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APPLICATIONS OF DECISION ANALYSIS IN THE ASSESSMENT OF ENERGY TECHNOLOGIES FOR BUILDINGS

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Title: Applications of decision analysis in the assessment of energy technologies for buildings

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Abstract: The transition to sustainable energy system calls for changes in both the production and consumption of energy, including issues such as the implementation of sustainable technologies and practices for energy conversion and the improvement of energy efficiency at the demand side.

This Thesis i) identifies the need of decision support in the commercialization of sustainable energy technologies in buildings, ii) characterizes decision-making problems related to the above context, iii) develops and implements a methodology to assess energy technologies for buildings, and iv) presents two fields of application where the above assessment is essential.

The decision-making problem is characterized by i) multiple objectives, ii) several interest groups with different preferences, iii) new alternatives with the lack of operational experiences and thus plenty of uncertainties, and iv) a broad portfolio of applicable technologies that have to be combined into a workable entity. Hence, an interdisciplinary decision support framework is required that combines basic theories of life cycle and decision analyses including sensitivity assessments.

In this Thesis, the above methodological framework is implemented in terms of two applications: i) the assessment of heating systems for a single-family house and ii) the selection of technology portfolio in a retrofit project that results in improved energy efficiency and thermal comfort, and reduced environmental burdens. Specifically, the competitiveness of a natural gas heating system containing a solid-oxide fuel cell (SOFC) is examined with respect to residential heating systems containing no electricity generation. Moreover, a multi-criteria portfolio model is applied to determine the most preferred retrofit measures in an apartment building. The above examples are selected because i) they represent a new field of research and ii) they are interesting due to the challenges they provide in decision-making.

In the assessment of heating systems that incorporate new technologies, the mutual ranking of alternatives often must be established on the basis of incomplete information. Here, the extensive framework of decision-making was useful. In the second application, the multi-criteria portfolio model was suitable in the search of optimal technological solutions in retrofit projects. According to computational studies, a small (1 kW_e) SOFC heating system is an attractive alternative to traditional heating systems and simple, inexpensive measures with good price-quality ratio were preferred as retrofit actions. While the methodological framework is generally applicable, the computational examples are mainly indicative and illustrative.

Keywords: Life cycle analysis, Decision analysis, Multi-criteria, Energy, Micro-cogeneration, Residential buildings

Academic dissertation

Systems Analysis Laboratory
Helsinki University of Technology

Applications of decision analysis in the assessment of energy technologies for buildings

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Official opponent:	Professor Lars J. Nilsson, Lund Institute of Technology, Sweden

List of publications

The doctoral thesis consists of the present summary article and the following papers:

[I] Alanne, K., Saari A. 2006. Distributed energy generation and sustainable development. *Renewable & Sustainable Energy Reviews* **10** (6) 539-558.

[II] Alanne, K. and Saari, A. 2004. Sustainable small-scale CHP technologies for buildings: the basis for multi-perspective decision-making. *Renewable & Sustainable Energy Reviews* **8** (5) 401-431.

[III] Alanne, K., Saari, A., Ugursal, V.I. and Good, J. 2006. The financial viability of SOFC cogeneration system in single-family dwellings. *Journal of Power Sources* **158** (1) 403-416.

[IV] Alanne, K., Saari, A. and Salo, A. 2006. Comparative analysis of the life-cycle costs of residential energy supply technologies. *Nordic Journal of Surveying and Real Estate Research* [accepted for publication].

[V] 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].

[VI] Alanne, K. 2004. Selection of renovation actions using multi-criteria "knapsack" model. *Automation in Construction* **13** (3) 377-391.

Contributions of the author

Kari Alanne has been the main researcher and author in all papers. Paper [III] has been finalized through joint efforts with Professor Ugursal and Papers [IV] and [V] with Professor Salo. Dr. Arto Saari has commented on Papers [I]-[V], MSc Joel Good on Paper [III] and Professor Stig-Inge Gustafsson on Paper [V].

Preface and acknowledgements

This Thesis is stimulated by a dream to make the world a better place to live. Our responsibility as the Crown of Creation is to take care of the nature and to secure the well-being of the generations living now and in the future. One of the major challenges is the supply of energy. The leading principle of this Thesis is that the transition to a sustainable energy system is not actually more than a matter of decision-making. The study focuses on supporting the decisions of energy consumers, who finally create the market of new energy technologies by their choices.

The Thesis is mainly carried out at Helsinki University of Technology. Furthermore, I have worked as a visiting research scientist at Ruhr-Universität Bochum (Germany) and the University of Victoria (British Columbia, Canada). First and foremost I would like to thank Professor Ahti Salo and Dr. Arto Saari for providing invaluable support. I would like to give special thanks to Professor V. Ismet Ugursal (UVic) for his great collaboration in the work related to Paper [III]. The visit to the University of Bochum was also a success, for which I wish to thank Professor Hermann-Josef Wagner. I am also grateful to Professor Stig-Inge Gustafsson who made it possible to start a new, fruitful Nordic "samarbete". The financial support of Fortum foundation, Helsinki University of Technology, and Jenny and Antti Wihuri foundation is gratefully acknowledged.

Finally, my dearest Merja, I thank you for staying beside me every day – with both greatest love and with joyous everyday realism.

Espoo, December 29, 2006,

Kari Alanne

LIST OF SYMBOLS

Acronym	Definition
AC	Alternating Current
AP	Acidification Potential
CANMET	Canada Centre for Mineral and Energy Technology
CHP	Combined Heat and Power
DHW	Domestic Hot Water
DC	Direct Current
GWP	Global Warming Potential
HHV	Higher Heating Value
LCA	Life Cycle Analysis
LCCA	Life Cycle Cost Analysis
LCIA	Life Cycle Impact Analysis
LHV	Lower Heating Value
MAUT	Multi Attribute Utility Theory
MAVT	Multi Attribute Value Theory
MCDM	Multi Criteria Decision Making
MIPS	Material Input Per Service unit
PEMFC	Polymer Electrolyte Membrane Fuel Cell
PRIME	Preference Ratios In Multiattribute Evaluation
SOFC	Solid Oxide Fuel Cell

Symbol	Unit	Definition
$a_1,...a_i,...a_n$	-	decision variables
a_j	any	achievement level with respect to the j-th attribute
$a_{j,max}$	any	the highest achievement level with respect to the j-th attribute
$a_{j,min}$	any	the lowest achievement level with respect to the j-th attribute
A_{sto}	m^2	heat transfer area of the heat storage tank
$c_{e,p}$	EUR kWh^{-1}	retail price of electricity
$c_{e,s}$	EUR kWh^{-1}	buyback price of electricity
c_i	EUR	installed unit cost assigned to the i-th subsystem
c_{pr}	EUR kWh^{-1}	price of input energy (e.g.fuel)
c_{rm}	EUR h^{-1}	estimated price for an hour of janitorial work
$c_{s,i}$	EUR h^{-1}	price for a hour of service work for the i-th subsystem
c_{sto}	J $kg^{-1}K^{-1}$	specific heat capacity of the heat storage tank
C_E	EUR	energy costs
$C_{fa,e}$	EUR a^{-1}	fixed annual electricity costs
$C_{fa,pr}$	EUR a^{-1}	fixed annual input energy costs
C_I	EUR	initial costs (project costs)
$C_{I,CHP}$	EUR	capital (investment) cost of an SOFC plant
$C_{I,i}$	EUR	capital cost of the i-th alternative
C_j	EUR	connection fee of the j-th interconnection
C_{LC}	EUR	life cycle costs
C_M	EUR	maintenance costs
C_{MAX}	EUR	maximum allowable total capital costs of the construction of retrofit project
$C_{m,i}$	EUR a^{-1}	annual maintenance cost for the i-th subsystem
C_S	EUR	service costs
$\Delta C_{I,ma}$	EUR a^{-1}	annual incremental cost of maintenance
G_i	kg	amount of greenhouse gas i released from the process
K_{sto}	W $m^{-2}K^{-1}$	specific tank loss coefficient

L_j	-	lower bound for weighting range with respect to the *j*-th attribute
m	-	number of twig-level attributes
n	-	number of years in a given time period
N	-	total number of years in a given time period
$N_{c,I}$	-	number of installed units assigned to the *i*-th subsystem
p_{or}	-	risk coefficient of unidentified risks
p_{pr}	-	risk coefficient of price changes
p_{ps}	-	fraction of the construction costs assigned to project services
p_{wr}	-	risk coefficient of extra works
Q_{DHW}	kWh	heat demand of the DHW system
Q_{env}	kWh	heat loss through envelope
$Q_{hl,util}$	kWh	utilizable heat load
Q_{hs}	kWh	thermal energy to the heat sink
$Q_{in,hd}$	kWh	total thermal energy to the heat distribution system
$Q_{in,DHW}$	kWh	total thermal energy to the domestic hot water (DHW) system
$Q_{l,CHP}$	kWh	heat loss from the SOFC plant
$Q_{l,DHW}$	kWh	heat loss of the DHW system
Q_{leak}	kWh	heat loss caused by air leaks
$Q_{l,f}$	kWh	heat loss of the boiler
$Q_{l,hd}$	kWh	heat loss of space heating
$Q_{l,int}$	kWh	heat loss from the interface
$Q_{l,sto}$	kWh	heat loss of the storage tank
$Q_{pr,CHP}$	kWh	total input energy consumption of the SOFC plant
$Q_{pr,f}$	kWh	steady-state input energy consumption of the backup boiler
$Q_{pr,ref}$	kWh a^{-1}	annual input energy consumptions in the reference case
$Q_{th,CHP}$	kWh	thermal energy from the SOFC plant
$Q_{th,f}$	kWh	thermal energy from a backup gas furnace/boiler
Q_{vent}	kWh	heat loss caused by ventilation
ΔQ	kWh	thermal surplus or shortage
r	%	discount rate
r_e	%	discount rate for energy costs
s_j	-	normalized single-attribute score on the *j*-th attribute
S	EUR	amount of governmental support
S_i	-	overall value of the *i*-th alternative
T_{min}	ºC (K)	minimum allowable storage temperature
T_{max}	ºC (K)	maximum allowable storage temperature
T_{sto}	ºC (K)	storage temperature
t_{rm}	h	estimated annual time required to energy supply management
$t_{s,i}$	h a^{-1}	required annual service time for the *i*-th subsystem
Δt	h	the length of time period
ΔT_{sto}	ºC (K)	storage temperature change
U_{sto}	kWh	internal energy in the heat storage tank
U_j	-	upper bound for weighting range with respect to the *j*-th attribute
ΔU_{sto}	kWh	change of internal energy of the heat storage tank
w_i	-	weight factor assigned to the *i*-th alternative/item
w_j	-	normalized weight of the *j*-th attribute
W_{app}	kWh	electricity demand of appliances
W_e	kWh	electricity consumption of the building
$W_{e,CHP}$	kWh	electrical output of the SOFC plant
$W_{e,p}$	kWh	electricity purchased from the grid
$W_{e,ref}$	kWh	electricity consumption of the reference case
$W_{e,s}$	kWh	electrical energy fed to the grid
$W_{in,CHP}$	kWh	electrical energy consumed by the SOFC plant

$W_{in,f}$	kWh	electrical energy to the furnace/boiler
W_l	kWh	electrical demand of lighting
W_{vent}	kWh	electrical demand of ventilation fans
V_{sto}	m^3	volume of the heat storage tank

Greek letter	**Unit**	**Definition**
α_{CHP}	-	ratio of generated electricity to generated heat
$\eta_{e,CHP}$	-	electrical efficiency of the SOFC plant
$\eta_{th,CHP}$	-	thermal efficiency of the SOFC plant
$\eta_{tot,CHP}$	-	overall efficiency of the SOFC plant
$\eta_{th,f}$	-	thermal efficiency of the furnace
$\eta_{tot,f}$	-	overall efficiency of a boiler system
ρ_{sto}	kg m^{-3}	density of the contents of the heat storage tank

1 INTRODUCTION

1.1 Background

The time people spend indoors in developed countries represents about 90 % of their total time (Dorre et al. 1990). The well-being of modern people is strongly related to energy that is required to maintain conditions and services in buildings. On the other hand, the supply of energy has become more challenging than ever. The desired characteristics of energy system are crystallized by Bonser (2002) who state that energy systems should "generate enough power for everybody's needs at an affordable price" and "help supply the clean, safe and reliable electricity". Recent technical advances have introduced numerous new solutions that i) implement sustainable technologies and practices in energy production and ii) improve the energy efficiency at the demand side. The importance of sustainable energy generation has been widely acknowledged and many steps have been taken towards the sustainable energy system. This is obvious, because the role of energy generation in this context is clear. In Finland, for example, the percentage of energy production of total carbon dioxide emissions was 62 % in 2003 (Finnish Energy Industries), whereas the percentage of space heating of the total end use of energy was 21 % in 2005 (Statistics Finland, 2006). The issue of sustainable energy system is discussed more extensively in Paper [I].

The world still depends on conventional practices and technologies. Several political, economic, social, and technological barriers hinder the transition to new technologies. There are many factors that cannot be influenced by humans, such as increases in energy prices due to natural disasters. Most of the barriers, however, are related to human decisions, either directly or indirectly. Dunn (2002) stated about hydrogen economy: "If we really *decided* that we wanted a clean hydrogen economy, we could have it by 2010". From the political perspective, a key factor would be putting into practice incentives and regulations, such as investment and tax subsidies and national building codes (e.g. Nilsson et al. (2006), Ericsson et al. (2004)). A good example of an economic barrier associated with the introduction of distributed energy generation is the tendency of large electricity producers to "dump" electricity prices to prevent the penetration of new competitors in the electricity market (Ambiente Italia srl et al., 2001). Technology prices are kept high by the early state-of-the-art of new technologies and the lack of fuel infrastructure – a problem that can be solved through research and development (Valkiainen et al., 2002). The final obstacle is the decision-maker himself; the introduction of new technologies presumes that authorities, designers, and real estate owners really make their choices not only on the basis of monetary values, but also sustainable development. The transition to sustainable energy system and the role of various interest groups in this development have been discussed with more details in Paper [II].

Because the transition to sustainable energy system is strongly linked to the attitudes of people who make decisions, the role of public administration as an opinion-former and policy-maker is highlighted in the first stage. Second, when new technologies appear in the market as products and services, it is important that individual real estate owners and designers have access to energy guidance as well as tools and databases with data on new products. Pertinent information may encourage decision-makers to put new alternatives on the same line with traditional ones. There are plenty of methods and tools for decision-support via technology assessment. The paper of Keefer et al. (2004) suggests, however, that there is a lack of applications in the assessment of residential energy technologies.

1.2 Research problem

The review in Paper [I] concludes that the commercialization of new technologies is desirable in terms of sustainability. Customers cannot be used as the "laboratory" of new technologies, however. Because there are no long-term experiences for new technologies, the decisions are based on technology assessment. The assessment of energy technologies is challenging, encompassing the estimation of energy use, life cycle costs, environmental burdens and usually factors with no numerical indicator, such as functionality or operability. Computer simulations, statistical information, literature and interviews may be the only source of data. In long-term assessments, the operational environment is affected by technological development, price changes etc. As a consequence, the technology assessment must be able to cope with uncertainties.

The situation may become even more challenging if technology assessment is followed by a selection among several alternatives. The selection is characterized by three major problems (Andresen (1998), Tanimoto et al. (2001)): i) large set of conflicting objectives and incommensurate attributes, ii) set of conflicting opinions among different interest groups, and iii) large amount of mutually compatible or non-compatible technological options among which the optimal combination should be found. The above "problem synthesis" can be derived especially from the review in Paper [VI], where the issue has been discussed in a more detailed way.

Specifically, the following cases have not been reported in recent decision analytical applications focusing on the assessment of building services and technologies (Keefer et al., 2004): i) multi-criteria optimization of technological portfolios incorporating mutual interactions between alternatives, and ii) extensive assessment and comparison of new technologies parallel to traditional ones in terms of multi-criteria decision analysis that tolerates uncertainties due to the lack of experimental information and due to simplifications in the estimation of energy use and costs.

1.3 Objectives and scope of this study

The aim of this Thesis is to implement the methodologies of life cycle analysis and multi-criteria decision-making in the assessment of energy technologies in the above applications. Specifically, the competitiveness of a solid-oxide fuel cell (SOFC) heating system is investigated with respect to traditional residential heating systems in terms of life cycle costs and environmental burdens, employing the multi-criteria valuation method WinPRE© that supports decision analysis when the information on alternatives is incomplete (Salo&Hämäläinen, 1992). Moreover, a multi-criteria portfolio model is developed and applied to the selection of retrofit actions for a residential building as a specified case of portfolio optimization. Both applications are demonstrated by computational studies.

The Thesis is application-oriented and takes existing methods into new fields of application rather than creates new theory or technology. Due to both the interdisciplinary and complex nature of this study and limited availability of data, a transparent but useful combination of methods is established. The energy consumption of a building is estimated through non-dynamic, monthly simulations. Specific values for heat losses and electricity consumption are employed instead of detailed thermodynamic modeling. The applications are focused on cold areas, wherefore cooling is omitted. The electric grid is considered an infinite electricity storage. Buildings with specific characteristics and locations are presented as example, resulting in that the numerical results are not applicable to whichever building. The justification of the above simplifications is discussed in the following chapters.

2 EARLIER STUDIES

The literature study for this Thesis is based on searches from the databases ScienceDirect, Energy, Inspec, Compendex, NTIS, INIS and Iconda/STN Int. Moreover, numerous Internet searches via Google have been carried out. Reported approaches have been classified according to the methodological premises of this Thesis as follows: i) estimation of energy use, ii) life cycle analysis and iii) decision analysis. Both methods and applications are briefly reviewed. Here, the viewpoint of decision analysis is highlighted, however, because the scientific contribution of this Thesis lies in the application of decision analysis on new areas. Moreover, some attention is paid to studies related to micro-cogeneration (especially residential solid-oxide fuel cells), due to their reference value for the computational example in the present work.

2.1 Estimation of energy use

The estimation of energy use is the first step in the analysis of energy technologies in buildings. There are two main strategies to predict and evaluate the behavior of energy systems: experimental investigations and theoretical calculations (Tuomaala, 2002). Studies on energy systems containing new technology are often constrained by the limited availability of experimental data. Here, the performance assessment may be based on theoretical calculations by either simulations or standard procedures.

There are several simulation tools suitable for the evaluation of energy consumption and system performance in buildings. The US Department of Energy (DOE) provides a list of tools that can be employed in the above task, including DOE-2, EnergyPlus, BDA (Building Design Advisor), Energy-10 and SPARK. Furthermore, the simulation programs IDA, ESP-r and TRNSYS are widely applied in the evaluation of the performance of buildings. Simulation programs often contain dynamic models for building components, wherefore they account for the storage of heat into the structures of buildings.

