Alanne, K., Salo, A., Saari, A. and Gustafsson, S.-I. 2006. Multi-criteria evaluation of residential energy supply systems. Energy and Buildings, accepted for publication.

Multi-Criteria Evaluation of Residential Energy Supply Systems

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Abstract

In this paper, we consider the selection of a residential energy supply system as a multi-criteria decision-making problem, which involves both financial and environmental issues. Specifically, we compare micro-CHP (micro-cogeneration) heating with traditional heating systems through an evaluation that accounts for (i) the decision-makers' subjective preferences, (ii) uncertainties in the performance of micro-CHP heating systems (which are partly caused by the lack of long-term operational experiences), (iii) the context-dependency of life-cycle costs and environmental burdens of heating systems. Motivated by these considerations, we employ the PAIRS multi-criteria decision-making methodology that captures incomplete information by way of interval-valued parameters and provides support for sensitivity analyses, too. Our comparative analysis of alternative heating systems suggests that micro-CHP is a reasonable alternative to traditional systems, particularly from the environmental point of view.

Keywords: multi-criteria evaluation, micro-cogeneration, micro-CHP, residential buildings

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1 Introduction

The introduction of sustainable energy systems is strongly associated to what choices real estate owners make among different heating options [1]. Earlier on, heating systems have been selected largely on the basis of capital costs and energy costs. Nowadays, such decisions are typically made on the basis of life-cycle costs; however, as environmental issues become increasingly important, it is necessary to consider the selection of technological alternatives a multi-criteria problem. Here, one of the challenges is that it may be difficult to obtain complete information about the decision-makers' preferences. Furthermore, there are no long-term experiences from new technological systems, wherefore the performance of alternative systems with regard to the evaluation criteria involves uncertainties.

Although real estate owners tend to prefer "soft" and "ecological" values, only few multi-criteria comparisons of residential heating systems have thus far been published: for example, Riihimäki et al. [2] and Huovila et al. [3] note that in Finland, good environmental value, good comfort, and safety are among the most important criteria. One possible reason for the apparent paucity of multi-criteria studies is that conventional multi-criteria approaches do not address uncertainties explicitly. A further reason may be that the costs have often remained the overriding criterion in the final decision.

More broadly seen, however, multi-criteria optimization methods have found uses in the analysis of residential buildings. Li et al. [4] define a "green heating system" and employ a multi-criteria optimization process to determine the trade-off between cost and environmental performances for this system. Burer et al. [5] optimize the design and operation of a residential heating, cooling and power generation system with regard to cost and CO_2 emissions by a multi-criteria analysis. Even fuzzy sets have been employed in an attempt to deal with uncertainties in multi-criteria evaluations: Mamlook et al. [6], for example, use them in the comparison of solar systems.

A timely example of a residential energy supply technology with limited operational experiences is small-scale combined heat and power generation (micro-CHP, micro-cogeneration) within a residential building. In this paper, we analyze the competitiveness of micro-CHP as one of ten alternative heating systems for a Finnish single-family house. These traditional systems are represented by district heating, geothermal heating, electrical heating applying baseboards, floor heating or auxiliary heat sources (fireplace, solar heating, air heat pump), oil heating (with or without solar heat collectors), and traditional natural gas heating. A micro-CHP heating system is defined as a traditional natural gas heating system equipped with a 1 kW_e Solid-Oxide Fuel Cell and floor heating.

In our analysis, we pay attention to the uncertainties that pertain to financial and environmental performance; we also account for incomplete information about the decision-maker’s preferences by using the PAIRS method (Preference Assessment by Imprecise Ratio Statements) [7] which is a multi-criteria decision making (MCDM) methodology based on multi-attribute value theory (MAVT) (see, e.g., Keeney&Raiffa [8]). In the MAVT framework, the problem is structured as a value tree where the topmost attribute stands for overall decision objectives and where the attributes on the lower levels are used to measure to what extent these objectives are attained. The relative importance of attributes is expressed through non-negative weights that are normalized so that they add up to one.

In the present context, one of the advantages of PAIRS is that it admits incomplete information through intervals and enables several modes of sensitivity analysis. As a result, PAIRS is suitable for examining how the competitiveness of a micro-CHP heating system depends on alternative assumptions about the decision makers' preferences, for example. While PAIRS and related methods (e.g., PRIME, Preference Ratios in Multiattribute Evaluation) [9], have been extensively applied in other contexts (e.g. Gustafsson et al. [10] estimate the market capitalization value of a new technology-based company), the evaluation of residential energy supply systems is a new field of application.

In the remainder of this paper, we first review results from the performance evaluation of residential heating systems and characterize relevant parameters through respective intervals. We then outline the PAIRS methodology, motivate its use in this evaluation problem, and present results from the comparison of ten heating systems for a Finnish single-family house.

