Modified PROMETHEE approach for assessing energy technologies

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Abstract

Purpose – The purpose of this paper is to elaborate a multi-criteria methodology for the performance assessment of energy supply technologies, which also takes into account the dynamics of technological change.

Design/methodology/approach – The approach chosen is based on the multi-criteria outranking methodology Preference Ranking Organisation METHod for Enrichment Evaluations (PROMETHEE), which is linked to the concept of technology's life cycle by assigning criteria weights depending on the actual development phase of a certain technology. The modifications to the PROMETHEE algorithm are described and the modified methodology is demonstrated by evaluating heat and power supply alternatives for a municipal area in Germany.

Findings – The methodology is suitable for the evaluation of energy technologies taking into account varying preferences depending on their stage of maturity. It is a feasible alternative to other methodologies which allow for interconnections like the analytic network process. The results show that, based on a multi-criteria life cycle approach, renewable energy technologies are competitive with conventional alternatives for supplying heat and power.

Practical implications – Appropriate methods are required to elicit life cycle-dependent preferences. Decision support should help decision makers (DMs) to articulate preferences according to different development phases and illustrate the results in the most meaningful way.

Originality/value – The methodology provides the basis for a comprehensive analysis of energy technologies at different life cycle stages. It can be used to support decision making in different situations and by various actors.

Keywords Germany, Energy technology, Assessment, Energy supply systems, Electricity industry

Paper type Research paper

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1. Introduction

In modern societies, it is taken for granted that the required amount of electricity and heat are always supplied at the right time and place. However, due to the expected increase in electricity demand and the ageing structure of current power plants, it will be necessary to install new and replace older power plants. Primary energy demand in Germany is currently mainly met by fossil fuels, in particular oil, gas, coal and lignite. The power sector relies heavily on lignite, coal and nuclear. These energy resources are exhaustible and this coincides with increasing energy demand in developing and emerging countries. Moreover, in Germany, a growing dependency on fossil and nuclear imports can be observed; while, at the same time, the prices for fossil fuels have increased over the last few years (Eurostat, 2009b; OECD/IEA, 2008b).

Apart from economic considerations, it has also become increasingly obvious that the environmental impacts of electricity and heat supply cannot be ignored (Canadell *et al.*, 2007; Smil, 2003). While a growing concern regarding environmental issues can be observed in society and industry in general, the energy sector plays an especially important role in the context of climate change, because the majority of carbon dioxide emissions in industrialized countries are due to the production and use of energy ((The) World Bank, 2007).

There is a wide variety of energy supply alternatives, ranging from technologies based on fossil fuels to renewable energy sources, from centralized to decentralized options, from implemented and well-established to innovative technologies. Some well-established technologies might be economically viable, at least under current framework conditions, whereas their environmental impacts might not be acceptable in the medium and long term. Other technologies with lower environmental impacts might have drawbacks regarding economic efficiency. Thus, in order to select the most appropriate technology, different goals of a sometimes conflicting nature must be taken into account concerning, for example, the security of supply, environmental and economic efficiency.

The decision situation is further complicated because the characteristics of technologies are usually not static, but subject to dynamic and complex developments over time. The performance level of new and innovative technologies is often lower when compared to well-established technologies; while, at the same time, the uncertainties and risks associated with new technologies are usually higher. Nevertheless, a decision could still be made in favour of a new technology due to expected increases in its performance level in the future which might then exceed that of the older technology (Perl, 2007). Thus, it has been observed that the life cycle phase of a product or technology influences the evaluation of the different aspects considered to be relevant when assessing the alternatives (Sarkis, 2003). This is especially important when well-established technologies are being compared to new and innovative ones.

Consequently, the purpose of this paper is to develop and elaborate a methodology for decision support that:

- allows different goals and criteria of (a sometimes) conflicting nature to be taken into account; and
- considers the variability of preferences depending on the development phase of a technology.

First, some fundamentals of multi-attribute decision making (MADM) are explained, methodologies that are able to handle qualitative and quantitative criteria of a sometimes conflicting nature. Second, the concept of a technology's or product's life cycle is described in order to develop an assessment framework which includes the possibility to consider varying preferences depending on the different development phases. The proposed approach is demonstrated based on an example application and the results are discussed. The paper concludes with some general remarks on the feasibility and limitations of the proposed methodology.

2. Methodology

As discussed above, various issues need to be considered when comprehensively assessing energy technologies, in particular economic efficiency, security of supply and environmental impacts. The potentials of each technology for achieving these goals can be measured using different criteria. Thus, the methods of MADM seem to be an appropriate choice for comparing energy technologies. These methodologies belong to the more general class of multi-criteria decision making (MCDM) methods and allow a set of previously known discrete alternatives to be assessed based on the simultaneous consideration of various criteria measured in different metric units, in some cases including qualitative criteria (Belton and Stewart, 2002; Figueira *et al.*, 2005). Owing to the inherently multi-criteria nature of energy planning problems and in particular due to the growing awareness of environmental issues, MCDM has been increasingly adopted in this area throughout the last decades. Greening and Bernow (2004) point out the potential of MCDM in energy and environmental policy planning. A recent review on MCDM used in sustainable energy planning can be found in Wang *et al.* (2009), while Zhou *et al.* (2006) provide an overview of decision aids in energy and environmental modelling. Major applications of MCDM in energy planning are summarized in Diakoulaki *et al.* (2005), Løken (2007) and Pohekar and Ramachandran (2004).

In general, two schools of thought of MADM are distinguished: the American and the French or European one. The former includes approaches such as multi-attribute utility theory (MAUT)/multi-attribute value theory (Dyer, 2005; Siskos, 2005) as well as the analytic hierarchy process (AHP) and analytic network process (ANP) (Saaty, 1980; Saaty and Vargas, 2006). One of the main underlying assumptions of these approaches is that decision makers (DMs) are aware of the utility of different criteria values and are able to express the relative importance of different criteria in an unambiguous way. The goal of decision making is then to disclose and interpret the preferences of DMs in a transparent way. The European school of thought evolved as an attempt to overcome the shortcomings of the American methods of MADM. It generally assumes that DMs are not fully aware of their preferences. Therefore, decision support is needed to help structure the decision situation and to demonstrate the influence of different criteria weightings (Geldermann and Rentz, 2001).

Some disadvantages of the approaches of the American school of thought include, for example, the loss of information due to the high aggregation of results and the fact that good and poor criteria values can fully compensate each other. However, because of their traceability and manageability in practice, these methods are often preferred to the so-called "outranking approaches" of the European school of thought. Nevertheless, the latter have advantages because they are not fully compensatory, usually need less information from the DM, are able to deal with both quantitative and qualitative data on an open scale, and can integrate uncertain information through probability distributions, fuzzy sets and threshhold values (Araz and Ozkarahan, 2007; Haralambopoulos and

Polatidis, 2003; Løken, 2007; Ren *et al.*, 2009; Geldermann *et al.*, 2000; Salo and Hämäläinen, 1995; Xu, 2005). Furthermore, in addition to strict preference and indifference, weak preferences and incomparabilities can also be described if there is not enough information to rank options unequivocally (Roy, 1980; Rogers and Bruen, 1998; Topcu and Ulengin, 2004). Compared to AHP/ANP fewer pair-wise comparisons are needed and the valuations are not restricted to Saaty's nine-point scale (Albadvi *et al.*, 2007; Anand and Kodali, 2008; Dagdeviren, 2008). Apart from these methodological advantages, real life observations show that DMs are often not fully aware of their preferences, or that they are not able to express these in an unambiguous way without appropriate support and outranking methods can provide this. For this reason, the outranking approach Preference Ranking Organisation METHod for Enrichment Evaluations (PROMETHEE) was selected here as the methodological basis for the comparative assessment of energy technologies. PROMETHEE methods developed by Brans (Brans *et al.*, 1986) are one of the best known and most widely used outranking approaches in sustainable energy planning (Table I) and other applications (Table II). A comprehensive overview of applications can be found in Behzadian *et al.* (2010).