Simulation programs solve a set of algebraic and differential equations that are mathematical expressions of the conservation of energy, mass and momentum in a pre-defined control volume. According to Hensen (1991) and Judcoff et al. (1983), the reasons for simulation errors are i) inappropriate simplifying assumptions, ii) differences between the reality and assumptions used in the program and databases, and iii) differences between real physical phenomena and the model used to illustrate them in algorithms and coding errors. In residential buildings, differences between empirical results and energy estimates based on simulations can be mainly explained by user-specific reasons (such as ventilation and the use of electrical appliances) that cannot be included into simulation albeit the program would otherwise model the physical behavior of the building perfectly. Henninger et al. (2004), Loutzenhiser et al. (2006), Pavlovas (2004), Raab et al. (2005) and Tuomaala (2002), for example, matched the accuracy of simulation results within 10 % of the empirical results. The difference between simulation and analytical results as well as “inter-model” results is commonly less than 3 %.

In Europe, the standards “EN 13790” and “ISO 13790” create a methodological framework for the simplified estimation of the energy consumption in buildings (CEN, 2004). Furthermore, there are national standards derived from the “EN 13790” and “ISO 13790”, such as “DIN” in Germany or “D5” in Finland. European standards are commonly non-dynamic, i.e. the storage of heat into the structures of buildings is not taken into account. In EN 13790, the demand of cooling energy is not estimated, but only heating demands. In ISO 13790, the cooling energy demand is also estimated. Energy estimates in the CEN-method (the procedure which “EN 13790” is based on) have been observed to deviate within 10 % from the results of dynamic simulations. On the other hand, tests between various users have shown differences up to 20 % (CEN, 1992).

Simulation tools for the evaluation of micro-cogeneration are gradually updated together with suitable models. Ferguson et al. (2004) developed a steady-state model for the sizing of a generic Polymer Electrolytic Membrane Fuel Cell (PEMFC) cogeneration system. The operation of a Solid Oxide Fuel Cell (SOFC) system has been modeled and demonstrated, for example, by Hawkes et al. (2006) and Beausoleil-Morrison et al. (2006). A fuel cell heating system is also modeled and simulated by Dorer et al. (2005), who established a transient computer simulation for assessing the performance of solid-oxide fuel cell (SOFC) heating systems. The implementation and local application (e.g. in Finland) of these models still calls for efforts. The literature survey in this Thesis did not provide references on the use of standard calculation procedures in the energy estimation of micro-cogeneration. A reason for this can be inferred, for example, from the results of Hawkes & Leech (2005b) who show that the performance assessment of micro-cogeneration is sensitive to temporal precision. Because standard calculation procedures often apply monthly time step, the justification of their use may remain poor, except if simplified methods are preferred and therefore uncertainties are accepted to some extent.

There are also experimental results on micro-cogeneration. Most of the data concerns tests carried out in laboratories, but some field tests also have been reported, mainly in Central Europe, North America and Japan. Entchev et al. (2004) present a Stirling engine micro-generation unit with the electrical output of 736 W_e and the thermal output of 6.5 kW_{th}, fuelled by natural gas and built to serve two demonstration houses in Canada. In Äetsä, Finland, a polymer electrolytic fuel cell (PEMFC) with the electrical power of 3 kW_e was installed into a single-family house, utilizing hydrogen released from a chemical process in an industrial plant close to the house. The results of this field test have not yet been published, anyway. In general, the findings of field tests are difficult to obtain due to the unwillingness of competitive actors to publish their results. The applicability of field tests also suffers from that the data are usually intermittent and continuous data are available from a time period shorter than a year. For the above reasons, the use of computational approach in this Thesis can be justified by that experimental data were not available.

2.2 Life cycle analysis

The concept "life cycle analysis" or "life cycle assessment" (LCA), also known as "life cycle impact assessment", commonly refers to the estimation of the environmental burdens of a product during its entire life span, from raw material extraction to final disposal (Consoli et al., 1993). The methodological framework of the life cycle analysis is well established through standards (such as ISO 14040-14043) and also widely conducted according to "good practice" (Seppälä, 2003). In the context of an interdisciplinary decision analysis, the evaluation of environmental effects is not enough, however. At least "life cycle cost analysis" (LCCA) is also needed, where Flanagan et al. (1989) defines life cycle costs as the sum of "the costs of acquisition, operation, maintenance, modification and disposal, for the purpose of making decision".

In the evaluation of environmental burdens, major issues are emissions of greenhouse gases and particles, acidification and the consumption of natural resources. A single number often expresses the amount of harmful emissions released by a process that aims at manufacturing some product or generating some amount of energy. In decision-making, however, the most interesting aspect is not the amount of emissions, but rather their impacts on the environment. Therefore, the effects of different emissions are often made commensurate using "equivalents". For example, International Panel on Climate Change (IPCC, 2001) presents the carbon dioxide equivalent as the indicator of global warming, i.e. the amount of carbon dioxide that causes the same global warming effect as some amount of reference gas.

Conventionally, the natural resource consumption is calculated on the basis of the mass of a product, when its composition is known. It is important, however, that the "ecological rucksack" – i.e. the consumption of natural resources attached to the exploitation and transfer of materials and energy – is taken into account in the above context. The Material Input Per Service unit (MIPS) methodology developed by Wuppertal Institute (Schmidt-Bleek, 1998) incorporates the "ecological rucksack" of a product. Although the MIPS method presents the natural resource consumption comprehensively, it ignores the properties of materials. It is obvious, for example, that the environmental burden for one kilogram of poisonous material (such as mercury) is different than that of non-poisonous material.

Seppälä (2003) outlines the life cycle impact analysis as "an iterative tool" including "life cycle inventory" – a procedure that collects data about products during their life span. In this Thesis, the environmental data of different products is assumed known. This may be justifiable because this Thesis focuses on the analysis of entire systems rather than single products. On the other hand, it is not unusual in the performance assessment of energy systems nowadays that environmental databases are employed (e.g. LCI Database at http://www.nrel.gov/lci/).

Applications of life cycle impact analysis and life cycle cost analysis have been quite eagerly reported in the context of buildings, but many of them refer to the work of private energy consultation offices rather than to scientific approaches of universities or research institutions. Case studies on building energy systems have been reported, for example, by Manczyk (2003), who assessed residential heating systems, Collins et al. (2001), who estimated the life cycle costs of a ground-source heat pump system, and Dombaycı (2005), who optimized insulation thickness. Natural resource consumption has been recently investigated, for example, by Balaras et al. (2005). MIPS is applied, for example, by Sinivuori&Saari (2006) who have estimated the material input for two university buildings in Finland.

In the life cycle analysis of micro-cogeneration, the work of Ossebaard et al. (1997) is worth mentioning. They have discussed the CO_2- and NO_x- emissions of various heat supply scenarios as well as estimated the operational costs of micro-cogeneration systems. The impact of small-scale power generation on CO_2-emissions on the domestic sector in the UK was considered by Peacock et al. (2005) and Kelly et al. (2006), whereas Hawkes et al. (2005a) examined the operation of a hypothetical solid-oxide fuel cell (SOFC) system to determine the driving factors behind investment in this technology. The life cycle costs of small-scale power production systems have been estimated, for example, by Isherwood et al. (2000) for a village, and by Hellgren (2005) and Granovskii (2006) for transport applications. A simplified although extensive independent environmental case study was reported by Prek (2004), who compared three heating systems (radiators, fan coil convector and floor heating) applying the life cycle impact assessment method Eco-indicator 95. Reported life cycle cost analyses for solid-oxide fuel cell systems in single buildings were not found. On the other hand, the application of MIPS in the assessment of residential energy systems has not been published so far.

Although the value of commodities is usually determined by their life cycle costs and environmental burdens, a life cycle assessment based on only those factors is not necessarily sufficient. Referring to the lists of sustainability indicators (e.g. Environmental Sustainability Index by Columbia University, http://sedac.ciesin.columbia.edu/es/esi/) there are several dimensions outside the financial and environmental factors that have not been taken into account in the design of buildings and their systems so far. These factors are often directly related to human himself. According to Riihimäki et al. (2001) and Huovila et al. (1999), for example, good comfort and safety were regarded as the most important preferences together with low life cycle costs and good environmental value. Häkkinen et al. (2002) define an extensive framework of sustainable construction including, for example, such indicators as usability and flexibility. As an application, Soebarto&Williamson (2001) present the multi-criteria assessment of building performance.

2.3 Decision analysis

Clemen (1996) and Kirkwood (1997) define decision analysis as “a set of quantitative methods for analyzing decisions” that “provides a systematic quantitative approach to making better decisions”. In this Thesis, decision analysis is applied to more or less technical problem, which implies that a proper way to define decision analysis would be “a set of methods of systems analysis and operations research” that “can be applied in supporting extensive decisions” (Bunn, 1984). The purpose of decision support is to help a decision-maker find the most preferred alternative on the basis of given information on alternatives (Leitch et al., 1992). Here, the value of energy calculations and life cycle analyses lies in their role as the source of background information rather than independent tools that directly assist decision-making.

The concept “decision support” is relatively extensive. In addition that decision analysis helps decision makers to make decisions, it also helps them organize data and understand the problem (Seppälä, 2003). The decision-maker is usually not the same person as the one who applies the decision analysis. In the present case, the analysis can be seen as the task of an energy advisor. Decision support should never replace judgment that is obviously associated with the decision-maker’s expertise. Hence, decision analysis as the tool for an energy guide contains at least an additional benefit: professionals usually have more expertise and experience than real estate owners, who can be regarded here as final decision-makers.

The justification of the decision analytical approach in this Thesis is implied by the characteristics of the decision-making problem. Large set of conflicting objectives and non-commensurate attributes and a set of conflicting opinions among different interest groups lead to the application of multiple criteria decision analysis (MCDA). On the other hand, the large amount of mutually compatible or non-compatible technological options suggests multiple objective optimizations (e.g. Chen&Hwang, 1992). Under multiple criteria decision analysis, there are still three categories: i) multi-attribute value theory (MAVT), ii) the analytical hierarchy process (AHP) and iii) outranking methods (Seppälä, 2003). The application of multi-attribute value theory called multi-attribute utility theory (MAUT) allows the value of an item to be expressed by a single number, which is the aggregate of an unlimited number of non-commensurate attributes with various importance under conditions of uncertainty (Keeney&Raiffa, 1976). Moreover, the above methodology has not been reported earlier in the context of the assessment of residential energy technologies, which makes it attractive and promising for the present application (Keefer et al., 2004).

Generally speaking, decision support may occur in expert systems, optimization algorithms, the applications of decision analysis, or some combination of these. Decision support tools may be either generic, stand-alone programs or they may interact with other procedures like simulations. On the other hand, simulation tools can be expanded to decision support systems. In the field of building systems, Papamichael (1999) presents an easy-to-use tool called Building Design Advisor (BDA) that allows the simple simulation of several design alternatives and their comparison parallel to each other. The analysis tool RETScreen, developed by Natural Resources Canada, is applicable to the evaluation of residential cogeneration systems, providing energy and cost analysis with sensitivity considerations. The drawback of above tools is that they are not capable of multi-criteria assessments. The MCDM23 tool is a stand-alone multi-criteria decision-making tool containing a default database (Tanimoto et al., 2001). PRIME Decisions is an advanced, generic decision-making tool that supports the use of incomplete source information (Salo&Hämäläinen, 2001).

As such, the above tools are not capable of portfolio optimization, i.e. establishing automatically the most preferred set of alternatives taking into account given constraints related to overall costs, benefits or mutual compatibility. Multi-criteria portfolio optimization tools have been recently developed, anyway. For example, the Robust Portfolio Modeling (RPM) method represents this type of decision-making tool (Liesiö et al., 2006).

There are few reported case studies that employ the above methodology. PRIME has been applied to estimate the market capitalization value of a new technology-based company (Gustafsson et al., 2001). Vanhanen&Loimaranta (1999) evaluated the performance of micro-cogeneration technologies using eight criteria. The results were illustrated by star diagrams. The methodological background of that work was not well established, however. Applications of multi-criteria portfolio optimization in the context of building technology have not been published so far.

2.4 Contribution of this Thesis

The most important contribution of this Thesis is the application of multi-attribute decision analysis methodology in the assessment of residential energy technologies. Particular attention has been paid to the nature of decision-making in the phase of preliminary design and before it. Specifically, the assessment of technologies under uncertainty conditions and the selection of technology portfolios through multi-objective optimization are highlighted. This Thesis also creates a basis for the development of new decision-making tools. Additional contributions relate to the use of MIPS method in the estimation of the natural resource consumption of residential energy systems. The comparison between micro-cogeneration and other heating systems is conducted in life cycle cost analysis from the viewpoint of real estate owner, which contains some value from the local (Finnish) perspective.

3 METHODOLOGY

3.1 Estimation of energy use

3.1.1 Energy use of the building

A major part of costs and environmental burdens is related to the energy use of a building. Thus, energy use has to be estimated before life cycle or decision analysis can be employed. Here, standard calculation has been selected as a method for the estimation of energy consumption in the decision analytical framework. The selection can be justified by the facts that i) designers commonly employ standard calculation in the pre-design phase, which naturally puts it into the same framework with decision analysis, ii) decision analysis can accommodate uncertainties and iii) the final decision is based on judgment and the results given by decision analysis are recommendations. Furthermore, the estimation of energy use on monthly basis is also supported by the fact that also the billing of heat and electricity is commonly monthly-based. Some support also can be found from the literature. Citherlet&Defaux (2007), for example, applied standard calculation in the life cycle impact assessment of buildings.

The following summarizes the draft (published in February 2006) of the new Finnish Building Regulation D5, which has its foundation on “EN 13790” standard (CEN, 2004). Here, energy demand is estimated by calculating monthly energy balance, using monthly average values for outdoor temperature, solar radiation etc. Annual energy demand is the sum of monthly demands. The building is regarded as a single space with equally distributed temperature (Ministry of Environment, 2006). The demand of cooling energy is not estimated, which is justifiable especially if the performance of energy systems is predicted in cold climates.

Referring to Fig.1, the total thermal energy consumption of the heat distribution system ($Q_{in,hd}$) is calculated from the steady-state energy balance

$$Q_{in,hd} = Q_{env} + Q_{leak} + Q_{vent} - Q_{hl,util} + Q_{l,hd} \quad (1)$$

where Q_{env} is the heat loss through envelope, Q_{leak} is the heat loss caused by air leaks, Q_{vent} is the heat loss caused by ventilation, $Q_{hl,util}$ is the utilizable heat load, and $Q_{l,hd}$ is the heat loss of space heating. The thermal consumption of the domestic hot water (DHW) system ($Q_{in,DHW}$) is

$$Q_{in,DHW} = Q_{l,DHW} + Q_{DHW} \qquad (2)$$

where $Q_{l,DHW}$ is the heat loss of the DHW system and Q_{DHW} is the heat demand of the DHW system. The electricity consumption of the building (W_e) is

$$W_e = W_l + W_{app} + W_{vent} \qquad (3)$$

where W_l, W_{app}, and W_{vent} are the electricity demands of lighting, appliances and ventilation fans, respectively.

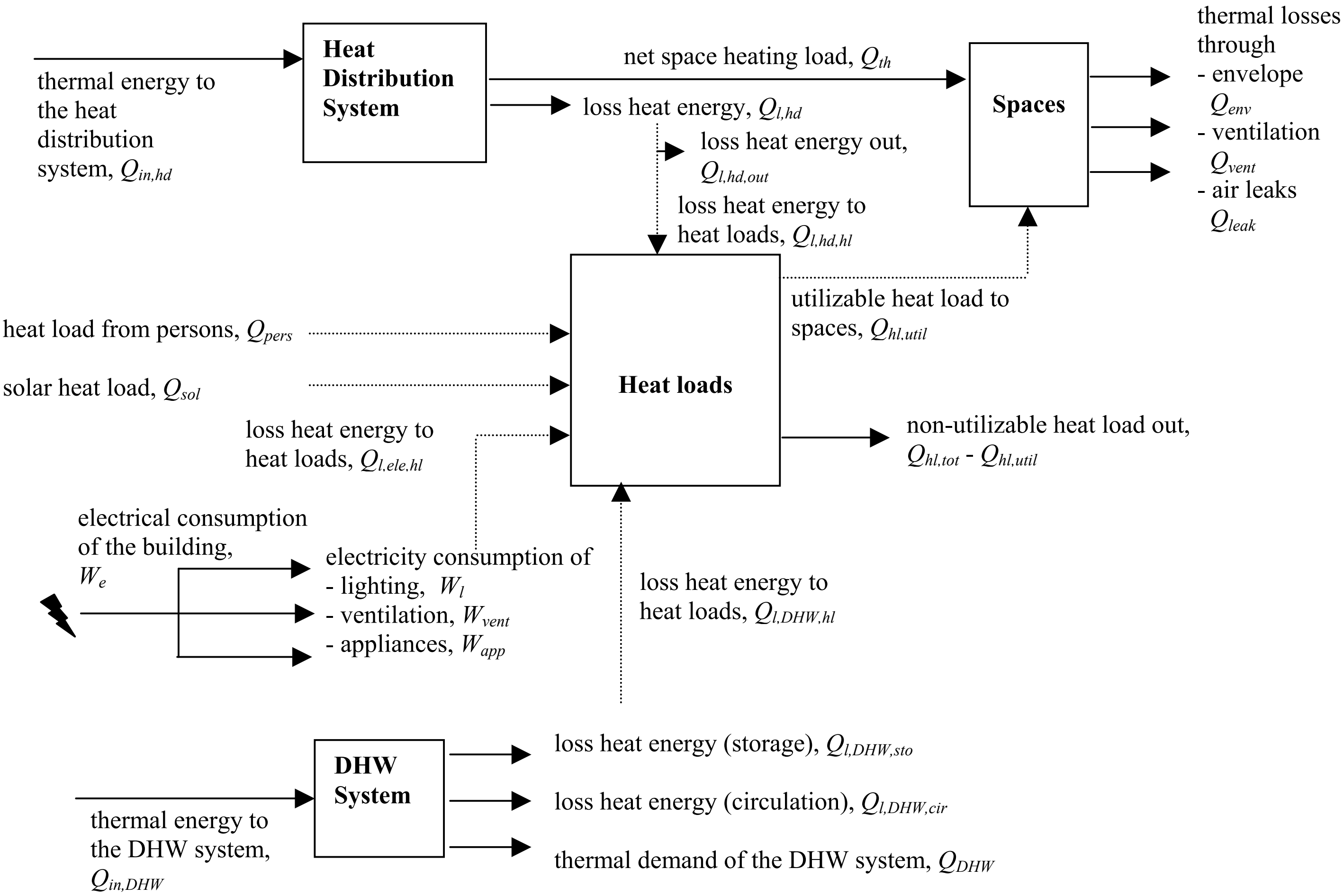

Figure 1. Schematic diagram of energy use in a building.

