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Using PROMETHEE to assess bioenergy pathways

Tim Schröder[a], Lars-Peter Lauven[a], Beatriz Beyer[a], Nils Lerche[a], Jutta Geldermann[a]

[a]: Professur für Produktion und Logistik, Georg-August-Universität Göttingen, Göttingen, Germany

Investment and policy decisions in the context of sustainable development are classic application areas for multi-criteria decision analysis. Ranking various pathways, i.e. conversion routes, for biomass use in the energy sector is particularly challenging. Depending on how ecological, economic, and social criteria are weighed, a multi-criteria decision analysis can lead to significantly contrasting recommendations. In this paper, we present a decision support for eleven energy pathways using decision criteria drawn from all three sustainability dimensions—ecological, economical, and social. For the graphical presentation of the relatively large number of pathways and criteria weightings, we introduce a novel visualization approach that combines the results of both PROMETHEE I and II. This visualization approach permits stakeholders to quickly and intuitively gather insights about the result structure and the consequences of different input parameters, for instance different criteria weightings.

1.1 Introduction

The transition towards a sustainable renewable energy supply calls for multi-criteria decision support to assess relevant technologies, since sustainability evaluations are often characterized by goal conflicts (Munda 2008, Madlener et al. 2007). Energy fuels are required for the provision of heat, electricity, and mobility (Martín-Gamboa et al. 2017, Strantzali and Aravossis 2016, Mardani et al. 2017), and numerous, alternative pathways exist to provide such fuels (Bohanec et al. 2017). Following Sapkota et al. (2015), a (bio)energy pathway is a conversion route that involves (bio)inputs, conversion technologies, intermediate products, and (bio)energy. Bioenergy pathways can play an important role for a stable energy supply based on renewable resources (Baskar et al. 2012, Kempener et al. 2009). The sustainability of several bioenergy pathways has already been the subject of both public discussion and scientific articles (e.g., Hayashi et al. 2014, Sinclair et al. 2015).

Thus, an evaluation of different energy pathways should consider environmental concerns, such as climate change and air pollution, simultaneously with economic aspects, such as production costs and the return on investments, and social criteria, such as employment and the impact on the regional economy. As the large number of sustainability criteria often results in goal conflicts, no single energy conversion pathway is likely to dominate all others (Eigner-Thiel et al. 2013, Langhans and Lienert 2016, Lerche et al. 2017). For such decision situations, Multi-Criteria Decision Analysis (MCDA) methods can be applied, providing a systematic structuring of the decision process (Belton and Stewart 2002).

The comparison of different bioenergy pathways with regard to sustainability criteria comprises a rather large number of alternatives and evaluation criteria. Therefore, the aim of this paper is to introduce a new approach to visualize the results of the multi-criteria outranking method PROMETHEE. In this article, we exemplarily apply this new visualization approach to assess the sustainability of several energy pathways in a case study and to track changes in the results over several stakeholder weightings.

The remainder of this article is structured as follows: In Section 1.2, we give a brief overview of MCDA and existing visualizations and take a closer look at the “Preference Ranking Organization Method for Enrichment Evaluations” (PROMETHEE) and corresponding visualization methods. In Section 1.3, we compare six bioenergy pathways and their fossil counterparts in a case study. Section 1.4 introduces a visualization approach for the application of PROMETHEE in the energy sector, before Section 1.5 concludes the paper.

1.2 MCDA in the energy sector

In the European energy sector, decisions about supporting certain energy pathways, as well as about ways of implementing incentives, are prepared and discussed by numerous parties. Therefore, a variety of people is involved in the decision making process on a national or European level, as well as several kinds of stakeholders. Stakeholders are all those parties who are affected, or who feel affected, by either the decision or the decision process (French and Geldermann 2005). In the energy sector, such stakeholders can include energy sector employees or lobbyists, non-governmental organizations and individuals affected by the construction or operation of energy plants.

Due to the significance of stakeholder involvement in the energy sector and the large number of people contributing to the decision-making process, it is very important to prepare decisions in a transparent way and to address stakeholder concerns. Although individual stakeholders may sometimes have extreme opinions, involving them in the decision-making process is nonetheless considered the best way to “make effective, efficient, fair, and morally acceptable decisions about [the] risk” associated with the decision (Renn and Schweizer 2009). The trend to increased citizen participation and ecological awareness leads to even more challenging decision-making processes (Thery and Zarate 2009, Kakogiannis et al. 2016). Applying MCDA methods should help to meet these challenges by improving the transparency of the decision-making process.

The added value of applying MCDA methods increases with a clear visualization of results. Therefore, the visualization of scientific research results is crucial for successful stakeholder communication. Early research comparing the use of tables and graphics to convey information led to the conclusion that the choice of visualization method is relevant for their suitability as decision aids (Remus 1987, Dickson et al. 1986, DeSanctis 1984). In some studies, the use of colors had an impact on the choices made by decision makers (Benbasat and Dexter 1985), while in another study it did not (Korhonen et al. 1990). More recently, researches have verified that, while one person may prefer linguistic statements, another may tend to memorize numerical expressions (Fasolo and Bana e Costa 2014).

The benefits of different existing visualizations have also been discussed specifically for MCDA methods, which visualize results with various approaches (Miettinen 2014, Vetschera 1994). Since three possible goals of an MCDA are to find the best alternative (α-problem), to

sort alternatives (β-problem), and to determine rankings (γ-problem) (Roy 2005), there are also visualization approaches suited to these purposes. Multi-attribute utility theory (MAUT) (Dyer 2005) seeks the best alternative by calculating overall utility scores for all alternatives. These scores are usually simply presented in a table. The "Technique for Order Preference by Similarity to Ideal Solution" (TOPSIS) uses graphical visualization at the level of the criteria, showing the distance to worst outcome (nadir-point) and best outcome (ideal-point) in a diagram (Hwang and Yoon 1981). In the "Analytical Hierarchy Process" (AHP), a nine-point scale is applied to measure weights or determine criteria values via pairwise comparisons. The numerical, relative performance of each alternative (concerning the criteria) is presented in a matrix and also represented by an overall value – typically presented in a row at the end of a table – reflecting the performance relative to other alternatives (Saaty 2005).

The Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE) is an outranking method whose results are usually presented in two kinds of rankings. A detailed introduction to PROMETHEE can be found in Brans and Mareschal (2005), while particularities of its application in the energy sector have been described by Oberschmidt et al. (2010). PROMETHEE can account for weak preferences and incomparabilities, and allows a partial compensation of criteria values. This means that a good score in one criterion can only offset a poor score in another if the difference between the scores exceeds a certain threshold (Spengler et al. 1998). This partial compensation is especially suitable for sustainability assessments, as no dimension of sustainability should easily be offset by another (Gervásio and Simões da Silva 2012, Munda 2005).

