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Multi criteria decision analysis for sustainability assessment of 2nd generation biofuels

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ABSTRACT

This paper presents results of the comparative sustainability assessment of three renewable and fossil fuel production routes, i.e. gasoline from straw or wood, and conventional gasoline. For the simultaneous consideration of the ecological, economic and social dimension a MS Excel-based tool is developed, which enables the assessment of energy technologies by choosing different MCDA (Multi Criteria Decision Analysis) methods, weighting sets, weighting methods and normalization methods for ecological indicators. Results for the MCDA method TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) show, that stakeholders who prioritize the economic dimension (Individualist) would choose conventional gasoline, while stakeholders who prioritize the ecological and the social dimension (Hierarchist and Egalitarian) would choose gasoline from wood.

1. Introduction

The transformation of the energy system is crucial for the sustainable development of European countries and to become climate-neutral by 2050 respectively. Innovative energy technologies can make an important contribution to increase the share of renewable energy and decrease greenhouse gas emissions, for example by using lignocellulose biomass (e.g. residual straw and wood) instead of fossil resources for the production of transportation fuels. These 2nd generation biofuels do not trigger land use competition with food and fodder production. Moreover, the production of 2nd generation biofuels from lignocellulose plants, such a trees, wheat straw or miscanthus, show higher area specific yields than the the production of 1st generation biofuels, since the whole plant is converted to energy and not only parts of the plants (e.g. oilseed or cereal grains).

Coming from the triple-bottom-line model, sustainability refers to the three dimensions ecology, economy, society and corresponding indicators (Guinée, 2016). Sustainability assessment is addressing these dimensions separately with different methods and techniques. The results from Life Cycle Assessment (LCA), Life Cycle Costing (LCC) and empirical social sciences are providing specific individual results. Since each energy technology has different intended and unintended impacts on the different indicators and there are trade-offs between indicators, decision-makers have to aggregate and evaluate the single results by their preferences, which can be on the economic, ecological or social side. The objective of this paper is to investigate how mathematical models can support this decision-making step by showing how normative weighting will influence priority setting among different choices. Based on (Haase and Rösch, 2019) this paper presents results of the comparative sustainability assessment of different fuel production routes with simultaneous consideration of ecological, economic and social indicators. In order to compare different (technological) alternatives taking into account all three sustainability dimensions and various indicators simultaneously, weighting and normalization of indicators and dimensions respectively is necessary. For this purpose, a MS Excel-based tool is developed, which enables the assessment of energy technologies by choosing e.g. different normalization methods for ecological indicators, MCDA (Multi-Criteria-Decision-Analysis) methods, weighting methods, and stakeholder profiles.

1.1. Sustainability indicators for the assessment of energy technologies

Starting point of our analyses are the methods and results of the economic and ecological assessment of different fuel production routes within the Helmholtz Initiative Energy System 2050 (ES2050) (Haase and Rösch, 2019). There, a life cycle based approach based on the modelling of material and energy flows and

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the preparation of a life cycle inventory (LCI) is applied as a basis for ecological and economic assessment. For ecological assessment, 13 environmental impact categories, methods and indicators at midpoint, as recommended in the International Reference Life Cycle Data System (ILCD) Handbook of the European Commission (Hausschild et al., 2011), are used. According to (Hausschild et al., 2011), indicators and corresponding impact assessment methods are classified as follows:

- I: recommended and satisfactory
- II: recommended but in need of some improvements
- III: recommended, but to be applied with caution
- Interim: not recommended to use

Three indicators are classified with intermediate classes, i.e. as "II/III". Indicators classified as III and interim are excluded from the assessment. In Table A1 in Appendix A the list of ILCD indicators and corresponding classes is given.

