Supporting information

Life cycle assessment of hydrogen and helium as carrier gases in gas chromatography analysis

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1. GC method

For this study, we employed a gas chromatographic (GC) method based on the U.S. Environmental Protection Agency (EPA) Method 8270E [1]. This method was selected due to its widespread use in environmental analysis and its applicability to a broad range of semivolatile organic compounds.

Table A1. GC method parameters used for calculations

Parameter, unit	Carrier gas	
	Helium	Hydrogen
Column flow, ml min^{-1}	1.2	1.5
Total flow, ml min^{-1}	13.2	16.5
Oven temperature program	Initial temperature: 40°C, hold for 1 min Ramp 1: 20°C/min to 280°C Ramp 2: 5°C/min to 320°C, hold for 1 min	Initial temperature: 40°C, hold for 0.6 min Ramp 1: 33.4°C/min to 280°C Ramp 2: 8.3°C/min to 320°C, hold for 0.6 min
Total run time, min	22.0	13.2
Linear velocity, cm sec^{-1}	40	66
Flow control mode	Constant linear velocity	
Split	1:10	
Injection volume, µL	1	

2. Life cycle inventory

Table A2. Inventory for the gas chromatography analysis per **1 sample**

Activity	Unit	Base case value		References / Comments
Inputs				
Carrier gas dependent		He	H_2	
Analysis time according to scenario	min	22.0	13.2	
Total flow	ml min^{-1}	13.2	16.2	
Carrier gas	g	0.052	0.019	
• Electricity *Electricity, low voltage, EU-28" (or region-specific)*	kWh	1.09	0.65	Ecoinvent 3.10
Not gas dependent				
• Solvent (e.g. dichloromethane) *Market for dichloromethane, RER*	L	0.002		2 mL per vial Ecoinvent 3.10
• Glass Vial	st	1		1 × 2 mL vial

Activity	Unit	Base case value	References / Comments
Market for glass tube, borosilicate, GLO			Ecoinvent 3.10
• Aluminium cap with septum	st	1	1 cap
Outputs			
• Solvent *"Market for hazardous waste, for incineration, Europe without Switzerland"*	L	0.002	Spent solvent & leftover sample Ecoinvent 3.10
• Waste: Glass Vial *"Market for waste glass | waste glass, SE"*	g	2.5	If single-use & recyclable in your region Ecoinvent 3.10
• Waste: Aluminum Cap *"Market for scrap aluminium, Europe without Switzerland"*	g	0.14	If collected separately from septum Ecoinvent 3.10
• Waste: PTFE Septum *"Market for residues, MSWI, waste rubber, unspecified, Europe without Switzerland"*	g	0.15	Usually ends up as general lab waste Ecoinvent 3.10

Table A3. Inventory for the as chromatography analysis per **10 years** ((8 h day^{-1}, 5 days $week^{-1}$, 50 weeks $year^{-1}$) the instrument is available for 2.0×10^3 h $year^{-1}$, or 2.0×10^4 h over ten years)

Activity	Unit	Base case value		References / Comments
Inputs				
Carrier gas dependent		He	H_2	
Analysis time according to scenario	min	22.0	13.2	
Number of analyses	st	54500	90900	
Total flow	ml min^{-1}	13.2	16.2	
Carrier gas	g	2834	1727	
• Electricity *Electricity, low voltage Market for electricity, low voltage, SE*	kWh	21800	13000	Ecoinvent 3.10
• Solvent (e.g. dichloromethane) *Market for dichloromethane, RER*	L	109	182	2 mL per vial Ecoinvent 3.10
• Glass vial *"glass tube production, borosilicate, RER"*	st	54500	90900	1 × 2 mL vial Ecoinvent 3.10

Activity	Unit	Base case value		References / Comments
Aluminium cap with septum	st	54500	90900	1 cap
Outputs				
• Solvent *"Market for hazardous waste, for incineration, Europe without Switzerland"*	L	109	182	Spent solvent & leftover sample Ecoinvent 3.10
• Spent glass vial *"Market for waste glass | waste glass, SE"*	g	136250	227250	Ecoinvent 3.10
• Spent aluminium cap *"Market for scrap aluminium, Europe without Switzerland"*	g	7630	12726	Ecoinvent 3.10 If collected separately from septum
• Spent PTFE septum *"Market for residues, MSWI, waste rubber, unspecified, Europe without Switzerland"*	g	8175	13635	Ecoinvent 3.10 Usually ends up as general lab waste

