Life Cycle Assessment of Marine Fuels in the Nordic Region

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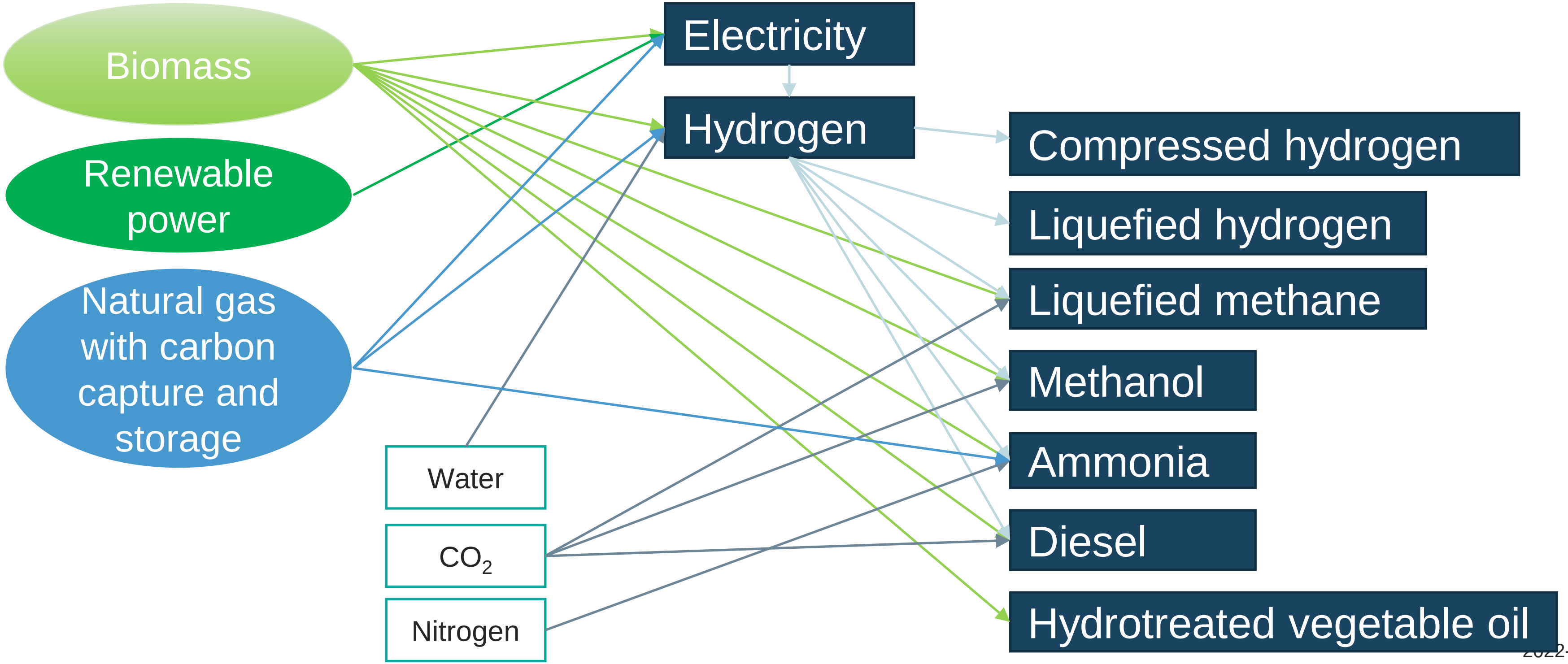
Possible pathways for low climate impact fuels in shipping



Goal and functional unit

- Goal: to assess the climate and environmental impact of selected potential zero-carbon fuels for marine use (including hydrogen, ammonia and methanol) using life cycle assessment (LCA)
- To increase knowledge of the sustainability of various marine fuels relevant for the Nordics, to verify under what conditions they represent sustainable zero-carbon fuels, and potential trade-offs connected to other environmental impact categories
- Functional unit: 1 kWh of mechanical energy to the propeller shaft and proportional aux. and thermal load
- Results provided for a limited number of typical ship types operating in the Nordics

Scope of the study

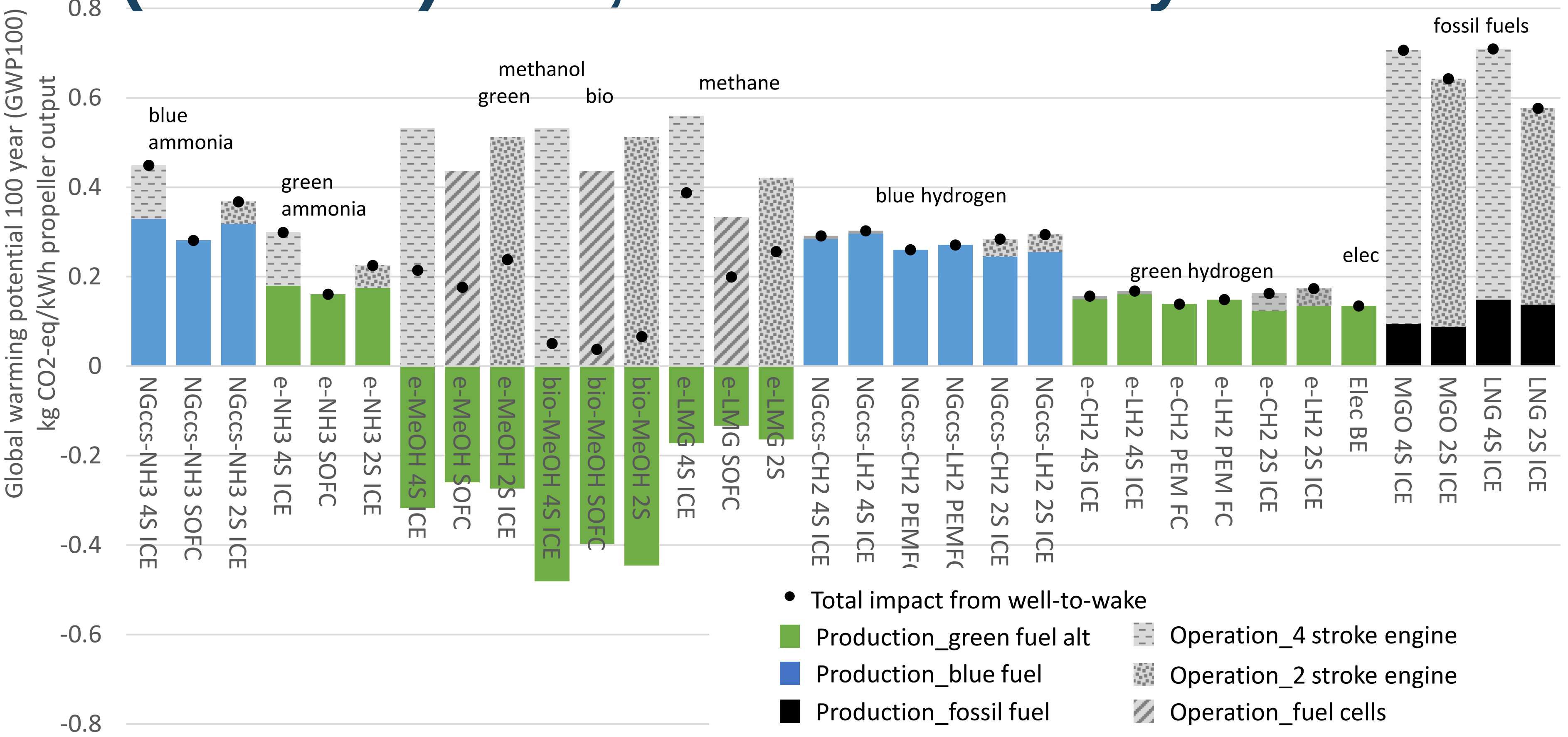
- Time horizon: ships operated during 2030 with an outlook to 2050
- Technical system boundaries: fuel production (incl. infrastructure) from cradle until delivered to tank onboard, onboard fuel use for ship transport and construction of propulsion system
- Geographical focus: Nordic fuel production (Norwegian natural gas, Nordic electricity mix etc.)
- Impact categories in focus: Climate change (GWP20 and GWP100), Acidification, Particulate matter.
- Additional impact categories considered for screening of potential environmental hot-spots
- Data: Specific data used when possible. Background data mainly from Ecoinvent 3.7.1.
- Extensive LCA literature review and comparison with proposed IMO guidelines