The following procedure is employed to calculate the components of energy balances:

1. Estimate the heat losses of spaces through ventilation, envelope and air leakages
2. Estimate the heat demand of domestic hot water system
3. Estimate the heat losses of heating system
4. Estimate the electricity consumption
5. Estimate the heat loads
6. Estimate the total energy consumption

The above procedure is presented in Appendix I in detail. One should note that the Finnish D5 is not the only standard calculation method that is suitable for the current methodological framework. It has been taken here as an example, which is reasonable because the same principles of energy estimation are valid in other standard procedures, too. The old version of D5 is still in use in Finland, but the reason why only the new draft is presented in this compendium is clear: the existing version is becoming obsolete and its use in future applications would be poorly justified.

3.1.2 Energy use of the energy supply system

The energy supply system incorporates a heat boiler system including a solid-oxide fuel cell (SOFC) plant plus a heat storage tank that is used to handle the excess heat and to deliver the heat to the heat distribution and domestic hot water (DHW) systems (Fig.2). All the heat is transferred to the heat distribution and the domestic hot water system via a heat storage tank. If the amount of excess heat is more than the capacity of the heat storage tank, a heat sink (cooling) is used. The gas boiler works in this system as a backup heat source. The building is connected to the electricity grid by an interface that makes it possible to feed the excess electricity into the grid.

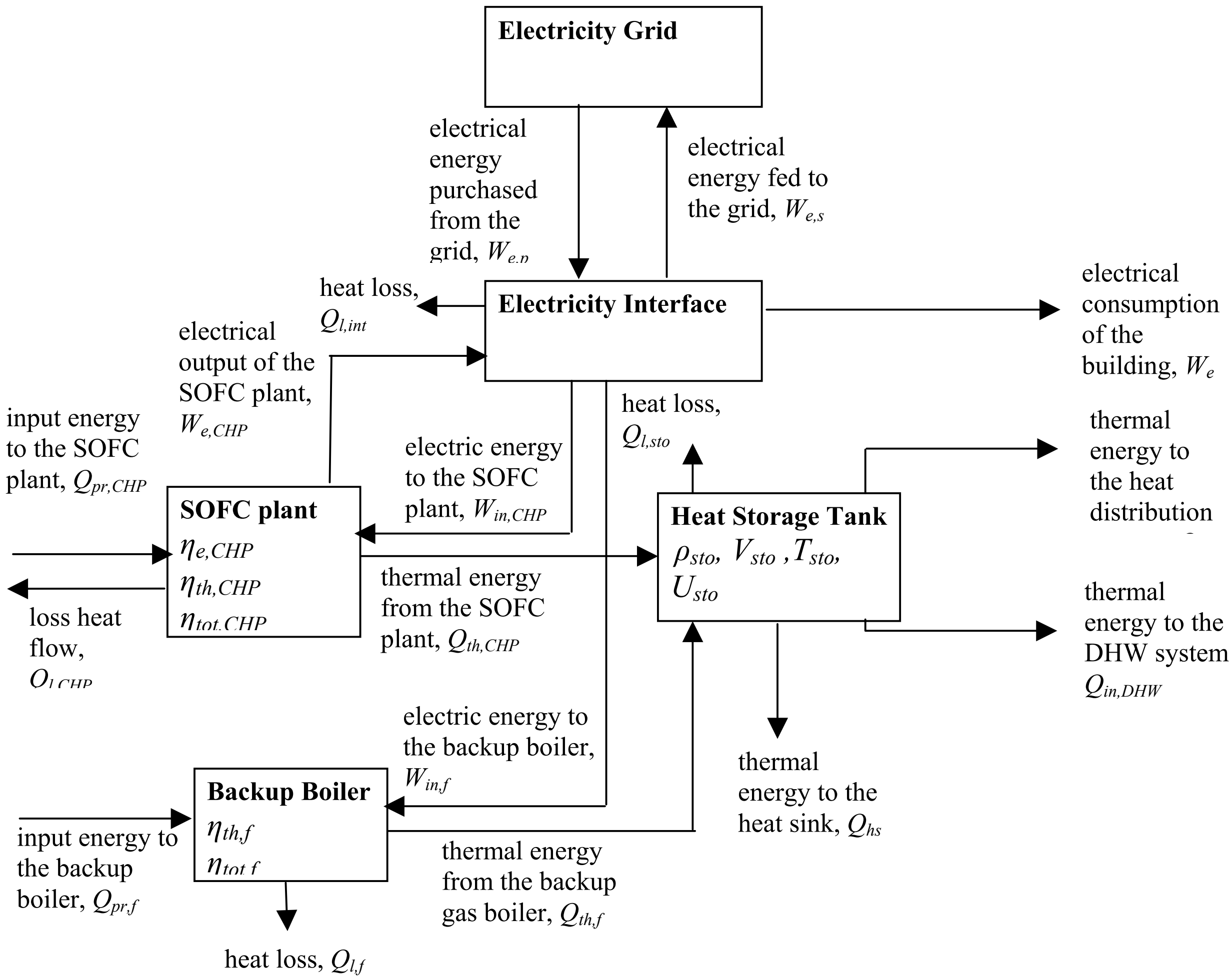

Figure 2. Schematic diagram of an energy supply system.

Referring to Fig.2, the change of internal energy of the heat storage tank (ΔU_{sto}) during the time period Δt is calculated from the energy balance of the tank

$$\Delta U_{sto} = Q_{th,CHP} + Q_{th,f} - Q_{in,hd} - Q_{in,DHW} - Q_{hs} - Q_{l,sto} = \rho_{sto} V_{sto} c_{sto} \Delta T_{sto} \quad (4)$$

where $Q_{th,CHP}$ is the thermal energy from the SOFC plant, $Q_{th,f}$ is the thermal energy from a backup gas boiler, $Q_{in,hd}$ is the total thermal energy to the heat distribution system, $Q_{in,DHW}$ is the total thermal energy to the domestic hot water (DHW) system, Q_{hs} is the thermal energy to the heat sink, $Q_{l,sto}$ is the heat loss from the storage, V_{sto} is the volume of the tank, ΔT_{sto} is the storage temperature change, c_{sto} and ρ_{sto} are the specific heat capacity and the density of the contents of the tank, respectively.

Generally speaking, input energy can be understood as energy transferred to a thermodynamic system. In this thesis, the phrase "input energy" primarily represents the energy lead to the SOFC plant and the backup boiler (i.e. energy content of the fuels that are used at the building site, sometimes referred as primary energy). On the other hand, in electrical heating the above term is used to express the amount of electricity used for heating, which might make it confusing to use, for example, the term "fuel energy". The total input energy consumption of the SOFC plant ($Q_{pr,CHP}$) is calculated from the steady-state energy balance of the SOFC plant

$$Q_{pr,CHP} = Q_{th,CHP} + Q_{l,CHP} + W_{e,CHP} - W_{in,CHP} \qquad (5)$$

where $Q_{th,CHP}$ is the thermal energy from the system, $Q_{l,CHP}$ is the heat loss from the system, $W_{in,CHP}$ is the electric energy consumed by the system, and $W_{e,CHP}$ is the electrical output of the system.

The steady-state input energy consumption of the backup boiler ($Q_{pr,f}$) is

$$Q_{pr,f} = Q_{th,f} + Q_{l,f} - W_{in,f} \qquad (6)$$

where $Q_{th,f}$ is the thermal energy from the boiler, $Q_{l,f}$ is the heat loss of the boiler, and $W_{in,f}$ is the electric energy to the boiler.

The electricity purchased from the grid ($W_{e,p}$) is

$$W_{e,p} = W_e + W_{in,CHP} + W_{in,f} + W_{e,s} - W_{e,CHP} + Q_{l,\text{int}} \qquad (7)$$

where W_e is the electrical consumption of the building, $W_{in,CHP}$ is the electric energy consumed by the SOFC plant, $W_{in,f}$ is the electric energy to the boiler, $W_{e,s}$ is the electrical energy fed to the grid, and $Q_{l,int}$ is the heat loss from the interface.

With the total thermal energy to the heat distribution system ($Q_{in,hd}$), the total thermal energy to the domestic hot water (DHW) system ($Q_{in,DHW}$), and the electrical consumption of the building (W_e) known, the following procedure can be given to estimate the energy consumption of the energy supply system:

1. Referring to the energy balance of the heat storage tank (Eq.(4)), estimate
    - the heat loss from the storage ($Q_{l,sto}$),
    - the thermal energy from the SOFC plant ($Q_{th,CHP}$),
    - new internal energy of the heat storage (U_{sto}),
    - the thermal energy from the boiler ($Q_{th,f}$),
    - the thermal energy to the heat sink (Q_{hs}), and
    - new storage temperature (T_{sto}).

2. Referring to the energy balance of the SOFC plant (Eq.(5)), estimate
   - the electrical output of the SOFC plant ($W_{e,CHP}$),
   - the electric energy consumed by the SOFC plant ($W_{in,CHP}$),
   - the heat loss from the SOFC plant ($Q_{l,CHP}$), and
   - the input energy to the SOFC plant ($Q_{pr,CHP}$).
3. Referring to the energy balance of backup boiler (Eq.(6)), estimate
   - the electric energy to the backup boiler ($W_{in,f}$),
   - the heat loss of the boiler ($Q_{l,f}$), and
   - the input energy to the boiler ($Q_{pr,f}$).
4. Referring to the energy balance of electrical interface (Eq.(7)), estimate
   - the heat loss from the interface ($Q_{l,int}$),
   - the electrical energy fed to the grid ($W_{e,s}$), and
   - the electrical energy purchased from the grid ($W_{e,p}$).
5. Return to step 1 for the next time step.

The heat storage tank is assumed to be of cylindrical shape and filled with water. The operational range of storage temperatures, dictated by factors such as the boiling temperature of the contents in the tank, is assumed to vary between T_{min} (where the internal energy is $U_{sto} = 0$) and T_{max} (where the internal energy is $U_{sto} = U_{max}$). The contents of the tank is assumed to be fully mixed. The amount of contents is supposed to remain constant during the operation. If the initial temperature is $T_{sto}(0) \in [T_{min},T_{max}]$, then the initial internal energy of the storage ($U_{sto}(0)$) is

$$U_{sto}(0) = \rho_{sto} V_{sto} c_{sto} \left(T_{sto}\left(0\right) - T_{\min}\right) \qquad (8)$$

where c_{sto}, ρ_{sto} and V_{sto} are the specific heat capacity, density, and the volume of the contents of the tank, respectively. When the index number 0 is refers to the past time step (initial time step) and the index number 1 to the present time step, the tank heat loss ($Q_{l,sto}$) is:

$$Q_{l,sto}\left(1\right) = K_{sto} A_{sto} \left(T_{sto}\left(0\right) - T_{amb}\right)\Delta t \qquad (9)$$

where K_{sto} is the specific tank loss coefficient that takes into account the heat transfer by convection, conduction and radiation from the water inside the tank to the ambient air, A_{sto} is the heat transfer area of the tank, and Δt is the length of time step.

When the thermal energy from the SOFC plant ($Q_{th,CHP}$) is known, the thermal surplus or shortage can be calculated from

$$\Delta Q\left(1\right) = Q_{th,CHP}\left(1\right) - Q_{in,hd}\left(1\right) - Q_{in,DHW}\left(1\right) - Q_{l,sto}\left(1\right) \qquad (10)$$

where ΔQ is the thermal surplus (when $\Delta Q > 0$) or the thermal shortage (when $\Delta Q > 0$).

In the case of thermal shortage ($\Delta Q < 0$),

- $Q_{hs}(1) = 0$
- if $U_{sto}(0) \geq \Delta Q(1)$, then $U_{sto}(1) = U_{sto}(0) - \Delta Q(1)$
- otherwise $U_{sto}(1) = 0$ and $Q_{th,f} = \Delta Q(1) - U_{sto}(0)$.

In the case of thermal surplus ($\Delta Q > 0$),

- $Q_{th,f}(1) = 0$
- if $U_{sto}(0) + \Delta Q(1) \leq U_{max}$, then $U_{sto}(1) = U_{sto}(0) + \Delta Q(1)$
- otherwise $U_{sto}(1) = U_{max}$ and $Q_{hs} = \Delta Q(1) - U_{sto}(0)$.

The new storage temperature ($T_{sto}(1)$) is calculated on the basis of the amount of energy stored in the tank. It is defined as

$$T_{sto}(1) = T_{sto}(0) + \frac{U_{sto}(1)}{c_{sto}\rho_{sto}V_{sto}} \qquad (11)$$

In the current framework, the initial parameters related to a cogeneration plant are the electrical output power ($P_{e,CHP}$), the electrical efficiency ($\eta_{e,CHP}$) and the overall efficiency ($\eta_{tot,CHP}$). The electrical output power ($P_{e,CHP}$) is ordinarily given as a plant-specific parameter which represents either the direct current (DC) or alternating current (AC) output power. In this Thesis, the output power is given as the AC output, including the electricity consumed by the power conditioning (inverter) system but excluding that of ancillaries (pumps, fans etc.). This idea can be also inferred from Fig.2. In these conditions, the electrical output energy is

$$W_{e,CHP} = P_{e,CHP}\Delta t \qquad (12)$$

where $P_{e,CHP}$ is the electrical output power and Δt is the length of time step. The electrical efficiency represents the ratio of generated electricity (output without ancillaries) to the input energy (fuel). A general expression for the electrical efficiency is

$$\eta_{e,CHP} = \frac{W_{e,CHP}}{Q_{pr,CHP}} \qquad (13)$$

where $W_{e,CHP}$ is the electrical output energy of the plant and $Q_{pr,CHP}$ is the input energy to the plant. Because the electrical efficiency is also a plant-specific parameter, the input energy ($Q_{pr,CHP}$) can be calculated from the Eq. (13). The electrical efficiency depends on both the features of the technology and the load (Fig. 3). The relation between the electrical efficiency and the electrical output power ($P_{e,CHP}$) can be determined either by simulating the electrochemical process of a fuel cell, or on the basis of experiments. Furthermore, the electrical efficiency depends on whether the input energy to the plant and ($Q_{pr,CHP}$) is defined on the basis of the higher (HHV) or lower (LHV) heating value of the fuel. According to Watson et al. (1997), the electrical power required by ancillaries (pumps, fans etc.) of a cogeneration plant ($W_{in,CHP}$) is approximately 6 % of the electrical output power of the plant. Without more specific data in the open literature, it would be of interest to consider this as uncertain parameter although it has been regarded as known here.

The overall efficiency of an SOFC plant determines the ratio between utilizable energy (electricity plus heat) and the input energy and it is given as

$$\eta_{tot,CHP} = \frac{W_{e,CHP} + Q_{th,CHP}}{Q_{pr,CHP}} \qquad (14)$$

where $W_{e,CHP}$ is the electrical output energy of the plant, $Q_{th,CHP}$ is the utilizable thermal output of the plant and $Q_{pr,CHP}$ is the input energy to the plant. The heat loss ($Q_{l,CHP}$) and thus the utilizable thermal output depends on skin losses, losses through exhaust gases, losses due to non-reacted fuel etc. The losses could be estimated by determining the flow and the temperatures of exhaust gases before and after heat exchanger, modeling the heat transfer from an SOFC plant to the environment etc. Further conclusions about opportunities to utilize the heat losses of SOFC plant would require further investigations, anyway. One should also note that this approach presumes that the chemical reaction of fuel cell is exothermic (i.e. both electricity and heat are always available as an output from the SOFC). In the present framework, the overall efficiency is considered "known", although an uncertain piece of data.

If both the electrical and overall efficiencies are known at certain operational conditions, the thermal efficiency (i.e. the ratio of utilizable thermal energy to input energy) can be expressed as follows:

$$\eta_{th,CHP} = \eta_{tot,CHP} - \eta_{e,CHP} \qquad (15)$$

where $\eta_{th,CHP}$, $\eta_{tot,CHP}$ and $\eta_{e,CHP}$ are the thermal, overall and electrical efficiencies of an SOFC plant, respectively. Load factor, which is here defined as the ratio of generated electricity to generated heat (α_{CHP}), can be then calculated from

$$\alpha_{CHP} = \frac{\eta_{e,CHP}}{\eta_{th,CHP}} = \frac{W_{e,CHP}}{Q_{th,CHP}} \qquad (16)$$

where $W_{e,CHP}$ is the electrical output of the system, $Q_{th,CHP}$ is the thermal energy from the system, and $\eta_{th,CHP}$ and $\eta_{e,CHP}$ are the thermal and electrical efficiencies of an SOFC plant, respectively. The utilizable thermal output of the SOFC plant ($Q_{th,CHP}$) can now be calculated from Eq. (16), whereas the heat loss ($Q_{l,CHP}$) can be calculated from Eq. (5). One should note in the current methodology that because the overall efficiency is uncertain, the utilizable thermal energy, the thermal efficiency and the load factor also remain uncertain.

In practice, the amount of utilizable thermal energy ($Q_{th,CHP}$) mainly depends on the sizing and operational strategy of the plant. Generally speaking, the cogeneration system can be operated by following either thermal or electrical loads, or by aiming at satisfying both of them either fully or partially. When the systems located in cold climates are evaluated, it is reasonable to operate the system at thermal "base load". The theoretical maximum of the utilizable thermal energy ($Q_{th,CHP}$) is the heat generated by a system running continuously at its specific power. Singhal et al. (2003) presents three reasons why this operation would be recommended: i) 100 % operation is associated with the best possible overall efficiency, ii) frequent shutdowns of an SOFC plant are not reasonable due to thermal stresses that significantly decrease the lifetime of a fuel cell stack, and iii) the turndown of about 70 % load in practice causes a heat leak that is more than the amount of heat generated by the SOFC plant itself. An obvious problem is the increased probability of generating non-utilizable heat.

For example, the performance curve of 5 kW SOFC cogeneration unit from the work of Hawkes et al. (2006) is depicted in Fig. 3. The area above the "overall efficiency"-line illustrates the proportion of input energy consumed by the losses. Correspondingly, the area between the "overall efficiency"- and "electrical efficiency"-lines represents the fraction of input energy that is utilizable as heat. The lowest region (below "electrical efficiency"-line) expresses the ratio of generated electricity to the amount of input (primary) energy. One should note that in Fig. 3 the horizontal axis represent the net DC output of the plant. Hawkes et al. (2006) do not clearly report whether the performance curve is given on the basis of lower or higher heating value. As seen in Fig.3, however, the electrical efficiency at maximum is relatively high, close to 50 %. Referring to the work of Braun et al. (2005), for example, who present the electrical efficiency to be 45 % at maximum on the basis of lower heating value, an attractive guess would be that the curve of Hawkes et al. (2006) is in an LHV basis.