Table A4. Inventory for the Helium production and transportation

Activity	Unit	Base case value	References / Comments
Inputs			
• Helium *Market for helium, liquid, RER*	kg	1	Ecoinvent 3.10
• Sea Freight Distance (US Gulf Coast - Rotterdam) *Transport, freight, sea, transoceanic ship, GLO*	km	6091 nautical miles 11280 km	http://ports.com/ Ecoinvent 3.10
• Port of Rotterdam to Sweden *Transport, freight, lorry >32t, EURO6, RER*	km	1300	Ecoinvent 3.10
• Intra-Sweden distribution *Transport, freight, lorry 16-32 t, EURO6, RER*	km	300	Ecoinvent 3.10

Table A5. Inventory for the Hydrogen lab generator (PEM Proton exchange membrane) 0.15 kW stack production of 250 ml of hydrogen for 10 years

Activity	Unit	1.0 MW stack	0.15 kW laboratory scale stack	References / Comments
Inputs				[2]
• Titanium *Market for titanium, GLO*	kg	528	0.46	Ecoinvent 3.10
• Aluminium *Market for aluminium, primary, liquid, GLO*	kg	27	0.024	Ecoinvent 3.10
• Steel *Market for steel, unalloyed, GLO*	kg	100	0.087	Ecoinvent 3.10
• copper *Market for copper, anode, GLO*	kg	4.5	0.0039	Ecoinvent 3.10
• Nafion (proxy-process)	kg	16	0.014	Proxy-process. See Table A6
• Activated carbon, granular *Market for activated carbon, granular, GLO*	kg	9	0.0078	Ecoinvent 3.10
Iridium *Iridium elementary flow*	kg	0.75	0.00065	Ecoinvent 3.10
• Platinum *Market for platinum, GLO*	kg	0.075	0.000065	Ecoinvent 3.10
• Electricity *Market group for electricity, low voltage, Europe without Switzerland*	kWh	5360	4.68	[3] Ecoinvent 3.10
Outputs				
• Hydrogen lab generator	st	-	1	

Table A6. Inventory for the proxy-process for Nafion, based on [3-5]

Activity	Unit	Base case value	References / Comments
Inputs			
• PTFE *Market for tetrafluoroethylene, GLO*	kg	0.57	Ecoinvent 3.10
• Sulfuric acid *Market for sulfuric acid, RER*	kg	0.43	Ecoinvent 3.10
• Laminating	m^2	10.15	Ecoinvent 3.10

Activity	Unit	Base case value	References / Comments
Laminating service, foil, with acrylic binder, RER			
Outputs			
• Nafion	kg	1	

To calculate the laminating area A, m^2 for 1 kg of Nafion, we use the following data:

$$A = \frac{m}{\rho \cdot t} \quad \text{Eq. S1}$$

Where:

Density, ρ: 1970 kg m^{-3}; Thickness, t: 50 10^{-6} m (50 µm); Mass, m: 1 kg

Table A7. Inventory for the Hydrogen production on-site by electrolysis (PEM Proton exchange membrane) 0.15 kW stack production of 0.25 L min^{-1} (15 L h^{-1}) of hydrogen for 10 years.

Activity	Unit	Base case value	References / Comments
Inputs			
Hydrogen lab generator	st	1	
• Electricity *Market for electricity, low voltage, SE*	kWh	3000	0.15 kWh x 2,000 h $year^{-1}$ x 10 years Ecoinvent 3.10
• Deionized water *Market for water, deionised, Europe without Switzerland*	L	243	~9 L per kg H_2 Ecoinvent 3.10
• Ion exchange resin *Market for ion exchange resin, RER*	kg	10	10 kg total (1 kg × 10 replacements). Ecoinvent 3.10
• Desiccant (silica gel / molecular sieve) *Market for activated silica, GLO*	kg	10	10 kg total (0.5 kg × 20 replacements). Ecoinvent 3.10
Outputs			
• Hydrogen (functional output)	kg	27	15 L h^{-1} x 0.0899 g L^{-1} x 2000 h $year^{-1}$ x 10 years
• Oxygen (by-product)	kg	216	~8 kg O_2 per 1 kg H_2. Likely vented. If modelling it as a co-product or waste stream, assign zero value or treat as an emission to air.
• Spent ion exchange resin	kg	10	Ecoinvent 3.10