2 The sources of uncertainty

2.1 Energy use

In the evaluation of residential energy supply systems, the error of energy demand is mainly related to simulation errors and user-specific reasons, such as the use of electrical appliances [11]. There are also other sources of error, such as the difference between statistical and measured electricity demand. Experiences suggest that the variation between actual energy demand and energy demand estimated on the basis of statistics or simulations is at most ± 10 % [12,13].

2.2 Techno-economic parameters

Data on techno-economic parameters is often acquired from i) the literature, ii) statistical data, and iii) expert judgments. The temporal (long-term) economic uncertainty in life cycle cost evaluations is mainly associated with the selection of discount rate, the prices of technology, electricity and fuels, the life span of technology and the characteristics of technology, such as efficiency. In liberalized energy markets, real estate owners may choose their energy supplier, which results in variability in end-user energy prices. At the moment, there is no consensus about the buyback price of electricity (i.e., the monetary compensation which an electricity producer receives per kWh of electricity he feeds into the grid). Actually, it may vary between zero and the full retail price of electricity.

2.3 Use of materials

The amount of materials can be determined if the exact composition of each product is known in the entire system. Because this information is rarely available, an estimate is needed. When evaluating environmental burdens due to the use of natural resources, one must consider resources contained by the end product as well as resources that are consumed by the production process; the latter constitute the “ecological rucksack” of the product. The total material input can be assessed employing the material input factor (*MI*) that indicates the amount of abiotic and biotic materials, water and air that is invested in producing a kilogram of a certain material or a kilowatt-hour of energy. Material input factors depend on several issues related to the production chains and technology and can vary significantly. A good example is copper whose abiotic material input factor varies from 179 kg kg^{-1} (the world average in 2003) to 500 kg kg^{-1} (produced in Germany in 1998); hence, the uncertainties in material input factors should be recognized [14].

2.4 Emissions

Carbon dioxide equivalent (CO_2 equivalent) and sulphur dioxide equivalent (SO_2 equivalent) indicate global warming and acidification, expressing the amount of carbon or sulphur dioxide that causes the same global warming or acidification as some amount of another gas. For example, according to the International Panel on Climate Change (IPCC), one kilogram of methane had a global warming potential equal to 23 kg of carbon dioxide in 2001. The equivalents – which depend on technology and production chains – can be determined for any material and form of energy, provided that the above relations (e.g. 23 $kg_{CO2}/kg_{methane}$) for various gases are known. For example, when light heating oil is burnt in a boiler the efficiency of which is 93 %, the amount of released CO_2 and methane is 0.284 kg and 0.004 g per one kilowatt of fuel, respectively [15]. The CO_2 equivalent is $0.284 + 0.001 \cdot 23 \cdot 0.004 \approx 0.284$ kg CO_2 per one kilowatt of fuel.

2.5 Conclusions of the uncertainty

Table 1 presents estimates for the ranges of above parameters, based on the above statements and the earlier review by Alanne et al. [11]. In effect, life-cycle costs are minimized when the energy demand and price are at their lower bound, when the discount rate is at its upper bound, the unit price of a micro-CHP plant as well as service and maintenance costs are at their lower bound, and when the buyback price of electricity, investment support and overall efficiency are at their upper bounds. Environmental burdens, in turn, are minimized when the life span of a system is as long as possible, and the use of material and emissions attain their lower bounds.

(Insert Table 1 around here.)

3 Methodology

3.1 General frame

If a decision is based solely on the minimization of costs, the decision maker's problem is simple (i.e., select the alternative with the lowest cost). However, the problem becomes more challenging when environmental burdens should be minimized at the same time when costs, too, are to be minimized. This is because the minimization of costs and environmental burdens are usually contradictory objectives, as it is often expensive to utilize environmentally friendly products.

In consequence, the selection of the heating system of a building is inherently a multi-criteria problem where both financial and environmental issues must be accounted for. This problem can be approached with value tree analysis that has a solid foundation in multi-attribute value theory (MAVT) [8]. In MAVT, the decision problem is structured as a tree (see: Figure 1) where the relevant objectives are modelled by corresponding attributes. Attributes on the higher level correspond to general objectives (e.g., minimization of life-cycle costs). These attributes are decomposed into more specific attributes on the lower levels such that numerical (or otherwise unambiguous) measurement scales can be attached to the twig-level attributes at the lowest level of the value tree.

(Insert Figure 1 around here.)