Pathways considered

Energy carriers
Ammonia (NH_3)[c]
Compressed hydrogen (CH_2)[c]
Liquid hydrogen (LH2)[c]
Methanol (MeOH)[c]
Liquid methane gas (LMG)[c]
Electricity
Liquid natural gas (LNG)
Marine gas oil (MGO)

Climate impact

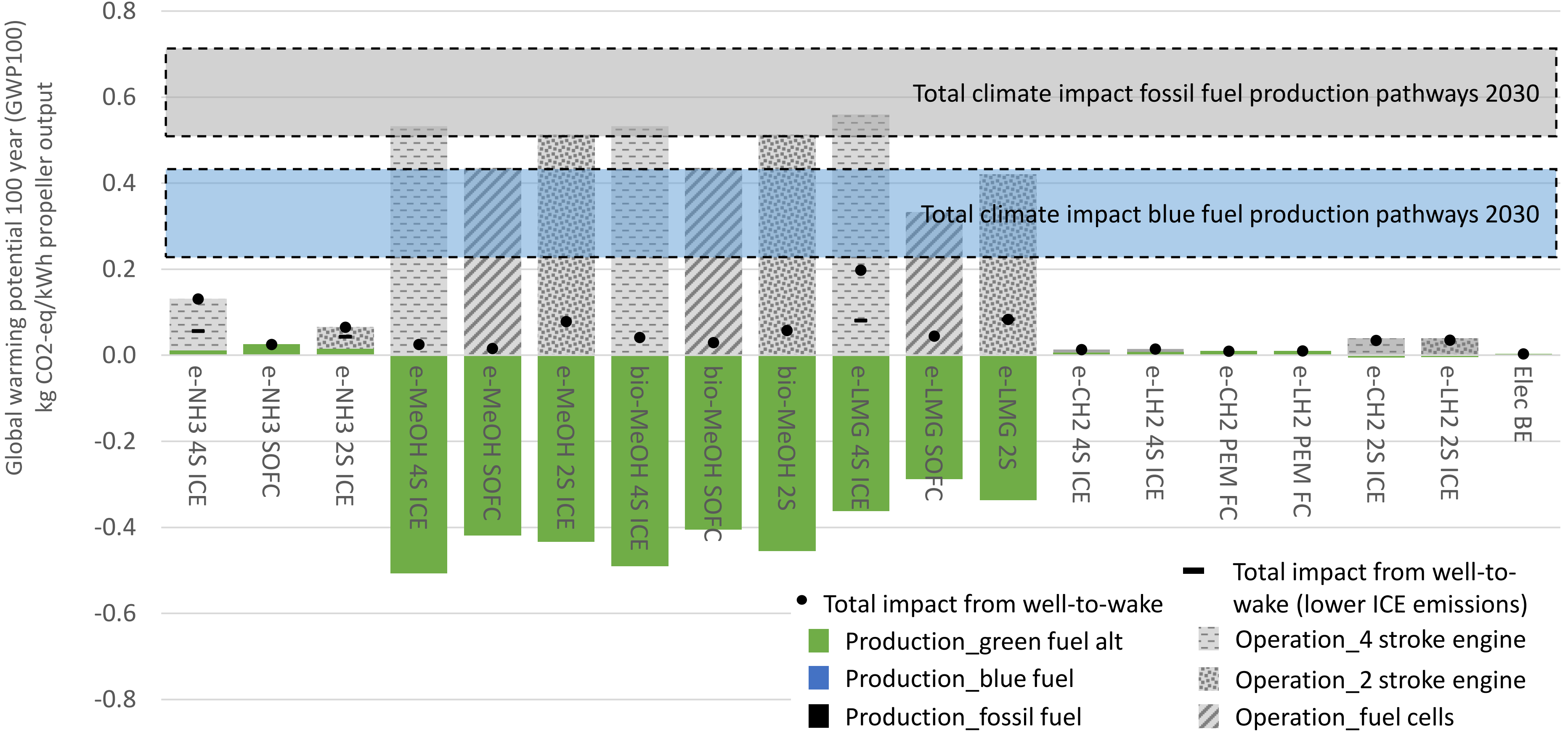
Estimated life cycle climate impact in 2030 (GWP100) WtW, Nordic electricity mix



Outlook for 2050

Parameter	Assumption used in 2030	Assumption used in 2050
Electricity used for fuel production	Nordic grid mix forecasted by Nordic Clean Energy Scenarios (79.6 g CO_2/kWh)	Low emission power production (2.4 g CO_2/kWh)
Fuel pathways	Green and blue	Green
Electrolysers	Alkaline	SOEC
Production and refining of materials used	Today's production	Assumed new process with close to zero GHG emissions
Urea production	From natural gas	From renewable resources
ICE emissions of CH_4 and N_2O for ammonia and methane engines	4SNH3ICE: N_2O of 0.3g/kWh 2SNH3ICE: N_2O of 0.09g/kWh 4SLNGICE: CH_4 of 3.4g/kWh 4SLMGICE: CH_4 of 3.4g/kWh	Two cases: (1) same as 2030 and (2) 1/10 of 2030 emissions 4SNH3ICE: **N_2O of 0.03g/kWh** 2SNH3ICE: **N2O of 0.009g/kWh** 4SLNGICE: **CH4 of 0.34g/kWh** 4SLMGICE: **CH4 of 0.34g/kWh**

Outlook life cycle climate impact in 2050 (GWP100), WtW, Nordic electricity mix



What about other environmental impact?