Activity	Unit	Base case value	References / Comments
Treatment of spent ion exchange resin, hazardous incineration			
• Spent Desiccant *Market for hazardous waste incineration*	kg		Ecoinvent 3.10

Table A8. Inventory for the steam methane reforming hydrogen production and transportation

Activity	Unit	Base case value	References / Comments
Inputs			
• Hydrogen *Market for hydrogen, gaseous, medium pressure, merchant*	kg	1	Ecoinvent 3.10
• Transportation Germany/the Netherlands to Sweden *Transport, freight, lorry >32t, EURO6, RER*	km	1300	Ecoinvent 3.10
• Intra-Sweden distribution *Transport, freight, lorry 16-32 t, EURO6, RER*	km	100-500	Ecoinvent 3.10

Table A9. Inventory for the Glass vial

Activity	Unit	Base case value	References / Comments
Inputs			
• Glass (borosilicate) *Market for glass tube, borosilicate, GLO*	g	2.5	Ecoinvent 3.10
Outputs			
• Glass vial	st	1	

Table A10. Inventory for the Aluminium cap with PTFE septa

Activity	Unit	Base case value	References / Comments
Inputs			
• Aluminum (cap)	g	0.14	Ecoinvent 3.10

Activity	Unit	Base case value	References / Comments
Market for aluminium, primary, liquid, GLO			
• Rubber (septum) *Market for synthetic rubber, GLO*	g	0.14	Represents the silicone or similar rubber portion. Ecoinvent 3.10
• PTFE (septum layer) *Market for tetrafluoroethylene, GLO*	g	0.01	Thin PTFE facing. Ecoinvent 3.10
Outputs			
• Aluminium cap with septum	st	1	

Table A11. Normalised environmental impacts

Impact category	GC H2 electrolysis	GC H2 SMR	GC He
Marine ecotoxicity	0.03614	0.03602	0.05962
Freshwater ecotoxicity	0.02347	0.0234	0.03879
Human carcinogenic toxicity	0.00899	0.00896	0.01379
Human non-carcinogenic toxicity	2.11E-03	0.0021	0.00343
Terrestrial ecotoxicity	0.00146	0.00146	0.00236
Ionizing radiation	0.00032	0.00032	0.00053
Freshwater eutrophication	4.95E-05	4.93E-05	7.67E-05
Water consumption	1.51E-05	1.51E-05	2.51E-05
Fossil resource scarcity	1.03E-05	1.03E-05	1.52E-05
Ozone formation, Terrestrial ecosystems	8.98E-06	8.96E-06	1.31E-05
Ozone formation, Human health	7.52E-06	7.50E-06	1.10E-05
Global warming	7.46E-06	7.46E-06	1.10E-05
Terrestrial acidification	7.37E-06	7.35E-06	1.13E-05
Fine particulate matter formation	4.51E-06	4.49E-06	6.86E-06
Marine eutrophication	2.91E-06	2.90E-06	4.77E-06
Land use	2.05E-06	2.05E-06	3.37E-06
Stratospheric ozone depletion	1.80E-06	1.78E-06	2.50E-06
Mineral resource scarcity	8.28E-09	8.25E-09	1.33E-08