3.2 The overall value of a heating system

Applications of MAVT [22] are often based on additive models where low performance with regard to some attribute can be compensated by high performance with regard to another (e.g., high life-cycle costs can be compensated by low environmental burdens). In the additive model, the overall value (see: main goal in Fig.1) of a heating system is the weighted sum of its attribute-specific scores with regard to the relevant attributes, i.e.,

$$S = \sum_{i=1}^{N} w_i s_i \quad (1)$$

where S is the overall value of a heating system, N is the number of twig-level attributes, w_i is the normalized weight (between 0 and 1) of the i-th attribute, and s_i is the normalized single-attribute score associated with the achievement level of a heating system on the i-th attribute.

The relative importance of the i-th attribute is expressed in terms of its normalized weight w_i in the unit interval [0,1]. At the two extremes, the case $w_i=0$ corresponds to the case where the i-th attribute is irrelevant, while $w_i=1$ means that the evaluation is based on the i-th attribute only.

Scores are typically normalized onto the [0,1] range. If the performance of the heating system with regard to the i-attribute is to be maximized and approximated by a linear value function, the normalized score s_i can be calculated from

$$s_i = \frac{a_i - a_{i,\min}}{a_{i,\max} - a_{i,\min}} \quad (2)$$

where a_i is the achievement level of a heating system with respect to the i-th attribute, $a_{i,min}$ is the lowest achievement level of all the alternative heating systems with respect to the i-th attribute, and $a_{i,max}$ is the highest achievement level of all the alternative heating systems with respect to the i-th attribute. Conversely, when the i-th attribute is to be *minimized* in the same way, the normalized score s_i is obtained from

$$s_i = \frac{a_{i,\max} - a_i}{a_{i,\max} - a_{i,\min}} \quad (3)$$

The following example illustrates the determination of overall value for a micro-CHP heating system using the value tree in Fig. 1. For the time being, we assume that the attributes are equally important in the sense that they have equal weights; explicit preference statements will be introduced later, i.e., the following computations are merely illustrative.

The weights of the higher level attributes (0.33 + 0.33 + 0.33 = 1) add up to one, as well as the weights of the twig-level attributes (0.167 + 0.167 + 0.167 + 0.167 + 0.33 = 1).

The alternatives consist of ten different heating systems, referred to as System 1 through 10, with micro-CHP heating as the last one. The corresponding achievement levels are shown in Table 2.

(Insert Table 2 around here.)

In terms of life-cycle costs, System 4 is the best alternative because its life-cycle costs are lowest (35,550 EUR), while System 8 has the highest costs (65,900 EUR). If the decision-maker's (DM) preferences for life-cycle costs are linear, the score for life-cycle costs for a micro-CHP heating system (System 10) can thus be obtained from Eq. (3) as

$$s_{LCC} = \frac{65900 - 65250}{65900 - 35550} = 0.02.$$

Normalized scores and criteria weights for a micro-CHP heating system are presented in Table 3.

(Insert Table 3 around here.)

Based on the above weight and score information, the overall value of a micro-CHP heating can thus be obtained from Eq. (1) as

$$S_{CHP} = 0.33 \cdot 0.02 + 0.167 \cdot 1.00 + 0.167 \cdot 1.00 + 0.167 \cdot 0.52 + 0.167 \cdot 0.71 = 0.55.$$

3.3 Application of PAIRS

PAIRS method (Preference Assessment by Imprecise Ratio Statements) [7]) is a multi-criteria decision making (MCDM) methodology where problem structuring is carried out in accordance with the usual principles of value tree analysis (see, e.g., [8]). In PAIRS, uncertainties about scores and weights are captured through interval-valued parameters. Based on these parameters, the corresponding lower and upper bounds for the alternatives´ overall values (value intervals) in Eq. (1) can be computed with linear programming.

More specifically, we consider *m* alternative heating systems (j=1,…,*m*) and *n* attributes (i=1,…,n). The lower bounds for normalized scores are denoted by $s_{min,11}$… $s_{min,ji}$… $s_{min,mn}$ and the upper bounds $s_{max,11}$… $s_{max,ji}$… $s_{max,mn}$. In PAIRS, information about the attribute weights is elicited through pairwise comparisons where the DM specifies lower and upper bounds for the relative importance between two attributes at a time. More specifically, such a comparison yields the linear constraints

$$l_{ij} \le \frac{w_i}{w_j} \le u_{ij} \qquad (4)$$

where l_{ij} and u_{ij} are the lower and upper bounds that for the ratio between the weights of the i-th and j-th attributes, respectively.

The overall value interval can be calculated from linear programs (LP)

$$S_j \in \left[\min \sum_{i=1}^{n} w_i s_{\min, ji}, \max \sum_{i=1}^{n} w_i s_{\max, ji} \right] \qquad (5)$$

where the minimization and maximization problems are solved subject to constraints that are imposed on the attribute weights (i.e., non-negativity constraints $w_i \ge 0 \ \forall i$, normalization constraints $\sum_{i=1}^{n} w_i = 1$, and preference statements in (4)).

