Supplementary material

Considering Life Cycle Greenhouse Gas Emissions in Power System Expansion Planning for Europe and North Africa Using Multi-Objective Optimization

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Contents

1 Illustrations for the scenario calculation without nuclear power

The pareto front illustrated in Figure S1 represents the trade-offs between system costs and climate impacts for both life cycle emissions (green dots) and the share of direct CO_2 emitted due to energy system operation (blue dots) for a system without nuclear power. Each point on the pareto frontier represents an energy system in the year 2050. According to the implementation of the ε-CM, the solution of the point in the upper left, represents the point with least GHG emissions, whereas the point on the very right represents the system with the least costs. Finally, the solutions for the points between these two extrema result from minimizing system costs while constraining life cycle GHG emissions for a given threshold.

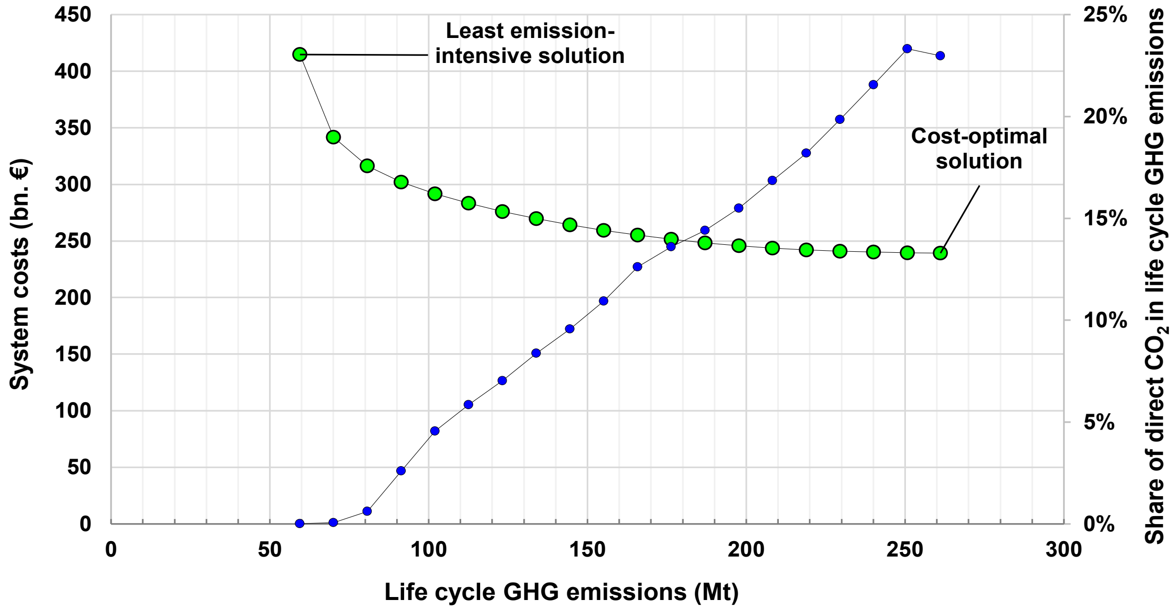

Figure S1. Pareto front to illustrate the trade-offs between system costs (left y-axis) and life cycle GHG emissions (x-axis) (green dots) for a system without nuclear power. Share of direct CO_2 emissions (right y-axis) in total life cycle GHG emissions for the individual solutions (blue dots); direct CO_2 emissions are based on the REMix output.

Figure S2 illustrates the evolution of life cycle metrics for the different areas of protection over the pareto frontier (Figure S1).