Table A12. Environmental impacts according to the attributional LCIA modelling

Impact category	GC H_2 electrolysis					GC H_2 SMR					GC He				
	Gases	Electricity	Transport-ation	Chemicals and consumables	End-of-life	Gases	Electricity	Transport-ation	Chemicals and consumables	End-of-life	Gases	Electricity	Transport-ation	Chemicals and consumables	End-of-life
Fine particulate matter formation, kg $PM_{2.5}$ eq	1.35E-07	8.90E-05	0	2.39E-05	2.26E-06	3.51E-08	8.87E-05	2.85E-09	2.39E-05	2.25E-06	3.86E-07	0.00015	4.57E-08	2.39E-05	2.25E-06
Fossil resource scarcity, kg oil eq	1.50E-05	0.00677	0	0.00259	0.00072	8.09E-05	0.00675	1.20E-06	0.00259	0.00072	0.00026	0.01131	5.05E-06	0.00259	0.00072
Freshwater ecotoxicity, kg 1,4-DCB	6.78E-06	0.02798	0	0.00049	0.00032	1.98E-06	0.02789	9.57E-08	0.00049	0.00032	7.86E-06	0.04677	3.15E-07	0.00049	0.00032
Freshwater eutrophication, kg P eq	1.95E-08	2.63E-05	0	3.67E-06	2.18E-06	1.17E-08	2.62E-05	2.51E-10	3.67E-06	2.17E-06	7.51E-08	4.39E-05	8.52E-10	3.67E-06	2.17E-06
Global warming, kg CO_2 eq	6.23E-05	0.04131	0	0.0115	0.00673	0.00022	0.04118	3.73E-06	0.0115	0.00671	0.0003	0.06905	1.66E-05	0.0115	0.00671
Human carcinogenic toxicity, kg 1,4-DCB	2.98E-05	0.01977	0	0.00374	0.00136	1.43E-05	0.0197	6.95E-07	0.00374	0.00136	5.40E-05	0.03304	2.72E-06	0.00374	0.00136
Human non-carcinogenic toxicity, kg 1,4-DCB	0.00015	0.29224	0	0.01226	0.0101	3.80E-05	0.29129	2.85E-06	0.01226	0.01009	0.00019	0.48848	8.48E-06	0.01226	0.01009
Ionizing radiation, kBq Co-60 eq	2.34E-06	0.1521	0	0.0005	0.00016	1.45E-06	0.1516	5.88E-08	0.0005	0.00016	1.84E-05	0.25423	1.88E-07	0.0005	0.00016
Land use, m^2a crop eq	1.49E-06	0.01205	0	0.00052	0.0001	5.69E-07	0.01202	2.17E-07	0.00052	0.0001	4.54E-06	0.02015	6.15E-07	0.00052	0.0001
Marine ecotoxicity, kg 1,4-DCB	9.51E-06	0.03608	0	0.00074	0.00047	3.35E-06	0.03596	2.11E-07	0.00074	0.00047	1.33E-05	0.0603	6.99E-07	0.00074	0.00047
Marine eutrophication, kg N eq	2.85E-09	1.28E-05	0	3.67E-07	2.32E-07	1.25E-09	1.28E-05	5.29E-11	3.67E-07	2.31E-07	1.04E-08	2.14E-05	1.94E-10	3.67E-07	2.31E-07
Mineral resource scarcity, kg Cu eq	8.03E-07	0.00089	0	8.99E-05	8.88E-06	2.26E-07	0.00089	8.86E-09	8.99E-05	8.86E-06	6.60E-07	0.0015	3.38E-08	8.99E-05	8.86E-06
Ozone formation, Human health, kg NOx eq	1.56E-07	0.0001	0	4.42E-05	5.49E-06	1.25E-07	0.0001	6.75E-09	4.42E-05	5.48E-06	6.93E-07	0.00018	1.39E-07	4.42E-05	5.48E-06
Ozone formation, Terrestrial ecosystems, kg NOx eq	1.61E-07	0.00011	0	4.51E-05	5.90E-06	1.58E-07	0.00011	7.68E-09	4.51E-05	5.88E-06	7.94E-07	0.00018	1.43E-07	4.51E-05	5.88E-06
Stratospheric ozone depletion, kg CFC11 eq	7.82E-10	6.39E-08	0	4.15E-08	1.52E-09	9.33E-12	6.37E-08	1.65E-12	4.15E-08	1.52E-09	8.18E-11	1.07E-07	7.60E-12	4.15E-08	1.52E-09
Terrestrial acidification, kg SO_2 eq	4.00E-07	0.00024	0	5.69E-05	5.74E-06	7.28E-08	0.00024	5.24E-09	5.69E-05	5.73E-06	6.88E-07	0.0004	1.32E-07	5.69E-05	5.73E-06
Terrestrial ecotoxicity, kg 1,4-DCB	0.00058	1.38852	0	0.09731	0.02725	0.00075	1.38403	0.00011	0.09731	0.0272	0.0027	2.32091	0.00034	0.09731	0.0272
Water consumption, m^3	5.74E-07	0.00395	0	5.81E-05	1.98E-05	7.68E-07	0.00394	8.22E-09	5.81E-05	1.98E-05	1.28E-06	0.0066	2.76E-08	5.81E-05	1.98E-05