Results from a screening life cycle assessment

Impact category	NGccs-NH3 4S ICE	NGccs-NH3 SOFC	NGccs-NH3 2S ICE	e-NH3 4S ICE	e-NH3 SOFC	e-NH3 2S ICE	e-MeOH 4S ICE	e-MeOH SOFC	e-MeOH 2S ICE	bio-MeOH 4S ICE	bio-MeOH SOFC	bio-MeOH 2S	e-CH4 4S ICE	e-CH4 SOFC	e-CH4 2S	NGccs-CH2 4S ICE	NGccs-LH2 4S ICE	NGccs-CH2 PEMFC	NGccs-LH2 PEMFC	NGccs-CH2 2S ICE	NGccs-LH2 2S ICE	e-CH2 4S ICE	e-LH2 4S ICE	e-CH2 PEM FC	e-LH2 PEM FC	e-CH2 2S ICE	e-LH2 2S ICE	Elec BE
Acidification	0.8	0.2	0.9	0.7	0.2	0.8	0.8	0.2	0.8	0.6	0.1	0.7	0.9	0.2	0.9	0.7	0.7	0.2	0.2	0.8	0.8	0.6	0.6	0.1	0.1	0.8	0.8	0.2
Ecotoxicity, freshwater	0.9	0.7	1	1.8	1.5	1.9	2	1.7	1.9	0.3	0.2	0.3	2.1	1.7	2.2	0.5	0.6	0.4	0.5	0.5	0.6	1.2	1.3	1.1	1.2	1.3	1.3	0.7
Ecotoxicity, freshwater - inorganics	0.2	0.2	0.3	0.2	0.2	0.2	0.3	0.3	0.3	0.1	0.1	0.1	0.3	0.2	0.3	0.1	0.1	0.1	0.1	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Ecotoxicity, freshwater - metals	1.5	1.2	1.6	3.1	2.5	3.3	3.4	2.8	3.2	0.4	0.3	0.4	3.6	2.9	3.7	0.8	0.9	0.7	0.8	0.8	0.9	2.1	2.2	1.9	2	2.2	2.3	1.3
Ecotoxicity, freshwater - organics	0	0	0	0	0	0	0.1	0	0	0.1	0	0	0.1	0	0	0	0	0	0	0.1	0.1	0	0	0	0	0.1	0.1	0
Eutrophication, freshwater	4.4	3.6	5.6	5.7	4.6	7.2	3.5	2.8	4	1.4	1	1.7	4.4	3.6	5.6	1.4	1.5	1.3	1.4	1.9	2.1	2.4	2.6	2.2	2.3	3.1	3.3	4
Eutrophication, marine	1.1	0.2	1.1	1.1	0.2	1.1	1.1	0.2	1	1	0.1	1	1.3	0.2	1.1	1.1	1.1	0.2	0.2	1	1	1	1	0.1	0.2	1	1	0.1
Eutrophication, terrestrial	1.1	0.2	1.1	1.1	0.2	1.1	1.2	0.3	1.1	1	0.1	1	1.4	0.3	1.1	1	1	0.2	0.2	1	1	1	1	0.2	0.2	1	1	0.2
Human toxicity, cancer	3.6	2.9	4.1	4.5	3.6	5.2	41.6	2.5	3.1	40.7	1.8	2.5	44.2	4.7	6.4	5.2	5.4	1.3	1.5	63	63.1	5.9	6.1	2	2.2	63.8	64	2.1
Human toxicity, cancer - metals	4.2	3.4	4.8	5	4	5.7	3	2.4	3.1	2.8	2.3	3.1	5.2	4.3	5.9	1.6	1.8	1.4	1.6	1.8	2.1	2.2	2.4	2	2.2	2.5	2.8	2.4
Human toxicity, non-cancer	2	1.6	2.2	3.5	2.8	3.9	3	2.4	2.9	0.8	0.6	0.8	3.2	2.5	3.4	0.8	0.9	0.7	0.8	0.9	1.1	2.1	2.2	1.8	2	2.3	2.4	2.5
Human toxicity, non-cancer - inorganics	0.8	0.6	0.8	1.7	1.3	1.8	1.8	1.5	1.7	0.2	0.2	0.2	2.3	1.9	2.4	0.5	0.6	0.5	0.5	0.5	0.6	1.3	1.4	1.2	1.2	1.3	1.4	3.8
Human toxicity, non-cancer - metals	2.5	2	2.8	4.4	3.5	4.9	3.4	2.8	3.4	1	0.8	1.1	3.5	2.9	3.9	0.9	1.1	0.8	1	1	1.2	2.4	2.6	2.2	2.4	2.6	2.8	2.2
Human toxicity, non-cancer - organics	3	2	4.6	2.1	1.3	3.1	1.6	0.4	0.9	1.7	0.5	1.2	1.6	0.4	1	1.2	1.2	1	1	2.7	2.7	0.5	0.5	0.3	0.3	1.4	1.4	0.9
Ionising radiation	1	0.8	1.1	9.5	7.6	9.9	10.8	9.1	10	0.6	0.5	0.6	10.8	8.8	10.8	0.9	1.4	0.8	1.3	0.9	1.4	8	8.6	7.2	7.8	7.9	8.5	11.7
Land use	1	0.8	1	6.9	5.6	7.2	7.8	6.5	7.2	1.3	1.1	1.3	7.7	6.3	7.8	0.7	1.1	0.6	1	0.7	1.1	5.7	6.1	5.2	5.5	5.7	6.1	0.5
Ozone depletion	0.7	0.6	0.7	0	0	0	0.1	0	0	0	0	0	0	0	0.1	0.6	0.6	0.5	0.5	0.6	0.6	0	0	0	0	0	0	0
Particulate matter	0.4	0.1	0.6	0.6	0.3	0.8	0.7	0.4	0.9	0.3	0.1	0.5	0.8	0.4	1	0.3	0.4	0.1	0.1	0.6	0.6	0.5	0.5	0.2	0.3	0.7	0.8	0.3
Photochemical ozone formation	1.1	0.2	1.1	1	0.1	1	1.2	0.2	1	1.1	0.1	0.9	1.3	0.2	1	0.9	1	0.2	0.2	1	1.1	0.8	0.9	0.1	0.1	1	1	0.1
Resource use, fossils	1.3	1.1	1.4	0.9	0.7	1	1	0.9	1	0.1	0.1	0.1	1	0.8	1.1	1.1	1.2	1	1.1	1.2	1.2	0.8	0.8	0.7	0.7	0.8	0.8	1.1
Resource use, minerals and metals	16.7	13.4	29.3	13.4	10.8	23.6	1.8	1.2	2.9	5.6	4.4	9.5	1.4	1.2	3.1	3.7	3.8	3.4	3.4	6.8	6.9	0.9	0.9	0.8	0.8	2.1	2.2	1.2
IPCC 2021 GWP 100	0.6	0.4	0.6	0.4	0.2	0.4	0.3	0.2	0.4	0.1	0.1	0.1	0.5	0.3	0.4	0.4	0.4	0.4	0.4	0.4	0.5	0.2	0.2	0.2	0.2	0.3	0.3	0.2
IPCC 2021 GWP 20	1	0.7	0.9	0.4	0.2	0.4	0.3	0.3	0.4	0.1	0.1	0.1	0.9	0.3	0.5	0.7	0.7	0.6	0.6	0.7	0.8	0.2	0.2	0.2	0.2	0.3	0.3	0.3