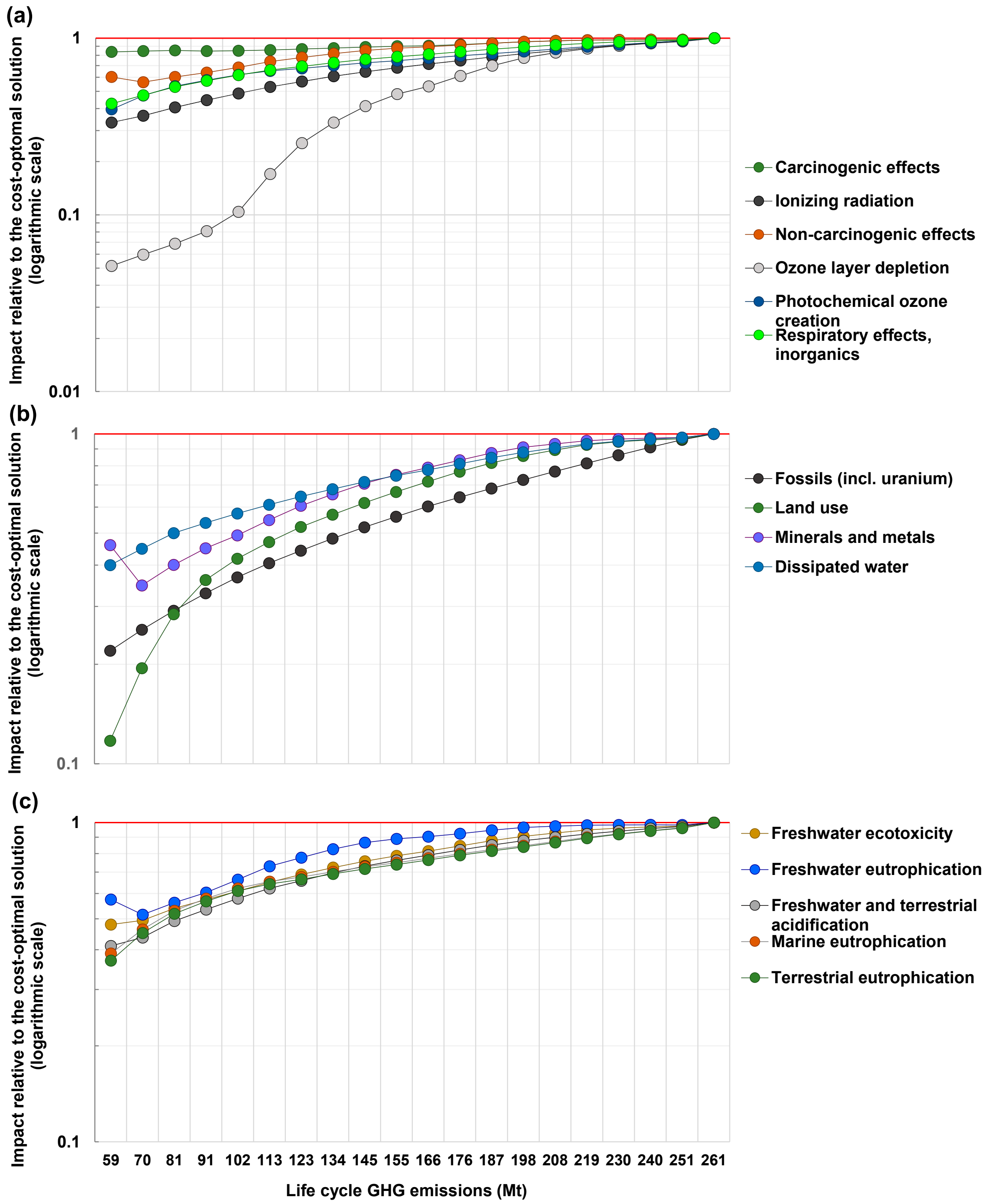

Figure S2. Impact on life cycle indicators as a function of life cycle GHG emissions over the pareto front (Figure S1) for a system without nuclear power. Panel (**a**): indicators related to human health; panel (**b**): indicators related to resource depletion; panel (**c**): indicators related to ecosystem quality. Impacts at the solution with minimal costs are scaled to 1. Reading the graph from right to left, impact values below 1 indicate co-benefits in reducing climate impacts, above 1 show adverse side-effects.

2 Cost assumptions

Table S1. Technology-specific cost assumptions.

Category	Technology (class)	Technology specification	Cost type	Values
	Biomass-fired power plants	Biomass power plants	Invest in EUR/kW	2.00×10^{3}
			Variable O&M in EUR/kWh	2.00×10^{-3}
			Fixed O&M in share of invest	4.00×10^{-2}
		Geothermal power plants	Invest in EUR/kW	7.60×10^{4}
			Variable O&M in EUR/kWh	1.00×10^{-4}
			Fixed O&M in share of invest	4.50×10^{-2}
	Hydrogen reconversion	SOFC fuel cell	Invest in EUR/kW	1.00×10^{3}
			Variable O&M in EUR/kWh	1.00×10^{-4}
			Fixed O&M in share of invest	6.00×10^{-2}
	Power generation from fluctuating renewable energy resources	Wind energy converters (Onshore)	Invest in EUR/kW	1.10×10^{3}
			Variable O&M in EUR/kWh	1.00×10^{-4}
			Fixed O&M in share of invest	4.00×10^{-2}
		Wind energy converters (Offshore)	Invest in EUR/kW	1.80×10^{3}
			Variable O&M in EUR/kWh	1.00×10^{-4}
			Fixed O&M in share of invest	5.50×10^{-2}
		Photovoltaic (open ground)	Invest in EUR/kW	4.45×10^{2}
			Variable O&M in EUR/kWh	1.00×10^{-4}
			Fixed O&M in share of invest	1.00×10^{-2}
		Photovoltaic (rooftop)	Invest in EUR/kW	5.00×10^{2}
			Variable O&M in EUR/kWh	1.00×10^{-3}
			Fixed O&M in share of invest	1.00×10^{-2}
		Run of river power plants	Invest in EUR/kW	4.00×10^{3}
Electricity			Variable O&M in EUR/kWh	1.00×10^{-4}
			Fixed O&M in share of invest	5.00×10^{-2}
	Conventional thermal power plants	Lignite-fired power plants	Invest in EUR/kW	1.64×10^{3}
			Variable O&M in EUR/kWh	2.40×10^{-3}
			Fixed O&M in share of invest	4.00×10^{-2}
		Open cycle gas turbines	Invest in EUR/kW	4.37×10^{2}
			Variable O&M in EUR/kWh	1.10×10^{-2}
			Fixed O&M in share of invest	4.00×10^{-2}
		Combined cycle gas turbines[1]	Invest in EUR/kW	8.50×10^{2}
			Variable O&M in EUR/kWh	2.00×10^{-3}
			Fixed O&M in share of invest	4.00×10^{-2}
		Nuclear power plants	Invest in EUR/kW	6.60×10^{4}
			Variable O&M in EUR/kWh	4.40×10^{-3}
			Fixed O&M in share of invest	4.00×10^{-2}
		Hard coal-fired power plants	Invest in EUR/kW	1.50×10^{3}
			Variable O&M in EUR/kWh	1.80×10^{-3}
			Fixed O&M in share of invest	4.00×10^{-2}
	Concentrated solar power plants	Steam turbine	Invest in EUR/kW	9.80×10^{2}
		Thermal energy storage	Invest in EUR/kWh	1.90×10^{2}
		Solar field	Invest in EUR/kW_{th}	1.92×10^{2}
			Variable O&M in EUR/kWh	2.20×10^{-3}
			Fixed O&M in share of invest	2.50×10^{-2}
	Electric vehicles	Electric vehicles	Variable O&M in EUR/kWh	1.00×10^{-2}
	Electrolysis	Electrolyzer at cavern	Invest in EUR/kW	3.05×10^{2}
			Variable O&M in EUR/kWh	1.00×10^{-3}
Renewable fuels and geographical load balancing			Fixed O&M in share of invest	1.50×10^{-2}
	Electrolysis	Electrolyzer at local storage	Invest in EUR/kW	8.53×10^{2}
			Variable O&M in EUR/kWh	1.00×10^{-3}
			Fixed O&M in share of invest	2.00×10^{-2}
		Overhead lines	Invest in EUR/MWkm	3.75×10^{2}

	HVDC electricity transmission		Fixed O&M in share of invest	1.00×10^{-2}
		Underground cables	Invest in EUR/MWkm	2.00×10^{3}
		Sea cables	Invest in EUR/MWkm	9.75×10^{2}
Temporal load balancing	Energy storage	Hydro reservoir power plants[1]	Invest in EUR/kW	1.20×10^{3}
			Variable O&M in EUR/kWh	1.00×10^{-3}
			Fixed O&M in share of invest	5.00×10^{-2}
		Pumped hydro storage	Invest in EUR/kWh	1.00×10^{1}
			Fixed O&M in share of invest	5.00×10^{-2}
		Pumped hydro power converters	Invest in EUR/kW	4.50×10^{2}
			Variable O&M in EUR/kWh	1.00×10^{-3}
			Fixed O&M in share of invest	1.00×10^{-2}
		Vanadium-Redox-Flow battery storage	Invest in EUR/kWh	1.00×10^{2}
		Vanadium-Redox-Flow battery power converters	Invest in EUR/kW	6.30×10^{2}
			Variable O&M in EUR/kWh	1.00×10^{-3}
			Fixed O&M in share of invest	3.20×10^{-2}
		Lithium-Ion battery storage	Invest in EUR/kWh	1.50×10^{2}
		Lithium-Ion battery power converter	Invest in EUR/kW	5.00×10^{1}
			Variable O&M in EUR/kWh	1.00×10^{-3}
			Fixed O&M in share of invest	5.00×10^{-3}
		Pressure vessels for hydrogen storage	Invest in EUR/kWh_{ch}	2.10×10^{1}
			Fixed O&M in share of invest	2.00×10^{-2}
		Caverns for hydrogen storage	Invest in EUR/kWh_{ch}	0.61×10^{1}
			Fixed O&M in share of invest	3.00×10^{-2}

[1] REMix only considers the costs for the converter of hydro reservoir power plants. In case the capacity expansion is to be optimized, country-specific c-rates are assumed. Note, however, that in our study the capacities of hydro reservoir power plants are fixed at current capacities. Thus, no additional capacities can be built.

