The International Journal of Life Cycle Assessment
https://doi.org/10.1007/s11367-023-02239-w

Supplementary Information for:

Life Cycle Assessment of a Marine Biorefinery Producing Protein, Bioactives and Polymeric Packaging Material.

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Summary:

This supporting information provides process contribution analysis on the SS and SG scenarios (Figure S1-5); summary of the overall LCIA results (Table S1); summary of literature values used to generate the comparative bar chart displayed in figure 3 (Table S2); and the full range of impact categories considered in the sensitivity analysis, assessing the impact of seaweed carbohydrate content and packaging material market value on overall environmental emissions (Figure S6).

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1 Abbreviations

The following abbreviations have been used for the ReCiPe midpoint categories:

GW	Global warming	MEu	Marine eutrophication
FRS	Fossil resource scarcity	MRS	Mineral resource scarcity
FE	Freshwater ecotoxicity	AC	Acidification
FEu	Freshwater eutrophication	TE	Terrestrial ecotoxicity
HCT	Human carcinogenic toxicity	W	Water consumption
HnCT	Human non-carcinogenic toxicity	LU	Land use
ME	Marine ecotoxicity		

Abbreviations used for the modelled scenarios:

EG	Economic allocation	with	Green energy mix
ES	Economic allocation	with	Standard energy mix
MG	Mass allocation	with	Green energy mix
MS	Mass allocation	with	Standard energy mix
SG	System expansion	with	Green energy mix
SS	System expansion	with	Standard energy mix

Abbreviations used for the unit processes comprising the product system:

AW	Acid washing	PP	Packaging material production
BP	Biorefinery products	SD1-3	Drying 1-3
DF	Filtration	SWC	Seaweed cultivation
M	Milling	WW	Water washing

Abbreviations used for alternative polymers:

HDPE	High-density polyethylene	PP	Polypropylene
LDPE	Low-density polyethylene	PS	Polystyrene
PET	Polyethylene terephthalate	PVC	Polyvinyl chloride
PHA	Polyhydroxyalkanoates	TPS	Thermoplastic starch
PLA	Polylactic acid		

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2 Contribution analysis

Figure S1 - Graph showing the relative process contributions for scenario SS (system expansion, standard energy) in each of the assessed environmental impact categories.