Impact category	NGccs-NH3 4S ICE	NGccs-NH3 SOFC	NGccs-NH3 2S ICE	e-NH3 4S ICE	e-NH3 SOFC	e-NH3 2S ICE	e-MeOH 4S ICE	e-MeOH SOFC	e-MeOH 2S ICE	bio-MeOH 4S ICE	bio-MeOH SOFC	bio-MeOH 2S	e-CH4 4S ICE	e-CH4 SOFC	e-CH4 2S	NGccs-CH2 4S ICE	NGccs-LH2 4S ICE	NGccs-CH2 PEMFC	NGccs-LH2 PEMFC	NGccs-CH2 2S ICE	NGccs-LH2 2S ICE	e-CH2 4S ICE	e-LH2 4S ICE	e-CH2 PEM FC	e-LH2 PEM FC	e-CH2 2S ICE	e-LH2 2S ICE	Elec BE
Acidification	0.8	0.2	0.9	0.7	0.2	0.8	0.8	0.2	0.8	0.6	0.1	0.7	0.9	0.2	0.9	0.7	0.7	0.2	0.2	0.8	0.8	0.6	0.6	0.1	0.1	0.8	0.8	0.2
Ecotoxicity, freshwater	0.9	0.7	1	1.8	1.5	1.9	2	1.7	1.9	0.3	0.2	0.3	2.1	1.7	2.2	0.5	0.6	0.4	0.5	0.5	0.6	1.2	1.3	1.1	1.2	1.3	1.3	0.7
Ecotoxicity, freshwater - inorganics	0.2	0.2	0.3	0.2	0.2	0.2	0.3	0.3	0.3	0.1	0.1	0.1	0.3	0.2	0.3	0.1	0.1	0.1	0.1	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Ecotoxicity, freshwater - metals	1.5	1.2	1.6	3.1	2.5	3.3	3.4	2.8	3.2	0.4	0.3	0.4	3.6	2.9	3.7	0.8	0.9	0.7	0.8	0.8	0.9	2.1	2.2	1.9	2	2.2	2.3	1.3
Ecotoxicity, freshwater - organics	0	0	0	0	0	0	0.1	0	0	0.1	0	0	0.1	0	0	0	0	0	0	0.1	0.1	0	0	0	0	0.1	0.1	0
Eutrophication, freshwater	4.4	3.6	5.6	5.7	4.6	7.2	3.5	2.8	4	1.4	1	1.7	4.4	3.6	5.6	1.4	1.5	1.3	1.4	1.9	2.1	2.4	2.6	2.2	2.3	3.1	3.3	4
Eutrophication, marine	1.1	0.2	1.1	1.1	0.2	1.1	1.1	0.2	1	1	0.1	1	1.3	0.2	1.1	1.1	1.1	0.2	0.2	1	1	1	1	0.1	0.2	1	1	0.1
Eutrophication, terrestrial	1.1	0.2	1.1	1.1	0.2	1.1	1.2	0.3	1.1	1	0.1	1	1.4	0.3	1.1	1	1	0.2	0.2	1	1	1	1	0.2	0.2	1	1	0.2
Human toxicity, cancer	3.6	2.9	4.1	4.5	3.6	5.2	41.6	2.5	3.1	40.7	1.8	2.5	44.2	4.7	6.4	5.2	5.4	1.3	1.5	63	63.1	5.9	6.1	2	2.2	63.8	64	2.1
Human toxicity, cancer - metals	4.2	3.4	4.8	5	4	5.7	3	2.4	3.1	2.8	2.3	3.1	5.2	4.3	5.9	1.6	1.8	1.4	1.6	1.8	2.1	2.2	2.4	2	2.2	2.5	2.8	2.4
Human toxicity, non-cancer	2	1.6	2.2	3.5	2.8	3.9	3	2.4	2.9	0.8	0.6	0.8	3.2	2.5	3.4	0.8	0.9	0.7	0.8	0.9	1.1	2.1	2.2	1.8	2	2.3	2.4	2.5
Human toxicity, non-cancer - inorganics	0.8	0.6	0.8	1.7	1.3	1.8	1.8	1.5	1.7	0.2	0.2	0.2	2.3	1.9	2.4	0.5	0.6	0.5	0.5	0.5	0.6	1.3	1.4	1.2	1.2	1.3	1.4	3.8
Human toxicity, non-cancer - metals	2.5	2	2.8	4.4	3.5	4.9	3.4	2.8	3.4	1	0.8	1.1	3.5	2.9	3.9	0.9	1.1	0.8	1	1	1.2	2.4	2.6	2.2	2.4	2.6	2.8	2.2
Human toxicity, non-cancer - organics	3	2	4.6	2.1	1.3	3.1	1.6	0.4	0.9	1.7	0.5	1.2	1.6	0.4	1	1.2	1.2	1	1	2.7	2.7	0.5	0.5	0.3	0.3	1.4	1.4	0.9
Ionising radiation	1	0.8	1.1	9.5	7.6	9.9	10.8	9.1	10	0.6	0.5	0.6	10.8	8.8	10.8	0.9	1.4	0.8	1.3	0.9	1.4	8	8.6	7.2	7.8	7.9	8.5	11.7
Land use	1	0.8	1	6.9	5.6	7.2	7.8	6.5	7.2	1.3	1.1	1.3	7.7	6.3	7.8	0.7	1.1	0.6	1	0.7	1.1	5.7	6.1	5.2	5.5	5.7	6.1	0.5
Ozone depletion	0.7	0.6	0.7	0	0	0	0.1	0	0	0	0	0	0	0	0.1	0.6	0.6	0.5	0.5	0.6	0.6	0	0	0	0	0	0	0
Particulate matter	0.4	0.1	0.6	0.6	0.3	0.8	0.7	0.4	0.9	0.3	0.1	0.5	0.8	0.4	1	0.3	0.4	0.1	0.1	0.6	0.6	0.5	0.5	0.2	0.3	0.7	0.8	0.3
Photochemical ozone formation	1.1	0.2	1.1	1	0.1	1	1.2	0.2	1	1.1	0.1	0.9	1.3	0.2	1	0.9	1	0.2	0.2	1	1.1	0.8	0.9	0.1	0.1	1	1	0.1
Resource use, fossils	1.3	1.1	1.4	0.9	0.7	1	1	0.9	1	0.1	0.1	0.1	1	0.8	1.1	1.1	1.2	1	1.1	1.2	1.2	0.8	0.8	0.7	0.7	0.8	0.8	1.1
Resource use, minerals and metals	16.7	13.4	29.3	13.4	10.8	23.6	1.8	1.2	2.9	5.6	4.4	9.5	1.4	1.2	3.1	3.7	3.8	3.4	3.4	6.8	6.9	0.9	0.9	0.8	0.8	2.1	2.2	1.2
IPCC 2021 GWP 100	0.6	0.4	0.6	0.4	0.2	0.4	0.3	0.2	0.4	0.1	0.1	0.1	0.5	0.3	0.4	0.4	0.4	0.4	0.4	0.4	0.5	0.2	0.2	0.2	0.2	0.3	0.3	0.2
IPCC 2021 GWP 20	1	0.7	0.9	0.4	0.2	0.4	0.3	0.3	0.4	0.1	0.1	0.1	0.9	0.3	0.5	0.7	0.7	0.6	0.6	0.7	0.8	0.2	0.2	0.2	0.2	0.3	0.3	0.3