For economic assessment, manufacturing costs of fuel are used as indicator. While methods and indicators for LCA and LCC are common practice, social life cycle assessment (S-LCA) is fragmented and a general theoretical concept and empirical experiences are widely missing. Within the ES2050 approach, three social issues and corresponding indicators are chosen from the Sustainability Indicator System (SIS) of the Helmholtz Alliance Energy-Trans (Rösch et al., 2017): innovation potential, public acceptance and local added-value. In this paper, the number of employees is used as a proxy for social assessment.

1.2. Normalization of ecological indicators

For the ecological dimension, indicator results need to be aggregated to one central key figure. In (Castellani et al., 2016) a distance-to-target approach for ecological indicators according to the ILCD Handbook (Hausschild et al., 2011) is provided. EU-wide emissions in 2010 are taken as a starting point and correspond to the actual situation. For 2020, the authors have worked out two possible targets for EU-wide emissions. In case A, the authors include all binding targets within the EU for calculating the target state for 2020. For case B, the authors additionally include non-binding declarations of intent for calculating the normalization values for the individual indicator values (Castellani et al., 2016).

1.3. Weighting methods

When evaluating different alternatives by several criteria, the criteria must be related to each other. In particular, the weight to be attached to each criterion must be determined. The weighting represents the importance of each criterion compared to every other criterion. Examples for different weighting methods are pairwise comparison standard, pairwise comparison according to Saaty and SMART (Simple Multi-Attribute Rating Technique) (Geldermann and Lerche, 2014).

1.4. MCDA methods

MCDA is a methodical approach to consider several criteria in a problem-solving process. In general, MCDA is divided into two areas: MODM (Multi Objective Decision Making) and MADM (Multi Attribute Decision Making) (Geldermann and Lerche, 2014): In MODM, a trade-off between criteria is made free of concrete alternatives (continuous solution space), while in MADM the best alternative between a discrete set of alternatives is found. In this paper, MADM methods are applied, as concrete alternatives are compared.

MADM assessment methods can be divided into classical American and European/French schools. The classical approaches of the American school are, for example, utility analysis (UTA) or AHP (Analytical Hierarchy Process). The European/French school provides outranking approaches such as those used in the PROMETHEE and ELECTRE. The classical approaches always have a compensatory approach. In this context, compensatory means that good results in one criterion can compensate for poor results in another criterion. The outranking approaches can be designed differently. Completely compensatory as well as not at all compensatory procedures are conceivable. The MADM method TOPSIS (Technique for order preference by similarity to ideal solution) used in this paper belongs to the compensatory methods (García-Cascales and Lamata 2012). In TOPSIS, the performance of an alternative (from a finite number of alternatives) is evaluated by determining the distance between the individual characteristic values of the considered alternative and two 'virtual alternatives' (Geldermann and Lerche, 2014).

1.5. Stakeholder profiles

The application of MCDA methods requires the engagement of stakeholders/decision makers/citizens in each step of the MCDA process. This engagement should comprise the definition of the decision problem, the selection of alternatives, evaluation criteria and indicators, and the weighting of criteria. If this is not possible by conducting e.g. stakeholder workshops or an expert survey, cultural profiles from literature can be used as a proxy to portray different ethical settings, values and points of views (Ekener et al., 2018).

In the cultural theory of risk it is described that people assess risks differently and react differently to them (Tsohou et al., 2015). This results in three cultural profiles (Individualist, Hierarchist, Egalitarian) which can be used in life cycle analyses. Behavior patterns of these cultural profiles can be described and differentiated in terms of time perspective, required level of evidence and manageability (Goedkoop and Spriensma, 2000; Sikdar et al., 2017) (see Table 1). In Ekener et al. (2018) (Ekener et al., 2018) these profiles are used to develop priorities for the three dimensions of sustainability (see Table 1).

2. MS-Excel-based tool

For the integrated ecological, economic and social sustainability assessment of energy technologies a MS Excel-based tool is developed.