3 Life cycle indicators

We calculate technology-specific life cycle impacts that are assumed to be representative for the entire region Europe and North Africa (EUNA). Thus, no regional differentiation is made with respect to the environmental impact of the foreground technologies. The foreground LCI data are largely based on the data as they were also used in Junne, et al. [1] and supplemented with technologies that are additionally implemented in the ESOM REMix (such as electricity grid). For the supply of wood chips for the operation of biomass power plants as well as for the supply of natural gas, European reference data sets (RER) [2] are used.

Another difference to Reference [1] is the avoidance of double counting by the electricity generation from markets in the background LCI database that can be assigned to the EUNA regions in REMix (instead of avoiding double counting only for Germany as in Reference [1]): in order to avoid double counting in the background LCI database for the electricity sector, the regions studied in REMix are first matched with the corresponding electricity markets in the ecoinvent v.3.3 LCI database (Table S2).

Table S2. Matching of the regions in REMix with the electricity markets in ecoinvent.

Country nodes in REMix	Electrcitiy market in ecoinvent v.3.3 [and country code]	Country nodes in REMix	Electrcitiy market in ecoinvent v.3.3 [and country code]
Albania	-	Luxembourg	✓ [LU]
Algeria	-	Macedonia	✓ [MK]
Austria	✓ [AT]	Montenegro	-
Belgium	✓ [BE]	Morocco	-
Bosnia and Herzegovina	✓ [BA]	Netherlands	✓ [NL]
Bulgaria	✓ [BG]	Norway	✓ [NO]
Croatia	✓ [HR]	Poland	✓ [PL]
Czech Republic	✓ [CZ]	Portugual	✓ [PT]
Denmark	✓ [DK]	Romania	✓ [RO]
Estonia	✓ [EE]	Serbia	✓ [RS]
Finland	✓ [FI]	Slovakia	✓ [SK]
France	✓ [FR]	Slovenia	✓ [SI]
Greece	✓ [GR]	Spain	✓ [ES]
Hungary	✓ [HU]	Sweden	✓ [SE]
Ireland	✓ [IE]	Switzerland	✓ [CH]
Italy	✓ [IT]	Tunisia	-
Latvia	✓ [LV]	UK	✓ [GB]
Lithuania	✓ [LT]		

Subsequently, the corresponding supplier processes of electricity to these markets (e.g., electricity generation of a gas turbine) are deleted from these markets. Thus, in the corresponding ecoinvent v.3.3 LCI background database used for this study, electricity from the electricity markets that can be matched to the regions defined in REMix (see Table S2) is free of environmental impacts. Note that this approach is based on the simplifying assumption that the electricity in the markets of the LCI database serves the same sectors as the electricity in REMix. Furthermore, double counting is not avoided for each country node in REMix and the technologies deployed there, but for the entire modelling region and the corresponding representative technologies. The avoidance of double counting on a country-specific (i.e., ESM node-specific) basis would involve considerable effort in terms of manipulating the background LCI database and is outside the scope of the present study. However, future studies that manipulate the background LCI database with programmable methods (e.g., by using Brightway [3] and packages such as wurst [4]) to link LCI data to ESMs could further explore more accurate methods to avoid double counting in the background LCI database.

In the background LCI database used, the global electricity mix is adjusted to the 2°C scenario of Teske et al. [5]. By avoiding double counting for the regions listed in Table S2, the reference power plants used for modeling the electricity mixes have to be reselected compared to Reference [1] for the scenario regions Eurasia and OECD Europe. The selection of reference power plants for the scenario regions Eurasia and OECD Europe is based on the remaining electricity markets in ecoinvent that are assigned to the scenario regions Eurasia and OECD Europe and the corresponding power plants. The selection of the reference power plants follows the method described in Reference [1].

The composition of the electricity mixes for Eurasia and OECD Europe of the 2°C background scenario for the 2050 used in this study is shown in Table S3. The electricity mix of the other background scenario regions remains unchanged compared to Reference [1].

The environmental impacts of the individual technologies as inputs for REMix are listed in Table S4.

Table S3. Electricity mix in 2050 in the background LCI database for Eurasia and OECD Europe.