Other outranking approaches have also been applied to energy planning issues, most notably the family of ELimination Et Choix Traduisant la REalité methods (Roy, 1980, 1996), for example, Beccali *et al.* (2003), Cloquell-Ballester *et al.* (2007), Georgopoulou *et al.* (2003), Karakosta *et al.* (2009), Neves *et al.* (2008) and Papadopoulos and Karagiannidis (2008), sometimes in combination with other methodologies such as data-envelopment analysis (Madlener *et al.*, 2009) and PROMETHEE (Goletsis *et al.*, 2003). When comparing different outranking methods, PROMETHEE stands out due to its fairly simple design, ease of computation and application and stability of results. Generalized preference functions allow hesitations in DMs' preferences and uncertainties in criteria performance values to be modelled.

Table I. Applications of PROMETHEE in energy planning

Application field	References
Comparing concentrating solar power technologies	Cavallaro (2009)
Regional energy planning with a focus on renewable energies	Polatidis and Haralambopoulos (2007), Terrados *et al.* (2009) and Tsoutsos *et al.* (2009)
Analysis of national energy scenarios in Greece with a focus on renewable energies	Diakoulaki and Karangelis (2007) and Georgopoulou *et al.* (1998)
Designing energy policy instruments	Doukas *et al.* (2006) and Madlener and Stagl (2005)
Evaluation of different heat supply options	Ghafghazi *et al.* (2009)
Prioritisation of geothermal energy projects	Goumas and Lygerou (2000), Goumas *et al.* (1999) and Haralambopoulos and Polatidis (2003)
Participatory analysis of national renewable energy scenarios in Austria	Kowalski *et al.* (2009) and Madlener *et al.*(2007)
Evaluation of biomass collection and transportation systems	Kumar *et al.* (2006)
Siting of hydropower stations	Mladineo *et al.* (1987)
Comparing cooking energy alternatives	Pohekar and Ramachandran (2004)
Evaluation of residential energy systems	Ren *et al.* (2009)
Comparing energy technologies based on renewable, fossil or nuclear resources	Topcu and Ulengin (2004)
Evaluation of energy research projects	Tzeng *et al.* (1992)

Application field	References
Selection of stocks in stock trading	Albadvi *et al.* (2007)
Choice of manufacturing systems	Anand and Kodalis (2008)
Supplier evaluation and outsourcing decisions	Araz *et al.* (2007), Araz and Ozkarahan (2007), Routroy and Kodali (2007) and Wang and Yang (2007)
Investigation of chemometric analysis results	Ayoko *et al.* (2007), Carmody *et al.* (2007), Ni *et al.* (2007) and Purcell *et al.* (2007)
Ranking of transportation vehicles	Beynon and Wells (2008) and Safaei Mohamadabadi *et al.* (2009)
Preventive maintenance planning	Cavalcante and de Almeida (2007)
Comparing river management alternatives	Chou *et al.* (2007) and Hermans *et al.* (2007)
Ranking of biopolymer options	Cornelissen *et al.* (2009)
Material and equipment selection	Dagdeviren (2008), Tuzkaya *et al.* (2009) and Zhu *et al.* (2010)
Prioritizing clean development mechanism projects	Diakoulaki *et al.* (2007)
Prioritizing nanotechnology areas	Ghazinoory *et al.* (2009)
Evaluation of waste management strategies	Kapepula *et al.* (2007), Mergias *et al.* (2007), Rousis *et al.* (2008) and Vego *et al.* (2008)
Formulation of water leakage management strategies	Morais and de Almeida (2007)
Evaluation of land use alternatives	Palma *et al.* (2007)
Site selection for recycling plants	Queiruga *et al.* (2008)
Ranking scheduling strategies	Roux *et al.* (2008)

Note: Other than energy planning issues

Table II. Recently published applications of PROMETHEE

Furthermore, the threshold values to be defined for applying generalized preference functions have an economic signification which facilitates their determination for the DM. Sensitivity analysis enables the influence of different preference functions and criteria weights to be depicted as well as weight stability intervals to be determined. In this way, the decision process becomes more transparent and the validation of results is facilitated. Also, PROMETHEE can be easily adapted for group decision aid, for example by including different weighting schemes (Al Shemmeri *et al.*, 1997; Løken, 2007; Wang *et al.*, 2009). Thus, in our work, PROMETHEE is preferred to other outranking approaches, because it is perceived to be more transparent and easier to understand even for DMs not familiar with MADM (Buchholz *et al.*, 2009; Løken, 2007; Polatidis *et al.*, 2006).

In general, outranking approaches are based on comparisons of pairs of alternatives regarding different criteria (Brans and Mareschal, 2005; Brans *et al.*, 1986; Roy, 1980; Roy and Bouyssou, 1993). However, in contrast to the AHP/ANP approaches, the DM is not required to make the comparisons himself; these are executed automatically instead. The input required concerns the evaluation of the criteria for all of the alternatives considered as well as the weightings needed to reflect their relative importance. In order to apply PROMETHEE, first the performance of the alternatives regarding all criteria needs to be determined on an ordinal or cardinal scale. Then, alternatives are compared in pairs for each criterion based on generalized preference functions. Based on the weighted sum of single criterion preferences, positive and negative outranking flows are calculated as a measure of dominance of alternatives. Criteria weights reflect the subjective relative importance of the criteria from the viewpoint of the DM(s). Based on positive and negative outranking flows, a partial preorder of alternatives can be defined according to PROMETHEE I. The net outranking flow can also be calculated to avoid incomparabilities and define a complete preorder on the set of alternatives according to PROMETHEE II. Details of the PROMETHEE algorithm are given in the Appendix.

Brans and Mareschal (2005) point out that the calculation of the net outranking flow in PROMETHEE II goes along with a loss of information compared to PROMETHEE I, because positive and negative criteria values can compensate each other, similar to utility functions in MAUT (Belton and Stewart, 2002). Thus, it is recommended to always use both options, because the complete ranking based on PROMETHEE II can only be fully understood if the partial ranking based on PROMETHEE I is also known.

Assuming that a common set of criteria can be defined for the alternatives, energy technologies can be compared based on PROMETHEE. However, it is also necessary for the DM to define weightings to reflect the relative importance subjectively assigned to the criteria under consideration according to his intrinsic value system. Normally, one set of weightings is defined, which is assumed to be valid for all alternatives. A sensitivity analysis usually serves to demonstrate the influence of different weightings on the results of the assessment. However, in this study, it is assumed that the relative importance of criteria is not necessarily the same for all alternatives even from the unique perspective of just one DM. This assumption is based on the complex and dynamic changes of a technology's development discussed below.

Technologies are usually subject to dynamic and complex developments over time. Even though innovative technologies usually imply more insecurities and risks as well as higher costs and lower performance levels to start with, it still might be reasonable to implement them, for example, due to expected performance improvements (Perl, 2007). From the perspective of the DM, this means that when an innovative technology is evaluated, the relative importance of the criteria considered in the assessment might be different compared to a well-established technology. Thus, a method for decision support which takes account of the varying importance of criteria depending on the state of development of the technology could be useful, for example, for an energy utility that has to rebuild or expand its power plant fleet[1]. Indeed, Polatidis *et al.* (2003, 2006) point out that criteria weights vary over time in multi-criteria energy system planning. However, Polatidis *et al.* (2003) suggest basing the criteria weights on the transition stage of the energy system as a whole instead of taking into account the individual development phase of a specific technology. In contrast, our approach aims at pointing out the differences between technologies related to different development phases and suggests applying different weights to different technologies at the same time.

To implement the idea of varying criteria weightings depending on the actual development phase of a technology, a concept is needed which permits technologies to be allocated to distinguishable phases within the technology life cycle. Life cycle models are commonly applied to forecast future technical developments and describe the development of the sales of a product over time (Dekimpe *et al.*, 1998; Lakhani, 1979; Snyder *et al.*, 2003)[2]. The time period for each stage of the product life cycle may vary, but the phases and their order of sequence are assumed to be the same for all types of products starting with market introduction, followed by a period of growth, then maturity and finally the saturation and/or degeneration stage. Based on the life cycle concept including the four phases of development from introduction to saturation of the market, weightings can be defined for the different development phases depending on the characteristics of each phase. Consequently, not only one weighting vector needs to be defined as is the case in the traditional PROMETHEE approach but one for each of the life cycle stages considered. Furthermore, the evaluated technologies need to be assigned to one of the defined development phases. Finally, for the calculation of outranking flows according to the modified PROMETHEE, the applied weightings for each technology depend on its actual development phase. Details of the modified algorithm are given in the Appendix.