2.1. User Interface and functions

The developed tool currently allows for the consideration of

- different sets of ecological indicators (three different sets of indicators, i.e. indicators of class I, indicators of class I and II, indicators of class I, II and II/III based on (Hausschild et al., 2011))
- different normalization methods for ecological indicators (six alternatives based on (Castellani et al., 2016))
- different numbers of energy technologies (three to four alternatives)
- different MCDA methods (UTA, TOPSIS)
- different weighting methods (weighting according to Ekener et al. (2018) (Ekener et al., 2018), pairwise comparison 0-1-2, pairwise comparison 0-1-2-3, SMART, free choice).

The tool also allows for sensitivity analysis with respect to the weighting of the three sustainability dimensions and the variation of selected input data/indicator values (in this study: manufacturing costs of fossil gasoline, manufacturing costs of gasoline from wood). All relevant entries are made on the start interface. The

Table 1
Time perspective, required level of evidence, manageability (according to (Goedkoop and Spriensma, 2000, Sikdar et al., 2017)) and resulting priority settings for the sustainability dimensions (according to (Ekener et al., 2018)) for cultural profiles Individualist, Hierarchist, Egalitarian.

		Individualist	Hierarchist	Egalitarian
Time perspective		Short-term	In between short and long-term	Long-term
Required level of evidence		Only proven effects	Effects on a consensus basis	All possible effects
Manageability		Technology can avoid many problems	Policy can avoid many problems	Problems can lead to catastrophic events
	1	Economy	Ecology	Social
Priority	2	Ecology	Economy	Ecology
	3	Social	Social	Economy

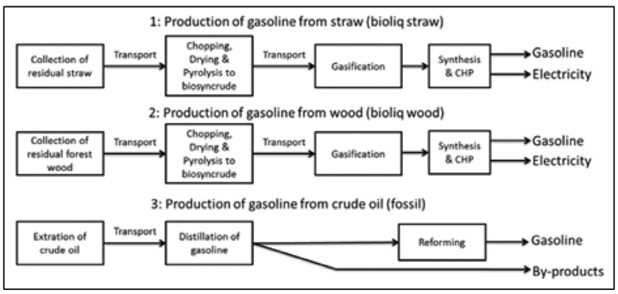


Fig. 1. Considered fuel production routes: bioliq straw (1), bioliq wood (2), fossil (3).

start interface is divided into three different sections: input, output and functions. Within the input section, alternatives are selected, the weighting method as well as the set and the normalization method of ecological indicators. Within the output section, the value table for MCDA is displayed as well as the results (tables and diagrams). In the functions section, e.g. sensitivity analyses can be performed using the corresponding buttons.

2.2. Considered energy technologies

As shown in Fig. 1, three different ways of producing gasoline are considered: the bioliq process with the feedstock wheat straw (bioliq straw) or forest residues (bioliq wood), and a classical refinery process as fossil reference (fossil). Main process steps of the classical refinery process are distillation and reforming. Main process steps of the production of gasoline from straw or wood are pyrolysis, gasification and fuel synthesis (see Fig. 1).

2.3. Input data for MCDA

The values for economic and ecological indicators (manufacturing costs of gasoline and 13 ecological indicators according to ILCD) are based on Haase and Rösch (2019). Since a cradle to gate approach is applied, contrary to (Haase and Rösch, 2019) the use phase is not included for ecological assessment in this paper. Ecological indicator values before normalization are given in Table B1 in Appendix B.

For bioliq straw and bioliq wood, values for the social indicator (number of employees) are estimated using labor coefficients for

- biomass provision (11.1) taken from (Statistisches Bundesamt, 2016)
- construction of the biofuel production plant (4.4) taken from (Lehr et al., 2011)
- operation of the biofuel production plant (6.8) taken from (Lehr et al., 2011)

Labor coefficients correspond to the ratio of employed persons to the production value of selected production sectors and include direct and indirect employees (Statistisches Bundesamt, 2016). For fossil gasoline, the number of direct and indirect employees of petroleum industry without petrol stations and the production capacity for Germany are taken as a basis for our estimates (Schmid et al., 2019). In Table 2 the input data (value table) for MCDA is given for standard settings (13 ecological indicators class I, II and II/III, normalization of ecological indicators according to the target reference B). Input data for MCDA refers to