Scenario region	Electricity market composition	Assigned markets in ecoinvent v.3.3	2050 shares of the 2°C background scenario
Eurasia	electricity production CSP mix, electricity high voltage, cut-off, U - GLO	CY, MT, RU, UA	0.0266
	electricity production, deep geothermal | electricity, high voltage | cut-off, U - RU		0.0652
	electricity production, hard coal | electricity, high voltage | cut-off, U - UA		0.0000
	electricity production, hydro, pumped storage | electricity, high voltage | cut-off, U - RU		0.0006
	electricity production, hydro, pumped storage | electricity, high voltage | cut-off, U - UA		0.0004
	electricity production, hydro, reservoir, non-alpine region | electricity, high voltage | cut-off, U - RU		0.0180
	electricity production, hydro, run-of-river | electricity, high voltage | cut-off, U - RU		0.0549
	electricity production, hydro, run-of-river | electricity, high voltage | cut-off, U - UA		0.0079
	electricity production, hydrogen, combined cycle power plant | electricity, high voltage | cut-off, U - RoW		0.0210
	electricity production, lignite | electricity, high voltage | cut-off, U - RoW		0.0000
	electricity production, natural gas, combined cycle power plant | electricity, high voltage | cut-off, U - RU		0.0000
	electricity production, natural gas, combined cycle power plant | electricity, high voltage | cut-off, U - UA		0.0000
	electricity production, natural gas, conventional power plant | electricity, high voltage | cut-off, U - RU		0.0000
	electricity production, natural gas, conventional power plant | electricity, high voltage | cut-off, U - UA		0.0000
	electricity production, nuclear, boiling water reactor | electricity, high voltage | cut-off, U - RU		0.0000
	electricity production, nuclear, pressure water reactor | electricity, high voltage | cut-off, U - RU		0.0000
	electricity production, nuclear, pressure water reactor | electricity, high voltage | cut-off, U - UA		0.0000
	electricity production, nuclear, pressure water reactor, heavy water moderated | electricity, high voltage | cut-off, U - RU		0.0000
	electricity production, oil | electricity, high voltage | cut-off, U - CY		0.0000
	electricity production, oil | electricity, high voltage | cut-off, U - MT		0.0000
	electricity production, oil | electricity, high voltage | cut-off, U - RU		0.0000
	electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted | electricity, low voltage | cut-off, U - CY		0.0214
	electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted | electricity, low voltage | cut-off, U - MT		0.0280
	electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted | electricity, low voltage | cut-off, U - UA		0.0080
	electricity production, photovoltaic, 3kWp slanted-roof installation, single-Si, panel, mounted | electricity, low voltage | cut-off, U - CY		0.0175
	electricity production, photovoltaic, 3kWp slanted-roof installation, single-Si, panel, mounted | electricity, low voltage | cut-off, U - MT		0.0229
	electricity production, photovoltaic, 3kWp slanted-roof installation, single-Si, panel, mounted | electricity, low voltage | cut-off, U - UA		0.0066
	electricity production, photovoltaic, 570kWp open ground installation, multi-Si | electricity, low voltage | cut-off, U - RoW		0.1044
	electricity production, wind, <1MW turbine, onshore | electricity, high voltage | cut-off, U - CY		0.0085
	electricity production, wind, <1MW turbine, onshore | electricity, high voltage | cut-off, U - RU		0.0037
	electricity production, wind, <1MW turbine, onshore | electricity, high voltage | cut-off, U - UA		0.0164
	electricity production, wind, >3MW turbine, onshore | electricity, high voltage | cut-off, U - UA		0.0235
	electricity production, wind, 1-3MW turbine, offshore | electricity, high voltage | cut-off, U - UA		0.1267
	electricity production, wind, 1-3MW turbine, onshore | electricity, high voltage | cut-off, U - CY		0.1279
	electricity production, wind, 1-3MW turbine, onshore | electricity, high voltage | cut-off, U - UA		0.1373
	heat and power co-generation, hard coal | electricity, high voltage | cut-off, U - RU		0.0000
	heat and power co-generation, hydrogen, combined cycle power plant, 400MW electrical | electricity, high voltage | cut-off, U - RoW		0.0651
	heat and power co-generation, lignite | electricity, high voltage | cut-off, U - RU		0.0000
	heat and power co-generation, natural gas, combined cycle power plant, 400MW electrical | electricity, high voltage | cut-off, U - RU		0.0000
	heat and power co-generation, natural gas, conventional power plant, 100MW electrical | electricity, high voltage | cut-off, U - RU		0.0000
	heat and power co-generation, natural gas, conventional power plant, 100MW electrical | electricity, high voltage | cut-off, U - UA		0.0000
	heat and power co-generation, oil | electricity, high voltage | cut-off, U - RU		0.0000
	heat and power co-generation, oil | electricity, high voltage | cut-off, U - UA		0.0000

	heat and power co-generation, wood chips, 6667 kW ǀ electricity, high voltage ǀ cut-off, U - RU		0.0191
	heat and power co-generation, wood chips, 6667 kW ǀ electricity, high voltage ǀ cut-off, U - UA		0.0474
	heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014 ǀ electricity, high voltage ǀ cut-off, U - CY		0.0212
OECD Europe	electricity production CSP mix, electricity high voltage, cut-off, U - GLO	IS, TR	0.0386
	electricity production, deep geothermal ǀ electricity, high voltage ǀ cut-off, U - IS		0.0266
	electricity production, deep geothermal ǀ electricity, high voltage ǀ cut-off, U - TR		0.0000
	electricity production, hard coal ǀ electricity, high voltage ǀ cut-off, U - TR		0.0000
	electricity production, hydro, reservoir, non-alpine region ǀ electricity, high voltage ǀ cut-off, U - IS		0.0205
	electricity production, hydro, reservoir, non-alpine region ǀ electricity, high voltage ǀ cut-off, U - TR		0.0482
	electricity production, hydro, run-of-river ǀ electricity, high voltage ǀ cut-off, U - TR		0.0482
	electricity production, hydrogen, combined cycle power plant ǀ electricity, high voltage ǀ cut-off, U - RoW		0.0132
	electricity production, lignite ǀ electricity, high voltage ǀ cut-off, U - TR		0.0000
	electricity production, natural gas, combined cycle power plant ǀ electricity, high voltage ǀ cut-off, U - TR		0.0000
	electricity production, natural gas, conventional power plant ǀ electricity, high voltage ǀ cut-off, U - TR		0.0000
	electricity production, nuclear, pressure water reactor ǀ electricity, high voltage ǀ cut-off, U - RoW		0.0000
	electricity production, oil ǀ electricity, high voltage ǀ cut-off, U - IS		0.0000
	electricity production, oil ǀ electricity, high voltage ǀ cut-off, U - TR		0.0000
	electricity production, photovoltaic, 3kWp slanted-roof installation, multi-Si, panel, mounted ǀ electricity, low voltage ǀ cut-off, U - RoW		0.0646
	electricity production, photovoltaic, 3kWp slanted-roof installation, single-Si, panel, mounted ǀ electricity, low voltage ǀ cut-off, U - RoW		0.0483
	electricity production, photovoltaic, 570kWp open ground installation, multi-Si ǀ electricity, low voltage ǀ cut-off, U - RoW		0.1129
	electricity production, wind, <1MW turbine, onshore ǀ electricity, high voltage ǀ cut-off, U - TR		0.0208
	electricity production, wind, >3MW turbine, onshore ǀ electricity, high voltage ǀ cut-off, U - TR		0.0404
	electricity production, wind, 1-3MW turbine, offshore ǀ electricity, high voltage ǀ cut-off, U - RoW		0.1585
	electricity production, wind, 1-3MW turbine, onshore ǀ electricity, high voltage ǀ cut-off, U - TR		0.2331
	heat and power co-generation, biogas, gas engine ǀ electricity, high voltage ǀ cut-off, U - TR		0.0890
	heat and power co-generation, hard coal ǀ electricity, high voltage ǀ cut-off, U - RoW		0.0000
	heat and power co-generation, hydrogen, combined cycle power plant, 400MW electrical ǀ electricity, high voltage ǀ cut-off, U - RoW		0.0320
	heat and power co-generation, lignite ǀ electricity, high voltage ǀ cut-off, U - RoW		0.0000
	heat and power co-generation, natural gas, combined cycle power plant, 400MW electrical ǀ electricity, high voltage ǀ cut-off, U - TR		0.0000
	heat and power co-generation, natural gas, conventional power plant, 100MW electrical ǀ electricity, high voltage ǀ cut-off, U - TR		0.0000
	heat and power co-generation, oil ǀ electricity, high voltage ǀ cut-off, U - TR		0.0000
	heat and power co-generation, wood chips, 6667 kW ǀ electricity, high voltage ǀ cut-off, U - TR		0.0053

Table S4. Technology-specific life cycle environmental impacts following the ILCD 2.0 2018 methodology [6].

