeable, prismatic	428.94	kilogram
motor drive*	17.2	MW
market for marine electric motor	45.036	unit
market for control cabinet, heat and power co-generation unit, 160kW electrical	394.875	unit
electric boiler, 100kW*	3.4	unit
Reliquefaction plant, 1 kg/h capacity*	9.21	unit

Table S4.72. Life cycle inventory of transport, container ship, liquid H_2-DFICE, size2 (1 t-nm)

Exchanges	Amount	Unit
Economic flows		
container ship production, liquid H_2-DFICE, size2*	4.85E-11	unit
fuel tank, heavy fuel oil*	1.38E-07	kilogram
fuel tank, cryogenic, liquid hydrogen*	2.70E-05	kilogram
market for maintenance, container ship	2.33E-11	unit
liquid hydrogen production*	2.84E-03	kilogram
marine gas oil, very low-sulphur*	4.19E-04	kilogram
urea solution, 40 wt%*	1.30E-03	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	1.96E-08	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	7.70E-06	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	1.70E-03	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	1.31E-04	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	6.96E-08	kilogram
Ammonia (to air, non-urban air or from high stacks)	8.74E-07	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	1.14E-06	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	1.22E-07	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	4.10E-06	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	0	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	1.40E-06	kilogram

Table S4.73. Life cycle inventory of container ship production, liquid H_2-DFICE, size2 (1 unit)

Exchanges	Amount	Unit
Economic flows		
hull production, container ship, for DWT 103800*	1.99E-01	unit
propulsion system, liquid H_2-DFICE, size2*	1	unit

Table S4.74. Life cycle inventory of propulsion system, liquid H_2-DFICE, size2 (1 unit)

Exchanges	Amount	Unit
Economic flows		
marine engine, CI, ICE*	16.52	MW
market for generator, 200kW electrical	17.75	unit
marine engine, CI, ICE*	3.55	MW
market for control cabinet, heat and power co-generation unit, 160kW electrical	63.94	unit
SCR*	16.52	MW
electric boiler, 100kW*	3.4	unit
Reliquefaction plant, 1 kg/h capacity*	18.47	unit

Table S4.75. Life cycle inventory of transport, container ship, liquid NH_3-DFICE, size2 (1 t-nm)

Exchanges	Amount	Unit
Economic flows		
container ship production, liquid NH_3-DFICE, size2*	4.95E-11	unit
fuel tank, heavy fuel oil*	1.47E-07	kilogram
fuel tank, cryogenic, liquid ammonia*	8.86E-06	kilogram
market for maintenance, container ship	2.37E-11	unit
ammonia production, liquid*	1.94E-02	kilogram
marine gas oil, very low-sulphur*	4.45E-04	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	2.08E-08	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	8.17E-06	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	1.40E-03	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	1.54E-04	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	6.50E-07	kilogram
Ammonia (to air, non-urban air or from high stacks)	1.78E-06	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	1.21E-06	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	1.29E-07	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	4.35E-06	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	0	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	1.48E-06	kilogram

Table S4.76. Life cycle inventory of container ship production, liquid NH_3-DFICE, size2 (1 unit)

Exchanges	Amount	Unit
Economic flows		
hull production, container ship, for DWT 103800*	1.99E-01	unit
propulsion system, liquid NH_3-DFICE, size2*	1	unit

Table S4.77. Life cycle inventory of propulsion system, liquid NH_3-DFICE, size2 (1 unit)

Exchanges	Amount	Unit
Economic flows		
marine engine, CI, ICE*	16.52	MW
market for generator, 200kW electrical	17.75	unit
marine engine, CI, ICE	3.55	MW
market for control cabinet, heat and power co-generation unit, 160kW electrical	63.94	unit
SCR*	20.06	MW
electric boiler, 100kW*	3.4	unit
Reliquefaction plant, 1 kg/h capacity*	12.35	unit

Table S4.78. Life cycle inventory of transport, container ship, MeOH-DFICE, size2 (1 t-nm)

Exchanges	Amount	Unit
Economic flows		
container ship production, MeOH-DFICE, size2*	4.90E-11	unit
fuel tank, heavy fuel oil*	1.39E-07	kilogram
fuel tank, methanol*	6.53E-06	kilogram
market for maintenance, container ship	2.35E-11	unit
methanol production, CO_2 from DAC*	1.70E-02	kilogram
marine gas oil, very low-sulphur*	4.21E-04	kilogram

urea solution, 40 wt%*	1.42E-03	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	1.97E-08	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	1.99E-04	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	2.56E-02	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	1.53E-04	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	7.00E-08	kilogram
Ammonia (to air, non-urban air or from high stacks)	1.15E-06	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	1.02E-06	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	5.14E-07	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	4.13E-06	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	9.22E-06	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	5.91E-06	kilogram

Table S4.79. Life cycle inventory of container ship production, MeOH-DFICE, size2 (1 unit)

Exchanges	Amount	Unit
Economic flows		
hull production, container ship, for DWT 103800*	1.99E-01	unit
propulsion system, MeOH-DFICE, size2*	1	unit

Table S4.80. Life cycle inventory of propulsion system, MeOH-DFICE, size2 (1 unit)

Exchanges	Amount	Unit
Economic flows		
propulsion system, MeOH-DFICE, size2*	1	unit
marine engine, CI, ICE*	16.52	MW
market for generator, 200kW electrical	17.75	unit
marine engine, CI, ICE*	3.55	MW
market for control cabinet, heat and power co-generation unit, 160kW electrical	63.94	unit
SCR*	20.06	MW
electric boiler, 100kW*	3.4	unit

Table S4.81. Life cycle inventory of transport, container ship, LNG-DFICE, size2 (1 t-nm)

Exchanges	Amount	Unit
Economic flows		
container ship production, LNG-DFICE, size2	4.77E-11	unit
fuel tank, heavy fuel oil	2.60E-08	kilogram
fuel tank, LNG	8.19E-06	kilogram
market for maintenance, container ship	2.29E-11	unit
natural gas, liquid	6.79E-03	kilogram
marine gas oil, very low-sulphur	7.88E-05	kilogram
urea solution, 40 wt%	1.28E-03	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	2.04E-04	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	5.37E-05	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	1.86E-02	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	1.28E-04	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	6.46E-07	kilogram
Ammonia (to air, non-urban air or from high stacks)	8.54E-07	kilogram

NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	2.08E-05	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	1.43E-07	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	7.71E-07	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	0	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	1.64E-06	kilogram

Table S4.82. Life cycle inventory of container ship production, LNG-DFICE, size2 (1 unit)

Exchanges	Amount	Unit
Economic flows		
hull production, container ship, for DWT 103800*	1.99E-01	unit
propulsion system, LNG-DFICE, size2*	1	unit

Table S4.83. Life cycle inventory of propulsion system, LNG-DFICE, size2 (1 unit)

Exchanges	Amount	Unit
Economic flows		
marine engine, CI, ICE*	16.52	MW
market for generator, 200kW electrical	17.75	unit
marine engine, CI, ICE*	3.55	MW
market for control cabinet, heat and power co-generation unit, 160kW electrical	63.9375	unit
SCR*	16.52	MW
market for gas boiler	34	unit
Reliquefaction plant, 1 kg/h capacity*	14.7	unit

Table S4.84. Life cycle inventory of transport, container ship, BIO-LNG-DFICE, size2 (1 t-nm)

Exchanges	Amount	Unit
Economic flows		
container ship production, LNG-DFICE, size2*	4.77E-11	unit
fuel tank, heavy fuel oil*	2.60E-08	kilogram
fuel tank, LNG*	8.19E-06	kilogram
market for maintenance, container ship	2.29E-11	unit
natural gas, liquid, woody biomass*	6.79E-03	kilogram
marine gas oil, very low-sulphur*	7.88E-05	kilogram
urea solution, 40 wt%	1.28E-03	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	2.04E-04	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	5.37E-05	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	1.86E-02	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	1.28E-04	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	6.46E-07	kilogram
Ammonia (to air, non-urban air or from high stacks)	8.54E-07	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	2.08E-05	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	1.43E-07	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	7.71E-07	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	0	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	1.64E-06	kilogram

Table S4.85. Life cycle inventory of transport, container ship, LOHC-SOFC, size2 (1 t-nm)

Exchanges	Amount	Unit

Economic flows		
container ship production, LOHC-SOFC, size2*	5.62E-11	unit
fuel tank, heavy fuel oil*	1.23E-05	kilogram
market for maintenance, container ship	2.69E-11	unit
dehydrogenation of perhydro-dibenzyltoluene (H18-DBT) for releasing hydrogen*	2.54E-03	kilogram
market group for electricity, low voltage*	7.92E-05	kilowatt hour

Table S4.86. Life cycle inventory of container ship production, LOHC-SOFC, size2 (1 unit)

Exchanges	Amount	Unit
Economic flows		
hull production, container ship, for DWT 103800*	1.99E-01	unit
propulsion system, LOHC-SOFC, size2*	1	unit

Table S4.87. Life cycle inventory of propulsion system, LOHC-SOFC, size2 (1 unit)

Exchanges	Amount	Unit
Economic flows		
SOFC*	107.45	MW
market for converter, for electric passenger car	1118.25	kilogram
market for inverter, 500kW	38.2	unit
market for battery, Li-ion, NMC111, rechargeable, prismatic	428.9361702	kilogram
motor drive*	17.2	MW
market for marine electric motor	45.036	unit
market for control cabinet, heat and power co-generation unit, 160kW electrical	394.875	unit
LOHC reactor*	11.97	MW H_2
electric boiler, 100kW*	3.4	unit

Table S4.88. Life cycle inventory of transport, container ship, LOHC-DFICE, size2 (1 t-nm)

Exchanges	Amount	Unit
Economic flows		
container ship production, LOHC-DFICE, size2*	5.64E-11	unit
fuel tank, heavy fuel oil*	1.60E-07	kilogram
fuel tank, heavy fuel oil*	1.58E-05	kilogram
market for maintenance, container ship	2.71E-11	unit
dehydrogenation of perhydro-dibenzyltoluene (H18-DBT) for releasing hydrogen*	3.28E-03	kilogram
marine gas oil, very low-sulphur*	4.85E-04	kilogram
urea solution, 40 wt%*	1.52E-03	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	2.27E-08	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	8.91E-06	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	1.97E-03	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	1.52E-04	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	8.05E-08	kilogram
Ammonia (to air, non-urban air or from high stacks)	1.02E-06	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	1.32E-06	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	1.41E-07	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	4.75E-06	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	0.00E+00	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	1.62E-06	kilogram

Table S4.89. Life cycle inventory of container ship production, LOHC-DFICE, size2 (1 unit)

Exchanges	Amount	Unit
Economic flows		
hull production, container ship, for DWT 103800*	1.99E-01	unit
propulsion system, LOHC-DFICE, size2*	1	unit

Table S4.90. Life cycle inventory of propulsion system, LOHC-DFICE, size2 (1 unit)

Exchanges	Amount	Unit
Economic flows		
marine engine, CI, ICE*	16.52	MW
market for generator, 200kW electrical	17.75	unit
marine engine, CI, ICE*	3.55	MW
market for control cabinet, heat and power co-generation unit, 160kW electrical	63.9375	unit
LOHC reactor*	16.18	MW H_2
SCR*	16.52	MW
electric boiler, 100kW*	3.4	unit

Table S4.91. Life cycle inventory of transport, container ship, HFO-ICE, size3 (1 t-nm)

Exchanges	Amount	Unit
Economic flows		
container ship production, HFO-ICE, size3*	2.69E-11	unit
fuel tank, heavy fuel oil*	1.55E-05	kilogram
market for maintenance, container ship	2.17E-11	unit
heavy fuel oil, very low-sulphur*	7.55E-03	kilogram
urea solution, 40 wt%*	1.36E-03	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	3.63E-07	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	3.93E-05	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	2.46E-02	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	1.32E-04	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	1.21E-06	kilogram
Ammonia (to air, non-urban air or from high stacks)	1.09E-06	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	1.79E-05	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	2.13E-06	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	7.57E-05	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	0	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	2.45E-05	kilogram

Table S4.92. Life cycle inventory of container ship production, HFO-ICE, size3 (1 unit)

Exchanges	Amount	Unit
Economic flows		
hull production, container ship, for DWT 103800*	3.34E-01	unit
propulsion system, HFO-ICE, size3*	1	unit

Table S4.93. Life cycle inventory of propulsion system, HFO-ICE, size3 (1 unit)

Exchanges	Amount	Unit
Economic flows		
marine engine, CI, ICE*	21.56	MW
market for generator, 200kW electrical	33.6	unit

marine engine, CI, ICE*	6.72	MW
market for control cabinet, heat and power co-generation unit, 160kW electrical	120.9375	unit
SCR*	28.28	MW
market for oil boiler, 100kW	4.6	unit

Table S4.94. Life cycle inventory of transport, container ship, liquid H_2-PEMFC, size3 (1 t-nm)

Exchanges	Amount	Unit
Economic flows		
container ship production, liquid H_2-PEMFC, size3*	2.66E-11	unit
fuel tank, cryogenic, liquid hydrogen*	4.08E-05	kilogram
market for maintenance, container ship	2.15E-11	unit
liquid hydrogen production*	2.46E-03	kilogram
market group for electricity, low voltage	1.01E-05	kilowatt hour

Table S4.95. Life cycle inventory of container ship production, liquid H_2-PEMFC, size3 (1 unit)

Exchanges	Amount	Unit
Economic flows		
hull production, container ship, for DWT 103800*	3.34E-01	unit
propulsion system, liquid H_2-PEMFC, size3*	1	unit

Table S4.96. Life cycle inventory of propulsion system, liquid H_2-PEMFC, size3 (1 unit)

Exchanges	Amount	Unit
Economic flows		
PEMFC*	150.8	MW
market for converter, for electric passenger car	1427.85	kilogram
market for inverter, 500kW	70.5	unit
market for battery, Li-ion, NMC111, rechargeable, prismatic	200.43	kilogram
motor drive*	22.45	MW
market for marine electric motor	58.81	unit
market for control cabinet, heat and power co-generation unit, 160kW electrical	554.06	unit
electric boiler, 100kW*	4.6	unit
Reliquefaction plant, 1 kg/h capacity*	50.82	unit

Table S4.97. Life cycle inventory of transport, container ship, liquid NH_3-SOFC, size3 (1 t-nm)

Exchanges	Amount	Unit
Economic flows		
container ship production, liquid NH_3-SOFC, size3*	2.88E-11	unit
fuel tank, cryogenic, liquid ammonia*	1.20E-05	kilogram
market for maintenance, container ship	2.32E-11	unit
ammonia production, liquid*	1.50E-02	kilogram
market group for electricity, low voltage	3.28E-05	kilowatt hour
Environmental flows		
Nitrogen oxides	1.44E-07	kilogram

Table S4.98. Life cycle inventory of container ship production, liquid NH_3-SOFC, size3 (1 unit)

Exchanges	Amount	Unit
Economic flows		
hull production, container ship, for DWT 103800*	3.34E-01	unit
propulsion system, liquid NH_3-SOFC, size3*	1	unit

Table S4.99. Life cycle inventory of propulsion system, liquid NH_3-SOFC, size3 (1 unit)

Exchanges	Amount	Unit
Economic flows		
SOFC*	150.8	MW
market for converter, for electric passenger car	1569.15	kilogram
market for inverter, 500kW	70.5	unit
market for battery, Li-ion, NMC111, rechargeable, prismatic	601.28	kilogram
motor drive*	22.45	MW
market for marine electric motor	58.81	unit
market for control cabinet, heat and power co-generation unit, 160kW electrical	554.06	unit
electric boiler, 100kW*	4.6	unit
Reliquefaction plant, 1 kg/h capacity*	28.59	unit

Table S4.100. Life cycle inventory of transport, container ship, liquid H_2-DFICE, size3 (1 t-nm)

Exchanges	Amount	Unit
Economic flows		
container ship production, liquid H_2-DFICE, size3*	2.75E-11	unit
fuel tank, heavy fuel oil*	2.19E-07	kilogram
fuel tank, cryogenic, liquid hydrogen*	4.27E-05	kilogram
market for maintenance, container ship	2.21E-11	unit
liquid hydrogen production*	2.58E-03	kilogram
marine gas oil, very low-sulphur*	3.81E-04	kilogram
urea solution, 40 wt%*	1.09E-03	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	1.79E-08	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	7.01E-06	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	1.52E-03	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	1.12E-04	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	6.33E-08	kilogram
Ammonia (to air, non-urban air or from high stacks)	7.33E-07	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	1.04E-06	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	1.11E-07	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	3.73E-06	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	0	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	1.27E-06	kilogram

Table S4.101. Life cycle inventory of container ship production, liquid H_2-DFICE, size3 (1 unit)

Exchanges	Amount	Unit
Economic flows		
hull production, container ship, for DWT 103800*	3.34E-01	unit
propulsion system, liquid H_2-DFICE, size3*	1	unit

Table S4.102. Life cycle inventory of propulsion system, liquid H_2-DFICE, size3 (1 unit)

Exchanges	Amount	Unit
Economic flows		
marine engine, CI, ICE*	21.56	MW
market for generator, 200kW electrical	33.6	unit

marine engine, CI, ICE*	6.72	MW
market for control cabinet, heat and power co-generation unit, 160kW electrical	120.94	unit
SCR*	21.56	MW
electric boiler, 100kW*	4.6	unit
Reliquefaction plant, 1 kg/h capacity*	51.5	unit

Table S4.103. Life cycle inventory of transport, container ship, liquid NH_3-DFICE, size3 (1 t-nm)

Exchanges	Amount	Unit
Economic flows		
container ship production, liquid NH_3-DFICE, size3*	2.85E-11	unit
fuel tank, heavy fuel oil*	2.35E-07	kilogram
fuel tank, cryogenic, liquid ammonia*	1.42E-05	kilogram
market for maintenance, container ship	2.30E-11	unit
ammonia production, liquid*	1.79E-02	kilogram
marine gas oil, very low-sulphur*	4.09E-04	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	1.92E-08	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	7.53E-06	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	1.29E-03	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	1.40E-04	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	5.98E-07	kilogram
Ammonia (to air, non-urban air or from high stacks)	1.64E-06	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	1.12E-06	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	1.19E-07	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	4.01E-06	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	0	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	1.37E-06	kilogram

Table S4.104. Life cycle inventory of container ship production, liquid NH_3-DFICE, size3 (1 unit)

Exchanges	Amount	Unit
Economic flows		
hull production, container ship, for DWT 103800*	3.34E-01	unit
propulsion system, liquid NH_3-DFICE, size3*	1	unit

Table S4.105. Life cycle inventory of propulsion system, liquid NH_3-DFICE, size3 (1 unit)

Exchanges	Amount	Unit
Economic flows		
marine engine, CI, ICE*	21.56	MW
market for generator, 200kW electrical	33.6	unit
marine engine, CI, ICE*	6.72	MW
market for control cabinet, heat and power co-generation unit, 160kW electrical	120.94	unit
SCR*	28.28	MW
electric boiler, 100kW*	4.6	unit
Reliquefaction plant, 1 kg/h capacity*	34.44	unit

Table S4.106. Life cycle inventory of transport, container ship, MeOH-DFICE, size3 (1 t-nm)

Exchanges	Amount	Unit
Economic flows		

container ship production, MeOH-DFICE, size3*	2.80E-11	unit
fuel tank, heavy fuel oil*	2.21E-07	kilogram
fuel tank, methanol*	1.04E-05	kilogram
market for maintenance, container ship	2.25E-11	unit
methanol production, CO_2 from DAC*	1.55E-02	kilogram
marine gas oil, very low-sulphur*	3.85E-04	kilogram
urea solution, 40 wt%*	1.23E-03	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	1.80E-08	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	1.82E-04	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	2.34E-02	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	1.37E-04	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	6.39E-08	kilogram
Ammonia (to air, non-urban air or from high stacks)	1.04E-06	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	9.33E-07	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	4.69E-07	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	3.77E-06	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	8.41E-06	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	5.39E-06	kilogram

Table S4.107. Life cycle inventory of container ship production, MeOH-DFICE, size3 (1 unit)

Exchanges	Amount	Unit
Economic flows		
hull production, container ship, for DWT 103800*	3.34E-01	unit
propulsion system, MeOH-DFICE, size3*	1	unit

Table S4.108. Life cycle inventory of propulsion system, MeOH-DFICE, size3 (1 unit)

Exchanges	Amount	Unit
Economic flows		
marine engine, CI, ICE*	21.56	MW
market for generator, 200kW electrical	33.6	unit
marine engine, CI, ICE*	6.72	MW
market for control cabinet, heat and power co-generation unit, 160kW electrical	120.9375	unit
SCR*	28.28	MW
electric boiler, 100kW*	4.6	unit

Table S4.109. Life cycle inventory of transport, container ship, LNG-DFICE, size3 (1 t-nm)

Exchanges	Amount	Unit
Economic flows		
container ship production, LNG-DFICE, size3*	2.66E-11	unit
fuel tank, heavy fuel oil*	4.04E-08	kilogram
fuel tank, LNG*	1.28E-05	kilogram
market for maintenance, container ship	2.14E-11	unit
natural gas, liquid*	6.07E-03	kilogram
marine gas oil, very low-sulphur*	7.04E-05	kilogram
urea solution, 40 wt%*	1.06E-03	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	1.82E-04	kilogram

Carbon monoxide, fossil (to air, non-urban air or from high stacks)	4.80E-05	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	1.66E-02	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	1.08E-04	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	5.77E-07	kilogram
Ammonia (to air, non-urban air or from high stacks)	7.05E-07	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	1.86E-05	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	1.28E-07	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	6.89E-07	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	0	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	1.47E-06	kilogram

Table S4.110. Life cycle inventory of container ship production, LNG-DFICE, size3 (1 unit)

Exchanges	Amount	Unit
Economic flows		
hull production, container ship, for DWT 103800*	3.34E-01	unit
propulsion system, LNG-DFICE, size3*	1	unit

Table S4.111. Life cycle inventory of propulsion system, LNG-DFICE, size3 (1 unit)

Exchanges	Amount	Unit
Economic flows		
marine engine, CI, ICE*	21.56	MW
market for generator, 200kW electrical	33.6	unit
marine engine, CI, ICE*	6.72	MW
market for control cabinet, heat and power co-generation unit, 160kW electrical	120.9375	unit
SCR*	21.56	MW
market for gas boiler	46	unit
Reliquefaction plant, 1 kg/h capacity*	40.98	unit

Table S4.112. Life cycle inventory of transport, container ship, BIO-LNG-DFICE, size3 (1 t-nm)

Exchanges	Amount	Unit
Economic flows		
container ship production, LNG-DFICE, size3*	2.66E-11	unit
fuel tank, heavy fuel oil*	4.04E-08	kilogram
fuel tank, LNG*	1.28E-05	kilogram
market for maintenance, container ship	2.14E-11	unit
natural gas, liquid, woody biomass*	6.07E-03	kilogram
marine gas oil, very low-sulphur*	7.04E-05	kilogram
urea solution, 40 wt%*	1.06E-03	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	1.82E-04	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	4.80E-05	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	1.66E-02	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	1.08E-04	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	5.77E-07	kilogram
Ammonia (to air, non-urban air or from high stacks)	7.05E-07	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	1.86E-05	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	1.28E-07	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	6.89E-07	kilogram

Formaldehyde (to air, non-urban air or from high stacks)	0	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	1.47E-06	kilogram

Table S4.113. Life cycle inventory of transport, container ship, LOHC-SOFC, size3 (1 t-nm)

Exchanges	Amount	Unit
Economic flows		
container ship production, LOHC-SOFC, size3*	3.55E-11	unit
fuel tank, heavy fuel oil*	2.41E-05	kilogram
market for maintenance, container ship	2.86E-11	unit
dehydrogenation of perhydro-dibenzyltoluene (H18-DBT) for releasing hydrogen*	2.86E-03	kilogram
market group for electricity, low voltage	4.03E-05	kilowatt hour

Table S4.114. Life cycle inventory of container ship production, LOHC-SOFC, size3 (1 unit)

Exchanges	Amount	Unit
Economic flows		
hull production, container ship, for DWT 103800*	3.34E-01	unit
propulsion system, LOHC-SOFC, size3*	1	unit

Table S4.115. Life cycle inventory of propulsion system, LOHC-SOFC, size3 (1 unit)

Exchanges	Amount	Unit
Economic flows		
SOFC*	150.8	MW
market for converter, for electric passenger car	1569.15	kilogram
market for inverter, 500kW	70.5	unit
market for battery, Li-ion, NMC111, rechargeable, prismatic	601.277	kilogram
motor drive*	22.45	MW
market for marine electric motor	58.806	unit
market for control cabinet, heat and power co-generation unit, 160kW electrical	554.0625	unit
LOHC reactor*	20.37	MW H_2
electric boiler, 100kW*	4.6	unit

Table S4.116. Life cycle inventory of transport, container ship, LOHC-DFICE, size3 (1 t-nm)

Exchanges	Amount	Unit
Economic flows		
container ship production, LOHC-DFICE, size3*	3.59E-11	unit
fuel tank, heavy fuel oil*	2.84E-07	kilogram
fuel tank, heavy fuel oil*	2.81E-05	kilogram
market for maintenance, container ship	2.90E-11	unit
dehydrogenation of perhydro-dibenzyltoluene (H18-DBT) for releasing hydrogen*	3.34E-03	kilogram
marine gas oil, very low-sulphur*	4.95E-04	kilogram
urea solution, 40 wt%*	1.43E-03	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	2.32E-08	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	9.09E-06	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	1.98E-03	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	1.46E-04	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	8.21E-08	kilogram
Ammonia (to air, non-urban air or from high stacks)	9.59E-07	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-	1.35E-06	kilogram

urban air or from high stacks)		
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	1.43E-07	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	4.84E-06	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	0.00E+00	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	1.65E-06	kilogram

Table S4.117. Life cycle inventory of container ship production, LOHC-DFICE, size3 (1 unit)

Exchanges	Amount	Unit
Economic flows		
hull production, container ship, for DWT 103800*	3.34E-01	unit
propulsion system, LOHC-DFICE, size3*	1	unit

Table S4.118. Life cycle inventory of propulsion system, LOHC-DFICE, size3 (1 unit)

Exchanges	Amount	Unit
Economic flows		
marine engine, CI, ICE*	21.56	MW
market for generator, 200kW electrical	33.6	unit
marine engine, CI, ICE*	6.72	MW
market for control cabinet, heat and power co-generation unit, 160kW electrical	120.9375	unit
LOHC reactor*	24.73	MW H_2
SCR*	21.56	MW
electric boiler, 100kW*	4.6	unit

Table S4.119. Life cycle inventory of transport, container ship, HFO-ICE, size4 (1 t-nm)

Exchanges	Amount	Unit
Economic flows		
container ship production, HFO-ICE, size4*	1.51E-11	unit
fuel tank, heavy fuel oil*	1.54E-05	kilogram
market for maintenance, container ship	1.81E-11	unit
heavy fuel oil, very low-sulphur*	6.97E-03	kilogram
urea solution, 40 wt%*	1.27E-03	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	3.35E-07	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	3.63E-05	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	2.27E-02	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	1.23E-04	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	1.12E-06	kilogram
Ammonia (to air, non-urban air or from high stacks)	1.01E-06	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	1.65E-05	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	1.97E-06	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	6.98E-05	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	0	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	2.26E-05	kilogram

Table S4.120. Life cycle inventory of container ship production, HFO-ICE, size4 (1 unit)

Exchanges	Amount	Unit
Economic flows		
hull production, container ship, for DWT 103800*	4.97E-01	unit

propulsion system, HFO-ICE, size4*	1	unit

Table S4.121. Life cycle inventory of propulsion system, HFO-ICE, size4 (1 unit)

Exchanges	Amount	Unit
Economic flows		
marine engine, CI, ICE*	31.64	MW
market for generator, 200kW electrical	42	unit
marine engine, CI, ICE*	8.4	MW
market for control cabinet, heat and power co-generation unit, 160kW electrical	151.3125	unit
SCR*	40.04	MW
market for oil boiler, 100kW	4.8	unit

Table S4.122. Life cycle inventory of transport, container ship, liquid H_2-PEMFC, size4 (1 t-nm)