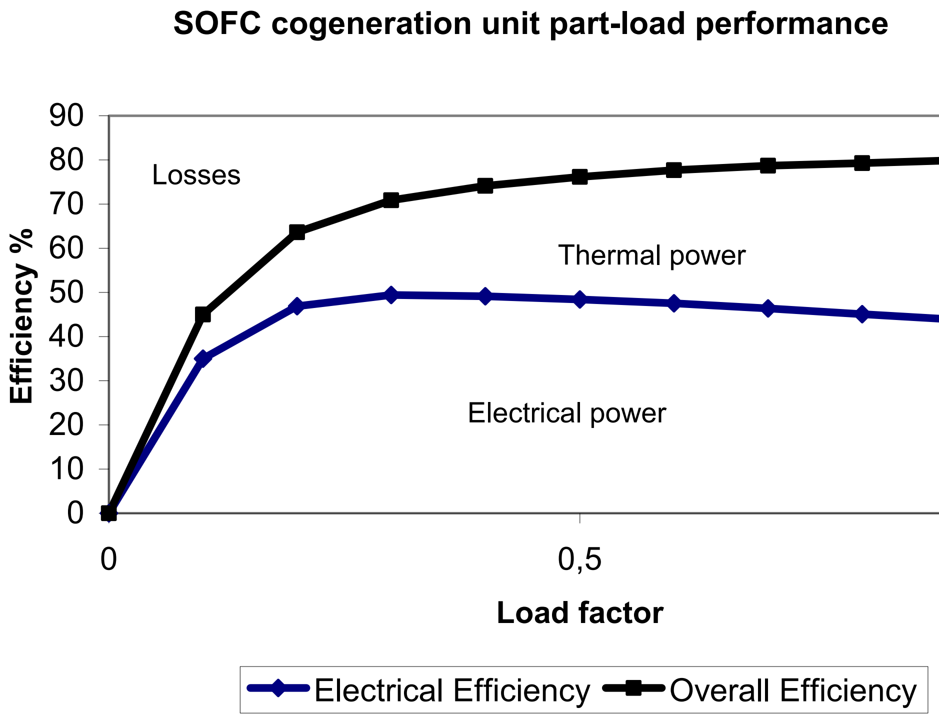

Figure 3. Electrical and overall efficiencies of an SOFC cogeneration unit (Hawkes et al., 2006).

In this Thesis, the performance of the backup boiler is evaluated on the basis of two efficiencies. Firstly, the thermal efficiency of the backup boiler, i.e the ratio of the utilizable thermal energy to the input energy to the boiler ($\eta_{th,f}$) is defined as

$$\eta_{th,f} = \frac{Q_{th,f}}{Q_{pr,f}} \qquad (17)$$

where $Q_{th,f}$ is the utilizable thermal energy from the boiler and $Q_{pr,f}$, is the input energy to the boiler. The above efficiency does not take into account the effect of the electrical draw of auxiliaries (combustion air fan, controls, air circulation etc.) and it is defined either on the basis of lower or higher heating value.

Secondly, the total efficiency of the boiler system is the ratio of the utilizable heat to the total energy input of the boiler, including the input energy consumption of the boiler and the electrical requirements of the auxiliaries, and it is

$$\eta_{tot,f} = \frac{Q_{th,f}}{Q_{pr,f} + W_{in,f}} \qquad (18)$$

where $Q_{th,f}$ is the thermal energy from the boiler, $W_{in,f}$ is the electric energy consumption of the auxiliaries and $Q_{pr,f}$ is the input energy to the backup boiler. From the viewpoint of decision analysis, these efficiencies are boiler-specific parameters that can be assumed known and constant. The thermal energy from the boiler equals to the thermal shortage, the input energy to the backup boiler is given by Eq. (17) and the electric energy consumption of the auxiliaries can be calculated from Eq. (18). The heat loss ($Q_{l,f}$) can be calculated from Eq. (6).

The purchased ($W_{e,p}$) and sold ($W_{e,s}$) electricity for each time step is estimated by Eq. (7). The need to purchase electricity from the grid occurs if the SOFC plant generates less electricity than required to meet the electrical demands of the building and the energy supply system (the shortage of electricity).

Estimating the heat loss from the interface ($Q_{l,int}$) would require modeling the heat transfer related to the interface. In normal operating conditions the interface temperature can be assumed to be close to the ambient temperature, which makes it justifiable to consider the heat loss insignificant. This assumption is also supported by the standard D5, where the specific loss factors related to electrical heating generation and distribution losses are assumed zeros (See: Appendix I).

Basically, the time step in the above methodology can be selected freely provided that relevant data on weather conditions, temporally changing internal and solar gains, and operational characteristics of the system is available. High precision is recommended especially in the performance evaluation of SOFC plants: for example Hawkes et al. (2005b) have concluded that the time step should be as short as only five minutes to accurately observe the distribution of electricity and heat surpluses and shortages.

3.2 Estimation of life cycle costs

A significant part of a real estate owner's costs occur during the life span of a building. Thus, determining project costs (initial investment) is not enough in terms of decision-making, but the estimation of life cycle costs is required, incorporating i) initial costs (project costs), ii) energy costs, iii) service costs, and iv) maintenance costs (Flanagan et al., 1989). Life cycle cost analysis (LCCA) can be seen as a cost estimation tool for designers in the early stages of design processes (e.g. Kosonen et al., 1999). It is often predictive by nature and thus suitable to be applied in decision analysis. The methodological choices relate to how the changes in the purchasing power of money (inflation, escalation) are taken into account. Life cycle cost analysis (LCCA) has a solid foundation in the present value method, which is also the most commonly used approach in life cycle evaluations in building sector (e.g. Cetiner&Özkan, 2005). In LCCA, the required data can be retrieved from databases, the literature, and if available, practical experiences.

The project costs of a residential building are distributed as presented in Table 1 (Haahtela&Kiiras, 2004). In the current approach, the project costs specifically refer to the capital costs of subsystems related to the energy supply, total workmanship assigned to their installation, transportation and energy costs and insurance. The initial costs are calculated from

$$C_I = \left(1+p_{pr}\right)\left(1+p_{ps}\right)\sum_i c_i N_{c,i} + \left(p_{wr}+p_{or}\right)\left(\left(1+p_{ps}\right)\sum_i c_i N_{c,i} + \sum_j C_j\right) + \sum_j C_j - S \qquad (19)$$

where C_I is the total initial costs, p_{pr} is the risk coefficient of price changes, p_{ps} is the fraction of the construction costs assigned to project services (design, establishing a building site etc.), c_i is the installed unit cost assigned to i-th subsystem, $N_{c,I}$ is the number of installed units assigned to i-th subsystem, p_{wr} is the risk coefficient of extra works, p_{or} is the risk coefficient of unidentified risks, C_j is the connection fee of j-th interconnection, and S is the amount of governmental support.

Table 1. Distribution of project costs (Haahtela&Kiiras, 2004).

Main system	Subsystem/sub-project	Costs, %
Structures	Site structures	4.5
	Building structures	31.5
	Infill structures	19.9
Mechanical, electrical and information services	Heating, water and sewer systems	7.7
	Air conditioning systems	2.1
	Electrical systems	3.6
	Information systems	0.7
	Other systems	
Project services	Construction services	17.8
	Design services	9.3
= BUILDING		97
Site and connections	Building site	
	Interconnections to municipal networks	0.9
= REAL ESTATE		97.9
User's equipment		
Marketing and financing	Marketing	
	Financing	
Risk factors	Change in price	1.3
	Other risks	0.8
= CONSTRUCTION PROJECT		100

Energy costs encompass electricity and input energy and they are accumulated during the period of time. Total energy costs for the energy supply system in section 3.1 are calculated from

$$C_E = \left[\left(C_{fa,e} + c_{e,p} W_{e,p} - c_{e,s} W_{e,s} \right) + \left(C_{fa,pr} + c_{pr} \left(Q_{pr,CHP} + Q_{pr,f} \right) \right) \right] \sum_{n=1}^{N} \frac{1}{\left(1 + r_e\right)^n} \tag{20}$$

where $C_{fa,e}$ is the fixed annual electricity costs, $c_{e,p}$ is the retail price of electricity, $W_{e,p}$ is the annual electricity purchased from the grid, $c_{e,s}$ is the buyback price of electricity, $W_{e,s}$ is the annual electricity delivered to the grid, $C_{fa,pr}$ is the fixed annual input energy costs, c_{pr} is the price of input energy (e.g.fuel), $Q_{pr,CHP}$ and $Q_{pr,f}$ are the annual input energy consumed by the SOFC plant and by the backup boiler, respectively, N is the total number of years of the time period, and r_e is the discount rate for energy prices. The definition in Eq. (20) presumes that the same fuel (natural gas) is utilizable both in an SOFC plant and in a backup boiler.

Service costs consist of the service costs of the building and its systems and the costs of janitorial services. Some systems may require service rarely or even be service-free, but here an annual cost is assigned to each subsystem. The accumulated service costs during the given period of time are:

$$C_S = \left(c_{rm} t_{rm} + \sum_i c_{s,i} t_{s,i} \right) \sum_{n=1}^{N} \frac{1}{\left(1 + r\right)^n} \tag{21}$$

where c_{rm} is the estimated price for an hour of janitorial work, t_{rm} is the estimated annual time required to energy supply management, $c_{s,i}$ is the price for a hour of service work for *i*-th subsystem, $t_{s,i}$ the required annual service time for *i*-th subsystem, and r is the discount rate.

Buildings and their systems are maintained through equipment upgrading or replacement. The costs incorporate purchasing a new subsystem and the demolition of obsolete one. Furthermore, an obsolete subsystem still may have some value. The issue of various operational lifetimes for each subsystem is solved here by assigning a constant annual maintenance cost for each subsystem. The costs accumulated during the given period of time are:

$$C_M = \sum_i C_{m,i} \sum_{n=1}^{N} \frac{1}{\left(1+r\right)^n} \quad (22)$$

where $C_{m,i}$ is the annual maintenance cost for *i*-th subsystem.

In equations (21-22), the discount rate r is selected on the basis of either nominal interest rate or real interest rate, i.e. nominal interest rate minus inflation. For energy costs (Eq. (20)), however, the discount rate r_e is the interest rate minus the percentage by which the annual rise of energy prices is expected to exceed inflation.

The life cycle costs are

$$C_{LC} = C_I + C_E + C_S + C_M \quad (23)$$

where C_{LC} is the life cycle costs, C_I is the initial costs (project costs), C_E is the energy costs, C_S is the service costs, and C_M is the maintenance costs.

If an SOFC plant is implemented in a residential heating system, both savings and incremental costs occur during operation, compared to gas heating without a fuel cell (reference case). The savings are mainly caused by the improved overall efficiency of the system and the possible compensation against the electricity fed into the grid. The costs associate with the acquisition of an SOFC plant and possible extra service and maintenance. The condition for the financial viability of an SOFC plant presumes that the discounted incremental cost equals to discounted cumulated savings during a given period of time. This condition is satisfied when

$$C_{I,CHP} + \frac{\left(1+r\right)^n - 1}{r\left(1+r\right)^n} \cdot \Delta C_{I,ma} - \frac{\left(1+r_e\right)^n - 1}{r_e\left(1+r_e\right)^n} \cdot \left[c_{e,p} W_{e,ref} + c_{pr} Q_{pr,ref} - \left(c_{e,p} W_{e,p} - c_{e,s} W_{e,s} + c_{pr} Q_{pr,CHP} \right) \right] = 0 \quad (24)$$

where $C_{I,CHP}$ is the capital (investment) cost of an SOFC plant, r is the discount rate, r_e is the discount rate for energy costs, n is the number of years on the time period, $\Delta C_{I,ma}$ is the annual incremental cost of maintenance, $W_{e,ref}$ and $Q_{pr,ref}$ are the annual electricity and input energy consumptions in the reference case, respectively, $c_{e,p}$ and c_{pr} are the purchasing prices for electricity and input energy, respectively, $c_{e,s}$ is the buyback price of electricity, $W_{e,p}$ is the annual amount of electricity to be purchased in the case of SOFC plant, $W_{e,s}$ is the annual amount of electricity a fed into the grid, and $Q_{pr,CHP}$ is the input energy consumption of the SOFC plant.

3.3 Estimation of environmental burdens

Commonly cited aspects of sustainability in both political and individual decision-making relate to environmental burdens. The estimation starts from single indicators. The total impact is obtained by aggregating several indicators in life cycle impact analysis (LCIA) like done, for example, by Seppälä (2003) and Citherlet&Defaux (2007). The selection of environmental indicators remains somewhat subjective, although there are widely accepted recommendations, such as the proposal of Heijungs et al. (1992). In the paper of Citherlet&Defaux (2007), the global warming potential (GWP) and acidification potential (AP) are mentioned among the most influential indicators in building industry. Instead, they do not pay attention to the consumption of natural resources as an environmental impact. This Thesis presents that the estimation of environmental burdens should incorporate two viewpoints: input and output. Here "input" represents the amount of natural resources consumed during the construction and operation of a building and its systems. "Output" refers to harmful emissions released to the atmosphere during the same period of time. The environmental burdens of a residential energy supply system are summarized in Fig. 4.

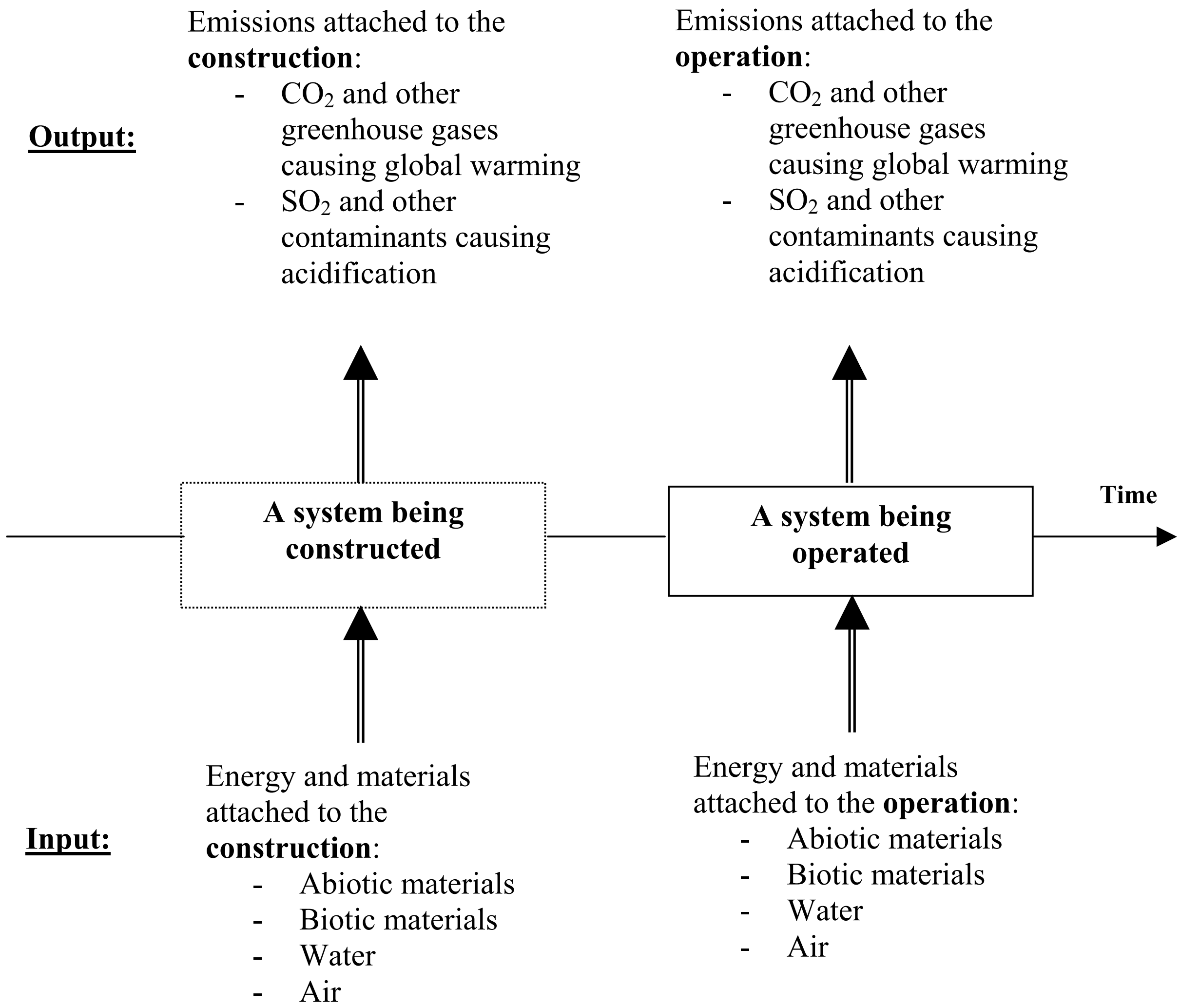

Figure 4. Schematic diagram of environmental burdens.

Here, the Material Input Per Service Unit (MIPS) method is selected to indicate the consumption of natural resources. The selection can be justified due to the ability of this method to take into account the "ecological rucksack" of a product. The MIPS method determines the total mass of abiotic and biotic materials, water and air (see: Table 2) that are consumed during the entire life cycle of a product.

Table 2. Examples of items in the various categories of natural resources (Sinivuori&Saari, 2006).

Abiotic materials	Biotic materials	Water	Air
- Mineral raw materials - Fossil fuels - Rock or earth moved when excavating abiotic raw materials	- Biomass	- Water extracted from the nature - Water flowing through hydro-power plants	- Air used by humans for combustion and other chemical and physical reactions

According to Schmidt-Bleek (1998), MIPS is defined as follows:

$$MIPS = \frac{MI}{S} \qquad (25)$$

where *MI* is the material input factor and *S* is the service unit.

The MI factor (*MI*) indicates the amount of natural resources that is invested in producing a kilogram of some material or a kilowatt-hour of energy. It is calculated separately for each material that a product consists of. In decision analysis, pre-calculated values can be applied when available. In the context of buildings, gross square meter is commonly used as a service unit (e.g. Sinivuori&Saari, 2006).