Table A13. Environmental impacts according to the consequential LCIA modelling

Impact category	GC H_2 electolysis					GC H_2 SMR					GC He				
	Gases	Electricity	Transport-ation	Chemicals and consumables	End-of-life	Gases	Electricity	Transport-ation	Chemicals and consumables	End-of-life	Gases	Electricity	Transport-ation	Chemicals and consumables	End-of-life
Fine particulate matter formation, kg $PM_{2.5}$ eq	-2.43E-07	0.0001	0	3.77E-05	2.96E-07	2.72E-08	9.97E-05	2.98E-09	3.77E-05	-5.95E-06	3.17E-07	0.00017	4.63E-08	3.77E-05	-5.95E-06
Fossil resource scarcity, kg oil eq	2.00E-05	0.05137	0	0.0047	0.00024	8.12E-05	0.0512	1.24E-06	0.0047	-0.00016	3.38E-05	0.08587	5.18E-06	0.0047	-0.00016
Freshwater ecotoxicity, kg 1,4-DCB	1.08E-05	0.02392	0	0.00032	0.00028	2.62E-06	0.02384	1.07E-07	0.00032	0.00017	5.98E-06	0.03997	3.72E-07	0.00032	0.00017
Freshwater eutrophication, kg P eq	4.93E-08	1.17E-05	0	4.69E-06	2.72E-06	1.14E-08	1.17E-05	3.43E-10	4.69E-06	-3.28E-06	7.49E-08	1.96E-05	1.17E-09	4.69E-06	-3.28E-06
Global warming, kg CO_2 eq	7.56E-05	0.14119	0	0.01999	0.00487	0.00022	0.14073	3.80E-06	0.01999	0.00261	0.00013	0.23599	1.69E-05	0.01999	0.00261
Human carcinogenic toxicity, kg 1,4-DCB	2.78E-05	0.01264	0	0.00242	0.00059	2.07E-06	0.0126	1.15E-07	0.00242	0.0002	1.42E-05	0.02113	5.25E-07	0.00242	0.0002
Human non-carcinogenic toxicity, kg 1,4-DCB	0.0003	0.13328	0	0.01174	0.00931	4.36E-05	0.13285	3.09E-06	0.01174	0.00207	0.00015	0.22278	9.37E-06	0.01174	0.00207
Ionizing radiation, kBq Co-60 eq	-1.37E-06	0.00019	0	-0.00043	-2.30E-05	6.54E-08	0.00019	2.23E-08	-0.00043	5.03E-05	1.55E-05	0.00032	7.76E-08	-0.00043	5.03E-05
Land use, m^2a crop eq	6.23E-06	0.07331	0	0.00085	-0.00081	6.18E-07	0.07308	2.29E-07	0.00085	-0.00086	5.78E-06	0.12254	6.46E-07	0.00085	-0.00086
Marine ecotoxicity, kg 1,4-DCB	1.53E-05	0.03109	0	0.00068	0.00038	4.75E-06	0.03099	2.58E-07	0.00068	0.00023	8.79E-06	0.05196	8.95E-07	0.00068	0.00023
Marine eutrophication, kg N eq	4.08E-09	3.58E-06	0	4.00E-07	1.59E-07	1.03E-09	3.57E-06	5.10E-11	4.00E-07	-1.92E-07	5.22E-09	5.99E-06	1.86E-10	4.00E-07	-1.92E-07
Mineral resource scarcity, kg Cu eq	4.50E-07	-4.20E-05	0	8.22E-05	-7.05E-06	3.55E-07	-4.19E-05	1.31E-08	8.22E-05	-5.13E-06	1.20E-07	-7.02E-05	5.30E-08	8.22E-05	-5.13E-06
Ozone formation, Human health, kg NOx eq	2.24E-07	0.0003	0	7.04E-05	-1.58E-06	1.24E-07	0.0003	6.77E-09	7.04E-05	-5.59E-06	2.95E-07	0.0005	1.39E-07	7.04E-05	-5.59E-06
Ozone formation, Terrestrial ecosystems, kg NOx eq	2.33E-07	0.00031	0	7.21E-05	-1.65E-06	1.57E-07	0.00031	7.70E-09	7.21E-05	-5.23E-06	3.03E-07	0.00052	1.43E-07	7.21E-05	-5.23E-06
Stratospheric ozone depletion, kg CFC11 eq	8.04E-10	1.26E-07	0	1.69E-07	-5.28E-11	7.37E-12	1.25E-07	1.65E-12	1.69E-07	2.67E-10	4.64E-11	2.10E-07	7.58E-12	1.69E-07	2.67E-10
Terrestrial acidification, kg SO_2 eq	-1.07E-06	0.00028	0	8.64E-05	2.92E-06	5.30E-08	0.00028	4.75E-09	8.64E-05	-1.49E-05	3.77E-07	0.00047	1.31E-07	8.64E-05	-1.49E-05
Terrestrial ecotoxicity, kg 1,4-DCB	0.00182	2.33469	0	0.23144	-0.0091	0.00125	2.32713	0.00013	0.23144	0.0011	0.00107	3.90241	0.00044	0.23144	0.0011
Water consumption, m^3	1.44E-06	0.0004	0	0.00012	8.57E-05	7.85E-07	0.0004	7.73E-09	1.20E-04	-8.04E-05	6.26E-07	0.00068	2.60E-08	1.20E-04	-8.04E-05