PROMETHEE is based on pairwise comparisons of several alternatives. Each alternative (in our case: energy pathway) is compared to all other alternatives regarding all chosen criteria. The comparison of two alternatives comprises both the strengths and weaknesses of the alternatives. In PROMETHEE I, a partial pre-order of the alternatives shows incomparabilities. In PROMETHEE II, a total pre-order of the alternatives is based on their net outranking flow (Φ^{net}), which is derived by subtracting the negative (Φ^{-}) outranking flows from the positive (Φ^{+}) ones. In the course of PROMETHEE II, however, information about incomparabilities is lost (Greco et al. 2016).

To visualize the PROMETHEE analysis without loss of information, a "PROMETHEE diamond" can be used representing negative and positive outranking flows and the net flow in a diagram (Mareschal and Smet 2009). The diamond provides a joint view of both rankings but can become less traceable due to the overlapping cones for an increasing number of incomparable alternatives. Another graphical visualization is the "Geometrical Analysis for Interactive Aid" (GAIA) plane, which analyzes the impact of the individual criteria (Brans and Mareschal 2005). Sensitivity analyses also permit a visualization of PROMETHEE results. Here, various approaches can be used to illustrate and analyze the effects of changes (e.g. in criteria attributes or weights) on the results. Especially, insensitivity intervals visualize the impact of varying weights on the PROMETHEE rankings (Seppälä and Hämäläinen 2001, Mareschal 1988, Geldermann 1999).

Although many MCDA methods are available for decision support in the energy sector, PROMETHEE is chosen due to its ability to express incomparabilities. It has been applied in environmental decision making in the past, as described in Vinodh and Jeya Girubha (2012) and Lerche et al. (2017), and is designed to deal with decision makers who are unable to accurately express their preferences (Stewart 1992). We apply both PROMETHEE I and II for our comparison of six bioenergy and five fossil energy pathways in the following case study. Afterwards, we propose a new visualization approach to combine all the information yielded by the two rankings into a single visualization.

1.3 Comparing bioenergy pathways with regard to sustainability criteria

Among renewable pathways, bioenergy pathways form a special subset as they compete for various forms of biomass as input (e.g., corn, wheat, wood residues). While biomass is a versatile energy carrier, it remains unclear which pathways (i.e. conversion routes consisting of (bio)inputs, conversion technologies, intermediate products, and (bio)energy) utilize the available biomasses best. As the basis for a multi-criteria assessment of several bioenergy pathways, we use comprehensive data collected in the course of the European research project BIOTEAM in six European countries (Finland, Lithuania, Poland, Italy, Germany, and the Netherlands). For each investigated country, PROMETHEE and the same criteria for the respective pathways and stakeholder weightings were used.1 In the following sub-chapters, we introduce our case study and application for Germany, before we specify the decision problem and introduce the weighting process.

1.3.1 Case study

In our case study, which is based on the German project data, we compare heterogeneous energy pathways using 19 sustainability criteria. Table 1 provides an overview of the selected pathways, which are six bioenergy pathways and five corresponding fossil pathways for Germany. The six bioenergy pathways are subdivided into three groups of two each, for solid, liquid, and gaseous intermediates (Beyer et al. 2014). As such bioenergy pathways produce either heat, electricity and/or transportation fuels, their contribution towards a sustainable energy system must be compared against the currently predominant fossil pathway that is likely to be replaced, referred to as their “baselines”. Wood pellets, for example, are used to provide heat. Because natural gas has the highest share in the German domestic heating market (BDEW 2016), it is used as the fossil basis of comparison for the wood pellet heating pathway. For the electricity-producing pathways we are not only considering the German electricity mix as baseline, but also electricity production from lignite – the most carbon-intensive energy carrier that could be replaced by bioenergy (BIOTEAM 2014).

Table 1: Selected bioenergy pathways and fossil baselines for Germany

Biomass state	solid		liquid		gaseous	
Bioenergy pathway	Wood pellets for domestic heating (sawdust)	Large biomass CHP (fresh wood)	Bioethanol (cultivated crops)	Biodiesel (cultivated canola)	Biogas (manure and cultivated maize)	Biomethane (manure and cultivated maize)
Key product	Heat	Electricity	Petrol	Diesel	Electricity	Heat
Corresponding fossil baseline	Natural gas	Lignite/ electricity mix	Fossil petrol	Fossil diesel	Lignite/ electricity mix	Natural gas

In the following, we apply the outranking method PROMETHEE. Figure 1 shows the adjustments to PROMETHEE and specific characteristics of our case study within the general structure of an MCDA decision process.