The relative superiority of one alternative to another can be determined through dominance structures and decision rules. In PAIRS, alternative A is better than alternative B in the sense of *absolute dominance*, if the least possible value (cf. benefit) of A is greater than the largest possible value of B; in this case the value intervals of the two alternatives do not overlap. If the value intervals overlap, it may be possible to conclude that one alternative is better than another on the basis of *pairwise dominance*: specifically, A dominates B in the sense of pairwise dominance if and only if the overall value of A exceeds that of B for all combinations of feasible score and weight parameters.

When dominance relationships do not hold, decision recommendations can be provided by using decision rules (see [8]). The rules are (i) *maximax* (choose the alternative with the highest possible overall value), (ii) *maximin* (choose the alternative for which the lowest possible value is highest), (iii) *minimax regret* (choose the alternative for which the greatest loss of value relative to some alternative is smallest), and (iv) *central values* (choose the alternative for which the midpoint of the value interval lies highest).

4 Comparative analysis of heating systems

4.1 Alternatives

In the following comparative analysis, we examine the overall performance of following heating systems:

1. District heating with floor heating (S1)
2. Geothermal heating (with heat pump and bore hole) with floor heating (S2)
3. Electrical floor heating (S3)
4. Electric baseboards (S4)
5. Electric baseboards + fireplace (heating 1-2 times per week) (S5)
6. Electric baseboards + fireplace (heating 1-2 times per week) + solar heating + air heat pump (S6)
7. Oil heating with floor heating (S7)
8. Solar oil heating with floor heating (S8)
9. Natural gas heating with floor heating (S9)
10. Natural gas heating with 1 kW_e Solid Oxide Fuel Cell and floor heating (S10)

System S10 represents micro-CHP where a Solid Oxide Fuel Cell plant (Fuel Cell Technologies Ltd) is added to the gas heating system. The Solid Oxide Fuel Cell system is run at its full power throughout a year so that all heat is led to the heat distribution and domestic hot water system via the heat storage tank. The excess heat and electricity are managed using the heat storage, a heat dump valve, the gas boiler, and an electricity service with bi-directional metering.

4.2 Life-cycle costs

The annual energy consumption and life cycle costs for Systems S1-S8 were obtained from the Finnish Energy Agency that estimates energy demand on the basis of the Finnish Standard D5. The energy demand of a Solid Oxide Fuel Cell heating system was determined as in Alanne et al. [23]. The parameters in Table 1 were modeled as intervals.

4.3 Environmental burdens

To determine the environmental burdens of Systems S1-S10, the composition of the equipment was evaluated by consulting the suppliers of energy systems, system designers and contractors, and the literature. The annual material input, the annual global warming (CO_2-equivalent) and the acidification (SO_2-equivalent) potential per one gross square meter of a house, including both the construction and operation of an energy supply system were estimated employing the factor data provided by Wuppertal Institute, the Intergovernmental Panel on Climate Change (IPCC), the Building Information Foundation (RTS) and the Technical Research Centre of Finland.

Material Input Per Service Unit (MIPS) method has not been previously applied to the evaluation of the environmental burdens of a residential micro-CHP heating system. Because the air consumption provided by the Material Input Per Service Unit (MIPS) method overlaps with the effects of emissions on global warming, the air input that is normally included into Material Input Per Service Unit (MIPS) method was omitted. Moreover, “the use of biotic materials” was not significant, either.

All the parameters in Table 1 were modeled as intervals. The intervals for life-cycle costs (30 yr) and environmental burdens for each system containing the accumulated uncertainty are summarized in Table 4.

(Insert Table 4 around here.)

4.4 PAIRS model

The PAIRS decision model was built with the WinPRE©[1] decision support tool. The attributes were defined so as to capture the most significant factors on which the "value" of a residential energy supply system depends.

The scores were set by normalizing the scores into the unit interval [0,1]. Based on the data in Table 4, the score information summarized in Table 5 was obtained from Eqs. (2) and (3).

(Insert Table 5 around here.)

4.5 Results

To illustrate the impact of uncertainties in both score and weight information, we show results from an illustrative example where the preference statements put considerable weight on the environmental point of view, based on the authors' perceptions. The score intervals in Table 5 are applied.

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[1] The WinPRE© software is available free of charge for research and teaching purposes at http://www.decisionarium.hut.fi.