Table A14. Environmental impacts across ten years of laboratory operation according to the attributional LCIA modelling

Impact category	GC H_2 electolysis					GC H_2 SMR					GC He				
	Gases	Electricity	Transport-ation	Chemicals and consumables	End-of-life	Gases	Electricity	Transport-ation	Chemicals and consumables	End-of-life	Gases	Electricity	Transport-ation	Chemicals and consumables	End-of-life
Fine particulate matter formation, kg $PM_{2.5}$ eq	1.23E-02	8.09E+00	0	2.18E+00	2.05E-01	3.19E-03	8.06E+00	2.60E-04	2.18E+00	2.05E-01	2.10E-02	8.10509	2.49E-03	1.30E+00	1.23E-01
Fossil resource scarcity, kg oil eq	1.37E+00	615.25452	0	235.73212	65.58334	7.35E+00	613.26273	1.09E-01	235.73212	65.42255	14.20547	616.58411	2.75E-01	141.33554	39.22474
Freshwater ecotoxicity, kg 1,4-DCB	6.17E-01	2543.46117	0	44.67059	29.43385	1.80E-01	2535.2271	8.70E-03	44.67059	29.4017	4.28E-01	2548.9577	1.72E-02	26.7827	17.62808
Freshwater eutrophication, kg P eq	1.77E-03	2.39E+00	0	3.33E-01	1.98E-01	1.06E-03	2.38E+00	2.29E-05	3.33E-01	1.98E-01	4.09E-03	2.39E+00	4.64E-05	2.00E-01	1.19E-01
Global warming, kg CO_2 eq	5.66E+00	3755.32966	0	1045.33688	611.33693	20.40896	3743.17234	3.39E-01	1045.33688	609.75848	16.25305	3763.44509	9.07E-01	626.74213	365.58677
Human carcinogenic toxicity, kg 1,4-DCB	2.71E+00	1796.76212	0	339.97489	123.83164	1.30E+00	1790.94538	6.31E-02	339.97489	123.54653	2.94E+00	1800.64501	1.48E-01	203.83533	74.07355
Human non-carcinogenic toxicity, kg 1,4-DCB	13.42616	2.66E+04	0	1114.83837	917.73388	3.45E+00	2.65E+04	2.59E-01	1114.83837	916.9857	10.33676	2.66E+04	4.62E-01	668.41245	549.7879
Ionizing radiation, kBq Co-60 eq	2.13E-01	1.38E+04	0	45.73414	14.38778	1.31E-01	1.38E+04	5.35E-03	45.73414	14.35158	1.00E+00	1.39E+04	1.02E-02	27.42036	8.60463
Land use, m^2a crop eq	1.35E-01	1095.71862	0	47.08633	9.28402	5.17E-02	1092.1714	1.97E-02	47.08633	9.274	2.47E-01	1098.08652	3.35E-02	28.23108	5.56032
Marine ecotoxicity, kg 1,4-DCB	8.65E-01	3279.32921	0	67.57605	42.65857	3.04E-01	3268.71288	1.92E-02	67.57605	42.61069	7.27E-01	3286.41599	3.81E-02	40.51589	25.54766
Marine eutrophication, kg N eq	2.60E-04	1.16E+00	0	3.33E-02	2.11E-02	1.10E-04	1.16E+00	4.80E-06	3.33E-02	2.10E-02	5.70E-04	1.17E+00	1.06E-05	2.00E-02	1.26E-02
Mineral resource scarcity, kg Cu eq	7.30E-02	81.34158	0	8.17E+00	8.07E-01	2.05E-02	81.07825	8.10E-04	8.17E+00	8.06E-01	3.60E-02	81.51736	1.84E-03	4.90E+00	4.83E-01
Ozone formation, Human health, kg NOx eq	1.42E-02	9.52724	0	4.02E+00	4.99E-01	1.14E-02	9.4964	6.10E-04	4.02E+00	4.98E-01	3.78E-02	9.54783	7.57E-03	2.41E+00	2.98E-01
Ozone formation, Terrestrial ecosystems, kg NOx eq	1.46E-02	9.85553	0	4.10E+00	5.36E-01	1.44E-02	9.82362	7.00E-04	4.10E+00	5.35E-01	4.33E-02	9.87683	7.79E-03	2.46E+00	3.21E-01
Stratospheric ozone depletion, kg CFC11 eq	7.11E-05	5.81E-03	0	3.77E-03	1.40E-04	8.48E-07	5.79E-03	1.50E-07	3.77E-03	1.40E-04	4.46E-06	5.82E-03	4.14E-07	2.26E-03	8.26E-05
Terrestrial acidification, kg SO_2 eq	3.64E-02	21.74225	0	5.17E+00	5.22E-01	6.62E-03	21.67186	4.80E-04	5.17E+00	5.21E-01	3.75E-02	21.78924	7.21E-03	3.10E+00	3.12E-01
Terrestrial ecotoxicity, kg 1,4-DCB	52.65566	1.26E+05	0	8845.50085	2476.9283	68.1868	1.26E+05	9.56769	8845.50085	2472.03004	147.36054	1.26E+05	18.67104	5303.4081	1482.13022
Water consumption, m^3	5.22E-02	359.06727	0	5.28E+00	1.80E+00	6.98E-02	357.90485	7.50E-04	5.28E+00	1.80E+00	6.97E-02	359.84323	1.50E-03	3.16E+00	1.08E+00