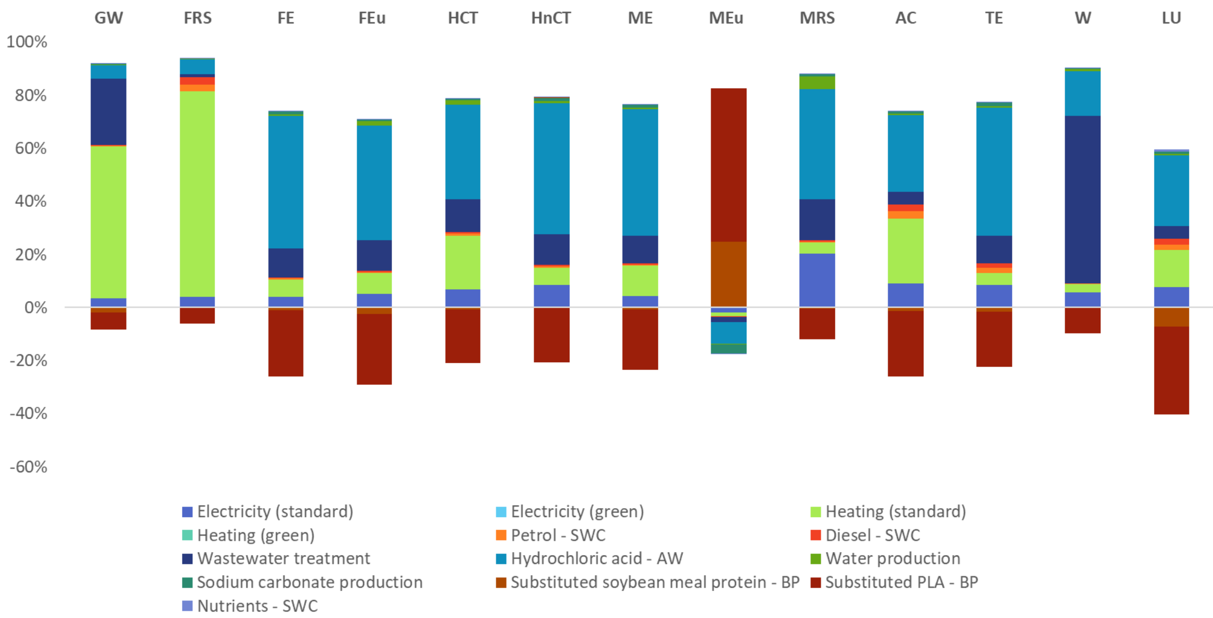
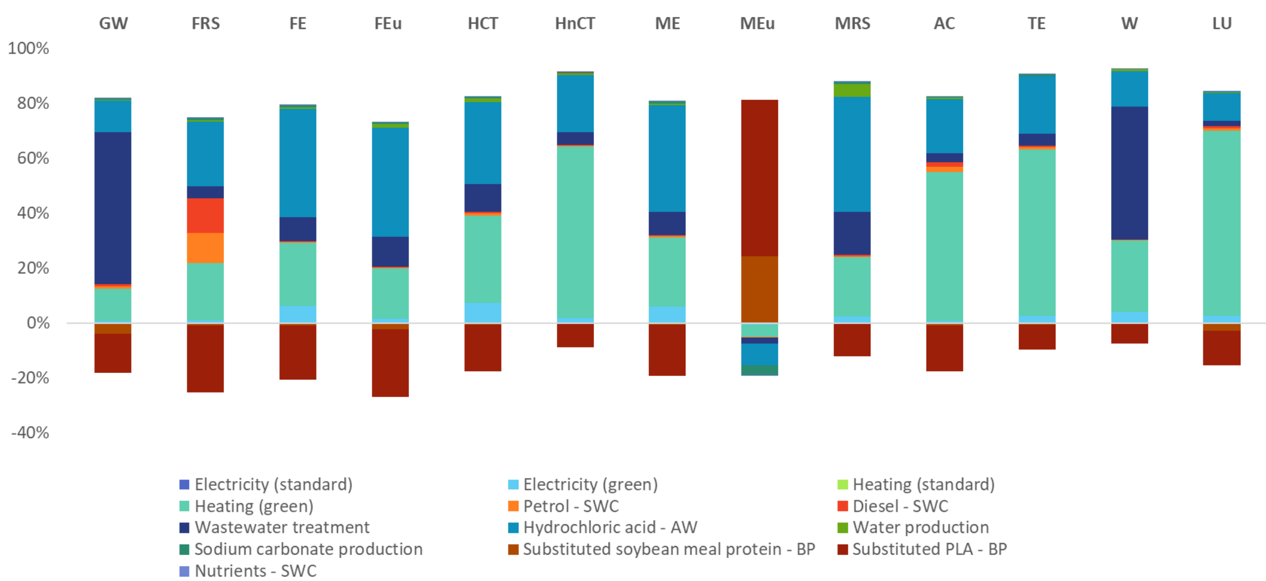


Figure S2 - Graph showing the relative process contributions for scenario SG (system expansion, green energy) in each of the assessed environmental impact categories.



https://doi.org/10.1007/s11367-023-02239-w

Figure S3 - Graph showing the overall environmental impacts generated from SS (blue) relative to that generated from SG (green).