The aim of these modifications is to provide a methodology which defines preferences more accurately by taking account of the dynamic changes through which a technology progresses and which thus improves the quality of decision support and the acceptance of the results. In the following, the proposed modified PROMETHEE approach is demonstrated based on an example application.

3. Case study

Against the background of rising energy prices, the dependence on increasingly scarce fossil fuels and the growing awareness of environmental issues such as climate change, some municipalities in Germany have decided to reorganize their energy supply system. This initiative known as "Bioenergiedörfer" (bio-energy villages) focuses on regional sustainability by applying energy supply concepts based on regionally available biomass which are organized independently of large energy utilities. The first of these projects to be realized was in Juehnde, which is regarded as a role model for other locations. Based on a coordinated decision process, the inhabitants chose to implement a concept mainly based on biogas and wood chips. However, MCDM was not applied in this project (Karpenstein-Machan and Schmuck, 2007). When implementing future bio-energy village concepts in other locations, multi-criteria methods could support the process of selecting the most suitable technological options for regional electricity and heat supply. Thus, the bio-energy village of Juehnde was chosen as an illustrative example application to demonstrate the modified PROMETHEE approach described above. The goal is to provide decision support for follow-up projects or similar decision situations.

3.1 Energy supply alternatives

Before 2005, the electricity supply of Juehnde was based on the German power supply mix, while room heating and hot water were usually provided by oil-fired boilers installed individually in the households. This is considered to be the reference case (alternative A1). The energy supply concept founded on regionally available biomass was introduced in 2005 and includes one biogas-cogeneration unit (680 kW_{el}), one heating station fired with wood chips (550 kW_{th}) to cover higher heat demands during winter and an oil-heating station (1.6 MW_{th}) to cover extremely high heat demands and to back-up eventual outages of the other plants (alternative A2) (Karpenstein-Machan and Schmuck, 2007). Two other (hypothetical) alternatives based on renewable energies are also considered in this case study. The third alternative (A3) includes a wind energy plant as well as photovoltaic (PV) roof-top installations for electricity generation. For heating, it is assumed that new gas-condensing boilers are installed. The fourth alternative (A4) includes solar flat plate collectors instead of PVs for heating in addition to the gas-condensing boilers, thus reducing the demand for natural gas (Table III).

3.2 Criteria for the assessment of energy technologies

For the assessment of energy technologies, the goals of security of supply, economic profitability and environmental sustainability shall be considered. Criteria need to be defined to measure to what degree the different energy technologies can contribute to achieving these goals. Seven criteria are applied to this case study (Table IV). Other goals and criteria could also be considered, for example job creation, safe operation, ease of installation, operation and maintenance, efforts regarding waste disposal.

Alternative	Technologies for electricity supply	Technologies for heat supply
A1	German electricity supply mix	Oil-condensing boilers
A2	Biogas cogeneration unit (mainly based on corn silage, triticale and liquid manure)	Biogas cogeneration unit Wood chips heating station Oil-heating station
A3	Wind energy plant PV roof-top installations	Gas-condensing boiler
A4	Wind energy plant	Gas-condensing boiler + solar flat plate collector

Notes: In general, for pre-selection of decentralized alternatives the regional potentials of available renewables should be investigated first. For Juehnde, the biomass potentials are well known. Potential for wind and solar energy can also be estimated quite easily based on literature data. No easily exploitable hydropower or geothermal potentials are known for the Juehnde area. As the village is located quite far away from coastal areas, ocean energy is not a feasible alternative. Thus, the pre-selection of alternatives has been limited to the four alternatives described

Table III. Alternatives for electricity and heat supply for Juehnde

Goal	Criterion	Formula
Security of supply	Electric efficiency (%)	$\eta_{el} = P_{el}/\dot{W}_{fuel}$
	Thermal efficiency (%)	$\eta_{th} = \dot{Q}_{use}/\dot{W}_{fuel}$
	Availability (h/a)	$t_{av} = 8,760(h/a) - t_{c\,lim} - t_{tech}$
Economic profitability	Specific electricity cost (Ct/kWh$_{el}$)	$c_{el} = c_{hh} + c_i + c_f + c_v - c_{feed-in}$
	Specific heat cost (Ct/kWh$_{th}$)	$c_{th} = c_i + c_f + c_v$
Environmental sustainability	GWP	$GWP = \sum_k GWP_k \cdot m_{k,i}$
	AP	$AP = \sum_k AP_k \cdot m_{k,i}$
	EP	$EP = \sum_k EP_k \cdot m_{k,i}$
	CEA	$CEA = CEA_P + CEA_U + CEA_D$

Notes: P_{el},produced electricity; W_{fuel}, fuel energy; Q_{use}, produced heat; t_{av}, hours available per year; $t_{clim/tech}$, non-availability due to climatic conditions/technical reasons; c_{el}, total costs of electricity supply to consumer; c_{hh}, household electricity price; $c_{i\,f\,v}$, specific investment/fixed/variable operational cost; $c_{feed\text{-}in}$, specific feed-in tariff depending on technology; c_{th}, specific cost of heat to consumer; GWP_k, global warming potential of substance k; AP_k, acidification potential of substance k; EP_k, eutrophication potential of substance k; $CEA_{P\,U\,D}$, cumulative energy demand due to production/use/disposal of the technology considered

Sources: Guinée *et al.* (2002); VDI (1997) and own assumptions

Table IV. Formula for calculation of criteria values

In practice, criteria should be determined in collaboration with stakeholders, for example using questionnaires or interview techniques. However, in this explanatory case study, the number of criteria has been limited for the sake of clarity in presenting the concept of life cycle-dependent criteria weights. Before the evaluation procedure with PROMETHEE can start, the criteria values have to be determined for each alternative (Tables V and VI).

With regard to the security of supply, the efficiency of energy conversion is of interest, because higher efficiency means that less primary energy is needed to produce the same amount of electricity or useful heat. The operational availability (in hours per year) also indicates the reliability of energy supply and thus the (short term) security of supply. Even though this is not able to reflect the fluctuating and non-dispatchable supply of wind and solar radiation, the availability in hours per year as a criterion represents a compromise between accuracy and practicability. Apart from weather conditions, the operational availability can also be restricted due to maintenance and servicing.

Regarding environmental sustainability, three ecological impact categories are calculated based on life cycle impact assessment (LCIA). The global warming potential (GWP) is of particular interest, because the energy sector contributes substantially to overall greenhouse gas emissions ((The) World Bank, 2007). Additionally, the acidification potential (AP) and the eutrophication potential (EP) are also used as criteria. Furthermore, the cumulative energy demand (CEA) for non-renewable energy sources is taken as an indicator for the total demand for non-renewable, primary energy resources (VDI, 1997). The functional unit for the LCIA is 1 kWh of electricity or useful heat, respectively. As suggested in ISO (2006, 14040 pp.), the impact assessment results are normalized, i.e. related to the total emissions (or the total consumption) per year within the region of interest. The normalization factors applied for the case study are based on Hillenbrand (2009).

For the biogas cogeneration technology, the environmental burdens are allocated to the products electricity and useful heat using an energy-based allocation factor. For electricity, which can be used in virtually all other energy-related applications, the exergy content of 1 kWh equals its energy content. For heat, the exergy content of 1 kWh depends on both the temperature of the heat and that of the environment (Szargut *et al.*, 1988; WEC, 1992).

To evaluate the economic profitability from the perspective of household consumers, for A1, the costs for electricity consumption correspond to the electricity price for households in Germany in 2008. For heat supply with oil-condensing boilers, the heat specific costs as calculated in Ruppert *et al.* (2008) are used.