Table A15. Life cycle impact sensitivity for different power grids

Impact categories	GC H_2 electolysis						GC H_2 SMR						GC He					
	CN	US	EU	BR	PTV	SE	CN	US	EU	BR	PTV	SE	CN	US	EU	BR	PTV	SE
Fine particulate matter formation, kg $PM_{2.5}$ eq	0.00103	0.00069	0.00039	0.00032	0.00014	0.00012	0.00103	0.00069	0.00039	0.00011	0.00016	0.00011	0.00171	0.00114	0.00064	0.00051	0.00022	0.00018
Fossil resource scarcity, kg oil eq	0.13127	0.09407	0.06391	0.04023	0.01621	0.0101	0.13133	0.09413	0.06398	0.01014	0.01825	0.01014	0.21812	0.15574	0.10517	0.06546	0.02518	0.01489
Freshwater ecotoxicity, kg 1,4-DCB	0.03149	0.03018	0.03337	0.02722	0.02165	0.0288	0.03149	0.03017	0.03337	0.02871	0.02168	0.02871	0.05226	0.05005	0.05541	0.04509	0.03575	0.04759
Freshwater eutrophication, kg P eq	0.00013	0.00023	0.00022	4.29E-05	3.71E-05	3.21E-05	0.00013	0.00023	0.00022	3.20E-05	4.03E-05	3.20E-05	0.00022	0.00038	0.00036	6.80E-05	5.84E-05	4.98E-05
Global warming, kg CO_2 eq	0.66216	0.33824	0.2418	0.18647	0.07024	0.0596	0.66231	0.33839	0.24195	0.05962	0.07864	0.05962	1.09825	0.55506	0.39333	0.30055	0.10565	0.08758
Human carcinogenic toxicity, kg 1,4-DCB	0.08421	0.04051	0.04073	0.02652	0.02824	0.0249	0.08419	0.04049	0.04071	0.02482	0.02873	0.02482	0.13777	0.06449	0.06484	0.04103	0.04391	0.0382
Human non-carcinogenic toxicity, kg 1,4-DCB	0.64794	0.45793	0.49837	0.26084	0.21778	0.31475	0.64783	0.45781	0.49825	0.31369	0.2224	0.31369	1.07135	0.75272	0.82053	0.42222	0.35001	0.51103
Ionizing radiation, kBq Co-60 eq	0.02691	0.10059	0.12851	0.01265	0.00433	0.15276	0.02691	0.10059	0.12851	0.15227	0.0051	0.15227	0.0447	0.16824	0.21507	0.02078	0.00683	0.25491
Land use, m^2a crop eq	0.00878	0.01052	0.01213	0.01052	0.00221	0.01268	0.00878	0.01052	0.01213	0.01264	0.00229	0.01264	0.0143	0.01722	0.01993	0.01723	0.00329	0.02077
Marine ecotoxicity, kg 1,4-DCB	0.04214	0.04088	0.04451	0.03839	0.02884	0.0373	0.04213	0.04087	0.0445	0.03718	0.02881	0.03718	0.06984	0.06773	0.07381	0.06356	0.04755	0.06153