Exchanges	Amount	Unit
Economic flows		
container ship production, liquid H_2-PEMFC, size4*	1.50E-11	unit
fuel tank, cryogenic, liquid hydrogen*	4.20E-05	kilogram
market for maintenance, container ship	1.80E-11	unit
liquid hydrogen production*	2.28E-03	kilogram
market group for electricity, low voltage	7.21E-06	kilowatt hour

Table S4.123. Life cycle inventory of container ship production, liquid H_2-PEMFC, size4 (1 unit)

Exchanges	Amount	Unit
Economic flows		
hull production, container ship, for DWT 103800*	4.97E-01	unit
propulsion system, liquid H_2-PEMFC, size4*	1	unit

Table S4.124. Life cycle inventory of propulsion system, liquid H_2-PEMFC, size4 (1 unit)

Exchanges	Amount	Unit
Economic flows		
PEMFC*	212.95	MW
market for converter, for electric passenger car	2016.45	kilogram
market for inverter, 500kW	87.1	unit
market for battery, Li-ion, NMC111, rechargeable, prismatic	283.40	kilogram
motor drive*	32.95	MW
market for marine electric motor	86.292	unit
market for control cabinet, heat and power co-generation unit, 160kW electrical	782.625	unit
electric boiler, 100kW*	4.8	unit
Reliquefaction plant, 1 kg/h capacity*	92.68	unit

Table S4.125. Life cycle inventory of transport, container ship, liquid NH_3-SOFC, size4 (1 t-nm)

Exchanges	Amount	Unit
Economic flows		
container ship production, liquid NH_3-SOFC, size4*	1.60E-11	unit
fuel tank, cryogenic, liquid ammonia*	1.11E-05	kilogram
market for maintenance, container ship	1.92E-11	unit
ammonia production, liquid*	1.25E-02	kilogram
market group for electricity, low voltage	2.31E-05	kilowatt hour
Environmental flows		

Nitrogen oxides (to air, non-urban air or from high stacks)	1.21E-07	kilogram

Table S4.126. Life cycle inventory of container ship production, liquid NH_3-SOFC, size4 (1 unit)

Exchanges	Amount	Unit
Economic flows		
hull production, container ship, for DWT 103800*	4.97E-01	unit
propulsion system, liquid NH_3-SOFC, size4*	1	unit

Table S4.127. Life cycle inventory of propulsion system, liquid NH_3-SOFC, size4 (1 unit)

Exchanges	Amount	Unit
Economic flows		
SOFC*	212.95	MW
market for converter, for electric passenger car	2215.8	kilogram
market for inverter, 500kW	87.1	unit
market for battery, Li-ion, NMC111, rechargeable, prismatic	848.94	kilogram
motor drive*	32.95	MW
market for marine electric motor	86.292	unit
market for control cabinet, heat and power co-generation unit, 160kW electrical	782.625	unit
electric boiler, 100kW*	4.8	unit
Reliquefaction plant, 1 kg/h capacity*	47.88	unit

Table S4.128. Life cycle inventory of transport, container ship, liquid H_2-DFICE, size4 (1 t-nm)

Exchanges	Amount	Unit
Economic flows		
container ship production, liquid H_2-DFICE, size4*	1.55E-11	unit
fuel tank, heavy fuel oil*	2.26E-07	kilogram
fuel tank, cryogenic, liquid hydrogen*	4.42E-05	kilogram
market for maintenance, container ship	1.85E-11	unit
liquid hydrogen production*	2.40E-03	kilogram
marine gas oil, very low-sulphur*	3.55E-04	kilogram
urea solution, 40 wt%*	1.08E-03	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	1.66E-08	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	6.51E-06	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	1.43E-03	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	1.09E-04	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	5.89E-08	kilogram
Ammonia (to air, non-urban air or from high stacks)	7.23E-07	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	9.66E-07	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	1.03E-07	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	3.47E-06	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	0	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	1.18E-06	kilogram

Table S4.129. Life cycle inventory of container ship production, liquid H_2-DFICE, size4 (1 unit)

Exchanges	Amount	Unit
Economic flows		
hull production, container ship, for DWT 103800*	4.97E-01	unit

propulsion system, liquid H_2-DFICE, size4*	1	unit

Table S4.130. Life cycle inventory of propulsion system, liquid H_2-DFICE, size4 (1 unit)

Exchanges	Amount	Unit
Economic flows		
marine engine, CI, ICE*	31.64	MW
market for generator, 200kW electrical	42	unit
marine engine, CI, ICE*	8.4	MW
market for control cabinet, heat and power co-generation unit, 160kW electrical	151.3125	unit
SCR*	31.64	MW
electric boiler, 100kW*	4.8	unit
Reliquefaction plant, 1 kg/h capacity*	94.55	unit

Table S4.131. Life cycle inventory of transport, container ship, liquid NH_3-DFICE, size4 (1 t-nm)

Exchanges	Amount	Unit
Economic flows		
container ship production, liquid NH_3-DFICE, size4*	1.61E-11	unit
fuel tank, heavy fuel oil*	2.45E-07	kilogram
fuel tank, cryogenic, liquid ammonia*	1.48E-05	kilogram
market for maintenance, container ship	1.94E-11	unit
ammonia production, liquid*	1.67E-02	kilogram
marine gas oil, very low-sulphur*	3.83E-04	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	1.79E-08	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	7.03E-06	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	1.20E-03	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	1.32E-04	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	5.59E-07	kilogram
Ammonia (to air, non-urban air or from high stacks)	1.53E-06	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	1.04E-06	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	1.11E-07	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	3.75E-06	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	0	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	1.28E-06	kilogram

Table S4.132. Life cycle inventory of container ship production, liquid NH_3-DFICE, size4 (1 unit)

Exchanges	Amount	Unit
Economic flows		
hull production, container ship, for DWT 103800*	4.97E-01	unit
propulsion system, liquid NH_3-DFICE, size4*	1	unit

Table S4.133. Life cycle inventory of propulsion system, liquid NH_3-DFICE, size4 (1 unit)

Exchanges	Amount	Unit
Economic flows		
marine engine, CI, ICE*	31.64	MW
market for generator, 200kW electrical	42	unit
marine engine, CI, ICE*	8.4	MW
market for control cabinet, heat and power co-generation unit, 160kW electrical	151.3125	unit

SCR*	40.04	MW
electric boiler, 100kW*	4.8	unit
Reliquefaction plant, 1 kg/h capacity*	63.21	unit

Table S4.134. Life cycle inventory of transport, container ship, MeOH-DFICE, size4 (1 t-nm)

Exchanges	Amount	Unit
Economic flows		
container ship production, MeOH-DFICE, size4*	1.58E-11	unit
fuel tank, heavy fuel oil*	2.29E-07	kilogram
fuel tank, methanol*	1.08E-05	kilogram
market for maintenance, container ship	1.89E-11	unit
methanol production, CO_2 from DAC*	1.45E-02	kilogram
marine gas oil, very low-sulphur*	3.58E-04	kilogram
urea solution, 40 wt%*	1.19E-03	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	1.68E-08	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	1.69E-04	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	2.18E-02	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	1.29E-04	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	5.94E-08	kilogram
Ammonia (to air, non-urban air or from high stacks)	9.73E-07	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	8.69E-07	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	4.36E-07	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	3.50E-06	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	7.83E-06	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	5.02E-06	kilogram

Table S4.135. Life cycle inventory of container ship production, MeOH-DFICE, size4 (1 unit)

Exchanges	Amount	Unit
Economic flows		
hull production, container ship, for DWT 103800*	4.97E-01	unit
propulsion system, MeOH-DFICE, size4*	1	unit

Table S4.136. Life cycle inventory of propulsion system, MeOH-DFICE, size4 (1 unit)

Exchanges	Amount	Unit
Economic flows		
marine engine, CI, ICE*	31.64	MW
market for generator, 200kW electrical	42	unit
marine engine, CI, ICE*	8.4	MW
market for control cabinet, heat and power co-generation unit, 160kW electrical	151.3125	unit
SCR*	40.04	MW
electric boiler, 100kW*	4.8	unit

Table S4.137. Life cycle inventory of transport, container ship, LNG-DFICE, size4 (1 t-nm)

Exchanges	Amount	Unit
Economic flows		
container ship production, LNG-DFICE, size4	1.49E-11	unit
fuel tank, heavy fuel oil	4.15E-08	kilogram

fuel tank, LNG	1.31E-05	kilogram
market for maintenance, container ship	1.78E-11	unit
natural gas, liquid	5.60E-03	kilogram
marine gas oil, very low-sulphur	6.49E-05	kilogram
urea solution, 40 wt%	1.04E-03	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	1.68E-04	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	4.43E-05	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	1.53E-02	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	1.04E-04	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	5.32E-07	kilogram
Ammonia (to air, non-urban air or from high stacks)	6.91E-07	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	1.72E-05	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	1.18E-07	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	6.35E-07	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	0	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	1.35E-06	kilogram

Table S4.138. Life cycle inventory of container ship production, LNG-DFICE, size4 (1 unit)

Exchanges	Amount	Unit
Economic flows		
hull production, container ship, for DWT 103800*	4.97E-01	unit
propulsion system, LNG-DFICE, size4*	1	unit

Table S4.139. Life cycle inventory of propulsion system, LNG-DFICE, size4 (1 unit)

Exchanges	Amount	Unit
Economic flows		
marine engine, CI, ICE*	31.64	MW
market for generator, 200kW electrical	42	unit
marine engine, CI, ICE*	8.4	MW
market for control cabinet, heat and power co-generation unit, 160kW electrical	151.3125	unit
SCR*	31.64	MW
market for gas boiler	48	unit
Reliquefaction plant, 1 kg/h capacity*	75.24	unit

Table S4.140. Life cycle inventory of transport, container ship, BIO-LNG-DFICE, size4 (1 t-nm)

Exchanges	Amount	Unit
Economic flows		
container ship production, LNG-DFICE, size4*	1.49E-11	unit
fuel tank, heavy fuel oil*	4.15E-08	kilogram
fuel tank, LNG*	1.31E-05	kilogram
market for maintenance, container ship	1.78E-11	unit
natural gas, liquid, woody biomass*	5.60E-03	kilogram
marine gas oil, very low-sulphur*	6.49E-05	kilogram
urea solution, 40 wt%*	1.04E-03	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	1.68E-04	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	4.43E-05	kilogram

Carbon dioxide, fossil (to air, non-urban air or from high stacks)	1.53E-02	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	1.04E-04	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	5.32E-07	kilogram
Ammonia (to air, non-urban air or from high stacks)	6.91E-07	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	1.72E-05	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	1.18E-07	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	6.35E-07	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	0	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	1.35E-06	kilogram

Table S4.141. Life cycle inventory of transport, container ship, LOHC-SOFC, size4 (1 t-nm)

Exchanges	Amount	Unit
Economic flows		
container ship production, LOHC-SOFC, size4*	2.00E-11	unit
fuel tank, heavy fuel oil*	2.27E-05	kilogram
market for maintenance, container ship	2.40E-11	unit
dehydrogenation of perhydro-dibenzyltoluene (H18-DBT) for releasing hydrogen*	2.43E-03	kilogram
market group for electricity, low voltage	2.88E-05	kilowatt hour

Table S4.142. Life cycle inventory of container ship production, LOHC-SOFC, size4 (1 unit)

Exchanges	Amount	Unit
Economic flows		
hull production, container ship, for DWT 103800*	4.97E-01	unit
propulsion system, LOHC-SOFC, size4*	1	unit

Table S4.143. Life cycle inventory of propulsion system, LOHC-SOFC, size4 (1 unit)

Exchanges	Amount	Unit
Economic flows		
SOFC*	212.95	MW
market for converter, for electric passenger car	2215.8	kilogram
market for inverter, 500kW	87.1	unit
market for battery, Li-ion, NMC111, rechargeable, prismatic	848.936	kilogram
motor drive*	32.95	MW
market for marine electric motor	86.292	unit
market for control cabinet, heat and power co-generation unit, 160kW electrical	782.625	unit
LOHC reactor*	27.39	MW H2
electric boiler, 100kW*	4.8	unit

Table S4.144. Life cycle inventory of transport, container ship, LOHC-DFICE, size4 (1 t-nm)

Exchanges	Amount	Unit
Economic flows		
container ship production, LOHC-DFICE, size4*	2.14E-11	unit
fuel tank, heavy fuel oil*	3.11E-07	kilogram
fuel tank, heavy fuel oil*	3.08E-05	kilogram
market for maintenance, container ship	2.57E-11	unit
dehydrogenation of perhydro-dibenzyltoluene (H18-DBT) for releasing hydrogen*	3.29E-03	kilogram
marine gas oil, very low-sulphur*	4.86E-04	kilogram
urea solution, 40 wt%*	1.50E-03	kilogram

Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	2.28E-08	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	8.94E-06	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	1.97E-03	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	1.50E-04	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	8.08E-08	kilogram
Ammonia (to air, non-urban air or from high stacks)	1.00E-06	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	1.33E-06	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	1.41E-07	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	4.76E-06	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	0.00E+00	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	1.62E-06	kilogram

Table S4.145. Life cycle inventory of container ship production, LOHC-DFICE, size4 (1 unit)

Exchanges	Amount	Unit
Economic flows		
hull production, container ship, for DWT 103800*	4.97E-01	unit
propulsion system, LOHC-DFICE, size4*	1	unit

Table S4.146. Life cycle inventory of propulsion system, LOHC-DFICE, size4 (1 unit)

Exchanges	Amount	Unit
Economic flows		
marine engine, CI, ICE*	31.64	MW
market for generator, 200kW electrical	42	unit
marine engine, CI, ICE*	8.4	MW
market for control cabinet, heat and power co-generation unit, 160kW electrical	151.3125	unit
LOHC reactor*	36.46	MW H_2
SCR*	31.64	MW
electric boiler, 100kW*	4.8	unit

Table S4.147. Life cycle inventory of transport, container ship, HFO-ICE, size5 (1 t-nm)

Exchanges	Amount	Unit
Economic flows		
container ship production, HFO-ICE, size5*	8.42E-12	unit
fuel tank, heavy fuel oil*	1.17E-05	kilogram
market for maintenance, container ship	1.54E-11	unit
heavy fuel oil, very low-sulphur*	6.32E-03	kilogram
urea solution, 40 wt%*	1.17E-03	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	3.04E-07	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	3.29E-05	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	2.06E-02	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	1.13E-04	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	1.01E-06	kilogram
Ammonia (to air, non-urban air or from high stacks)	9.15E-07	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	1.49E-05	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	1.78E-06	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	6.33E-05	kilogram

Formaldehyde (to air, non-urban air or from high stacks)	0	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	2.05E-05	kilogram

Table S4.148. Life cycle inventory of container ship production, HFO-ICE, size5 (1 unit)

Exchanges	Amount	Unit
Economic flows		
hull production, container ship, for DWT 103800*	7.58E-01	unit
propulsion system, HFO-ICE, size5*	1	unit

Table S4.149. Life cycle inventory of propulsion system, HFO-ICE, size5 (1 unit)

Exchanges	Amount	Unit
Economic flows		
marine engine, CI, ICE*	54.9	MW
market for generator, 200kW electrical	58	unit
marine engine, CI, ICE*	11.6	MW
market for control cabinet, heat and power co-generation unit, 160kW electrical	208.6875	unit
SCR*	66.5	MW
market for oil boiler, 100kW	5.9	unit

Table S4.150. Life cycle inventory of transport, container ship, liquid H_2-PEMFC, size5 (1 t-nm)

Exchanges	Amount	Unit
Economic flows		
container ship production, liquid H_2-PEMFC, size5*	8.41E-12	unit
fuel tank, cryogenic, liquid hydrogen*	3.80E-05	kilogram
market for maintenance, container ship	1.54E-11	unit
liquid hydrogen production*	2.07E-03	kilogram
market group for electricity, low voltage	6.75E-06	kilowatt hour

Table S4.151. Life cycle inventory of container ship production, liquid H_2-PEMFC, size5 (1 unit)

Exchanges	Amount	Unit
Economic flows		
hull production, container ship, for DWT 103800*	7.58E-01	unit
propulsion system, liquid H_2-PEMFC, size5*	1	unit

Table S4.152. Life cycle inventory of propulsion system, liquid H_2-PEMFC, size5 (1 unit)

Exchanges	Amount	Unit
Economic flows		
PEMFC*	353.35	MW
market for converter, for electric passenger car	3346.2	kilogram
market for inverter, 500kW	119.4	unit
motor drive*	57.17	MW
market for marine electric motor	149.742	unit
market for control cabinet, heat and power co-generation unit, 160kW electrical	1298.625	unit
market for battery, Li-ion, NMC111, rechargeable, prismatic	471.06	kilogram
electric boiler, 100kW*	5.9	unit
Reliquefaction plant, 1 kg/h capacity*	149.31	unit

Table S4.153. Life cycle inventory of transport, container ship, liquid NH_3-SOFC, size5 (1 t-nm)

Exchanges	Amount	Unit

Economic flows		
container ship production, liquid NH_3-SOFC, size5*	9.16E-12	unit
fuel tank, cryogenic, liquid ammonia*	1.13E-05	kilogram
market for maintenance, container ship	1.68E-11	unit
ammonia production, liquid*	1.28E-02	kilogram
market group for electricity, low voltage	2.20E-05	kilowatt hour
Environmental flows		
Nitrogen oxides (to air, non-urban air or from high stacks)	1.23E-07	kilogram

Table S4.154. Life cycle inventory of container ship production, liquid NH_3-SOFC, size5 (1 unit)

Exchanges	Amount	Unit
Economic flows		
hull production, container ship, for DWT 103800*	7.58E-01	unit
propulsion system, liquid NH_3-SOFC, size5*	1	unit

Table S4.155. Life cycle inventory of propulsion system, liquid NH_3-SOFC, size5 (1 unit)

Exchanges	Amount	Unit
Economic flows		
SOFC*	353.35	MW
market for converter, for electric passenger car	3676.95	kilogram
market for inverter, 500kW	119.4	unit
market for battery, Li-ion, NMC111, rechargeable, prismatic	1409.36	kilogram
motor drive*	57.17	MW
market for marine electric motor	149.742	unit
market for control cabinet, heat and power co-generation unit, 160kW electrical	1298.625	unit
electric boiler, 100kW*	5.9	unit
Reliquefaction plant, 1 kg/h capacity*	84.9	unit

Table S4.156. Life cycle inventory of transport, container ship, liquid H_2-DFICE, size5 (1 t-nm)

Exchanges	Amount	Unit
Economic flows		
container ship production, liquid H_2-DFICE, size5*	8.70E-12	unit
fuel tank, heavy fuel oil*	2.06E-07	kilogram
fuel tank, cryogenic, liquid hydrogen*	4.02E-05	kilogram
market for maintenance, container ship	1.59E-11	unit
liquid hydrogen production*	2.19E-03	kilogram
marine gas oil, very low-sulphur*	3.24E-04	kilogram
urea solution, 40 wt%*	1.02E-03	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	1.52E-08	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	5.95E-06	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	1.32E-03	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	1.02E-04	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	5.38E-08	kilogram
Ammonia (to air, non-urban air or from high stacks)	6.84E-07	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	8.83E-07	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	9.39E-08	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	3.17E-06	kilogram

Formaldehyde (to air, non-urban air or from high stacks)	0	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	1.08E-06	kilogram

Table S4.157. Life cycle inventory of container ship production, liquid H_2-DFICE, size5 (1 unit)

Exchanges	Amount	Unit
Economic flows		
hull production, container ship, for DWT 103800*	7.58E-01	unit
propulsion system, liquid H_2-DFICE, size5*	1	unit

Table S4.158. Life cycle inventory of propulsion system, liquid H_2-DFICE, size5 (1 unit)

Exchanges	Amount	Unit
Economic flows		
marine engine, CI, ICE*	54.9	MW
market for generator, 200kW electrical	58	unit
marine engine, CI, ICE*	11.6	MW
market for control cabinet, heat and power co-generation unit, 160kW electrical	208.6875	unit
SCR*	54.9	MW
electric boiler, 100kW*	5.9	unit
Reliquefaction plant, 1 kg/h capacity*	152.77	unit

Table S4.159. Life cycle inventory of transport, container ship, liquid NH_3-DFICE, size5 (1 t-nm)

Exchanges	Amount	Unit
Economic flows		
container ship production, liquid NH_3-DFICE, size5*	9.11E-12	unit
fuel tank, heavy fuel oil*	2.23E-07	kilogram
fuel tank, cryogenic, liquid ammonia*	1.35E-05	kilogram
market for maintenance, container ship	1.67E-11	unit
ammonia production, liquid*	1.53E-02	kilogram
marine gas oil, very low-sulphur*	3.50E-04	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	1.64E-08	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	6.44E-06	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	1.10E-03	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	1.22E-04	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	5.12E-07	kilogram
Ammonia (to air, non-urban air or from high stacks)	1.40E-06	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	9.54E-07	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	1.02E-07	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	3.43E-06	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	0	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	1.17E-06	kilogram

Table S4.160. Life cycle inventory of container ship production, liquid NH_3-DFICE, size5 (1 unit)

Exchanges	Amount	Unit
Economic flows		
hull production, container ship, for DWT 103800*	7.58E-01	unit
propulsion system, liquid NH_3-DFICE, size5*	1	unit

Table S4.161. Life cycle inventory of propulsion system, liquid NH_3-DFICE, size5 (1 unit)

Exchanges	Amount	Unit
Economic flows		
marine engine, CI, ICE*	54.9	MW
market for generator, 200kW electrical	58	unit
marine engine, CI, ICE*	11.6	MW
market for control cabinet, heat and power co-generation unit, 160kW electrical	208.6875	unit
SCR*	66.5	MW
electric boiler, 100kW*	5.9	unit
Reliquefaction plant, 1 kg/h capacity*	102.13	unit

Table S4.162. Life cycle inventory of transport, container ship, MeOH-DFICE, size5 (1 t-nm)

Exchanges	Amount	Unit
Economic flows		
container ship production, MeOH-DFICE, size5	8.89E-12	unit
fuel tank, heavy fuel oil	2.08E-07	kilogram
fuel tank, methanol	9.79E-06	kilogram
market for maintenance, container ship	1.63E-11	unit
methanol production, CO_2 from DAC	1.32E-02	kilogram
marine gas oil, very low-sulphur	3.27E-04	kilogram
urea solution, 40 wt%	1.12E-03	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	1.53E-08	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	1.55E-04	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	1.99E-02	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	1.19E-04	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	5.43E-08	kilogram
Ammonia (to air, non-urban air or from high stacks)	8.90E-07	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	7.94E-07	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	3.99E-07	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	3.20E-06	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	7.16E-06	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	4.59E-06	kilogram

Table S4.163. Life cycle inventory of container ship production, MeOH-DFICE, size5 (1 unit)

Exchanges	Amount	Unit
Economic flows		
hull production, container ship, for DWT 103800*	7.58E-01	unit
propulsion system, MeOH-DFICE, size5*	1	unit

Table S4.164. Life cycle inventory of propulsion system, MeOH-DFICE, size5 (1 unit)

Exchanges	Amount	Unit
Economic flows		
marine engine, CI, ICE*	54.9	MW
market for generator, 200kW electrical	58	unit
marine engine, CI, ICE*	11.6	MW
market for control cabinet, heat and power co-generation unit, 160kW electrical	208.6875	unit
SCR*	66.5	MW
electric boiler, 100kW*	5.9	unit

Table S4.165. Life cycle inventory of transport, container ship, LNG-DFICE, size5 (1 t-nm)

Exchanges	Amount	Unit
Economic flows		
container ship production, LNG-DFICE, size5*	8.34E-12	unit
fuel tank, heavy fuel oil*	3.76E-08	kilogram
fuel tank, LNG*	1.19E-05	kilogram
market for maintenance, container ship	1.53E-11	unit
natural gas, liquid*	5.10E-03	kilogram
marine gas oil, very low-sulphur*	5.91E-05	kilogram
urea solution, 40 wt%*	9.78E-04	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	1.53E-04	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	4.04E-05	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	1.40E-02	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	9.76E-05	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	4.85E-07	kilogram
Ammonia (to air, non-urban air or from high stacks)	6.52E-07	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	1.57E-05	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	1.07E-07	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	5.79E-07	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	0	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	1.23E-06	kilogram

Table S4.166. Life cycle inventory of container ship production, LNG-DFICE, size5 (1 unit)

Exchanges	Amount	Unit
Economic flows		
hull production, container ship, for DWT 103800*	7.58E-01	unit
propulsion system, LNG-DFICE, size5*	1	unit

Table S4.167. Life cycle inventory of propulsion system, LNG-DFICE, size5 (1 unit)

Exchanges	Amount	Unit
Economic flows		
marine engine, CI, ICE*	54.9	MW
market for generator, 200kW electrical	58	unit
marine engine, CI, ICE*	11.6	MW
market for control cabinet, heat and power co-generation unit, 160kW electrical	208.6875	unit
SCR*	54.9	MW
market for gas boiler	59	unit
Reliquefaction plant, 1 kg/h capacity*	121.57	unit

Table S4.168. Life cycle inventory of transport, container ship, BIO-LNG-DFICE, size5 (1 t-nm)

Exchanges	Amount	Unit
Economic flows		
container ship production, LNG-DFICE, size5*	8.34E-12	unit
fuel tank, heavy fuel oil*	3.76E-08	kilogram
fuel tank, LNG*	1.19E-05	kilogram
market for maintenance, container ship	1.53E-11	unit
natural gas, liquid, woody biomass*	5.10E-03	kilogram

marine gas oil, very low-sulphur*	5.91E-05	kilogram
urea solution, 40 wt%*	9.78E-04	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	1.53E-04	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	4.04E-05	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	1.40E-02	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	9.76E-05	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	4.85E-07	kilogram
Ammonia (to air, non-urban air or from high stacks)	6.52E-07	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	1.57E-05	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	1.07E-07	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	5.79E-07	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	0	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	1.23E-06	kilogram

Table S4.169. Life cycle inventory of transport, container ship, LOHC-SOFC, size5 (1 t-nm)

Exchanges	Amount	Unit
Economic flows		
container ship production, LOHC-SOFC, size5*	1.19E-11	unit
fuel tank, heavy fuel oil*	2.41E-05	kilogram
market for maintenance, container ship	2.18E-11	unit
dehydrogenation of perhydro-dibenzyltoluene (H18-DBT) for releasing hydrogen*	2.58E-03	kilogram
market group for electricity, low voltage	2.87E-05	kilowatt hour

Table S4.170. Life cycle inventory of container ship production, LOHC-SOFC, size5 (1 unit)

Exchanges	Amount	Unit
Economic flows		
hull production, container ship, for DWT 103800*	7.58E-01	unit
propulsion system, LOHC-SOFC, size5*	1	unit

Table S4.171. Life cycle inventory of propulsion system, LOHC-SOFC, size5 (1 unit)

Exchanges	Amount	Unit
Economic flows		
SOFC*	353.35	MW
market for converter, for electric passenger car	3676.95	kilogram
market for inverter, 500kW	119.4	unit
market for battery, Li-ion, NMC111, rechargeable, prismatic	1409.362	kilogram
motor drive*	57.17	MW
market for marine electric motor	149.742	unit
market for control cabinet, heat and power co-generation unit, 160kW electrical	1298.625	unit
LOHC reactor*	46.5	MW H_2
electric boiler, 100kW*	5.9	unit

Table S4.172. Life cycle inventory of transport, container ship, LOHC-DFICE, size5 (1 t-nm)

Exchanges	Amount	Unit
Economic flows		
container ship production, LOHC-DFICE, size5*	1.23E-11	unit
fuel tank, heavy fuel oil*	2.89E-07	kilogram

fuel tank, heavy fuel oil*	2.86E-05	kilogram
market for maintenance, container ship	2.25E-11	unit
dehydrogenation of perhydro-dibenzyltoluene (H18-DBT) for releasing hydrogen*	3.06E-03	kilogram
marine gas oil, very low-sulphur*	4.53E-04	kilogram
urea solution, 40 wt%*	1.44E-03	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	2.12E-08	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	8.32E-06	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	1.85E-03	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	1.44E-04	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	7.52E-08	kilogram
Ammonia (to air, non-urban air or from high stacks)	9.67E-07	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	1.23E-06	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	1.31E-07	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	4.44E-06	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	0.00E+00	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	1.51E-06	kilogram