Global warming and acidification are the most notable implications of harmful emissions. Carbon (CO_2) and sulphur dioxide (SO_2) equivalents offer a useful way to indicate the global warming (GWP) and acidification (AP) potentials due to harmful emissions released during a product's life cycle. The carbon dioxide equivalent for an arbitrary process (e.g. producing one kilowatt heat using some fuel) that emits *N* greenhouse gases, is calculated from

$$GWP = \sum_{i=1}^{N} w_{GWP,i} G_i \qquad (26)$$

where G_i is the amount of greenhouse gas *i* released from the process, and w_i is a weight factor that represents the amount of carbon dioxide required to produce the same GWP as produces that amount of the gas *i* (G_i). The sulphur dioxide equivalent (AP) is calculated similarly. The carbon and sulphur dioxide equivalents can be determined only if each emission type is known. Nowadays, there are environmental profiles available both because a lot of research work has been done and because manufacturers are eager to publish environmental data to market their products.

In the present methodology, "input" and "output" may overlap in some respects and complement each other in other respects. For example, if biomass is used in a combustion process, then CO_2 from biomass is released back into the atmosphere, and the ecological balance is not distorted. Overlapping evaluations should be avoided in decision analysis (e.g. Tanimoto et al., 2001), but this does not make the present approach inapplicable if the environmental indicators are selected properly.

3.4 Estimation of other factors

Apart from life cycle costs and environmental burdens, there are also other factors that deserve a brief discussion. Thermal comfort i) affects strongly the life quality of the residents but ii) it is difficult to predict, which causes uncertainties in decision analysis (de Wit&Augenbroe, 2002). The experience of comfort is individual and subjective and thus it cannot be evaluated explicitly although the distribution of room temperatures and air velocities nowadays can be calculated through simulations (e.g. Yongson et al., 2007).

A simple and traditional method to estimate the thermal comfort of buildings is an empirical relation between room temperature and comfort (e.g. Seppänen, 1996). To achieve this relation, several people have been asked to score their thermal experience according to the scale in Table 3.

Table 3. Scale for the evaluation of thermal experience (Seppänen, 1996).

Scale	Thermal experience
+3	hot
+2	warm
+1	moderately warm (lukewarm)
0	neutral
-1	moderately cool
-2	cool
-3	cold

The result indicates how many test persons find the thermal conditions agreeable. In Fig. 5, test results with the sample of 1000 persons are summarized as an example. For the sake of clarity, only the scores between –1 and +1 have been presented.

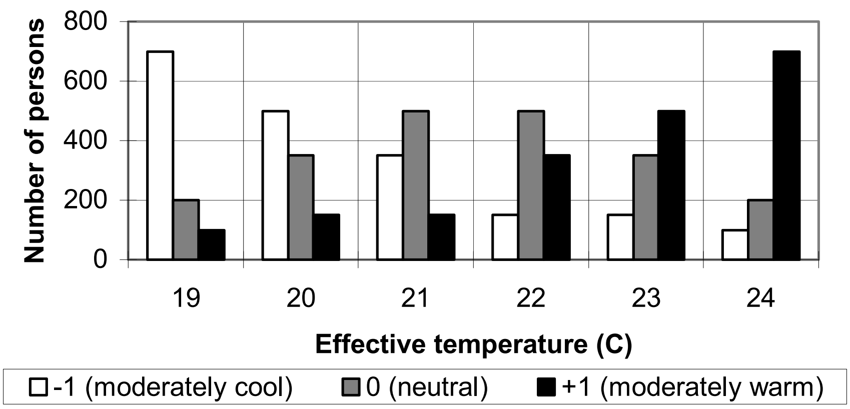

Figure 5. Results from a thermal experience test (Seppänen, 1996).

There are several studies on the dependence of thermal comfort on room temperature, beginning from the early 1970's (Fanger, 1970). The results commonly agree with Fig.5, which makes it justifiable to utilize this information, for example, when the effect of temperature drops on thermal comfort is estimated in decision analyses.

Other issues, such are safety and the appearance of buildings, are mentioned, for example, in the paper of Hsieh et al. (2004), who applied fuzzy approach to the comparison of design alternatives. The safety of known technologies can be derived from statistical information, for example, the average annual number of accidents. In many cases, the best or even the only possible method of evaluation may be an enlightened expert valuation.

3.5 Decision analysis

The above methods help decision-maker to establish sufficient premises for his decision by providing data on different alternatives. The purpose of decision analysis is to help him to make his decision on the basis of that data. According to ISO 14040 standard, the alternatives may be generally regarded as i) product systems[1] or ii) unit processes[2] (ISO, 1997). In this thesis, "unit processes" refer to technological choices made in terms of construction or renovation projects and the "product system" may be seen as a construction project or a building service system (e.g. heating system). Here, the decision-making problem is characterized by i) large set of conflicting objectives and incommensurate attributes, ii) set of conflicting opinions among different interest groups, iii) large amount of mutually compatible or non-compatible technological options among which the optimal combination should be found, and iv) considerable uncertainties linked to the application of new technology (e.g. Andresen (1998), Tanimoto et al. (2001)). The above statements have been established on the basis of the research presented in Papers [I], [II] and [VI]. Furthermore, the decision-making methodology should i) be relatively easy to use, ii) require a moderate amount of computing power, and iii) support interactive decision processes.

Due to the above premises, a general approach to the problem supports the application of multiple criteria decision analysis (MCDA). Value tree analysis has a solid foundation in multi-attribute value theory (MAVT) (Keeney & Raiffa, 1976), which makes the use of value tree analysis justifiable as the decision analytical framework in the present application. Here, the decision-making problem is modeled as a tree (see: Fig. 6) where the top corresponds to overall objectives. The relevant objectives are modeled by attributes. The tree is decomposed into more specific levels, until the level indicateable by means of numerical (or otherwise unambiguous) attributes (twig-level attributes) is reached.

Main objective
(e.g. maximum "value" of a heating system)

Sub-objectives
(e.g. minimum use of natural resources)

Attributes
(e.g. use of abiotic resources)

Indicators
(e.g. kg (gross)m^{-2} a^{-1})

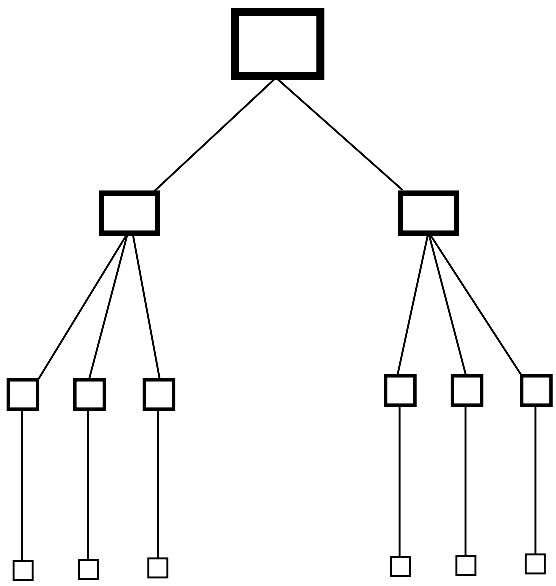

Figure 6. A value tree.

In value tree analysis, the overall value representing the main goal is an aggregate of all the values representing sub-objectives. Generally speaking, the literature recognizes three alternative aggregating models to generate the overall value: i) additive, ii) multiplicative, and iii) multilinear (e.g. Keeney (1974), Dyer et al. (1992)). In this Thesis, multi-criteria models with an additive

[1] Product system is the collection of materially and energetically connected unit processes which perform one or more defined functions (ISO, 1997)
[2] Unit process is the smallest portion of a product system for which data are collected when performing a life cycle assessment (ISO, 1997).

structure are employed. Additive models are the most common applications of multi-attribute value theory, partly because they are transparent and relatively easy to use (Keefer, 2004). The disadvantage of this approach is that attributes with high value compensate those with less value, and vice versa. The suitability of this approach to the present application is discussed later in more detail.

In the additive portfolio model, the value of a construction project is defined as the sum of the values of alternatives that become selected. Thus, we have decision variables $a_1,...a_i,...a_n$ where the i-th alternative represents a subsystem or a measure related to the construction, retrofit or refurbishment project. Here, $a_i = 1$ if decision a_i becomes true, else $a_i = 0$. The objective function is

$$MAX \sum_{i=1}^{n} a_i S_i \ , \qquad (27)$$

where S_i is value added to the project when decision a_i becomes true, i.e. i-th alternative is selected. The problem is formulated subject to at least the constraints

$$a_i \in \{0,1\}$$

$$\sum_{i=1}^{n} a_i C_{I,i} \leq C_{MAX} \ , \qquad (28)$$

where $C_{I,i}$ is the capital cost of i-th alternative and C_{MAX} is the maximum allowable total capital costs of the construction of a retrofit project. Moreover, there may be i) compatibility constraints to determine which alternatives can be technically carried out in the same project, ii) case-based constraints to determine, for example, which alternatives are necessary at the current project to keep the building in an acceptable condition, iii) possible user-defined constraints to determine, for example, minimum required performance levels of selected systems, and iv) possible other constraints to ensure that the requirements of laws or regulations are fulfilled.

In the additive model, the overall value (see: main objective in Fig.6) of i-th alternative (S_i) is defined as the weighted sum of attribute-specific scores:

$$S_i = \sum_{j=1}^{m} w_j s_j \qquad (29)$$

where m is the number of twig-level attributes, w_j is the normalized weight of the j-th attribute, and s_j is the normalized single-attribute score associated with the achievement level of i-th alternative on the j-th attribute.

The relative importance of the j-th attribute is expressed in terms of its normalized weight w_j which lies in the interval [0,1]. In other words, the purpose of weights is to make various attributes commensurate in the eyes of the decision-maker. Hence, w_j=0 corresponds to the situation where the j-th attribute is irrelevant, while w_j=1 is the case where only this attribute matters. Normalized weights add up to one, i.e.,

$$\sum_{j=1}^{m} w_j = 1 \qquad (30)$$

There are several methods to the elicitation of attribute weights. The Analytical Hierarchy Process (AHP) (Saaty, 1980) and SWING are often mentioned (e.g. von Winterfeldt and Edwards, 1986). So called "Grading Method" is recommended by Tanimoto et al. (2001) in the context of residential application because its is relatively simple to use. The procedure commonly starts with selecting the most important attribute (reference attribute), to which, for example, 10 or 100 points are assigned. All the other attributes are then compared to this in accordance with their perceived importance. Finally, the weights are normalized between 0 and 1 so that they add up to unity (see: Eq.(30)).

In the multi-attribute value theory (MAVT), a commensurate value scale is established for each attribute employing normalized single-attribute scores. Basically, the scores can be normalized into whatever range. Here, the least preferred achievement level (i.e. quantitative or qualitative indicator determined for each alternative through operational experience, building simulation etc.) refers to the lowest value of the range and the most preferred to the highest one. The score – also known as value function $s_j(a_j)$, where a_j is the achievement level of an alternative with respect to j-th attribute – may have either linear or non-linear dependence on the corresponding achievement level.

The value function is normalized customarily so that i) the scores referring to the least preferred achievement levels $a_{j,min}$ are set equal to zero, i.e. $s_j(a_{j,min}) = 0$, ii) the scores of the most preferred achievement levels $a_{j,max}$ are mapped to one, i.e. $s_j(a_{j,max}) = 1$. For example, if a linear value function is assumed so that the j-th attribute is directly proportional to the achievement level, the normalized value function for the j-th attribute, $s_j(a_j)$, is calculated from

$$s_j\left(a_j\right) = \frac{a_j - a_{j,\min}}{a_{j,\max} - a_{j,\min}} \qquad (31)$$

where a_j is the achievement level with respect to the j-th attribute, $a_{j,min}$ is the lowest achievement level of all the alternatives with respect to the j-th attribute, and $a_{j,max}$ is the highest achievement level of all the alternatives with respect to the j-th attribute.

Above, single numbers are assigned to both scores and weights, making the approach incapable of handling incomplete information (including uncertainties). Methods to attack this problem have been developed, for example, by Kirkwood & Sarin (1985), Weber (1985), White et al. (1984), Salo & Hämäläinen (1992), and Kim & Han (1999). The application of these methods, however, has been hindered by the lack of appropriate software (Gustafsson et al., 2001).

Here, the multi-criteria decision making (MCDM) method *PAIRS* (Preference Assessment by Imprecise Ratio Statements) is applied (Salo&Hämäläinen, 1992). The method is available as a computer program Winpre©[3] that is capable of handling input and output information in intervals rather than single numerical values (Salo&Hämäläinen (1992) and Lindstedt et al. (2000)).

Based on linear programming, PAIRS determines lower and upper bounds for the overall value (value intervals). Considering n alternatives (1…i…n) and m attributes (1…j…m), the lower bounds for normalized scores are $s_{min,11}\ldots s_{min,ji}\ldots s_{min,mn}$ and the upper bounds $s_{max,11}\ldots s_{max,ji}\ldots s_{max,mn}$. In PAIRS, the upper and lower bounds of attribute weights are defined as

$$L_j \leq \frac{w_j}{w_{ref}} \leq U_j \qquad (32)$$

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

where L_j and U_j are the lower and upper bounds of the above ratio for the *j*-th attribute, respectively, w_j is the normalized weight for the *j*-th attribute and w_{ref} is the normalized weight for the attribute that is considered the most important, $w_{ref} \in [w_1, w_m]$.

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

$$S_i \in \left[\min \sum_{j=1}^{m} w_j s_{\min,ij}, \max \sum_{j=1}^{m} w_j s_{\max,ij} \right] \qquad (33)$$

where the minimization and maximization problems are solved subject to constraints that are imposed on the attribute weights (i.e., non-negativity constraints $w_j \geq 0 \ \forall j$, normalization constraints $\sum_{j=1}^{m} w_j = 1$, and preference statements in Eq. (32)).

The alternatives can be ranked using 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 which case the value intervals of the two alternatives do not overlap. When the value intervals do overlap, then the possible superiority of an alternative can be concluded on the basis of *pairwise dominance* which checks for simultaneous variations in multiple parameters affecting the value function. In this case, the inequalities

$$\max\left(S_B - S_A\right) < 0 \qquad (34)$$

hold and A is preferred to B even if the value intervals overlap.

If the available information does not allow the decision to be reached on the basis of dominance structures, decision rules can be employed (Salo&Hämäläinen, 2001). 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* (the greatest possible loss of value is least for the selected alternative), and (iv) *central values* (choose the alternative for which the midpoint of the value interval lies highest).

4 COMPUTATIONAL STUDIES

The application of decision analysis was demonstrated in two computational studies: i) the valuation of the competitiveness of a solid-oxide fuel cell (SOFC) heating system as the heating alternative of a single-family house (Papers [III]-[V]) and ii) the selection of retrofit actions for a residential building (Paper [VI]). The former represents the multi-attribute technology assessment of single alternatives; the latter is a specified case of portfolio optimization.

4.1 The viability of an SOFC heating system

Although the expectations on fuel cell-based residential micro-cogeneration are high, it has been rarely regarded as a “serious” alternative to traditional heating systems, apparently due to its early phase of commercialization. Moreover, there is a lack of long-term (~30 a) operational experiences on fuel-cell-based micro-cogeneration in residential dwellings. Hence, the evaluation of an SOFC heating system provides both i) an attractive opportunity to a comparison with traditional heating systems and, ii) a good example of technology assessment under uncertainty conditions.

While the computational study was motivated by the conclusion of reviews in Papers [I] and [II], the subject matter was acquired through literature, interviews, cost and weather databases, and energy calculations. The data were collected in 2004 and 2005 in Canada and Finland – for the following reasons. Canada is one of the most potential countries for distributed energy generation because it is a large and sparsely settled country with long distances. Finland is a country with strong traditions of cogeneration and positive opinions towards new energy solutions. On the other hand, there are no Finnish case studies on the viability of SOFC as a heat source for households.

The Canadian study (Paper [III]) investigates the maximum allowable capital cost of an SOFC plant in the sense of system sizing, acceptable payback period, energy price and the electricity buyback strategy of an energy utility. The comparative decision analysis is implemented in the Finnish study (Papers [IV] and [V]). Both countries represent cold climates, wherefore an SOFC plant is considered heating equipment rather than an electricity generation system.

4.1.1 Canadian study (Paper [III])

The Canadian study deals with a two-floor, four-bedroom single-family house as built for the test houses of the Canadian Centre for Housing Technology (CCHT) in Ottawa. The basic data on the house, energy prices in Canada and energy consumptions are presented in Appendix II. The contribution of the Canadian study to this Thesis is to assess the justification of monthly analysis in achieving the energy estimates of an SOFC heating system and to identify a reasonable SOFC system size for decision analysis.

Here, the first assumption was that the operation of a solid-oxide fuel cell could be taken constant throughout the year due to the reasons mentioned by Singhal et al. (2003) (See: Section 3.1.2). The utilizable proportion of input energy is dictated by i) the electrical and overall efficiencies of the system, ii) the electrical and thermal demand profiles of the house and iii) the capacities of electrical grid and heat storage to absorb and release energy according to the demand profile.

The electrical efficiency of a micro-cogeneration plant depends on the technology and load. Hence, if an SOFC plant runs at constant power, then also the electrical efficiency remains constant. Furthermore, the operating temperature and skin losses as well as losses related to exhaust gases, non-reacted fuels etc. remain constant. Thus, it is justifiable to also assume the ratio of thermal output of the plant to the input energy (i.e. the overall efficiency) constant. In Canadian study, the electrical efficiency 36 % and the overall efficiency 82 % were considered reference values. These values are quite theoretical partly because the availability of suitable product data were poor at the moment when the study was done. Here, the electrical efficiency is relatively low with respect to the recently published studies on SOFC plants (e.g. Braun et al., 2005).

The temporal distribution of electrical and thermal surpluses and shortages plays a key role when the financial viability of an SOFC heating system is estimated. Canadian Standards Association (CSA) (CSA, 1999) presents hourly distributions for the use of domestic hot water (DHW) and electricity in single-family houses (Fig. 7).