Marine eutrophication, kg N eq	9.35E-06	2.00E-05	2.13E-05	8.66E-06	5.00E-06	1.34E-05	9.35E-06	2.00E-05	2.13E-05	1.34E-05	5.60E-06	1.34E-05	1.53E-05	3.31E-05	3.54E-05	1.41E-05	7.99E-06	2.20E-05
Mineral resource scarcity, kg Cu eq	0.00097	0.00101	0.00109	0.00088	0.00081	0.00099	0.00097	0.001	0.00109	0.00099	0.0008	0.00099	0.00156	0.00162	0.00176	0.00141	0.0013	0.0016
Ozone formation, Human health, kg NOx eq	0.00182	0.00046	0.00047	0.00036	0.00019	0.00015	0.00182	0.00046	0.00047	0.00015	0.00021	0.00015	0.00301	0.00073	0.00076	0.00057	0.00029	0.00023
Ozone formation, Terrestrial ecosystems, kg NOx eq	0.00183	0.00048	0.00049	0.00037	0.0002	0.00016	0.00183	0.00048	0.00049	0.00016	0.00022	0.00016	0.00303	0.00078	0.00079	0.00059	0.0003	0.00023
Stratospheric ozone depletion, kg CFC11 eq	1.85E-07	1.67E-07	1.67E-07	4.11E-07	6.44E-08	1.08E-07	1.84E-07	1.66E-07	1.66E-07	1.07E-07	6.66E-08	1.07E-07	2.80E-07	2.49E-07	2.50E-07	6.58E-07	7.76E-08	1.50E-07
Terrestrial acidification, kg SO_2 eq	0.00235	0.00079	0.00097	0.00077	0.00033	0.0003	0.00235	0.00079	0.00097	0.0003	0.00035	0.0003	0.00389	0.00129	0.00158	0.00125	0.0005	0.00046
Terrestrial ecotoxicity, kg 1,4-DCB	2.23826	2.41105	2.25336	3.11492	2.1681	1.51366	2.23849	2.41128	2.25358	1.50939	2.08043	1.50939	3.6711	3.96086	3.69642	5.14118	3.55344	2.44846
Water consumption, m^3	0.00189	0.00263	0.00529	0.01417	0.00193	0.00403	0.00189	0.00263	0.00529	0.00402	0.00168	0.00402	0.00311	0.00435	0.00883	0.02371	0.00318	0.00668

References

1. U. S. EPA, *Journal*, 2014.
2. K. Bareiß, C. de la Rua, M. Möckl and T. Hamacher, *Appl Energ*, 2019, **237**, 862-872.
3. S. Evangelisti, C. Tagliaferri, D. J. L. Brett and P. Lettieri, *J Clean Prod*, 2017, **142**, 4339-4355.
4. A. Simons and C. Bauer, *Appl Energ*, 2015, **157**, 884-896.
5. G. Gottardo, A. Basso Peressut, S. Colnago, S. Latorrata, L. Piegari and G. Dotelli, *Energies*, 2023, **16**, 6782.