Technology specification	Impact type	Climate change (kg CO_2 eq)	Freshwater and terrestrial acidification (mol H+ eq)	Freshwater ecotoxicity (CTUe)	Freshwater eutrophication (kg P eq)	Marine eutrophication (kg N eq)	Terrestrial eutrophication (mol N eq)	Carcinogenic effects (CTUh)	Ionising radiation (kg U235 eq)	Non-carcinogenic effects (CTUh)	Ozone layer depletion (kg CFC-11 eq)	Photochemical ozone creation (kg NMVOC eq)	Respiratory effects, inorganics (disease incidence)	Dissipated water (m³ water eq)	Fossils (incl. uranium) (MJ)	Land use (points)	Minerals and metals (kg Sb eq)
Biomass power plants	Impact/GW	3.45×10^{8}	2.56×10^{6}	6.65×10^{8}	2.70×10^{5}	4.52×10^{5}	4.79×10^{6}	4.45×10^{1}	5.73×10^{6}	1.34×10^{2}	2.67×10^{1}	1.86×10^{6}	3.55×10^{1}	1.04×10^{8}	4.07×10^{9}	4.52×10^{9}	4.29×10^{3}
	Impact/GWh	2.33×10^{5}	9.17×10^{2}	2.49×10^{4}	1.42×10^{1}	4.27×10^{2}	4.71×10^{3}	2.97×10^{-4}	1.82×10^{3}	1.69×10^{-3}	6.91×10^{-3}	1.26×10^{3}	3.16×10^{-3}	2.93×10^{3}	4.29×10^{5}	1.53×10^{8}	5.93×10^{-2}
Geothermal power plants	Impact/GW	7.54×10^{9}	3.97×10^{7}	2.48×10^{10}	3.01×10^{6}	7.81×10^{6}	8.69×10^{7}	9.55×10^{2}	1.23×10^{8}	2.89×10^{3}	8.01×10^{2}	3.20×10^{7}	5.32×10^{2}	3.92×10^{9}	8.87×10^{10}	2.84×10^{11}	5.55×10^{4}
	Impact/GWh	2.39×10^{4}	1.26×10^{2}	7.89×10^{4}	9.57×10^{1}	2.48×10^{1}	2.76×10^{2}	3.03×10^{-3}	3.91×10^{2}	9.18×10^{-3}	2.54×10^{-3}	1.03×10^{2}	1.69×10^{-3}	1.24×10^{4}	2.82×10^{5}	9.01×10^{5}	1.76×10^{-1}
SOFC fuel cell	Impact/GW	6.12×10^{7}	7.98×10^{5}	1.67×10^{8}	5.38×10^{4}	7.87×10^{4}	8.99×10^{5}	1.08×10^{1}	1.24×10^{6}	2.50×10^{1}	6.79×10^{1}	3.25×10^{5}	5.26×10^{1}	2.52×10^{7}	7.75×10^{8}	8.99×10^{8}	2.17×10^{3}
	Impact/GWh	2.25×10^{3}	3.41×10^{1}	6.04×10^{3}	6.62×10^{-1}	9.27×10^{1}	1.15×10^{2}	4.40×10^{-4}	7.68×10^{1}	4.45×10^{-4}	4.90×10^{-4}	2.71×10^{1}	1.90×10^{-4}	6.82×10^{3}	3.56×10^{4}	3.42×10^{4}	3.16×10^{-2}
Wind energy converters (Onshore)	Impact/GW	6.84×10^{8}	7.58×10^{6}	1.77×10^{9}	1.05×10^{6}	1.11×10^{6}	1.04×10^{7}	8.52×10^{1}	1.24×10^{7}	4.80×10^{2}	5.70×10^{1}	3.76×10^{6}	6.77×10^{1}	2.97×10^{8}	8.31×10^{9}	1.14×10^{10}	2.25×10^{4}
	Impact/GWh	1.34×10^{2}	4.86×10^{-1}	6.27×10^{1}	1.19×10^{-2}	5.57×10^{-2}	6.09×10^{-1}	9.14×10^{-7}	1.54×10^{1}	6.77×10^{-6}	5.84×10^{-5}	7.47×10^{-1}	2.90×10^{-6}	6.08×10^{1}	3.53×10^{3}	4.31×10^{2}	2.68×10^{-4}
Wind energy converters (Offshore)	Impact/GW	6.45 × 108	4.66 × 106	1.93 × 109	4.43 × 105	8.69 × 105	7.82 × 106	1.36×10^{2}	9.06 × 106	3.39×10^{2}	4.30 × 101	2.83 × 106	5.21 × 101	3.54 × 108	7.95 × 109	5.79 × 109	2.16 × 104
	Impact/GWh	1.57×10^{2}	5.69×10^{-1}	7.33×10^{1}	1.40×10^{-2}	6.52×10^{-2}	7.13×10^{-1}	1.07×10^{-6}	1.81×10^{1}	7.92×10^{-6}	6.83×10^{-5}	8.74×10^{-1}	3.39×10^{-6}	7.11×10^{1}	4.13×10^{3}	5.05×10^{2}	3.14×10^{-4}
Multi-Si photovoltaic (open ground)	Impact/GW	1.43×10^{9}	1.18×10^{7}	2.72×10^{9}	8.80×10^{5}	1.84×10^{6}	1.99×10^{7}	6.80×10^{1}	2.05×10^{7}	4.46×10^{2}	9.83×10^{1}	5.64×10^{6}	1.02×10^{2}	5.38×10^{8}	1.55×10^{10}	1.86×10^{11}	6.88×10^{4}
