Supplementary Information for Das et al., 2024

FIGURES

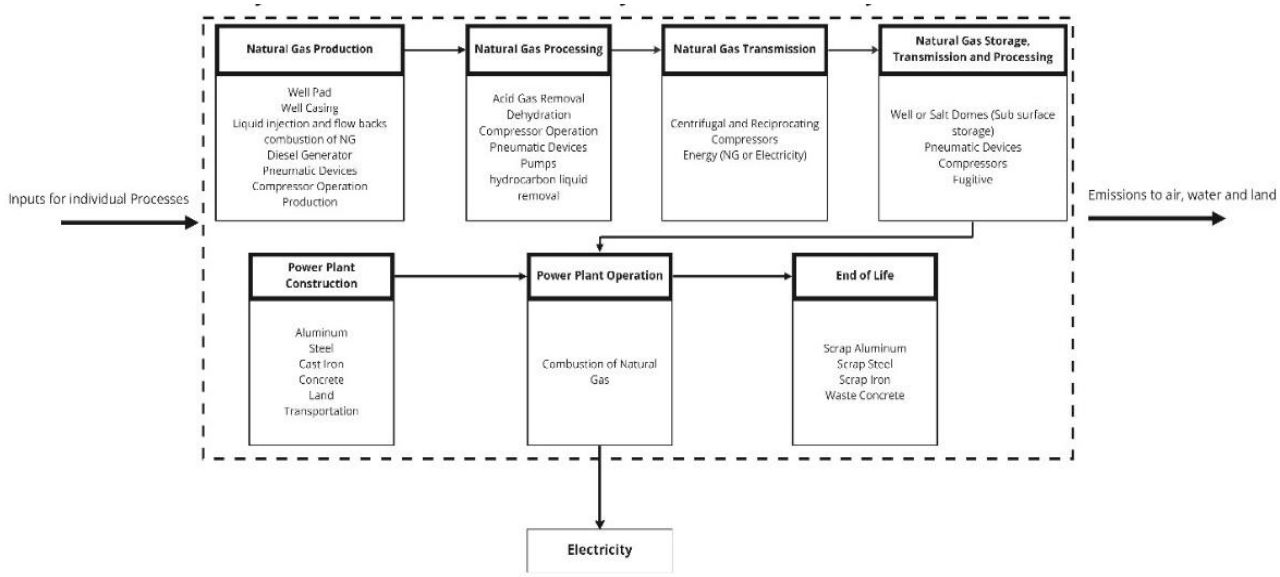


Figure S1. System boundary of the CCGT plant under study

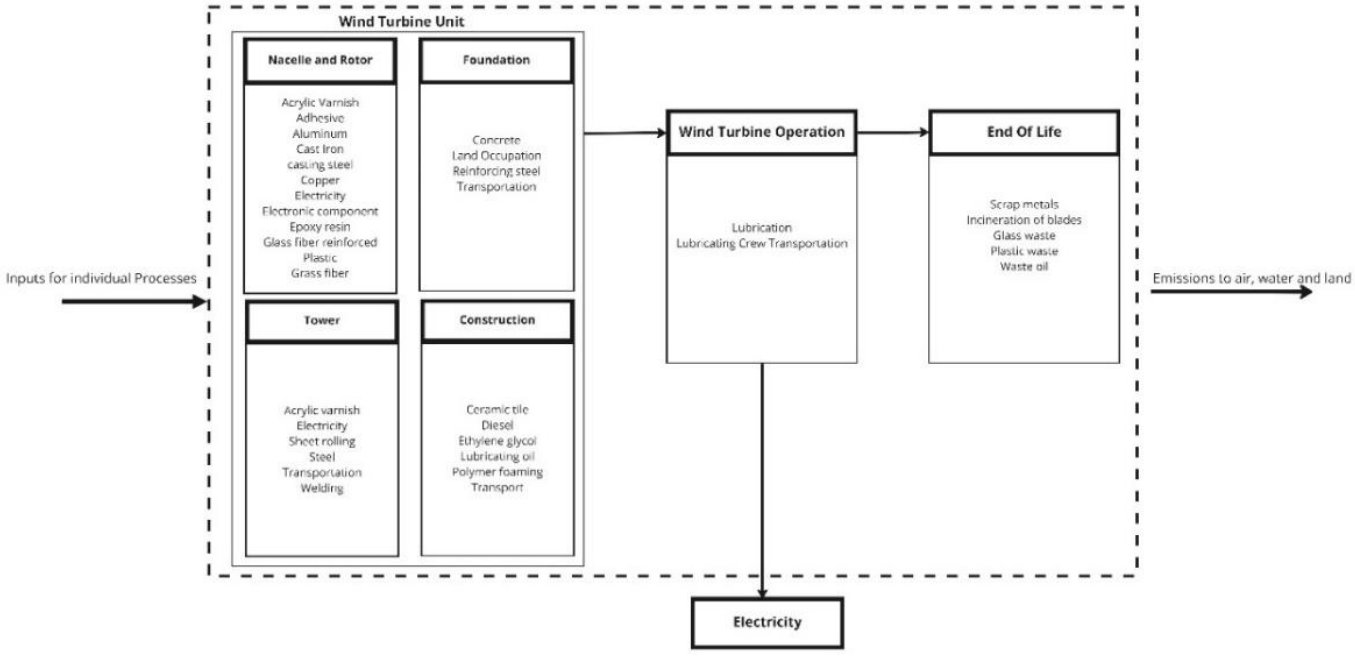


Figure S2. System boundary of the wind turbine under study

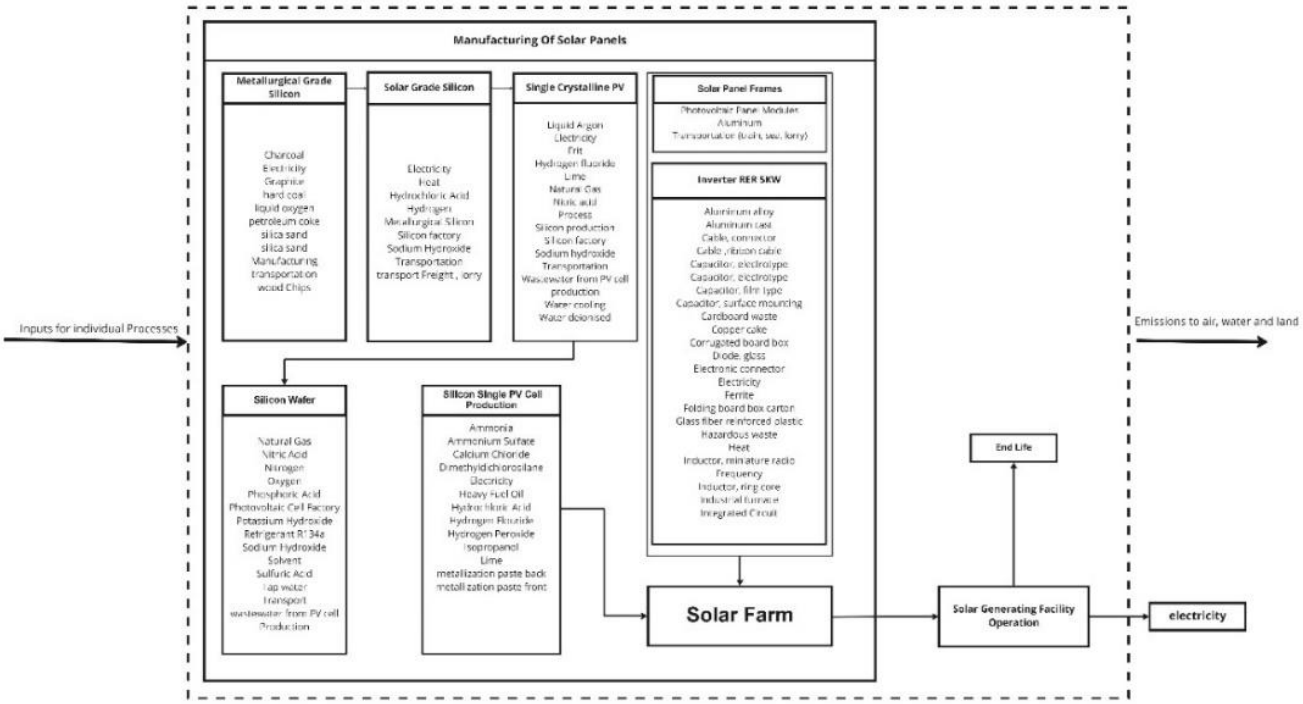


Figure S3. System boundary of the PV system under study

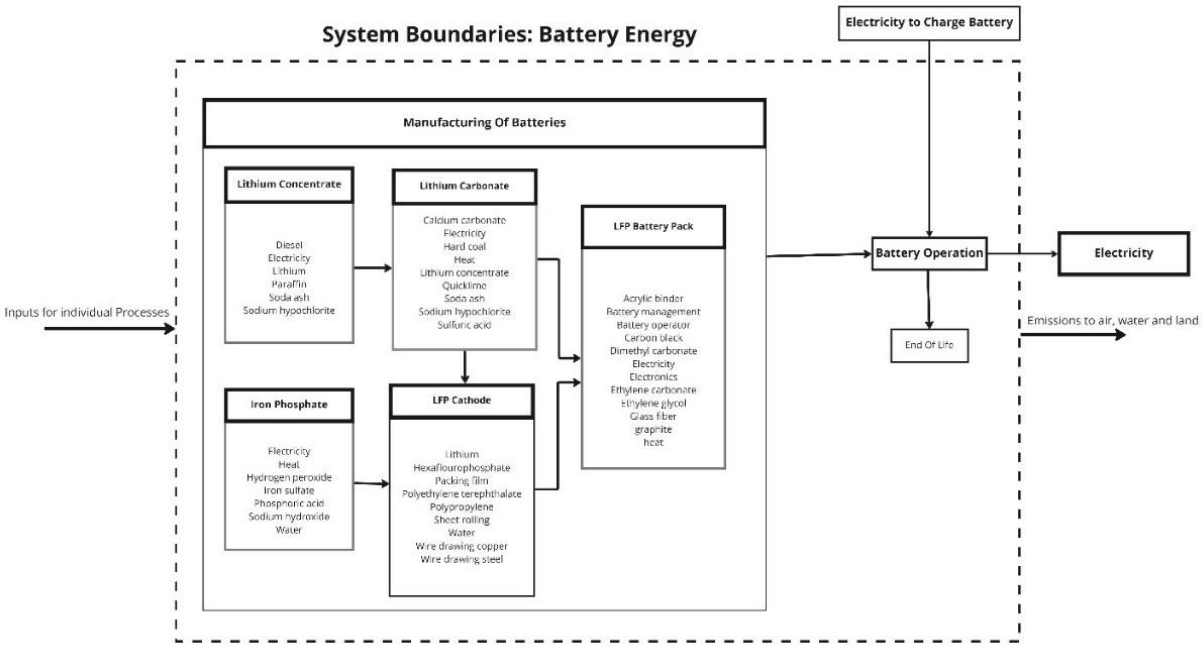
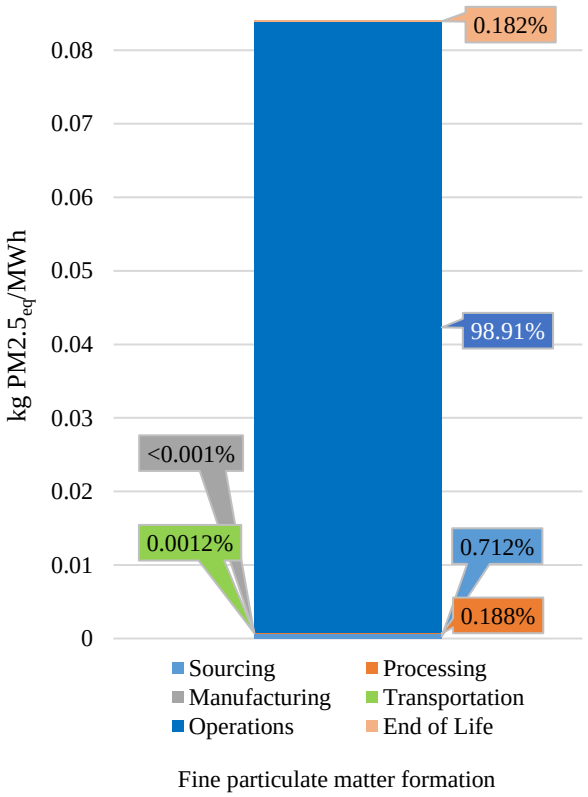
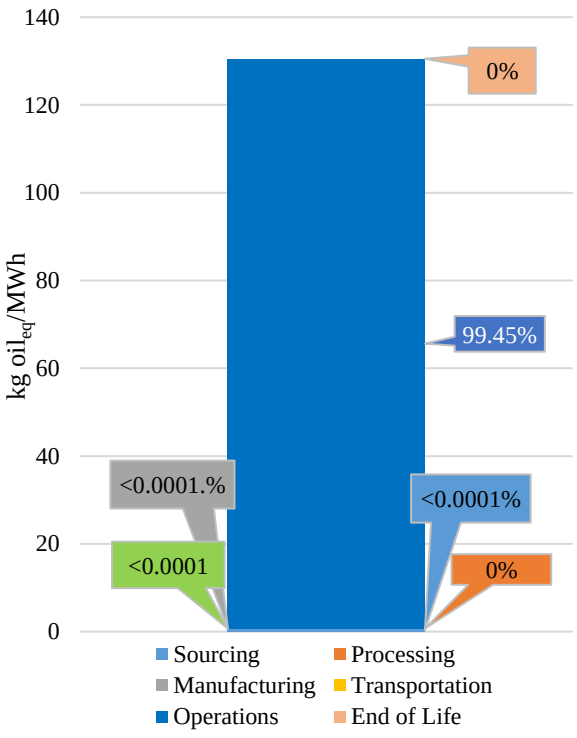