Impact category	NGccs-NH3 4S ICE	NGccs-NH3 SOFC	NGccs-NH3 2S ICE	e-NH3 4S ICE	e-NH3 SOFC	e-NH3 2S ICE	e-MeOH 4S ICE	e-MeOH SOFC	e-MeOH 2S ICE	bio-MeOH 4S ICE	bio-MeOH SOFC	bio-MeOH 2S	e-CH4 4S ICE	e-CH4 SOFC	e-CH4 2S	NGccs-CH2 4S ICE	NGccs-LH2 4S ICE	NGccs-CH2 PEMFC	NGccs-LH2 PEMFC	NGccs-CH2 2S ICE	NGccs-LH2 2S ICE	e-CH2 4S ICE	e-LH2 4S ICE	e-CH2 PEM FC	e-LH2 PEM FC	e-CH2 2S ICE	e-LH2 2S ICE	Elec BE
Acidification	0.8	0.2	0.9	0.7	0.2	0.8	0.8	0.2	0.8	0.6	0.1	0.7	0.9	0.2	0.9	0.7	0.7	0.2	0.2	0.8	0.8	0.6	0.6	0.1	0.1	0.8	0.8	0.2
Ecotoxicity, freshwater	0.9	0.7	1	1.8	1.5	1.9	2	1.7	1.9	0.3	0.2	0.3	2.1	1.7	2.2	0.5	0.6	0.4	0.5	0.5	0.6	1.2	1.3	1.1	1.2	1.3	1.3	0.7
Ecotoxicity, freshwater - inorganics	0.2	0.2	0.3	0.2	0.2	0.2	0.3	0.3	0.3	0.1	0.1	0.1	0.3	0.2	0.3	0.1	0.1	0.1	0.1	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Ecotoxicity, freshwater - metals	1.5	1.2	1.6	3.1	2.5	3.3	3.4	2.8	3.2	0.4	0.3	0.4	3.6	2.9	3.7	0.8	0.9	0.7	0.8	0.8	0.9	2.1	2.2	1.9	2	2.2	2.3	1.3
Ecotoxicity, freshwater - organics	0	0	0	0	0	0	0.1	0	0	0.1	0	0	0.1	0	0	0	0	0	0	0.1	0.1	0	0	0	0	0.1	0.1	0
Eutrophication, freshwater	4.4	3.6	5.6	5.7	4.6	7.2	3.5	2.8	4	1.4	1	1.7	4.4	3.6	5.6	1.4	1.5	1.3	1.4	1.9	2.1	2.4	2.6	2.2	2.3	3.1	3.3	4
Eutrophication, marine	1.1	0.2	1.1	1.1	0.2	1.1	1.1	0.2	1	1	0.1	1	1.3	0.2	1.1	1.1	1.1	0.2	0.2	1	1	1	1	0.1	0.2	1	1	0.1
Eutrophication, terrestrial	1.1	0.2	1.1	1.1	0.2	1.1	1.2	0.3	1.1	1	0.1	1	1.4	0.3	1.1	1	1	0.2	0.2	1	1	1	1	0.2	0.2	1	1	0.2
Human toxicity, cancer	3.6	2.9	4.1	4.5	3.6	5.2	41.6	2.5	3.1	40.7	1.8	2.5	44.2	4.7	6.4	5.2	5.4	1.3	1.5	63	63.1	5.9	6.1	2	2.2	63.8	64	2.1
Human toxicity, cancer - metals	4.2	3.4	4.8	5	4	5.7	3	2.4	3.1	2.8	2.3	3.1	5.2	4.3	5.9	1.6	1.8	1.4	1.6	1.8	2.1	2.2	2.4	2	2.2	2.5	2.8	2.4
Human toxicity, non-cancer	2	1.6	2.2	3.5	2.8	3.9	3	2.4	2.9	0.8	0.6	0.8	3.2	2.5	3.4	0.8	0.9	0.7	0.8	0.9	1.1	2.1	2.2	1.8	2	2.3	2.4	2.5
Human toxicity, non-cancer - inorganics	0.8	0.6	0.8	1.7	1.3	1.8	1.8	1.5	1.7	0.2	0.2	0.2	2.3	1.9	2.4	0.5	0.6	0.5	0.5	0.5	0.6	1.3	1.4	1.2	1.2	1.3	1.4	3.8
Human toxicity, non-cancer - metals	2.5	2	2.8	4.4	3.5	4.9	3.4	2.8	3.4	1	0.8	1.1	3.5	2.9	3.9	0.9	1.1	0.8	1	1	1.2	2.4	2.6	2.2	2.4	2.6	2.8	2.2
Human toxicity, non-cancer - organics	3	2	4.6	2.1	1.3	3.1	1.6	0.4	0.9	1.7	0.5	1.2	1.6	0.4	1	1.2	1.2	1	1	2.7	2.7	0.5	0.5	0.3	0.3	1.4	1.4	0.9
Ionising radiation	1	0.8	1.1	9.5	7.6	9.9	10.8	9.1	10	0.6	0.5	0.6	10.8	8.8	10.8	0.9	1.4	0.8	1.3	0.9	1.4	8	8.6	7.2	7.8	7.9	8.5	11.7
Land use	1	0.8	1	6.9	5.6	7.2	7.8	6.5	7.2	1.3	1.1	1.3	7.7	6.3	7.8	0.7	1.1	0.6	1	0.7	1.1	5.7	6.1	5.2	5.5	5.7	6.1	0.5
Ozone depletion	0.7	0.6	0.7	0	0	0	0.1	0	0	0	0	0	0	0	0.1	0.6	0.6	0.5	0.5	0.6	0.6	0	0	0	0	0	0	0
Particulate matter	0.4	0.1	0.6	0.6	0.3	0.8	0.7	0.4	0.9	0.3	0.1	0.5	0.8	0.4	1	0.3	0.4	0.1	0.1	0.6	0.6	0.5	0.5	0.2	0.3	0.7	0.8	0.3
Photochemical ozone formation	1.1	0.2	1.1	1	0.1	1	1.2	0.2	1	1.1	0.1	0.9	1.3	0.2	1	0.9	1	0.2	0.2	1	1.1	0.8	0.9	0.1	0.1	1	1	0.1
Resource use, fossils	1.3	1.1	1.4	0.9	0.7	1	1	0.9	1	0.1	0.1	0.1	1	0.8	1.1	1.1	1.2	1	1.1	1.2	1.2	0.8	0.8	0.7	0.7	0.8	0.8	1.1
Resource use, minerals and metals	16.7	13.4	29.3	13.4	10.8	23.6	1.8	1.2	2.9	5.6	4.4	9.5	1.4	1.2	3.1	3.7	3.8	3.4	3.4	6.8	6.9	0.9	0.9	0.8	0.8	2.1	2.2	1.2
IPCC 2021 GWP 100	0.6	0.4	0.6	0.4	0.2	0.4	0.3	0.2	0.4	0.1	0.1	0.1	0.5	0.3	0.4	0.4	0.4	0.4	0.4	0.4	0.5	0.2	0.2	0.2	0.2	0.3	0.3	0.2
IPCC 2021 GWP 20	1	0.7	0.9	0.4	0.2	0.4	0.3	0.3	0.4	0.1	0.1	0.1	0.9	0.3	0.5	0.7	0.7	0.6	0.6	0.7	0.8	0.2	0.2	0.2	0.2	0.3	0.3	0.3