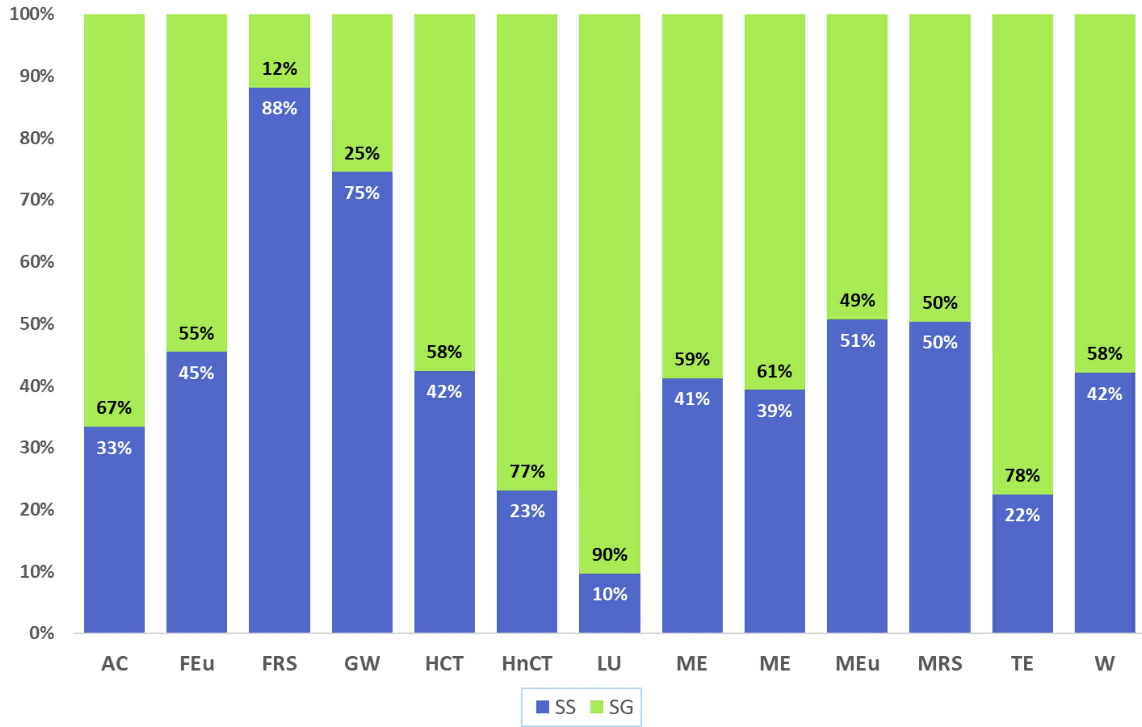


Figure S4 - Bar charts highlighting the percentage contribution of key activities/processes (namely electricity, heating, water supply, wastewater treatment, nutrients added during the cultivation (nursery phase), petrol and diesel used during cultivation (out-sea growth phase), HCl production, NaOH production, and substituted products PLA and soybean protein) to the overall potential environmental impacts, in the **standard energy** scenario (**SS**).