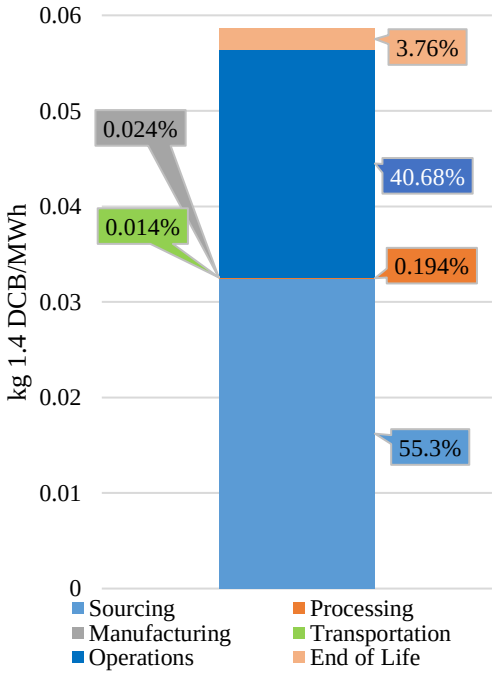
Figure S4. System boundary of BESS under study



Fine particulate matter formation



Fossil Resource Scarcity



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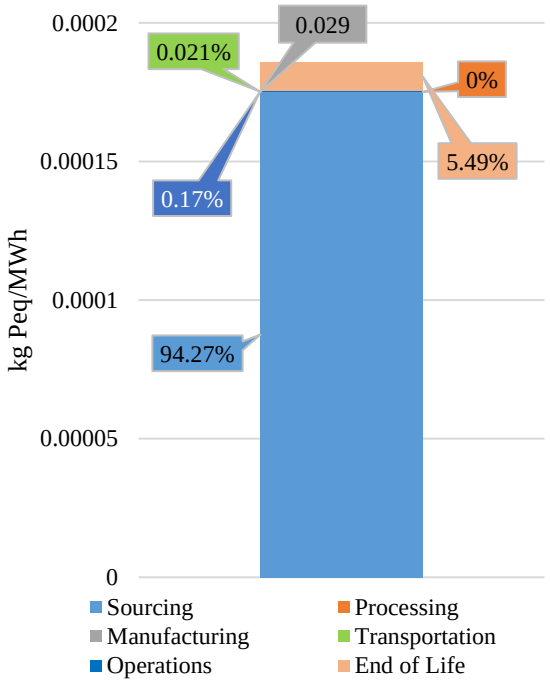
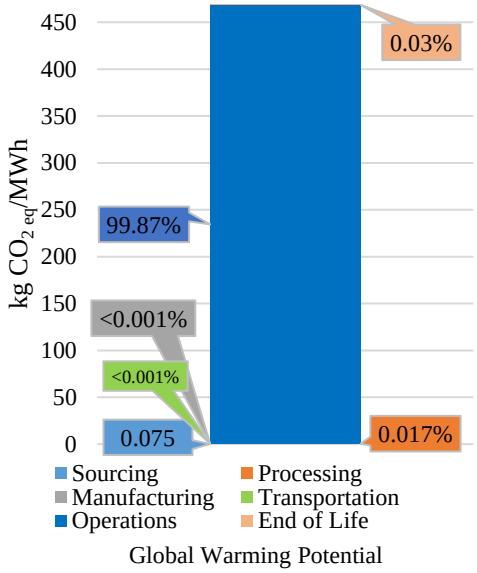
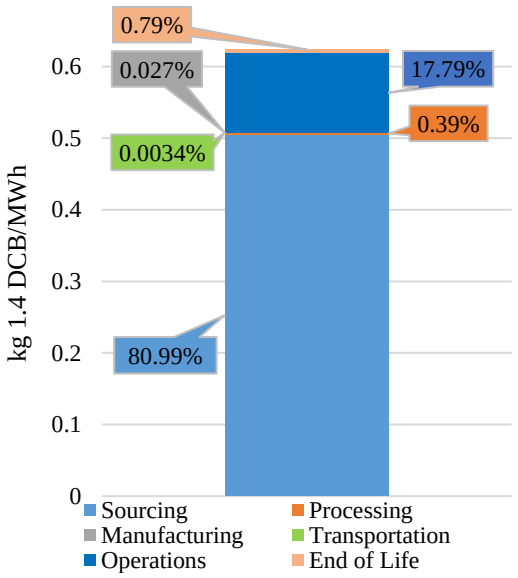