- normalized impacts of ILCD indicators per liter (ecology)
- manufacturing costs in cent/l (economy)
- number of employees per liter (social)

2.4. Weighting of priorities

For the weighting of the three sustainability dimensions, priority settings of standardized stakeholder profiles, i.e. cultural profiles Individualist, Hierarchist, Egalitarian (see Table 1) together with the weighting of priorities according to Ekener (2018) (Ekener et al., 2018), pairwise comparison 0-1-2 and pairwise comparison 0-1-2-3 are used (see Table 3).

2.5. Implementation of MCDA method TOPSIS

TOPSIS is selected for the prototypical application of the MS Excel tool. The TOPSIS method starts with the normalization of the input data (see Table 4): for each dimension (a, b, c), the root is taken from the sum of the squared values of the different alternatives (1, 2, 3). The resulting normalization factors ($a_{norm}, b_{norm}, c_{norm}$) are taken to normalize the input data for the three sustainability dimensions.

The normalization is carried out by dividing the input values by the normalization factors. The normalized values have no units and are multiplied with the weighting factor of the respective category (w_j). In Eqs. (1) and (2) normalization and weighting is described exemplarily for the ecological dimension (a). In Eq. (1) the calculation of the normalized values a'_i and in Eq. (2) the calculation of the normalized and weighted values A_i is described. For the economic (b) and the social (c) dimension the procedure is the same.

$$a'_i = {}^{a_i}/_{a_{norm}} \tag{1}$$

$$A_i = a'_i * w_j \tag{2}$$

With the normalized and weighted values, the alternatives can be interpreted as points $P_i(A_i/B_i/C_i)$ depending on the three dimensions. Besides, two theoretical points are calculated: A point $P_{max}(A_{max}/B_{max}/C_{max})$ that corresponds to the best value in each category over all considered alternatives and a point $P_{min}(A_{min}/B_{min}/C_{min})$, which corresponds to the worst value over all alternatives. With the generated points (one per alternative plus two auxiliary points), distance calculations are carried out for each alternative (see Eqs. (3) and (4)): the distance to the point of the best possible value ($S_i{}^+$) and the distance to the point of the worst possible value ($S_i{}^-$) is calculated.

$$S_i{}^+ = \sqrt{(A_i - A_{max})^2 + (B_i - B_{max})^2 + (C_i - C_{max})^2} \tag{3}$$

Table 2
Input data for MCDA (standard settings).

Dimension	Unit	Alternative bioliq straw (1)	bioliq wood (2)	fossil (3)
Ecology (a)	Impact/l	4.44E−13	8.12E−14	4.43E−13
Economy (b)	Cent/l	147.48	157.67	38.84
Social (c)	Employees/l	1.12E−05	1.24E−05	1.72 E−06

Table 3
Weighting of priorities according to Ekener et al. (2018), pairwise comparison 0-1-2, pairwise comparison 0-1-2-3.

		Ekener et al. (2018)	Pairwise Comparison 0-1-2	Pairwise Comparison 0-1-2-3
Priority	1	60%	67%	56%
	2	28%	33%	33%
	3	12%	0%	11%

Table 4
Normalization of input data within TOPSIS.

Dimension	bioliq straw	bioliq wood	fossil	Normalization factors
Ecology	a_1	a_2	a_3	$a_{norm} = \sqrt{{a_1}^2 + {a_2}^2 + {a_3}^2}$
Economy	b_1	b_2	b_2	$b_{norm} = \sqrt{{b_1}^2 + {b_2}^2 + {b_3}^2}$
Social	c_1	c_2	c_3	$c_{norm} = \sqrt{{c_1}^2 + {c_2}^2 + {c_3}^2}$

$$S_i^- = \sqrt{(A_i - A_{min})^2 + (B_i - B_{min})^2 + (C_i - C_{min})^2} \quad (4)$$

The calculated distances are summed up and interpreted as the total length, which varies depending on the alternative. The degree of fulfillment or 'performance value' for each alternative (PV_i) is then calculated over the total length and the distance to the theoretically worst alternative (Eq. (5)).

$$PV_i = S_i^- / \left(S_i^+ + S_i^-\right) \quad (5)$$

The best choice according to TOPSIS is the alternative, which is the closest to the best possible value and the farthest from the worst possible value.