The attribute weights are characterized through intervals, where the decision maker (DM) specifies through ratio comparisons how many times more (or less) important one attribute is with regard to another. Fig. 2 illustrates the weight elicitation in the present analysis as a WinPRE© screenshot. For example, the expression "w(LifeCycl)< 0,3 w(Abiotic)" in the first row in Fig. 2 indicates that life-cycle costs have been evaluated less than 0.3 times as important as the use of abiotic resources.

(Insert Figure 2 around here.)

The alternatives' value intervals and dominance structures are in Fig.3 and Fig.4, respectively.

(Insert Figure 3 around here.)
(Insert Figure 4 around here.)

The pairwise comparison in Figure 4 suggests that micro-CHP (S10) is a preferred alternative at least to district heating (S1), electrical heating (S3-S5), oil heating (S7) and natural gas heating without electricity generation (S9). The status of micro-CHP (S10) as a recommended alternative is also highlighted by both the *maximin* and *maximax* decision criteria. This can be explained by noting that the life-cycle costs of micro-CHP are relatively high and involve considerable uncertainties. Thus, if cost considerations are deemed less important, the impacts of changes in cost-related achievement levels become less significant; this is a major reason for why the micro-CHP performs so well.

5 Summary and conclusions

In this paper, we have formulated the selection of a residential energy supply system as a multi-criteria decision-making problem where both life-cycle costs and environmental impacts are addressed (e.g., global warming, acidification, consumption of natural resources). Specifically, we have examined the competitiveness of a micro-CHP heating system with traditional heating alternatives for a single-family house in Finland, with a particular emphasis on the impact of several sources of uncertainties. The analyses have been carried out with the PAIRS methodology by introducing preference statements that place considerable weight on the minimization of environmental burdens.

The numerical results suggest that micro-CHP heating can be a viable alternative, although no definitive conclusions about the overall value of different energy supply options can be made due to the presence of uncertainties. In practice, the overall value of alternatives depends on decision-makers' preferences and techno-economic data, which in turn, are strongly affected by the location. Thus, caution is called for when interpreting the results of this work for the purpose of giving advice in settings where cogeneration is considered as an energy supply alternative for single-family houses. This notwithstanding, the results suggest that PAIRS can be a useful tool in the evaluation of residential heating systems.

This research opens up several possibilities for future work. For example, one can combine similar multi-criteria decision analyses with forecasting models so that score information is obtained from confidence intervals around the forecasts. Such analyses would make it possible to assess when specific technologies are likely to outperform others, which would give support for the development of optimal investment strategies. Furthermore, it would be of interest to construct portfolio optimization problems where the techno-economic parameters of micro-CHP are utilized to determine the optimal project configuration of residential energy system in new construction and renovation projects. In future work, it would also be of interest to expand the set of attributes (for example, safety and reliability issues were not covered here).

Acknowledgements

The funding of Fortum Foundation for this research is gratefully acknowledged.