Table S4.173. Life cycle inventory of container ship production, LOHC-DFICE, size5 (1 unit)

Exchanges	Amount	Unit
Economic flows		
hull production, container ship, for DWT 103800*	7.58E-01	unit
propulsion system, LOHC-DFICE, size5*	1	unit

Table S4.174. Life cycle inventory of propulsion system, LOHC-DFICE, size5 (1 unit)

Exchanges	Amount	Unit
Economic flows		
marine engine, CI, ICE*	54.9	MW
market for generator, 200kW electrical	58	unit
marine engine, CI, ICE*	11.6	MW
market for control cabinet, heat and power co-generation unit, 160kW electrical	208.6875	unit
LOHC reactor*	56.41	MW H_2
SCR*	54.9	MW
electric boiler, 100kW*	5.9	unit

Table S4.175. Life cycle inventory of transport, container ship, HFO-ICE, size6 (1 t-nm)

Exchanges	Amount	Unit
Economic flows		
container ship production, HFO-ICE, size6*	5.93E-12	unit
fuel tank, heavy fuel oil*	9.25E-06	kilogram
market for maintenance, container ship	1.59E-11	unit
heavy fuel oil, very low-sulphur*	4.75E-03	kilogram
urea solution, 40 wt%*	8.64E-04	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	2.29E-07	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	2.48E-05	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	1.55E-02	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	8.38E-05	kilogram

Dinitrogen monoxide (to air, non-urban air or from high stacks)	7.62E-07	kilogram
Ammonia (to air, non-urban air or from high stacks)	6.87E-07	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	1.12E-05	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	1.34E-06	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	4.76E-05	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	0	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	1.54E-05	kilogram

Table S4.176. Life cycle inventory of container ship production, HFO-ICE, size6 (1 unit)

Exchanges	Amount	Unit
Economic flows		
hull production, container ship, for DWT 103800*	1.11	unit
propulsion system, HFO-ICE, size6*	1	unit

Table S4.177. Life cycle inventory of propulsion system, HFO-ICE, size6 (1 unit)

Exchanges	Amount	Unit
Economic flows		
marine engine, CI, ICE*	58.1	MW
market for generator, 200kW electrical	73	unit
marine engine, CI, ICE*	14.6	MW
market for control cabinet, heat and power co-generation unit, 160kW electrical	262.875	unit
SCR*	72.7	MW
market for oil boiler, 100kW	6.2	unit

Table S4.178. Life cycle inventory of transport, container ship, liquid H_2-PEMFC, size6 (1 t-nm)

Exchanges	Amount	Unit
Economic flows		
container ship production, liquid H_2-PEMFC, size6*	6.11E-12	unit
fuel tank, cryogenic, liquid hydrogen*	5.30E-05	kilogram
market for maintenance, container ship	1.64E-11	unit
liquid hydrogen production*	1.61E-03	kilogram
market group for electricity, low voltage	2.98E-06	kilowatt hour

Table S4.179. Life cycle inventory of container ship production, liquid H_2-PEMFC, size6 (1 unit)

Exchanges	Amount	Unit
Economic flows		
hull production, container ship, for DWT 103800*	1.11	unit
propulsion system, liquid H_2-PEMFC, size6*	1	unit

Table S4.180. Life cycle inventory of propulsion system, liquid H_2-PEMFC, size6 (1 unit)

Exchanges	Amount	Unit
Economic flows		
PEMFC*	385.6	MW
market for converter, for electric passenger car	3651.3	kilogram
market for inverter, 500kW	149.1	unit
market for battery, Li-ion, NMC111, rechargeable, prismatic	513.19	kilogram
motor drive*	60.51	MW
market for marine electric motor	158.46	unit

market for control cabinet, heat and power co-generation unit, 160kW electrical	1416.94	unit
electric boiler, 100kW*	6.2	unit
Reliquefaction plant, 1 kg/h capacity*	284.6	unit

Table S4.181. Life cycle inventory of transport, container ship, liquid NH_3-SOFC, size6 (1 t-nm)

Exchanges	Amount	Unit
Economic flows		
container ship production, liquid NH_3-SOFC, size6*	6.61E-12	unit
fuel tank, cryogenic, liquid ammonia*	1.57E-05	kilogram
market for maintenance, container ship	1.77E-11	unit
ammonia production, liquid*	9.89E-03	kilogram
market group for electricity, low voltage	9.65E-06	kilowatt hour
Environmental flows		
Nitrogen oxides	9.52E-08	kilogram

Table S4.182. Life cycle inventory of container ship production, liquid NH_3-SOFC, size6 (1 unit)

Exchanges	Amount	Unit
Economic flows		
hull production, container ship, for DWT 103800*	1.11	unit
propulsion system, liquid NH_3-SOFC, size6*	1	unit

Table S4.183. Life cycle inventory of propulsion system, liquid NH_3-SOFC, size6 (1 unit)

Exchanges	Amount	Unit
Economic flows		
SOFC*	385.6	MW
market for converter, for electric passenger car	4012.65	kilogram
market for inverter, 500kW	149.1	unit
market for battery, Li-ion, NMC111, rechargeable, prismatic	1538.30	kilogram
motor drive*	60.51	MW
market for marine electric motor	158.46	unit
market for control cabinet, heat and power co-generation unit, 160kW electrical	1416.94	unit
electric boiler, 100kW*	6.2	unit
Reliquefaction plant, 1 kg/h capacity*	163.46	unit

Table S4.184. Life cycle inventory of transport, container ship, liquid H_2-DFICE, size6 (1 t-nm)

Exchanges	Amount	Unit
Economic flows		
container ship production, liquid H_2-DFICE, size6	6.30E-12	unit
fuel tank, heavy fuel oil	2.88E-07	kilogram
fuel tank, cryogenic, liquid hydrogen	5.62E-05	kilogram
market for maintenance, container ship	1.69E-11	unit
liquid hydrogen production	1.71E-03	kilogram
marine gas oil, very low-sulphur	2.53E-04	kilogram
urea solution, 40 wt%	7.45E-04	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	1.18E-08	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	4.65E-06	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	1.02E-03	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	7.58E-05	kilogram

Dinitrogen monoxide (to air, non-urban air or from high stacks)	4.20E-08	kilogram
Ammonia (to air, non-urban air or from high stacks)	5.00E-07	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	6.89E-07	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	7.33E-08	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	2.48E-06	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	0	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	8.43E-07	kilogram

Table S4.185. Life cycle inventory of container ship production, liquid H_2-DFICE, size6 (1 unit)

Exchanges	Amount	Unit
Economic flows		
hull production, container ship, for DWT 103800*	1.11	unit
propulsion system, liquid H_2-DFICE, size6*	1	unit

Table S4.186. Life cycle inventory of propulsion system, liquid H_2-DFICE, size6 (1 unit)

Exchanges	Amount	Unit
Economic flows		
marine engine, CI, ICE*	58.1	MW
market for generator, 200kW electrical	73	unit
marine engine, CI, ICE*	14.6	MW
market for control cabinet, heat and power co-generation unit, 160kW electrical	262.875	unit
SCR*	58.1	MW
electric boiler, 100kW*	6.2	unit
Reliquefaction plant, 1 kg/h capacity*	292.48	unit

Table S4.187. Life cycle inventory of transport, container ship, liquid NH_3-DFICE, size6 (1 t-nm)

Exchanges	Amount	Unit
Economic flows		
container ship production, liquid NH_3-DFICE, size6*	6.70E-12	unit
fuel tank, heavy fuel oil*	3.14E-07	kilogram
fuel tank, cryogenic, liquid ammonia*	1.90E-05	kilogram
market for maintenance, container ship	1.79E-11	unit
ammonia production, liquid*	1.20E-02	kilogram
marine gas oil, very low-sulphur*	2.75E-04	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	1.29E-08	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	5.06E-06	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	8.66E-04	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	9.47E-05	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	4.02E-07	kilogram
Ammonia (to air, non-urban air or from high stacks)	1.10E-06	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	7.49E-07	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	7.98E-08	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	2.69E-06	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	0	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	9.17E-07	kilogram

Table S4.188. Life cycle inventory of container ship production, liquid NH_3-DFICE, size6 (1 unit)

Exchanges	Amount	Unit
Economic flows		
hull production, container ship, for DWT 103800*	1.11	unit
propulsion system, liquid NH_3-DFICE, size6*	1	unit

Table S4.189. Life cycle inventory of propulsion system, liquid NH_3-DFICE, size6 (1 unit)

Exchanges	Amount	Unit
Economic flows		
marine engine, CI, ICE*	58.1	MW
market for generator, 200kW electrical	73	unit
marine engine, CI, ICE*	14.6	MW
market for control cabinet, heat and power co-generation unit, 160kW electrical	262.875	unit
SCR*	72.7	MW
electric boiler, 100kW*	6.2	unit
Reliquefaction plant, 1 kg/h capacity*	195.54	unit

Table S4.190. Life cycle inventory of transport, container ship, MeOH-DFICE, size6 (1 t-nm)

Exchanges	Amount	Unit
Economic flows		
container ship production, MeOH-DFICE, size6*	6.48E-12	unit
fuel tank, heavy fuel oil*	2.91E-07	kilogram
fuel tank, methanol*	1.37E-05	kilogram
market for maintenance, container ship	1.73E-11	unit
methanol production, CO_2 from DAC*	1.03E-02	kilogram
marine gas oil, very low-sulphur*	2.55E-04	kilogram
urea solution, 40 wt%*	8.35E-04	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	1.19E-08	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	1.20E-04	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	1.55E-02	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	9.16E-05	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	4.23E-08	kilogram
Ammonia (to air, non-urban air or from high stacks)	6.92E-07	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	6.18E-07	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	3.11E-07	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	2.49E-06	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	5.57E-06	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	3.57E-06	kilogram

Table S4.191. Life cycle inventory of container ship production, MeOH-DFICE, size6 (1 unit)

Exchanges	Amount	Unit
Economic flows		
hull production, container ship, for DWT 103800*	1.11	unit
propulsion system, MeOH-DFICE, size6*	1	unit

Table S4.192. Life cycle inventory of propulsion system, MeOH-DFICE, size6 (1 unit)

Exchanges	Amount	Unit
Economic flows		

marine engine, CI, ICE*	58.1	MW
market for generator, 200kW electrical	73	unit
marine engine, CI, ICE*	14.6	MW
market for control cabinet, heat and power co-generation unit, 160kW electrical	262.875	unit
SCR*	72.7	MW
electric boiler, 100kW*	6.2	unit

Table S4.193. Life cycle inventory of transport, container ship, LNG-DFICE, size6 (1 t-nm)

Exchanges	Amount	Unit
Economic flows		
container ship production, LNG-DFICE, size6*	5.95E-12	unit
fuel tank, heavy fuel oil*	5.16E-08	kilogram
fuel tank, LNG*	1.63E-05	kilogram
market for maintenance, container ship	1.59E-11	unit
natural gas, liquid*	3.90E-03	kilogram
marine gas oil, very low-sulphur*	4.52E-05	kilogram
urea solution, 40 wt%*	7.04E-04	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	1.17E-04	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	3.08E-05	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	1.07E-02	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	7.13E-05	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	3.71E-07	kilogram
Ammonia (to air, non-urban air or from high stacks)	4.70E-07	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	1.20E-05	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	8.20E-08	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	4.42E-07	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	0	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	9.43E-07	kilogram

Table S4.194. Life cycle inventory of container ship production, LNG-DFICE, size6 (1 unit)

Exchanges	Amount	Unit
Economic flows		
hull production, container ship, for DWT 103800*	1.11	unit
propulsion system, LNG-DFICE, size6*	1	unit

Table S4.195. Life cycle inventory of propulsion system, LNG-DFICE, size6 (1 unit)

Exchanges	Amount	Unit
Economic flows		
marine engine, CI, ICE*	58.1	MW
market for generator, 200kW electrical	73	unit
marine engine, CI, ICE*	14.6	MW
market for control cabinet, heat and power co-generation unit, 160kW electrical	262.875	unit
SCR*	58.1	MW
market for gas boiler*	62	unit
Reliquefaction plant, 1 kg/h capacity*	232.74	unit

Table S4.196. Life cycle inventory of transport, container ship, BIO-LNG-DFICE, size6 (1 t-nm)

Exchanges	Amount	Unit
Economic flows		
container ship production, LNG-DFICE, size6	5.95E-12	unit
fuel tank, heavy fuel oil	5.16E-08	kilogram
fuel tank, LNG	1.63E-05	kilogram
market for maintenance, container ship	1.59E-11	unit
natural gas, liquid, woody biomass	3.90E-03	kilogram
marine gas oil, very low-sulphur	4.52E-05	kilogram
urea solution, 40 wt%	7.04E-04	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	1.17E-04	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	3.08E-05	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	1.07E-02	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	7.13E-05	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	3.71E-07	kilogram
Ammonia (to air, non-urban air or from high stacks)	4.70E-07	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	1.20E-05	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	8.20E-08	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	4.42E-07	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	0	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	9.43E-07	kilogram

Table S4.197. Life cycle inventory of transport, container ship, LOHC-SOFC, size6 (1 t-nm)

Exchanges	Amount	Unit
Economic flows		
container ship production, LOHC-SOFC, size6*	9.46E-12	unit
fuel tank, heavy fuel oil*	3.67E-05	kilogram
market for maintenance, container ship	2.53E-11	unit
dehydrogenation of perhydro-dibenzyltoluene (H18-DBT) for releasing hydrogen*	2.19E-03	kilogram
market group for electricity, low voltage	1.38E-05	kilowatt hour

Table S4.198. Life cycle inventory of container ship production, LOHC-SOFC, size6 (1 unit)

Exchanges	Amount	Unit
Economic flows		
hull production, container ship, for DWT 103800*	1.11	unit
propulsion system, LOHC-SOFC, size6*	1	unit

Table S4.199. Life cycle inventory of propulsion system, LOHC-SOFC, size6 (1 unit)

Exchanges	Amount	Unit
Economic flows		
SOFC*	385.6	MW
market for converter, for electric passenger car	4012.65	kilogram
market for inverter, 500kW	149.1	unit
market for battery, Li-ion, NMC111, rechargeable, prismatic	1538.298	kilogram
motor drive*	60.51	MW
market for marine electric motor	158.463	unit
market for control cabinet, heat and power co-generation unit, 160kW electrical	1416.9375	unit
LOHC reactor*	49.36	MW H_2

electric boiler, 100kW*	6.2	unit

Table S4.200. Life cycle inventory of transport, container ship, LOHC-DFICE, size6 (1 t-nm)

Exchanges	Amount	Unit
Economic flows		
container ship production, LOHC-DFICE, size6*	1.02E-11	unit
fuel tank, heavy fuel oil*	4.56E-07	kilogram
fuel tank, heavy fuel oil*	4.52E-05	kilogram
market for maintenance, container ship	2.72E-11	unit
dehydrogenation of perhydro-dibenzyltoluene (H18-DBT) for releasing hydrogen*	2.70E-03	kilogram
marine gas oil, very low-sulphur*	3.99E-04	kilogram
urea solution, 40 wt%*	1.20E-03	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	1.87E-08	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	7.34E-06	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	1.61E-03	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	1.22E-04	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	6.63E-08	kilogram
Ammonia (to air, non-urban air or from high stacks)	8.05E-07	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	1.09E-06	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	1.16E-07	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	3.91E-06	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	0.00E+00	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	1.33E-06	kilogram

Table S4.201. Life cycle inventory of container ship production, LOHC-DFICE, size6 (1 unit)

Exchanges	Amount	Unit
Economic flows		
hull production, container ship, for DWT 103800*	1.11	unit
propulsion system, LOHC-DFICE, size6*	1	unit

Table S4.202. Life cycle inventory of propulsion system, LOHC-DFICE, size6 (1 unit)

Exchanges	Amount	Unit
Economic flows		
marine engine, CI, ICE*	58.1	MW
market for generator, 200kW electrical	73	unit
marine engine, CI, ICE*	14.6	MW
market for control cabinet, heat and power co-generation unit, 160kW electrical	262.875	unit
LOHC reactor*	59.54	MW H_2
SCR*	58.1	MW
electric boiler, 100kW*	6.2	unit

Table S4.203. Life cycle inventory of transport, container ship, HFO-ICE, size7 (1 t-nm)

Exchanges	Amount	Unit
Economic flows		
container ship production, HFO-ICE, size7*	5.00E-12	unit
fuel tank, heavy fuel oil*	7.56E-06	kilogram
market for maintenance, container ship	1.71E-11	unit

heavy fuel oil, very low-sulphur*	3.65E-03	kilogram
urea solution, 40 wt%*	6.60E-04	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	1.75E-07	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	1.90E-05	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	1.19E-02	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	6.41E-05	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	5.84E-07	kilogram
Ammonia (to air, non-urban air or from high stacks)	5.27E-07	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	8.62E-06	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	1.03E-06	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	3.65E-05	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	0	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	1.18E-05	kilogram

Table S4.204. Life cycle inventory of container ship production, HFO-ICE, size7 (1 unit)

Exchanges	Amount	Unit
Economic flows		
hull production, container ship, for DWT 103800*	1.42	unit
propulsion system, HFO-ICE, size7*	1	unit

Table S4.205. Life cycle inventory of propulsion system, HFO-ICE, size7 (1 unit)

Exchanges	Amount	Unit
Economic flows		
marine engine, CI, ICE*	59.78	MW
market for generator, 200kW electrical	73	unit
marine engine, CI, ICE*	14.6	MW
market for control cabinet, heat and power co-generation unit, 160kW electrical	262.875	unit
SCR*	74.38	MW
market for oil boiler, 100kW	6.3	unit

Table S4.206. Life cycle inventory of transport, container ship, liquid H_2-PEMFC, size7 (1 t-nm)

Exchanges	Amount	Unit
Economic flows		
container ship production, liquid H_2-PEMFC, size7*	5.14E-12	unit
fuel tank, cryogenic, liquid hydrogen*	4.94E-05	kilogram
market for maintenance, container ship	1.76E-11	unit
liquid hydrogen production*	1.24E-03	kilogram
market group for electricity, low voltage	2.11E-06	kilowatt hour

Table S4.207. Life cycle inventory of container ship production, liquid H_2-PEMFC, size7 (1 unit)

Exchanges	Amount	Unit
Economic flows		
hull production, container ship, for DWT 103800*	1.42	unit
propulsion system, liquid H_2-PEMFC, size7*	1	unit

Table S4.208. Life cycle inventory of propulsion system, liquid H_2-PEMFC, size7 (1 unit)

Exchanges	Amount	Unit

Economic flows		
PEMFC*	394.55	MW
market for converter, for electric passenger car	3736.35	kilogram
market for inverter, 500kW	149.2	unit
market for battery, Li-ion, NMC111, rechargeable, prismatic	525.96	kilogram
motor drive*	62.26	MW
market for marine electric motor	163.053	unit
market for control cabinet, heat and power co-generation unit, 160kW electrical	1449.9375	unit
electric boiler, 100kW*	6.3	unit
Reliquefaction plant, 1 kg/h capacity*	314.92	unit

Table S4.209. Life cycle inventory of transport, container ship, liquid NH_3-SOFC, size7 (1 t-nm)

Exchanges	Amount	Unit
Economic flows		
container ship production, liquid NH_3-SOFC, size7*	5.42E-12	unit
fuel tank, cryogenic, liquid ammonia*	1.36E-05	kilogram
market for maintenance, container ship	1.86E-11	unit
ammonia production, liquid*	7.07E-03	kilogram
market group for electricity, low voltage	6.68E-06	kilowatt hour
Environmental flows		
Nitrogen oxides (to air, non-urban air or from high stacks)	6.81E-08	kilogram

Table S4.210. Life cycle inventory of container ship production, liquid NH_3-SOFC, size7 (1 unit)

Exchanges	Amount	Unit
Economic flows		
hull production, container ship, for DWT 103800*	1.42	unit
propulsion system, liquid NH_3-SOFC, size7*	1	unit

Table S4.211. Life cycle inventory of propulsion system, liquid NH_3-SOFC, size7 (1 unit)

Exchanges	Amount	Unit
Economic flows		
SOFC	394.55	MW
market for converter, for electric passenger car	4105.8	kilogram
market for inverter, 500kW	149.2	unit
market for battery, Li-ion, NMC111, rechargeable, prismatic	1574.04	kilogram
motor drive*	62.26	MW
market for marine electric motor	163.053	unit
market for control cabinet, heat and power co-generation unit, 160kW electrical	1449.9375	unit
electric boiler, 100kW*	6.3	unit
Reliquefaction plant, 1 kg/h capacity*	172.97	unit

Table S4.212. Life cycle inventory of transport, container ship, liquid H_2-DFICE, size7 (1 t-nm)

Exchanges	Amount	Unit
Economic flows		
container ship production, liquid H_2-DFICE, size7	5.26E-12	unit
fuel tank, heavy fuel oil	2.67E-07	kilogram
fuel tank, cryogenic, liquid hydrogen	5.21E-05	kilogram
market for maintenance, container ship	1.81E-11	unit
heavy fuel oil, very low-sulphur	0	kilogram

liquid hydrogen production	1.31E-03	kilogram
marine gas oil, very low-sulphur	1.93E-04	kilogram
market group for electricity, low voltage	0	kilowatt hour
urea solution, 40 wt%	5.60E-04	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	9.04E-09	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	3.55E-06	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	7.72E-04	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	5.71E-05	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	3.20E-08	kilogram
Ammonia (to air, non-urban air or from high stacks)	3.75E-07	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	5.26E-07	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	5.59E-08	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	1.89E-06	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	0	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	6.43E-07	kilogram

Table S4.213. Life cycle inventory of container ship production, liquid H_2-DFICE, size7 (1 unit)

Exchanges	Amount	Unit
Economic flows		
hull production, container ship, for DWT 103800*	1.42	unit
propulsion system, liquid H_2-DFICE, size7*	1	unit

Table S4.214. Life cycle inventory of propulsion system, liquid H_2-DFICE, size7 (1 unit)

Exchanges	Amount	Unit
Economic flows		
marine engine, CI, ICE*	59.78	MW
market for generator, 200kW electrical	73	unit
marine engine, CI, ICE*	14.6	MW
market for control cabinet, heat and power co-generation unit, 160kW electrical	262.875	unit
SCR*	59.78	MW
electric boiler, 100kW	6.3	unit
Reliquefaction plant, 1 kg/h capacity*	323.6	unit

Table S4.215. Life cycle inventory of transport, container ship, liquid NH_3-DFICE, size7 (1 t-nm)

Exchanges	Amount	Unit
Economic flows		
container ship production, liquid NH_3-DFICE, size7*	5.53E-12	unit
fuel tank, heavy fuel oil*	2.87E-07	kilogram
fuel tank, cryogenic, liquid ammonia*	1.74E-05	kilogram
market for maintenance, container ship	1.90E-11	unit
ammonia production, liquid*	9.02E-03	kilogram
marine gas oil, very low-sulphur*	2.07E-04	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	9.69E-09	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	3.80E-06	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	6.52E-04	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	7.10E-05	kilogram

Dinitrogen monoxide (to air, non-urban air or from high stacks)	3.02E-07	kilogram
Ammonia (to air, non-urban air or from high stacks)	8.27E-07	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	5.64E-07	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	6.00E-08	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	2.03E-06	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	0	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	6.90E-07	kilogram

Table S4.216. Life cycle inventory of container ship production, liquid NH_3-DFICE, size7 (1 unit)

Exchanges	Amount	Unit
Economic flows		
hull production, container ship, for DWT 103800*	1.42	unit
propulsion system, liquid NH_3-DFICE, size7*	1	unit

Table S4.217. Life cycle inventory of propulsion system, liquid NH_3-DFICE, size7 (1 unit)

Exchanges	Amount	Unit
Economic flows		
marine engine, CI, ICE*	59.78	MW
market for generator, 200kW electrical	73	unit
marine engine, CI, ICE*	14.6	MW
market for control cabinet, heat and power co-generation unit, 160kW electrical	262.875	unit
SCR*	74.38	MW
electric boiler, 100kW*	6.3	unit
Reliquefaction plant, 1 kg/h capacity*	216.35	unit

Table S4.218. Life cycle inventory of transport, container ship, MeOH-DFICE, size7 (1 t-nm)

Exchanges	Amount	Unit
Economic flows		
container ship production, MeOH-DFICE, size7*	5.39E-12	unit
fuel tank, heavy fuel oil*	2.67E-07	kilogram
fuel tank, methanol*	1.26E-05	kilogram
market for maintenance, container ship	1.85E-11	unit
methanol production, CO_2 from DAC*	7.78E-03	kilogram
marine gas oil, very low-sulphur*	1.93E-04	kilogram
urea solution, 40 wt%*	6.26E-04	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	9.02E-09	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	9.10E-05	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	1.17E-02	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	6.91E-05	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	3.20E-08	kilogram
Ammonia (to air, non-urban air or from high stacks)	5.23E-07	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	4.68E-07	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	2.35E-07	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	1.89E-06	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	4.22E-06	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	2.70E-06	kilogram

Table S4.219. Life cycle inventory of container ship production, MeOH-DFICE, size7 (1 unit)

Exchanges	Amount	Unit
Economic flows		
hull production, container ship, for DWT 103800*	1.42	unit
propulsion system, MeOH-DFICE, size7*	1	unit

Table S4.220. Life cycle inventory of propulsion system, MeOH-DFICE, size7 (1 unit)

Exchanges	Amount	Unit
Economic flows		
marine engine, CI, ICE*	59.78	MW
market for generator, 200kW electrical	73	unit
marine engine, CI, ICE*	14.6	MW
market for control cabinet, heat and power co-generation unit, 160kW electrical	262.875	unit
SCR*	74.38	MW
electric boiler, 100kW*	6.3	unit

Table S4.221. Life cycle inventory of transport, container ship, LNG-DFICE, size7 (1 t-nm)

Exchanges	Amount	Unit
Economic flows		
container ship production, LNG-DFICE, size7	5.02E-12	unit
fuel tank, heavy fuel oil	4.82E-08	kilogram
fuel tank, LNG	1.52E-05	kilogram
market for maintenance, container ship	1.72E-11	unit
natural gas, liquid	3.00E-03	kilogram
marine gas oil, very low-sulphur	3.48E-05	kilogram
urea solution, 40 wt%	5.34E-04	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	9.00E-05	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	2.37E-05	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	8.21E-03	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	5.43E-05	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	2.85E-07	kilogram
Ammonia (to air, non-urban air or from high stacks)	3.56E-07	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	9.20E-06	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	6.31E-08	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	3.40E-07	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	0	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	7.25E-07	kilogram

Table S4.222. Life cycle inventory of container ship production, LNG-DFICE, size7 (1 unit)

Exchanges	Amount	Unit
Economic flows		
hull production, container ship, for DWT 103800*	1.42	unit
propulsion system, LNG-DFICE, size7*	1	unit

Table S4.223. Life cycle inventory of propulsion system, LNG-DFICE, size7 (1 unit)

Exchanges	Amount	Unit
Economic flows		
marine engine, CI, ICE*	59.78	MW

market for generator, 200kW electrical	73	unit
marine engine, CI, ICE*	14.6	MW
market for control cabinet, heat and power co-generation unit, 160kW electrical	262.875	unit
SCR*	59.78	MW
market for gas boiler	63	unit
Reliquefaction plant, 1 kg/h capacity*	257.49	unit

Table S4.224. Life cycle inventory of transport, container ship, BIO-LNG-DFICE, size7 (1 t-nm)

Exchanges	Amount	Unit
Economic flows		
container ship production, LNG-DFICE, size7*	5.02E-12	unit
fuel tank, heavy fuel oil*	4.82E-08	kilogram
fuel tank, LNG*	1.52E-05	kilogram
market for maintenance, container ship	1.72E-11	unit
natural gas, liquid, woody biomass*	3.00E-03	kilogram
marine gas oil, very low-sulphur*	3.48E-05	kilogram
urea solution, 40 wt%*	5.34E-04	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	9.00E-05	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	2.37E-05	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	8.21E-03	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	5.43E-05	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	2.85E-07	kilogram
Ammonia (to air, non-urban air or from high stacks)	3.56E-07	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	9.20E-06	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	6.31E-08	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	3.40E-07	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	0	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	7.25E-07	kilogram