3. Results and discussion

The results of the MCDA for standard settings (see Section 2.3) are presented in Fig. 2 for the stakeholder profiles Individualist, Hierarchist and Egalitarian. Weighting is carried out using pairwise comparison 0-1-2-3.

For these settings, stakeholders who prioritize the economic dimension (Individualist - Ind) would choose conventional gasoline, while stakeholders who prioritize the ecological and the social dimension (Hierarchist – Hier and Egalitarian - Egal) would choose gasoline from wood (see Fig. 2). While the Hierarchist would choose fossil gasoline in second place, the Egalitarian would choose bioliq straw in second place. These results provide evidence that different cultural profiles i.e. different weighting of sustainability dimensions, results in different rankings of the alternatives to be compared. The influence of the weighting of the dimensions on the ranking of the alternatives is investigated through sensitivity analyses (see Section 3.1).

In Table 5, performance values PVi and rankings Ri of the three alternatives are given for standard settings as well as varied settings (only three ecological indicators of class I). These results show that the choice and number of ecological indicators influences the performance values and the ranking of alternatives. Table 5 also shows that the presentation of performance values instead of the rankings has the advantage that supposedly unambiguous results (e.g., ranking fossil is better than ranking bioliq wood) are put into perspective.

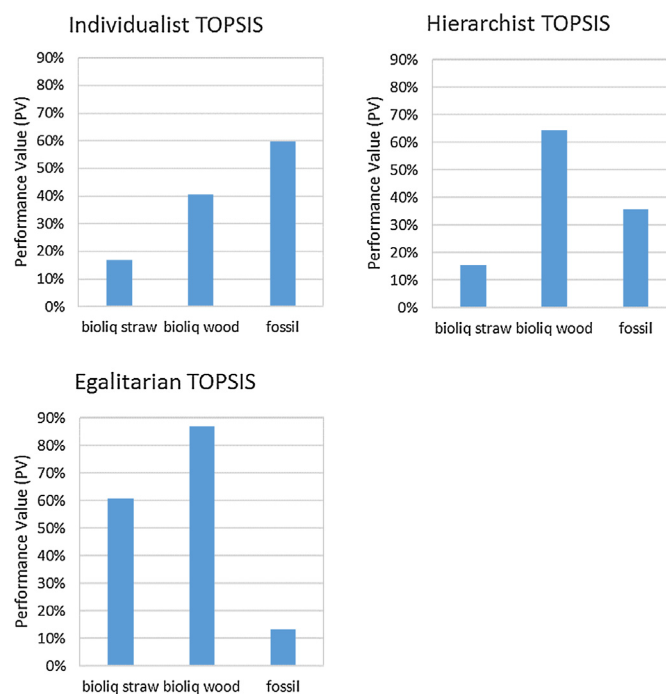


Fig. 2. Performance values of bioliq straw, bioliq wood and fossil gasoline for standardized stakeholder profiles (Individualist, Hierarchist, Egalitarian).