	Impact/GWh	1.80×10^{-2}	$1.7 6 \times 10^{-4}$	1.51×10^{-1}	3.60×10^{-5}	7.08×10^{-4}	4.63×10^{-4}	4.56×10^{-9}	2.57×10^{-4}	5.95×10^{-8}	1.84×10^{-9}	9.45×10^{-5}	1.72×10^{-9}	3.68×10^{-1}	1.96×10^{-1}	4.05×10^{-1}	1.28×10^{-7}
Single-Si photovoltaic (open ground)	Impact/GW	1.66×10^{9}	1.25×10^{7}	2.75×10^{9}	8.56×10^{5}	2.34×10^{6}	2.22×10^{7}	6.76×10^{1}	2.08×10^{7}	4.61×10^{2}	1.20×10^{2}	6.43×10^{6}	1.08×10^{2}	5.91×10^{8}	1.76×10^{10}	1.92×10^{11}	5.53×10^{4}
	Impact/GWh	1.80×10^{-2}	1.76×10^{-4}	1.51×10^{-1}	3.60×10^{-5}	7.08×10^{-4}	4.63×10^{-4}	4.56×10^{-9}	2.57×10^{-4}	5.95×10^{-8}	1.84×10^{-9}	9.45×10^{-5}	1.72×10^{-9}	3.68×10^{-1}	1.96×10^{-1}	4.05×10^{-1}	1.28×10^{-7}
Multi-Si photovoltaic (rooftop)	Impact/GW	1.28×10^{9}	1.31×10^{7}	1.62×10^{9}	1.41×10^{6}	1.91×10^{6}	1.91×10^{7}	4.62×10^{1}	2.07×10^{7}	5.06×10^{2}	1.05×10^{2}	5.67×10^{6}	9.02×10^{1}	4.85×10^{8}	1.45×10^{10}	2.54×10^{10}	8.86×10^{4}
	Impact/GWh	3.43×10^{1}	3.35×10^{-2}	2.87×10^{1}	6.85×10^{-3}	1.34×10^{-1}	8.80×10^{-2}	8.66×10^{-7}	4.88×10^{-2}	1.13×10^{-5}	3.50×10^{-7}	1.80×10^{-2}	3.26×10^{-7}	6.99×10^{1}	3.73×10^{1}	7.69×10^{1}	2.43×10^{-5}
Single-Si photovoltaic (rooftop)	Impact/GW	1.57×10^{9}	1.42×10^{7}	1.74×10^{9}	1.41×10^{6}	2.47×10^{6}	2.21×10^{7}	5.26×10^{1}	2.24×10^{7}	5.40×10^{2}	1.33×10^{2}	6.66×10^{6}	1.02×10^{2}	5.61×10^{8}	1.70×10^{10}	3.57×10^{10}	7.62×10^{4}
	Impact/GWh	3.32×10^{1}	3.24×10^{-2}	2.78×10^{1}	6.63×10^{-3}	1.30×10^{-1}	8.52×10^{-2}	8.39×10^{-7}	4.73×10^{-2}	1.09×10^{-5}	3.39×10^{-7}	1.74×10^{-2}	3.16×10^{-7}	6.77×10^{1}	3.61×10^{1}	7.44×10^{1}	2.36×10^{-5}
Run of river power plants	Impact/GW	8.76×10^{8}	4.53×10^{6}	1.31×10^{9}	2.43×10^{5}	1.34×10^{6}	1.48×10^{7}	9.54×10^{1}	2.09×10^{7}	2.17×10^{2}	8.63×10^{1}	4.55×10^{6}	9.82×10^{1}	1.57×10^{8}	8.05×10^{9}	9.24×10^{9}	4.43×10^{3}
	Impact/GWh	2.07×10^{1}	7.47×10^{-2}	9.64×10^{1}	1.84×10^{-3}	8.57×10^{-3}	9.38×10^{-2}	1.41×10^{-7}	2.37×10^{1}	1.04×10^{-6}	8.98×10^{-6}	1.15×10^{-1}	4.46×10^{-7}	9.35×10^{-1}	5.43×10^{2}	6.63×10^{1}	4.12×10^{-5}
Lignite-fired power plants	Impact/GW	5.25×10^{8}	4.15×10^{6}	8.57×10^{8}	3.58×10^{5}	8.31×10^{5}	8.89×10^{6}	5.65×10^{1}	1.04×10^{7}	1.77×10^{2}	4.62×10^{1}	3.11×10^{6}	6.27×10^{1}	1.32×10^{8}	6.25×10^{9}	6.55×10^{9}	5.60×10^{3}
	Impact/GWh	1.21×10^{6}	1.86×10^{3}	1.89×10^{5}	2.91×10^{3}	9.22×10^{2}	3.65×10^{3}	6.62×10^{-3}	1.41×10^{3}	5.39×10^{-2}	1.65×10^{-3}	9.41×10^{2}	2.63×10^{-3}	1.02×10^{5}	1.51×10^{7}	4.34×10^{5}	5.57×10^{-2}
Open cycle gas turbines	Impact/GW	5.48×10^{7}	6.88×10^{5}	7.83×10^{7}	7.43×10^{4}	1.09×10^{5}	1.12×10^{6}	2.69×10^{1}	1.16×10^{6}	2.73×10^{1}	4.57×10^{1}	3.49×10^{5}	6.80×10^{1}	1.14×10^{7}	7.03×10^{8}	2.24×10^{9}	1.50×10^{3}
	Impact/GWh	7.93×10^{5}	1.98×10^{3}	9.46×10^{4}	4.08×10^{1}	3.80×10^{2}	4.06×10^{3}	1.16×10^{-3}	6.69×10^{3}	6.50×10^{-3}	1.62×10^{-1}	1.39×10^{3}	9.10×10^{-3}	4.07×10^{4}	1.24×10^{7}	3.87×10^{5}	7.81×10^{-2}
	Impact/GW	1.63×10^{8}	1.68×10^{6}	3.00×10^{8}	1.35×10^{5}	3.06×10^{5}	3.24×10^{6}	1.88×10^{1}	3.53×10^{6}	6.31×10^{1}	1.44×10^{1}	1.04×10^{6}	2.13×10^{1}	3.28×10^{7}	2.11×10^{9}	2.33×10^{9}	2.92×10^{3}