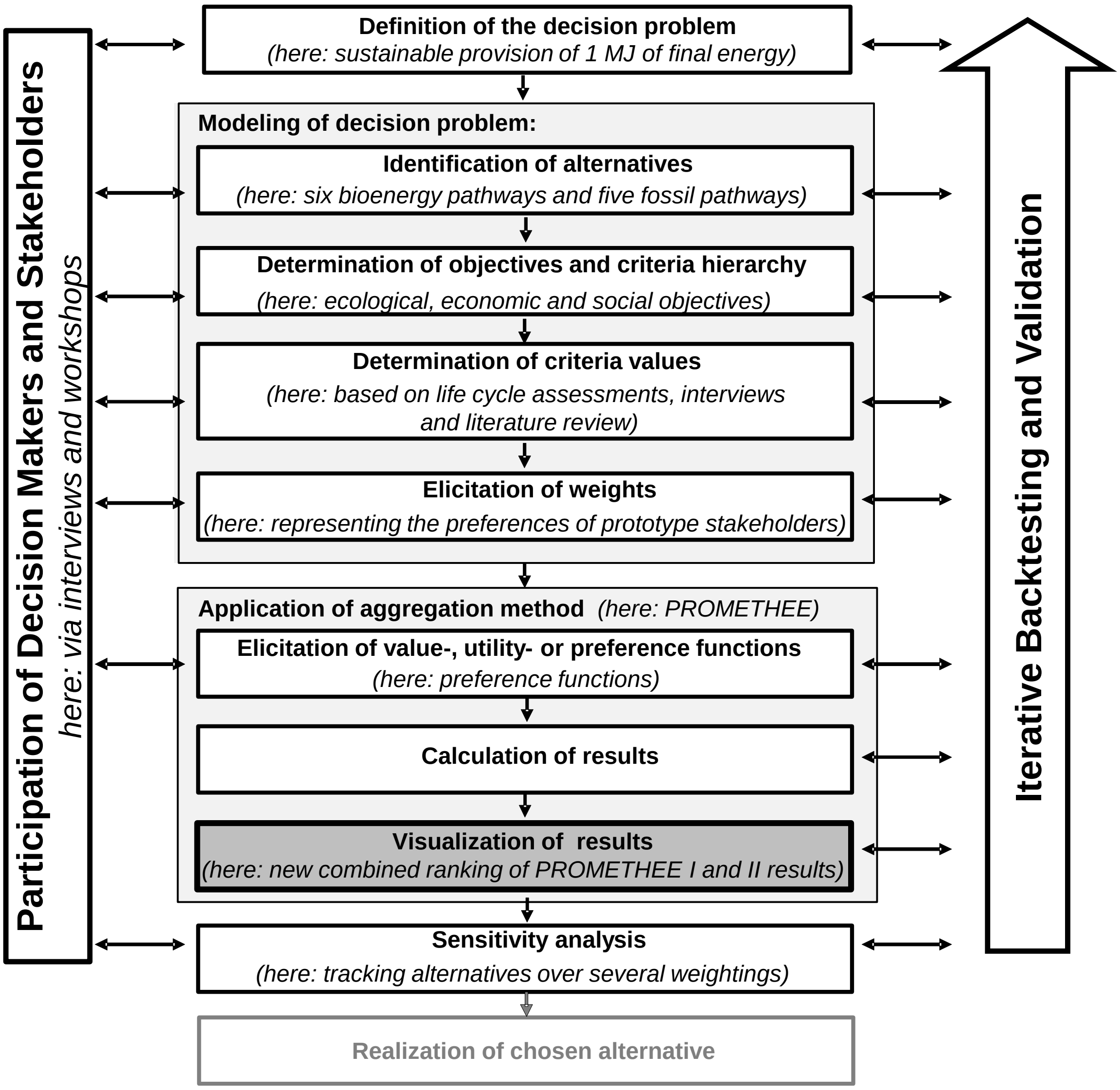

Figure 1: Decision process in MCDA methods (adapted from Lerche et al. 2017)

1.3.2 Decision problem

As the annually available biomass resources for bioenergy are limited, a choice has to be made about the preferred pathways. As these resources are insufficient to replace fossil fuels in all areas of application, several renewable and fossil pathways are needed to supply different forms of final energy. In order to identify and compare the potential alternatives with regard to sustainability criteria, we use the functional unit “1 MJ of final energy”, which can be used for a comparison of heat, electricity, and transportation fuels. As final energy in these three forms can be supplied by both fossil and bioenergy pathways, we assess the strengths and weaknesses of all pathways in one analysis using PROMETHEE to evaluate how the different pathways perform in comparison to each other. Ultimately, we aim to generate and illustrate the entire rankings of the eleven pathways for different stakeholder weightings to how where replacing fossil pathways with bioenergy results in the greatest improvement with regard to sustainability criteria.

Figure 2 shows the criteria hierarchy with the 19 criteria that were used for the sustainability assessment. The three top-level criteria – ecological, economic, and social – are further split into five to eight quantifiable or ordinal sub-criteria characterizing the sustainability of the energy pathways. The criteria descriptions and values are presented in Table 2. These 19 criteria were among the most frequently used sustainability indicators found in a review of 14 sustainability certification schemes approved in the EU and of other research projects (BIOTEAM 2014).

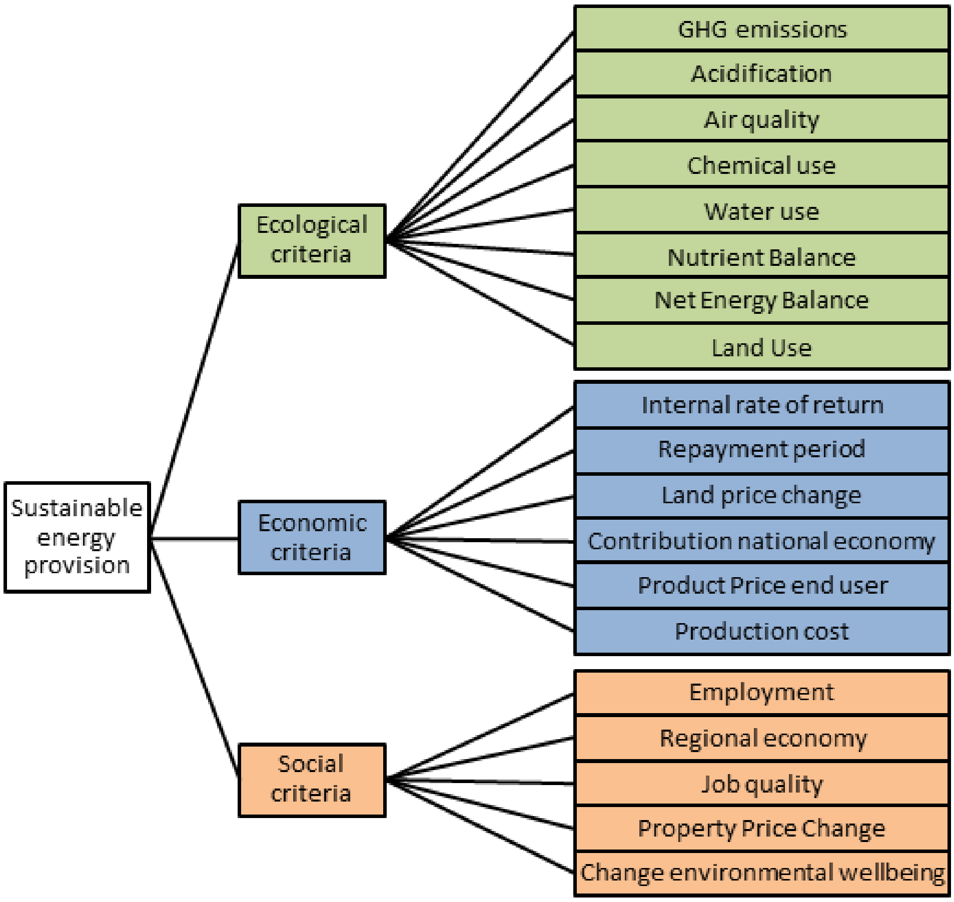

Figure 2: Criteria hierarchy for comparing energy pathways

Table 2: Decision table for comparing bioenergy pathways (Beyer et al., 2014)