Impact category	NGccs-NH3 4S ICE	NGccs-NH3 SOFC	NGccs-NH3 2S ICE	e-NH3 4S ICE	e-NH3 SOFC	e-NH3 2S ICE	e-MeOH 4S ICE	e-MeOH SOFC	e-MeOH 2S ICE	bio-MeOH 4S ICE	bio-MeOH SOFC	bio-MeOH 2S	e-CH4 4S ICE	e-CH4 SOFC	e-CH4 2S	NGccs-CH2 4S ICE	NGccs-LH2 4S ICE	NGccs-CH2 PEMFC	NGccs-LH2 PEMFC	NGccs-CH2 2S ICE	NGccs-LH2 2S ICE	e-CH2 4S ICE	e-LH2 4S ICE	e-CH2 PEM FC	e-LH2 PEM FC	e-CH2 2S ICE	e-LH2 2S ICE	Elec BE
Acidification	0.8	0.2	0.9	0.7	0.2	0.8	0.8	0.2	0.8	0.6	0.1	0.7	0.9	0.2	0.9	0.7	0.7	0.2	0.2	0.8	0.8	0.6	0.6	0.1	0.1	0.8	0.8	0.2
Ecotoxicity, freshwater	0.9	0.7	1	1.8	1.5	1.9	2	1.7	1.9	0.3	0.2	0.3	2.1	1.7	2.2	0.5	0.6	0.4	0.5	0.5	0.6	1.2	1.3	1.1	1.2	1.3	1.3	0.7
Ecotoxicity, freshwater - inorganics	0.2	0.2	0.3	0.2	0.2	0.2	0.3	0.3	0.3	0.1	0.1	0.1	0.3	0.2	0.3	0.1	0.1	0.1	0.1	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Ecotoxicity, freshwater - metals	1.5	1.2	1.6	3.1	2.5	3.3	3.4	2.8	3.2	0.4	0.3	0.4	3.6	2.9	3.7	0.8	0.9	0.7	0.8	0.8	0.9	2.1	2.2	1.9	2	2.2	2.3	1.3
Ecotoxicity, freshwater - organics	0	0	0	0	0	0	0.1	0	0	0.1	0	0	0.1	0	0	0	0	0	0	0.1	0.1	0	0	0	0	0.1	0.1	0
Eutrophication, freshwater	4.4	3.6	5.6	5.7	4.6	7.2	3.5	2.8	4	1.4	1	1.7	4.4	3.6	5.6	1.4	1.5	1.3	1.4	1.9	2.1	2.4	2.6	2.2	2.3	3.1	3.3	4
Eutrophication, marine	1.1	0.2	1.1	1.1	0.2	1.1	1.1	0.2	1	1	0.1	1	1.3	0.2	1.1	1.1	1.1	0.2	0.2	1	1	1	1	0.1	0.2	1	1	0.1
Eutrophication, terrestrial	1.1	0.2	1.1	1.1	0.2	1.1	1.2	0.3	1.1	1	0.1	1	1.4	0.3	1.1	1	1	0.2	0.2	1	1	1	1	0.2	0.2	1	1	0.2
Human toxicity, cancer	3.6	2.9	4.1	4.5	3.6	5.2	41.6	2.5	3.1	40.7	1.8	2.5	44.2	4.7	6.4	5.2	5.4	1.3	1.5	63	63.1	5.9	6.1	2	2.2	63.8	64	2.1
Human toxicity, cancer - metals	4.2	3.4	4.8	5	4	5.7	3	2.4	3.1	2.8	2.3	3.1	5.2	4.3	5.9	1.6	1.8	1.4	1.6	1.8	2.1	2.2	2.4	2	2.2	2.5	2.8	2.4
Human toxicity, non-cancer	2	1.6	2.2	3.5	2.8	3.9	3	2.4	2.9	0.8	0.6	0.8	3.2	2.5	3.4	0.8	0.9	0.7	0.8	0.9	1.1	2.1	2.2	1.8	2	2.3	2.4	2.5
Human toxicity, non-cancer - inorganics	0.8	0.6	0.8	1.7	1.3	1.8	1.8	1.5	1.7	0.2	0.2	0.2	2.3	1.9	2.4	0.5	0.6	0.5	0.5	0.5	0.6	1.3	1.4	1.2	1.2	1.3	1.4	3.8
Human toxicity, non-cancer - metals	2.5	2	2.8	4.4	3.5	4.9	3.4	2.8	3.4	1	0.8	1.1	3.5	2.9	3.9	0.9	1.1	0.8	1	1	1.2	2.4	2.6	2.2	2.4	2.6	2.8	2.2
Human toxicity, non-cancer - organics	3	2	4.6	2.1	1.3	3.1	1.6	0.4	0.9	1.7	0.5	1.2	1.6	0.4	1	1.2	1.2	1	1	2.7	2.7	0.5	0.5	0.3	0.3	1.4	1.4	0.9
Ionising radiation	1	0.8	1.1	9.5	7.6	9.9	10.8	9.1	10	0.6	0.5	0.6	10.8	8.8	10.8	0.9	1.4	0.8	1.3	0.9	1.4	8	8.6	7.2	7.8	7.9	8.5	11.7
Land use	1	0.8	1	6.9	5.6	7.2	7.8	6.5	7.2	1.3	1.1	1.3	7.7	6.3	7.8	0.7	1.1	0.6	1	0.7	1.1	5.7	6.1	5.2	5.5	5.7	6.1	0.5
Ozone depletion	0.7	0.6	0.7	0	0	0	0.1	0	0	0	0	0	0	0	0.1	0.6	0.6	0.5	0.5	0.6	0.6	0	0	0	0	0	0	0
Particulate matter	0.4	0.1	0.6	0.6	0.3	0.8	0.7	0.4	0.9	0.3	0.1	0.5	0.8	0.4	1	0.3	0.4	0.1	0.1	0.6	0.6	0.5	0.5	0.2	0.3	0.7	0.8	0.3
Photochemical ozone formation	1.1	0.2	1.1	1	0.1	1	1.2	0.2	1	1.1	0.1	0.9	1.3	0.2	1	0.9	1	0.2	0.2	1	1.1	0.8	0.9	0.1	0.1	1	1	0.1
Resource use, fossils	1.3	1.1	1.4	0.9	0.7	1	1	0.9	1	0.1	0.1	0.1	1	0.8	1.1	1.1	1.2	1	1.1	1.2	1.2	0.8	0.8	0.7	0.7	0.8	0.8	1.1
Resource use, minerals and metals	16.7	13.4	29.3	13.4	10.8	23.6	1.8	1.2	2.9	5.6	4.4	9.5	1.4	1.2	3.1	3.7	3.8	3.4	3.4	6.8	6.9	0.9	0.9	0.8	0.8	2.1	2.2	1.2
IPCC 2021 GWP 100	0.6	0.4	0.6	0.4	0.2	0.4	0.3	0.2	0.4	0.1	0.1	0.1	0.5	0.3	0.4	0.4	0.4	0.4	0.4	0.4	0.5	0.2	0.2	0.2	0.2	0.3	0.3	0.2
IPCC 2021 GWP 20	1	0.7	0.9	0.4	0.2	0.4	0.3	0.3	0.4	0.1	0.1	0.1	0.9	0.3	0.5	0.7	0.7	0.6	0.6	0.7	0.8	0.2	0.2	0.2	0.2	0.3	0.3	0.3