For the biomass concept (A2), the cost for the electricity supply also corresponds to the household electricity price, because the electricity generated by biogas cogeneration is fed into the grid and households purchase their electricity from the grid. Feed-in-tariffs received according to the German Renewable Energy Act (Erneuerbare-Energien-Gesetz) (Bundestag, 2008) are used to recover some of the plant's operating costs. The cost of heat results from a one-off charge for the connection to the district heating system, a fixed yearly charge, variable specific heating costs and the cost of dismantling old heating boilers and installing new components (Karpenstein-Machan and Schmuck, 2007; Ruppert *et al.*, 2008).

The electricity generated using wind and PV technology (A3) is fed into the grid and feed-in tariffs are paid to the households. Costs for the consumer result from

Table V.
Decision matrix for the evaluation of electricity supply technologies

Technology	Criterion: Electric efficiency (%)	Availability (h/a)	Specific electricity costs (Ct/kWh_e)	GWP (GWP100)[a]	AP[b]	EP[c]	CEA (non-renewable)[d]
Min./Max.	Max.	Max.	Min.	Min.	Min.	Min.	Min.
Type of preference function [e]	6	6	6	6	6	6	6
Threshold	15	3,800	6.23	$3.42 \times^{-13}$	$2.13 \times^{-13}$	$1.63 \times^{-13}$	$4.26 \times^{-13}$
German supply mix	41.9	8,500	24.08	$7.05 \times^{-13}$	$4.49 \times^{-13}$	$2.67 \times^{-13}$	$8.65 \times^{-13}$
Biogas cogeneration unit (allocation exergy 89 per cent)	40.3	7,143	24.08	$2.09 \times^{-13}$	$4.47 \times^{-13}$	$3.43 \times^{-13}$	$1.17 \times^{-13}$
PV	12	900	11.62	$8.21 \times^{-14}$	$1.72 \times^{-13}$	$1.10 \times^{-13}$	$1.00 \times^{-13}$
Wind	35	1,700	23.77	$1.15 \times^{-14}$	$2.26 \times^{-14}$	$1.62 \times^{-14}$	$1.30 \times^{-14}$
Sources	Reichmuth *et al.* (2006), Ruppert *et al.* (2008) and Staiß (2007)	Reichmuth *et al.* (2006), Ruppert *et al.* (2008) and Staiß (2007)	Reichmuth *et al.* (2006), Ruppert *et al.* (2008), European Commission (2009) and Bundestag (2008)	Frischknecht *et al.* (2007a, b), Guinée *et al.* (2002) and Hillenbrand (2009)	Frischknecht *et al.* (2007a, b), Guinée *et al.* (2002) and Hillenbrand (2009)	Frischknecht *et al.* (2007a, b), Guinée *et al.* (2002) and Hillenbrand (2009)	Frischknecht *et al.* (2007a, b), Guinée *et al.* (2002), Hillenbrand (2009) and VDI (1997)

Notes: [a]Kilograms of CO_2-equivalents per kWh_e related to the total greenhouse gas emissions in Germany in 2003; [b]kilograms of SO_2-equivalents per kWh_e related to the total emissions of acidifying agents in Germany in 2003; [c]kilograms of PO_4-equivalents per kWh_e related to the total emissions with EP in Germany in 2003; [d]mega joule-equivalents per kWh_e related to the total energy demand in Germany in 2003; [e]according to Brans and Mareschal (2005)

Technology	Thermal efficiency (%)	Availability (h/a)	Specific heat cost (Ct/kWh_{th})	GWP (GWP100)[a]	AP[b]	EP[c]	CEA, (non-renewable)[d]
	Criterion						
Min./Max.	Max.	Max.	Min.	Min.	Min.	Min.	Min.
Type of preference function[e]	6	6	6	6	6	6	6
Threshold	30	590	0.65	$1.60 \times ^{-13}$	$1.58 \times ^{-13}$	$1.07 \times ^{-13}$	$1.76 \times ^{-13}$
Oil-condensing boiler	100	8,322	10.8	$3.32 \times ^{-13}$	$3.03 \times ^{-13}$	$1.66 \times ^{-13}$	$3.63 \times ^{-13}$
Biogas cogeneration unit (allocation exergy 11per cent)	39.8	7,143	10.7	$2.70 \times ^{-14}$	$5.76 \times ^{-14}$	$4.42 \times ^{-14}$	$1.51 \times ^{-14}$
Wood chips heating station	88	8,322	10.7	$1.77 \times ^{-14}$	$1.44 \times ^{-13}$	$2.59 \times ^{-13}$	$2.55 \times ^{-14}$
Oil-heating station	75	8,322	10.7	$3.39 \times ^{-13}$	$3.73 \times ^{-13}$	$2.07 \times ^{-13}$	$3.67 \times ^{-13}$
Gas-condensing boiler	100	8,322	9.5	$2.66 \times ^{-13}$	$9.46 \times ^{-14}$	$5.12 \times ^{-14}$	$3.32 \times ^{-13}$
Gas-condensing boiler + solar collector	100	8,322	10.3	$2.12 \times ^{-13}$	$9.75 \times ^{-14}$	$5.58 \times ^{-14}$	$2.70 \times ^{-13}$
Sources	BMWi (2009), Reichmuth *et al.* (2006), Ruppert *et al.* (2008) and Staiß (2007)	Reichmuth *et al.* (2006), Ruppert *et al.* (2008) and Staiß (2007)	Ruppert *et al.* (2008), BMU (2009) and DIN (2003)	Dones *et al.* (2007), Frischknecht *et al.* (2007a, b), Guinée *et al.* (2002) and Hillenbrand (2009)	Dones *et al.* (2007), Frischknecht *et al.* (2007a, b), Guinée *et al.* (2002) and Hillenbrand (2009)	Dones *et al.* (2007), Frischknecht *et al.* (2007a, b), Guinée *et al.* (2002) and Hillenbrand (2009)	Dones *et al.* (2007), Frischknecht *et al.* (2007a, b), Guinée *et al.* (2002), Hillenbrand (2009) and VDI (1997)

Notes: [a]Kilograms of CO_2-equivalents per kWh of useful heat related to the total greenhouse gas emissions in Germany in 2003; [b]kilograms of SO_2-equivalents per kWh of useful heat related to the total emissions of acidifying agents in Germany in 2003; [c]Kilograms of PO_4-equivalents per kWh of useful heat related to the total emissions with EP in Germany in 2003; [d]Mega joule-equivalents kWh of useful heat related to the total energy demand in Germany in 2003; [e]according to Brans and Mareschal (2005)

Table VI.
Decision matrix for the evaluation of heat supply technologies

the capital investment as well as operation and maintenance costs for the installations. Furthermore, consumers still have to purchase electricity from the grid. Thus, the total costs amount to the specific costs for installing and operating the equipment minus the feed-in tariffs for wind- or PV-generated electricity, respectively, plus the price for household electricity. For gas heating systems (with and without solar collectors), costs are assumed according to BMU (2009) and the German norm DIN4701-10 (DIN, 2003).

3.3 Determination of preference functions

After the criteria values have been determined for each alternative, the first step of the PROMETHEE procedure outlined above is to select the type of preference function. Six types of generalized preference function have been proposed by Brans *et al.* (1986). Some guidelines to help choosing appropriate preference functions are given in Routroy and Kodali (2007) and Anand and Kodali (2008). Generally, it is acknowledged that preference functions should be determined in accordance with the nature of the criteria, the hesitations in DMs preferences and uncertainty in data. In our illustrative case study, the Gaussian type is selected for all the criteria, because it shows robust results, is the least sensitive to small variations in the input parameters and is widely used (Brans *et al.*, 1986; Queiruga *et al.*, 2008):

$$p_j(a_{i^*}, a_i) = 1 - e^{-((f_j(a_{i^*}) - f_j(a_i))/2\sigma_j^2)} \quad \text{where} \quad \sigma_j = \frac{f_j^{\max} - f_j^{\min}}{2}$$

This type of preference function neither requires the definition of a preference nor an indifference threshold, but only the inflection point σ_j. The respective value for each criterion in our case study is displayed in Tables V and VI. It assumes a normal distribution of preferences and indicates that smaller differences in the criteria values result in weaker preferences, while preferences become stronger with increasing differences. This seems to be a reasonable assumption when comparing the performance of energy technologies. However, in practice preference functions and thresholds (if applicable) should be defined according to DMs' preferences.