Table 5
Rankings Ri and performance values PVi for standard and varied settings (Var 1)

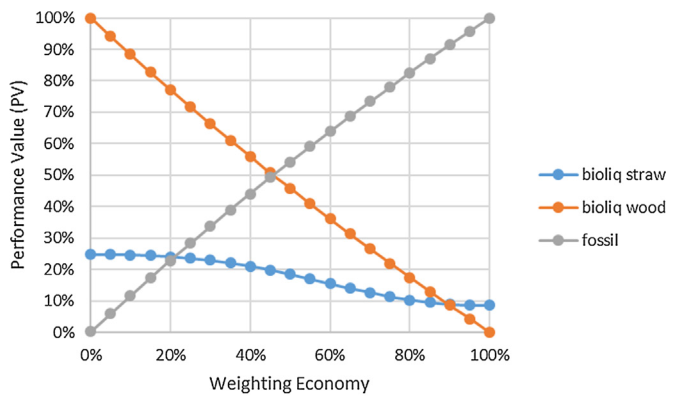
		Standard Ind	Hier	Egal	Var 1 Ind	Hier	Egal
bioliq	R_1	3	3	2	3	2	2
straw	PV_1	0.17	0.15	0.61	0.44	0.63	0.78
bioliq	R_2	2	1	1	2	1	1
wood	PV_2	0.40	0.64	0.87	0.50	0.73	0.88
fossil	R_3	1	2	3	1	3	3
	PV_3	0.60	0.36	0.13	0.50	0.27	0.12

3.1. Sensitivity analysis

Sensitivity analyses are presented for the variation of

- weighting of dimension economy, with the other two dimensions remaining in the same proportion (Fig. 3A)
- manufacturing costs of fossil gasoline (Fig. 3B)
- manufacturing costs of gasoline from wood (bioliq wood)

For the former, the weighting value of economy increases linearly while the sum of the weighting values of the other two di-



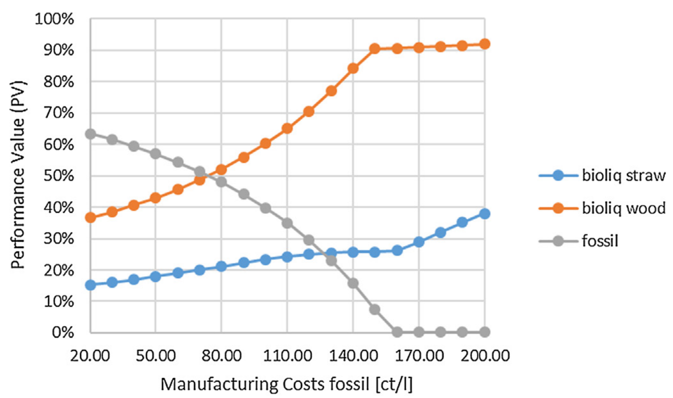


Fig. 3. Sensitivity analysis: variation of weighting of dimension economy (A) and variation of manufacturing costs of fossil gasoline (B).

mensions decreases. Fig. 3A shows the course of the performance values of the alternatives at standard settings (see Section 2.3). In this case, the ratio of ecology to social is 33:11 (3:1) and corresponds to the weighting of sustainability dimensions according to the Individualist profile using pairwise comparison 0-1-2-3. From Fig. 3A one can interpret that the Individualist would chose bioliq wood as a first priority if the dimension economy is weighted with less than 45%.

Fig. 3B shows the results for the variation of the manufacturing costs of fossil gasoline based on standard settings and the Individualist profile. The results depicted in Fig. 3B indicate that the Individualist would choose bioliq wood as first priority if the manufacturing costs of fossil gasoline would exceed 70 ct/l. Political framework conditions but also rising crude oil prices could favor this cost increase. Vice versa, as a result from sensitivity analysis for the variation of manufacturing costs of gasoline from wood (bioliq wood), the Individualist would choose bioliq wood as first priority, if manufacturing costs of bioliq wood would be lower than 90 ct/l. A reduction in bioliq wood manufacturing costs could be achieved e.g. through considerably lower biomass costs or through redesigning the process in order to e.g. obtain higher fuel yields. Redesigning of the process would also have implications on the ecological indicators though and therefore, implications of redesigning on stakeholder decisions can be analyzed only if all chosen indicators are included. This will be subject of further research but cannot be included in this paper.