Main goal	Criterion	Unit	(Min/ Max)	Weight (%)	Wood pellets	Biomass CHP	Bio-diesel	Bio-ethanol	Biogas	Bio-methane	Natural Gas	Electricity Mix	Electricity Lignite	Fossil Diesel	Fossil Petrol	PF	p	q
Environmental	Greenhouse gas emissions	g CO_2 eq/MJ output energy	Min	5.6%	3.1	15	41.5	42.2	21	31.5	95.2	187.8	342	110.0	112	3	101.7	0
	Acidification	g SO_2 eq/MJ output energy	Min	4.4%	0.0191	0.098	0.598	0.280	0.597	0.105	0.029	0.232	0.331	0.326	0.250	3	0.174	0
	Air quality	g PM_{10}/MJ output energy	Min	4.3%	0.0758	0.056	0.124	0.077	0.104	0.037	0.011	0.086	0.115	0.142	0.080	3	0.039	0
	Chemical use	Scale 0 to 4	Min	4.6%	1	1	2	2	2	2	2	3	3	3	3	4	1.5	0.5
	Water use	l/MJ output energy	Min	4.5%	0.002	0.119	0.590	0.890	0.215	0.073	0.003	0.184	0.180	0.0159	0.0138	3	0.27	0
	Nutrient balance	(g N + g P)/MJ output energy	Max	4.7%	-2.36	-6.48	-16.11	-16.11	-13.7	-13.7	0	0	0	0	0	3	4.83	0
	Net energy balance	MJ/MJ output energy	Min	5.3%	0.23	0.2	0.37	0.28	0.15	0.2	0.1	0.12	0.52	0.16	0.28	3	0.126	0
	Land use	m^2/MJ output energy	Min	4.5%	0	0	0.0718	0.0921	0.11	0.069	0	0.0005	0	0	0	3	0.033	0
Economic	Internal rate of return	%	Max	5.2%	22.9	12.3	23.2	17	7.9	7.4	29.9	13.2	13.2	36	60	3	15.78	0
	Repayment period	year	Min	5.9%	6.67	10.3	5.16	7.8	12	15.5	5.58	16	16	4.46	2.9	3	3.93	0
	Land price change	%	Max	4.1%	0	0	4.5	1.2	6.9	0.9	0	0.16	0.16	0	0	3	2.07	0
	Contribution to national economy	ppm	Max	4.5%	24	400	500	180	2300	200	7000	14000	14000	13800	12500	3	4192.8	0
	Product price to the end user	€/MJ output energy	Min	5.9%	0.14	0.0818	0.047	0.044	0.1179	0.0086	0.0194	0.0614	0.0614	0.037	0.05	3	0.039	0
	Production cost	€/MJ output energy	Min	5.9%	0.01	0.006	0.0251	0.021	0.025	0.02	0.007	0.0065	0.0065	0.013	0.012	3	0.006	0
Social	Employment	FTE/MJ	Max	7.1%	7.8	0.0039	0.019	0.030	0.0220	0.0002	0.0023	0.0026	0.0013	0.0043	0.0027	3	2.340	0
	Domestic share of end-user price (incl. taxes)	%	Max	7.7%	90	60	90	80	95	80	48	75	90	72	72	3	14.1	0
	Job quality (level of wage)	€/year	Max	5.7%	41880	41880	65000	65000	41880	41880	54480	54480	54480	74800	74800	3	9876	0
	Property price change	Scale -2 to 2	Max	4.0%	0	-1	-1	-1	1	0	-1	-2	-2	-1	-1	4	1.5	0.5
	Change in environmental status and wellbeing (noise, smell, aesthetic)	Scale 1 to 5	Min	6.0%	2	4	4	3	2	2	3	5	5	5	5	4	1.5	0.5

FTE = full time equivalent, PF = Preference function. p,q: Threshold values

1.3.3 Weighting by stakeholders

We derived the criteria weighting for Germany in a one-day workshop with 34 participants from universities, businesses, and public institutions. The 19 criteria were explained to the participants, including their units of measurement, their contexts, and the data sources. After the participants had asked some open questions, they weighted the criteria according to the method described below by filling in a questionnaire (see Appendix). The questionnaire consisted of two parts: an initial weighting and a refined weighting. For the latter, we asked the participants to discuss their own initial weightings with other workshop participants and refine their input scores if they so wished. The average of all 34 resulting weightings obtained at the workshop for the three top-level sustainability criteria is depicted in Figure 3. On average, the participants assigned the highest input scores to the ecological dimension (an average score of 91 points, resulting in a weighting of 38%) (Beyer et al. 2016).

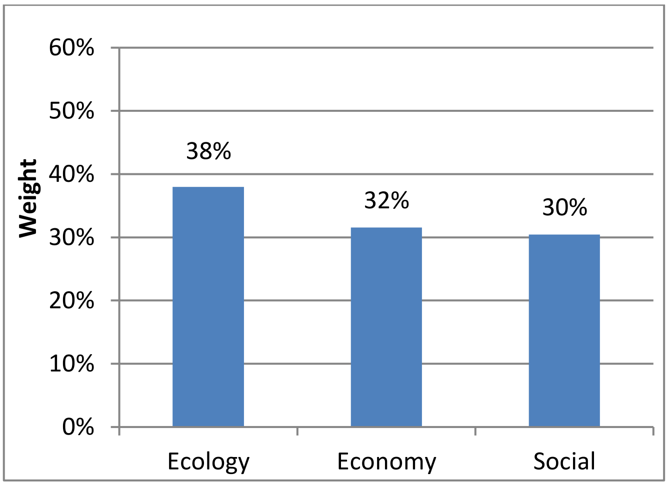

Figure 3: Average weighting of the sustainability dimensions

To keep the weighting process simple, yet meaningful, we used a weighting method oriented on the weighting step in the Simple Multi-Attribute Rating Technique (SMART) (Edwards 1977, von Winterfeldt and Edwards 1986). In a slightly adjusted version of the original SMART weighting method, each participant selected his or her most important criterion and assigned 100 points to it. The second most important criterion was then selected, and points were derived relative to the points assigned to the most important criterion. This process was undergone for all criteria. Then, the points were normalized, that is, the relations between the point assessments were converted into percentages totaling 100%.

To account for the two levels in the criteria hierarchy, we applied a hierarchical weighting process. Thus, goals and criteria were weighted for each level of the criteria hierarchy separately in a top-down process (Pöyhönen et al. 2001, Belton and Stewart 2002). The SMART-oriented method was first applied to the top-level sustainability criteria: ecology, economy, and social (see Figure 3). Afterwards, each set of sub-criteria was assessed individually. The final weighting of a criterion is equal to the product of the weights of the sustainability dimension and the sub-criterion. The weighting of the sub-criteria was performed independently for each of the three sustainability dimensions.

The resulting weights on the lower level are shown in Figure 4, with the lowest average weighting at about 4%, compared to the highest overall rating of 7.7%. Naturally, Stakeholders may have varying preferences concerning the weightings. In order to investigate how sensitive the resulting PROMETHEE ranking is with regard to different criteria weightings, it can be helpful to consider stakeholders with rather extreme weightings. This allows exploration of both the potential for conflicts and the potential for compromise (Steinhilber et al. 2016).