Combined cycle gas turbines	Impact/GWh (gas)	4.75×10^{5}	1.11×10^{3}	5.90×10^{4}	2.54×10^{1}	1.76×10^{2}	1.86×10^{3}	7.29×10^{-4}	4.16×10^{3}	4.34×10^{-3}	1.01×10^{-1}	7.08×10^{2}	5.63×10^{-3}	2.97×10^{4}	7.72×10^{6}	2.41×10^{5}	4.86×10^{-2}
	Impact/GWh (H_2)	1.87×10^{3}	1.20×10^{2}	1.86×10^{1}	2.45×10^{-3}	6.33×10^{1}	6.93×10^{2}	8.29×10^{-7}	1.68×10^{-1}	2.07×10^{-6}	8.79×10^{-7}	1.63×10^{2}	3.49×10^{-5}	6.18×10^{3}	9.69×10^{1}	1.40×10^{2}	6.08×10^{-5}
Nuclear power plants	Impact/GW	2.95×10^{8}	2.50×10^{6}	9.23×10^{8}	2.12×10^{5}	4.26×10^{5}	4.56×10^{6}	6.59×10^{1}	6.61×10^{6}	1.46×10^{2}	3.14×10^{1}	1.52×10^{6}	3.00×10^{1}	1.05×10^{8}	3.41×10^{9}	1.16×10^{10}	6.43×10^{3}
	Impact/GWh	5.21×10^{3}	4.47×10^{1}	1.92×10^{4}	2.11×10^{1}	4.89×10^{1}	1.25×10^{2}	3.19×10^{-4}	6.31×10^{5}	2.64×10^{-3}	5.19×10^{-2}	3.51×10^{1}	2.40×10^{-3}	1.46×10^{5}	1.26×10^{7}	7.83×10^{4}	4.28×10^{-2}
Hard coal-fired power plants	Impact/GW	3.45×10^{8}	2.56×10^{6}	6.65×10^{8}	2.70×10^{5}	4.52×10^{5}	4.79×10^{6}	4.45×10^{1}	5.73×10^{6}	1.34×10^{2}	2.67×10^{1}	1.86×10^{6}	3.55×10^{1}	1.04×10^{8}	4.07×10^{9}	4.52×10^{9}	4.29×10^{3}
	Impact/GWh	1.11×10^{6}	1.49×10^{3}	3.73×10^{4}	1.43×10^{2}	2.89×10^{2}	2.87×10^{3}	1.10×10^{-3}	1.23×10^{3}	3.99×10^{-2}	1.37×10^{-3}	7.79×10^{2}	1.97×10^{-3}	7.06×10^{4}	1.63×10^{7}	2.27×10^{6}	5.13×10^{-2}
CSP-Steam turbine,	Impact/GW	4.08×10^{8}	3.32×10^{6}	5.82×10^{8}	2.88×10^{5}	4.71×10^{5}	4.64×10^{6}	3.02×10^{1}	7.95×10^{6}	1.10×10^{2}	2.23×10^{1}	1.68×10^{6}	2.76×10^{1}	2.19×10^{8}	6.63×10^{9}	3.80×10^{9}	6.40×10^{3}
thermal energy storage,	Impact/GWhth	2.78×10^{7}	1.89×10^{5}	3.49×10^{7}	7.24×10^{3}	3.40×10^{4}	3.75×10^{5}	1.22×10^{1}	4.07×10^{5}	3.54×10^{1}	2.63×10^{1}	1.22×10^{5}	1.78×10^{1}	4.43×10^{6}	2.95×10^{8}	2.57×10^{8}	7.40×10^{1}
solar field,	Impact/GWth	2.45×10^{8}	2.66×10^{6}	5.30×10^{8}	9.69×10^{4}	6.89×10^{5}	7.11×10^{6}	2.64×10^{1}	3.56×10^{6}	6.29×10^{1}	2.95×10^{1}	2.15×10^{6}	2.54×10^{1}	1.27×10^{8}	3.13×10^{9}	3.58×10^{10}	1.78×10^{3}
and operation	Impact/GWh	1.44×10^{3}	3.77×10^{1}	4.49×10^{3}	3.59×10^{-1}	1.15×10^{1}	1.14×10^{2}	2.84×10^{-5}	2.08×10^{1}	2.18×10^{-4}	4.24×10^{-4}	2.91×10^{1}	1.89×10^{-4}	1.74×10^{3}	2.40×10^{4}	1.85×10^{4}	1.39×10^{-2}
Electrolyzer	Impact/GW	1.73×10^{8}	2.77×10^{7}	6.81×10^{8}	5.81×10^{5}	3.83×10^{5}	4.13×10^{6}	5.36×10^{1}	6.24×10^{6}	1.54×10^{2}	1.67×10^{2}	2.67×10^{6}	3.69×10^{1}	4.92×10^{7}	2.11×10^{9}	3.11×10^{9}	1.50×10^{4}
	Impact/GWhch	3.90×10^{2}	1.52×10^{1}	3.36×10^{2}	2.41×10^{-2}	2.11×10^{-1}	2.25×10^{1}	2.12×10^{-5}	9.74×10^{1}	8.36×10^{-5}	6.99×10^{-5}	8.40×10^{-1}	1.50×10^{-5}	1.01×10^{2}	5.78×10^{3}	1.18×10^{3}	8.27×10^{-4}
Overhead lines	Impact/GWkm	5.86×10^{5}	3.66×10^{3}	6.78×10^{5}	1.88×10^{2}	5.68×10^{2}	5.98×10^{3}	3.95×10^{-2}	9.40×10^{3}	2.74×10^{-1}	3.07×10^{-2}	2.09×10^{3}	3.93×10^{-2}	1.36×10^{5}	6.33×10^{6}	2.97×10^{6}	1.22×10^{1}
Underground cables	Impact/GWkm	2.52×10^{5}	1.45×10^{4}	1.79×10^{6}	2.38×10^{3}	1.66×10^{3}	1.56×10^{4}	1.44×10^{-2}	1.51×10^{4}	9.53×10^{-1}	6.24×10^{-2}	4.53×10^{3}	7.15×10^{-2}	1.05×10^{5}	4.75×10^{6}	8.82×10^{6}	1.29×10^{2}
Sea cables	Impact/GWkm	2.27×10^{5}	1.18×10^{4}	1.76×10^{6}	1.77×10^{3}	8.89×10^{2}	9.10×10^{3}	3.88×10^{-2}	1.11×10^{4}	8.66×10^{-1}	4.94×10^{-2}	2.49×10^{3}	5.26×10^{-2}	1.02×10^{5}	4.20×10^{6}	8.82×10^{6}	1.40×10^{2}
Hydro reservoir power plants, converter, and operation[1]	Impact/GW	1.81×10^{8}	6.85×10^{5}	9.23×10^{7}	5.47×10^{4}	1.58×10^{5}	1.75×10^{6}	1.03×10^{1}	2.21×10^{6}	2.14×10^{1}	7.27×10^{1}	4.71×10^{5}	5.14×10^{1}	9.79×10^{6}	8.50×10^{8}	9.84×10^{8}	1.12×10^{3}
	Impact/GWh	3.06×10^{2}	5.53×10^{-3}	7.28×10^{-1}	1.42×10^{-4}	6.30×10^{-4}	6.91×10^{-3}	1.09×10^{-8}	1.82×10^{-1}	8.07×10^{-8}	6.88×10^{-7}	4.21×10^{-2}	3.27×10^{-8}	6.95×10^{1}	4.16×10^{1}	5.44×10^{1}	3.20×10^{-6}
Pumped hydro power storage, converter, and operation	Impact/GWh	2.37×10^{7}	9.59×10^{4}	2.56×10^{7}	5.20×10^{3}	2.85×10^{4}	3.18×10^{5}	1.46×10^{1}	4.69×10^{5}	3.87×10^{1}	1.79×10^{1}	9.73×10^{4}	2.53×10^{1}	2.94×10^{6}	1.85×10^{8}	1.95×10^{8}	7.51×10^{1}
	Impact/GW	1.81×10^{8}	6.85×10^{5}	9.23×10^{7}	5.47×10^{4}	1.58×10^{5}	1.75×10^{6}	1.03×10^{1}	2.21×10^{6}	2.14×10^{1}	7.27×10^{1}	4.71×10^{5}	5.14×10^{1}	9.79×10^{6}	8.50×10^{8}	9.84×10^{8}	1.12×10^{3}
	Impact/GWh	3.06×10^{2}	5.53×10^{-3}	7.28×10^{-1}	1.42×10^{-4}	6.30×10^{-4}	6.91×10^{-3}	1.09×10^{-8}	1.82×10^{-1}	8.07×10^{-8}	6.88×10^{-7}	4.21×10^{-2}	3.27×10^{-8}	6.95×10^{1}	4.16×10^{1}	5.44×10^{1}	3.20×10^{-6}
Vanadium-Redox-Flow battery storage, and converter	Impact/GWh	1.26×10^{8}	3.63×10^{6}	1.24×10^{9}	4.29×10^{4}	1.69×10^{5}	1.74×10^{6}	8.99×10^{1}	5.10×10^{6}	9.78×10^{2}	8.02×10^{1}	7.91×10^{5}	4.84×10^{1}	1.03×10^{8}	2.55×10^{9}	1.52×10^{9}	1.17×10^{3}
	Impact/GW	2.07×10^{8}	6.03×10^{5}	1.65×10^{8}	1.05×10^{5}	6.56×10^{5}	8.55×10^{5}	3.51×10^{1}	9.84×10^{5}	3.42×10^{1}	3.24×10^{3}	3.38×10^{5}	4.43×10^{1}	3.49×10^{7}	1.05×10^{9}	1.09×10^{9}	5.72×10^{3}
Lithium-Ion battery storage	Impact/GWh	2.44×10^{8}	1.83×10^{6}	3.72×10^{8}	1.34×10^{5}	1.72×10^{5}	2.05×10^{6}	1.48×10^{1}	3.34×10^{6}	5.50×10^{1}	8.44×10^{2}	7.10×10^{5}	1.25×10^{1}	8.55×10^{7}	2.90×10^{9}	2.33×10^{9}	5.22×10^{3}