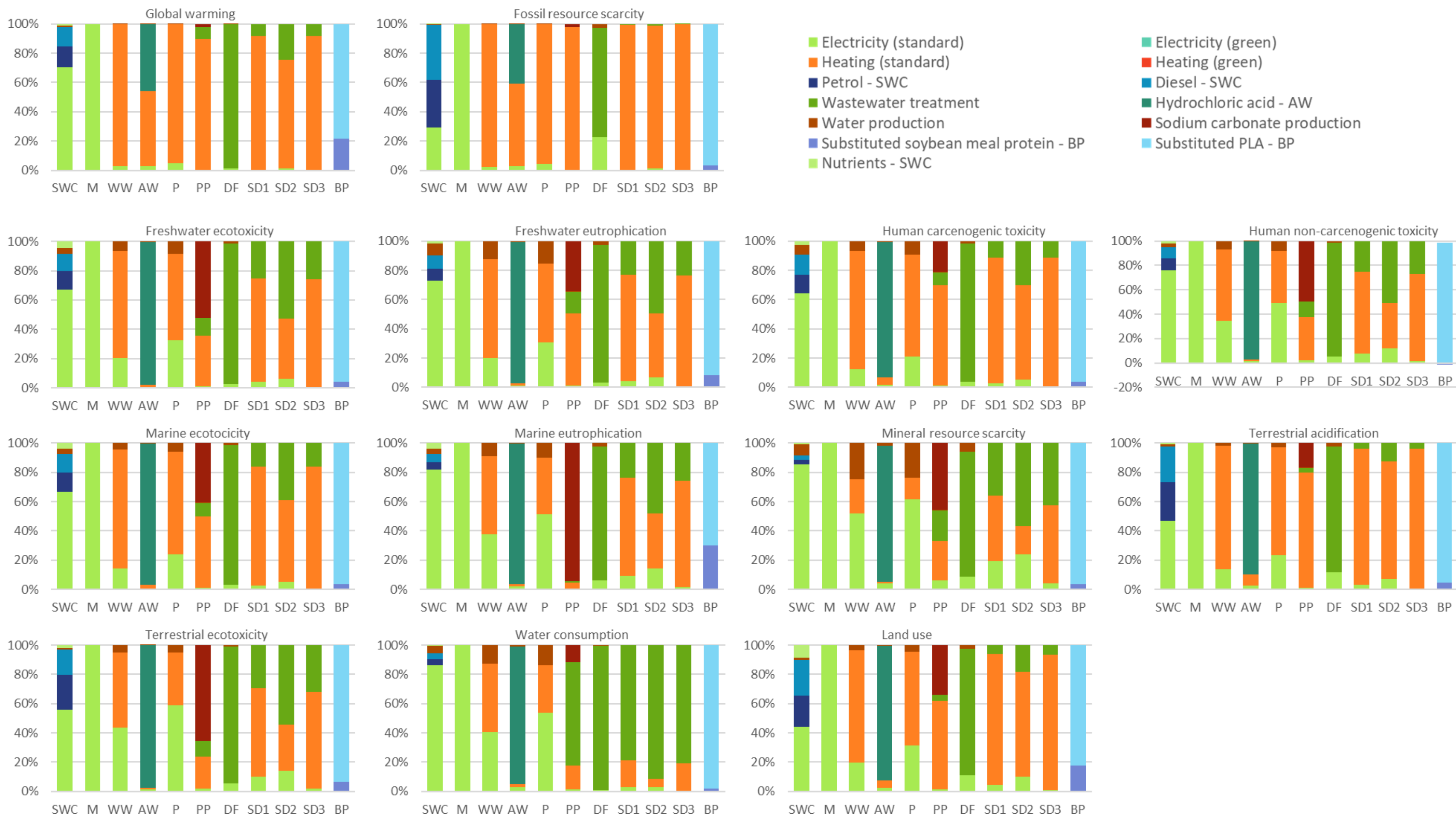