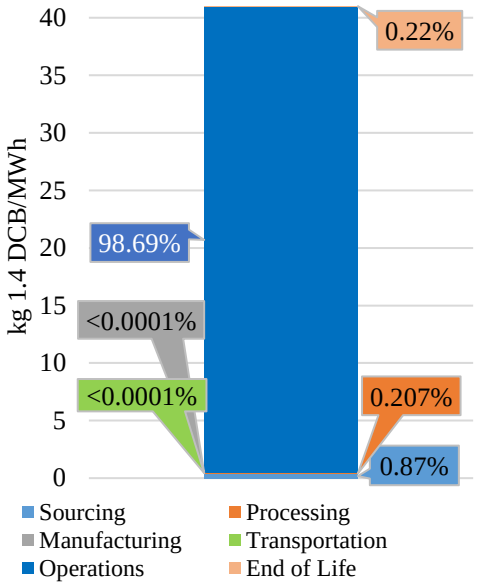
Freshwater Eutrophication



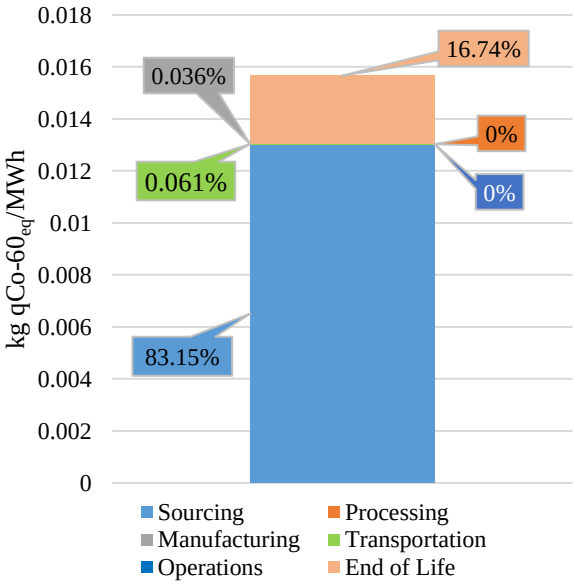
Global Warming Potential



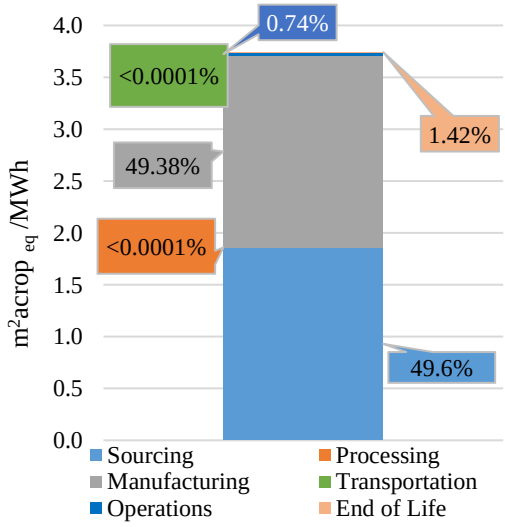
Human carcinogenic toxicity



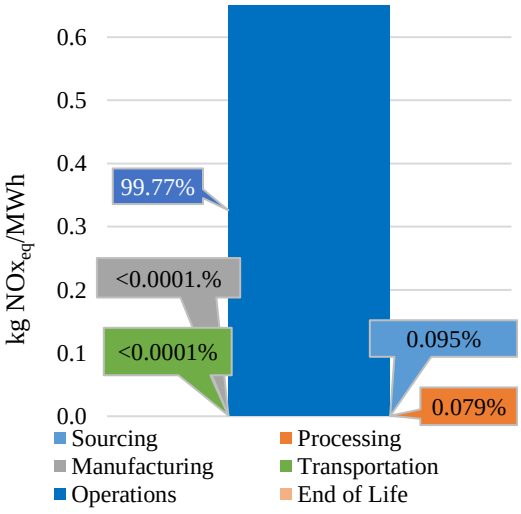
Human non-carcinogenic toxicity



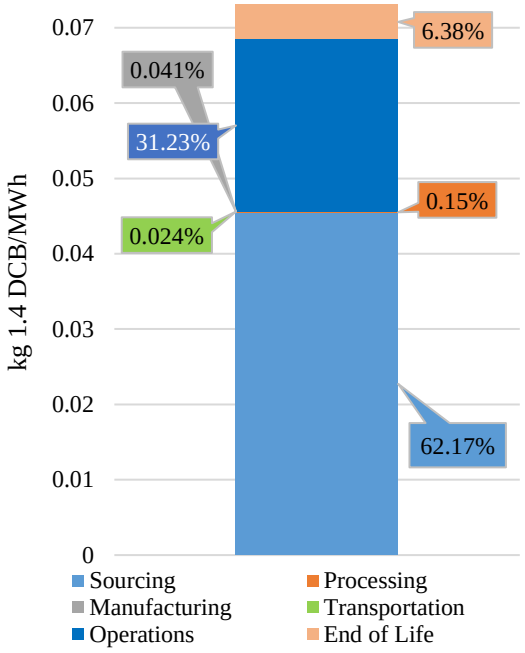
Ionizing radiation



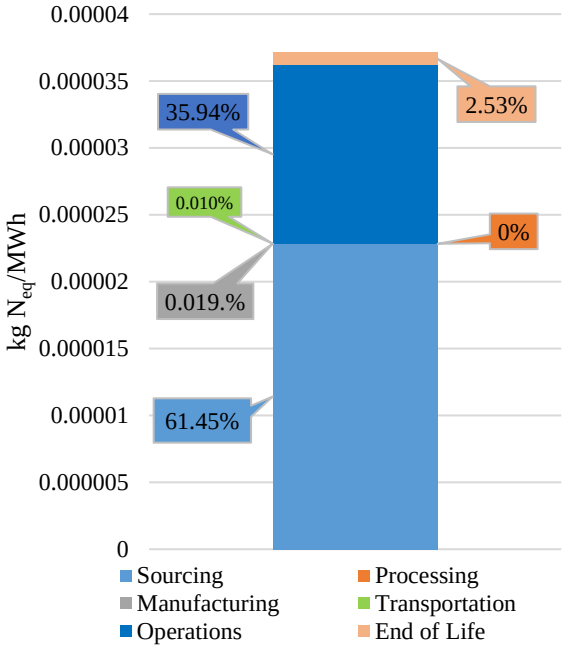
Land Use



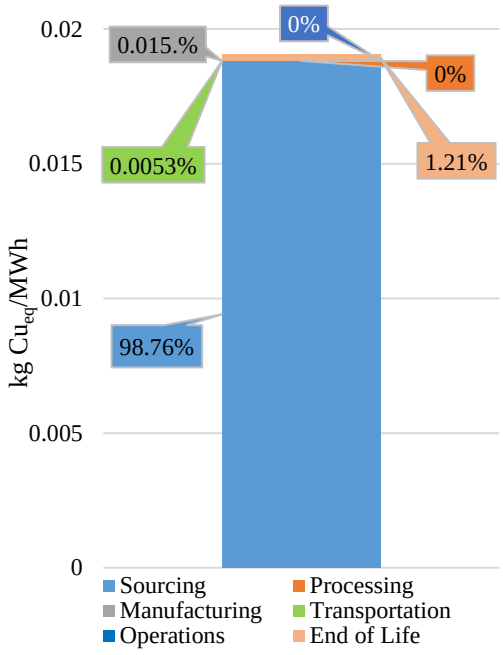
Ozone Formation, Terrestrial Ecosystems



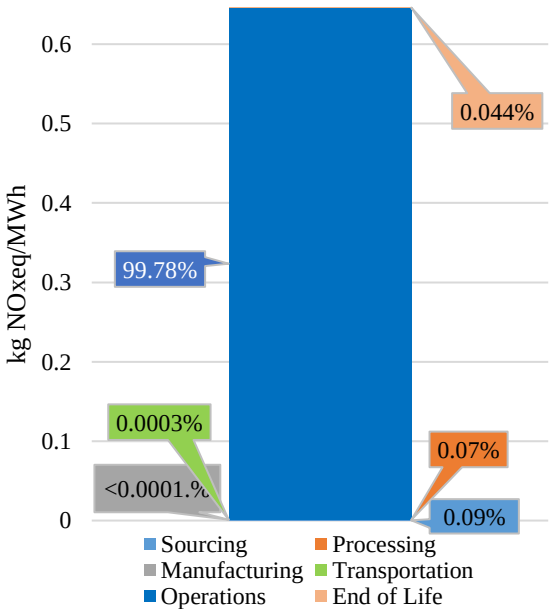
Marine ecotoxicity



Marine Eutrophication



Mineral Resource Scarcity



Ozone Formation, Human Health

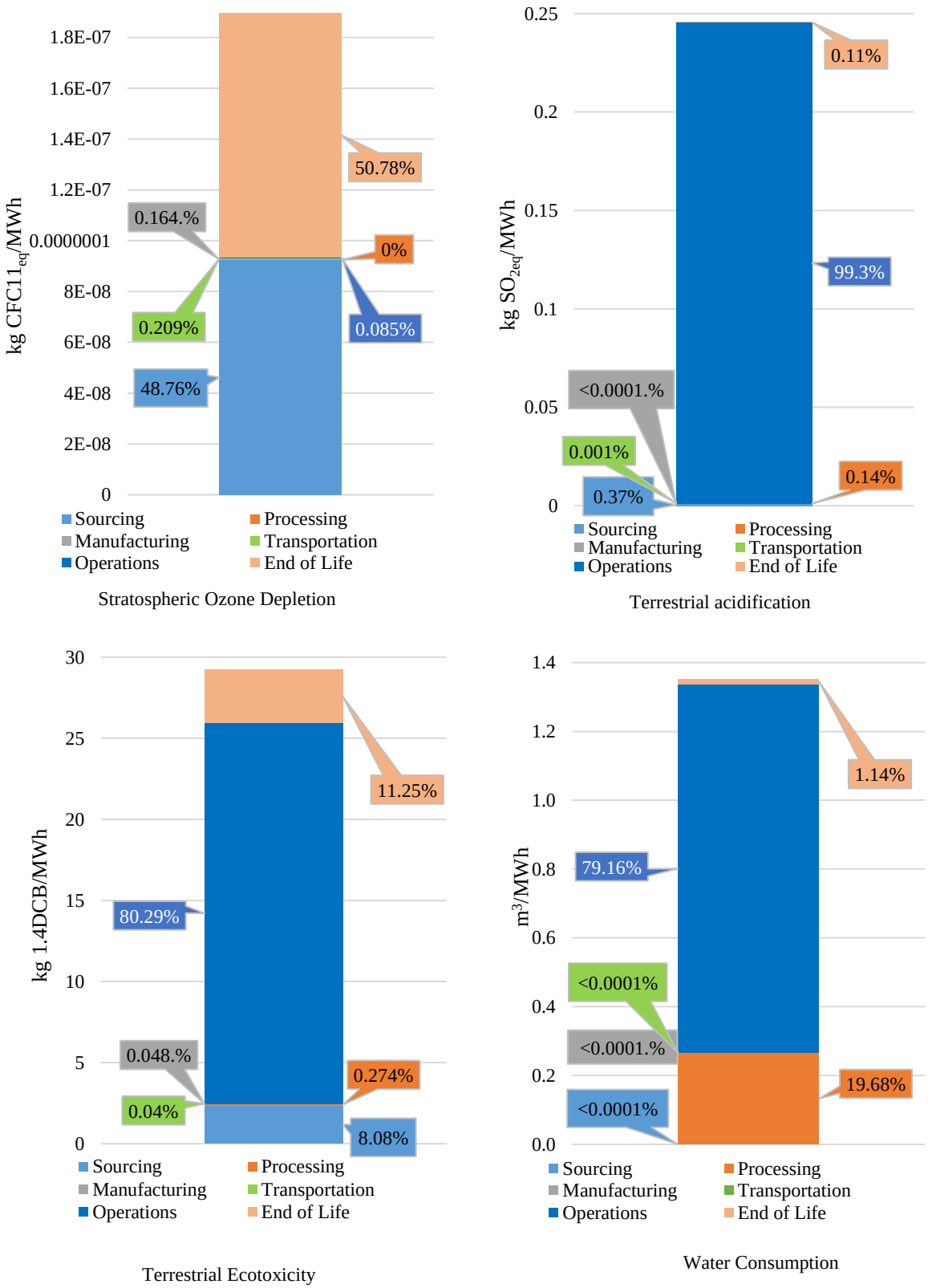


Figure S5. Per MWh environmental impacts of CCGT (500 MW)

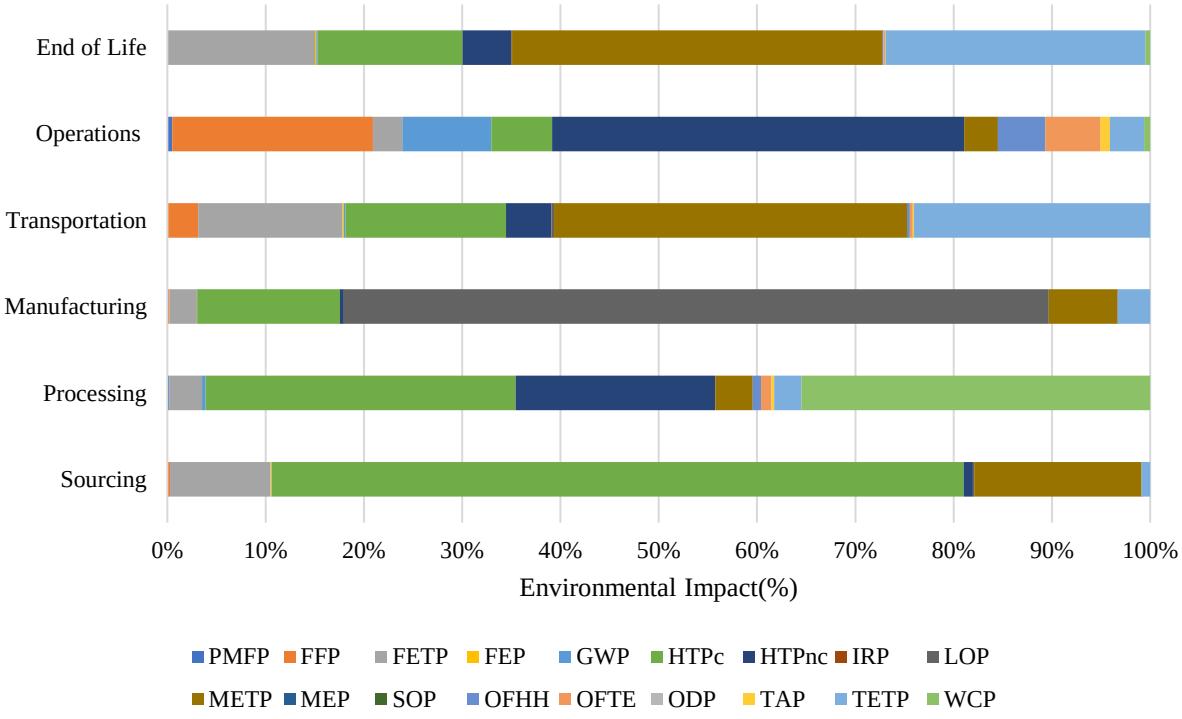


Figure S6(a). Single score environmental impacts of CCGT

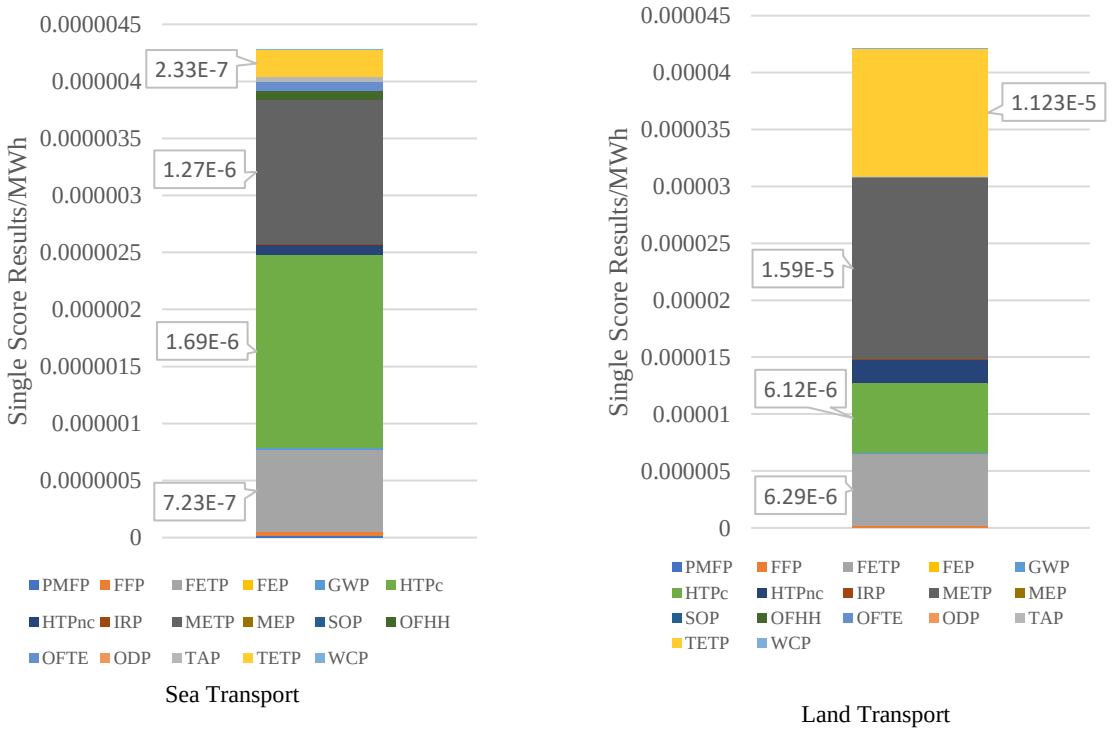
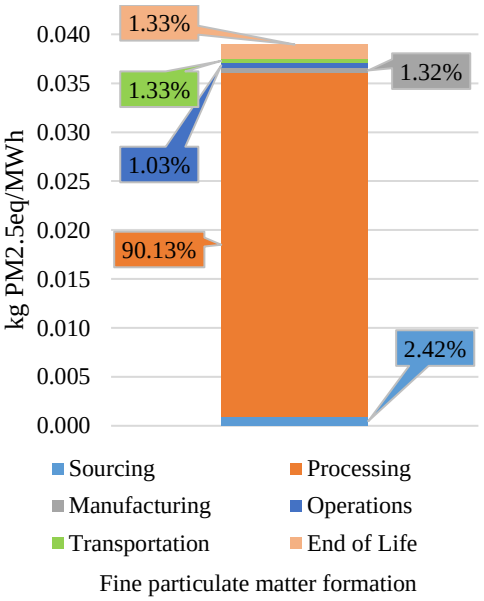
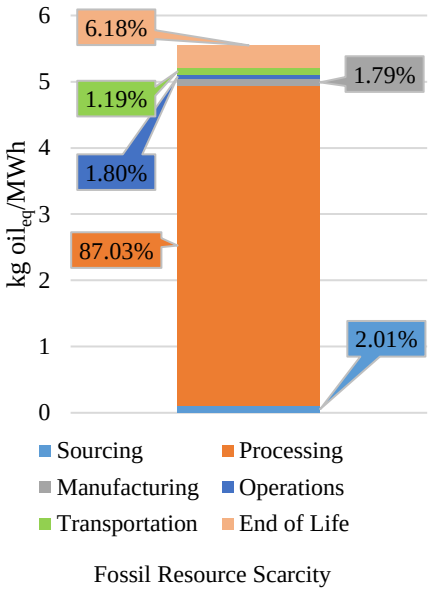