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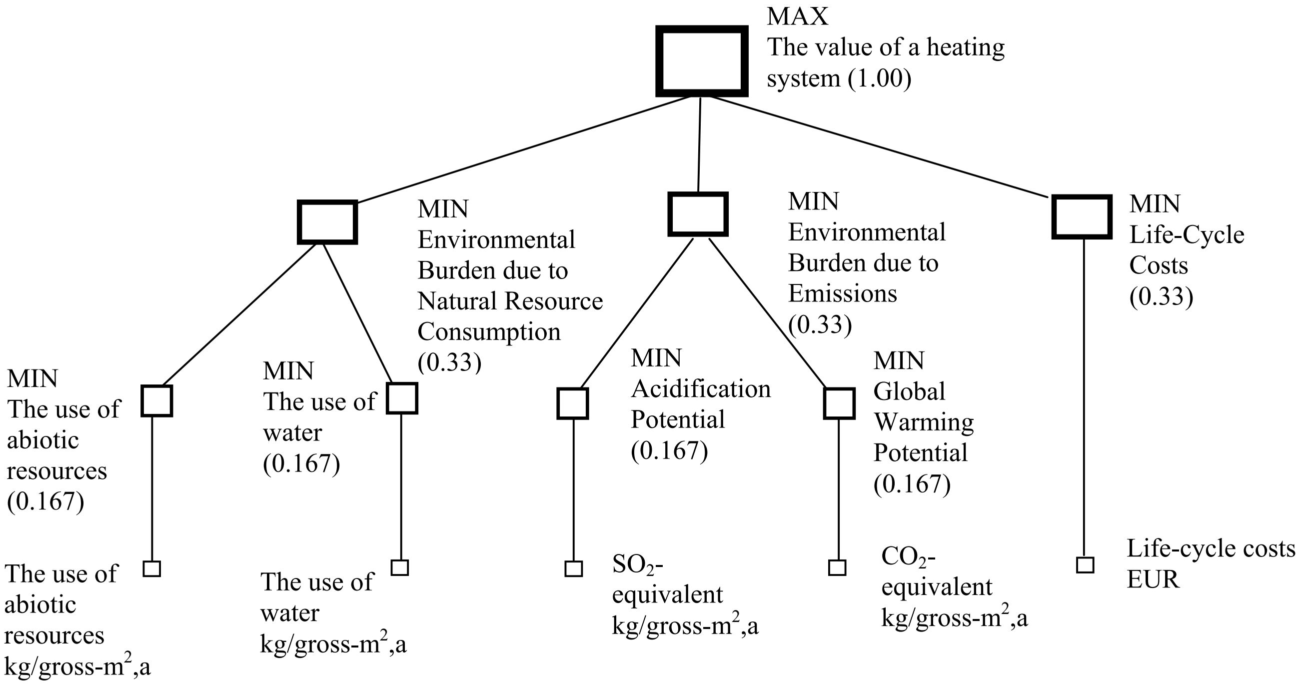
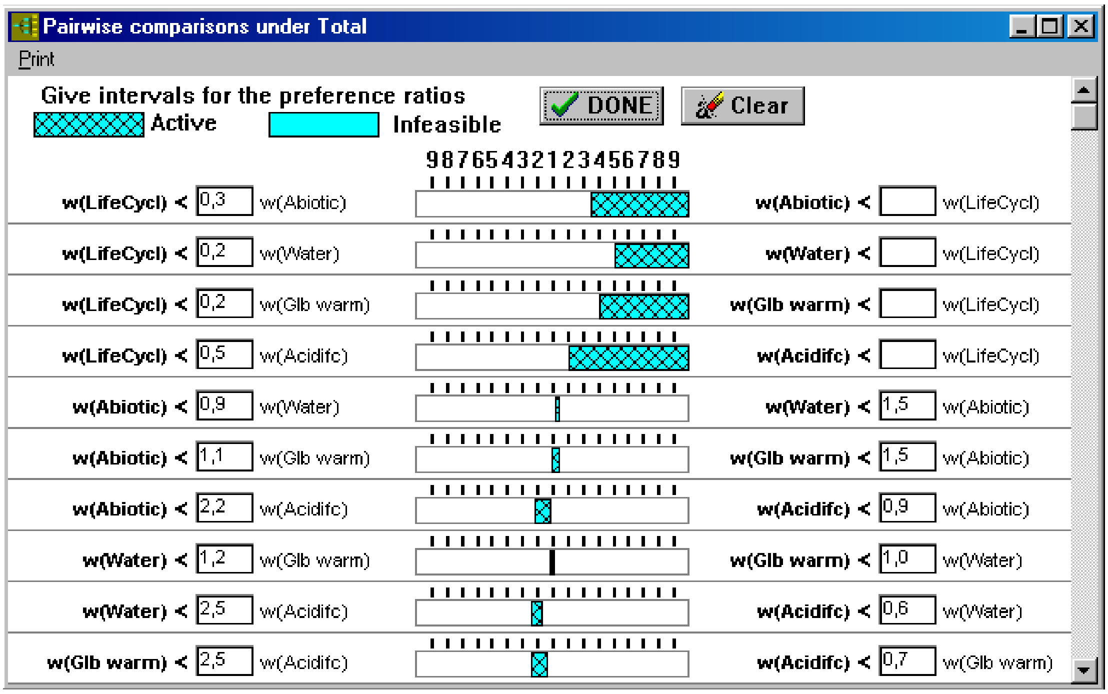


Figure 1. A value tree with higher-level and twig-level attributes.



Give intervals for the preference ratios

w(LifeCycl) <	0,3	w(Abiotic)	w(Abiotic) <		w(LifeCycl)
w(LifeCycl) <	0,2	w(Water)	w(Water) <		w(LifeCycl)
w(LifeCycl) <	0,2	w(Glb warm)	w(Glb warm) <		w(LifeCycl)
w(LifeCycl) <	0,5	w(Acidifc)	w(Acidifc) <		w(LifeCycl)
w(Abiotic) <	0,9	w(Water)	w(Water) <	1,5	w(Abiotic)
w(Abiotic) <	1,1	w(Glb warm)	w(Glb warm) <	1,5	w(Abiotic)
w(Abiotic) <	2,2	w(Acidifc)	w(Acidifc) <	0,9	w(Abiotic)
w(Water) <	1,2	w(Glb warm)	w(Glb warm) <	1,0	w(Water)
w(Water) <	2,5	w(Acidifc)	w(Acidifc) <	0,6	w(Water)
w(Glb warm) <	2,5	w(Acidifc)	w(Acidifc) <	0,7	w(Glb warm)

Figure 2. Weight elicitation in the numerical example.