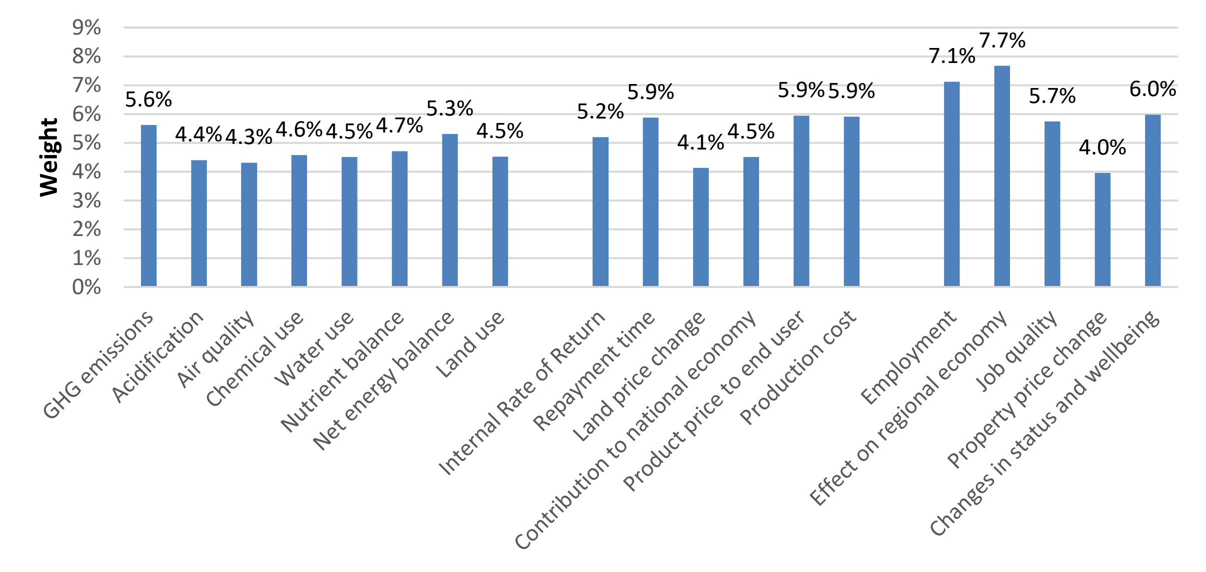

Figure 4: Average weightings for all sustainability criteria

An investigation about the consequences of different weightings benefits from a clear visualization. For our comparison of German energy pathways in this particular case study, we chose the three most extreme weightings from individual workshop participants as stakeholder prototypes and labeled them: “ecological”, “economic”, and “social”. In addition to the prototype weightings of the three sustainability dimensions, we also considered the associated prototype weightings of the 19 criteria. The differences among these weightings are shown in Figure 5.

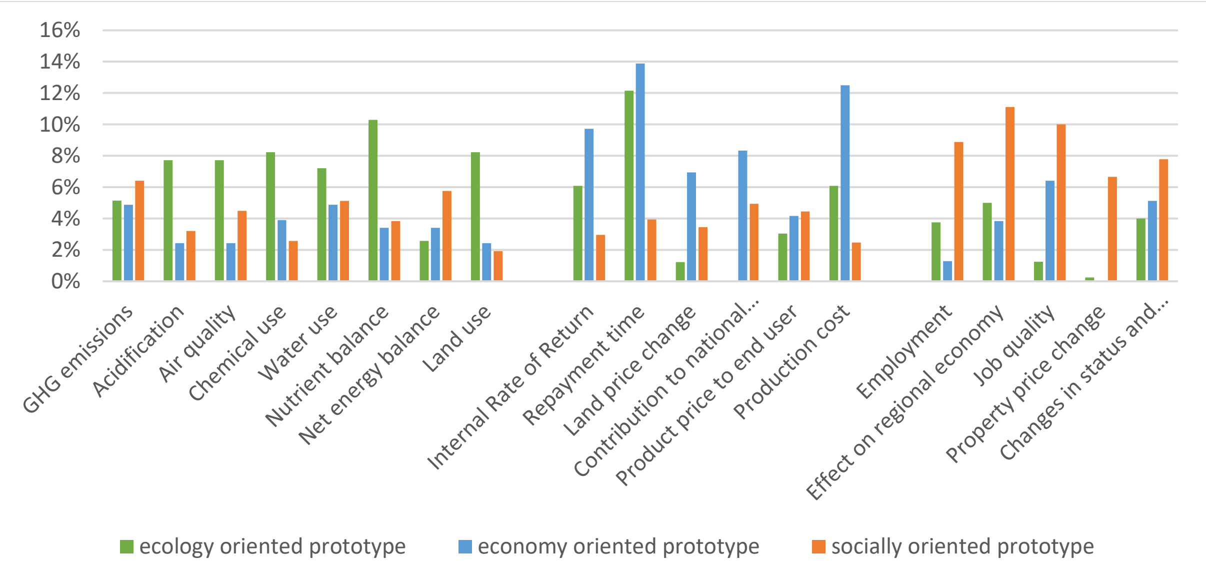

Figure 5: Weightings of sub-criteria according to overall preferences for the three prototype stakeholders

Such an exemplary analysis is of course not representative for the public opinion in Germany or the other countries in which analyses have been conducted in the course of the project. Nevertheless, the analysis helps to understand the consequences of different stakeholder goals on the ranking of the alternatives. To further improve this understanding and the resulting rankings, we propose a new visualization approach in the next chapter.

1.4 Results: PROMETHEE rankings of German energy pathways

The PROMETHEE application in this selected case study yields the outranking flows depicted in Figure 6. The alternatives are ordered according to the values of Φ^{net} (solid bars in the diagrams) derived from PROMETHEE II. The Φ^{+} and Φ^{-} bars are shown as positive and negative stacked bars respectively, where each of the three sections represents the positive and negative outranking flows for the social, economic, and ecological criteria. This shows how the outranking flows of each alternative are influenced by the attributes and weightings of the three sustainability dimensions, similar to the stacked bar charts used in other environmental problems (Geldermann et al. 2009).