Table S4.225. Life cycle inventory of transport, container ship, LOHC-SOFC, size7 (1 t-nm)

Exchanges	Amount	Unit
Economic flows		
container ship production, LOHC-SOFC, size7*	7.05E-12	unit
fuel tank, heavy fuel oil*	2.90E-05	kilogram
market for maintenance, container ship	2.42E-11	unit
dehydrogenation of perhydro-dibenzyltoluene (H18-DBT) for releasing hydrogen*	1.42E-03	kilogram
market group for electricity, low voltage	8.68E-06	kilowatt hour

Table S4.226. Life cycle inventory of container ship production, LOHC-SOFC, size7 (1 unit)

Exchanges	Amount	Unit
Economic flows		
hull production, container ship, for DWT 103800*	1.42	unit
propulsion system, LOHC-SOFC, size7*	1	unit

Table S4.227. Life cycle inventory of propulsion system, LOHC-SOFC, size7 (1 unit)

Exchanges	Amount	Unit
Economic flows		

SOFC*	394.55	MW
market for converter, for electric passenger car	4105.8	kilogram
market for inverter, 500kW	149.2	unit
market for battery, Li-ion, NMC111, rechargeable, prismatic	1574.043	kilogram
motor drive*	62.26	MW
market for marine electric motor	163.053	unit
market for control cabinet, heat and power co-generation unit, 160kW electrical	1449.9375	unit
LOHC reactor*	45.61	MW H_2
electric boiler, 100kW*	6.3	unit

Table S4.228. Life cycle inventory of transport, container ship, LOHC-DFICE, size7 (1 t-nm)

Exchanges	Amount	Unit
Economic flows		
container ship production, LOHC-DFICE, size7*	7.62E-12	unit
fuel tank, heavy fuel oil*	3.78E-07	kilogram
fuel tank, heavy fuel oil*	3.75E-05	kilogram
market for maintenance, container ship	2.61E-11	unit
dehydrogenation of perhydro-dibenzyltoluene (H18-DBT) for releasing hydrogen*	1.84E-03	kilogram
marine gas oil, very low-sulphur*	2.73E-04	kilogram
urea solution, 40 wt%*	8.10E-04	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	1.28E-08	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	5.01E-06	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	1.10E-03	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	8.22E-05	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	4.53E-08	kilogram
Ammonia (to air, non-urban air or from high stacks)	5.43E-07	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	7.43E-07	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	7.91E-08	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	2.67E-06	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	0.00E+00	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	9.09E-07	kilogram

Table S4.229. Life cycle inventory of container ship production, LOHC-DFICE, size7 (1 unit)

Exchanges	Amount	Unit
Economic flows		
hull production, container ship, for DWT 103800*	1.42	unit
propulsion system, LOHC-DFICE, size7*	1	unit

Table S4.230. Life cycle inventory of propulsion system, LOHC-DFICE, size7 (1 unit)

Exchanges	Amount	Unit
Economic flows		
marine engine, CI, ICE*	59.78	MW
market for generator, 200kW electrical	73	unit
marine engine, CI, ICE*	14.6	MW
market for control cabinet, heat and power co-generation unit, 160kW electrical	262.875	unit
LOHC reactor*	57.52	MW H_2
SCR*	59.78	MW

electric boiler, 100kW*	6.3	unit

Table S4.231. Life cycle inventory of transport, container ship, HFO-ICE, size8 (1 t-nm)

Exchanges	Amount	Unit
Economic flows		
container ship production, HFO-ICE, size8	3.48E-12	unit
fuel tank, heavy fuel oil	6.69E-06	kilogram
market for maintenance, container ship	1.51E-11	unit
heavy fuel oil, very low-sulphur	3.14E-03	kilogram
urea solution, 40 wt%	5.69E-04	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	1.51E-07	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	1.64E-05	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	1.02E-02	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	5.52E-05	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	5.04E-07	kilogram
Ammonia (to air, non-urban air or from high stacks)	4.54E-07	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	7.43E-06	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	8.87E-07	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	3.15E-05	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	0	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	1.02E-05	kilogram

Table S4.232. Life cycle inventory of container ship production, HFO-ICE, size8 (1 unit)

Exchanges	Amount	Unit
Economic flows		
hull production, container ship, for DWT 103800*	1.80	unit
propulsion system, HFO-ICE, size8*	1	unit

Table S4.233. Life cycle inventory of propulsion system, HFO-ICE, size8 (1 unit)

Exchanges	Amount	Unit
Economic flows		
marine engine, CI, ICE*	59.78	MW
market for generator, 200kW electrical	90	unit
marine engine, CI, ICE*	18	MW
market for control cabinet, heat and power co-generation unit, 160kW electrical	324	unit
SCR*	77.78	MW
market for oil boiler, 100kW	6.3	unit

Table S4.234. Life cycle inventory of transport, container ship, liquid H_2-PEMFC, size8 (1 t-nm)

Exchanges	Amount	Unit
Economic flows		
container ship production, liquid H_2-PEMFC, size8*	3.58E-12	unit
fuel tank, cryogenic, liquid hydrogen*	4.23E-05	kilogram
market for maintenance, container ship	1.55E-11	unit
liquid hydrogen production*	1.06E-03	kilogram
market group for electricity, low voltage	1.54E-06	kilowatt hour

Table S4.235. Life cycle inventory of container ship production, liquid H_2-PEMFC, size8 (1 unit)

Exchanges	Amount	Unit
Economic flows		
hull production, container ship, for DWT 103800*	1.80	unit
propulsion system, liquid H_2-PEMFC, size8*	1	unit

Table S4.236. Life cycle inventory of propulsion system, liquid H_2-PEMFC, size8 (1 unit)

Exchanges	Amount	Unit
Economic flows		
PEMFC*	411.55	MW
market for converter, for electric passenger car	3897.45	kilogram
market for inverter, 500kW	182.5	unit
market for battery, Li-ion, NMC111, rechargeable, prismatic	548.94	kilogram
motor drive*	62.26	MW
market for marine electric motor	163.053	unit
market for control cabinet, heat and power co-generation unit, 160kW electrical	1512.5625	unit
electric boiler, 100kW*	6.3	unit
Reliquefaction plant, 1 kg/h capacity*	387.83	unit

Table S4.237. Life cycle inventory of transport, container ship, liquid NH_3-SOFC, size8 (1 t-nm)

Exchanges	Amount	Unit
Economic flows		
container ship production, liquid NH_3-SOFC, size8*	3.76E-12	unit
fuel tank, cryogenic, liquid ammonia*	1.19E-05	kilogram
market for maintenance, container ship	1.63E-11	unit
ammonia production, liquid*	6.22E-03	kilogram
market group for electricity, low voltage	4.83E-06	kilowatt hour
Environmental flows		
Nitrogen oxides um (to air, non-urban air or from high stacks)	5.99E-08	kilogram

Table S4.238. Life cycle inventory of container ship production, liquid NH_3-SOFC, size8 (1 unit)

Exchanges	Amount	Unit
Economic flows		
hull production, container ship, for DWT 103800*	1.80	unit
propulsion system, liquid NH_3-SOFC, size8*	1	unit

Table S4.239. Life cycle inventory of propulsion system, liquid NH_3-SOFC, size8 (1 unit)

Exchanges	Amount	Unit
Economic flows		
SOFC*	411.55	MW
market for converter, for electric passenger car	4282.65	kilogram
market for inverter, 500kW	182.5	unit
market for battery, Li-ion, NMC111, rechargeable, prismatic	1641.70	kilogram
motor drive*	62.26	MW
market for marine electric motor	163.053	unit
market for control cabinet, heat and power co-generation unit, 160kW electrical	1512.5625	unit
electric boiler, 100kW*	6.3	unit
Reliquefaction plant, 1 kg/h capacity*	219.22	unit

Table S4.240. Life cycle inventory of transport, container ship, liquid H_2-DFICE, size8 (1 t-nm)

Exchanges	Amount	Unit
Economic flows		
container ship production, liquid H_2-DFICE, size8	3.65E-12	unit
fuel tank, heavy fuel oil	2.29E-07	kilogram
fuel tank, cryogenic, liquid hydrogen	4.47E-05	kilogram
market for maintenance, container ship	1.59E-11	unit
liquid hydrogen production	1.12E-03	kilogram
marine gas oil, very low-sulphur	1.66E-04	kilogram
urea solution, 40 wt%	4.79E-04	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	7.77E-09	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	3.05E-06	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	6.63E-04	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	4.90E-05	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	2.76E-08	kilogram
Ammonia (to air, non-urban air or from high stacks)	3.21E-07	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	4.52E-07	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	4.81E-08	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	1.62E-06	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	0	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	5.53E-07	kilogram

Table S4.241. Life cycle inventory of container ship production, liquid H_2-DFICE, size8 (1 unit)

Exchanges	Amount	Unit
Economic flows		
hull production, container ship, for DWT 103800*	1.80	unit
propulsion system, liquid H_2-DFICE, size8*	1	unit

Table S4.242. Life cycle inventory of propulsion system, liquid H_2-DFICE, size8 (1 unit)

Exchanges	Amount	Unit
Economic flows		
marine engine, CI, ICE*	59.78	MW
market for generator, 200kW electrical	90	unit
marine engine, CI, ICE*	18	MW
market for control cabinet, heat and power co-generation unit, 160kW electrical	324	unit
SCR*	59.78	MW
electric boiler, 100kW*	6.3	unit
Reliquefaction plant, 1 kg/h capacity*	400.26	unit

Table S4.243. Life cycle inventory of transport, container ship, liquid NH_3-DFICE, size8 (1 t-nm)

Exchanges	Amount	Unit
Economic flows		
container ship production, liquid NH_3-DFICE, size8*	3.83E-12	unit
fuel tank, heavy fuel oil*	2.46E-07	kilogram
fuel tank, cryogenic, liquid ammonia*	1.49E-05	kilogram
market for maintenance, container ship	1.66E-11	unit
ammonia production, liquid*	7.74E-03	kilogram
marine gas oil, very low-sulphur*	1.77E-04	kilogram

Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	8.30E-09	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	3.26E-06	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	5.59E-04	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	6.09E-05	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	2.59E-07	kilogram
Ammonia (to air, non-urban air or from high stacks)	7.09E-07	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	4.83E-07	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	5.14E-08	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	1.74E-06	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	0	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	5.92E-07	kilogram

Table S4.244. Life cycle inventory of container ship production, liquid NH_3-DFICE, size8 (1 unit)

Exchanges	Amount	Unit
Economic flows		
hull production, container ship, for DWT 103800*	1.80	unit
propulsion system, liquid NH_3-DFICE, size8*	1	unit

Table S4.245. Life cycle inventory of propulsion system, liquid NH_3-DFICE, size8 (1 unit)

Exchanges	Amount	Unit
Economic flows		
marine engine, CI, ICE*	59.78	MW
market for generator, 200kW electrical	90	unit
marine engine, CI, ICE*	18	MW
market for control cabinet, heat and power co-generation unit, 160kW electrical	324	unit
SCR*	77.78	MW
electric boiler, 100kW*	6.3	unit
Reliquefaction plant, 1 kg/h capacity*	267.61	unit

Table S4.246. Life cycle inventory of transport, container ship, MeOH-DFICE, size8 (1 t-nm)

Exchanges	Amount	Unit
Economic flows		
container ship production, MeOH-DFICE, size8*	3.73E-12	unit
fuel tank, heavy fuel oil*	2.29E-07	kilogram
fuel tank, methanol*	1.08E-05	kilogram
market for maintenance, container ship	1.62E-11	unit
methanol production, CO_2 from DAC*	6.68E-03	kilogram
marine gas oil, very low-sulphur*	1.65E-04	kilogram
urea solution, 40 wt%*	5.36E-04	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	7.75E-09	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	7.81E-05	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	1.01E-02	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	5.93E-05	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	2.75E-08	kilogram
Ammonia (to air, non-urban air or from high stacks)	4.49E-07	kilogram

NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	4.01E-07	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	2.02E-07	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	1.62E-06	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	3.62E-06	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	2.32E-06	kilogram

Table S4.247. Life cycle inventory of container ship production, MeOH-DFICE, size8 (1 unit)

Exchanges	Amount	Unit
Economic flows		
hull production, container ship, for DWT 103800*	1.80	unit
propulsion system, MeOH-DFICE, size8*	1	unit

Table S4.248. Life cycle inventory of propulsion system, MeOH-DFICE, size8 (1 unit)

Exchanges	Amount	Unit
Economic flows		
marine engine, CI, ICE*	59.78	MW
market for generator, 200kW electrical	90	unit
marine engine, CI, ICE*	18	MW
market for control cabinet, heat and power co-generation unit, 160kW electrical	324	unit
SCR*	77.78	MW
electric boiler, 100kW*	6.3	unit

Table S4.249. Life cycle inventory of transport, container ship, LNG-DFICE, size8 (1 t-nm)

Exchanges	Amount	Unit
Economic flows		
container ship production, LNG-DFICE, size8*	3.49E-12	unit
fuel tank, heavy fuel oil*	4.14E-08	kilogram
fuel tank, LNG*	1.31E-05	kilogram
market for maintenance, container ship	1.52E-11	unit
natural gas, liquid*	2.58E-03	kilogram
marine gas oil, very low-sulphur*	2.99E-05	kilogram
urea solution, 40 wt%*	4.58E-04	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	7.76E-05	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	2.04E-05	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	7.07E-03	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	4.66E-05	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	2.46E-07	kilogram
Ammonia (to air, non-urban air or from high stacks)	3.06E-07	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	7.93E-06	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	5.43E-08	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	2.93E-07	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	0	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	6.25E-07	kilogram

Table S4.250. Life cycle inventory of container ship production, LNG-DFICE, size8 (1 unit)

Exchanges	Amount	Unit
Economic flows		

hull production, container ship, for DWT 103800*	1.80	unit
propulsion system, LNG-DFICE, size8*	1	unit

Table S4.251. Life cycle inventory of propulsion system, LNG-DFICE, size8 (1 unit)

Exchanges	Amount	Unit
Economic flows		
marine engine, CI, ICE*	59.78	MW
market for generator, 200kW electrical	90	unit
marine engine, CI, ICE*	18	MW
market for control cabinet, heat and power co-generation unit, 160kW electrical	324	unit
SCR*	59.78	MW
market for gas boiler	63	unit
Reliquefaction plant, 1 kg/h capacity*	318.5	unit

Table S4.252. Life cycle inventory of transport, container ship, BIO-LNG-DFICE, size8 (1 t-nm)

Exchanges	Amount	Unit
Economic flows		
container ship production, LNG-DFICE, size8*	3.49E-12	unit
fuel tank, heavy fuel oil*	4.14E-08	kilogram
fuel tank, LNG*	1.31E-05	kilogram
market for maintenance, container ship	1.52E-11	unit
natural gas, liquid, woody biomass*	2.58E-03	kilogram
marine gas oil, very low-sulphur*	2.99E-05	kilogram
urea solution, 40 wt%*	4.58E-04	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	7.76E-05	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	2.04E-05	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	7.07E-03	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	4.66E-05	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	2.46E-07	kilogram
Ammonia (to air, non-urban air or from high stacks)	3.06E-07	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	7.93E-06	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	5.43E-08	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	2.93E-07	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	0	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	6.25E-07	kilogram

Table S4.253. Life cycle inventory of transport, container ship, LOHC-SOFC, size8 (1 t-nm)

Exchanges	Amount	Unit
Economic flows		
container ship production, LOHC-SOFC, size8*	4.85E-12	unit
fuel tank, heavy fuel oil*	2.52E-05	kilogram
market for maintenance, container ship*	2.10E-11	unit
dehydrogenation of perhydro-dibenzyltoluene (H18-DBT) for releasing hydrogen*	1.24E-03	kilogram
market group for electricity, low voltage	6.23E-06	kilowatt hour

Table S4.254. Life cycle inventory of container ship production, LOHC-SOFC, size8 (1 unit)

Exchanges	Amount	Unit

Economic flows		
hull production, container ship, for DWT 103800*	1.80	unit
propulsion system, LOHC-SOFC, size8*	1	unit

Table S4.255. Life cycle inventory of propulsion system, LOHC-SOFC, size8 (1 unit)

Exchanges	Amount	Unit
Economic flows		
SOFC*	411.55	MW
market for converter, for electric passenger car	4282.65	kilogram
market for inverter, 500kW	182.5	unit
market for battery, Li-ion, NMC111, rechargeable, prismatic	1641.702	kilogram
motor drive*	62.26	MW
market for marine electric motor	163.053	unit
market for control cabinet, heat and power co-generation unit, 160kW electrical	1512.5625	unit
LOHC reactor*	57	MW H_2
electric boiler, 100kW*	6.3	unit

Table S4.256. Life cycle inventory of transport, container ship, LOHC-DFICE, size8 (1 t-nm)

Exchanges	Amount	Unit
Economic flows		
container ship production, LOHC-DFICE, size8*	5.17E-12	unit
fuel tank, heavy fuel oil*	3.18E-07	kilogram
fuel tank, heavy fuel oil*	3.15E-05	kilogram
market for maintenance, container ship	2.25E-11	unit
dehydrogenation of perhydro-dibenzyltoluene (H18-DBT) for releasing hydrogen*	1.55E-03	kilogram
marine gas oil, very low-sulphur*	2.29E-04	kilogram
urea solution, 40 wt%*	6.78E-04	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	1.07E-08	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	4.22E-06	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	9.22E-04	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	6.89E-05	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	3.81E-08	kilogram
Ammonia (to air, non-urban air or from high stacks)	4.55E-07	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	6.25E-07	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	6.65E-08	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	2.25E-06	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	0.00E+00	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	7.65E-07	kilogram

Table S4.257. Life cycle inventory of propulsion system, LOHC-DFICE, size8 (1 t-nm)

Exchanges	Amount	Unit
Economic flows		
hull production, container ship, for DWT 103800*	1.80	unit
propulsion system, LOHC-DFICE, size8*	1	unit

Table S4.258. Life cycle inventory of propulsion system, LOHC-DFICE, size8 (1 t-nm)

Exchanges	Amount	Unit

Economic flows		
marine engine, CI, ICE*	59.78	MW
market for generator, 200kW electrical	90	unit
marine engine, CI, ICE*	18	MW
market for control cabinet, heat and power co-generation unit, 160kW electrical	324	unit
LOHC reactor*	70.15	MW H_2
SCR*	59.78	MW
electric boiler, 100kW*	6.3	unit

Table S4.259. Life cycle inventory of transport, container ship, HFO-ICE, size9 (1 t-nm)

Exchanges	Amount	Unit
Economic flows		
container ship production, HFO-ICE, size9*	3.90E-12	unit
fuel tank, heavy fuel oil*	8.69E-06	kilogram
market for maintenance, container ship	1.81E-11	unit
heavy fuel oil, very low-sulphur*	2.93E-03	kilogram
urea solution, 40 wt%*	5.26E-04	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	1.41E-07	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	1.53E-05	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	9.56E-03	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	5.13E-05	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	4.71E-07	kilogram
Ammonia (to air, non-urban air or from high stacks)	4.24E-07	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	6.94E-06	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	8.28E-07	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	2.94E-05	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	0	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	9.52E-06	kilogram

Table S4.260. Life cycle inventory of container ship production, HFO-ICE, size9 (1 unit)

Exchanges	Amount	Unit
Economic flows		
hull production, container ship, for DWT 103800*	1.92	unit
propulsion system, HFO-ICE, size9*	1	unit

Table S4.261. Life cycle inventory of propulsion system, HFO-ICE, size9 (1 unit)

Exchanges	Amount	Unit
Economic flows		
marine engine, CI, ICE*	59.3	MW
market for generator, 200kW electrical	96	unit
marine engine, CI, ICE*	19.2	MW
market for control cabinet, heat and power co-generation unit, 160kW electrical	345.75	unit
SCR*	78.51	MW
market for oil boiler, 100kW	7	unit

Table S4.262. Life cycle inventory of transport, container ship, liquid H_2-PEMFC, size9 (1 t-nm)

Exchanges	Amount	Unit

Economic flows		
container ship production, liquid H_2-PEMFC, size9*	4.01E-12	unit
fuel tank, cryogenic, liquid hydrogen*	5.07E-05	kilogram
market for maintenance, container ship	1.86E-11	unit
liquid hydrogen production*	9.94E-04	kilogram
market group for electricity, low voltage	1.36E-06	kilowatt hour

Table S4.263. Life cycle inventory of container ship production, liquid H_2-PEMFC, size9 (1 unit)

Exchanges	Amount	Unit
Economic flows		
hull production, container ship, for DWT 103800*	1.92	unit
propulsion system, liquid H_2-PEMFC, size9*	1	unit

Table S4.264. Life cycle inventory of propulsion system, liquid H_2-PEMFC, size9 (1 unit)

Exchanges	Amount	Unit
Economic flows		
PEMFC*	415.4	MW
market for converter, for electric passenger car	3933.9	kilogram
market for inverter, 500kW	195	unit
market for battery, Li-ion, NMC111, rechargeable, prismatic	554.04	kilogram
motor drive*	61.76	MW
market for marine electric motor	161.757	unit
market for control cabinet, heat and power co-generation unit, 160kW electrical	1526.625	unit
electric boiler, 100kW*	7	unit
Reliquefaction plant, 1 kg/h capacity*	413.87	unit

Table S4.265. Life cycle inventory of transport, container ship, liquid NH_3-SOFC, size9 (1 unit)

Exchanges	Amount	Unit
Economic flows		
container ship production, liquid NH_3-SOFC, size9*	4.18E-12	unit
fuel tank, cryogenic, liquid ammonia*	1.36E-05	kilogram
market for maintenance, container ship	1.94E-11	unit
ammonia production, liquid*	5.52E-03	kilogram
market group for electricity, low voltage	4.24E-06	kilowatt hour
Environmental flows		
Nitrogen oxides (to air, non-urban air or from high stacks)	5.31E-08	kilogram

Table S4.266. Life cycle inventory of container ship production, liquid NH_3-SOFC, size9 (1 unit)

Exchanges	Amount	Unit
Economic flows		
hull production, container ship, for DWT 103800*	1.92	unit
propulsion system, liquid NH_3-SOFC, size9*	1	unit

Table S4.267. Life cycle inventory of propulsion system, liquid NH_3-SOFC, size9 (1 unit)

Exchanges	Amount	Unit
Economic flows		
SOFC*	415.4	MW
market for converter, for electric passenger car	4322.7	kilogram
market for inverter, 500kW	195	unit

market for battery, Li-ion, NMC111, rechargeable, prismatic	1657.02	kilogram
motor drive*	61.76	MW
market for marine electric motor	161.757	unit
market for control cabinet, heat and power co-generation unit, 160kW electrical	1526.625	unit
electric boiler, 100kW*	7	unit
Reliquefaction plant, 1 kg/h capacity*	223.63	unit

Table S4.268. Life cycle inventory of transport, container ship, liquid H_2-DFICE, size9 (1 t-nm)

Exchanges	Amount	Unit
Economic flows		
container ship production, liquid H_2-DFICE, size9	4.09E-12	unit
fuel tank, heavy fuel oil*	2.74E-07	kilogram
fuel tank, cryogenic, liquid hydrogen*	5.36E-05	kilogram
market for maintenance, container ship	1.90E-11	unit
liquid hydrogen production*	1.05E-03	kilogram
marine gas oil, very low-sulphur*	1.55E-04	kilogram
urea solution, 40 wt%*	4.34E-04	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	7.27E-09	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	2.85E-06	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	6.17E-04	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	4.48E-05	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	2.58E-08	kilogram
Ammonia (to air, non-urban air or from high stacks)	2.91E-07	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	4.23E-07	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	4.50E-08	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	1.52E-06	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	0	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	5.18E-07	kilogram

Table S4.269. Life cycle inventory of container ship production, liquid H_2-DFICE, size9 (1 unit)

Exchanges	Amount	Unit
Economic flows		
hull production, container ship, for DWT 103800*	1.92	unit
propulsion system, liquid H_2-DFICE, size9*	1	unit

Table S4.270. Life cycle inventory of propulsion system, liquid H_2-DFICE, size9 (1 unit)

Exchanges	Amount	Unit
Economic flows		
marine engine, CI, ICE*	59.3	MW
market for generator, 200kW electrical	96.05	unit
marine engine, CI, ICE*	19.21	MW
SCR*	59.3	MW
market for control cabinet, heat and power co-generation unit, 160kW electrical	345.75	unit
electric boiler, 100kW*	7	unit
Reliquefaction plant, 1 kg/h capacity*	427.09	unit

Table S4.271. Life cycle inventory of transport, container ship, liquid NH_3-DFICE, size9 (1 t-nm)

Exchanges	Amount	Unit
Economic flows		
container ship production, liquid NH_3-DFICE, size9	4.29E-12	unit
fuel tank, heavy fuel oil	2.94E-07	kilogram
fuel tank, cryogenic, liquid ammonia	1.78E-05	kilogram
market for maintenance, container ship	1.99E-11	unit
ammonia production, liquid	7.23E-03	kilogram
marine gas oil, very low-sulphur	1.66E-04	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	7.77E-09	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	3.05E-06	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	5.22E-04	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	5.66E-05	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	2.42E-07	kilogram
Ammonia (to air, non-urban air or from high stacks)	6.63E-07	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	4.52E-07	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	4.81E-08	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	1.62E-06	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	0	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	5.53E-07	kilogram

Table S4.272. Life cycle inventory of container ship production, liquid NH_3-DFICE, size9 (1 unit)

Exchanges	Amount	Unit
Economic flows		
hull production, container ship, for DWT 103800*	1.92	unit
propulsion system, liquid NH_3-DFICE, size9*	1	unit

Table S4.273. Life cycle inventory of propulsion system, liquid NH_3-DFICE, size9 (1 unit)

Exchanges	Amount	Unit
Economic flows		
marine engine, CI, ICE*	59.3	MW
market for generator, 200kW electrical	96.05	unit
marine engine, CI, ICE*	19.21	MW
market for control cabinet, heat and power co-generation unit, 160kW electrical	345.75	unit
SCR*	78.51	MW
electric boiler, 100kW*	7	unit
Reliquefaction plant, 1 kg/h capacity*	285.56	unit

Table S4.274. Life cycle inventory of transport, container ship, MeOH-DFICE, size9 (1 t-nm)

Exchanges	Amount	Unit
Economic flows		
container ship production, MeOH-DFICE, size9*	4.18E-12	unit
fuel tank, heavy fuel oil*	2.74E-07	kilogram
fuel tank, methanol*	1.29E-05	kilogram
market for maintenance, container ship	1.94E-11	unit
methanol production, CO_2 from DAC*	6.24E-03	kilogram
marine gas oil, very low-sulphur*	1.55E-04	kilogram
urea solution, 40 wt%*	4.91E-04	kilogram

Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	7.24E-09	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	7.30E-05	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	9.39E-03	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	5.51E-05	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	2.57E-08	kilogram
Ammonia (to air, non-urban air or from high stacks)	4.19E-07	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	3.75E-07	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	1.88E-07	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	1.51E-06	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	3.38E-06	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	2.17E-06	kilogram

Table S4.275. Life cycle inventory of container ship production, MeOH-DFICE, size9 (1 unit)

Exchanges	Amount	Unit
Economic flows		
hull production, container ship, for DWT 103800*	1.92	unit
propulsion system, MeOH-DFICE, size9*	1	unit

Table S4.276. Life cycle inventory of propulsion system, MeOH-DFICE, size9 (1 unit)

Exchanges	Amount	Unit
Economic flows		
marine engine, CI, ICE*	59.3	MW
market for generator, 200kW electrical	96.05	unit
marine engine, CI, ICE*	19.21	MW
market for control cabinet, heat and power co-generation unit, 160kW electrical	345.75	unit
SCR*	78.51	MW
electric boiler, 100kW*	7	unit

Table S4.277. Life cycle inventory of transport, container ship, LNG-DFICE, size9 (1 t-nm)