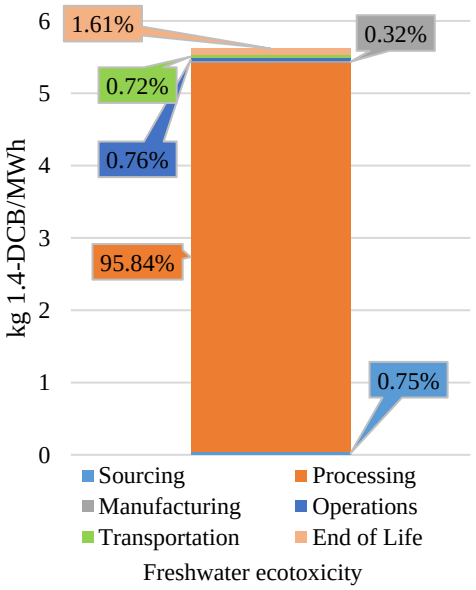
Figure S6(b). Single score environmental impacts of sea and land transport for CCGT



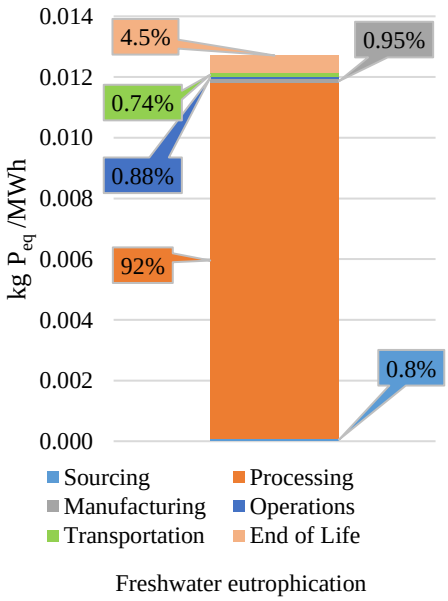
Fine particulate matter formation



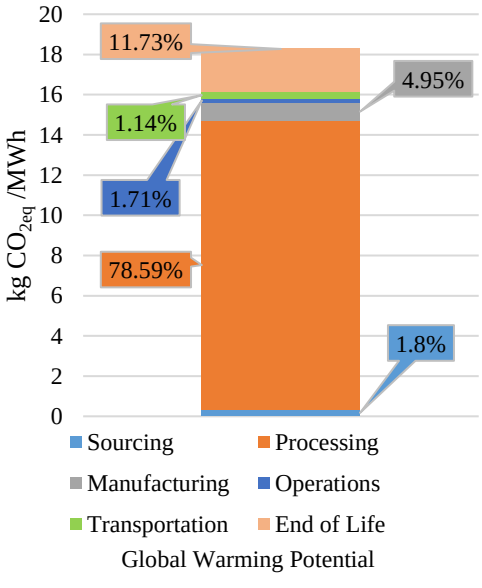
Fossil Resource Scarcity



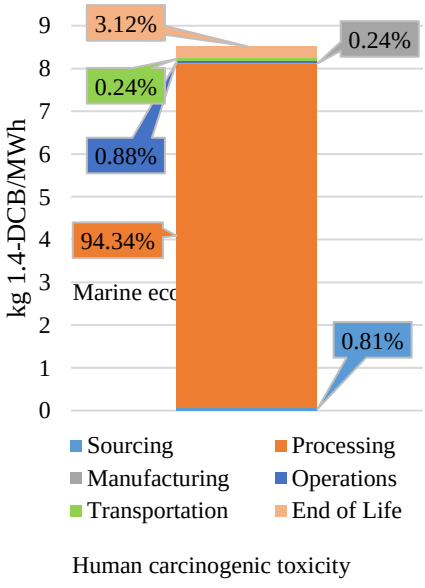
Freshwater ecotoxicity



Freshwater eutrophication

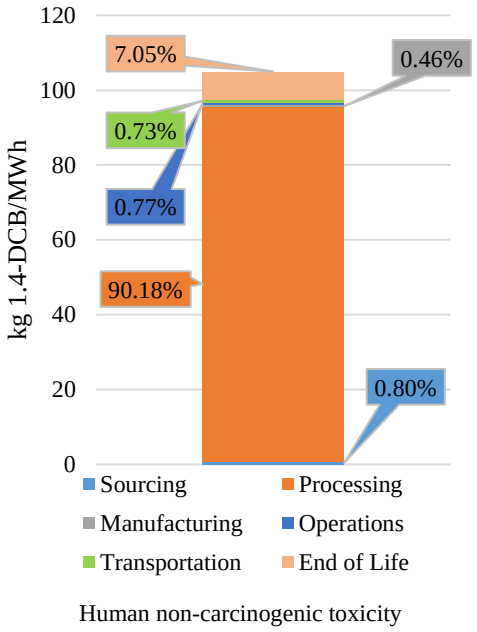


Global Warming Potential

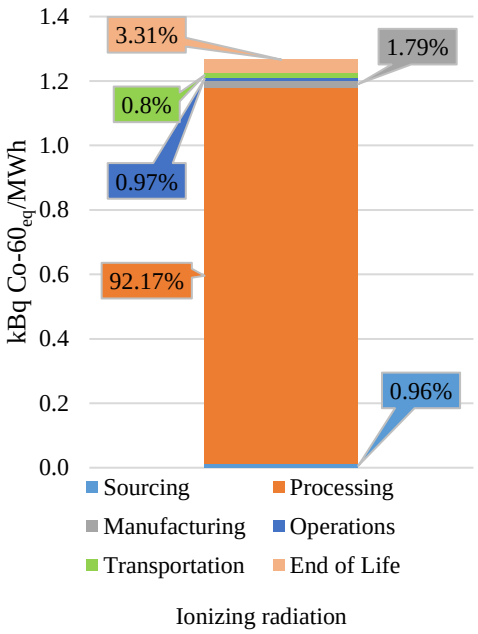


Marine ecc

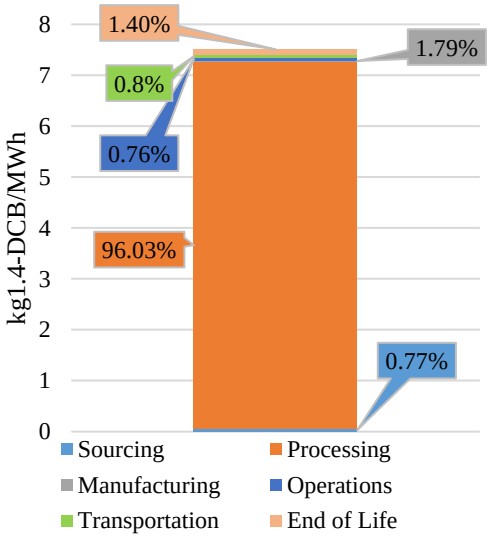
Human carcinogenic toxicity



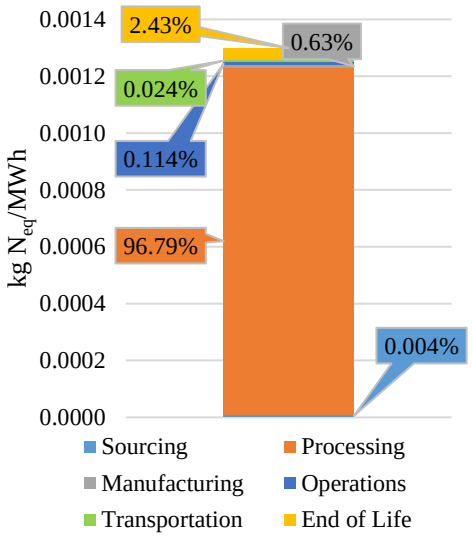
Human non-carcinogenic toxicity



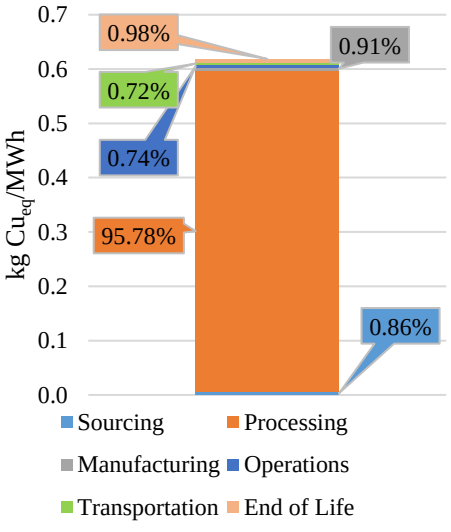