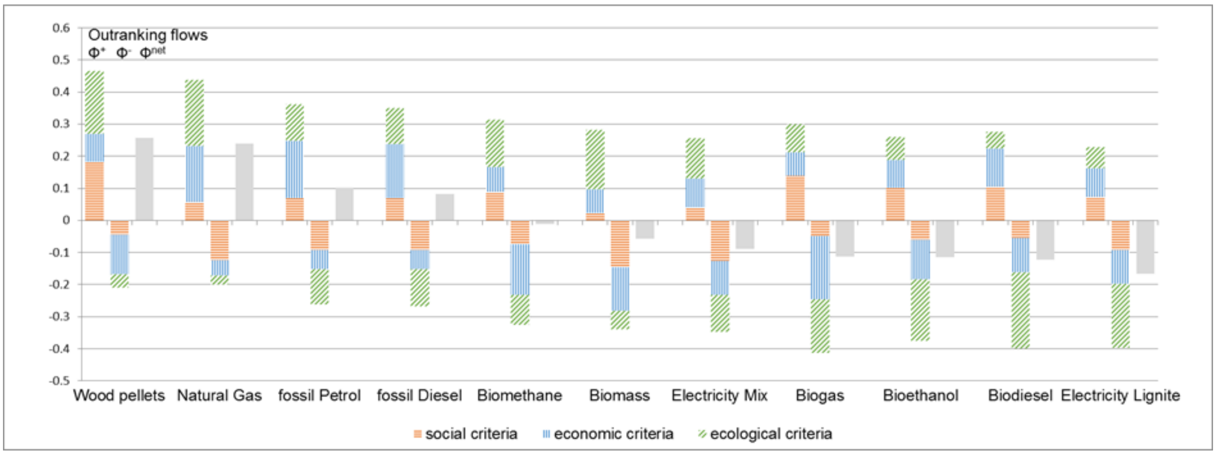

Figure 6: Outranking flows for all alternatives, based on the average weightings of all workshop participants

The best-ranked alternative according to PROMETHEE II in this exemplary case study is the wood pellets pathway, with the highest Φ^{net} of 0.258. When comparing those eleven alternatives, the wood pellet pathway is the preferred pathway to provide one MJ of final energy. As Figure 6 shows, wood pellets have a slightly higher Φ^{net} than natural gas, and a distinctly higher Φ^{net} than the remaining alternatives. As indicated by the stacked bar charts, this alternative shows more strengths than weaknesses in the ecological and social dimensions, but more weaknesses than strengths in the economic dimension. The positive Φ^{net} bar (solid) indicates that overall, the wood pellet pathway has more strengths than weaknesses when the average weightings of all 34 workshop participants are used.

1.4.1 Modified visualization of results

To maintain the advantages of both PROMETHEE I and PROMETHEE II, we propose a combined representation of PROMETHEE results. This new visualization is not meant to replace the classical PROMETHEE result presentation. Instead, it serves as an additional approach to analyze and interpret PROMETHEE results.

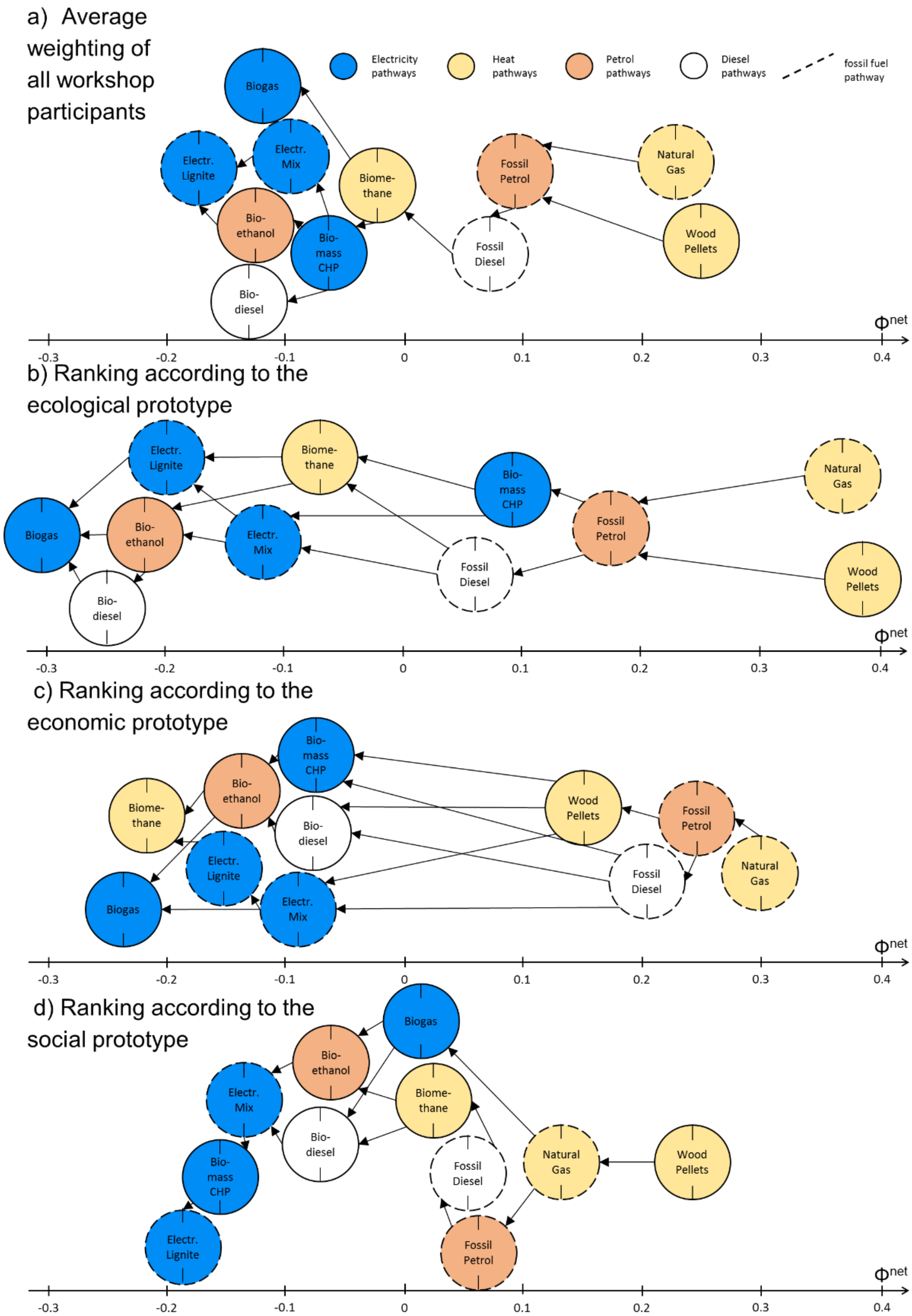

Figure 7: PROMETHEE pre-orders on a Φ^{net} scale for the four investigated weightings. The vertical lines indicate a pathway's Φ^{net} flow.