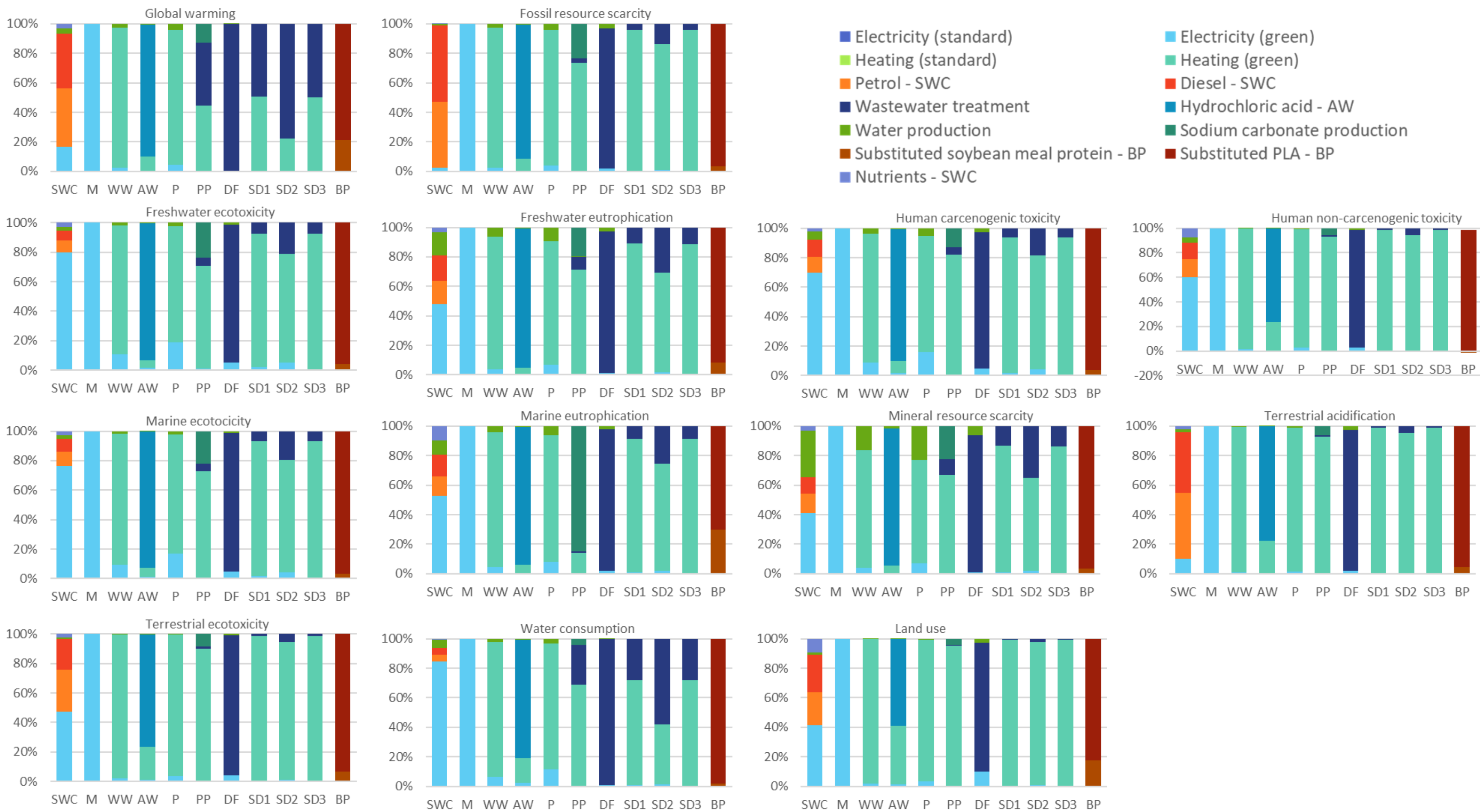