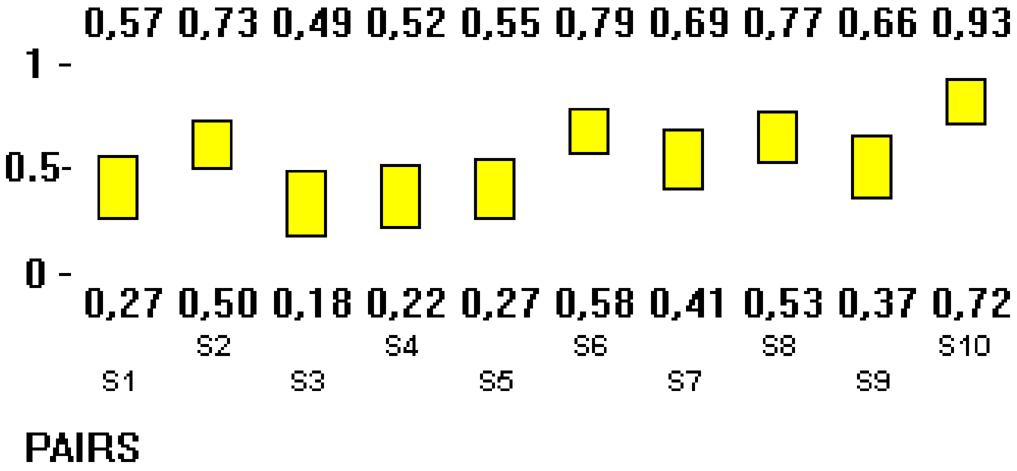
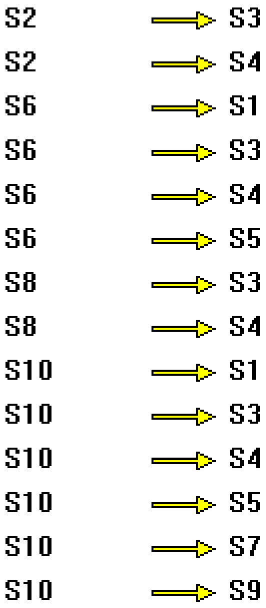


Figure 3. Value intervals for incomplete score and preference information.