Our modified visualization of PROMETHEE results includes arranging the figurative PROMETHEE I partial pre-order over a horizontal axis representing the net flows of the PROMETHEE II method (see Figure 7). The average weightings of all stakeholders at the workshop can be seen as a compromise between stakeholder groups that favor any of the sustainability dimensions in a more pronounced way. In this section, we compare the PROMETHEE results using the three prototype weightings introduced in Section 1.3.3, in order to exemplarily investigate the sensitivity of the results to the weightings. In Figure 7, in addition to the horizontal scaling, the various alternatives are shaded differently and the fossil pathways have dashed frames to facilitate tracking one alternative's ranking through the four assessments. Part a) depicts the average weightings of all stakeholders; parts b), c), and d) show the partial pre-orders resulting from the prototype stakeholders' weightings. The alternatives have been arranged according to their Φ^{net} flow, indicated by the vertical lines in the center of the circles. This graphical representation in Figure 7 provides additional insight in comparison to the partial and complete pre-order yielded by PROMETHEE I and II: The new visualization comprehensively and transparently depicts differences between stakeholder weightings or possible scenarios.

- It visualizes existing clusters. In Figure 7a), for instance, three clusters can be distinguished. The two best alternatives, wood pellets and natural gas, show a larger distance to the next ranked alternatives, the fossil transportation fuels, which also have positive values of Φ^{net}. The remaining alternatives form the last cluster and have negative Φ^{net} values. It should be noted that the sum of all Φ^{net} values is zero (Geldermann and Schöbel 2011).
- The degree of "stretch" in the graph makes visible the differences of all alternatives across the entire Φ^{net} range, along with the differences in clustering. The different degrees to which the graph is stretched for the different prototypes can be easily observed.

This visualization is also in line with the European school of MCDA, which advocates making the whole decision process more transparent, instead of just pointing out the best alternative (Stewart 1992). Moreover this visualization approach remains easily comprehensible,

especially for users familiar with PROMETHEE I visualization tools. The modified visualization allows stakeholders to gain insights about the influence of different weightings on the outcomes.

Concerning the results of our exemplary evaluation, Figure 7b) illustrates that in this case, focusing on the ecological criteria leads to values of Φ^{net} for the wood pellet and the natural gas pathways that are distinctly higher than those of the remaining alternatives. Although this result can also be observed in the average weightings, here it is even more pronounced in absolute terms. The biomass CHP belongs to a second cluster that also contains fossil diesel and petrol. The remaining alternatives have negative values of Φ^{net} and exhibit some incomparabilities. Overall, the entire ranking is stretched out across a broader area of the Φ^{net} scale. This indicates that the pathways are distinctly different regarding their ecological impact – a conclusion highlighted here via the higher weighting of the ecological criteria. It should be kept in mind, however, that the stretch of the ranking is also determined by the choice of compared alternatives and criteria.

Using the weightings of the economic prototype (Figure 7c) reduces the number of clusters from three to two. The economic weightings shift the fossil mobility fuels closer to natural gas and wood pellets. Here, unlike in the other three evaluations, the wood pellets pathway no longer has the best Φ^{net} value. It ranks only fourth, according to PROMETHEE II. In PROMETHEE I, wood pellets are incomparable to fossil diesel, but outranked by natural gas and fossil petrol. The second cluster containing the remaining alternatives is also denser, with less stretch in the Φ^{net} values. This results in some additional incomparabilities, as illustrated in Figure 7c).

The results in Figure 7d) show the ranking based on the social prototype weighting. The ranking is relatively similar to the average ranking, but the lower weight for economic criteria favors the bioenergy pathways. Wood pellets have a lower Φ^{net} flow than in b), but nevertheless outrank natural gas and all other pathways. Electricity from lignite is the least preferred pathway.

Summing up, natural gas and wood pellets always perform relatively well in this exemplary case study, while the fossil electricity pathways generally rank among the least preferred alternatives. In between, there are rank reversals, depending on the criteria weightings. Figure 8 provides an overview of the pathway rankings for the average criteria weightings and the three additional stakeholder prototype weightings discussed in Section 1.3.3.

It becomes apparent in Figure 8 that the investigated bioenergy pathways are ranked worst when the weighting of the economic prototype is used. The ranking based on the weighting of the ecological prototype is less clear, as some of the alternative bioenergy pathways require dedicated crops as inputs (corn for biogas and biomethane, canola for biodiesel, wheat for bioethanol), which significantly affects their ecological performance.

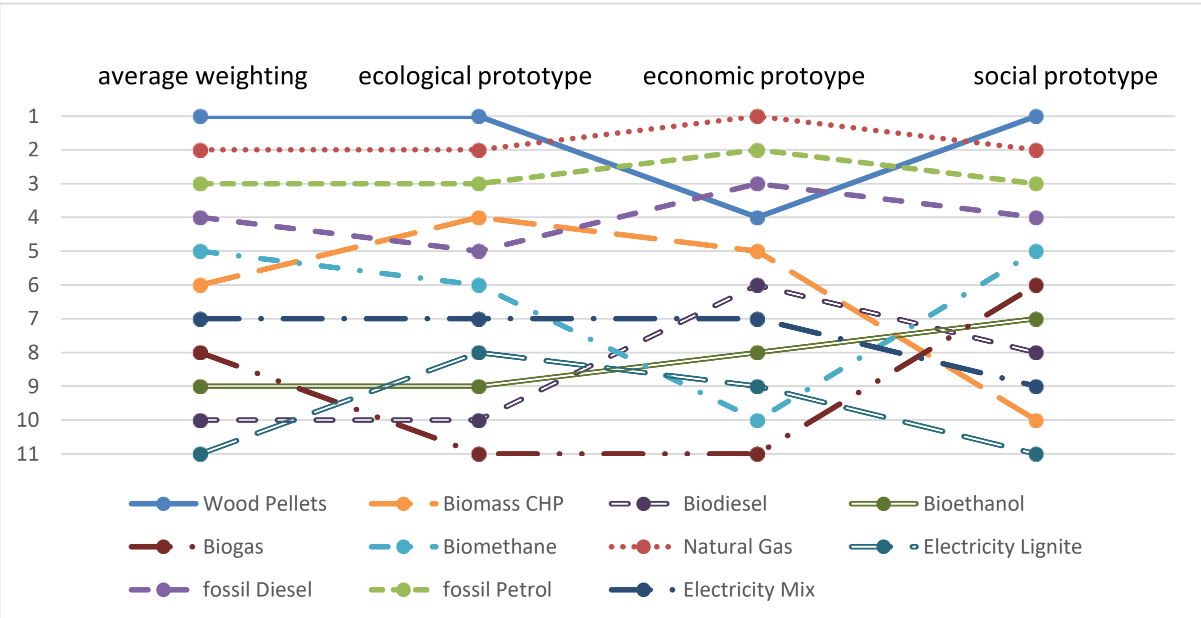

Figure 8: Rankings of alternatives for the average weightings and those of the ecology, economy, and social prototypes.