Exchanges	Amount	Unit
Economic flows		
container ship production, LNG-DFICE, size9*	3.91E-12	unit
fuel tank, heavy fuel oil*	4.95E-08	kilogram
fuel tank, LNG*	1.56E-05	kilogram
market for maintenance, container ship	1.82E-11	unit
natural gas, liquid*	2.41E-03	kilogram
marine gas oil, very low-sulphur*	2.79E-05	kilogram
urea solution, 40 wt%*	4.15E-04	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	7.24E-05	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	1.91E-05	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	6.59E-03	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	4.25E-05	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	2.29E-07	kilogram
Ammonia (to air, non-urban air or from high stacks)	2.77E-07	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	7.40E-06	kilogram

Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	5.07E-08	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	2.74E-07	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	0	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	5.83E-07	kilogram

Table S4.278. Life cycle inventory of container ship production, LNG-DFICE, size9 (1 unit)

Exchanges	Amount	Unit
Economic flows		
hull production, container ship, for DWT 103800	1.92	unit
propulsion system, LNG-DFICE, size9	1	unit

Table S4.279. Life cycle inventory of propulsion system, LNG-DFICE, size9 (1 unit)

Exchanges	Amount	Unit
Economic flows		
marine engine, CI, ICE*	59.3	MW
market for generator, 200kW electrical	96.05	unit
marine engine, CI, ICE*	19.21	MW
market for control cabinet, heat and power co-generation unit, 160kW electrical	345.75	unit
SCR*	59.3	MW
market for gas boiler	70	unit
Reliquefaction plant, 1 kg/h capacity*	339.84	unit

Table S4.280. Life cycle inventory of transport, container ship, BIO-LNG-DFICE, size9 (1 t-nm)

Exchanges	Amount	Unit
Economic flows		
container ship production, LNG-DFICE, size9*	3.91E-12	unit
fuel tank, heavy fuel oil*	4.95E-08	kilogram
fuel tank, LNG*	1.56E-05	kilogram
market for maintenance, container ship	1.82E-11	unit
natural gas, liquid, woody biomass*	2.41E-03	kilogram
marine gas oil, very low-sulphur*	2.79E-05	kilogram
urea solution, 40 wt%*	4.15E-04	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	7.24E-05	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	1.91E-05	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	6.59E-03	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	4.25E-05	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	2.29E-07	kilogram
Ammonia (to air, non-urban air or from high stacks)	2.77E-07	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	7.40E-06	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	5.07E-08	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	2.74E-07	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	0	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	5.83E-07	kilogram

Table S4.281. Life cycle inventory of transport, container ship, LOHC-SOFC, size9 (1 t-nm)

Exchanges	Amount	Unit
Economic flows		

container ship production, LOHC-SOFC, size9*	5.35E-12	unit
fuel tank, heavy fuel oil*	2.84E-05	kilogram
market for maintenance, container ship	2.48E-11	unit
dehydrogenation of perhydro-dibenzyltoluene (H18-DBT) for releasing hydrogen*	1.09E-03	kilogram
market group for electricity, low voltage	5.42E-06	kilowatt hour

Table S4.282. Life cycle inventory of container ship production, LOHC-SOFC, size9 (1 unit)

Exchanges	Amount	Unit
Economic flows		
hull production, container ship, for DWT 103800*	1.92	unit
propulsion system, LOHC-SOFC, size9*	1	unit

Table S4.283. Life cycle inventory of propulsion system, LOHC-SOFC, size9 (1 unit)

Exchanges	Amount	Unit
Economic flows		
SOFC*	415.4	MW
market for converter, for electric passenger car	4322.7	kilogram
market for inverter, 500kW	195	unit
market for battery, Li-ion, NMC111, rechargeable, prismatic	1657.0213	kilogram
motor drive*	61.76	MW
market for marine electric motor	161.757	unit
market for control cabinet, heat and power co-generation unit, 160kW electrical	1526.625	unit
LOHC reactor*	54.04	MW H_2
electric boiler, 100kW*	7	unit

Table S4.284. Life cycle inventory of transport, container ship, LOHC-DFICE, size9 (1 t-nm)

Exchanges	Amount	Unit
Economic flows		
container ship production, LOHC-DFICE, size9*	5.85E-12	unit
fuel tank, heavy fuel oil*	3.83E-07	kilogram
fuel tank, heavy fuel oil*	3.80E-05	kilogram
market for maintenance, container ship	2.72E-11	unit
dehydrogenation of perhydro-dibenzyltoluene (H18-DBT) for releasing hydrogen*	1.46E-03	kilogram
marine gas oil, very low-sulphur*	2.16E-04	kilogram
urea solution, 40 wt%*	6.21E-04	kilogram
Environmental flows		
Methane, fossil (to air, non-urban air or from high stacks)	1.01E-08	kilogram
Carbon monoxide, fossil (to air, non-urban air or from high stacks)	3.97E-06	kilogram
Carbon dioxide, fossil (to air, non-urban air or from high stacks)	8.63E-04	kilogram
Nitrogen oxides (to air, non-urban air or from high stacks)	6.35E-05	kilogram
Dinitrogen monoxide (to air, non-urban air or from high stacks)	3.59E-08	kilogram
Ammonia (to air, non-urban air or from high stacks)	4.16E-07	kilogram
NMVOC, non-methane volatile organic compounds, unspecified origin (to air, non-urban air or from high stacks)	5.89E-07	kilogram
Particulates, > 2.5 um, and < 10um (to air, non-urban air or from high stacks)	6.27E-08	kilogram
Sulfur dioxide (to air, non-urban air or from high stacks)	2.12E-06	kilogram
Formaldehyde (to air, non-urban air or from high stacks)	0.00E+00	kilogram
Particulates, < 2.5 um (to air, non-urban air or from high stacks)	7.21E-07	kilogram

Table S4.285. Life cycle inventory of container ship production, LOHC-DFICE, size9 (1 unit)

Exchanges	Amount	Unit
Economic flows		
hull production, container ship, for DWT 103800*	1.92	unit
propulsion system, LOHC-DFICE, size9*	1	unit

Table S4.286. Life cycle inventory of propulsion system, LOHC-DFICE, size9 (1 unit)

Exchanges	Amount	Unit
Economic flows		
marine engine, CI, ICE*	59.3	MW
market for generator, 200kW electrical	96.05	unit
marine engine, CI, ICE*	19.21	MW
market for control cabinet, heat and power co-generation unit, 160kW electrical	345.75	unit
LOHC reactor*	69.57	MW H_2
SCR*	59.3	MW
electric boiler, 100kW*	7	unit

Table S4.287. Life cycle inventory of liquid hydrogen production, onshore wind PEM (1 kg)

Exchanges	Amount	Unit
Economic flows		
hydrogen production, gaseous, 30 bar, wind onshore, pem*	1.0162	kilogram
hydrogen liquefaction plant construction*	3.43E-09	unit
electricity production, wind, 1-3MW turbine, onshore	10.5	kilowatt hour
Environmental flows		
Hydrogen (to air)	0.0162	kilogram

Data source: Al Ghafri et al.[176] and Wulf and Zapp[175]

Table S4.288. Life cycle inventory of ammonia production, liquid, onshore wind PEM (1 kg)

Exchanges	Amount	Unit
Economic flows		
hydrogen production, gaseous, 30 bar, wind onshore, pem*	1.76E-01	kilogram
nitrogen, gaseous, from cryogenic distillation, without compression*	8.15E-01	kilogram
ammonia synthesis catalyst*	5.15E-05	kilogram
market for chemical factory, organics	3.29E-10	unit
electricity production, wind, 1-3MW turbine, onshore	1.44	kilowatt hour
treatment of inert waste, inert material landfill	-5.15E-05	kilogram
Environmental flows		
Water, cooling, unspecified natural origin (from natural resource)	1.49E-01	cubic meter
Hydrogen (to air)	7.67E-04	kilogram
Ammonia(to air)	1.63E-03	kilogram
Nitrogen oxides(to air)	1.00E-03	kilogram
Water(to air)	4.76E-02	cubic meter
Water(to water)	1.01E-01	cubic meter

Data source: D'Angelo et al.[54]

Table S4.289. Life cycle inventory of methanol production, CO_2 from DAC, onshore wind PEM (1 kg)

Exchanges	Amount	Unit
Economic flows		
CO_2 from DAC, onshore wind*	1.51	kilogram

hydrogen production, gaseous, 30 bar, wind onshore, pem*	2.08E-01	kilogram
electricity production, wind, 1-3MW turbine, onshore	2.72E-01	kilowatt hour
market for steel, chromium steel 18/8	1.53E-04	kilogram
market for aluminium oxide, non-metallurgical	1.20E-05	kilogram
market for copper oxide	6.20E-05	kilogram
market for zinc oxide	2.90E-05	kilogram
market for heat, from steam, in chemical industry	-4.40E-01	megajoule
market for wastewater, average	-5.71E-04	cubic meter
Environmental flows		
Carbon dioxide, fossil (air)	7.70E-02	kilogram
Methanol (air)	1.00E-02	kilogram
Nitrogen oxides (air)	1.78E-06	kilogram

Data source: González-Garay et al.[177]

Table S4.290. Life cycle inventory of CO_2 from DAC, onshore wind (1 kg)

Exchanges	Amount	Unit
Economic flows		
electricity production, wind, 1-3MW turbine, onshore	0.366	kilowatt hour
market group for tap water	3.105	kilogram
market group for natural gas, high pressure	0.1895	cubic meter
market for calcium carbonate, precipitated	0.02	kilogram
Environmental flows		
Carbon dioxide, in air	1	kilogram

Data source: Keith et al.[178]

Table S4.291. Life cycle inventory of hydrogen production, gaseous, 30 bar, wind onshore, pem (1 kg)

Exchanges	Amount	Unit
Economic flows		
electrolyzer, PEM, Balance of Plant	3.45E-07	unit
electrolyzer, PEM, Stack	1.04E-06	unit
electricity production, wind, 1-3MW turbine, onshore	57.47	kilowatt hour
market for water, deionised	12	kilogram
Environmental flows		
Oxygen	8	kilogram
Water, cooling, unspecified natural origin	0.0881	cubic meter

Data source: Wei et al.[53]

Background data

Table S4.292. The electricity mixes[66] used for H_2-based fuel production under different scenarios and their GHG emissions in 2020 and 2050. In this table, CHP=Combined heat and power plant, IGCC=Integrated gasification combined cycle, PC=Conventional coal power plant, CCS=Carbon capture and storage, OC=Gas turbine, CC= Natural gas combined cycle, ST=Diesel oil turbine, CSP=Concentrating solar power and PV=photovoltaic.

	Less Ambitious		Ambitious		Very Ambitious	
	2020	2050	2020	2050	2020	2050
Electricity mix						
Biomass CHP (%)	0.57	0.25	0.63	0.22		
Biomass IGCC CCS (%)	0	0.02	0	1.00		
Biomass IGCC (%)	1.78	0.54	1.73	0.51		
Coal PC (%)	31.66	0	29.33	0		
Coal IGCC (%)	0.01	0.01	0.07	0		

Coal PC CCS (%)	0	0	0	0		
Coal IGCC CCS (%)	0	0	0	0		
Coal CHP (%)	5.12	0.16	4.22	0		
Gas OC (%)	0.99	0.72	0.71	0.21		
Gas CC (%)	16.98	1.91	20.40	0		
Gas CHP (%)	1.99	0.20	3.32	0		
Gas CC CCS (%)	0	0	0	0		
Geothermal (%)	0.95	0.54	1.07	0.70		
Hydro (%)	17.70	9.05	17.26	11.50		
Nuclear (%)	10.85	3.75	9.49	4.85		
Oil ST (%)	2.16	0	1.80	0		
Solar CSP (%)	0.09	0.44	0.08	0.37		
Solar PV Centralized (%)	3.40	51.52	3.62	49.99		
Wind Onshore (%)	5.53	25.02	5.94	24.64	100	100
Wind Offshore (%)	0.22	5.87	0.34	6.00		
GHG emissions of the electricity mix (kg CO_2-eq/kWh)						
	0.65	0.03	0.63	0.005	0.014	0.01

S4.2 Future transport work demand

The contribution of different ship sizes to global containerized transport demand over time is shown in Figure S4.2. These ratios are the same across different scenarios.

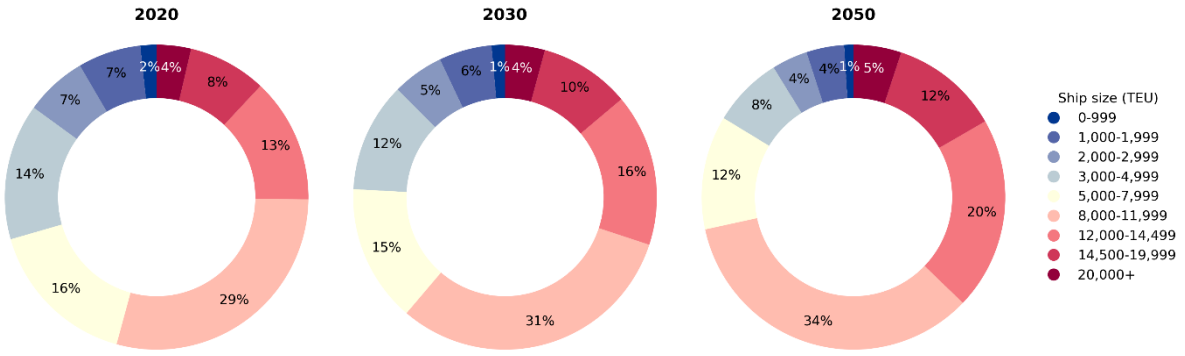

Figure S4.2. Contribution of different ship sizes to global containerized transport demand in 2020, 2030, and 2050. Ship size categories in this figure are measured in twenty-foot equivalent units (TEU).

The future containerized transport work by propulsion system for each ship size, as estimated by the logistic model (upper bound) and the gravity model (lower bound), is shown in Figure S4.3 and Figure S4.4, respectively.

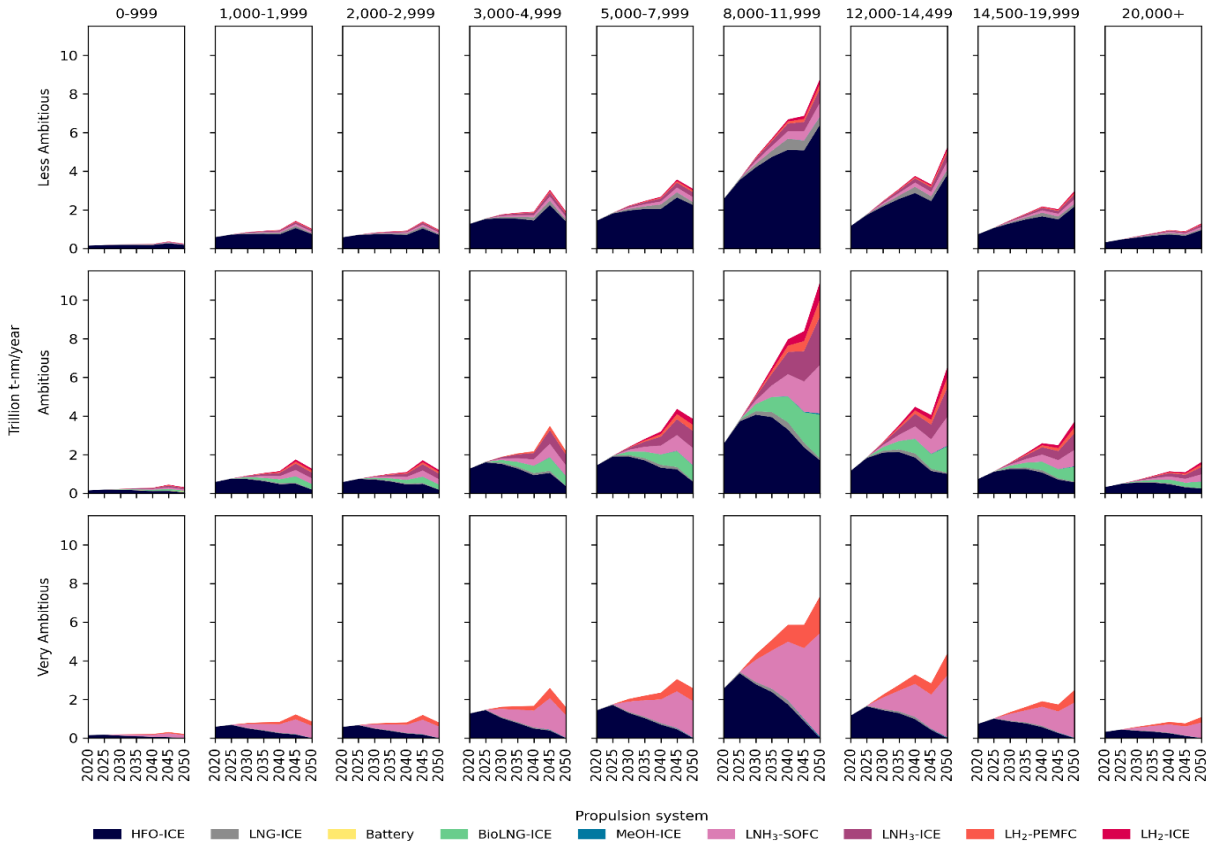

Figure S4.3. Global containerized transport demand by propulsion system for each ship size, based on logistic model. Ship size categories in this figure are measured in twenty-foot equivalent units (TEU).

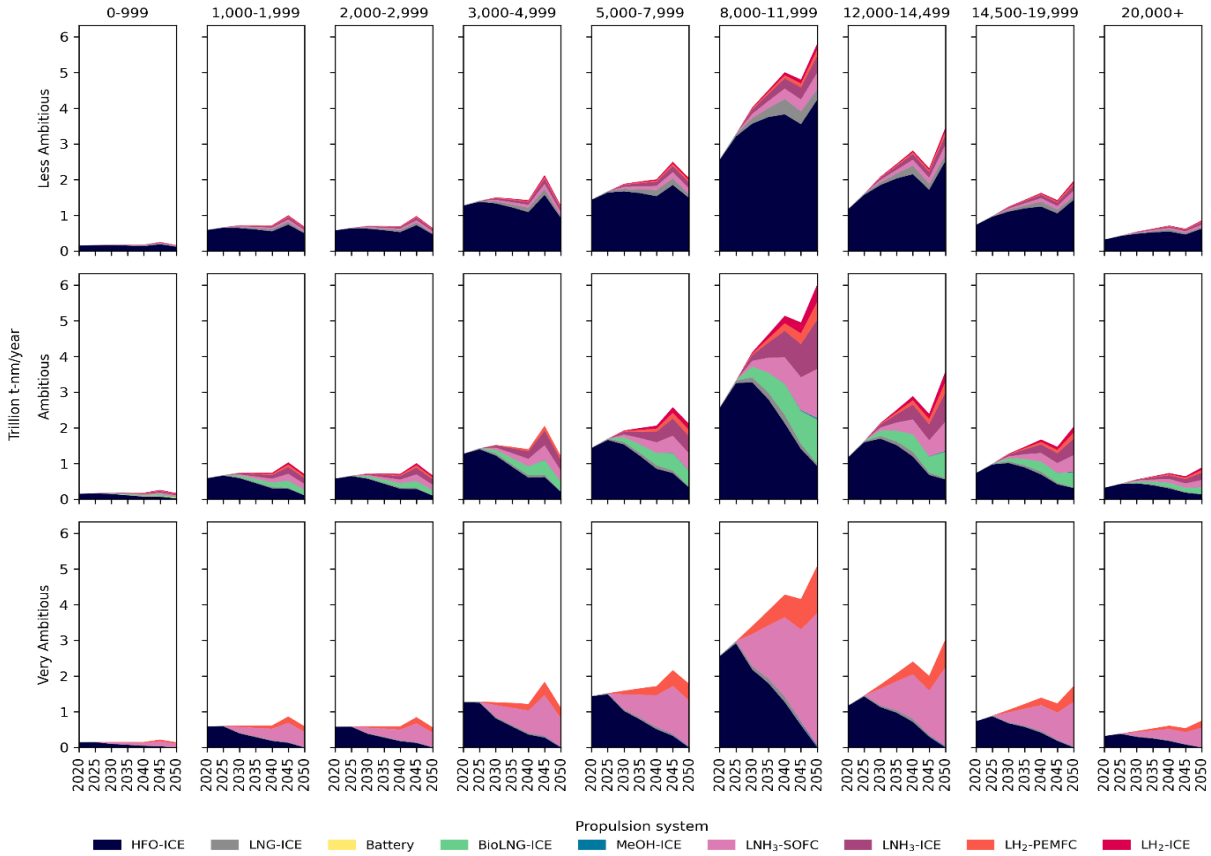

Figure S4.4. Global containerized transport demand by propulsion system for each ship size, based on gravity model. Ship size categories in this figure are measured in twenty-foot equivalent units (TEU).

S4.3 Supplementary results

Model validation

To validate the model of energy demand for ship operation, the direct CO_2 emissions of HFO ships representing different ship sizes calculated in this study were compared with the monitoring results reported under the EU Monitoring, Reporting and Verification (EU-MRV) Maritime Regulation[273] and with calculated results from the IMO report.[7] In EU-MRV results, CO_2 emissions were recorded for 1,859 container ships in 2020,[273] which account for about one third of the global container ship fleet at that time. The above CO_2 emission records were classified by ship size to obtain the emission range for each ship size. In the IMO report, the CO_2 emissions for the global container ship fleet in 2018 were reported by ship size category. As shown in Figure S4.5, our results are generally in good agreement with both sets of measured data. The higher CO_2 emissions for ships of 0–999 TEU in the EU-MRV data can possibly be attributed to the low payload utilization rate of these ships. The monitored feeder ships primarily operate near the shore within the EU, and the limited coverage of the monitoring data does not include ships operating in other regions. Overall, this discrepancy does not compromise the general validity of the model used in this study.

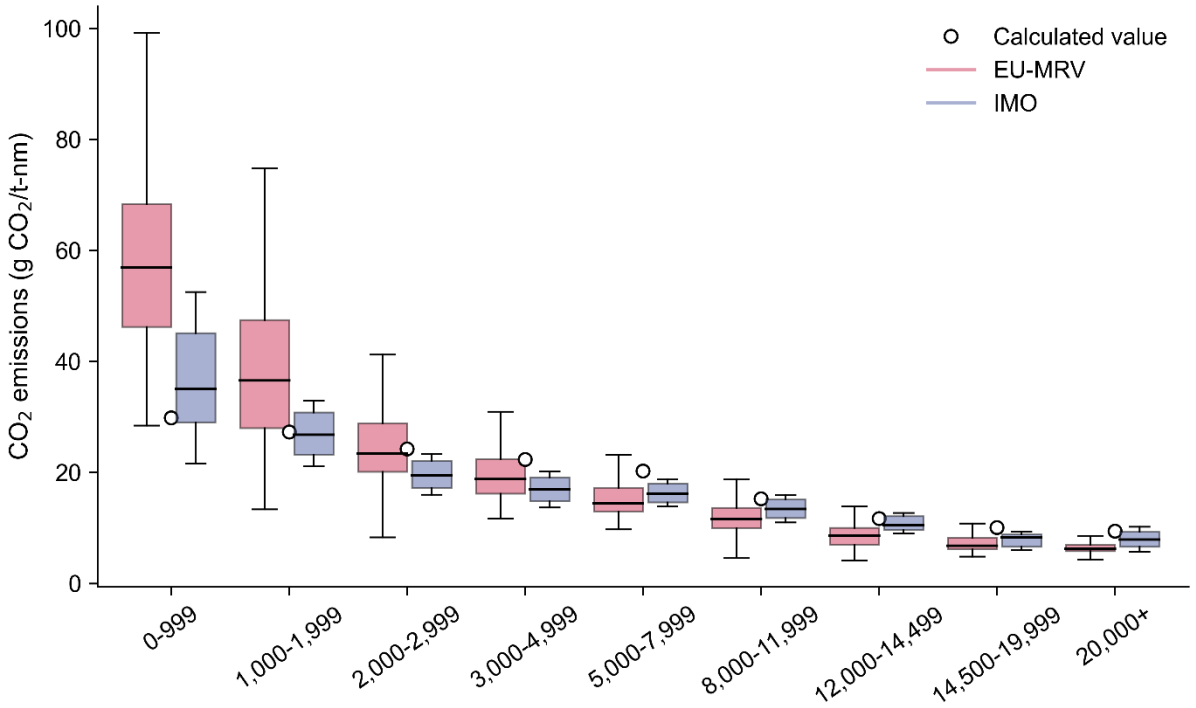

Figure S4.5. Comparison of calculated CO_2 emissions of representative HFO ships with EU-MRV and IMO results by ship size (TEU).

Sensitivity analysis

In this sensitivity analysis, four parameters, namely main engine efficiency, propulsion system mass, ship speed, and voyage length, that can potentially affect the energy consumption per transport work are considered. Each parameter is modeled with a ±5% variation to examine its effect on the GHG emissions per t-nm for different propulsion

systems. As shown in Figure S4.6, ship speed is the most influential factor determining the results and can cause a more pronounced percentage change in GHG emissions for feeder ships than the ±5% variation applied to the input, because the load factor of the main engine, which determines its energy consumption, is correlated with the cube of the ratio between the ship's operating speed and its maximum speed. For Ultra Large Container Vessels (ULCVs), the effect of main engine efficiency on energy consumption can be comparable to that of ship operating speed, because ULCVs require a higher power increase to account for adverse weather conditions (weather correction factor of 0.867, resulting in a 15% power increase) than feeder ships (weather correction factor of 0.909, resulting in a 10% power increase),[7] which reduces the relative influence of operating speed on the load factor and energy consumption of the main engine. In the Very Ambitious scenario, the GHG emissions of liquid H_2-PEMFC and liquid NH_3-SOFC ships are primarily determined by ship production, with the effects of ship speed and main engine efficiency remaining similar over time. Changes in voyage length and propulsion system mass have little impact across all scenarios.

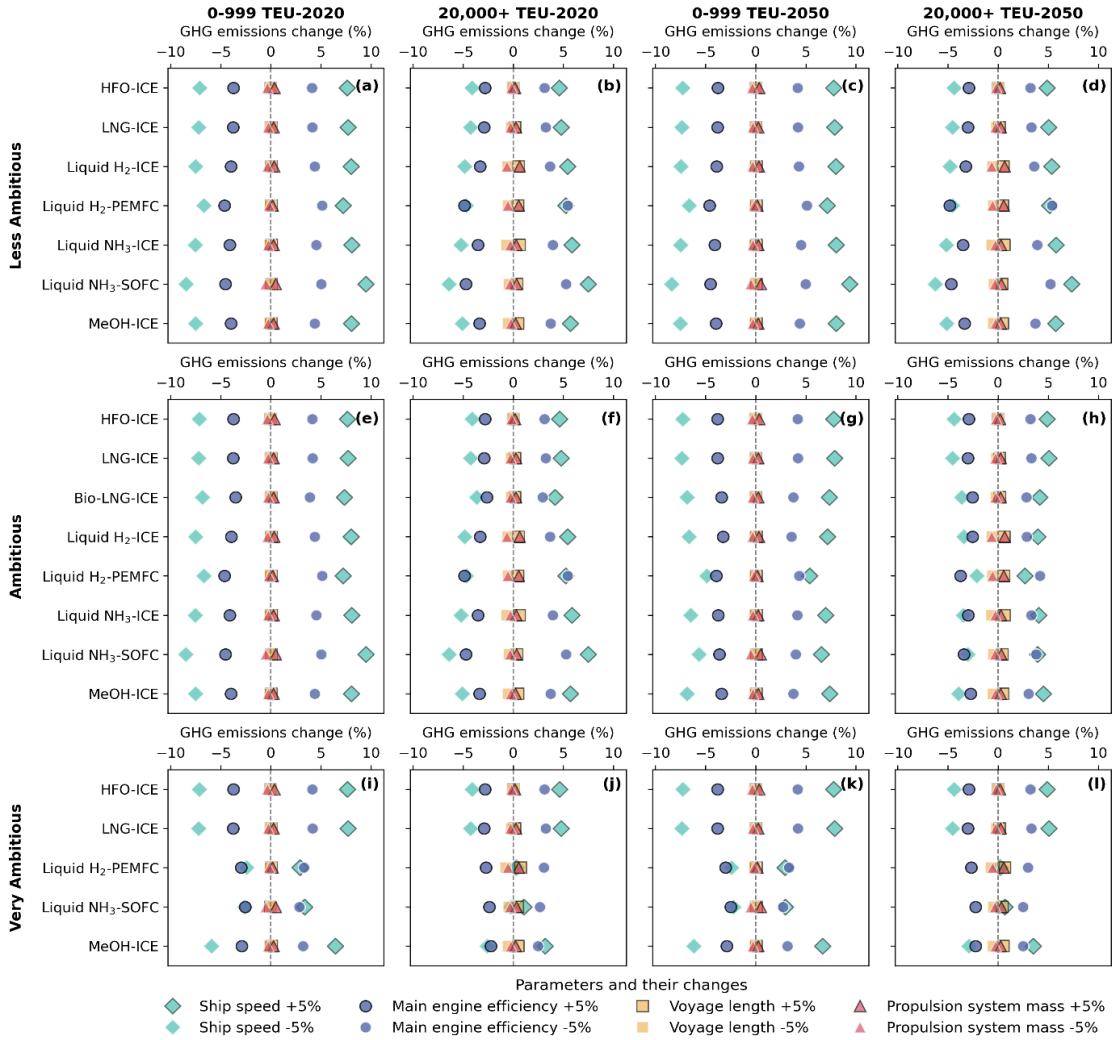

Figure S4.6. Sensitivity analysis of the effects of main parameter changes on GHG emissions per t-nm for different propulsion systems by ship size and time under different scenarios. (a)-(d), (e)-(h) and (i-l) show the results for the Less Ambitious, Ambitious and Very Ambitious scenarios, respectively. In the Ambitious scenario, the battery system is not included in this sensitivity analysis as the decisive factor is its gravimetric energy density.