Figure S5 - Bar charts highlighting the percentage contribution of key activities/processes (namely electricity, heating, water supply, wastewater treatment, nutrients added during the cultivation (nursery phase), petrol and diesel used during cultivation (out-sea growth phase), HCl production, NaOH production, and substituted products PLA and soybean protein) to the overall potential environmental impacts, in the **green energy** scenario (**SG**).



3 Overall life cycle impact assessment results

Table S1 - Summary of the overall LCIA results, across all 18 of the midpoint impact categories made available through the ReCiPe 2016 (Hierarchist) assessment method. Impact values have been reported in reference to the production of 1kg polymeric resin (the functional unit).

		Scenario					
Impact category	**units**	**MS**	**ES**	**SS**	**MG**	**EG**	**SG**
Stratospheric ozone depletion	kg CFC11 eq	2.70E-06	1.30E-06	-1.67E-06	4.96E-06	2.49E-06	3.81E-06
Ionizing radiation	kBq Co-60 eq	4.09E-01	1.03E-01	3.02E+00	3.84E-01	1.35E-01	2.09E+00
Ozone formation, Human health	kg NOx eq	5.90E-03	2.90E-03	2.29E-02	3.00E-02	1.71E-02	1.11E-01
Ozone formation, Terrestrial ecosystems	kg NOx eq	6.09E-03	3.01E-03	2.35E-02	3.06E-02	1.74E-02	1.12E-01
Terrestrial acidification	kg SO2 eq	7.99E-03	2.92E-03	2.77E-02	2.35E-02	9.30E-03	5.54E-02
Fine particulate matter formation	kg PM2.5 eq	2.90E-03	1.05E-03	9.32E-03	1.47E-02	6.90E-03	4.21E-02
Global warming	kg CO2 eq	7.06E+00	4.52E+00	4.15E+01	3.58E+00	1.25E+00	1.42E+01
Marine eutrophication	kg N eq	1.30E-04	8.77E-05	-1.48E-03	2.99E-04	1.30E-04	-1.44E-03
Human non-carcinogenic toxicity	kg 1,4-DCB	1.36E+00	3.28E-01	5.57E+00	1.02E+01	3.48E+00	1.86E+01
Fossil resource scarcity	kg oil eq	2.65E+00	1.63E+00	1.26E+01	9.60E-01	2.58E-01	1.68E+00
Freshwater ecotoxicity	kg 1,4-DCB	1.02E-01	2.51E-02	3.55E-01	9.59E-01	2.18E-01	5.48E-01
Freshwater eutrophication	kg P eq	5.81E-04	1.41E-04	1.94E-03	1.84E-03	4.55E-04	2.33E-03
Mineral resource scarcity	kg Cu eq	8.51E-04	1.99E-04	4.54E-03	2.92E-03	7.26E-04	4.48E-03
Marine ecotoxicity	kg 1,4-DCB	1.43E-01	3.97E-02	5.28E-01	1.21E+00	2.79E-01	7.51E-01
Water consumption	m3	8.95E+00	3.59E+00	1.04E+02	1.11E+02	2.86E+01	1.44E+02
Land use	m2a crop eq	3.18E-03	1.06E-03	5.46E-03	3.97E-02	1.31E-02	5.10E-02
Terrestrial ecotoxicity	kg 1,4-DCB	5.95E+00	1.50E+00	2.26E+01	5.27E+01	1.67E+01	7.80E+01
Human carcinogenic toxicity	kg 1,4-DCB	6.55E-02	2.25E-02	2.73E-01	6.77E-01	1.57E-01	3.70E-01

4 Comparison of seaweed biopolymer with commercial alternatives

Table S2 - Summary of literature values used to generate the comparative bar chart displayed in figure 3. Data is inclusive of studies where LCA was conducted from the cradle-to-gate perspective, specifically from raw material acquisition through to the production of 1 kg of polymer resin/pellet.

	This study						Renewable			Fossil					
Reference	**MS**	**ES**	**SS**	**MG**	**EG**	**SG**	**PHA**	**PLA**	**TPS**	**HDPE**	**LDPE**	**PET**	**PP**	**PS**	**PVC**
This study	7.06086	4.5236	41.51901	3.58485	1.24844	14.19045									
(Gironi and Piemonte 2011)								1.086169				2.647536			
(Detzel and Krüger 2006)								1.860095				3.2846	1.973609	3.494898	
(Sommerhuber et al. 2017)										2.18					
										0.76					
										1.73					
										0.78					
(Yu and Chen 2008)							0.49								
(Akiyama et al. 2003)							0.26			1.7	1.9	3.1	1.9	2.6	
							0.45								
Ecoinvent (Frischknecht et al. 2005)								3.11551		1.99541	2.04612	2.81805	1.97489	3.84625	1.97374
(Vink et al. 2010)								1.3							
											2.1	3.4	1.9	3.4	1.9
												3.2			
(Fröhlich et al. 2014)										1.8	1.87				
											1.79				
(Fröhlich et al. 2016)													1.63		
(Hottle et al. 2013)									2						
(Kurdikar et al. 2000)							-4								
							3.8								
(Moretti et al. 2020)													0.63		
													-2.51		
(Madival et al. 2009)								1.9646				1.9914		2.8045	
(Braskem 2016)										-3.09					