4. Outlook

Further research will focus on the further development of the MS Excel tool with regard to the inclusion of additional MCDA methods, such as AHP and PROMETHEE, aiming at the further elaboration of the influence of the choice of MCDA methods on the results. In addition, more technology alternatives will be implemented and the influence of addition and removal of alternatives on the results will be examined in more detail as well as implications of redesigning processes on stakeholder decisions. Furthermore, cultural profiles and underlying assumptions will be analysed more profoundly and last but not least, instead of using cultural profiles, stakeholder workshops and experts interviews are planned to be included for MCDA of 2nd generation biofuels.

CRediT authorship contribution statement

Martina Haase: Conceptualization, Methodology, Writing - original draft, Writing - review & editing. **Nils Babenhauserheide:** Methodology, Software. **Christine Rösch:** Methodology, Writing - review & editing, Supervision.

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Appendix A. Ecological indicators

Table A1.

Table A1
Ecological impact categories, indicators and methodical quality classes according to (Guinée, 2016).

Impact category	Indicator	Class
Acidification (Acid)	Accumulated Exceedance (AE)	II
Climate change (CC)	Global Warming Potential (GWP)	I
Freshwater ecotoxicity (Ecotox-fw)	Comparative Toxic Unit for Ecosystems (CTU-e)	II/III
Freshwater eutrophication (Eutr-fw)	Fraction of nutrients reaching freshwater (FN-fw)	II
Human toxicity – carcinogenics (HT-c)	Comparative Toxic Unit for Humans (CTU-h)	II/III
Human toxicity – non-carcinogenics (HT-nc)	Comparative Toxic Unit for Humans (CTU-h)	II/III
Ionizing radiation – ecosystems (IR-ecosys)	Comparative Toxic Unit for Ecosystems (CTU-e)	Interim
Ionizing radiation – human health (IR-hh)	Human exposure efficiency relative to U^{235} (HExp-U235)	II
Land use (LU)	Soil organic matter (SOM)	III
Marine eutrophication (Eutr-mar)	Fraction of nutrients reaching marine water (FN-mar)	II
Ozone depletion (OD)	Ozone Depletion Potential (ODP)	I
Particulate matter/Respiratory inorganics (PM)	Intake fraction for fine particles (PM2.5-eq) (IF-FP)	I
Photochemical ozone formation (POF)	TOC Tropospheric ozone concentration increase (TOC)	II
Resource depletion - mineral, fossils and renewables (RD)	Scarcity (Scarc)	II
Resource depletion – water (RD-water)	Water use related to local scarcity of water (WU)	III
Terrestrial eutrophication (Eutr-ter)	Accumulated Exceedance (AE)	II

Table B1
Input data for ecological indicators (per t of fuel) (Haase and Rösch, 2019).

Impact category/Indicator	Unit	bioliq straw	Bioliq wood	fossil
Acid/AE	molc H^+ eq	4.84	2.74	8.41
CC/GWP	kg CO_2 eq	−358.04	−573.40	798.60
Ecotox-fw/CTU-e	CTUe	2556.04	874.25	2142.04
Eutr-fw/FN-fw	kg P eq	−1.02	−1.09	0.11
HT-c/CTU-h	CTUh	−0.00001	0.00002	0.000023
HT-nc/CTU-h	CTUh	0.0007	0.0004	0.000094
IR-hh/HExp-U235	kBq U^{235} eq	−124.65	−133.79	271.85
Eutr-mar/FN-mar	kg N eq	1.18	0.53	0.87
OD/ODP	kg CFC-11 eq	0.00001	0.000002	0.000711
PM/IF-FP	kg PM2.5eq	0.54	0.33	0.77
POF/TOC	kg NMVOC eq	4.65	5.10	4.10
RD/Scarc	kg Sb eq	0.17	0.13	0.01
Eutr-ter/AE	molc N eq	15.67	8.16	9.45

Appendix B. Input data

Table B1

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