GHG emissions of different propulsion systems

Table S4.293. GHG emissions of different propulsion systems by ship size from 2020 to 2050 in the Less Ambitious scenario (g CO_2-eq/t-nm).

Ship size (TEU)	Propulsion system	2020	2025	2030	2035	2040	2045	2050
0-999	HFO-ICE	38	37	37	37	37	37	37
	LNG-ICE	36	36	36	36	35	35	35
	Liquid H_2-ICE	69	63	57	53	48	45	44
	Liquid H_2-PEMFC	66	60	54	50	46	42	41
	Liquid NH_3-ICE	74	68	63	58	54	51	49
	Liquid NH_3-SOFC	62	57	53	49	45	42	41
	MeOH-ICE	68	66	63	60	57	54	53
1,000-1,999	HFO-ICE	35	34	34	34	34	34	34
	LNG-ICE	33	33	33	33	32	32	32
	Liquid H_2-ICE	64	58	53	49	45	42	40
	Liquid H_2-PEMFC	60	54	49	45	41	38	37
	Liquid NH_3-ICE	69	64	59	55	51	48	46
	Liquid NH_3-SOFC	54	49	45	42	39	36	35
	MeOH-ICE	63	61	59	56	53	51	49
2,000-2,999	HFO-ICE	31	30	30	30	30	30	30
	LNG-ICE	30	29	29	29	29	29	29
	Liquid H_2-ICE	58	53	48	45	41	38	37
	Liquid H_2-PEMFC	54	49	44	41	37	35	33
	Liquid NH_3-ICE	64	59	55	51	47	44	42
	Liquid NH_3-SOFC	54	50	46	42	39	37	35
	MeOH-ICE	58	56	54	51	48	46	45
3,000-4,999	HFO-ICE	28	28	28	28	27	27	27
	LNG-ICE	27	27	27	27	27	27	27
	Liquid H_2-ICE	54	49	45	41	38	36	34
	Liquid H_2-PEMFC	50	45	41	37	34	32	30
	Liquid NH_3-ICE	60	55	51	47	44	41	39
	Liquid NH_3-SOFC	45	41	38	35	33	31	29
	MeOH-ICE	54	52	50	48	45	43	42
5,000-7,999	HFO-ICE	26	25	25	25	25	25	25
	LNG-ICE	25	25	24	24	24	24	24
	Liquid H_2-ICE	49	45	41	38	35	32	31
	Liquid H_2-PEMFC	45	41	37	34	31	29	28
	Liquid NH_3-ICE	54	50	46	43	40	37	36
	Liquid NH_3-SOFC	45	42	39	36	33	31	30
	MeOH-ICE	49	47	46	43	41	39	38
8,000-11,999	HFO-ICE	26	25	25	25	25	25	25
	LNG-ICE	25	25	24	24	24	24	24
	Liquid H_2-ICE	49	45	41	38	35	32	31
	Liquid H_2-PEMFC	45	41	37	34	31	29	28
	Liquid NH_3-ICE	54	50	46	43	40	37	36
	Liquid NH_3-SOFC	45	42	39	36	33	31	30
	MeOH-ICE	49	47	46	43	41	39	38
12,000-14,499	HFO-ICE	15	15	15	15	15	15	15

	LNG-ICE	15	15	15	15	15	15	15
	Liquid H_2-ICE	30	27	25	23	21	20	19
	Liquid H_2-PEMFC	28	25	23	21	19	18	17
	Liquid NH_3-ICE	33	30	28	26	24	23	22
	Liquid NH_3-SOFC	26	24	22	20	19	18	17
	MeOH-ICE	30	29	27	26	25	24	23
14,500-19,999	HFO-ICE	13	13	13	13	13	13	13
	LNG-ICE	13	13	13	13	13	13	13
	Liquid H_2-ICE	26	24	22	20	18	17	16
	Liquid H_2-PEMFC	24	21	20	18	16	15	15
	Liquid NH_3-ICE	28	26	24	22	21	19	19
	Liquid NH_3-SOFC	23	21	19	18	17	16	15
	MeOH-ICE	25	25	24	22	21	20	20
20,000+	HFO-ICE	13	12	12	12	12	12	12
	LNG-ICE	13	12	12	12	12	12	12
	Liquid H_2-ICE	25	22	20	19	17	16	16
	Liquid H_2-PEMFC	23	20	19	17	16	15	14
	Liquid NH_3-ICE	27	25	23	21	20	18	18
	Liquid NH_3-SOFC	21	19	18	16	15	14	14
	MeOH-ICE	24	23	22	21	20	19	19

Table S4. 294. GHG emissions of different propulsion systems by ship size from 2020 to 2050 in the Ambitious scenario (g CO_2-eq/t-nm).

Ship size (TEU)	Propulsion system	2020	2025	2030	2035	2040	2045	2050
0-999	HFO-ICE	38	37	37	37	37	37	37
	LNG-ICE	36	36	36	35	35	35	35
	Battery	63	47	20	7	4	3	3
	Bio-LNG-ICE	22	20	17	16	15	15	15
	Liquid H_2-ICE	68	66	40	23	16	14	12
	Liquid H_2-PEMFC	66	63	38	20	14	11	10
	Liquid NH_3-ICE	73	72	44	24	17	14	12
	Liquid NH_3-SOFC	62	61	37	20	14	11	10
	MeOH-ICE	68	70	45	27	20	17	15
1,000-1,999	HFO-ICE	35	34	34	34	34	34	34
	LNG-ICE	33	33	33	32	32	32	32
	Bio-LNG-ICE	20	18	16	14	14	14	14
	Liquid H_2-ICE	63	61	37	21	15	13	12
	Liquid H_2-PEMFC	59	57	34	18	12	10	9
	Liquid NH_3-ICE	69	68	41	23	16	13	12
	Liquid NH_3-SOFC	53	52	32	18	12	10	9
	MeOH-ICE	63	65	42	25	18	16	14
2,000-2,999	HFO-ICE	31	30	30	30	30	30	30
	LNG-ICE	30	29	29	29	29	29	29
	Bio-LNG-ICE	18	16	14	13	13	12	12
	Liquid H_2-ICE	58	56	34	19	14	12	11
	Liquid H_2-PEMFC	53	52	31	17	11	9	8
	Liquid NH_3-ICE	63	62	38	21	15	12	11
	Liquid NH_3-SOFC	54	53	32	18	12	10	9

	MeOH-ICE	58	59	38	23	17	14	13
3,000-4,999	HFO-ICE	28	28	28	27	27	27	27
	LNG-ICE	27	27	27	27	27	27	27
	Bio-LNG-ICE	16	15	13	12	12	11	11
	Liquid H_2-ICE	54	52	32	18	13	11	10
	Liquid H_2-PEMFC	49	47	28	15	10	8	7
	Liquid NH_3-ICE	59	58	35	20	14	11	10
	Liquid NH_3-SOFC	45	44	27	15	10	8	7
	MeOH-ICE	54	55	35	21	16	13	12
5,000-7,999	HFO-ICE	25	25	25	25	25	25	25
	LNG-ICE	25	25	24	24	24	24	24
	Bio-LNG-ICE	15	14	12	11	10	10	10
	Liquid H_2-ICE	49	47	29	16	12	10	9
	Liquid H_2-PEMFC	45	43	26	14	9	7	7
	Liquid NH_3-ICE	54	53	32	18	13	10	9
	Liquid NH_3-SOFC	45	44	27	15	10	8	7
	MeOH-ICE	49	50	32	19	14	12	11
8,000-11,999	HFO-ICE	19	19	19	19	19	19	19
	LNG-ICE	19	19	19	19	19	19	19
	Bio-LNG-ICE	12	11	9	8	8	8	8
	Liquid H_2-ICE	39	37	23	13	9	8	7
	Liquid H_2-PEMFC	35	34	20	11	8	6	5
	Liquid NH_3-ICE	43	42	26	14	10	8	8
	Liquid NH_3-SOFC	35	35	21	12	8	7	6
	MeOH-ICE	38	39	25	15	11	10	9
12,000-14,499	HFO-ICE	15	15	15	15	15	15	15
	LNG-ICE	15	15	15	15	15	15	15
	Bio-LNG-ICE	9	9	7	7	7	7	7
	Liquid H_2-ICE	30	29	18	10	7	6	6
	Liquid H_2-PEMFC	27	27	16	9	6	5	5
	Liquid NH_3-ICE	33	32	20	11	8	7	6
	Liquid NH_3-SOFC	26	25	15	9	6	5	5
	MeOH-ICE	29	30	20	12	9	8	7
14,500-19,999	HFO-ICE	13	13	13	13	13	13	13
	LNG-ICE	13	13	13	13	13	13	13
	Bio-LNG-ICE	8	7	6	6	6	6	6
	Liquid H_2-ICE	26	25	15	9	6	5	5
	Liquid H_2-PEMFC	24	23	14	8	5	4	4
	Liquid NH_3-ICE	28	28	17	10	7	6	5
	Liquid NH_3-SOFC	23	22	14	8	5	4	4
	MeOH-ICE	25	26	17	10	8	7	6
20,000+	HFO-ICE	13	12	12	12	12	12	12
	LNG-ICE	13	12	12	12	12	12	12
	Bio-LNG-ICE	8	7	6	6	6	6	6
	Liquid H_2-ICE	24	24	15	9	6	5	5
	Liquid H_2-PEMFC	22	22	13	7	5	4	4
	Liquid NH_3-ICE	27	26	16	9	7	6	5
	Liquid NH_3-SOFC	21	20	12	7	5	4	4

	MeOH-ICE	24	25	16	10	7	6	6

Table S4.295. GHG emissions of different propulsion systems by ship size from 2020 to 2050 in the Very Ambitious scenario (g CO_2-eq/t-nm).

Ship size (TEU)	Propulsion system	2020	2025	2030	2035	2040	2045	2050
0-999	HFO-ICE	38	37	37	37	37	37	37
	LNG-ICE	36	36	36	35	35	35	35
	Liquid H_2-PEMFC	7	6	5	5	5	5	5
	Liquid NH_3-SOFC	8	7	6	5	5	5	5
	MeOH-ICE	11	11	10	9	9	9	9
1,000-1,999	HFO-ICE	35	34	34	34	34	34	34
	LNG-ICE	33	33	33	32	32	32	32
	Liquid H_2-PEMFC	6	6	5	5	5	4	4
	Liquid NH_3-SOFC	7	7	6	5	5	5	5
	MeOH-ICE	11	10	9	9	9	8	8
2,000-2,999	HFO-ICE	31	30	30	30	30	30	30
	LNG-ICE	30	29	29	29	29	29	29
	Liquid H_2-PEMFC	6	5	5	4	4	4	4
	Liquid NH_3-SOFC	7	6	5	5	5	5	5
	MeOH-ICE	10	9	8	8	8	8	8
3,000-4,999	HFO-ICE	28	28	28	27	27	27	27
	LNG-ICE	27	27	27	27	27	27	27
	Liquid H_2-PEMFC	5	5	4	4	4	4	4
	Liquid NH_3-SOFC	6	5	4	4	4	4	4
	MeOH-ICE	9	8	8	7	7	7	7
5,000-7,999	HFO-ICE	25	25	25	25	25	25	25
	LNG-ICE	25	25	24	24	24	24	24
	Liquid H_2-PEMFC	5	4	4	3	3	3	3
	Liquid NH_3-SOFC	5	5	4	4	4	4	4
	MeOH-ICE	8	8	7	7	7	6	6
8,000-11,999	HFO-ICE	19	19	19	19	19	19	19
	LNG-ICE	19	19	19	19	19	19	19
	Liquid H_2-PEMFC	4	4	3	3	3	3	3
	Liquid NH_3-SOFC	5	4	4	3	3	3	3
	MeOH-ICE	7	6	6	5	5	5	5
12,000-14,499	HFO-ICE	15	15	15	15	15	15	15
	LNG-ICE	15	15	15	15	15	15	15
	Liquid H_2-PEMFC	4	3	3	3	3	3	3
	Liquid NH_3-SOFC	4	3	3	3	3	3	3
	MeOH-ICE	5	5	5	4	4	4	4
14,500-19,999	HFO-ICE	13	13	13	13	13	13	13
	LNG-ICE	13	13	13	13	13	13	13
	Liquid H_2-PEMFC	3	3	2	2	2	2	2
	Liquid NH_3-SOFC	3	3	3	2	2	2	2
	MeOH-ICE	5	4	4	4	4	4	4
20,000+	HFO-ICE	13	12	12	12	12	12	12
	LNG-ICE	13	12	12	12	12	12	12
	Liquid H_2-PEMFC	3	3	3	2	2	2	2

	Liquid NH_3-SOFC	3	3	3	2	2	2	2
	MeOH-ICE	5	4	4	4	4	4	4

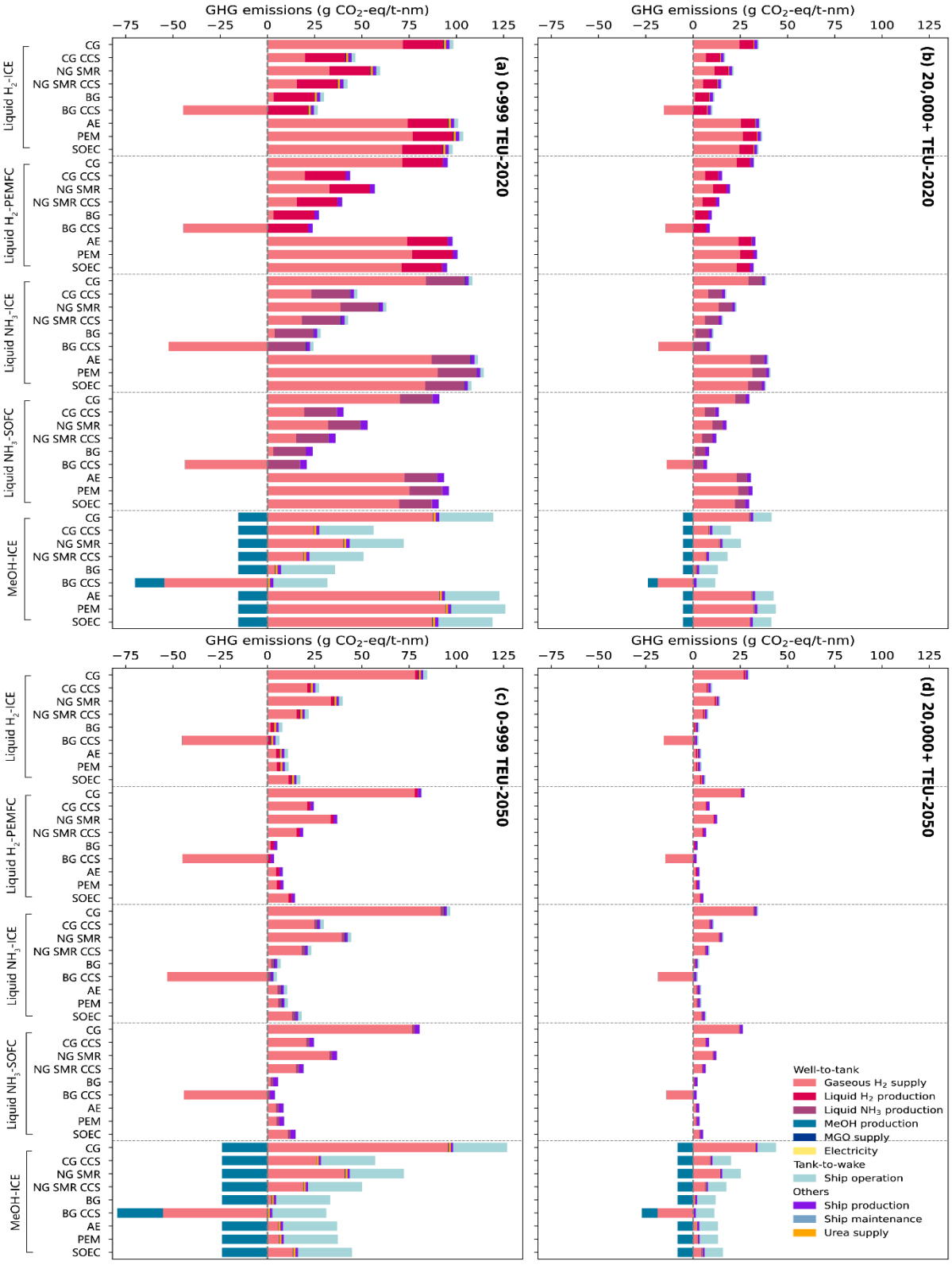

Figure S4.7. Prospective GHG emissions from H_2-based propulsion systems for container ships in 2020 and 2050 by H_2 source in the Less Ambitious scenario.

Comparison between liquid organic H2 carrier and liquid NH3 systems

Liquid organic hydrogen carrier (LOHC) systems can provide gaseous H_2 through catalytic exothermic hydrogenation and endothermic dehydrogenation reactions of a liquid organic compound. Compared with liquid NH_3, LOHCs can be handled under ambient conditions in a manner similar to diesel and exhibit low toxicity.[175, 293] LOHC systems are currently in the demonstration phase (TRL 7–8) and are expected to be fully commercialized by the late 2030s.[256] In this study, we further model the LOHC systems to enable a comparison with liquid NH_3 systems. Two LOHC-based propulsion systems are considered: LOHC–ICE and LOHC–SOFC. It is assumed that the waste heat on board can be utilized to sustain the dehydrogenation process without the need for additional fuel combustion.[324] Dibenzyltoluene (DBT), a widely studied LOHC with a H_2 storage capacity of 6.2 wt%,[57, 323] is selected for this study. During the hydrogenation process, 1% of the H_2 and 0.1% LOHC are lost.[323] The LOHC is assumed to withstand 1000 hydrogenation–dehydrogenation cycles.[323] A ten-chamber tank system, with one chamber kept empty at the start of the trip, is used to handle both loaded and unloaded LOHC.[324] The workflow charts of the LOHC systems and the LCI are provided in Section S4.1.

Figure S4.8 shows the GHG emissions of ships powered by liquid NH_3 systems and LOHC systems under different scenarios. Due to the lower gravimetric energy density of LOHC compared with liquid NH_3 (1.9 MWh/t vs. 5.2 MWh/t for the fuel carrier/fuel itself, and 1.66 MWh/t vs. 4.2 MWh/t for the fuel carrier/fuel plus tank),[233, 324, 325] the ships powered by LOHC systems always experience greater cargo weight loss (see Table S2) and higher energy consumption per t-nm. For feeder ships, these adverse impacts on GHG emissions are not significant, and LOHC systems exhibit lower GHG emissions primarily because the GHG emissions from gaseous H_2 supply via the LOHC cycle are currently lower than those from liquid NH_3 production. By 2050, the GHG emissions of ships powered by LOHC systems are slightly lower than those of ships powered by liquid NH_3 systems in the Less Ambitious scenario and comparable in the Ambitious scenario. For Ultra Large Container Vessels (ULCVs), the higher energy demand per t-nm leads to greater gaseous H_2 demand in LOHC systems than in liquid NH_3 systems. Because liquid NH_3 production involves higher electricity use, ships powered by liquid NH_3 systems still show slightly higher GHG emissions than those powered by LOHC systems at present. However, as electricity becomes decarbonized, LOHC ships are expected to exhibit higher GHG emissions than liquid NH_3 ships. In the Very Ambitious scenario, where both liquid NH_3 and gaseous H_2 supplied via the LOHC cycle are fully sourced from renewables, the GHG emissions of LOHC-SOFC ships remain similar to those of liquid NH_3-SOFC ships for feeder ships, but are slightly higher for ULCVs from now to 2050.

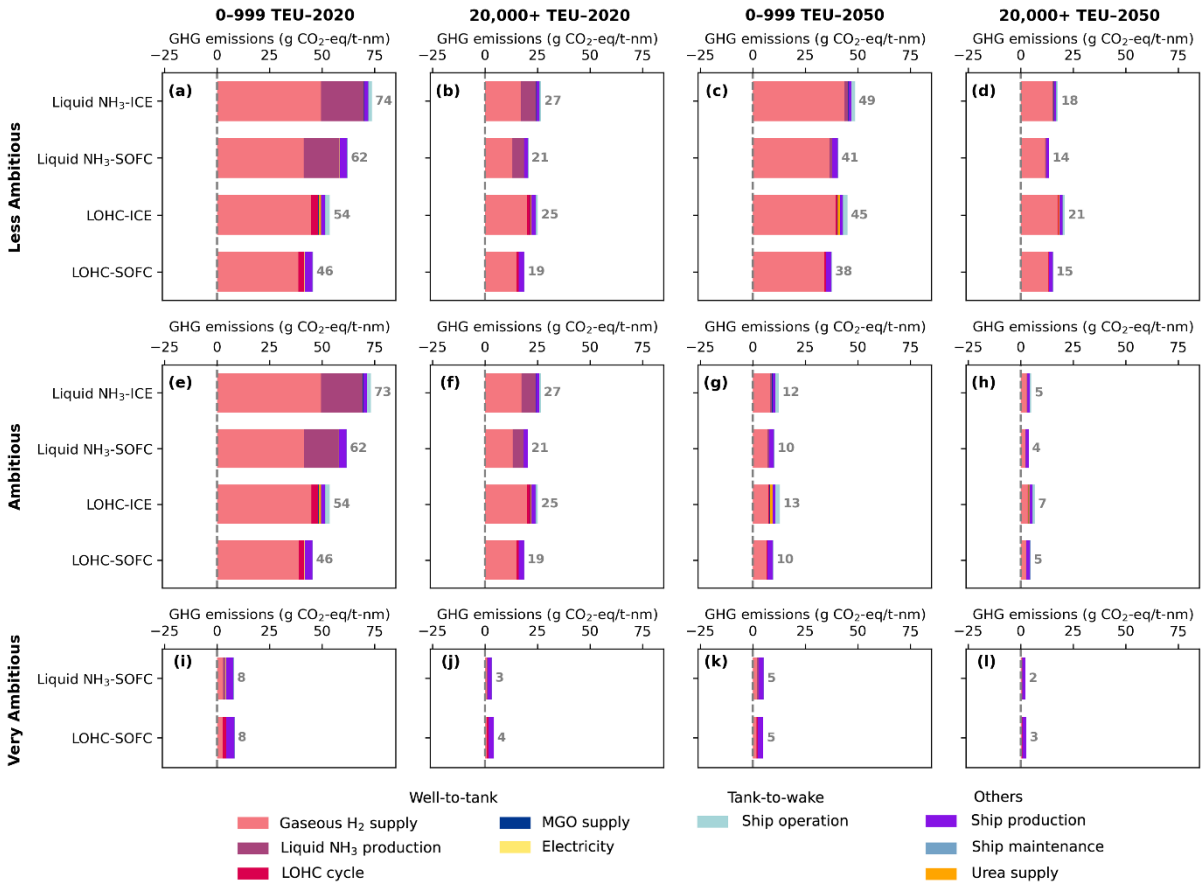

Figure S4.8. Prospective GHG emissions of liquid NH_3 and liquid organic H_2 carrier (LOHC) systems across various scenarios, by ship size and time. (a)-(d), (e)-(h) and (i-l) show the results for the Less Ambitious, Ambitious and Very Ambitious scenarios, respectively. The LOHC cycle consists of hydrogenation and dehydrogenation processes.

We further examined the impacts of adopting LOHC systems instead of liquid NH_3 systems at a large scale on the cumulative GHG emissions from global container shipping. As shown in Figure S4.9, replacing liquid NH_3 systems with LOHC systems can lead to a slight increase in cumulative GHG emissions between 2020 and 2050, by 1.7–1.8%, 2.8–3.3% and 2.2–2.5% in the Less Ambitious, Ambitious and Very Ambitious scenarios, respectively.

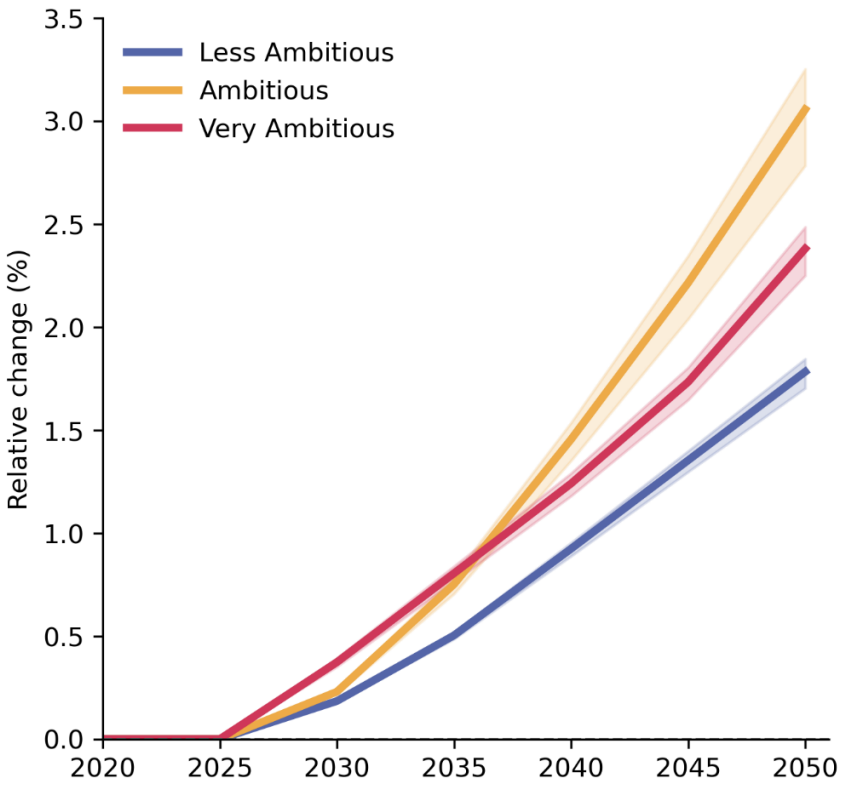

Figure S4.9. The relative change in cumulative GHG emissions under different scenarios when replacing liquid NH_3 systems with LOHC systems.