Ionizing radiation



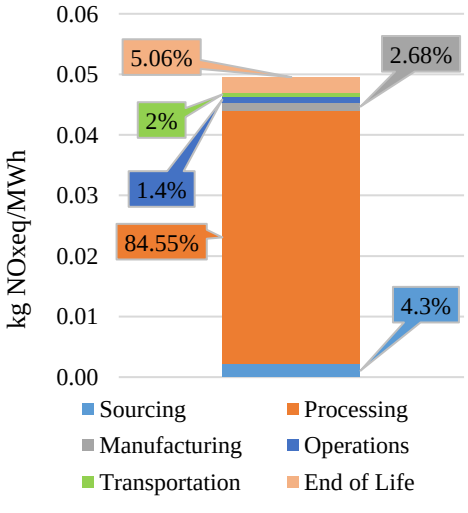
Marine ecotoxicity



Marine Eutrophication



Mineral resource scarcity



Ozone formation, Human health

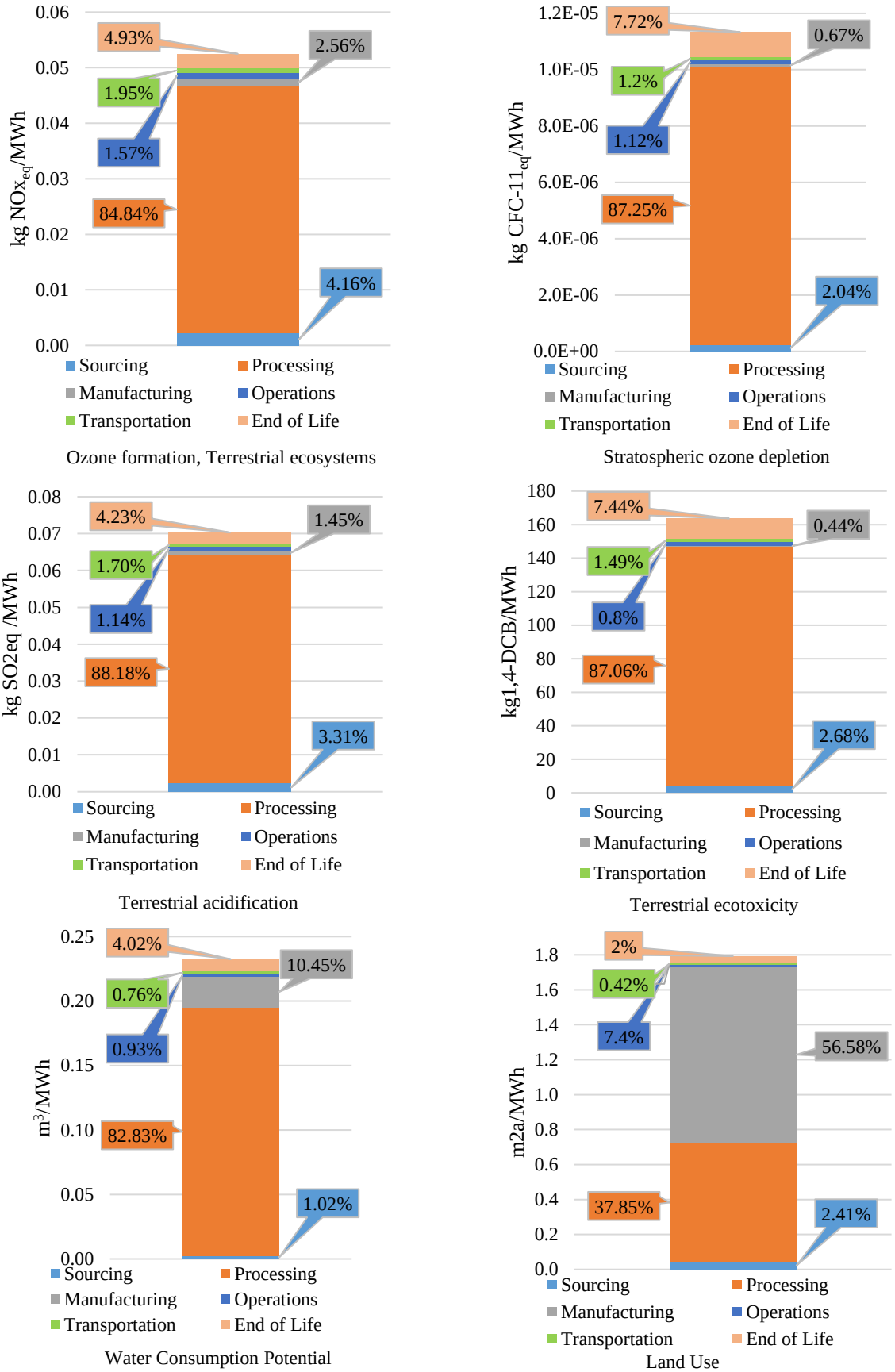


Figure S7. Per MWh environmental impacts of 3 MW (424 nos) Wind Turbine

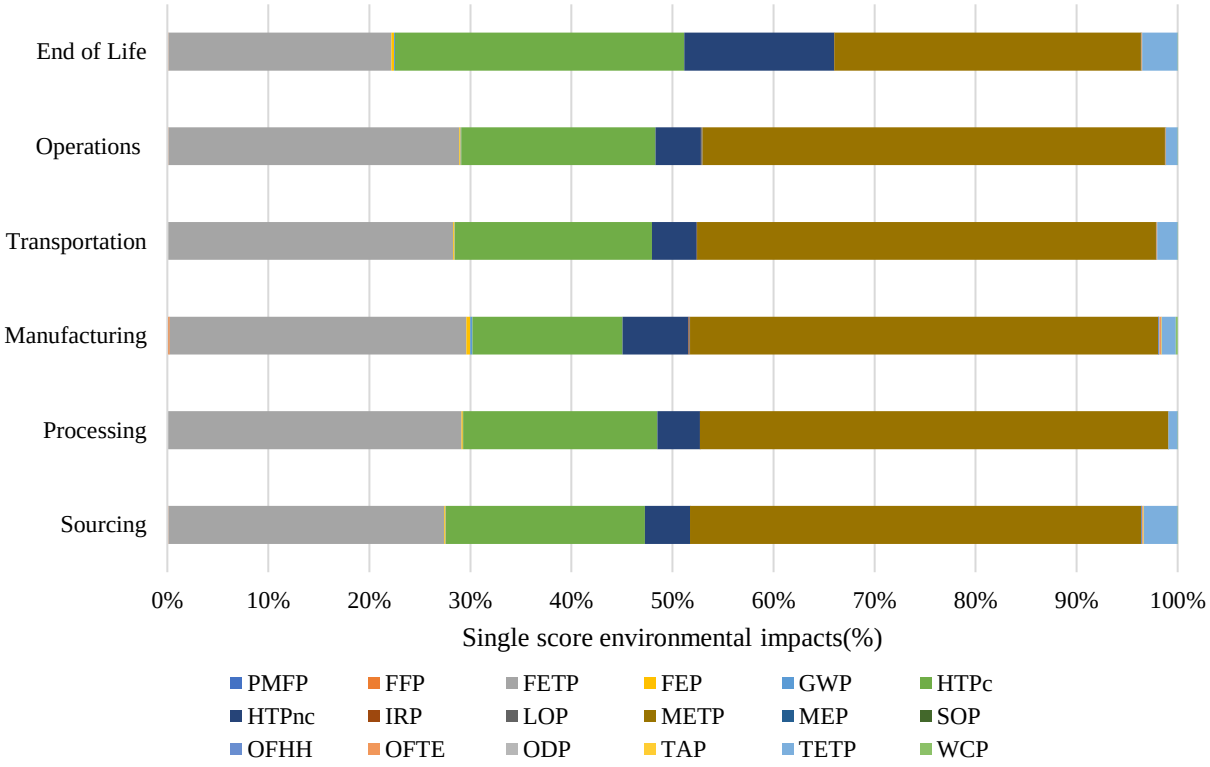


Figure S8(a). Per MWh Single Score Results/ life cycle phase for the WTG

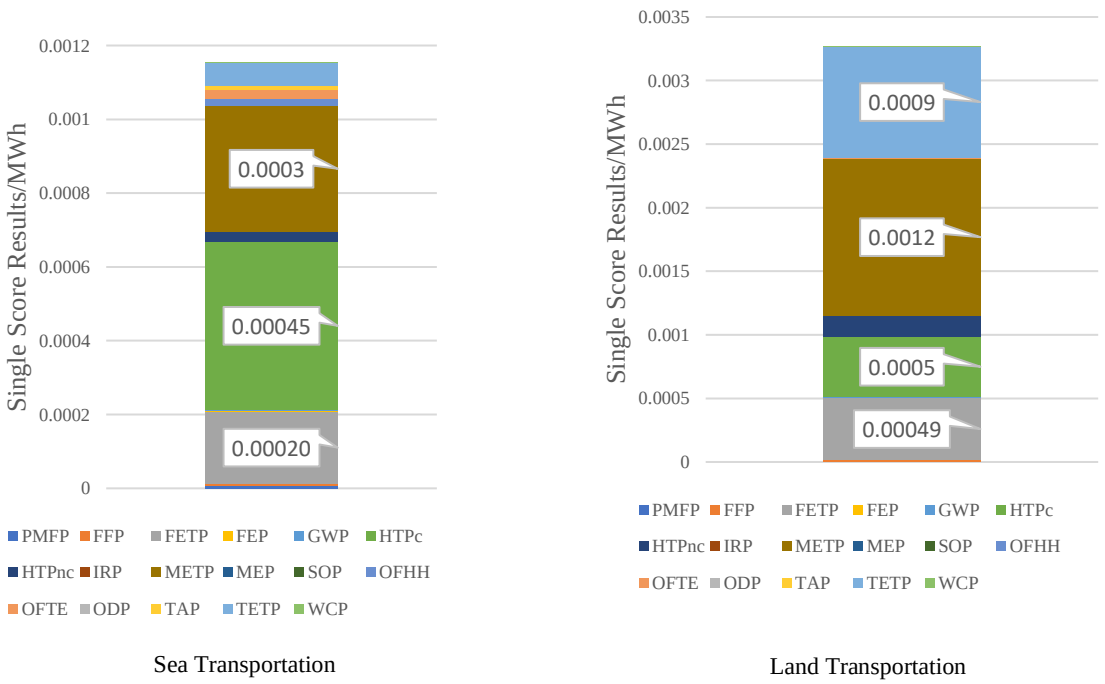


Figure S8(b). Single score environmental impacts of sea and land transport for the WTG

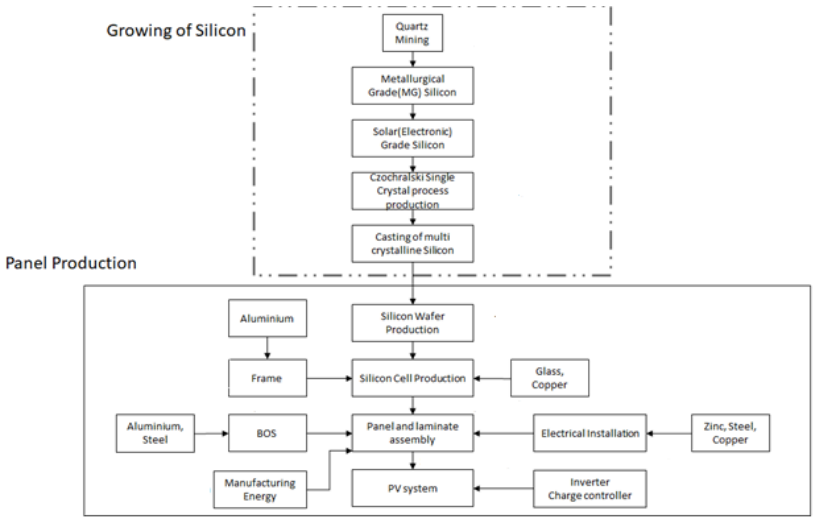
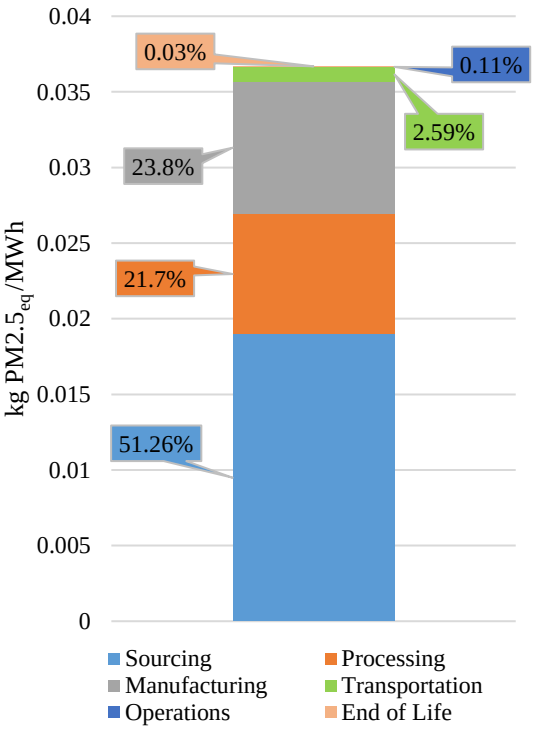
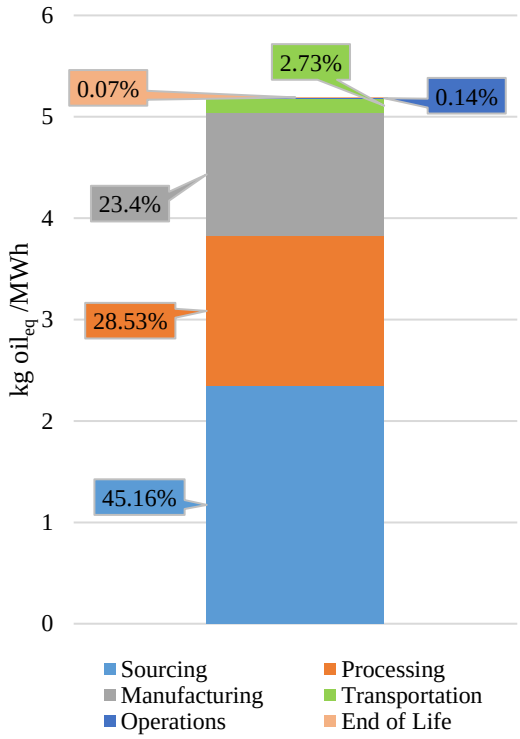