3.4 Weighting of criteria depending on technology development phase

For the second step of the modified PROMETHEE procedure described above weightings need to be defined for each technology life cycle phase and the technologies assigned to their current phase. The weightings presented in Table VII for the maturity phase are based on (Oberschmidt and Klobasa (2008)) and complemented by own assumptions of the authors. For instance, it is assumed that total specific costs are most important in the maturity and saturation stage because only profitable technologies can be applied successfully on the market. During earlier stages, costs might not be the most important decision variable, in particular if future cost reductions is expected. Availability is assumed to become more important with increasing market share. Environmental aspects might be considered to be more important in earlier stages against the background of climate change and ongoing resource depletion. In practice, weightings depend on the subjective relative importance assigned to the criteria by stakeholders and should be defined using appropriate techniques for weight elicitation in groups.

Before the analysis can proceed, technologies are assigned to different life cycle phases as described in Section 2.2 in order to be able to calculate preference indices

Criterion	Phase of development Introduction (%)	Growth (%)	Maturity (%)	Saturation (%)
Electric/thermal efficiency	26	17	6	6
Availability	6	8	14	10
Economic profitability (total specific costs)	16	36	56	58
GWP (GWP100)	26	13	9	9
AP	8	8	4	6
EP	6	9	3	5
CEA	11	8	8	6
Total	100	100	100	100

Source: Own assumptions based on Oberschmidt and Klobasa (2008)

Table VII. Assumed relative weightings of criteria depending on different life cycle phases

based on life cycle-dependent weightings (Table VIII). Most technologies are assigned to the growth phase, including biogas cogeneration, PV and wind as well as heating with wood chips and gas-condensing boilers in combination with solar collectors. The German power generation mix and gas-condensing boilers for heating are assumed to be further developed and in the maturity phase, while oil-condensing boilers and oil-heating stations are assigned to the phase of saturation.

Based on the two matrices (Tables VII and VIII), the third step of the modified PROMETHEE procedure described in Section 2.2 is to calculate the outranking relation for each alternative based on life cycle-dependent weightings. The following steps, four to six are identical to the standard PROMETHEE procedure described in Section 2.1.

4. Results

Figure 1 shows the life cycle-dependent outranking flows of the technologies for electricity supply, i.e. ϕ^+ as a measure of relative strengths and ϕ^- as a measure of relative weaknesses compared to all other technologies as well as the net flow $\phi = \phi^+ - \phi^-$. The renewable technologies of wind and PV show the greatest strengths, although PV shows more weaknesses and not as many strengths as wind. Thus, wind is ranked first followed by PV. No complete ranking is achieved based on

	Introduction	Growth	Maturity	Saturation
German power generation mix			X	
Biogas cogeneration		X		
PV		X		
Wind		X		
Oil-condensing boiler				X
Wood chips heating station		X		
Oil-heating station				X
Gas-condensing boiler			X	
Gas + solar collector		X		

Sources: Based on installation rates elicited from Eurostat (2009a); Observ'ER *et al.* (2009); OECD/IEA (2008a)

Table VIII. Allocation of technologies to life cycle phases

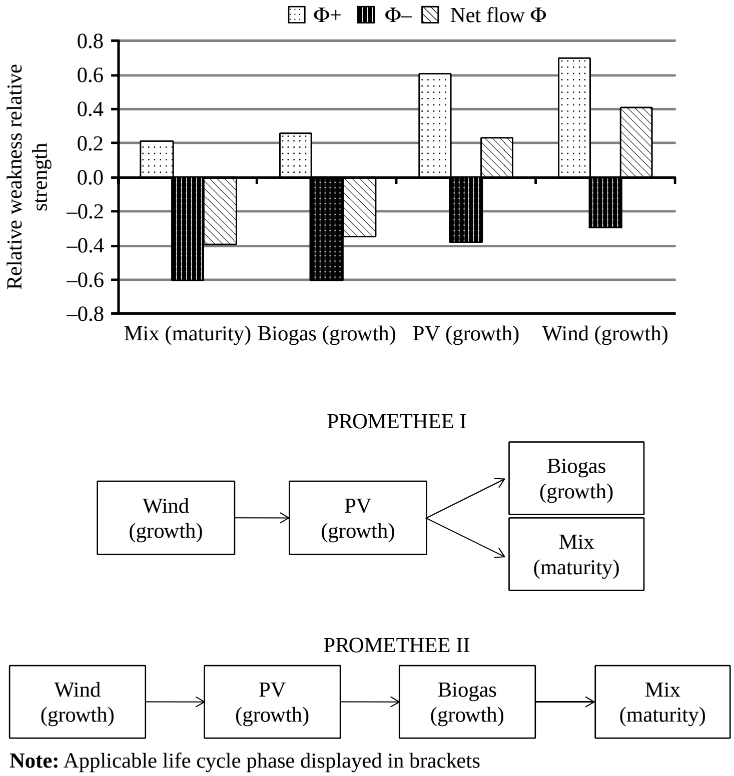
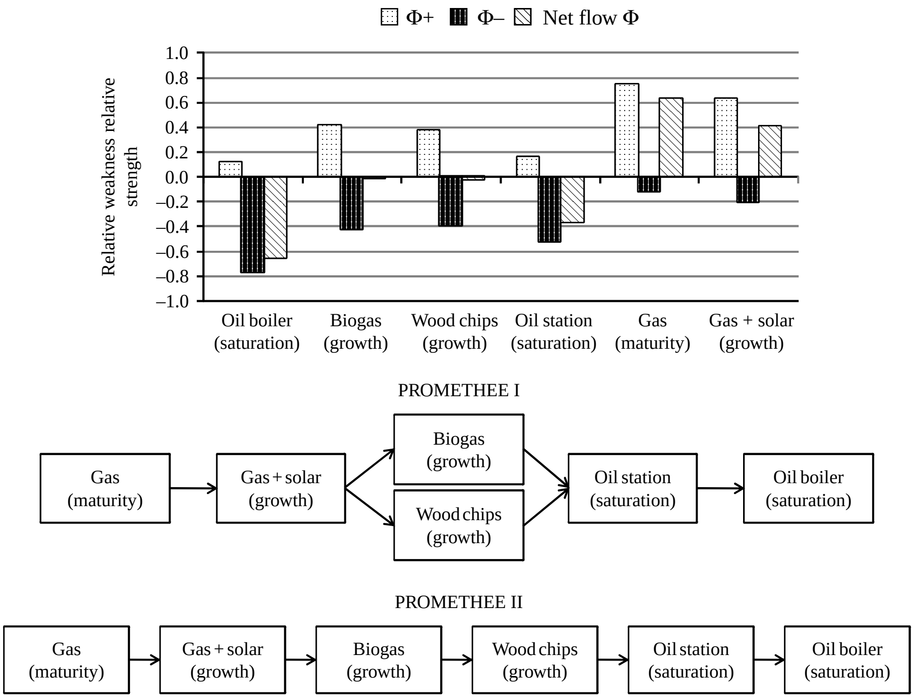


Figure 1.
Aggregated preference flows of electricity supply technologies and ranking according to PROMETHEE I and II based on life cycle-dependent weightings

PROMETHEE I because the biogas cogeneration unit shows more strengths but also slightly more weaknesses than the German electricity mix. However, the net-outranking flow of the biogas cogeneration unit is higher than that of the electricity mix. Therefore, the biogas cogeneration unit is ranked higher based on PROMETHEE II. Looking at these results, it is necessary to remember that nearly all the environmental burdens of the biogas cogeneration unit are assigned to electricity generation due to the allocation factor based on exergy.