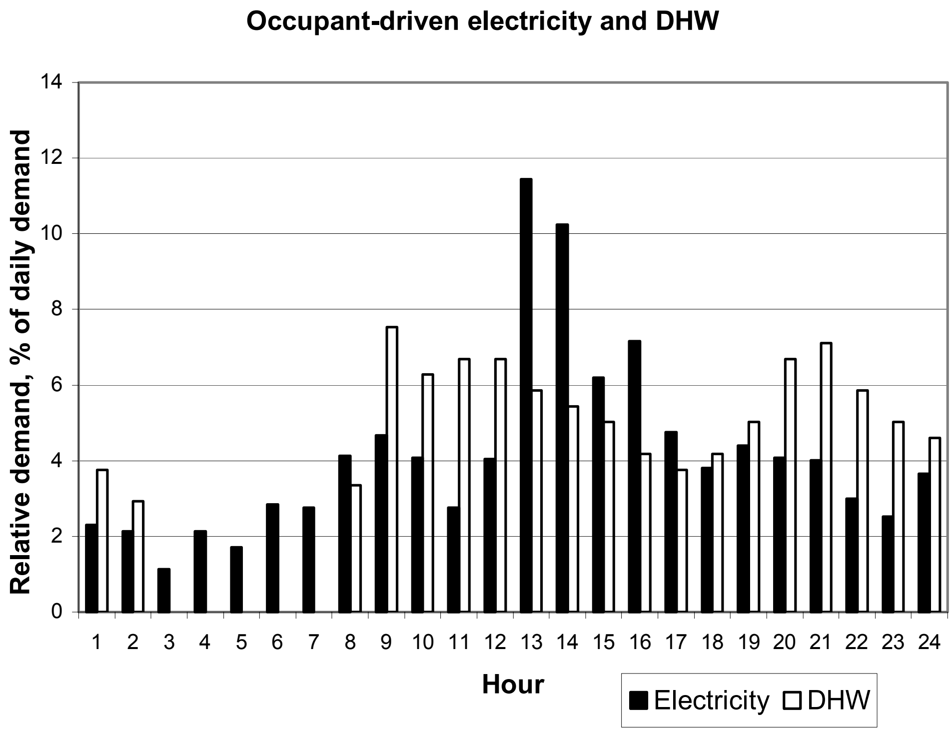

Figure 7. Hourly distribution of electricity and DHW demands in a single-family house (CSA, 1999).

Fig. 7 shows that the hourly variations of both electricity and domestic hot water consumption are significant. In the present decision analytical framework, however, monthly average estimates are suggested for the reasons mentioned in Section 3.1.1, which results in the situation that is illustrated in Fig. 8.

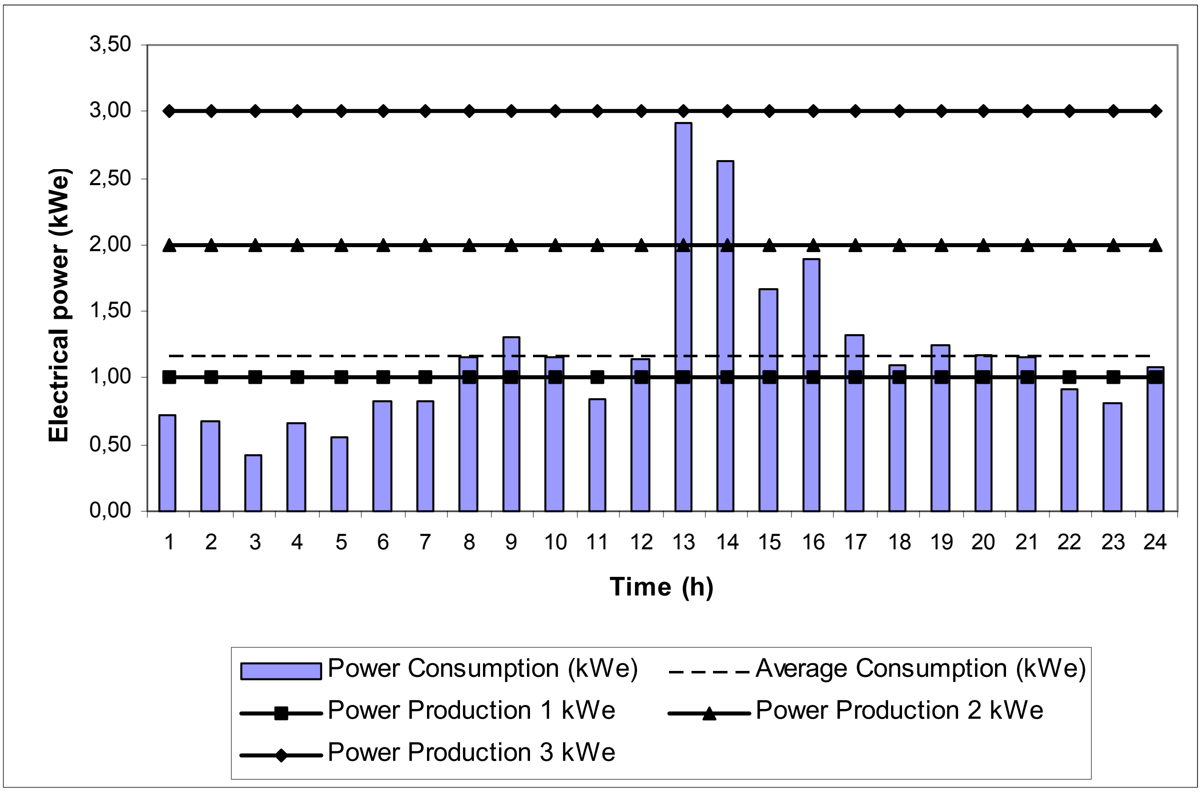

Figure 8. Hourly relation between consumed and produced electrical power (January 1).

Fig. 8 presents the relation between consumed and produced electrical power when a micro-cogeneration system generates electricity at constant power. The daily average consumption of electricity of the case building is also shown. The relative demand of occupant driven electricity (including lighting and appliances) has been used here to convert monthly averages according to consumption profile presented in Fig. 7.

The chart suggests that there would be no need to purchase electricity at all if a 2 kW_e SOFC was applied and the electricity consumption was estimated on the average basis. In fact, however, electricity shortage occurs during the hours 13 and 14. In life cycle cost analysis (LCCA), the effect of this error would be compensated if the retail and buyback prices of electricity were the same. In practice, however, this assumption would be too optimistic in all probability.

For the above reasons, an hourly analysis is strongly recommended for the performance evaluation of SOFC heating systems. Therefore, hourly data on thermal demand should be obtained although the standard method is monthly-based. An improved approach would be to convert monthly thermal demand for space heating to hourly demands by means of "degree hours". The weather file by Canadian Weather for Energy Calculations (CWEC) presents the degree hours that have been applied in Paper [III].

Table 4 illustrates the difference between the time step of one hour and one month in the present analysis. Here, the SOFC plant is run at constant power, which results in that there is no difference in the annual energy characteristics of SOFC between monthly and hourly analyses. The monthly average demands of thermal energy for space heating and the electricity consumption of lighting and appliances also remain the same.

Table 4. Energy consumptions estimated through monthly and hourly analysis.

SOFC	Analysis	Space Heating Load (kWh)	Electrical Demand* (kWh)	Storage losses (kWh)	Thermal Surplus (kWh)	Thermal Shortage (kWh)	Backup Thermal Output (kWh/a)	Backup Input (kWh/a)	Heat sink (kWh/a)	Electricity shortage (kWh/a)	Electricity surplus (kWh/a)
1 kWe	hourly	15421	10485	3316	1211	13739	13575	14634	1047	3135	626
	monthly	15421	10485	3377**	1318	13908	13908	14993	1250	2515	0
2 kWe	hourly	15421	10485	3444	6800	8277	8169	8806	6692	713	6542
	monthly	15421	10485	3377**	6951	8361	8361	9014	6883	0	5825
3 kWe	hourly	15421	10485	3598	13853	4305	3989	4301	13538	51	14193
	monthly	15421	10485	3377**	13820	4050	4050	4366	13752	0	14141

* Represents the monthly average electrical demand of lighting and appliances
** Average storage temperature 85ºC

The data in Table 4 suggests that the use of the thermal backup boiler would be slightly overestimated in monthly analysis. The reason is that a monthly model estimates inaccurately i) the charge and discharge of the heat storage, ii) the impact of storage losses, and iii) the use of hot water with respect to thermal energy received from the SOFC plant. For the reasons mentioned earlier, the monthly model clearly underestimates the annual electrical shortage when the SOFC plant is small (1 kW_e). Otherwise, the differences remain less than 10 %.

It is important to note that the above analysis does not show the monthly evaluation sufficient for decision analysis, but it rather points out problems related to monthly estimates. In the prediction of thermal demands, the justification to use dynamic simulation would be stronger than that of a standard analysis that ignores factors, such as the temporal distribution of internal and solar gains and the operational characteristics of an SOFC plant (Beausoleil-Morrison et al. (2006), Fig. 8 and Hawkes&Leach (2005b)). Taking into account the reasons mentioned in Section 3.1.1, however, the conclusion is that a monthly evaluation is acceptable in the present framework. Moreover, deriving hourly loads from monthly estimates offers an improvement compared to the monthly procedure.

Another key issue in the evaluation of micro-cogeneration systems is non-utilizable thermal energy that will have to be dumped. Thermal energy consumption may be zero in summer when there is neither space heating nor hot water demand. Hence, heat dump is practically unavoidable if an SOFC plant runs at constant power throughout the year. The heat loss could be decreased by a seasonal heat storage that would allow long-term balancing between the supply of and demand for heat. Considering that the maximum allowable size of a heat storage tank in households is 3 m^3, the relation between the size of an SOFC plant, storage tank size and the annual amount of non-utilizable heat (annual heat loss) in the present example, is illustrated in Fig. 9.

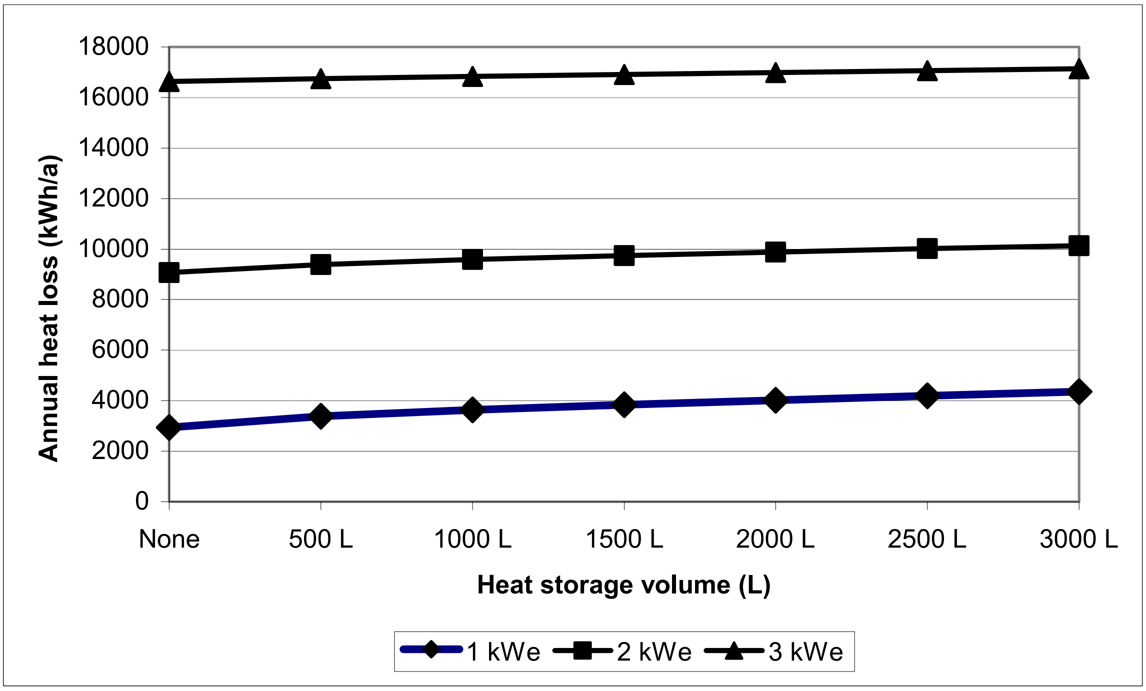

Figure 9. Annual heat loss.

The conclusion about Fig. 9 is that the need of heat dump appears in all system sizes, but it is far more acceptable for 1 kW_e systems than 2 or 3 kW_e systems. In the first case, the heat loss is approximately 3000 kWh a^{-1}, which represents 20 % of thermal energy demand of space heating (15421 kWh a^{-1}). As seen in Fig. 9, the heat storage did not decrease the annual heat loss in the present case, but rather increased it. The explanation would be that the annual skin loss of the tank exceeds the annual amount of thermal energy that can be saved by using the storage. On the other hand, heat storage tanks smaller than 3000 L are too small to work as seasonal heat storages. The work of Zhang et al. (2007), for example, implies that the size of residential seasonal heat storage should be more than 3000 m^3 rather than 3000 L. The use of heat storage tanks may be justifiable, however, because they help cutting short peak thermal demands, which in turn, may allow smaller backup boiler systems.

It is also obvious that a part of storage losses can be utilized as a heat load during the heating period. The combination of 1 kW_e solid-oxide fuel cell plant and 3000 L storage tank, results in the annual storage losses of 3316 kWh a^{-1} (Table 4), which suggests that there is a large potential to utilize storage heat losses in space heating. On the other hand, the situation would change significantly if the fuel cell could be run following the thermal load. These aspects were not studied in the present analysis, however, and the generalization of the above results should be avoided.

One of the major advantages related to residential micro-cogeneration is the local possibility to generate electricity for buildings. Self-sufficiency in the electricity supply may be the aim of a real estate owner, provided that the self-generated electricity remains financially viable. Basically, the larger the system is, the less electricity must be purchased from the grid. On the other hand, the larger the system is, the larger is the amount of electricity that must be either stored or fed into the grid. The relation between the size of an SOFC heating system and the annual electrical shortage and surplus in the present study is illustrated in Fig.10.

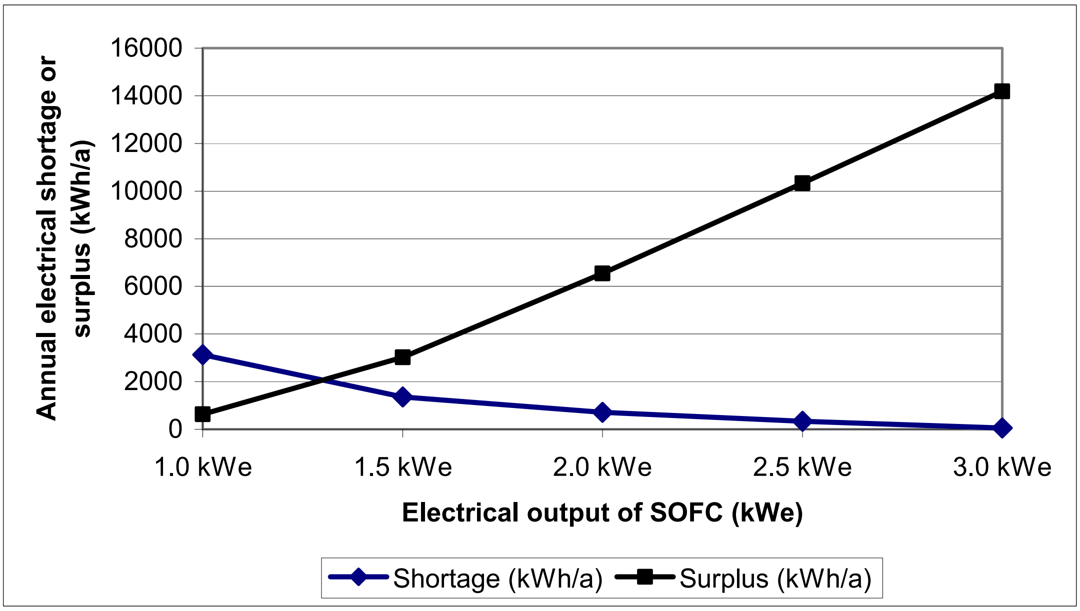

Figure 10. Annual electrical shortage and surplus.

Fig. 10 implies that the complete independency of purchased electricity is achieved, when the plant size 3 kW_e is applied. In practice, this number is too low, however, because there may be peak consumptions that were not revealed by the input data. On the other hand, the situation of equal surplus and shortage (the system is moderately self-sufficient) is achieved already with the system size of approximately 1.3 kW_e.

This application is based on the assumption that the electricity grid is infinite electricity storage; the annual electrical shortage can be always purchased from the grid and the annual surplus of electricity can be fed into the grid. From the point of view of consumers, the above assumption may be exaggerated, because in electrical blackouts, for example, auxiliary power supply such as batteries might be required anyway. Moreover, if the monetary compensation for the electricity fed into the grid was zero, it would be reasonable to keep the amount of surplus electricity small.

Small-scale electricity production should be considered also from the viewpoint of the electrical network, where the penetration of small-scale producers may become an issue. If the penetration was high, then there would be a risk that the production of electricity under a low-voltage network (group of households) exceeds the consumption. The problem occurs if transformers that link medium and low voltage networks cannot adapt to voltage changes – a situation, which is common to conventional transformers (Paatero&Lund, 2007). The assumption of infinite grid is justifiable if the penetration of small-scale producers is small. The work of Fung et al. (2003) suggests that the average standby power requirement in Canada is 49 W. Here, a conclusion could be made that a 1 kW_e SOFC plant would serve the group of about 20 households without the above problems. In a global level the penetration is not a problem. Power plants can be shut down if the production and consumption of electricity threatens to become unbalanced.

The above discussion suggests that a relevant SOFC plant size at the moment would be no more than 3 kW_e. Here, a small system size is also supported by the role of an SOFC plant as a heat source that generates electricity as a "bi-product", primarily for the use of only one household. Moreover, the buyback prices for private producers are not well established at the moment, which concludes that a small cogeneration system would contain fewer risks for real-estate owners who must pay for the fuel, anyway. In conclusion, a 1 kW_e plant has been selected here for further considerations to minimize the annual thermal losses and to justify the assumption of infinite grid.

4.1.2 Finnish study (Papers [IV] and [V])

The Finnish study (papers [IV] and [V]) concerns a low-energy-single-family house with the heated area of 131 m^2. The source (input) data are presented in Table 1 in Appendix III. The study represents the application of decision analysis, where the following heating systems are regarded as alternatives:

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 + 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)

Both life cycle cost and impact assessments are employed to generate input data for the decision analysis. The life cycle costs and environmental burdens related to a residential energy supply system depend on more than one hundred parameters. Here, the relevant parameters were first identified through both a literature research (e.g. Haahtela&Kiiras (2004), Vanhanen et al. (1999)) and reasoning. Moreover, a sensitivity analysis was conducted to omit irrelevant parameters. Secondly, a reference value was assigned to each parameter. To capture uncertainties, reference parameters were converted to intervals. Thirdly, the lower and upper bounds of life cycle costs and environmental burdens were found out to determine the overall effect of uncertainties, using the Solver function of MicroSoft Excel and applying the intervals of parameters as constraints. The results were checked manually. Finally, a multi-attribute decision analysis was carried out to evaluate the viability of an SOFC heating system when the preference statements put weight on the environmental point of view.