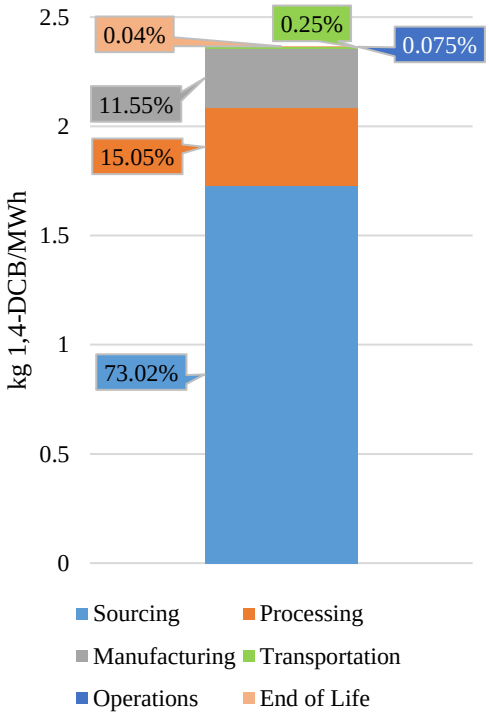
Figure S9. PV panel production process



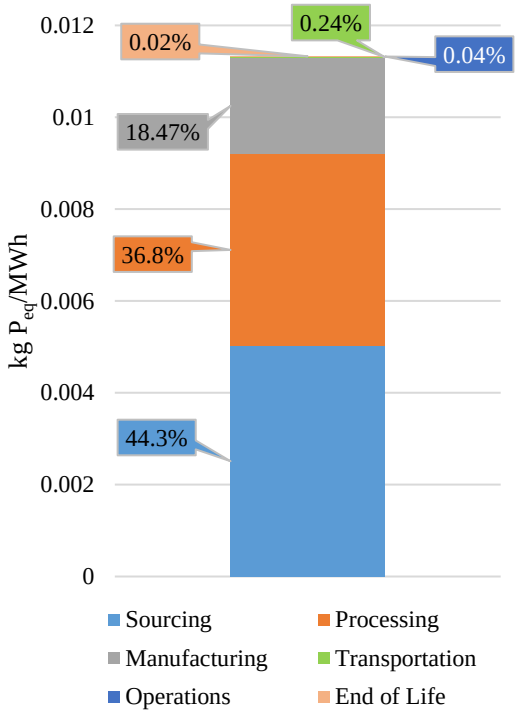
Fine particulate matter formation



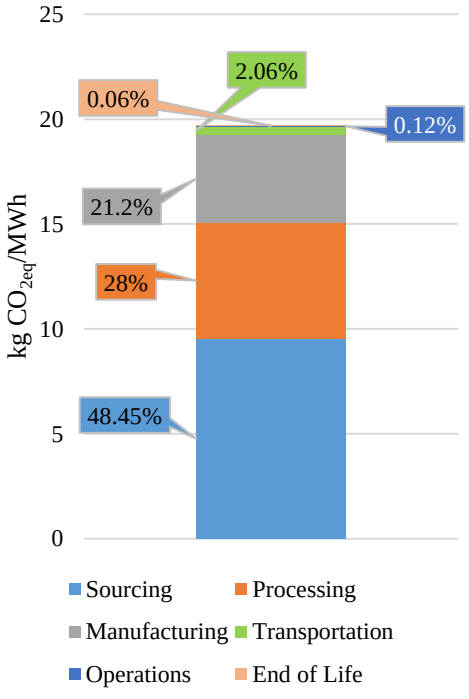
Fossil resource scarcity



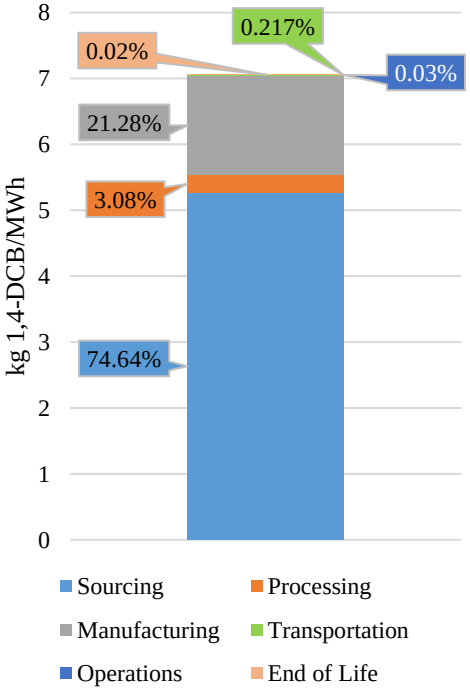
Freshwater Ecotoxicity



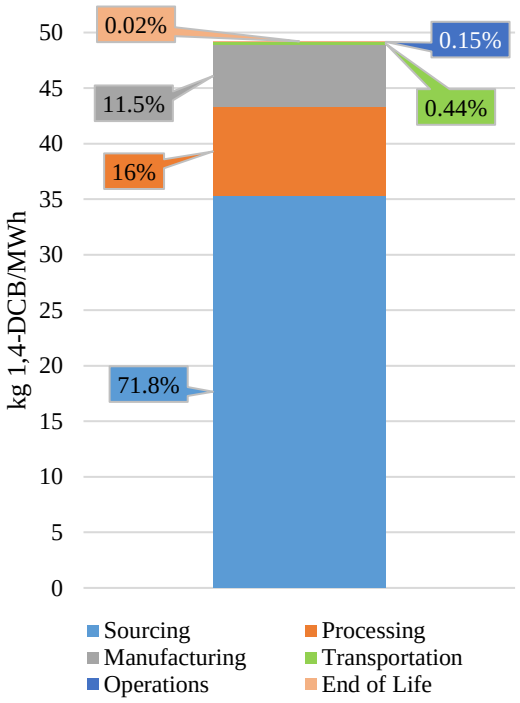
Freshwater Eutrophication



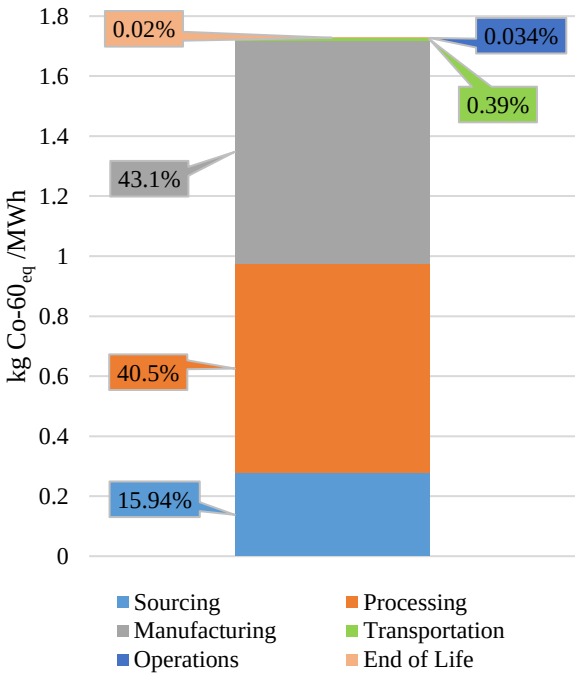
Global Warming



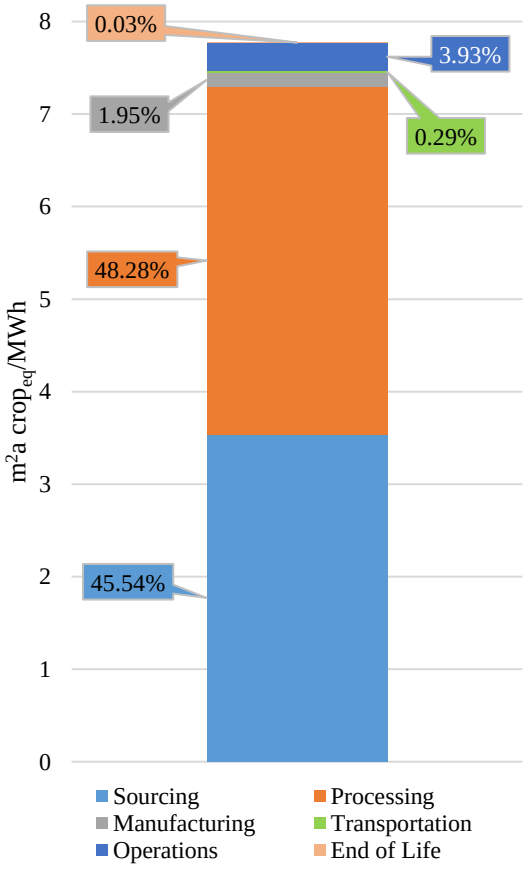
Human Carcinogenic Toxicity



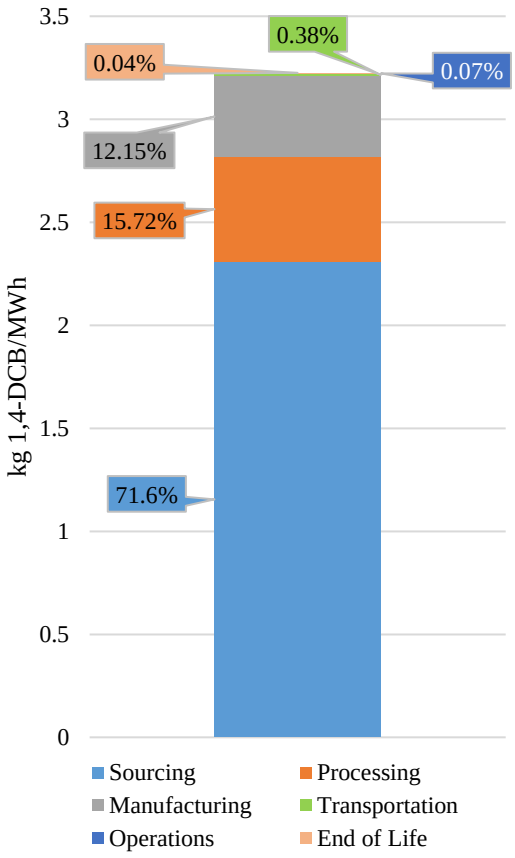
Human Non-Carcinogenic Toxicity



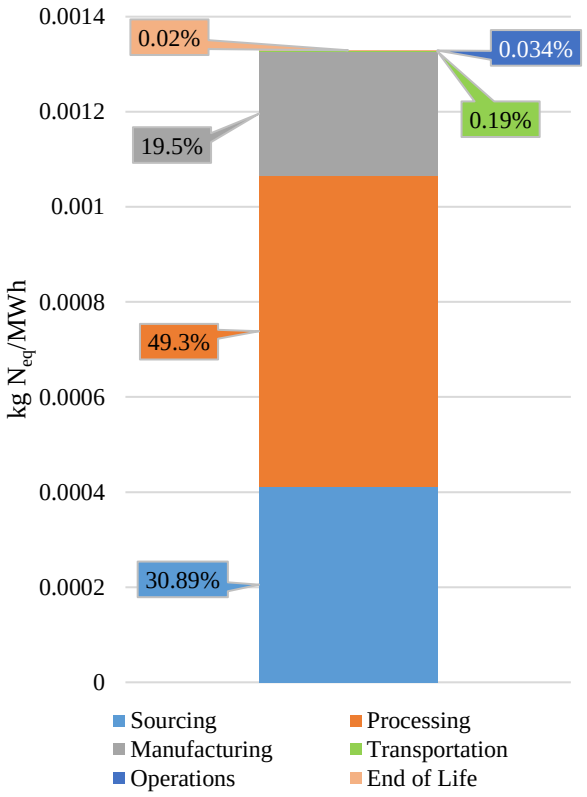
Ionization Radiation Potential



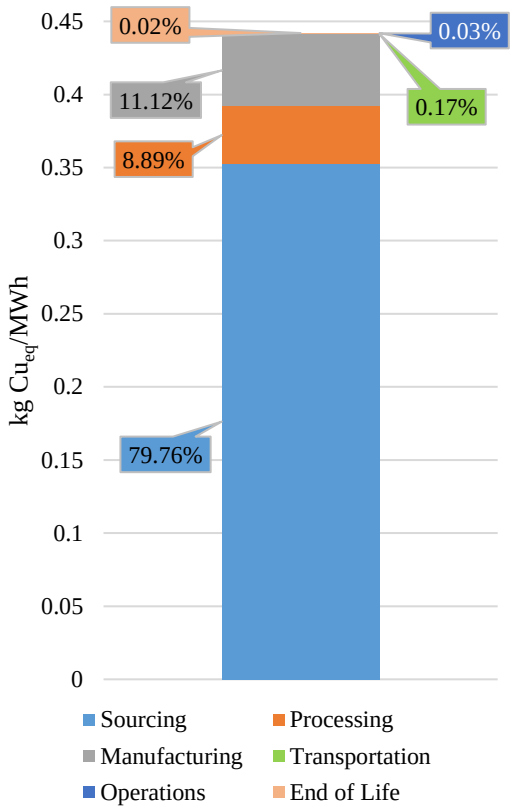
Land Use Potential



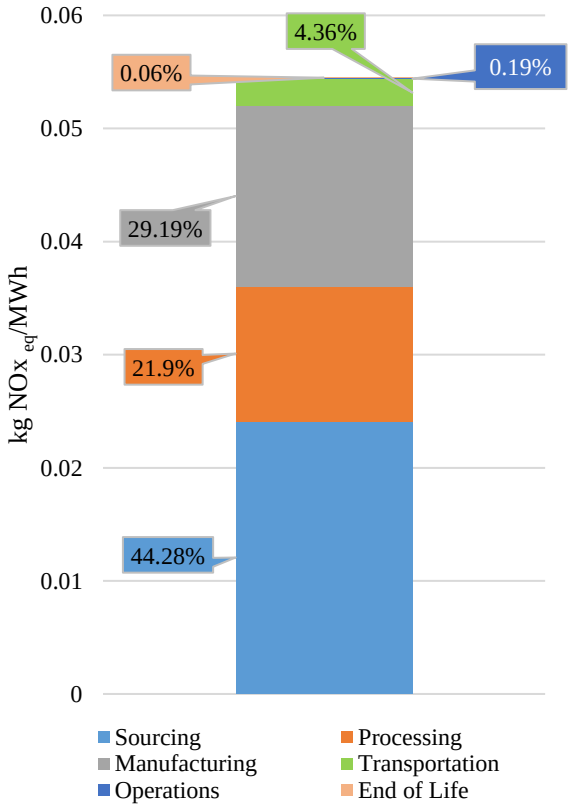