The comparison of heat supply technologies (Figure 2) shows the best result for the gas-condensing boiler followed by the integrated gas and solar heating system. This is because the cost for the solar heating system is slightly higher than heating with gas-condensing boilers only. Furthermore, the solar heating system performs slightly worse regarding the criteria of acidification and EP. The biogas cogeneration unit for heating shows more strengths than the wood chips heating system, but also more weaknesses. These can be traced back to the lower assumed availability and thermal efficiency as well as the high GWP due to higher methane emissions for biogas production and combustion. The heating technologies based on fuel oil clearly perform the worst, mainly because of their environmental disadvantages.

The results depend on the specific weighting, which in turn depends on the technology's development phase. Figures 3 and 4 show the difference due to life cycle-dependent criteria



Note: Applicable life cycle phase displayed in brackets

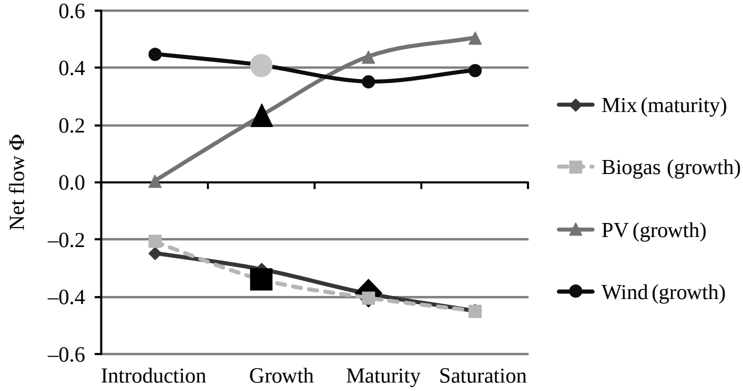
Figure 2. Aggregated preference flows of heat supply technologies and ranking according to PROMETHEE I and II based on life cycle-dependent weightings

weightings instead of identical weightings to all technologies. For electricity supply technologies (Figure 3), the life cycle-dependent ranking based on PROMETHEE II is Wind → PV → Biogas → Mix. If the introduction phase weightings were applied to all the technologies, the resulting ranking would incidentally be the same. However, if the growth phase weightings were applied to all the technologies the ranking would be Wind → PV → Mix → Biogas, i.e. Biogas and Mix would swop places. Applying the weighting of the maturity or saturation phase to all the technologies, would result in the ranking PV → Wind → Mix → Biogas, i.e. PV and Wind would also swop places.

The life cycle-dependent ranking of the heat supply technologies (Figure 4) is Gas → Gas + Solar → Biogas → Wood Chips → Oil station → Oil boiler. If the weightings of the introduction phase were applied to all the technologies, the rank ordering of gas and gas + solar as well as oil-heating station and oil boiler would be reversed. Applying the weightings of the growth phase to all the technologies would alter the rank ordering of oil boiler and oil-heating station compared to the life cycle-dependent ranking. If the weighting corresponding to the maturity or saturation phase were applied to all the technologies, the ranking would incidentally be identical to the one based on life cycle-dependent preferences.

4.1 Remarks on sensitivity analysis

While applying sensitivity analysis, usually the weight of one criterion is varied while the relative weights of the other criteria remain constant. In this way, weight stability



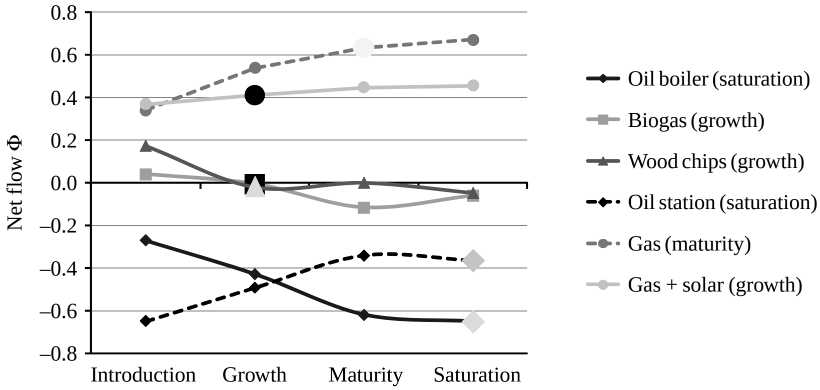
Weight stability intervals with regard to net flow:	W_{min}(%)	W_{max}(%)
Electric efficiency	0.0	54,0
Availability	0.0	29,6
Specific electricity cost	26.2	48,4
GWP100	0.0	100,0
AP	0.0	100,0
EP	0,0	18,2
CEA, non–renewable	0,0	100,0

Note: Enlarged symbol indicates actual development phase

Figure 3.
Dependency of the results for electricity supply technologies on the weighting in different life cycle phases

intervals can be defined as shown in Figures 3 and 4. Within the interval [w_{min}; w_{max}] the weight of the considered criterion can be varied without changing the final ranking according to PROMETHEE II, with the relative weights of the other criteria remaining constant. However, this does not necessarily hold if life cycle-dependent weights are applied, because then the relative weights of the criteria are not the same for all alternatives to start with. As an example, this is illustrated for the weight of specific heat cost in Figure 5. First, the weight according to the growth phase is taken as a starting point, which was actually applied to biogas cogeneration, wood chips heating and the combined gas and solar heating system. In this case, the lower boundary of the weight stability interval is $w_{min} = 10$ per cent, where the rank order of gas + solar and biogas is reversed. At the upper boundary $w_{max} = 37.5$ per cent, the rank order of gas + solar and oil boiler are reversed. However, if the weights according to the maturity or saturation phase (originally applied to gas-condensing boiler and alternatives based on oil, respectively) are taken as a starting point, the upper and lower boundaries of the weight stability interval must be defined differently. At the lower boundary $w_{min} = 55.6$ per cent, the rank order of gas and gas + solar is reversed. At the upper boundary $w_{max} = 85.6$ per cent, the rank order of biogas and wood chips is reversed.

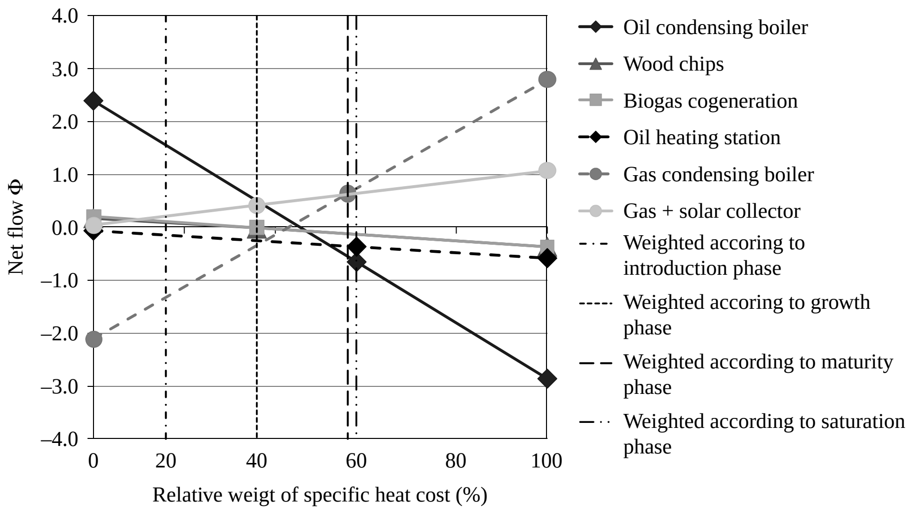
The example shows that sensitivity analysis is getting more complicated if life cycle-dependent weights are applied. Thus, new ways to conduct meaningful sensitivity analysis based on the life cycle-oriented PROMETHEE should be elaborated, as well as user-friendly graphical representations.