Impact category	NGccs-NH3 4S ICE	NGccs-NH3 SOFC	NGccs-NH3 2S ICE	e-NH3 4S ICE	e-NH3 SOFC	e-NH3 2S ICE	e-MeOH 4S ICE	e-MeOH SOFC	e-MeOH 2S ICE	bio-MeOH 4S ICE	bio-MeOH SOFC	bio-MeOH 2S	e-CH4 4S ICE	e-CH4 SOFC	e-CH4 2S	NGccs-CH2 4S ICE	NGccs-LH2 4S ICE	NGccs-CH2 PEMFC	NGccs-LH2 PEMFC	NGccs-CH2 2S ICE	NGccs-LH2 2S ICE	e-CH2 4S ICE	e-LH2 4S ICE	e-CH2 PEM FC	e-LH2 PEM FC	e-CH2 2S ICE	e-LH2 2S ICE	Elec BE
Acidification	0.8	0.2	0.9	0.7	0.2	0.8	0.8	0.2	0.8	0.6	0.1	0.7	0.9	0.2	0.9	0.7	0.7	0.2	0.2	0.8	0.8	0.6	0.6	0.1	0.1	0.8	0.8	0.2
Ecotoxicity, freshwater	0.9	0.7	1	1.8	1.5	1.9	2	1.7	1.9	0.3	0.2	0.3	2.1	1.7	2.2	0.5	0.6	0.4	0.5	0.5	0.6	1.2	1.3	1.1	1.2	1.3	1.3	0.7
Ecotoxicity, freshwater - inorganics	0.2	0.2	0.3	0.2	0.2	0.2	0.3	0.3	0.3	0.1	0.1	0.1	0.3	0.2	0.3	0.1	0.1	0.1	0.1	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Ecotoxicity, freshwater - metals	1.5	1.2	1.6	3.1	2.5	3.3	3.4	2.8	3.2	0.4	0.3	0.4	3.6	2.9	3.7	0.8	0.9	0.7	0.8	0.8	0.9	2.1	2.2	1.9	2	2.2	2.3	1.3
Ecotoxicity, freshwater - organics	0	0	0	0	0	0	0.1	0	0	0.1	0	0	0.1	0	0	0	0	0	0	0.1	0.1	0	0	0	0	0.1	0.1	0
Eutrophication, freshwater	4.4	3.6	5.6	5.7	4.6	7.2	3.5	2.8	4	1.4	1	1.7	4.4	3.6	5.6	1.4	1.5	1.3	1.4	1.9	2.1	2.4	2.6	2.2	2.3	3.1	3.3	4
Eutrophication, marine	1.1	0.2	1.1	1.1	0.2	1.1	1.1	0.2	1	1	0.1	1	1.3	0.2	1.1	1.1	1.1	0.2	0.2	1	1	1	1	0.1	0.2	1	1	0.1
Eutrophication, terrestrial	1.1	0.2	1.1	1.1	0.2	1.1	1.2	0.3	1.1	1	0.1	1	1.4	0.3	1.1	1	1	0.2	0.2	1	1	1	1	0.2	0.2	1	1	0.2
Human toxicity, cancer	3.6	2.9	4.1	4.5	3.6	5.2	41.6	2.5	3.1	40.7	1.8	2.5	44.2	4.7	6.4	5.2	5.4	1.3	1.5	63	63.1	5.9	6.1	2	2.2	63.8	64	2.1
Human toxicity, cancer - metals	4.2	3.4	4.8	5	4	5.7	3	2.4	3.1	2.8	2.3	3.1	5.2	4.3	5.9	1.6	1.8	1.4	1.6	1.8	2.1	2.2	2.4	2	2.2	2.5	2.8	2.4
Human toxicity, non-cancer	2	1.6	2.2	3.5	2.8	3.9	3	2.4	2.9	0.8	0.6	0.8	3.2	2.5	3.4	0.8	0.9	0.7	0.8	0.9	1.1	2.1	2.2	1.8	2	2.3	2.4	2.5
Human toxicity, non-cancer - inorganics	0.8	0.6	0.8	1.7	1.3	1.8	1.8	1.5	1.7	0.2	0.2	0.2	2.3	1.9	2.4	0.5	0.6	0.5	0.5	0.5	0.6	1.3	1.4	1.2	1.2	1.3	1.4	3.8
Human toxicity, non-cancer - metals	2.5	2	2.8	4.4	3.5	4.9	3.4	2.8	3.4	1	0.8	1.1	3.5	2.9	3.9	0.9	1.1	0.8	1	1	1.2	2.4	2.6	2.2	2.4	2.6	2.8	2.2
Human toxicity, non-cancer - organics	3	2	4.6	2.1	1.3	3.1	1.6	0.4	0.9	1.7	0.5	1.2	1.6	0.4	1	1.2	1.2	1	1	2.7	2.7	0.5	0.5	0.3	0.3	1.4	1.4	0.9
Ionising radiation	1	0.8	1.1	9.5	7.6	9.9	10.8	9.1	10	0.6	0.5	0.6	10.8	8.8	10.8	0.9	1.4	0.8	1.3	0.9	1.4	8	8.6	7.2	7.8	7.9	8.5	11.7
Land use	1	0.8	1	6.9	5.6	7.2	7.8	6.5	7.2	1.3	1.1	1.3	7.7	6.3	7.8	0.7	1.1	0.6	1	0.7	1.1	5.7	6.1	5.2	5.5	5.7	6.1	0.5
Ozone depletion	0.7	0.6	0.7	0	0	0	0.1	0	0	0	0	0	0	0	0.1	0.6	0.6	0.5	0.5	0.6	0.6	0	0	0	0	0	0	0
Particulate matter	0.4	0.1	0.6	0.6	0.3	0.8	0.7	0.4	0.9	0.3	0.1	0.5	0.8	0.4	1	0.3	0.4	0.1	0.1	0.6	0.6	0.5	0.5	0.2	0.3	0.7	0.8	0.3
Photochemical ozone formation	1.1	0.2	1.1	1	0.1	1	1.2	0.2	1	1.1	0.1	0.9	1.3	0.2	1	0.9	1	0.2	0.2	1	1.1	0.8	0.9	0.1	0.1	1	1	0.1
Resource use, fossils	1.3	1.1	1.4	0.9	0.7	1	1	0.9	1	0.1	0.1	0.1	1	0.8	1.1	1.1	1.2	1	1.1	1.2	1.2	0.8	0.8	0.7	0.7	0.8	0.8	1.1
Resource use, minerals and metals	16.7	13.4	29.3	13.4	10.8	23.6	1.8	1.2	2.9	5.6	4.4	9.5	1.4	1.2	3.1	3.7	3.8	3.4	3.4	6.8	6.9	0.9	0.9	0.8	0.8	2.1	2.2	1.2
IPCC 2021 GWP 100	0.6	0.4	0.6	0.4	0.2	0.4	0.3	0.2	0.4	0.1	0.1	0.1	0.5	0.3	0.4	0.4	0.4	0.4	0.4	0.4	0.5	0.2	0.2	0.2	0.2	0.3	0.3	0.2
IPCC 2021 GWP 20	1	0.7	0.9	0.4	0.2	0.4	0.3	0.3	0.4	0.1	0.1	0.1	0.9	0.3	0.5	0.7	0.7	0.6	0.6	0.7	0.8	0.2	0.2	0.2	0.2	0.3	0.3	0.3