Marine Ecotoxicity



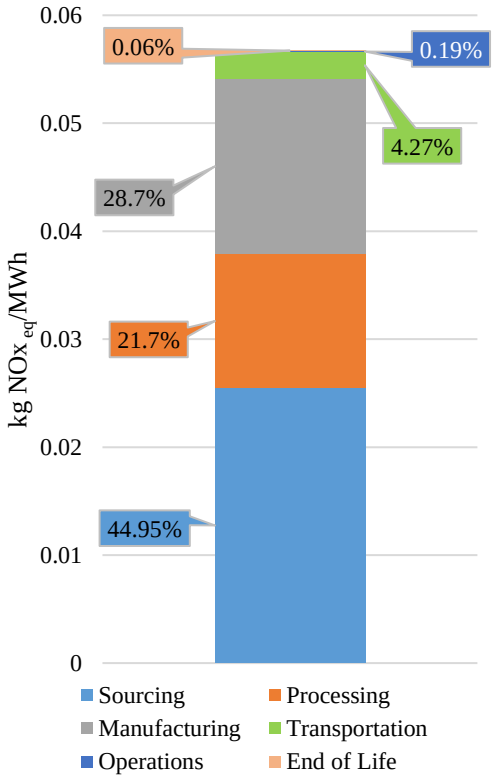
Marine Eutrophication



Mineral Resource Scarcity



Ozone formation, Human health



Ozone formation, Terrestrial Ecosystems

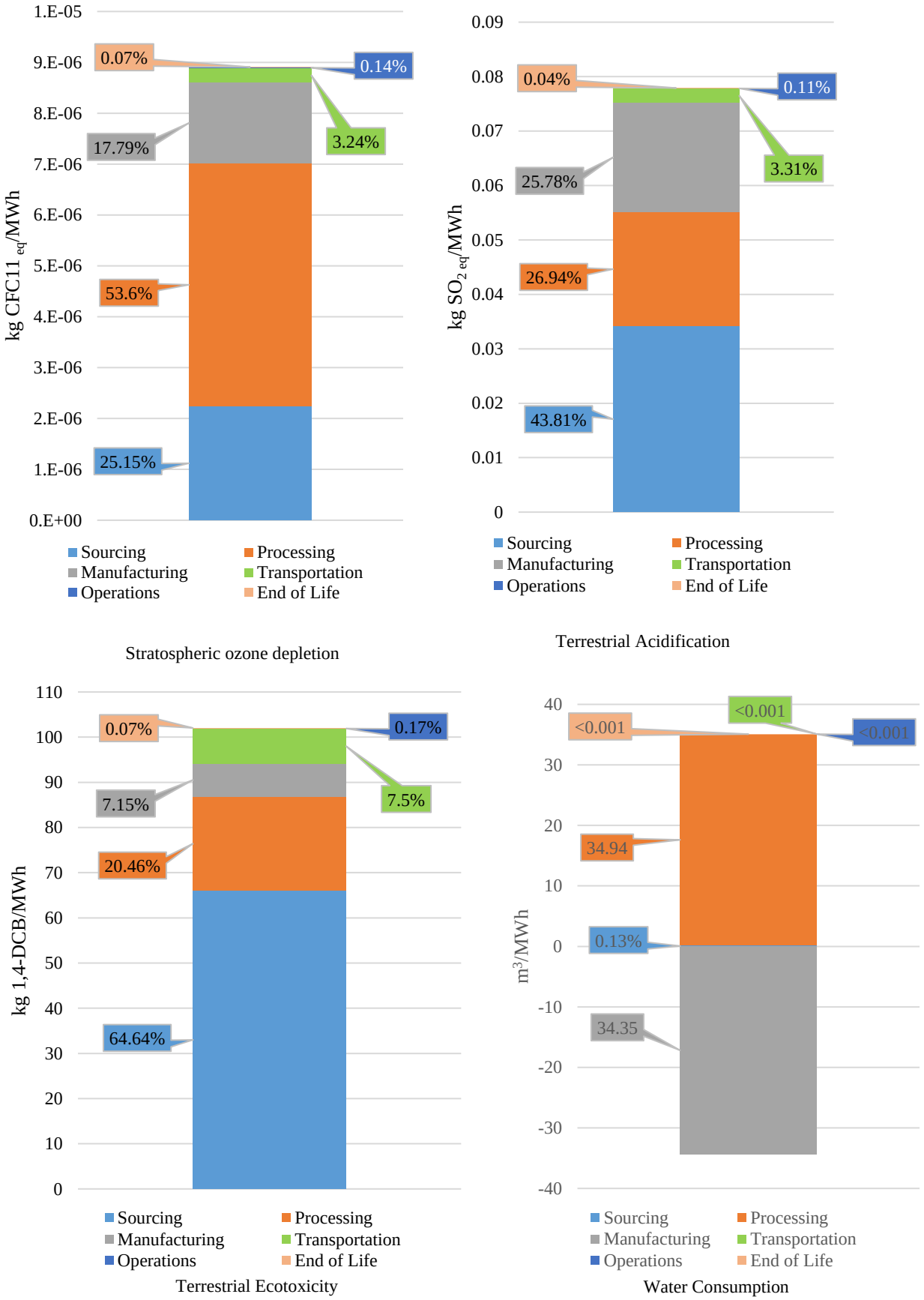


Figure S10. Per MWh environmental impacts of 1435 MW PV Power generation

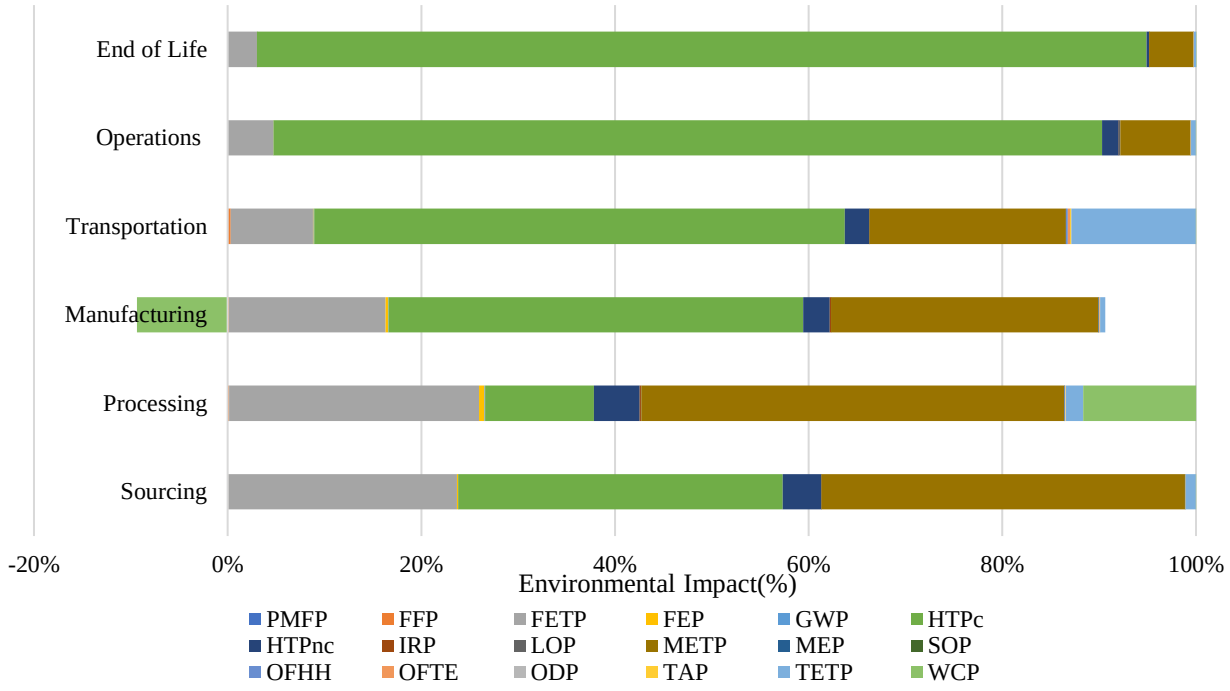


Figure S11(a). Per MWh Single Score Results/ life cycle phase for the 1435 MW solar panels

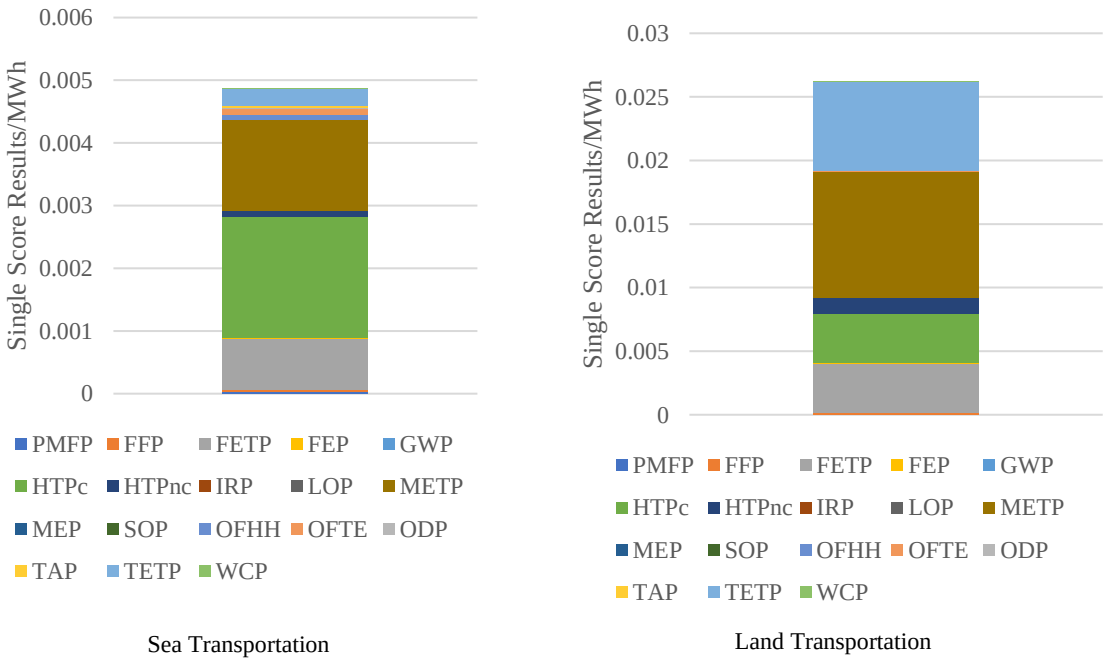


Figure S11(b). Single score environmental impacts of sea and land transport for solar panels

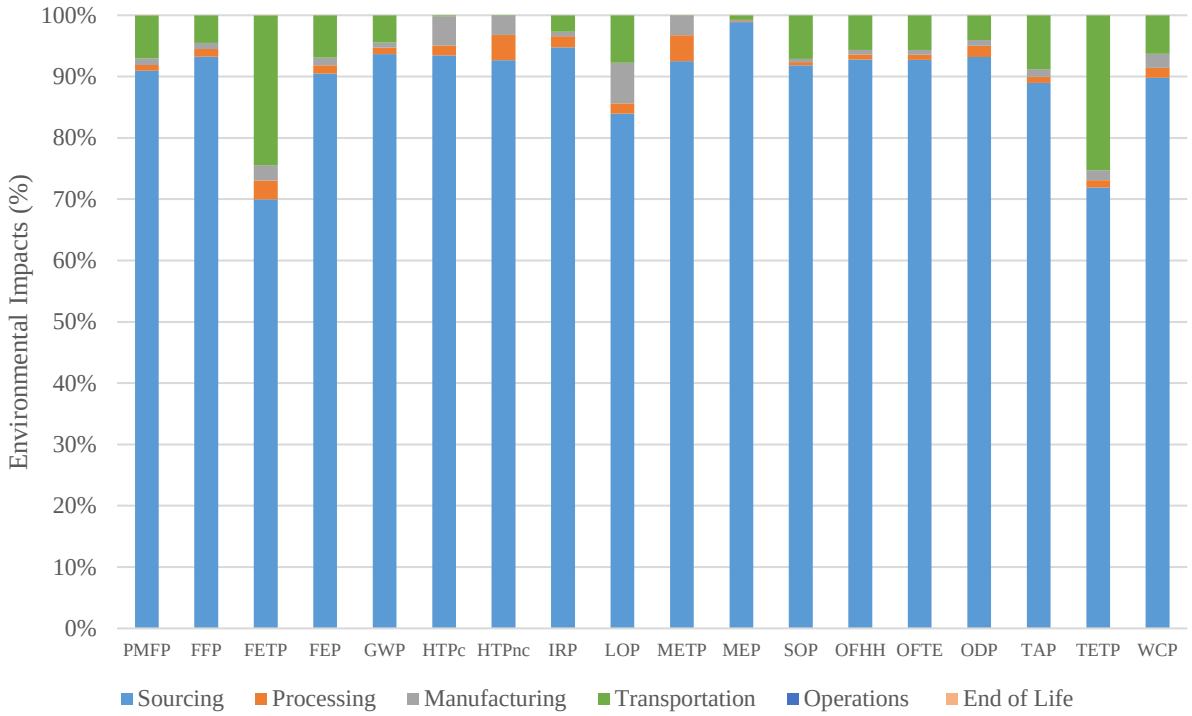


Figure S12. Percentage life cycle phase wise environmental impacts of 1MWh BESS

TABLES

Table S1. Normalization Factors used in ReCiPe Midpoint (H)