Weight stability intervals with regard to net flow:	W_{min}(%)	W_{max}(%)
Thermal efficiency	0.0	18.6
Availability	0.0	10.6
Specific heat cost	10.0/55.6*	37.5/85.6*
GWP100	0.0	17.4
AP	5.2	61.0
EP	7.5	57.6
CEA, non-renewable	0.0	61.1
*For technologies weighted according to growth phase/maturity and saturation phase		

Note: Enlarged symbol indicates actual development phase

Figure 4. Dependency of the results for heat supply technologies on the weighting in different life cycle phases



Note: The curve of wood chips is hidden by the curve of biogas cogeneration

Figure 5. Sensitivity analysis regarding the weight of specific heat cost considering life cycle-dependent preferences

4.2 Ranking of energy supply mixes

It is not obvious at first sight which concept is "best" when looking at the results based on the individual technologies. Therefore, the results (outranking flows) are further aggregated for each technology and concept according to their share of electricity/heat supply to obtain a measure of preference for each electricity and heat supply concept. For A1, it is assumed that 100 per cent of the electricity demand is met by the German electricity supply mix and that 100 per cent of the heat demand is covered by oil-condensing boilers. For A2, a share of 100 per cent electricity is assumed for biogas. According to target figures of the bio-energy village project Juehnde, the heat demand is covered by the biogas cogeneration unit (60 per cent), the wood chips heating station (35 per cent) and the oil-heating station (5 per cent) for peak loads. In concept 3, electricity is generated by wind and PV installations. For wind, two plants with 800 kW_e each and 1,700 full load hours per year are assumed, totalling 2,720 MWh_e per year. For PV based on available roof area an installed capacity of around 166 kW_p is assumed. If 900 full load hours per year are assumed, this results in a production of around 149 MWh_e per year. The electricity produced by wind and PV then sums up to 2,869 MWh_e per year. Thus, a share of around 5 per cent PV and 95 per cent wind is taken into account. The heat demand is assumed to be fully covered by gas-condensing boilers. For A4, 100 per cent electricity production from two wind plants with 800 KW_e each is assumed for the evaluation. For heating, it is assumed that gas-condensing boilers in combination with the solar flat plat collectors cover the total heat demand.

For this rather simple example, the results of alternatives A1-A4 as combinations of one or more technologies for electricity and heat supply are quite similar to the evaluation results for individual technologies (Figure 6). This could differ if larger and more complex systems comprising more energy options are considered. From the intersection of the results for the electricity supply alternatives on the one hand and for heat supply on the other, it is not clear whether the combination of wind, PV and gas-condensing boilers (A3) or the combination of wind and gas together with solar collectors (A4) performs better. The result for the biomass concept (A2) is clearly better than the reference case (A1). If the net outranking flows for electricity and heat supply are added up for each alternative, the result for the combination of wind, PV and gas-condensing boiler is better than the alternative with additional solar heating.

5. Discussion

A method for multi-criteria assessment considering criteria weights depending on the development phase of a technology has been introduced. The applicability of this approach to comparing alternatives for electricity and heat supply has been demonstrated based on the bio-energy village Juehnde in Germany. The results of the case study show that, compared to the reference case, the biomass-concept introduced in Juehnde is preferable from the viewpoint of domestic electricity and heat consumers. Based on the seven criteria considered, other alternatives including renewable wind and solar technologies as well as gas heating systems show even better results. However, it is important to remember that the relative criteria weightings applied in this case study do not represent the preferences of a specific stakeholder group. Including "real" preference information could significantly change the final results. On the other hand, MCDM was not applied to the decision process in Juehnde and might have resulted in a different final decision to the observed one. In any case,

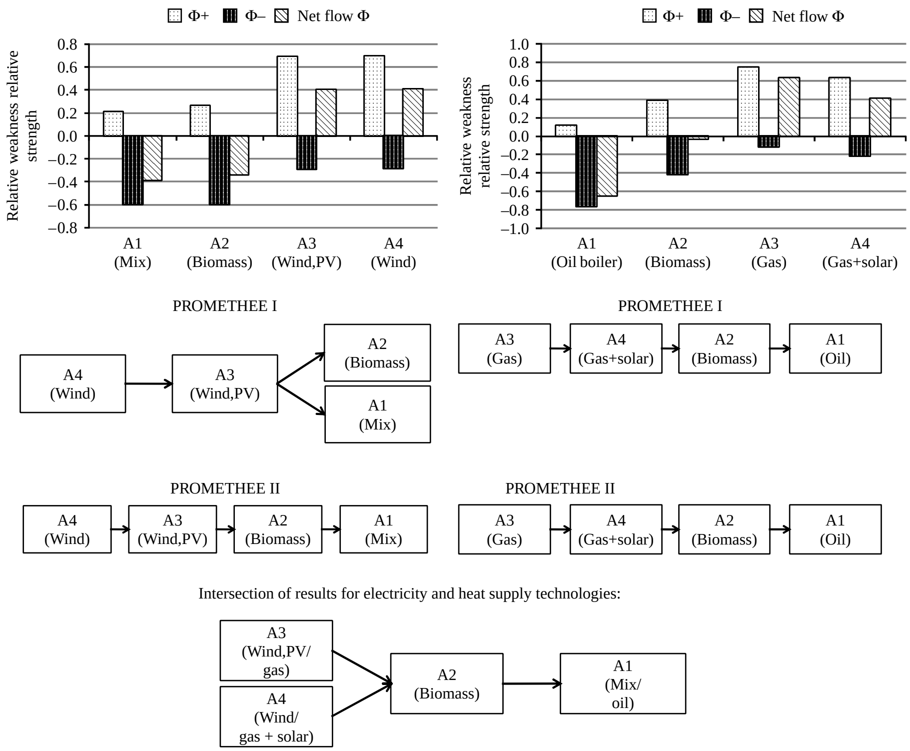


Figure 6.
Comparison of different combinations of energy technologies for electricity and heat supply

for follow-up projects, MCDM can help to make the decision process more transparent while taking into account the viewpoints of all the stakeholders based on appropriate preference modelling.

Regarding environmental impacts, renewable technologies obviously outrank those based on fossil fuels. However, the environmental effects of different renewables including up-stream processes can vary greatly and should be evaluated carefully. If future learning effects and economies of scale are accounted for, renewable technologies such as wind, PV, solar heating and biogas cogeneration could become even more preferable in economic terms when compared to well-established technologies based on fossil fuels. Furthermore, the example application was based on today's prices for electricity and fossil fuels in Germany. Considering future price increases would have had adverse effects on the results of technologies relying on these energy sources.

Limitations to the proposed methodology may arise because additional information is needed from the DM compared to the traditional PROMETHEE methodology, and because it may not be easy to retrieve information about life cycle-dependent preferences. However, the requirements for information input are still lower than those for the AHP and ANP. Regarding the concept of a technology's life cycle, it may be difficult to unambiguously allocate a technology to a phase because the boundaries between the different phases may well be blurred. Furthermore, an energy technology might not have a clear profile; there is often a multitude of sometimes only slightly varying alternatives that can be subsumed according to different criteria or rules. However, data on market penetration and other indicators such as those based on patent statistics can help determine the current development phase of specific energy technologies (Jochem, 2009).

From the methodological point of view, the hypothesis of varying preferences depending on the development phase of a product or technology should be verified more thoroughly in future work. Furthermore, the mathematical implications of applying different weightings to one set of alternatives at the same time should be investigated in more detail. New ways to conduct meaningful sensitivity analyses need to be elaborated.

For future applications in the energy sector, expected future price increases for fossil fuels but also for biomass as well as the costs of emission certificates for CO_2 should be analysed systematically, for example based on different scenarios of future developments in the energy sector. Furthermore, future developments in the performance standards of energy technologies should be analysed explicitly, especially with regard to electrical and thermal efficiency increases as well as cost reductions, e.g. based on economies of scale. To account for varying preferences depending on the technology development life cycle phase, suitable methods need to be developed to retrieve the necessary information in practice. Decision support needs to be designed in such a way to help DMs articulate preferences according to different technology development phases and to visualize the results in the most meaningful way.

Notes

1. The idea of the varying importance of criteria depending on the development stage of a technology can be illustrated by the following example: an automotive manufacturer is developing a new car and can choose to integrate either a well-established motor technology or a newly developed innovative one. The innovative alternative has the advantage of greater flexibility so that it can be more easily adapted to the developer's requests. The well-established technology is more reliable, but it might not fully match the vision of the car developer.
2. This type of life cycle model, which describes the rise and decline of a whole group of products penetrating the market, is not to be confused with LCIA, where the environmental impact of a process is quantified "from the cradle to the grave", i.e. including production, distribution, usage and disposal.