CO2 demand from DAC for container shipping

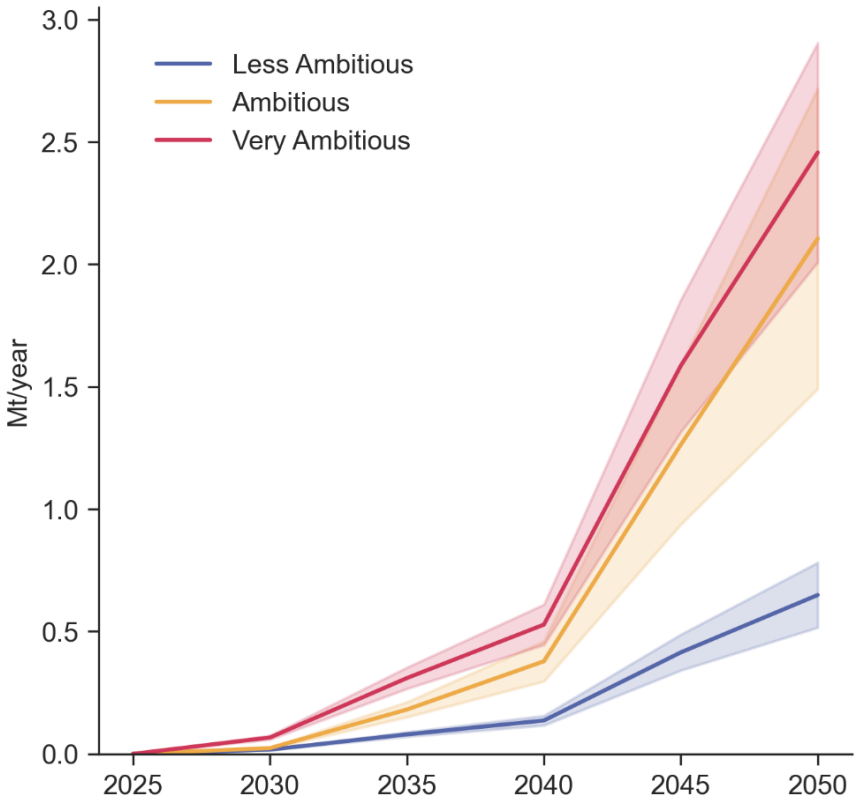

Figure S4.10. CO_2 demand from DAC for container shipping in different scenarios.

References

1. IPCC, *Climate Change 2023 Synthesis Report*, Intergovernmental Panel on Climate Change, Geneva, 2023.
2. IPCC, *Global Warming of 1.5°C: IPCC Special Report on Impacts of Global Warming of 1.5°C above Pre-industrial Levels in Context of Strengthening Response to Climate Change, Sustainable Development, and Efforts to Eradicate Poverty*, Report 9781009157957, Intergovernmental Panel on Climate Change, Cambridge, 2018.
3. S. J. Davis, N. S. Lewis, M. Shaner, S. Aggarwal, D. Arent, I. L. Azevedo, S. M. Benson, T. Bradley, J. Brouwer, Y.-M. Chiang, C. T. M. Clack, A. Cohen, S. Doig, J. Edmonds, P. Fennell, C. B. Field, B. Hannegan, B.-M. Hodge, M. I. Hoffert, E. Ingersoll, P. Jaramillo, K. S. Lackner, K. J. Mach, M. Mastrandrea, J. Ogden, P. F. Peterson, D. L. Sanchez, D. Sperling, J. Stagner, J. E. Trancik, C.-J. Yang and K. Caldeira, *Science*, 2018, **360**, eaas9793.
4. X. Yang, C. P. Nielsen, S. Song and M. B. McElroy, *Nature Energy*, 2022, **7**, 955-965.
5. UNCTAD, *Review of Maritime Transport 2023*, United Nations Conference on Trade and Development, Geneva, 2023.
6. C. European Commission: Joint Research, M. Crippa, D. Guizzardi, E. Schaaf, F. Monforti-Ferrario, R. Quadrelli, A. Risquez Martin, S. Rossi, E. Vignati, M. Muntean, J. Brandao De Melo, D. Oom, F. Pagani, M. Banja, P. Taghavi-Moharamli, J. Köykkä, G. Grassi, A. Branco and J. San-Miguel, *GHG emissions of all world countries – 2023*, Publications Office of the European Union, 2023.
7. IMO, *Fourth Greenhouse Gas Study 2020*, International Maritime Organization, London, 2021.
8. S. Lagouvardou, B. Lagemann, H. N. Psaraftis, E. Lindstad and S. O. Erikstad, *Nature Energy*, 2023, **8**, 1209-1220.
9. J. Kersey, N. D. Popovich and A. A. Phadke, *Nature Energy*, 2022, **7**, 664-674.
10. B. Stolz, M. Held, G. Georges and K. Boulouchos, *Nature Energy*, 2022, **7**, 203-212.
11. IRENA, *A pathway to decarbonise the shipping sector by 2050*, International Renewable Energy Agency, Abu Dhabi, 2021.
12. IMO, *Study on the readiness and availability of low- and zero-carbon ship technology and marine fuels*, International Maritime Organization, Didcot, 2023.
13. IEA, *Net Zero by 2050-A Roadmap for the Global Energy Sector*, International Energy Agency, Paris, 2021.
14. EC, Fit for 55, https://www.consilium.europa.eu/en/policies/green-deal/fit-for-55/, (accessed 29th, September, 2024).
15. K. de Kleijne, M. A. J. Huijbregts, F. Knobloch, R. van Zelm, J. P. Hilbers, H. de Coninck and S. V. Hanssen, *Nature Energy*, 2024, **9**, 1139-1152.
16. R. Bhandari, C. A. Trudewind and P. Zapp, *Journal of Cleaner Production*, 2014, **85**, 151-163.
17. O. Siddiqui and I. Dincer, *International Journal of Hydrogen Energy*, 2019, **44**, 5773-5786.
18. G. Palmer, A. Roberts, A. Hoadley, R. Dargaville and D. Honnery, *Energy & Environmental Science*, 2021, **14**, 5113-5131.
19. C. Bauer, K. Treyer, C. Antonini, J. Bergerson, M. Gazzani, E. Gencer, J. Gibbins, M. Mazzotti, S. T. McCoy, R. McKenna, R. Pietzcker, A. P. Ravikumar, M. C. Romano, F.

Ueckerdt, J. Vente and M. van der Spek, *Sustainable Energy & Fuels*, 2022, **6**, 66-75.
20. A. Valente, D. Iribarren and J. Dufour, *The International Journal of Life Cycle Assessment*, 2017, **22**, 346-363.
21. M. Delpierre, J. Quist, J. Mertens, A. Prieur-Vernat and S. Cucurachi, *Journal of Cleaner Production*, 2021, **299**, 126866.
22. P. Lamers, T. Ghosh, S. Upasani, R. Sacchi and V. Daioglou, *Environmental Science & Technology*, 2023, **57**, 2464-2473.
23. IEA, *The Future of Hydrogen - Seizing today's opportunities*, International Energy Agency, 2019.
24. Y. Bicer and I. Dincer, *International Journal of Hydrogen Energy*, 2018, **43**, 4583-4596.
25. F. M. Kanchiralla, S. Brynolf, E. Malmgren, J. Hansson and M. Grahn, *Environmental Science & Technology*, 2022, **56**, 12517-12531.
26. F. M. Kanchiralla, S. Brynolf, T. Olsson, J. Ellis, J. Hansson and M. Grahn, *Applied Energy*, 2023, **350**, 121773.
27. G. Finnveden, M. Z. Hauschild, T. Ekvall, J. Guinée, R. Heijungs, S. Hellweg, A. Koehler, D. Pennington and S. Suh, *Journal of Environmental Management*, 2009, **91**, 1-21.
28. J. B. Guinée, R. Heijungs, G. Huppes, A. Zamagni, P. Masoni, R. Buonamici, T. Ekvall and T. Rydberg, *Environmental Science & Technology*, 2011, **45**, 90-96.
29. R. Arvidsson, A.-M. Tillman, B. A. Sandén, M. Janssen, A. Nordelöf, D. Kushnir and S. Molander, *Journal of Industrial Ecology*, 2018, **22**, 1286-1294.
30. N. Thonemann, A. Schulte and D. Maga, *Sustainability*, 2020, **12**, 1192.
31. M. Caduff, M. A. J. Huijbregts, H.-J. Althaus, A. Koehler and S. Hellweg, *Environmental Science & Technology*, 2012, **46**, 4725-4733.
32. T. Gibon, R. Wood, A. Arvesen, J. D. Bergesen, S. Suh and E. G. Hertwich, *Environmental Science & Technology*, 2015, **49**, 11218-11226.
33. R. Kothari, D. Buddhi and R. L. Sawhney, *Renewable and Sustainable Energy Reviews*, 2008, **12**, 553-563.
34. B. Parkinson, M. Tabatabaei, D. C. Upham, B. Ballinger, C. Greig, S. Smart and E. McFarland, *International Journal of Hydrogen Energy*, 2018, **43**, 2540-2555.
35. F. Mueller-Langer, E. Tzimas, M. Kaltschmitt and S. Peteves, *International Journal of Hydrogen Energy*, 2007, **32**, 3797-3810.
36. IPCC, *Carbon Dioxide Capture and Storage*, Intergovernmental Panel on Climate Change, New York, 2005.
37. K. Volkart, C. Bauer and C. Boulet, *International Journal of Greenhouse Gas Control*, 2013, **16**, 91-106.
38. C. Antonini, K. Treyer, A. Streb, M. van der Spek, C. Bauer and M. Mazzotti, *Sustainable Energy & Fuels*, 2020, **4**, 2967-2986.
39. C. Antonini, K. Treyer, E. Moioli, C. Bauer, T. J. Schildhauer and M. Mazzotti, *Sustainable Energy & Fuels*, 2021, **5**, 2602-2621.
40. N. Gerloff, *Journal of Energy Storage*, 2021, **43**, 102759.
41. K. Bareiß, C. de la Rua, M. Möckl and T. Hamacher, *Applied Energy*, 2019, **237**, 862-872.
42. F. M. Kanchiralla, S. Brynolf and A. Mjelde, *Energy & Environmental Science*, 2024, **17**, 6393-6418.

43. H. Lindstad, B. E. Asbjørnslett and A. H. Strømman, *Energy Policy*, 2011, **39**, 3456-3464.
44. R. T. Poulsen, M. Viktorelius, H. Varvne, H. B. Rasmussen and H. von Knorring, *Transportation Research Part D: Transport and Environment*, 2022, **102**, 103120.
45. V. Zhaka and B. Samuelsson, *Energy Reports*, 2024, **12**, 5249-5267.
46. J. Cui and M. Aziz, *International Journal of Hydrogen Energy*, 2023, **48**, 15737-15747.
47. C. J. McKinlay, S. R. Turnock and D. A. Hudson, *International Journal of Hydrogen Energy*, 2021, **46**, 28282-28297.
48. OECD, *CO_2 emissions from global shipping – a new experimental database*, Organisation for Economic Co-operation and Development, Paris, 2023.
49. E. Müller-Casseres, F. Leblanc, M. van den Berg, P. Fragkos, O. Dessens, H. Naghash, R. Draeger, T. Le Gallic, I. S. Tagomori, I. Tsiropoulos, J. Emmerling, L. B. Baptista, D. P. van Vuuren, A. Giannousakis, L. Drouet, J. Portugal-Pereira, H.-S. de Boer, N. Tsanakas, P. R. R. Rochedo, A. Szklo and R. Schaeffer, *Nature Climate Change*, 2024, **14**, 600-607.
50. G. Lee, J. Kim, K. Jung, H. Park, H. Jang, C. Lee and J. Lee, *Journal of Marine Science and Engineering*, 2022, **10**, 755.
51. S. Hwang, S. Gil, G. Lee, J. Lee, H. Park, K. Jung and S. Suh, *Journal of Marine Science and Engineering*, 2020, **8**, 660.
52. M. Perčić, N. Vladimir, I. Jovanović and M. Koričan, *Applied Energy*, 2022, **309**, 118463.
53. S. Wei, R. Sacchi, A. Tukker, S. Suh and B. Steubing, *Energy & Environmental Science*, 2024, **17**, 2157-2172.
54. S. C. D'Angelo, S. Cobo, V. Tulus, A. Nabera, A. J. Martín, J. Pérez-Ramírez and G. Guillén-Gosálbez, *ACS Sustainable Chemistry & Engineering*, 2021, **9**, 9740-9749.
55. Á. Galán-Martín, V. Tulus, I. Díaz, C. Pozo, J. Pérez-Ramírez and G. Guillén-Gosálbez, *One Earth*, 2021, **4**, 565-583.
56. IEA, *Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach*, International Energy Agency, Paris, 2023.
57. L. Van Hoecke, L. Laffineur, R. Campe, P. Perreault, S. W. Verbruggen and S. Lenaerts, *Energy & Environmental Science*, 2021, **14**, 815-843.
58. M. Perčić, N. Vladimir and A. Fan, *Applied Energy*, 2020, **279**, 115848.
59. IEA, *Net Zero by 2050*, International Energy Agency, 2021.
60. I. Staffell, D. Scamman, A. Velazquez Abad, P. Balcombe, P. E. Dodds, P. Ekins, N. Shah and K. R. Ward, *Energy & Environmental Science*, 2019, **12**, 463-491.
61. IEA, *Global Hydrogen Review 2021*, International Energy Agency, Paris, 2021.
62. A. Odenweller, F. Ueckerdt, G. F. Nemet, M. Jensterle and G. Luderer, *Nature Energy*, 2022, **7**, 854-865.
63. C. F. Blanco, S. Cucurachi, J. B. Guinée, M. G. Vijver, W. J. G. M. Peijnenburg, R. Trattnig and R. Heijungs, *Journal of Cleaner Production*, 2020, **259**, 120968.
64. T. Weidner, V. Tulus and G. Guillén-Gosálbez, *International Journal of Hydrogen Energy*, 2023, **48**, 8310-8327.
65. R. Sacchi, T. Terlouw, K. Siala, A. Dirnaichner, C. Bauer, B. Cox, C. Mutel, V. Daioglou and G. Luderer, *Renewable and Sustainable Energy Reviews*, 2022, **160**, 112311.
66. L. Baumstark, N. Bauer, F. Benke, C. Bertram, S. Bi, C. C. Gong, J. P. Dietrich, A. Dirnaichner, A. Giannousakis, J. Hilaire, D. Klein, J. Koch, M. Leimbach, A.

Levesque, S. Madeddu, A. Malik, A. Merfort, L. Merfort, A. Odenweller, M. Pehl, R. C. Pietzcker, F. Piontek, S. Rauner, R. Rodrigues, M. Rottoli, F. Schreyer, A. Schultes, B. Soergel, D. Soergel, J. Strefler, F. Ueckerdt, E. Kriegler and G. Luderer, *Geosci. Model Dev.*, 2021, **14**, 6571-6603.
67. IEA, *World Energy Outlook 2022*, International Energy Agency, Paris, 2022.
68. IEA, *Hydrogen in Latin America: From near-term opportunities to large-scale deployment*, International Energy Agency, Paris, 2021.
69. IEA, *Hydrogen Production Projects Database*, International Energy Agency, Paris, 2022.
70. NREL, Current Hydrogen from Coal without CO_2 Capture and Sequestration, https://www.nrel.gov/hydrogen/assets/docs/current-central-coal-without-co2-sequestration-v2-1-1.xls, (accessed 4th May, 2022).
71. A. Wokaun and E. Wilhelm, *Transition to Hydrogen: Pathways toward Clean Transportation*, Cambridge University Press, Cambridge, 2011.
72. IEA, *The Future of Hydrogen*, International Energy Agency, Paris, 2019.
73. NREL, Current Central Hydrogen from Coal with CO_2 Capture and Sequestration, https://www.nrel.gov/hydrogen/h2a-production-models.html, (accessed 4th May, 2022).
74. DEA, *Technology Data for Renewable Fuels*, Danish Energy Agency, 2022.
75. J. Alcalde, S. Flude, M. Wilkinson, G. Johnson, K. Edlmann, C. E. Bond, V. Scott, S. M. V. Gilfillan, X. Ogaya and R. S. Haszeldine, *Nature Communications*, 2018, **9**, 2201.
76. R. Heijungs, K. Allacker, E. Benetto, M. Brandão, J. Guinée, S. Schaubroeck, T. Schaubroeck and A. Zamagni, *Frontiers in Sustainability*, 2021, **2**.
77. B. Singh, A. H. Strømman and E. G. Hertwich, *International Journal of Greenhouse Gas Control*, 2011, **5**, 911-921.
78. DEA, *Technology Data for Carbon Capture, Transport and Storage* Danish Energy Agency, Copenhagen, 2021.
79. A. Aspelund and K. Jordal, *International Journal of Greenhouse Gas Control*, 2007, **1**, 343-354.
80. F. Donda, V. Volpi, S. Persoglia and D. Parushev, *International Journal of Greenhouse Gas Control*, 2011, **5**, 327-335.
81. IEAGHG, *The Costs of CO_2 Storage - Post-demonstration CCS in the EU*, Brussels, 2019.
82. V. Vishal, *Fuel*, 2017, **192**, 201-207.
83. IEAGHG, *Techno-Economic Evaluation of SMR Based Standalone (Merchant) Hydrogen Plant with CCS*, The IEA Greenhouse Gas R&D Programme, 2017.
84. P. Nikolaidis and A. Poullikkas, *Renewable and Sustainable Energy Reviews*, 2017, **67**, 597-611.
85. D. Hospital-Benito, I. Díaz and J. Palomar, *Sustainable Production and Consumption*, 2023, **38**, 283-294.
86. S. Fuss, J. G. Canadell, G. P. Peters, M. Tavoni, R. M. Andrew, P. Ciais, R. B. Jackson, C. D. Jones, F. Kraxner, N. Nakicenovic, C. Le Quéré, M. R. Raupach, A. Sharifi, P. Smith and Y. Yamagata, *Nature Climate Change*, 2014, **4**, 850-853.
87. Y. X. Chen, A. Lavacchi, H. A. Miller, M. Bevilacqua, J. Filippi, M. Innocenti, A. Marchionni, W. Oberhauser, L. Wang and F. Vizza, *Nature Communications*, 2014, **5**, 4036.

88. G. Zhao, M. R. Kraglund, H. L. Frandsen, A. C. Wulff, S. H. Jensen, M. Chen and C. R. Graves, *International Journal of Hydrogen Energy*, 2020, **45**, 23765-23781.
89. K. E. Ayers, C. Capuano and E. B. Anderson, *ECS Transactions*, 2012, **41**, 15.
90. A. H. Reksten, M. S. Thomassen, S. Møller-Holst and K. Sundseth, *International Journal of Hydrogen Energy*, 2022, **47**, 38106-38113.
91. R. J. Ouimet, J. R. Glenn, D. De Porcellinis, A. R. Motz, M. Carmo and K. E. Ayers, *ACS Catalysis*, 2022, **12**, 6159-6171.
92. M. A. Laguna-Bercero, *Journal of Power Sources*, 2012, **203**, 4-16.
93. G. Lo Basso, A. Mojtahed, L. M. Pastore and L. De Santoli, *International Journal of Hydrogen Energy*, 2023, DOI: https://doi.org/10.1016/j.ijhydene.2023.04.231.
94. E. R. Morgan, J. F. Manwell and J. G. McGowan, *International Journal of Hydrogen Energy*, 2013, **38**, 15903-15909.
95. M. H. Ali Khan, R. Daiyan, Z. Han, M. Hablutzel, N. Haque, R. Amal and I. MacGill, *iScience*, 2021, **24**, 102539.
96. A. Simons and C. Bauer, *Applied Energy*, 2015, **157**, 884-896.
97. IRENA, *Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5^{0}C Climate Goal*, International Renewable Energy Agency, Abu Dhabi, 2020.
98. FCE, *FuelCell Energy Announces Solid Oxide Electrolysis and Fuel Cell Platform to Improve Control and Flexibility of Energy Investments*, FuelCell Energy, Inc., 2022.
99. R. E. Lester, D. Gunasekera, W. Timms and D. Downie, *Water requirements for use in hydrogen production in Australia: Potential public policy and industry-related issues*, Deakin University, 2022.
100. GCCSI, *Replacing 10% of NSW Natural Gas Supply with Clean Hydrogen: Comparison of Hydrogen Production Options*, Global CCS Institute, Melbourne, 2020.
101. O. Schmidt, A. Gambhir, I. Staffell, A. Hawkes, J. Nelson and S. Few, *International Journal of Hydrogen Energy*, 2017, **42**, 30470-30492.
102. NREL, H2A: Hydrogen Analysis Production Models, https://www.nrel.gov/hydrogen/h2a-production-models.html, (accessed 10 th, December, 2023).
103. IEA, *Global Energy and Climate Model* International Energy Agency, 2022.
104. IEA, *Global Hydrogen Review 2022*, International Energy Agency, Paris, 2022.
105. A. Mendoza Beltran, B. Cox, C. Mutel, D. P. van Vuuren, D. Font Vivanco, S. Deetman, O. Y. Edelenbosch, J. Guinée and A. Tukker, *Journal of Industrial Ecology*, 2020, **24**, 64-79.
106. K. Riahi, D. P. van Vuuren, E. Kriegler, J. Edmonds, B. C. O'Neill, S. Fujimori, N. Bauer, K. Calvin, R. Dellink, O. Fricko, W. Lutz, A. Popp, J. C. Cuaresma, S. Kc, M. Leimbach, L. Jiang, T. Kram, S. Rao, J. Emmerling, K. Ebi, T. Hasegawa, P. Havlik, F. Humpenöder, L. A. Da Silva, S. Smith, E. Stehfest, V. Bosetti, J. Eom, D. Gernaat, T. Masui, J. Rogelj, J. Strefler, L. Drouet, V. Krey, G. Luderer, M. Harmsen, K. Takahashi, L. Baumstark, J. C. Doelman, M. Kainuma, Z. Klimont, G. Marangoni, H. Lotze-Campen, M. Obersteiner, A. Tabeau and M. Tavoni, *Global Environmental Change*, 2017, **42**, 153-168.
107. O. Fricko, P. Havlik, J. Rogelj, Z. Klimont, M. Gusti, N. Johnson, P. Kolp, M. Strubegger, H. Valin, M. Amann, T. Ermolieva, N. Forsell, M. Herrero, C. Heyes, G. Kindermann, V. Krey, D. L. McCollum, M. Obersteiner, S. Pachauri, S. Rao, E.

Schmid, W. Schoepp and K. Riahi, *Global Environmental Change*, 2017, **42**, 251-267.
108. J. Rogelj, A. Popp, K. V. Calvin, G. Luderer, J. Emmerling, D. Gernaat, S. Fujimori, J. Strefler, T. Hasegawa, G. Marangoni, V. Krey, E. Kriegler, K. Riahi, D. P. van Vuuren, J. Doelman, L. Drouet, J. Edmonds, O. Fricko, M. Harmsen, P. Havlík, F. Humpenöder, E. Stehfest and M. Tavoni, *Nature Climate Change*, 2018, **8**, 325-332.
109. G. Wernet, C. Bauer, B. Steubing, J. Reinhard, E. Moreno-Ruiz and B. Weidema, *The International Journal of Life Cycle Assessment*, 2016, **21**, 1218-1230.
110. IPCC, *Climate Change 2013 – The Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Report 9781107057999, Intergovernmental Panel on Climate, Change, Cambridge, 2013.
111. N. Warwick, P. Griffiths, J. Keeble, A. Archibald, J. Pyle and K. Shine, *Atmospheric implications of increased Hydrogen use*, Department for Business, Energy and Industrial Strategy, 2022.
112. S. Fazio, F. Biganzioli, V. De Laurentiis, L. Zampori and S. D. Sala, E., *Supporting information to the characterisation factors of recommended EF Life Cycle Impact Assessment methods, Version 2, from ILCD to EF 3.0*, European Commission, Ispra, 2018.
113. B. Steubing, D. de Koning, A. Haas and C. L. Mutel, *Software Impacts*, 2020, **3**, 100012.
114. B. Steubing and D. de Koning, *The International Journal of Life Cycle Assessment*, 2021, **26**, 2248-2262.
115. R. W. Howarth and M. Z. Jacobson, *Energy Science & Engineering*, 2021, **9**, 1676-1687.
116. T. Lepage, M. Kammoun, Q. Schmetz and A. Richel, *Biomass and Bioenergy*, 2021, **144**, 105920.
117. EBA, *Decarbonising Europe's hydrogen production with biohydrogen*, European Biogas Association, Brussels, 2023.
118. J. P. W. Scharlemann and W. F. Laurance, *Science*, 2008, **319**, 43-44.
119. R. Birdsey, P. Duffy, C. Smyth, W. A. Kurz, A. J. Dugan and R. Houghton, *Environmental Research Letters*, 2018, **13**, 050201.
120. K. Navare, W. Arts, G. Faraca, G. V. d. Bossche, B. Sels and K. V. Acker, *Resources, Conservation and Recycling*, 2022, **186**, 106588.
121. M. van der Spek, C. Banet, C. Bauer, P. Gabrielli, W. Goldthorpe, M. Mazzotti, S. T. Munkejord, N. A. Røkke, N. Shah, N. Sunny, D. Sutter, J. M. Trusler and M. Gazzani, *Energy & Environmental Science*, 2022, **15**, 1034-1077.
122. J. B. Hansen, *Topsoe's Road Map to All Electric Ammonia Plants*, Pittsburgh, 2018.
123. B. Atilgan and A. Azapagic, *Journal of Cleaner Production*, 2015, **106**, 555-564.
124. M. Tammaro, A. Salluzzo, J. Rimauro, S. Schiavo and S. Manzo, *Journal of Hazardous Materials*, 2016, **306**, 395-405.
125. K. Treyer, C. Bauer and A. Simons, *Energy Policy*, 2014, **74**, S31-S44.
126. J. Nijnens, P. Behrens, O. Kraan, B. Sprecher and R. Kleijn, *Joule*, 2023, DOI: 10.1016/j.joule.2023.10.005.
127. G. Luderer, M. Pehl, A. Arvesen, T. Gibon, B. L. Bodirsky, H. S. de Boer, O. Fricko, M. Hejazi, F. Humpenöder, G. Iyer, S. Mima, I. Mouratiadou, R. C. Pietzcker, A. Popp,

M. van den Berg, D. van Vuuren and E. G. Hertwich, *Nature Communications*, 2019, **10**, 5229.
128. C. Minke, M. Suermann, B. Bensmann and R. Hanke-Rauschenbach, *International Journal of Hydrogen Energy*, 2021, **46**, 23581-23590.
129. K. D. Rasmussen, H. Wenzel, C. Bangs, E. Petavratzi and G. Liu, *Environmental Science & Technology*, 2019, **53**, 11541-11551.
130. A. Månberger and B. Johansson, *Energy Strategy Reviews*, 2019, **26**, 100394.
131. R. Fu, K. Peng, P. Wang, H. Zhong, B. Chen, P. Zhang, Y. Zhang, D. Chen, X. Liu, K. Feng and J. Li, *Nature Communications*, 2023, **14**, 3703.
132. R. R. Beswick, A. M. Oliveira and Y. Yan, *ACS Energy Letters*, 2021, **6**, 3167-3169.
133. FAO, *AQUASTAT*, United Nations Food and Agriculture Organization, 2024.
134. IEA, *Clean energy can help to ease the water crisis*, International Energy Agency, Paris, 2023.
135. WaterSMART, *Water for the Hydrogen Economy*, Calgary, 2020.
136. K. T. Solutions, Hydrogen Production & Distribution, (accessed 16th December, 2023).
137. C. E. Raptis, J. M. Boucher and S. Pfister, *Science of The Total Environment*, 2017, **580**, 1014-1026.
138. H. Xie, Z. Zhao, T. Liu, Y. Wu, C. Lan, W. Jiang, L. Zhu, Y. Wang, D. Yang and Z. Shao, *Nature*, 2022, **612**, 673-678.
139. M. N. Dods, E. J. Kim, J. R. Long and S. C. Weston, *Environmental Science & Technology*, 2021, **55**, 8524-8534.
140. P. Brandl, M. Bui, J. P. Hallett and N. Mac Dowell, *International Journal of Greenhouse Gas Control*, 2021, **105**, 103239.
141. H. D. Matthews, K. Zickfeld, R. Knutti and M. R. Allen, *Environmental Research Letters*, 2018, **13**, 010201.
142. IPCC, *Climate Change 2022: Mitigation of Climate Change*, Intergovernmental Panel on Climate Change, Cambridge, UK and New York, NY, USA, 2022.
143. C. Delft, *Additionality of renewable electricity for green hydrogen production in the EU*, CE Delft, Delft, 2022.
144. M. A. Giovanniello, A. N. Cybulsky, T. Schittekatte and D. S. Mallapragada, *Nature Energy*, 2024, DOI: 10.1038/s41560-023-01435-0.
145. US-DOE, Biden-Harris Administration Announces $7 Billion For America's First Clean Hydrogen Hubs, Driving Clean Manufacturing and Delivering New Economic Opportunities Nationwide, https://www.energy.gov/articles/biden-harris-administration-announces-7-billion-americas-first-clean-hydrogen-hubs-driving, (accessed 11th December, 2023).
146. P. J. Vergragt, N. Markusson and H. Karlsson, *Global Environmental Change*, 2011, **21**, 282-292.
147. E. Martin-Roberts, V. Scott, S. Flude, G. Johnson, R. S. Haszeldine and S. Gilfillan, *One Earth*, 2021, **4**, 1569-1584.
148. D. Tonelli, L. Rosa, P. Gabrielli, K. Caldeira, A. Parente and F. Contino, *Nature Communications*, 2023, **14**, 5532.
149. G. Wang, J. Xu, L. Ran, R. Zhu, B. Ling, X. Liang, S. Kang, Y. Wang, J. Wei, L. Ma, Y. Zhuang, J. Zhu and H. He, *Nature Sustainability*, 2023, **6**, 81-92.
150. S. H. Farjana, N. Huda, M. A. Parvez Mahmud and R. Saidur, *Journal of Cleaner Production*, 2019, **231**, 1200-1217.