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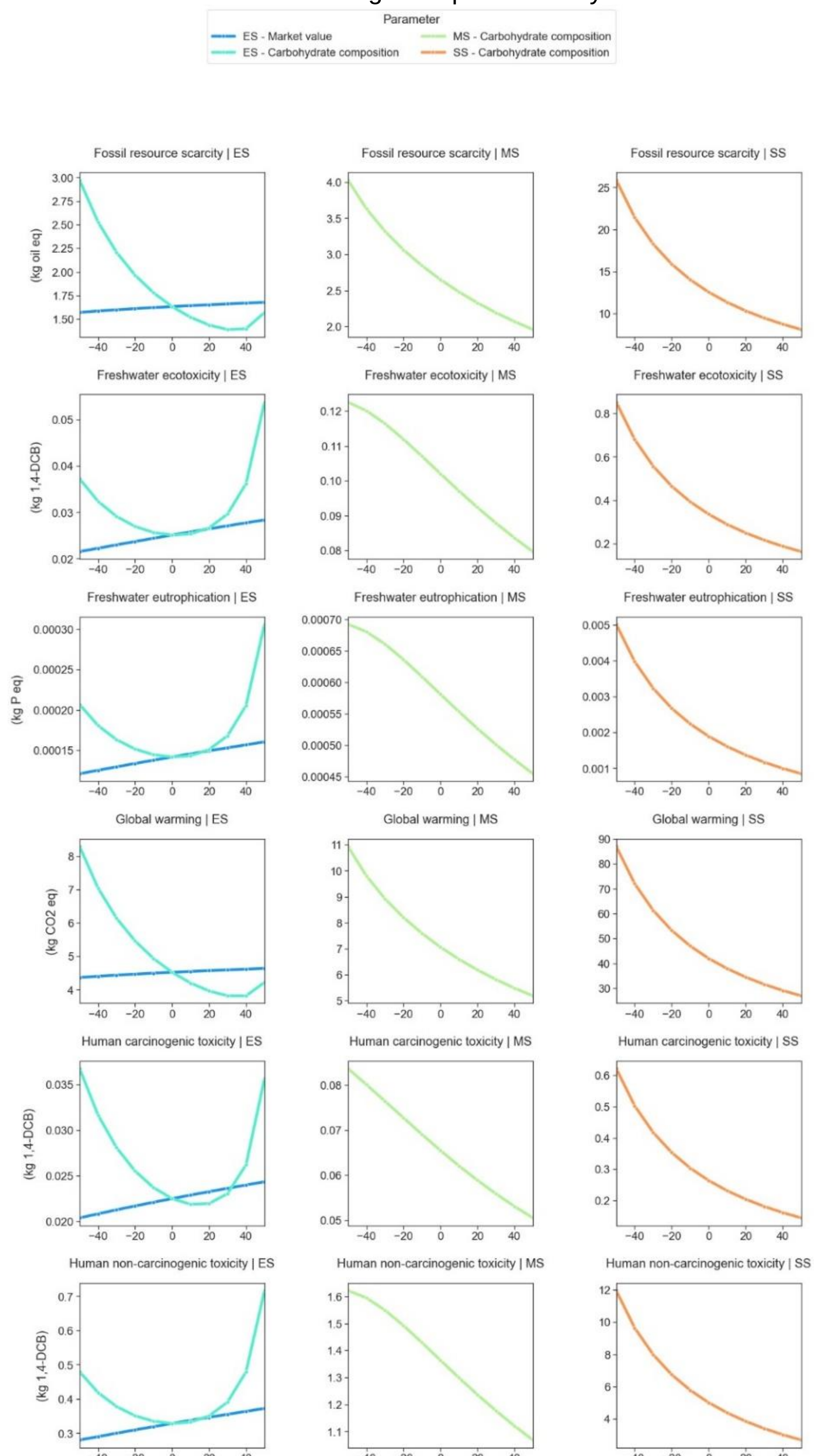
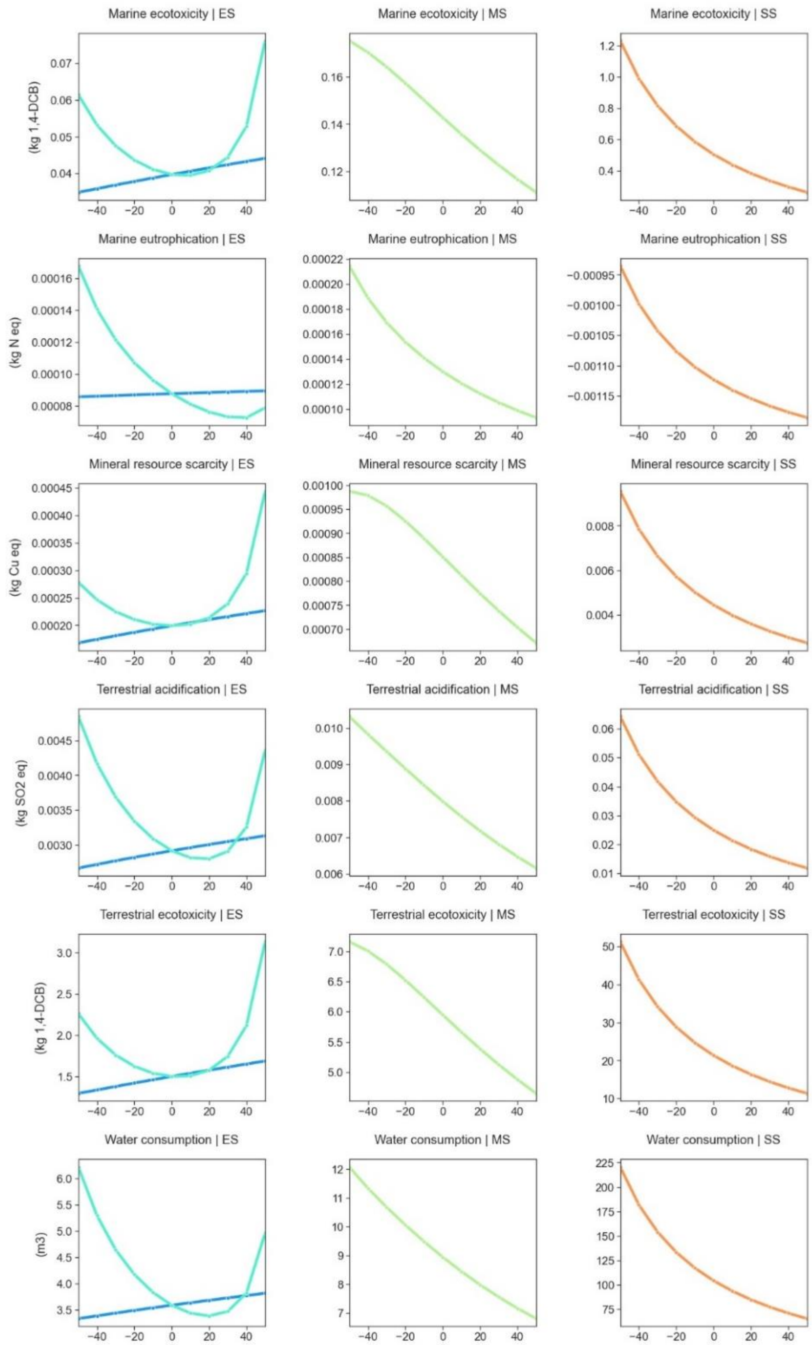
5 Sensitivity analysis

Figure S6 - Sensitivity analysis showing the relative influence of various parameters on potential environmental impacts generated in each standard energy scenario. Parameters assessed included biomass carbohydrate (specifically alginate and cellulose) composition and the market value of the packaging polymer. Parameter inputs were varied at 10% increments within ±50% of the original input/inventory values.




Marine ecotoxicity | ES
Marine ecotoxicity | MS
Marine ecotoxicity | SS
(kg 1,4-DCB)
Marine eutrophication | ES
Marine eutrophication | MS
Marine eutrophication | SS
(kg N eq)
Mineral resource scarcity | ES
Mineral resource scarcity | MS
Mineral resource scarcity | SS
(kg Cu eq)
Terrestrial acidification | ES
Terrestrial acidification | MS
Terrestrial acidification | SS
(kg SO2 eq)
Terrestrial ecotoxicity | ES
Terrestrial ecotoxicity | MS
Terrestrial ecotoxicity | SS
(kg 1,4-DCB)
Water consumption | ES
Water consumption | MS
Water consumption | SS
(m3)