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S2     ⇒ S3
S2     ⇒ S4
S6     ⇒ S1
S6     ⇒ S3
S6     ⇒ S4
S6     ⇒ S5
S8     ⇒ S3
S8     ⇒ S4
S10    ⇒ S1
S10    ⇒ S3
S10    ⇒ S4
S10    ⇒ S5
S10    ⇒ S7
S10    ⇒ S9
```

Figure 4. Pairwise dominance for incomplete preference information.

Table 1. Confidence intervals for various parameters.

	Parameter	MIN	MAX
Energy Use	Electricity demand, error-% [A]	-10	+10
	Primary energy demand, error-% [A]	-10	+10
Economic parameters	Real interest rate, % [B]	2	6
	Price of district heat, error-% [C]	-5	+5
	Price of natural gas, error-% [C]	-5	+5
	Price of electricity, error-% [D]	-10	+10
	Price of oil, error-% [E]	-10	+10
	The buyback price of electricity, %[F]	0	100
	Investment support, %[G]	0	50
	The unit price of a micro-CHP plant, EUR [H]	5,000	8,000
	Micro-CHP service costs, EUR a^{-1}	0	160[I]
	Micro-CHP maintenance costs, EUR a^{-1} [J]	200	500
Technological parameters	Micro-CHP total efficiency, % [K]	75	85
	Life span error, a [L]	-5	5
Material use	Material use, error-% [M]	-5	+5
	Abiotic material input factor, error-% [N]	-20	+20
	Biotic material input factor, error-% [N]	0	0
	Material input factor of water, error-% [N]	-30	+30
	Material input factor of air, error-% [N]	-15	+15
Emissions	Global Warming Potential, error-% [O]	-10	+10
	Acidification Potential, error-% [O]	-10	+10

A	an estimate on the basis of Tuomaala [12], Fuehrlein et al. [13]
B	an estimate based on market interest rates and the works of e.g. Manczyk [16], Collins et al. [17]
C	the maximum difference between the average price and the price given by a selected company
D	estimated on the basis of data provided by the Finnish Energy Market Authority
E	an estimate based on the uncertainty related to other energy prices
F	expressed as the ratio of the buyback price and retail price of electricity
G	an estimated percentage of the capital costs of a micro-CHP plant.
H	estimated on the basis of price list provided by www.fuelcellstore.com
I	the estimate of Finnish Energy Agency for the annual service cost of a heat conversion system in a Finnish single-family house.
J	If a micro-CHP plant is substituted by a new one 1-2 times during the time period of 30 years, and the capital cost of a micro-CHP plant is 5000 - 8000 EUR kWh_e^{-1}, the annual maintenance costs vary between 200-500 EUR a^{-1}. The interest rate, however, is not accounted for in this estimate.
K	an estimate based on Ellis [18] and Onovwiona et al. [19]
L	an estimate based on the interview of a Finnish life-cycle specialist
M	an estimate based on the composition given by a Finnish trader of energy equipment and reference estimate presented by the Technical Research Centre of Finland (VTT)
N	an estimate based on three sources (Vihermaa et al. [20], Sinivuori et al.[21], and Wuppertal Institute)
O	an estimate based on [15], the boiler efficiency is assumed to vary between 85 % and 95 %

Table 2. Source data for the comparative analysis.

System	Life-cycle Costs (EUR) (30 yr)	The use of abiotic resources (kg m^{-2} a^{-1})	The use of water (ton m^{-2} a^{-1})	Global Warming Potential (kg CO_2 m^{-2} a^{-1})	Acidification Potential (kg SO_2 m^{-2} a^{-1})
1	47,550	81	7.54	33	0.11
2	56,700	49	15.83	22	0.07
3	36,500	64	22.59	30	0.10
4	35,550	61	22.00	29	0.10
5	38,250	59	20.79	28	0.09
6	41,200	42	14.39	19	0.06
7	60,850	45	9.14	40	0.07
8	65,900	40	7.65	35	0.06
9	55,600	43	9.05	37	0.10
10	65,250	25	0.05	29	0.07

Table 3. Scores and weights of a micro-CHP heating system in the example.

Attribute	a	->	s_i	w_i
Life-cycle Costs (30 a), EUR	**65,250**	**->**	**0.02**	0.330
The use of abiotic resources, kg m^{-2} a^{-1}	25	->	1.00	0.167
The use of water, t m^{-2} a^{-1}	0.05	->	1.00	0.167
Global Warming Potential, kg m^{-2} a^{-1}	29	->	0.52	0.167
Acidification Potential, kg m^{-2} a^{-1}	0.07	->	0.71	0.167

Table 4. Intervals for life-cycle costs and environmental burdens.

System	Life-cycle costs (30 a) (EUR)	Abiotic (kg m^{-2} a^{-1})	Water (ton m^{-2} a^{-1})	Global warming (kg CO_2 -m^{-2} a^{-1})	Acidification (kg SO_2 -m^{-2} a^{-1})
S1	37,300...57,800	73...89	7…8	27…40	0.088…0.131
S2	46,000…67,400	45...54	14…17	17…26	0.058…0.086
S3	24,900…48,100	58...70	20…25	25…37	0.081…0.121
S4	23,300...47,800	55...67	20…24	24…36	0.078…0.117
S5	26,600…49,900	53...65	19…23	23…34	0.074…0.111
S6	32,300…50,100	38…47	13…16	16…24	0.051…0.077
S7	45,800…75,900	41…49	8…10	32…48	0.057…0.082
S8	52,300…79,500	36…44	7…8	28…42	0.050…0.071
S9	43,400…67,800	39…47	8…10	30…44	0.084…0.125
S10(CHP)	44,600…85,900	23…27	0…0	23…35	0.060…0.091
Lowest	23,300	23	0	16	0.050
Highest	85,900	89	25	48	0.131

Table 5. Normalized score intervals for life-cycle costs and environmental burdens.

System	Life-cycle costs (30 a)	Abiotic	Water	Global warming	Acidification
S1	0.45…0.78	0.00…0.24	0.67…0.73	0.26…0.66	0.00…0.53
S2	0.30…0.64	0.52…0.67	0.30…0.43	0.68…0.95	0.55…0.90
S3	0.60…0.97	0.29…0.48	0.00…0.18	0.36…0.73	0.12…0.61
S4	0.61…1.00	0.33…0.52	0.03…0.20	0.39…0.75	0.18…0.65
S5	0.58…0.95	0.36…0.54	0.08…0.25	0.44…0.79	0.25…0.70
S6	0.57…0.86	0.63…0.77	0.36…0.48	0.76…1.00	0.67…0.98
S7	0.16…0.64	0.60…0.73	0.60…0.67	0.00…0.49	0.60…0.90
S8	0.10…0.54	0.68…0.80	0.66…0.72	0.19…0.61	0.74…1.00
S9	0.29…0.68	0.64…0.76	0.60…0.67	0.12…0.57	0.08…0.58
S10 (CHP)	0.00…0.66	0.93…1.00	1.00…1.00	0.41…0.77	0.50…0.87