The parameters and their intervals were primarily estimated on the basis of the literature (see also: Chapter 2), but also statistical information and interviews were utilized as well as local quotations for price information. Life cycle costs were obtained using the cost database of the Finnish Energy Agency. The annual energy consumptions were estimated following the methodology presented in Chapter 3, employing monthly time step. Here, the estimates are based on the existing version of D5, however, because the calculation was carried out using software provided by Finnish Energy Agency and the updated version was not implemented at the time when the calculations were made. The source data are presented in Tables 2-7 in Appendix III. The selected parameters, their reference values and intervals are summarized in Tables 8 and 9 in Appendix III. The reference energy consumptions, life cycle costs (30 yr) and environmental burdens for each alternative are in Table 5.

Table 5. Reference output for the Finnish study.

System	Annual electricity from the grid (kWh a^{-1})	Annual input energy demand (kWh a^{-1})	Life cycle costs (30 a, 3 %) 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	6200	13100	49000	81	7.5	33	0.11
S2	8400	4700	58200	49	15.8	22	0.07
S3	6200	12500	37600	64	22.6	30	0.10
S4	6200	12000	36700	61	22.0	29	0.10
S5	6200	11000	39300	59	20.8	28	0.09
S6	6300	5600	42200	42	14.4	19	0.06
S7	7500	16000	62400	45	9.1	40	0.07
S8	6300	14200	67500	40	7.7	35	0.06
S9	7500	16000	57500	43	9.0	37	0.10
S10(CHP)	0	18867	57000	25	0.05	30	0.00

In Table 5, the annual input energy demand represents the energy content of fuel or the amount of district heat or electricity that is used for space heating and the production of hot water. According to the Finnish Energy Market Authority, the annual electricity consumption of a typical single-family house with electrical baseboard heating is 18000 kWh a^{-1}. For a low energy house, the input energy demands presented in column 2 in Table 5 are thus reasonable.

The Finnish Energy Market Authority estimates that the annual electricity consumption of a typical single-family house without electrical heating is 5000 kWh a^{-1}. On the other hand, the specific electricity consumption of a single-family house is 50 kWh gross-m^{-2} a^{-1} according to the updated version of D5, which means that the total electricity demand is 7650 kWh a^{-1} in the present case (Ministry of the Environment, 2006). Hence, the electrical demands in the first column of Table 5 can be considered reasonable. The electrical demands account for various electrical demands of ancillaries (e.g. pumps, fans, etc.) and "free" heat (e.g. the use of solar heat) related to different energy supply systems. For example, a part of input energy (column 2) is "converted" into increased electricity consumption (column 1) when a heat pump is applied (S2).

Table 5 implies that there would be no need to purchase electricity from the grid in the case of micro-cogeneration (S10). This conclusion is apparently too optimistic and supports the discussion presented in Section 4.1.1 about the justification of a monthly analysis. Thus, using the reference output in Table 5 to compare an SOFC heating system with other heating options would with all probability lead to incorrect conclusions about the ranking of this alternative. The situation may change, however, if the reference value is considered incomplete (underestimated) as default. The average electrical demand also contains peak consumptions. Moreover, in single-family houses peaks may be somewhat limited or even reduced (e.g. Sidler (2002), Lombard et al. (1999)). For example, there is often only one sauna stove and one kitchen oven in a house and the peaks occur typically in certain times, such as evenings and weekends (Yao&Steemers, (2005), Paatero&Lund (2007)). Therefore, the more the average consumption exceeds the amount of produced electricity, the more probably the average values correspond to the reality. The conclusion is that it would be reasonable to capture this problem by assuming the average electrical demand higher than that suggested by the energy estimation procedure.

The software used to the estimation of energy consumptions can be considered an extra source of error in the present analysis. Without knowing the details of the source code, however, further conclusions cannot be made about the significance of the above issue in the final results. On the other hand, the existing version of D5 provides here a method of energy estimation as "correct" as the new version. Both methods represent monthly-based standard calculation and thus they cannot be considered an optimal choice in the evaluation of micro-cogeneration. For the above reason, the difference between these approaches was not examined in the present study, either.

For the decision analysis, a value-tree-model was formulated using the WinPRE© software as illustrated in Fig. 11.

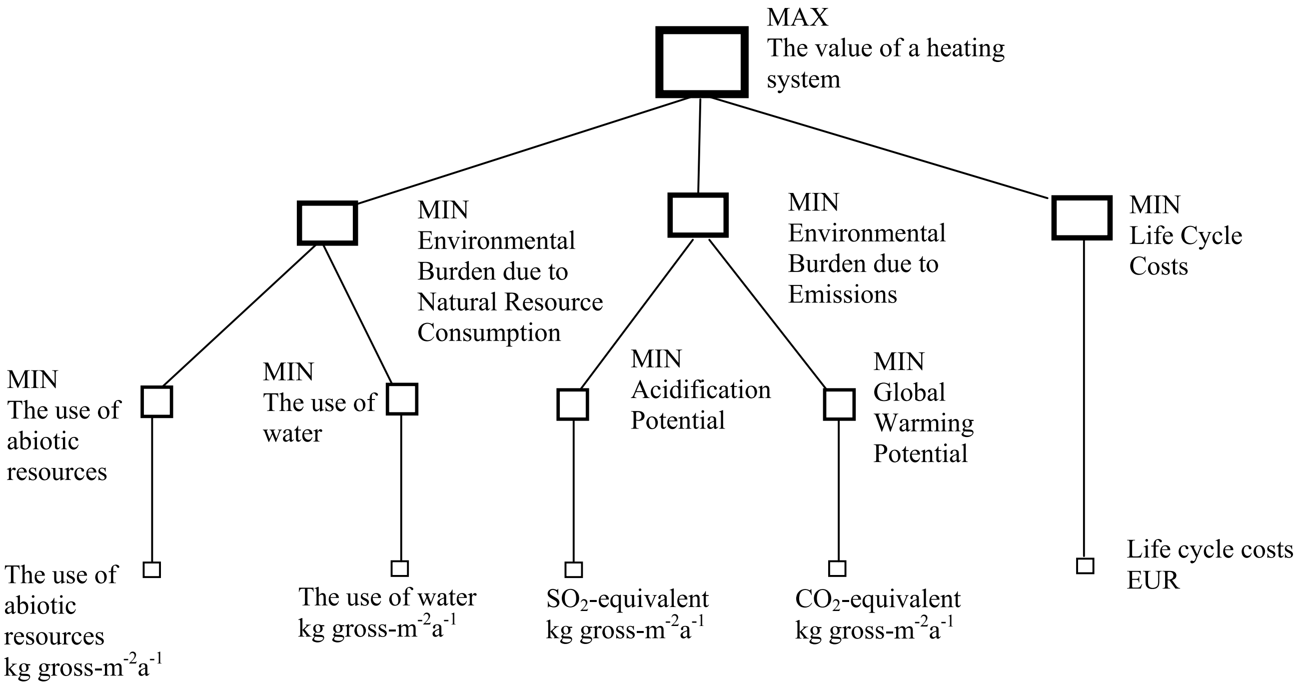

Figure 11. Value tree used in the present model.

Table 6 summarizes the intervals (lower and upper bounds) that were acquired by minimizing and maximizing the life cycle costs (30 a) and environmental burdens of each alternative subject to constraints derived from the intervals of parameters which they depend on (Appendix III: Table 9).

Table 6. Intervals for output values for systems S1-S10.

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	37300...57800	73...89	7…8	27…40	0.088…0.131
S2	46000…67400	45...54	14…17	17…26	0.058…0.086
S3	24900…48100	58...70	20…25	25…37	0.081…0.121
S4	23300...47800	55...67	20…24	24…36	0.078…0.117
S5	26600…49900	53...65	19…23	23…34	0.074…0.111
S6	32300…50100	38…47	13…16	16…24	0.051…0.077
S7	45800…75900	41…49	8…10	32…48	0.057…0.082
S8	52300…79500	36…44	7…8	28…42	0.050…0.071
S9	43400…67800	39…47	8…10	30…44	0.084…0.125
S10(CHP)	44600…85900	23…27	0…0	23…35	0.060…0.091

The data in Table 6 would already as such provide a useful tool to compare various heating systems. Table 6 suggests, for example, that an SOFC heating system (S10) would be the most preferred heating alternative in terms of abiotic resources because the upper bound of abiotic resources (27) is lower than the lower bound of abiotic resources (36) for the second best alternative (S8). A simultaneous comparison in the sense of multiple attributes would be still impossible, because the attributes are not commensurate. Therefore, the normalized score intervals were established by assuming a linear value function between the lowest and highest achievement levels for each attribute (Eq. (31)). Here, for example, the minimum cost in Table 6 (23300 EUR) results in the maximum score (1.00) and the maximum cost (85900 EUR) corresponds the minimum score (0.00). The data used as the input of WinPRE© evaluation is summarized in Table 7.

Table 7. Normalized score intervals for Systems S1-S10.

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

Although the normalized score intervals in Table 7 are dimensionless, they cannot be considered commensurate yet, because the final decision depends on the decision-maker's preferences (weights). Here, the impact of preference data was examined by eliciting weights in the sense of environmental values. This viewpoint is justified by various reasons mentioned throughout this Thesis and, for example, in the work of Zimmermann et al. (2005) concerning the standardization of the design of "green buildings".

The weight intervals were selected on the basis of common sense; by specifying through ratio comparisons how many times more (or less) important one attribute is with regard to another. Fig. 12 illustrates the weight elicitation as a WinPRE© screenshot. For example, the expression "w(LifeCycl)< 0,3 w(Abiotic)" in the first row indicates that life cycle costs have been evaluated less than 0.3 times as important as abiotic resources.

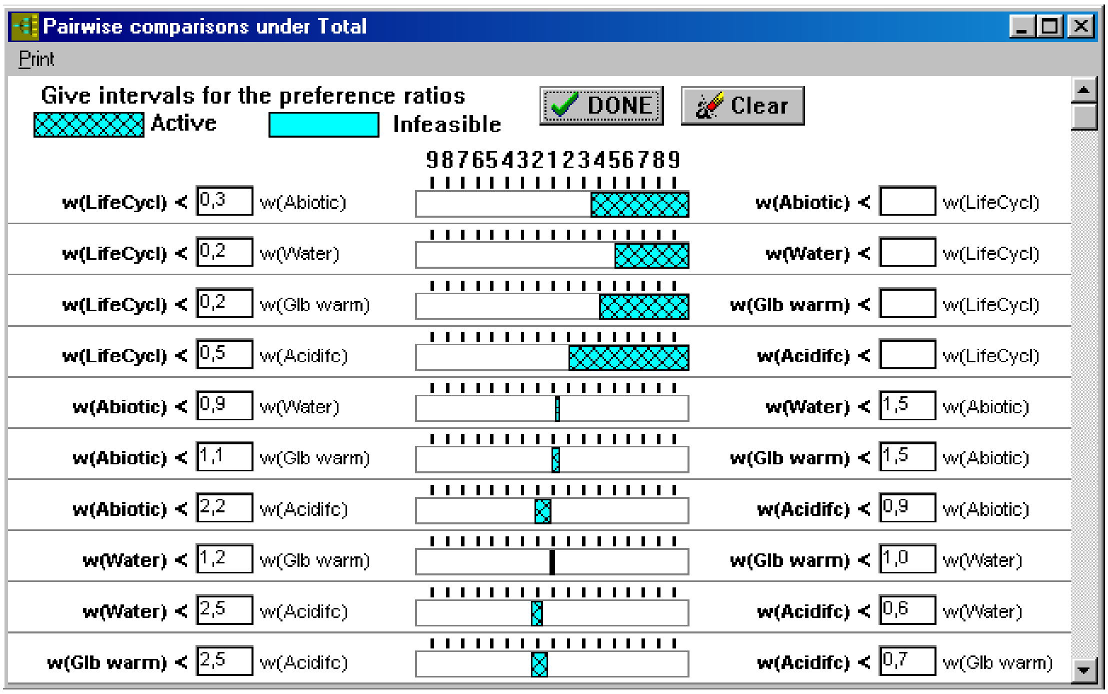

Figure 12. Weight elicitation in the numerical example.

The value intervals and dominance structures are presented as WinPRE© screenshots in Figures 13 and 14, respectively.

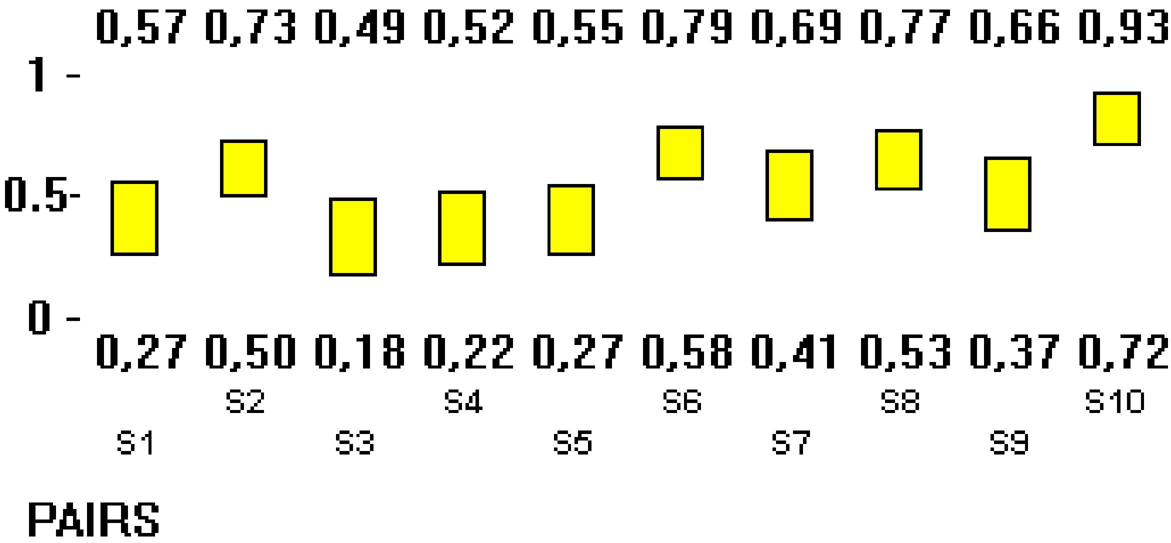

Figure 13. Value intervals for incomplete weight and score information.

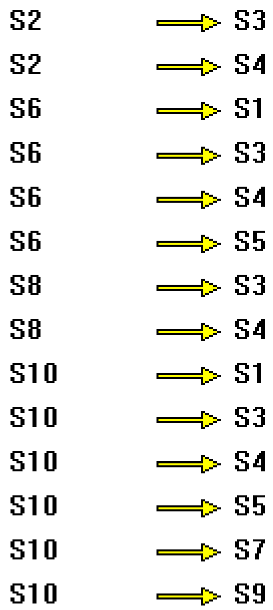

Figure 14. Pairwise dominance for incomplete weight and score information.

The pairwise comparison in Fig. 14 suggests that an SOFC heating system (S10) would be 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 same conclusion can be drawn on the basis of both the *maximin* and *maximax* decision criteria. The selection of ground-source heat pump (S2), electric baseboards with a fireplace, solar heating and air heat pump (S6), or solar-oil heating (S8) is also supported.

The result is not unexpected, taking into account the good performance of an SOFC heating system with respect to environmental attributes (Table 6). Here, the environmental approach does not prefer the use of grid electricity. One explanation may be the large consumption of water in electricity production. The proportion of hydropower in Finland in 2004 was 18 % (Statistics Finland, 2004). The poor overall efficiency of electricity production in conventional plants would be another explanation, which is not probable here because the average efficiency in Finland nowadays is relatively high, more than 65 % (IEA, 2002a).

Although subjectivity is generally regarded as a problem in decision analysis, it may also help a decision-maker to cope with uncertainties. As seen in Table 7, normalized score intervals reveal significant uncertainties related to the life cycle costs of an SOFC heating system, but the overall value intervals in Fig. 13 remain relatively short. This suggests that when the life cycle costs are deemed less important in preference statements, the impacts of changes in cost-related achievement levels also become less significant. This is one of the reasons for why an SOFC heating system performs so well.

In the present application, WinPRE© offered a useful tool for the technology assessment in the sense of multiple attributes. The PAIRS methodology also provides a foundation to the development of new, more specified tools in the field of building technology. In the future applications, the techno-economic environment should be evaluated more comprehensively. Factors such as the usefulness of a complicated system or the availability of fuels should be combined with life cycle cost and impact assessments. A study added by these attributes would obviously give different recommendations.

4.2 The selection of renovation actions (Paper [VI])

In Section 4.1, decision analysis aimed at the comparison of single construction projects on the basis of their overall values. The retrofit of a building can be regarded as a collection of single projects that will improve the functionality of a building. These projects may be anything from installing thermostatic valves into the radiator network to upgrading a natural gas heating system to an SOFC heating system. Therefore, the viewpoint is enlarged to portfolio analysis.

Portfolio analysis can be considered the application of financial modeling where a strategic question is established which projects one should invest in (Sharplin, 1985). If the selection of a retrofit strategy was established as a decision-making problem, the application of portfolio analysis would be an obvious approach. On the other hand, the multi-attribute approach is clearly recommended in the literature (e.g. Häkkinen et al., 2002). Here, the overall value of a retrofit project should be maximized at least in the sense of environmental value and functionality. There are plenty of both methodological approaches and applications of portfolio optimization and they are well documented (e.g. Liesiö et al., 2006), but applications in the above context cannot be found in the recent literature.

The computational study deals with an apartment building located in Kirkkonummi (Finland). The building was constructed in 1983 and it has 29 dwellings in 3 stairways and 3 floors. Alternative technological and operational actions (27) with direct effect on energy efficiency (and thus environment) were studied (Ministry of the Environment, 2000). The source data of the study are presented in Appendix IV in detail.

Here, the overall value of a retrofit project was determined by two attributes (environmental value and functionality), subject to a capital cost constraint and eight other constraints establishing that i) maximum one window type, roof and wall insulation and temperature drop can be selected, ii) flow rate adjustment and economizer jets are mutually exclusive ways of adjustment, iii) flow rate adjustment is necessary, if new water fittings or pressure reductions are installed, and iv) the improvement of lighting control urges on the installation of new light fittings. Additive, linear value functions were given on the scale –10…+10, where –10 represents a significant deterioration and +10 a significant improvement to the present condition with respect to that attribute.