Reference unit	Factor
Fine particulate matter formation	25.6
Fossil resource scarcity	980.4
Freshwater ecotoxicity	1.2
Freshwater eutrophication	0.6
Global warming	7987.2
Human carcinogenic toxicity	2.8
Human non-carcinogenic toxicity	149.0
Ionizing radiation	480.8
Land use	6172.8
Marine ecotoxicity	1.0
Marine eutrophication	4.6
Mineral resource scarcity	120048
Ozone formation, Human health	20.6
Ozone formation, Terrestrial ecosystems	17.8
Stratospheric ozone depletion	0.1
Terrestrial acidification	41.0
Terrestrial ecotoxicity	1036.3
Water consumption	266.7

Table S2. Environmental Impact for sea and land transport in per tkm

Environmental Parameter	**Unit**	**Transport Raw Material**	
		Sea (per tkm)	Land (per tkm)
Fine particulate matter formation	kg $PM2.5_{eq}$	0.00004	0.00010
Fossil resource scarcity	kg oil_{eq}	0.00192	0.03286
Freshwater ecotoxicity	kg 1,4-DCB	0.00007	0.00147
Freshwater eutrophication	kg P_{eq}	0.00000	0.00001
Global warming	kg CO_{2eq}	0.00654	0.08975
Human carcinogenic toxicity	kg 1,4-DCB	0.00035	0.00322
Human non-carcinogenic toxicity	kg 1,4-DCB	0.00105	0.05982
Ionizing radiation	kBq $Co\text{-}60_{eq}$	0.00007	0.00165
Land use	m^2a $crop_{eq}$	0.00002	0.00665
Marine ecotoxicity	kg 1,4-DCB	0.00010	0.00312
Marine eutrophication	kg N_{eq}	0.00000	0.00000
Mineral resource scarcity	kg Cu_{eq}	0.00002	0.00015
Ozone formation, Human health	kg NOx eq	0.00011	0.00018
Ozone formation, Terrestrial ecosystems	kg NOx_{eq}	0.00011	0.00019
Stratospheric ozone depletion	kg $CFC\text{-}11_{eq}$	0.00000	0.00000
Terrestrial acidification	kg SO_{2eq}	0.00012	0.00019
Terrestrial ecotoxicity	kg 1,4-DCB	0.01790	2.21417
Water consumption	m^3	0.00001	0.00021

Table S3. Per MWh environmental impacts for the five electricity generating options

Reference unit		CCGT-500 MW	Wind-3MW (424 Nos)	Solar PV 1435 MW	Wind 3 (424 Nos) MW + BESS 500MWh	Solar 1435 MW +BESS 500MWh
kg $PM_{2.5eq}$	PMFP	0.084	0.039	0.037	0.111	0.109
kg oil_{eq}	FFP	130.5	5.5	5.2	13.4	13.0
kg 1,4-DCB	FETP	0.059	5.6	2.4	8.3	5.1
kg P_{eq}	FEP	0.0002	0.0127	0.0113	0.0298	0.0285
kg CO_{2eq}	GWP	468.5	18.3	19.7	46.6	48.0
kg 1,4-DCB	HTPc	0.6	8.5	7.7	137.3	136.5
kg 1,4-DCB	HTPnc	41.0	104.9	49.2	8920.6	8864.9
kBq $Co\text{-}60_{eq}$	IRP	0.016	1.3	1.7	4.5	5.0
$m^2a\ crop_{eq}$	LOP	3.7	1.8	7.8	2.2	8.2
kg 1,4-DCB	METP	0.073	7.5	3.2	10254.5	10250.2
kg N_{eq}	MEP	0.00004	0.00130	0.00133	0.01545	0.01548
kg Cu_{eq}	SOP	0.019	0.6	0.4	1.9	1.7
kg NO_{xeq}	OFHH	0.6	0.0495	0.054	0.142	0.147
kg NO_{xeq}	OFTE	0.7	0.053	0.057	0.146	0.150
kg $CFC11_{eq}$	ODP	1.90E-07	1.13E-05	8.91E-06	2.89E-05	2.65E-05
kg SO_{2eq}	TAP	0.246	0.070	0.078	0.237	0.245
kg 1,4-DCB	TETP	29.2	163.6	102.1	438.6	377.0
m^3	WCP	1.352	0.232	0.738	0.663	1.168

Table S4. Per MWh sensitivity of CF to impact pathways of a CCGT

	Environmental Impact	CF-56% 612 MW	CF-68% 500MW	CF-76% 451MW
kg $PM2.5_{eq}$	Fine particulate matter formation	0.0842	0.0840	0.0839
kg oil_{eq}	Fossil resource scarcity	130.69	130.53	130.46
kg 1,4-DCB	Freshwater ecotoxicity	0.066	0.059	0.055
kg P_{eq}	Freshwater eutrophication	2.27E-04	1.86E-04	1.68E-04
kg CO_{2eq}	Global warming	468.64	468.51	468.46
kg 1,4-DCB	Human carcinogenic toxicity	0.74	0.62	0.57
kg 1,4-DCB	Human non-carcinogenic toxicity	41.16	41.04	40.99
kBq $Co\text{-}60_{eq}$	Ionizing radiation	0.019	0.016	0.014
$m^2a\ crop_{eq}$	Land use	4.58	3.75	3.38
kg 1,4-DCB	Marine ecotoxicity	0.08	0.07	0.07
kg N_{eq}	Marine eutrophication	4.25E-05	3.71E-05	3.48E-05
kg Cu_{eq}	Mineral resource scarcity	0.02	0.02	0.02
kg NO_{xeq}	Ozone formation, Human health	0.65	0.65	0.65
kg NO_{xeq}	Ozone formation, Terrestrial ecosystems	0.65	0.65	0.65
kg $CFC11_{eq}$	Stratospheric ozone depletion	2.32E-07	1.90E-07	1.71E-07
kg SO_{2eq}	Terrestrial acidification	0.25	0.25	0.25
kg 1,4-DCB	Terrestrial ecotoxicity	30.51	29.22	28.66
m^3	Water consumption	1.41	1.35	1.32

Table S5. Per MWh sensitivity of CF to impact pathways of the Wind turbine generation

Environmental Impact		CF-14% 2819 MW	CF-31% 1273 MW	CF-48% 822 MW
kg $PM2.5_{eq}$	Fine particulate matter formation	0.09	0.04	0.03
kg oil $_{eq}$	Fossil resource scarcity	12.30	5.55	3.59
kg 1,4-DCB	Freshwater ecotoxicity	12.45	5.62	3.63
kg P_{eq}	Freshwater eutrophication	0.0282	0.0127	0.0082
kg CO_{2eq}	Global warming	40.51	18.27	11.81
kg 1,4-DCB	Human carcinogenic toxicity	18.89	8.52	5.51
kg 1,4-DCB	Human non-carcinogenic toxicity	232.65	104.94	67.82
kBq Co-60 $_{eq}$	Ionizing radiation	2.81	1.27	0.82
m^2a crop $_{eq}$	Land use	1.19	0.53	0.35
kg 1,4-DCB	Marine ecotoxicity	16.64	7.51	4.85
kg N_{eq}	Marine eutrophication	0.00288	0.00130	0.00084
kg Cu_{eq}	Mineral resource scarcity	1.37	0.62	0.40
kg NO_{xeq}	Ozone formation, Human health	0.1098	0.0495	0.0320
kg NO_{xeq}	Ozone formation, Terrestrial ecosystems	0.1164	0.0525	0.0339
kg $CFC11_{eq}$	Stratospheric ozone depletion	2.51E-05	1.13E-05	7.32E-06
kg SO_{2eq}	Terrestrial acidification	0.16	0.07	0.05
kg 1,4-DCB	Terrestrial ecotoxicity	362.78	163.64	105.75
m^3	Water consumption	0.52	0.23	0.15

Table S6. Per MWh sensitivity of CF to impact pathways of the solar PV generation

Environmental Impact		CF-21% 1777 MW	CF-26% 1435 MW	CF-31% 1204 MW
kg $PM2.5_{eq}$	Fine particulate matter formation	0.041	0.037	0.034
kg oil $_{eq}$	Fossil resource scarcity	5.95	5.19	4.68
kg 1,4-DCB	Freshwater ecotoxicity	2.62	2.37	2.19
kg P_{eq}	Freshwater eutrophication	0.0125	0.0113	0.0105
kg CO_{2eq}	Global warming	22.22	19.68	17.97
kg 1,4-DCB	Human carcinogenic toxicity	7.24	7.06	6.93
kg 1,4-DCB	Human non-carcinogenic toxicity	52.68	49.21	46.86
kBq Co-60 $_{eq}$	Ionizing radiation	2.08	1.73	1.49
m^2a crop $_{eq}$	Land use	7.86	7.77	7.72
kg 1,4-DCB	Marine ecotoxicity	3.57	3.23	2.99
kg N_{eq}	Marine eutrophication	1.47E-03	1.33E-03	1.24E-03
kg Cu_{eq}	Mineral resource scarcity	0.46	0.44	0.43
kg NO_{xeq}	Ozone formation, Human health	0.062	0.054	0.050
kg NO_{xeq}	Ozone formation, Terrestrial ecosystems	0.064	0.057	0.052
kg $CFC11_{eq}$	Stratospheric ozone depletion	1.01E-05	8.91E-06	8.08E-06
kg SO_{2eq}	Terrestrial acidification	0.088	0.078	0.071
kg 1,4-DCB	Terrestrial ecotoxicity	109.62	102.06	96.96
m^3	Water consumption	0.85	0.76	0.70

Table S7. Per MWh sensitivity of CF to impact pathways of the wind + BESS generation

	Environmental Impact	CF-14% 2819 MW	CF-31% 1273 MW	CF-48% 822 MW
kg $PM2.5_{eq}$	Fine particulate matter formation	0.16	0.11	0.10
kg oil $_{eq}$	Fossil resource scarcity	20.11	13.36	11.40
kg 1,4-DCB	Freshwater ecotoxicity	15.19	8.35	6.36
kg P_{eq}	Freshwater eutrophication	0.045	0.030	0.025
kg CO_{2eq}	Global warming	68.87	46.64	40.17
kg 1,4-DCB	Human carcinogenic toxicity	147.68	137.31	134.29
kg 1,4-DCB	Human non-carcinogenic toxicity	9048.34	8920.63	8883.51
kBq Co-60 $_{eq}$	Ionizing radiation	6.08	4.54	4.09
m^2a crop $_{eq}$	Land use	1.60	0.95	0.76
kg 1,4-DCB	Marine ecotoxicity	10263.59	10254.45	10251.79
kg N_{eq}	Marine eutrophication	0.0170	0.0154	0.0150
kg Cu_{eq}	Mineral resource scarcity	2.61	1.86	1.64
kg NO_{xeq}	Ozone formation, Human health	0.20	0.14	0.12
kg NO_{xeq}	Ozone formation, Terrestrial ecosystems	0.21	0.15	0.13
kg $CFC11_{eq}$	Stratospheric ozone depletion	4.27E-05	2.89E-05	2.49E-05
kg SO_{2eq}	Terrestrial acidification	0.32	0.24	0.21
kg 1,4-DCB	Terrestrial ecotoxicity	637.71	438.57	380.68
m^3	Water consumption	0.95	0.66	0.58

Table S8. Per MWh sensitivity of CF to impact pathways of the solar PV +BESS generation

	Environmental Impact	CF-21% 1777 MW	CF-26% 1435 MW	CF-31% 1204 MW
kg $PM2.5_{eq}$	Fine particulate matter formation	0.113	0.109	0.106
kg oil $_{eq}$	Fossil resource scarcity	13.757	13.001	12.491
kg 1,4-DCB	Freshwater ecotoxicity	5.355	5.097	4.923
kg P_{eq}	Freshwater eutrophication	0.030	0.028	0.028
kg CO_{2eq}	Global warming	50.586	48.049	46.335
kg 1,4-DCB	Human carcinogenic toxicity	136.031	135.845	135.719
kg 1,4-DCB	Human non-carcinogenic toxicity	8868.372	8864.900	8862.556
kBq Co-60 $_{eq}$	Ionizing radiation	5.349	5.001	4.767
m^2a crop $_{eq}$	Land use	8.266	8.184	8.128
kg 1,4-DCB	Marine ecotoxicity	10250.510	10250.168	10249.936
kg N_{eq}	Marine eutrophication	0.016	0.015	0.015
kg Cu_{eq}	Mineral resource scarcity	1.704	1.686	1.673
kg NO_{xeq}	Ozone formation, Human health	0.154	0.147	0.142
kg NO_{xeq}	Ozone formation, Terrestrial ecosystems	0.157	0.150	0.145
kg $CFC11_{eq}$	Stratospheric ozone depletion	2.77E-05	2.65E-05	2.56E-05
kg SO_{2eq}	Terrestrial acidification	0.255	0.245	0.238
kg 1,4-DCB	Terrestrial ecotoxicity	384.6	377.0	371.9
m^3	Water consumption	1.284	1.193	1.126