Summary

Findings climate impact

- Possible to substantially reduce climate impact by introducing the assessed fuel-propulsion options by 2030 (2050 even more).
- Blue pathways have higher climate impacts than green pathways.
- Green methanol, hydrogen and electricity pathways show lower climate impact compared to ammonia and methane pathways
- Fuel cells lower climate impact compared to internal combustion engine pathways.

Regarding ship emissions

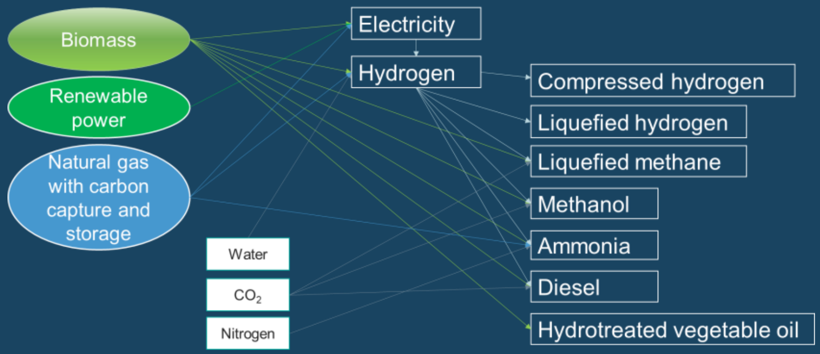
- Several fuel and powertrain options under development (NH_3,H_2) -> their actual climate and environmental performance in 2030-2050 uncertain - lack of knowledge on emissions
- Possible to reduce fuel related emissions of CH_4 and N_2O (methane and NH_3 pathways) but with a cost. Regulation needed for these emissions too!
- More emission measurements from ships in operation for different operational profiles needed to verify and improve environmental performance

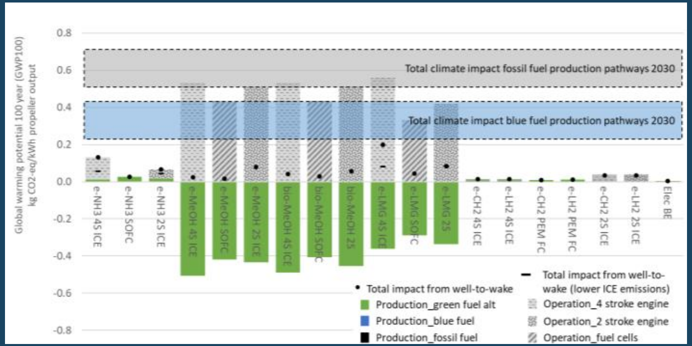
Other types of environmental impacts

- Other environmental impacts also need to be assessed
- Some impact categories need more investigation

In general

- LCA need to be updated as new data become available
- Detailed ship specific LCAs also needed





Thank you for listening!
Questions?

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