Pressure vessels for hydrogen storage	Impact/GWhch	2.04×10^{6}	7.35×10^{3}	7.60×10^{5}	5.71×10^{1}	1.42×10^{3}	1.16×10^{4}	1.83×10^{-2}	1.52×10^{4}	7.07×10^{-2}	2.20×10^{-1}	3.54×10^{3}	6.26×10^{-2}	3.22×10^{5}	3.23×10^{7}	1.58×10^{6}	1.50×10^{1}
Caverns for hydrogen storage[2]	Impact/GWhch	0.00×10^{1}	0.00×10^{1}	0.00×10^{1}	0.00×10^{1}	0.00×10^{1}	0.00×10^{1}	0.00×10^{1}	0.00×10^{1}	0.00×10^{1}	0.00×10^{1}	0.00×10^{1}	0.00×10^{1}	0.00×10^{1}	0.00×10^{1}	0.00×10^{1}	0.00×10^{1}

[1] Due to the high level of data uncertainty in the LCI data for this type of power plant (as for hydropower in general), only the converter capacity is assigned with environmental impacts (corresponding to the impacts of the pumped hydro power converter). Note that this power plant type cannot be additionally expanded in the model setup used in our study. The power plant park would therefore not change if the model node-specific storage capacities were also assigned with environmental impacts. However, the environmental impact of the entire power system would be higher. [2] For the construction of the cavern storage in Benitez et al. [7], only electricity and non-dissipative water is assumed as an input for the drilling and the extraction of the brine. Since the electricity production is already accounted for in the foreground system, the cavern storage is assumed to be emission-free to avoid double counting of impacts.

References

1. Junne, T.; Simon, S.; Buchgeister, J.; Saiger, M.; Baumann, M.; Haase, M.; Wulf, C.; Naegler, T. Environmental Sustainability Assessment of Multi-Sectoral Energy Transformation Pathways: Methodological Approach and Case Study for Germany. **2020**, *12*, 8225.
2. Wernet, G.; Bauer, C.; Steubing, B.; Reinhard, J.; Moreno-Ruiz, E.; Weidema, B. The ecoinvent database version 3 (part I): overview and methodology. *The International Journal of Life Cycle Assessment* **2016**, *21*, 1218-1230, doi:10.1007/s11367-016-1087-8.
3. Mutel, C. Brightway: An open source framework for Life Cycle Assessment. *Journal of Open Source Software* **2017**, *2*, 236, doi:10.21105/joss.00236.
4. Cox, B.; Mutel, C.; Beltran, A.M.; Vuuren, D.v. Using integrated assessment model results to develop background databases for prospective LCA. http://lcm-conferences.org/wp-content/uploads/2017/presentations/Monday/MO-102/1_LCI%20of%20future%20mobility%20technologies.pdf: 2017.
5. Teske, S.; Pregger, T.; Simon, S.; Naegler, T.; Schmid, S.; Meinshausen, M. *Achieving the Paris Climate Agreement Goals - Global and Regional 100% Renewable Energy Scenarios with Non-energy GHG Pathways for +1.5°C and +2°C*; Springer International Publishing: 2019; https://doi.org/10.1007/978-3-030-05843-2.
6. EC-JRC. *Supporting information to the characterisation factors of recommended EF Life Cycle Impact Assessment method*; https://eplca.jrc.ec.europa.eu/permalink/supporting_Information_final.pdf, 2018.
7. Benitez, A.; Wulf, C.; de Palmenaer, A.; Lengersdorf, M.; Röding, T.; Grube, T.; Robinius, M.; Stolten, D.; Kuckshinrichs, W. Ecological assessment of fuel cell electric vehicles with special focus on type IV carbon fiber hydrogen tank. *Journal of Cleaner Production* **2021**, *278*, 123277, doi:https://doi.org/10.1016/j.jclepro.2020.123277.