151. S. Guo, X. Li, J. Li and B. Wei, *Nature Communications*, 2021, **12**, 1343.
152. M. Z. Rahman and J. Gascon, *Chem Catalysis*, 2023, **3**, 100536.
153. IRENA, *A pathway to decarbonise the shipping sector by 2050*, International Renewable Energy Agency, Abu Dhabi, 2021.
154. IMO, *Fourth IMO GHG Study 2020*, International Maritime Organization, London, 2021.
155. IMO, *2023 IMO Strategy on Reduction of GHG Emissions from Ships*, International Maritime Organization, 2023.
156. P. Balcombe, J. Brierley, C. Lewis, L. Skatvedt, J. Speirs, A. Hawkes and I. Staffell, *Energy Conversion and Management*, 2019, **182**, 72-88.
157. L. Bilgili, *Renewable and Sustainable Energy Reviews*, 2021, **144**, 110985.
158. A. D. Korberg, S. Brynolf, M. Grahn and I. R. Skov, *Renewable and Sustainable Energy Reviews*, 2021, **142**, 110861.
159. K. Kim, G. Roh, W. Kim and K. Chun, *Journal*, 2020, **8**.
160. IRENA, *Innovation Outlook: Renewable Methanol*, International Renewable Energy Agency, 2021.
161. J. Fuhrman, A. Clarens, K. Calvin, S. C. Doney, J. A. Edmonds, P. O'Rourke, P. Patel, S. Pradhan, W. Shobe and H. McJeon, *Environmental Research Letters*, 2021, **16**, 114012.
162. T. Terlouw, K. Treyer, C. Bauer and M. Mazzotti, *Environmental Science & Technology*, 2021, **55**, 11397-11411.
163. GMH, *Efficiency Evaluation of Global 20 Major Container Ports*, Global Maritime Hub, 2019.
164. ICCT, *Refueling assessment of a zero-emission container corridor between China and the United States: Could hydrogen replace fossil fuels?*, International Council on Clean Transportation, Washington, DC, 2020.
165. J. J. Minnehan and J. W. Pratt, *Practical Application Limits of Fuel Cells and Batteries for Zero Emission Vessels*, Sandia National Laboratories, United States, 2017.
166. MI, *What is The Speed of a Ship at Sea?*, Marine Insight, 2019.
167. K. P. Jain, J. F. J. Pruyn and J. J. Hopman, *Resources, Conservation and Recycling*, 2016, **107**, 1-9.
168. P. J. Notten, H.-J. Althaus, M. Burke and A. Läderach, *Life cycle inventories of global shipping - Global*, ecoinvent Association, Zürich, 2018.
169. SRI, *Life cycle inventories of global shipping - Global*, Sustainable Recycling Industries, Cape Town, 2018.
170. E. C. Tupper, in *Introduction to Naval Architecture (Fifth Edition)*, ed. E. C. Tupper, Butterworth-Heinemann, Oxford, 2013, DOI: https://doi.org/10.1016/B978-0-08-098237-3.00002-3, pp. 9-32.
171. Scheepvaartwest, Colombo Express - IMO 9295244, https://www.scheepvaartwest.be/CMS/index.php/containerships/9641-colombo-express-imo-9295244, (accessed 5th, February, 2023).
172. A. Papanikolaou, *Ship Design - Methodologies of Preliminary Design*, 2014.
173. IMO, *The 2020 global sulphur limit*, International Maritime Organization, 2021.
174. M. Silva, Master, Norwegian University of Science and Technology, 2017.
175. C. Wulf and P. Zapp, *International Journal of Hydrogen Energy*, 2018, **43**, 11884-11895.

176. S. Z. S. Al Ghafri, S. Munro, U. Cardella, T. Funke, W. Notardonato, J. P. M. Trusler, J. Leachman, R. Span, S. Kamiya, G. Pearce, A. Swanger, E. D. Rodriguez, P. Bajada, F. Jiao, K. Peng, A. Siahvashi, M. L. Johns and E. F. May, *Energy & Environmental Science*, 2022, **15**, 2690-2731.
177. A. González-Garay, M. S. Frei, A. Al-Qahtani, C. Mondelli, G. Guillén-Gosálbez and J. Pérez-Ramírez, *Energy & Environmental Science*, 2019, **12**, 3425-3436.
178. D. W. Keith, G. Holmes, D. St. Angelo and K. Heidel, *Joule*, 2018, **2**, 1573-1594.
179. J. Gao, S. Xing, G. Tian, C. Ma, M. Zhao and P. Jenner, *Fuel*, 2021, **285**, 119210.
180. EMSA, *Possible Technical Modifications on Pre-2000 Marine Diesel Engines for NO_x Reductions*, European Maritime Safety Agency, 2008.
181. Z. Liang, X. Ma, H. Lin and Y. Tang, *Applied Energy*, 2011, **88**, 1120-1129.
182. E. Westberg, Independent thesis Advanced level (degree of Master (Two Years)) Student thesis, 2020.
183. ABB, *ACS 6000 Medium Voltage AC drive for speedand torque control for power of 3 MW to 27 MW motors*, ABB, Zurich, 2003.
184. MAN, *Propulsion trends in container vessels*, MAN Energy Solutions, Copenhagen, 2024.
185. H. Lee, Y. Shao, S. Lee, G. Roh, K. Chun and H. Kang, *International Journal of Hydrogen Energy*, 2019, **44**, 15056-15071.
186. J. Lee, Y. Choi and J. Choi, *Journal*, 2022, **10**.
187. Q. Song, R. R. Tinoco, H. Yang, Q. Yang, H. Jiang, Y. Chen and H. Chen, *Carbon Capture Science & Technology*, 2022, **4**, 100056.
188. ABS, *Setting the Course to Low Carbon Shipping: View of the Value Chain*, American Bureau of Shipping, Texas, 2021.
189. IEA-AMF, *Alternative Fuels for Marine Applications*, International Energy Agency-Advanced Motor Fuels, Wieselburg, 2013.
190. IEA, *The Role of E-fuels in Decarbonising Transport*, International Energy Agency, Paris, 2024.
191. S. V. Hanssen, V. Daioglou, Z. J. N. Steinmann, J. C. Doelman, D. P. Van Vuuren and M. A. J. Huijbregts, *Nature Climate Change*, 2020, **10**, 1023-1029.
192. S. Fujimori, W. Wu, J. Doelman, S. Frank, J. Hristov, P. Kyle, R. Sands, W.-J. van Zeist, P. Havlik, I. P. Domínguez, A. Sahoo, E. Stehfest, A. Tabeau, H. Valin, H. van Meijl, T. Hasegawa and K. Takahashi, *Nature Food*, 2022, **3**, 110-121.
193. A. Pozzer, M. G. Schultz and D. Helmig, *Environmental Science & Technology*, 2020, **54**, 12423-12433.
194. Y. Chen, Y. Fan, Y. Huang, X. Liao, W. Xu and T. Zhang, *Ecotoxicology and Environmental Safety*, 2024, **269**, 115905.
195. B. Gu, L. Zhang, R. Van Dingenen, M. Vieno, H. J. M. Van Grinsven, X. Zhang, S. Zhang, Y. Chen, S. Wang, C. Ren, S. Rao, M. Holland, W. Winiwarter, D. Chen, J. Xu and M. A. Sutton, *Science*, 2021, **374**, 758-762.
196. UNCAD, *Review of maritime transport 2021*, United Nations Conference on Trade and Development, Geneva, 2021.
197. IEA, *Tracking Clean Energy Progress 2023*, International Energy Agency, Paris, 2023.
198. A. Monteiro, M. Russo, C. Gama and C. Borrego, *Environmental Pollution*, 2018, **242**, 565-575.
199. H. Liu, Z.-H. Meng, Z.-F. Lv, X.-T. Wang, F.-Y. Deng, Y. Liu, Y.-N. Zhang, M.-S. Shi, Q. Zhang and K.-B. He, *Nature Sustainability*, 2019, **2**, 1027-1033.

200. J. Fernández-González, M. Rumayor, A. Domínguez-Ramos, A. Irabien and I. Ortiz, *JACS Au*, 2023, **3**, 2631-2639.
201. B. A. Wender, R. W. Foley, V. Prado-Lopez, D. Ravikumar, D. A. Eisenberg, T. A. Hottle, J. Sadowski, W. P. Flanagan, A. Fisher, L. Laurin, M. E. Bates, I. Linkov, T. P. Seager, M. P. Fraser and D. H. Guston, *Environmental Science & Technology*, 2014, **48**, 10531-10538.
202. Z. Wang, B. Dong, Y. Wang, M. Li, H. Liu and F. Han, *Energy Conversion and Management: X*, 2024, **21**, 100482.
203. Z. Fu, L. Lu, C. Zhang, Q. Xu, X. Zhang, Z. Gao and J. Li, *Sustainable Energy Technologies and Assessments*, 2023, **57**, 103181.
204. ISO, *Journal*, 2006.
205. J. Eyres David, *Journal*, 2007.
206. U.S.DOE, *Comparison of Fuel Cell Technologies*, U.S. Department of Energy, Washington, DC, 2016.
207. MAN-SE, *Marine engine programme-2nd edition 2023*, MAN Energy Solutions, Augsburg, 2023.
208. MANES, *Basic principles of ship propulsion*, MAN Energy Solutions, Copenhagen, 2018.
209. C. Guellec, C. Doudard, B. Levieil, L. Jian, A. Ezanno and S. Calloch, *Marine Structures*, 2023, **87**, 103325.
210. Y. Zhao, Y. Fan, K. Fagerholt and J. Zhou, *Transportation Research Part D: Transport and Environment*, 2021, **90**, 102641.
211. S. Shih-Tung, Master's Thesis, University of Rostock, 2013.
212. PowerCell, *Fuel Cells - PowerCell AB*, Göteborg, 2019.
213. L. Usai, C. R. Hung, F. Vásquez, M. Windsheimer, O. S. Burheim and A. H. Strømman, *Journal of Cleaner Production*, 2021, **280**, 125086.
214. F. IISB, *High Power SiC DC/DC Converters*, Fraunhofer Institute for Integrated Systems and Device Technology, Erlangen, 2014.
215. PPS, Railway and Industry 2000W DC/DC Converter, https://premiumpsu.com/product/crs-2000-industrial-railway-2000w-dc-dc-converter/, (accessed 15th, March, 2024).
216. ABB, *Solar Inverters—ABB Medium Voltage Compact Skid (PVS-175-MVCS)*, ABB, Zurich, 2019.
217. GEPC, *MV6 Medium Voltage Drive-Leading next generation technology*, GE Power Conversion, Paris, 2017.
218. RA, *PowerFlex 7000 Medium Voltage AC VFD—Air-Cooled*, Rockwell Automation, Milwaukee, 2024.
219. ABB, *Medium Voltage AC Drive ACS 5000, 1.5 MW–36 MW, 6.0–6.9 kV*, ABB, Zurich, 2013.
220. S. Grzesiak, *New Trends in Production Engineering*, 2018, **1**, 399-407.
221. HE, *Induction Motors Medium & High Voltage*, Hyundai Electric, Seongnam-si, 2019.
222. E. Tazelaar, PhD, Technische Universiteit Eindhoven, 2013.
223. GPhilos, FUEL CELL INVERTER, http://g-philos.co.kr/en/sub/product/fuel_cell_inverter_building.php#anc01, (accessed 10th, March, 2024).
224. ABB, *Central Inverters—PVS800, 100 to 1000 kW*, ABB, Zurich, 2014.

225. L. A.-W. Ellingsen, G. Majeau-Bettez, B. Singh, A. K. Srivastava, L. O. Valøen and A. H. Strømman, *Journal of Industrial Ecology*, 2014, **18**, 113-124.
226. MANSE, *Diesel-electric Propulsion Plants: A brief guideline how to engineer a diesel-electric propulsion system*, MAN Energy Solutions, Munich, 2012.
227. EPD, Switchboard Maintenance: Safeguarding Your Electrical System's Longevity, https://www.electronicpowerdesign.com/news/switchboard-maintenance/, (accessed 12th, March, 2024).
228. SIEMENS, *Air-Insulated Medium-Voltage Switchgear NXAirS, up to 12 kV*, Shanghai, 2020.
229. S. SARCO, Boiler Efficiency and Combustion, https://www.spiraxsarco.com/learn-about-steam/the-boiler-house/boiler-efficiency-and-combustion?sc_lang=en-GB, (accessed 11th, February, 2025).
230. PARAT, *Marine Boilers*, Flekkefjord, 2024.
231. BOSCH, Electric steam boiler ELSB, https://www.bosch-industrial.com/global/en/ocs/commercial-industrial/electric-steam-boiler-elsb-19175285-p/, (accessed 5th, February, 2025).
232. A. M. A. Abbas, Master, An-Najah National University, 2015.
233. TNO, *E-fuels: Towards a more sustainable future for truck transport, shipping and aviation*, Netherlands Organisation for Applied Scientific Research, Delft, 2020.
234. N. G. Dlamini, K. Fujimura, E. Yamasue, H. Okumura and K. N. Ishihara, *The International Journal of Life Cycle Assessment*, 2011, **16**, 410-419.
235. E. W. M. Abbas, Master, Chalmers University of Technology, 2022.
236. EMSA, *Potential of Ammonia as Fuel in Shipping*, European Maritime Safety Agency, Lisbon, 2022.
237. J. M. Ryste, Master, Norwegian University of Science and Technology, 2012.
238. Cryocan, Ammonia Storage Tank, https://cryocan.com/en/chemichal/ammonia-storage-tanks/, (accessed 19th, December, 2024).
239. E. C. D. Tan, T. R. Hawkins, U. Lee, L. Tao, P. A. Meyer, M. Wang and T. Thompson, *Environmental Science & Technology*, 2021, **55**, 7561-7570.
240. K. Andersson and H. Winnes, *Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment*, 2011, **225**, 33-42.
241. EGCSA, NOx Reduction by Exhaust Gas Recirculation – MAN explains, https://www.egcsa.com/exhaust-gas-recirculation-explained/, (accessed 11th, June, 2024).
242. IMO, *Fourth IMO GHG Study 2020*, International Maritime Organization, London, 2020.
243. S. S. Hwang, S. J. Gil, G. N. Lee, J. W. Lee, H. Park, K. H. Jung and S. B. Suh, *Journal of Marine Science and Engineering*, 2020, **8**.
244. DNV, *IMO Net-Zero Framework*, Det Norske Veritas, 2025.
245. DNV, *FuelEU Maritime*, Det Norske Veritas, 2025.
246. OceanScore, *FuelEU Maritime Compliance: Why Pooling Is Infinitely Better Than Paying the Penalty*, 2025.
247. ICAP, *EU Emissions Trading System (EU ETS)*, International Carbon Action Partnership Berlin, 2025.
248. EC, *Reducing emissions from the shipping sector*, European Commission, 2025.
249. DNV, *EU ETS – Emissions Trading System*, Det Norske Veritas, 2025.

250. EC, *Commission launches first European Hydrogen Bank auction with €800 million of subsidies for renewable hydrogen production*, European Commission, 2023.
251. X. Jin, P. Behrens, J. W. Erisman and J. M. Mogollón, *Scientific Data*, 2025, **12**, 1493.
252. H. Nishiyama, T. Yamada, M. Nakabayashi, Y. Maehara, M. Yamaguchi, Y. Kuromiya, Y. Nagatsuma, H. Tokudome, S. Akiyama, T. Watanabe, R. Narushima, S. Okunaka, N. Shibata, T. Takata, T. Hisatomi and K. Domen, *Nature*, 2021, **598**, 304-307.
253. P. Zhou, I. A. Navid, Y. Ma, Y. Xiao, P. Wang, Z. Ye, B. Zhou, K. Sun and Z. Mi, *Nature*, 2023, **613**, 66-70.
254. A. L. Moghaddam, S. Hejazi, M. Fattahi, M. G. Kibria, M. J. Thomson, R. AlEisa and M. A. Khan, *Energy & Environmental Science*, 2025, **18**, 2747-2790.
255. IMO, *Revised GHG reduction strategy for global shipping adopted*, International Maritime Organization, London, 2023.
256. DNV, *Study on the readiness and availability of low- and zero-carbon ship technology and marine fuels*, Det Norske Veritas, Oxfordshire, 2023.
257. AEA, Testing underway for 100 kW, direct ammonia SOFC, https://ammoniaenergy.org/articles/testing-underway-for-100-kw-direct-ammonia-sofc/#:~:text=A%202%20MW%20version%20of,a%20role%20onboard%20the%20vessel., (accessed 5th, September, 2025).
258. SCHEEPVAARTWEST, https://www.scheepvaartwest.be/CMS/index.php, 2024).
259. myShipTracking, https://www.myshiptracking.com/, 2024).
260. ICCT, *The climate implications of using LNG as a marine fuel*, International Council on Clean Transportation, Washington, DC, 2020.
261. GR, *Review of Methane Slip from LNG Engines*, Green Ray, Espoo, 2023.
262. S. Brynolf, M. Magnusson, E. Fridell and K. Andersson, *Transportation Research Part D: Transport and Environment*, 2014, **28**, 6-18.
263. MANES, *Marine engine programme-2nd edition 2023*, Man Energy Solutions, Augsburg, 2023.
264. K. Kim, G. Roh, W. Kim and K. Chun, *Journal of Marine Science and Engineering*, 2020, **8**, 183.
265. E. Westberg, Master, Linköping University, 2020.
266. IMO, *Ships face lower sulphur fuel requirements in emission control areas from 1 January 2015*, International Maritime Organization, 2015.
267. M. Gustafsson, I. Cruz, N. Svensson and M. Karlsson, *Journal of Cleaner Production*, 2020, **256**, 120473.
268. M. D. B. Watanabe, F. Cherubini and O. Cavalett, *Journal of Cleaner Production*, 2022, **364**, 132662.
269. I. Bioenergy, *The Role of Renewable Transport Fuels in Decarbonizing Road Transport: Production Technologies and Costs*, IEA Bioenergy Technology Collaboration Programme, Paris, 2020.
270. IEA, *Direct Air Capture-A key technology for net zero*, International Energy Agency, Paris, 2022.
271. F. Bisotti, K. A. Hoff, A. Mathisen and J. Hovland, *Chemical Engineering Science*, 2024, **283**, 119416.
272. MAN-ES, SNG: Synthetic gas for the maritime transition, https://www.man-es.com/marine/strategic-expertise/future-fuels/sng-biogas, (accessed 5th September, 2025).

273. EMSA, *2020-v207-23082025-EU MRV Publication of information*, European Maritime Safety Agency 2025.
274. NCEMCT, *Life cycle assessment of maritime propulsion systems*, NCE Maritime CleanTech, Trondheim, 2020.
275. T. Park, S. So, B. Jeong, P. Zhou and J.-u. Lee, *Journal of Cleaner Production*, 2021, **285**, 124832.
276. Wärtsilä, *Compact Reliq-Revolutionary Product Based on Proven Technology*, 2019.
277. MONJASA, *Heavy Fuel Oil*, Fredericia, 2017.
278. CGH, Methanol tanks, https://cgh-rsa.co.za/tanks-for-the-industry/methanol-tanks, (accessed 19th, December, 2024).
279. E. Malmgren, S. Brynolf, E. Fridell, M. Grahn and K. Andersson, *Sustainable Energy & Fuels*, 2021, **5**, 2753-2770.
280. G. Kallis, J. Hickel, D. W. O'Neill, T. Jackson, P. A. Victor, K. Raworth, J. B. Schor, J. K. Steinberger and D. Ürge-Vorsatz, *The Lancet Planetary Health*, 2025, **9**, e62-e78.
281. UNCTAD, *Review of Maritime Transport 2022*, United Nations Conference on Trade and Development Geneva, 2022.
282. HE, *How Hydrogen Can Help Decarbonise the Maritime Sector*, Hydrogen Europe, Brussels, 2021.
283. E. Kato and Y. Yamagata, *Earth's Future*, 2014, **2**, 421-439.
284. O. Y. Edelenbosch, A. F. Hof, M. van den Berg, H. S. de Boer, H.-H. Chen, V. Daioglou, M. M. Dekker, J. C. Doelman, M. G. J. den Elzen, M. Harmsen, S. Mikropoulos, M. A. E. van Sluisveld, E. Stehfest, I. S. Tagomori, W.-J. van Zeist and D. P. van Vuuren, *Nature Climate Change*, 2024, **14**, 715-722.
285. F. Creutzig, C. Breyer, J. Hilaire, J. Minx, G. P. Peters and R. Socolow, *Energy & Environmental Science*, 2019, **12**, 1805-1817.
286. T. Hasegawa, S. Fujimori, S. Frank, F. Humpenöder, C. Bertram, J. Després, L. Drouet, J. Emmerling, M. Gusti, M. Harmsen, K. Keramidas, Y. Ochi, K. Oshiro, P. Rochedo, B. van Ruijven, A.-M. Cabardos, A. Deppermann, F. Fosse, P. Havlik, V. Krey, A. Popp, R. Schaeffer, D. van Vuuren and K. Riahi, *Nature Sustainability*, 2021, **4**, 1052-1059.
287. V. Heck, D. Gerten, W. Lucht and A. Popp, *Nature Climate Change*, 2018, **8**, 151-155.
288. D. P. van Vuuren, E. Stehfest, D. E. H. J. Gernaat, M. van den Berg, D. L. Bijl, H. S. de Boer, V. Daioglou, J. C. Doelman, O. Y. Edelenbosch, M. Harmsen, A. F. Hof and M. A. E. van Sluisveld, *Nature Climate Change*, 2018, **8**, 391-397.
289. B. Bell, Ageing Fleet To Be Replaced By Massive Container Ship Orderbook, https://www.brookesbell.com/news-and-knowledge/article/ageing-fleet-to-be-replaced-by-massive-container-ship-orderbook-159256, (accessed 20th September, 2025).
290. UNCTAD, *Review of maritime transport 2024*, UN Trade and Development, Geneva, 2024.
291. OECD, New estimates provide insights on CO_2 emissions from global shipping, https://oecdstatistics.blog/2023/06/15/new-estimates-provide-insights-on-co2-emissions-from-global-shipping/, (accessed 12th, December, 2024).
292. ISPT, *Clean Ammonia Roadmap*, Institute for Sustainable Process Technology, Amersfoort, 2024.

293. A. Peecock, B. Hull-Bailey, A. Hastings, A. Martinez-Felipe and L. B. Wilcox, *International Journal of Hydrogen Energy*, 2024, **94**, 971-983.
294. G. Eliseev, *The Ammonia Market Today and a Bridge to the Future*, S&P Global Commodity Insights, New Orleans, 2024.
295. IRENA, *Innovation Outlook: Renewable Ammonia*, International Renewable Energy Agency, Abu Dhabi, 2022.
296. IEA, Direct Air Capture, https://www.iea.org/energy-system/carbon-capture-utilisation-and-storage/direct-air-capture, (accessed 15th, September, 2025).
297. IEA, *Global Hydrogen Review 2024*, International Energy Agency, Paris, 2024.
298. A. Odenweller and F. Ueckerdt, *Nature Energy*, 2025, **10**, 110-123.
299. IEA, *World Energy Outlook 2024*, International Energy Agency, Paris, 2024.
300. ProBas, Umweltbundesamt, Umweltaspekte von Iridium, (accessed 13th, March, 2022).
301. I. Staffell, A. Ingram and K. Kendall, *International Journal of Hydrogen Energy*, 2012, **37**, 2509-2523.
302. T. Smolinka, M. Günther, J. Garche, F.-I. f. S. Energiesysteme, F. Cell and B. C.-. FCBAT, *Stand und Entwicklungspotenzial der Wasserelektrolyse zur Herstellung von Wasserstoff aus regenerativen Energien: NOW-Studie : Kurzfassung des Abschlussberichts*, Fraunhofer ISE, 2011.
303. X. Zhang, C. Bauer, C. L. Mutel and K. Volkart, *Applied Energy*, 2017, **190**, 326-338.
304. BEIS, *KEW H_2: ZERO-CARBON BULK SUPPLY*, Department for Business, Energy & Industrial Strategy, 2019.
305. H. C. S. GmbH, Indoor Electrolyser HydroCab 5kg H_2/Day, https://hyfindr.com/marketplace/systems/electrolysers/aem-electrolysers/indoor-electrolyser-hydrocab-5kg-h2-day/, (accessed 5th, June, 2023).
306. Enapter, Technical Presentation - The AEM Electrolyser, (accessed 5th, June, 2023).
307. elogen, *Elogen_Product_sheet-Elyte260*, 2023.
308. H. Titanium, PEM Electrolyzer, https://heletitanium.com/titanium-anode/pem-electrolyzer/, (accessed 8th, June, 2023).
309. S. Häfele, M. Hauck and J. Dailly, *International Journal of Hydrogen Energy*, 2016, **41**, 13786-13796.
310. F. Petipas, A. Brisse and C. Bouallou, *Journal of Power Sources*, 2013, **239**, 584-595.
311. J. Sanz-Bermejo, J. Muñoz-Antón, J. Gonzalez-Aguilar and M. Romero, *International Journal of Hydrogen Energy*, 2015, **40**, 8291-8303.
312. P. Colombo, A. Saeedmanesh, M. Santarelli and J. Brouwer, *Energy Conversion and Management*, 2020, **204**, 112322.
313. ISPT, *Next Level Solid Oxide Electrolysis: Upscaling potential and techno-economical evaluation for 3 industrial use cases*, Institute for Sustainable Process Technology, 2023.
314. IEA, *Africa Energy Outlook 2022*, International Energy Agency, Paris, 2022.
315. Advisian, *Australian hydrogen market study*, Brisbane, 2021.
316. AE, Hydrogen calculation, https://atomicexpert.com/vodorod_po_raschetu, (accessed 11th October, 2022).

317. GEA, Kuzbass in Siberia launches hydrogen production, https://globalenergyprize.org/en/2021/09/22/kuzbass-in-siberia-launches-hydrogen-production/, (accessed 11th November, 2022).
318. I. Dincer, *Comprehensive energy systems*, Elsevier, 2018.
319. TATSA, *LPG and anhydrous ammonia storage tanks*, Mexico City, 2021.
320. T. Uekert, H. M. Wikoff and A. Badgett, *Advanced Sustainable Systems*, 2024, **8**, 2300449.
321. *Fuel Cells Bulletin*, 2019, **2019**, 14-14.
322. M. Shafique, A. Akbar, M. Rafiq, A. Azam and X. Luo, *Waste Management & Research*, 2022, **41**, 376-388.
323. C. Wulf, M. Reuß, T. Grube, P. Zapp, M. Robinius, J.-F. Hake and D. Stolten, *Journal of Cleaner Production*, 2018, **199**, 431-443.
324. G. Pawelec, *System-Based Solutions for H_2-Fuelled Water Transport in North-West Europe - Comparative report on alternative fuels for ship propulsion*, Lille, 2020.
325. P. T. Aakko-Saksa, C. Cook, J. Kiviaho and T. Repo, *Journal of Power Sources*, 2018, **396**, 803-823.