No currently available MCDA software has been developed yet to fully automatically generate partial pre-orders scaled according to the net flows, but it can be easily achieved by using point cloud charts in common spreadsheet applications. Each alternative's position in such a chart is determined by its x-coordinates, and y-coordinates. If the Φ^{net} values are used as x-coordinates and y-coordinates are chosen from a set of four levels (e.g. simply the numbers 1 through 4) depending on the proximity of other alternatives with regard to their Φ^{net}, the resulting positions of the alternatives' points can be arranged as in Figure 7. Using these semi-automated cloud charts, the user may change the coloring and scale of the circles representing the alternatives flexibly.

1.4.2 Discussion

We applied PROMETHEE to rank six bioenergy and five fossil pathways for sustainability. During a workshop, we elicited the weightings for our exemplary case study from stakeholders drawn from universities, businesses, and public institutions. We used the average stakeholder weightings and three sets of stakeholder prototype weightings to develop PROMETHEE I and II pre-orders. To obtain a better overview and facilitate comparison of the PROMETHEE I and II results for the different alternatives and weightings, we proposed a novel visualization that incorporates the results from both PROMETHEE I and II.

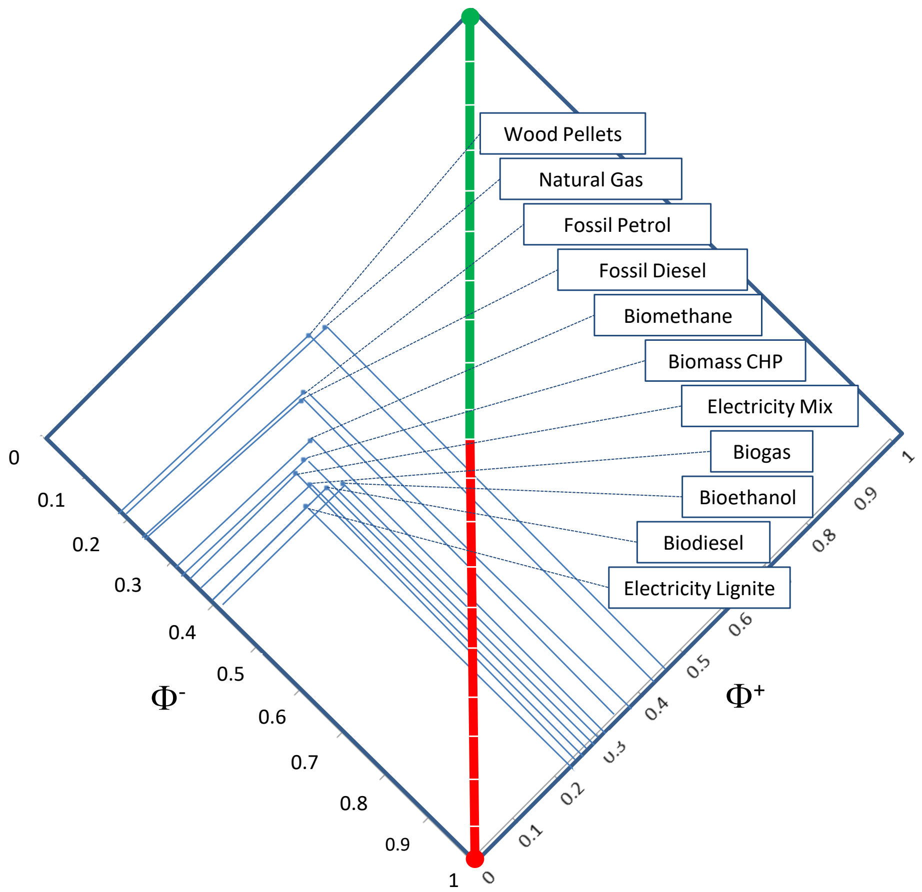

Figure 9: PROMETHEE Diamond according to the average weighting of the workshop participants

The scaling of partial pre-orders according to the net flows allows for a more comprehensive overview that includes incomparabilities, net outranking flows, and clusters. For comparison, Figure 9 shows a PROMETHEE diamond for the ranking according to the average weighting of the workshop participants that is also shown in Figure 7a). While the same information is given in principle, it is much harder to identify incomparabilities between the seven alternatives with the lowest Φ^{net} values, let alone identify them clearly enough to observe changes between several rankings as in Figure 7 a) to d).

Particularly when the alternative set is larger than ten alternatives, the visualization approach used in Figure 7 provides a comprehensible overview of the MCDA results. This could be especially valuable when communicating results to many stakeholders, such as the public or to policy makers. Nevertheless, with a very large number of alternatives, such as more than 20 or 30 alternatives, this visualization can be overloaded as well.

The proposed visualization may complement stacked bar charts (see Figure 6), illustrating the positive and negative outranking flows for each sustainability dimension and helps highlight the advantages and disadvantages of each alternative. It could also be used not only to compare different prototypes' weightings, but different scenarios with different weightings and/or criteria values.

The focus of this paper is on demonstrating the procedure for incorporating various prototype stakeholders and improving the visualization of analysis results. The findings of our case study must however be viewed cautiously. A comprehensive assessment of criteria weightings should include a larger stakeholder population. The weightings obtained in our workshop cannot be taken to be representative for Germany. In a population of 34, a selection bias is likely. Moreover, some criteria could have been merged (repayment time and return on investment), an approach that might change the weightings and thus the results (Langhans and Lienert 2016).

Naturally, a sustainability assessment performed with MCDA methods – especially those based on pairwise comparison, such as PROMETHEE – can only result in a relative ranking of the alternatives under consideration. For example, it remains unclear how other renewable alternatives, such as wind power or photovoltaics, would be ranked. To perform such an extended analysis however might require different criteria and may result in distinctly different weightings.

1.5 Conclusion

In this paper, we used PROMETHEE to assess six bioenergy pathways and their fossil counterparts. We developed a new visualization that combines PROMETHEE I and II results in one diagram for an overview of the structure of PROMETHEE results – an advantage that we expect to be especially helpful when considering many alternatives in the MCDA analysis or when comparing different scenarios or stakeholder weightings.

The new visualization – especially when combined with prototype stakeholder weightings, as illustrated in this paper – should help in analyzing how potential stakeholders may evaluate the alternatives. It also provides another tool for exploring the potential for both conflicts and compromise. The visualization reveals gaps between clusters and incomparabilities between alternatives for various prototype stakeholders or for different scenarios. The visualization of these rankings could serve as a basis for an assessment of potential pathway combinations. Even though the proposed visualization's benefit of combining the PROMETHEE I and II rankings in a single visualization is not applicable to other MCDA methods, many of these also produce a ranking based on quantitative values. The proposed visualization could therefore be adjusted to add information about the differences between two alternatives' values in addition to their ranks clearly and easy to understand.

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