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Appendix. Modified PROMETHEE algorithm

Let $A = \{a_1, \ldots, a_i, \ldots, a_m\}$ be the discrete set of alternatives under consideration and $C = \{c_1, \ldots, c_j, \ldots, c_n\}$ the set of relevant criteria. After determining the criteria values $f_j(a_i)$ for each alternative a_i and each criterion c_j, the procedure for preference elicitation using the proposed modified approach based on the original PROMETHEE I and II (Brans *et al.*, 1986) includes the following steps performed for all the alternatives under consideration:

(1) For each criterion c_j, one preference function p_j is determined, which reflects the degree of preference of alternative a_{i^*} over alternative a_i regarding the respective criterion depending on the difference in criteria values:

$$p_j(d_j(a_{i^*}, a_i)) = p_j(f_j(a_{i^*}) - f_j(a_i)) \quad \text{where } p_j \in [0;1].$$

For a usual criterion, the two alternatives are considered to be indifferent if $p_j = 0$. Alternative a_{i^*} is strictly preferred over a_i regarding criterion c_j, if $p_j = 1$. Other types of preference function allow an indifference threshold q (alternatives a_{i^*} and a_i are indifferent if $p_j \leq q$) as well as a threshold for strict preference p (alternative a_{i^*} is strictly preferred over a_i if $p_j \geq p$), with (gradually increasing) weak preference between the two threshold values. Further details on preference functions can be found in Brans *et al.* (1986), Routroy and Kodali (2007) and Anand and Kodali (2008).

(2) Usually, one weighting vector $\mathbf{w}^T = [w_1, \ldots, w_j, \ldots, w_n]$ to be applied for all alternatives is defined to reflect the (subjective) relative importance of the criteria, where $\sum_{j=1}^{n} w_j = 1$. However, it is suggested that the relative importance of criteria depends on the actual development phase of a technology. Thus, weightings are defined depending on different development phases. Consequently, not only one weighting vector needs to be defined as is the case in the traditional PROMETHEE approach, but one for each of the four life cycle stages considered:

$$W_{jk} = \begin{array}{cccccc} & t_1 & \cdots & t_k & \cdots & t_o \\ w_1 & w_1(t_1) & \cdots & w_1(t_k) & \cdots & w_1(t_o) \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ w_j & w_j(t_1) & \cdots & w_j(t_k) & \cdots & w_j(t_o) \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ w_n & w_n(t_1) & \cdots & w_n(t_k) & \cdots & w_n(t_o) \end{array}$$

where t_k denotes the life-cycle phase with $k = (1, \ldots, o)$, $o =$ number of life-cycle phases considered. Furthermore, the evaluated technologies need to be assigned to one of the defined development phases:

$$T_{ki} = \begin{array}{cccccc} & a_1 & \cdots & a_i & \cdots & a_m \\ t_1 & t_1(a_1) & \cdots & t_1(a_i) & \cdots & t_1(a_m) \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ t_k & t_k(a_1) & \cdots & t_k(a_i) & \cdots & t_k(a_m) \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ t_o & t_o(a_1) & \cdots & t_o(a_i) & \cdots & t_o(a_m) \end{array} \quad \text{where} \quad t_k(a_j) \in [0,1]$$

$$\text{and} \sum_{k=1}^{u} t_k(a_i) = 1$$

By multiplying the two matrices, the weighting applying to each specific alternative results:

$$w_j(a_i) = \begin{pmatrix} w_1(t_1) & \dots & w_1(t_k) & \cdots & w_1(t_o) \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ w_j(t_1) & \cdots & w_j(t_k) & \cdots & w_j(t_o) \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ w_n(t_1) & \cdots & w_n(t_k) & \cdots & w_n(t_o) \end{pmatrix} \cdot \begin{pmatrix} t_1(a_1) & \dots & t_1(a_i) & \cdots & t_1(a_m) \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ t_k(a_1) & \cdots & t_k(a_i) & \cdots & t_k(a_m) \\ \vdots & \ddots & \vdots & \ddots & \vdots \\ t_o(a_1) & \cdots & t_o(a_i) & \cdots & t_o(a_m) \end{pmatrix}$$

$$= \begin{pmatrix} w_1(t(a_1)) & \dots & w_1(t(a_i)) & w_1(t(a_m)) \\ \vdots & \ddots & \vdots & \\ w_j(t(a_1)) & \cdots & w_j(t(a_i)) & w_j(t(a_m)) \\ & & & \\ w_n(t(a_1)) & & w_n(t(a_i)) & w_n(t(a_m)) \end{pmatrix} = [w_j(t(a_i))]$$

(3) To determine the degree of dominance of alternative a_{i^*} over a_i with regard to all criteria, the outranking relation π is calculated with life cycle-dependent weightings:

$$\pi(a_{i^*}, a_i) = \sum_{j=1}^{n} w_j(t(a_{i^*})) \cdot p_j(a_{i^*}, a_i), \quad \text{where} \quad \pi(a_{i^*}, a_i) \in [0; 1].$$

This measure allows the comparison of two alternatives with regard to all criteria based on life cycle-dependent preferences.

(4) To compare one alternative with all of the other available alternatives based on all criteria, the outranking flows ϕ are calculated:

- The positive or leaving outranking flow ϕ^+ is a measure of the outranking character of alternative a_{i^*}:

$$\phi^+(a_{i^*}) = \sum_{\substack{i=1 \\ i \neq i^*}}^{m} \pi(a_{i^*}, a_i) = \sum_{\substack{i=1 \\ i \neq i^*}}^{m} \sum_{j=1}^{n} w_j(t(a_{i^*})) \cdot p_j(a_{i^*}, a_i).$$

Based on the positive outranking flows, the following preorders are induced:

– $a_{i^*} P^+ a_i$, i.e. a_{i^*} is preferred to a_i if $\phi^+(a_{i^*}) > \phi^+(a_i)$.

– $a_{i^*} I^+ a_i$, i.e. a_{i^*} and a_i are indifferent if $\phi^+(a_{i^*}) = \phi^+(a_i)$.

- The negative or entering outranking flow ϕ^- is a measure of the outranked character of alternative:

$$\phi^-(a_{i^*}) = \sum_{\substack{i=1 \\ i \neq i^*}}^{m} \pi(a_i, a_{i^*}) = \sum_{\substack{i=1 \\ i \neq i^*}}^{m} \sum_{j=1}^{n} w_j(t(a_{i^*})) \cdot p_j(a_i, a_{i^*}) a_{i^*}.$$

Based on the negative outranking flows, the following preorders are induced:

– $a_{i^*} P^- a_i$, i.e. a_{i^*} is preferred to a_i if $\phi^-(a_{i^*}) < \phi^-(a_i)$.

– $a_{i^*} I^- a_i$, i.e. a_{i^*} and a_i are indifferent if $\phi^-(a_{i^*}) = \phi^-(a_i)$.

(5) The partial preorder according to PROMETHEE I can be defined based on the intersection of the two preorders from the positive and the negative outranking flows:

- a_{i^*} is preferred to a_i if:
  - $a_{i^*}P^+a_i$ and $a_{i^*}P^-a_i$ or
  - $a_{i^*}P^+a_i$ and $a_{i^*}I^-a_i$ or
  - $a_{i^*}P^-a_i$and $a_{i^*}I^+a_i$
- a_{i^*} and a_i are indifferent if $a_{i^*}I^+a_i$ and $a_{i^*}I^-a_i$.
- otherwise a_{i^*} and a_i are incomparable ($a_{i^*}Ra_i$).

(6) A complete preorder avoiding incomparability can be defined according to PROMETHEE II based on the net flow $\phi(a_{i^*}) = \phi^+(a_{i^*}) - \phi^-(a_{i^*})$:

- a_{i^*} is preferred to a_i if $\phi(a_{i^*}) > \phi(a_i)$.
- a_{i^*} and a_i are indifferent if $\phi(a_{i^*}) = \phi(a_i)$.

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