The environmental value can be indicated by CO_2-emission reduction potential. There are two major reasons for this: i) CO_2-emissions relate to one of the main environmental problems – greenhouse effect – and ii) the sum of single CO_2-emission reduction potentials represents relatively well the overall environmental value in an additive model. Reservations such as emissions due to increased fan electricity consumption caused by the pressure loss of heat recovery should be taken into account, anyway. In the present study, the energy saving potential was estimated for each retrofit action and converted to emission reduction potential employing specific emission factors for district heat production (337 kg MWh^{-1}) and electricity production (160 kg MWh^{-1}) (Ministry of the Environment, 2001). A linear value function was assumed so that 20 % cut of the total emissions corresponds to the highest value (10) of the scale –10…+10 [4].

Functionality is a qualitative (immeasurable) and subjective issue, which exposes the evaluation to several uncertainties. Bohanec et al. (1995) suggest an expert system to capture these difficulties in portfolio analyses. Well-established practices and measures in retrofit projects might support the use of a "learning" expert system, meaning that a large database of expert opinions (initial estimates) would be first recorded and the database would be updated on the basis of lessons learned in completed projects. Here, alternative retrofit actions would be evaluated in terms of various issues against the scale –10…+10. At least the following issues should be addressed (e.g. Häkkinen et al., 2002):

1. How easy this retrofit action is to carry out?
2. What is its effect on thermal comfort?
3. What is its effect on the reliability of building services?
4. Does it require other retrofit actions to be useful?
5. Does it presume the application of new technology that is not yet commercially available?
6. What is its space requirement?
7. What is its adaptability to existing structures?
8. What is its impact on the physical characteristics of the building?
9. What is its impact on usability?
10. What is its impact on serviceability?

The above list only contains ten issues related to functionality, which may not be enough. On the other hand, the list contains issues (such as reliability and thermal comfort) that might be indicateable by numerical values and thus be considered separate twig-level attributes as well. Furthermore, it is not clear whether additive model is justifiable in terms of functionality, i.e. whether the functionalities of different retrofit actions can be summed up. For the above reasons, the present method to evaluate functionality is rather illustrative than instructive. Data on the retrofit actions 1-27 are presented in Appendix IV.

In the computational example, both weight information and maximum allowable investment costs were considered incomplete and sensitivity analysis was employed. The optimization model was constructed as presented in Paper [VI], following the principles in Section 3.5. The model was solved using the Solver function of MS Excel. In the sensitivity analysis, maximum allowable investment costs between 10,000 € and 100,000 € were examined, the interval being 10,000 €. Five weight combinations were analyzed: i) completely environmentally oriented case (hundred points were assigned to environmental value, zero points to functionality), ii) slightly environmentally oriented case (hundred points to environmental value, 50 points to functionality), iii) equal importance case (hundred points to both environmental value and functionality), iv) slightly functionality oriented case (hundred points to functionality, 50 points to environmental value), and v) completely functionality oriented case (hundred points to functionality, 50 points to environmental value). The result is shown in the Table 8, indicating the percentage of scenarios (50 scenarios total) in which each alternative was recommended.

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[4] According to Ministry of Trade and Industry (2002), Finland should cut its CO_2 emission rates about 15 % during years 2008-2012.

Table 8. Preferential treatment of each retrofit option.

Retrofit action	Recommended in % of cases
Radiator Network Adjustment, Installation of Thermostatic Valves	90
Flow Rate Adjustment of Water Fittings	64
Improvement of Control of Electrified Parking Space	60
Installation of Peak Power Limit	58
Adding Heat Recovery to Ventilation	50
Installation of New Light Fittings	46
Installation of New Windows: 3x Glass Selective + Argon	44
Installation of Pressure Reducer into Water Distribution System	38
Improvement of Lighting Control	30
Decrease and Adjustment of Indoor Temperatures: -4 C	30
Additional Insulation to Walls: 200 mm	20
Additional Insulation to Roof: 150 mm	18
Installation of Economizer Jets into Water Fittings	16
Installation of New Water Fittings	14
Energy Consumption Measurement into Apartment Level	14
Decrease and Adjustment of Indoor Temperatures: -1 C	12
Installation of New Windows: 3x Glass Selective	6
Water Consumption Measurement into Apartment Level	4
Installation of New Windows: 3x Glass	2
Additional Insulation to Roof: 50 mm	2
Decrease and Adjustment of Indoor Temperatures: -2 C	0
Decrease and Adjustment of Indoor Temperatures: -3 C	0
Additional Insulation to Roof: 100 mm	0
Additional Insulation to Roof: 200 mm	0
Additional Insulation to Walls: 50 mm	0
Additional Insulation to Walls: 100 mm	0
Additional Insulation to Walls: 150 mm	0

As seen in Table 8, the most preferred retrofit actions are the adjustment of radiator network and the flow rate adjustment of water fittings, which can be explained by their good price-quality ratio with respect to both the environmental value and functionality. Additional insulation was not recommended despite energy savings, obviously due to the requirement of structural work and thus relatively high capital costs. The model suggests that the drop of 4 ºC (30 % of cases) in indoor temperatures would be more preferred than the drop of 1 ºC (12 % of cases), implying that the trade-off between energy savings and thermal comfort may be difficult to find. The present model remained small (27 decision variables), although the real number of feasible retrofit scenarios would be much larger. Hence, the methodology can be considered useful in the above application.

Simple software called "System Selection Tool" has been also developed in this Thesis for portfolio optimization (Alanne&Klobut, 2003). The tool allows decision-makers to select retrofit measures applying an expert database. The "before" condition is first described by checking listed technological solutions that best illustrate the present system configuration. Secondly, the relative importance (weights) of 17 twig-level attributes is determined using slide bars. Thirdly, such options are checked on a list that a user wants to be considered alternatives. The program finally prints out the overall values for the five most preferred portfolios and ranks them according to their overall values. Furthermore, the program incorporates tools to update and record pre-defined scores into an expert database. The System Selection Tool is rather simplistic and rigid at the current phase of development, anyway. Specifically, a lot of further work would be required to develop the procedures related to the expert database. Selected screenshots of the System Selection Tool are presented in Appendix V.

5 DISCUSSION

5.1 Main findings

In this Thesis, decision-making problems related to the commercialization of sustainable energy technologies in buildings have been discussed and a methodological framework has been established to evaluate residential energy technologies in terms of multiple attributes under uncertainty conditions. Moreover, two new interdisciplinary applications of multi-attribute decision analysis in the field of residential energy technology have been implemented and illustrated.

This Thesis presents that the above decision-making problem is characterized by: i) a large set of conflicting objectives and incommensurate attributes that arise from the features of sustainable energy system and “green buildings”, ii) several interest groups with various perspectives and thus a large set of conflicting opinions, iii) large amount of mutually compatible or non-compatible technological options among which the optimal combination should be found and iv) uncertainties related to the application of new technology without long-term experiences and the evaluation of the building performance in the pre-design phase. The Thesis suggests that the monthly estimation of energy use, life cycle cost and impact analyses and a multi-attribute decision analysis would form a useful interdisciplinary methodological framework to capture the present problem.

The first application considered the comparison of heating systems for a single-family house in terms of multiple attributes. Specifically, the competitiveness of a natural gas heating system containing a solid-oxide fuel cell (an SOFC heating system) was examined with respect to residential heating systems that incorporate no electricity generation. The numerical results suggested that small (1-2 kW_e) SOFC plants would provide an attractive alternative as the energy source of single-family houses, when environmental factors are emphasized. In the above analysis, the selection of ground-source heat pump, electric baseboards with a fireplace, solar heating and air heat pump, or solar-oil heating was also supported. Monthly energy estimates can be considered acceptable in decision analysis if more accurate data are not available. Managing the surplus heat and electricity is a common problem in micro-cogeneration, but this issue only had a minor impact on the viability of micro-cogeneration in this example due to small plant size. As can be proved, however, the above conclusions are valid only when an SOFC plant is considered the energy source of single-family houses in certain locations and operated at constant power.

WinPRE© provided a useful decision analytical tool to assess residential energy technologies in the sense of multiple attributes. The numerical results imply that decision-maker’s preferences may affect the final selection of a heating system even more than uncertain source data. Eliciting large weight factors on the attributes with narrow confidence intervals clearly decrease the impact of attributes with large confidence intervals. Further conclusions cannot be drawn on the basis of this study, anyway.

The other application considered the selection of retrofit measures as the case of portfolio optimization. In a computational study, a multi-criteria portfolio model was applied to find out the most preferred retrofit actions for a residential building in terms of two attributes: functionality and environmental value. Here, a “learning” expert database was proposed as the source of preference information. The present model proved to be useful in the above task, where the amount of decision variables was limited to 27 although the number of alternative project portfolios would be significantly larger. The numerical results suggest that retrofit measures with a good price-quality ratio would be preferred, such as radiator network adjustment. On the other hand, the trade-off between energy savings and thermal comfort may be difficult to find. Furthermore, simple software called “System Selection Tool” was developed in this Thesis for the above application. The System Selection Tool is at the early phase of development, however, and further efforts are required to make it into a useful decision-making tool.

5.2 Limitations

The first limitation of this Thesis is related to the simplified estimation of energy consumption. Firstly, heat demand is estimated through non-dynamic calculations on monthly basis, ignoring the effect of the temporal distribution of gains, losses and the relation between locally produced and consumed energy. Moreover, the consumption of cooling energy is excluded. The study evaluates the suitability of a monthly model to the present problem but does not show that this approach would be sufficient. In the present model, electricity consumption and some heat losses are estimated through specific values instead of mathematical models for thermodynamic and – chemical processes. Compared to the other limitations this may not be a major issue, however. Secondly, managing the surplus heat and electricity has been simplified in terms of micro-cogeneration. Here, the electric grid is considered ”infinite” electricity storage. On the other hand, no conclusion can be made on the basis of this study on the feasibility of heat storage. This approach does not do justice to micro-cogeneration either, because the utilization of the heat losses of a micro-cogeneration plant is not evaluated.

In life cycle analysis, the limited availability of proper source data in the assessment of new technologies can be seen as a problem. Here, the estimation of life cycle costs and environmental burdens is based on the literature, statistics and expert estimates, which may remain relatively far from data concerning an actual construction project. Moreover, the applications are demonstrated locally and the numerical results on energy consumptions, life cycle costs and environmental impacts are practically valid only for the examined case buildings.

In decision analysis, an additive model is employed to both attributes and alternatives (in the portfolio optimization). This presumes that in decision-maker’s preferences, the low performance in terms of some attributes or alternatives can be compensated by the high performance related to some others and vice versa. The additive model is supported here, for example, because the overall emission reduction potential of a retrofit scenario represents well the sum of the emission reduction potentials of single measures and because functionality and emission reduction potential may be considered separate issues without significant inter-dependencies. But does good ventilation compensate poor heating? Does an emission free fuel cell compensate the long transportation of hydrogen? Do good windows compensate the indoor temperature drop of four degrees? The application of alternative models was not examined here, which can be seen as a limitation. The overall value of alternatives was determined in terms of two attributes only, which suggests that there is still need for further studies.

5.3 Applicability and relevance of the results

The expected audience of this Thesis consists of researchers, building services designers, and political decision-makers. The tools and applications based on this Thesis are especially directed to professional energy guides who introduce customers (real estate owners or designers) the benefits and drawbacks of alternative technologies and practices in the pre-design phase of construction or retrofit projects. The present decision analytical framework can be also utilized in terms of societal embedding (e.g. Väyrynen, 2002) and the energy audits of residential buildings (recommendations for the use of renewable energy sources).

In the commercialization of sustainable energy technologies it is important to encourage real estate owners consider new technologies an alternative to traditional ones. Thus, energy guides should always be “one step ahead”. This Thesis helps fill the lack of tools to assess residential energy technologies with minor experience. One should note, however, that the final evaluation of strengths, opportunities, weaknesses and threats associated with new technology always depends on the judgment of an energy guide.

This Thesis is an application-oriented union of three disciplines: i) energy science, ii) construction economics, and iii) decision analysis. Firstly, the study presents guidelines how a micro-cogeneration system can be modeled in terms of simple, monthly energy estimation procedures. Secondly, this study acknowledges new technologies parallel to traditional ones, emphasizing the viewpoint of private real estate owners in decision-making related to the commercialization of micro-cogeneration technologies – an issue that has been linked mainly to energy industry so far. The computational study may have some value from the viewpoint of the forthcoming versions of the Finnish Construction Cost Database. Thirdly, this Thesis implements theories of multi-attribute decision analysis and portfolio optimization into new fields of application and presents methods and tools to refine the results of energy simulation and life cycle analysis into the form interpretable by persons without education or expertise on energy science or construction economics.

5.4 Implications and future research directions

Two general limitations were identified: i) the estimation of energy consumption is simplified and ii) only minor attention is paid to modeling random phenomena and phenomena that depend on time and location. The Thesis thus opens up several avenues for further research in the field of decision analysis. First, dynamic simulation algorithms could be implemented in the estimation of energy consumption, containing models for new energy technologies. Second, dynamic methods should be employed to "modeling and assessing probabilistic dependence among random variables" (Keefer et al., 2004). A potential field for further research would be the dynamic feasibility analysis of new residential energy technologies, combining measured time series and a statistical forecast for various parameters. This would make it possible to recognize temporal changes in the status of competition and to help identify optimal investment strategies. Thirdly, the applicability of multiplicative (non-compensatory; scores are multiplied by each other) or multilinear (combined additive and multiplicative) models should be examined. The applicability of various portfolio optimization tools (e.g. Robust Portfolio Management (RPM)) in the context of retrofit projects would be also an interesting research topic. From the practical perspective, it is important that the cost and environmental databases are updated by the data on new technologies and that the use and accessibility of databases is improved.

6 SUMMARY

The aim of this Thesis was to identify a decision-making problem related to the commercialization of sustainable energy technologies in buildings and to implement a decision analytical framework in the assessment of energy technologies for residential buildings. The following applications were investigated: i) the assessment of new energy technologies in terms of incomplete preference data and ii) the multi-objective portfolio optimization in the selection of technologies, incorporating mutual interdependencies between alternatives. Both applications were demonstrated through numerical examples. Specifically, the competitiveness of a solid-oxide fuel cell (SOFC) heating system was investigated in a comparison with traditional residential energy supply systems, considering life cycle costs and environmental burdens the evaluation criteria. Moreover, a multi-criteria portfolio model was developed and applied to the selection of retrofit actions for a residential building. Here, the objective was to minimize environmental impacts and to maximize functionality at given maximum allowable capital costs. Simple software called "System Selection Tool" was also developed for the above application.

The decision-making problem arises from the requirements of sustainable energy system and "green buildings", resulting in a multiple attribute decision-making with several alternatives and uncertainties. The evaluation is related to the energy guidance in the pre-design phase of construction or retrofit projects. The Thesis suggests that the monthly estimation of energy use, life cycle cost and impact analyses and a multi-attribute decision analysis would form a useful, interdisciplinary methodological framework to capture the present problem. Furthermore, a "learning" expert database is suggested as the storage and source of preference data that may not have numerical expression.

The numerical results related to the first application imply that small (1-2 kW_e) SOFC plants would provide an attractive alternative as the energy source for Finnish single-family houses, when environmental factors are emphasized. The selection of ground-source heat pump, electric baseboards with a fireplace, solar heating and air heat pump, or solar-oil heating was also supported. Monthly energy estimates can be considered acceptable in decision analysis if more accurate data are not available. The results of decision analysis confirmed that the selection of a heating system finally remains strongly value-based although the source data are exposed to uncertainties. Hence, the final recommendation seems to be more sensitive to the decision-maker's preferences than the uncertainties in the source data. In the selection of retrofit actions, the application of multi-criteria portfolio model allowed to limit the amount of decision variables to 27 although the number of alternative retrofit scenarios would be significantly larger. The numerical results imply that retrofit measures with a good price-quality ratio would be preferred. On the other hand, the trade-off between energy savings and thermal comfort proved to be difficult to find.

The most important contribution of this Thesis is the application of multi-attribute decision analysis methods in new fields of application. Partly due to its interdisciplinary nature, however, a simplified method is implemented in the estimation of energy consumption and only minor attention is paid to modeling random and dynamic phenomena. Therefore, extensions could be made in terms of methodology and also new research topics for the future are suggested. A potential field would be the dynamic feasibility analysis of new residential energy technologies, combining dynamic simulations with models for new energy technologies, measured time series and a statistical forecast for relevant parameters to recognize temporal changes in the status of competition and to help identify optimal investment strategies. From the viewpoint of decision analysis, the applicability of multiplicative or multilinear models and various portfolio optimization tools would be interesting research topics. From the practical perspective, the future updates and improvements of cost and environmental databases may be suggested.

REFERENCES

Alanne, K., Klobut, K. 2003. A decision-making tool to support integration of sustainable technologies in refurbishment projects. *Proceedings of Building Simulation '03 (Eindhoven, Netherlands)*. **1** 55-61.

Ambiente Italia srl, Kraftwärmeanlagen GmbH, Eicher + Pauli AG and CIT Energy Management AB. 2001. Risks and changes for small scale combined heat and power in the liberalized energy market. Final project report, European Comission SAVE Contract: XVII/4.1031/Z/99-063. Brussels, Belgium.

Andresen, I. 1998. Multiple Criteria Decision Analysis (MCDA), A Survey of methods (1st draft). Department of building technology, Faculty of Architecture, Norwegian University of Science and Technology, Trondheim, Norway.

Balaras, C.A., Droutsa, K., Dascalaki, E. and Kontoyiannidis, S. 2005. Heating energy consumption and resulting environmental impact of European apartment buildings. *Energy and Buildings* **37** (5) 429-442.

Beausoleil-Morrison I., Schatz A., Maréchal F. 2006. A Model for Simulating the Thermal and Electrical Production of Small-Scale Solid-Oxide Fuel Cell Cogeneration Systems within Building Simulation Programs. HVAC&R Research **12** (3a) 641-667.

Bohanec, M., Rajkovič, V.**,** Semolič, B. and Pogačnik, A. 1995. Knowledge-based portfolio analysis for project evaluation**.** *Information & Management* **28**(5) 293-302.

Bonser D. 2002. Nuclear Now for Sustainable Development. Annual Symposium 2002. The World Nuclear Association.

Braun, R.J., Klein, S.A. and Reindl, D.T. 2005. Evaluation of system configurations for solid oxide fuel cell-based micro-combined heat and power generators in residential applications. *Journal of Power Sources* **158** (2) 1290-1305.

Bunn, D.W. 1984. Applied decision analysis. McGraw-Hill Publishing Company, New York.

Chen, S.J. and Hwang, C.L. 1992. Fuzzy multiple attribute decision-making. Springer-Verlag, Berlin.

CEN-pre-standard prEN832. Thermal performance of buildings – Calculation of energy use for heating – Residential buildings. Commité Europén de Normalisation, 1992.

European Committee for Standardisation (CEN). EN ISO 13790— thermal performance of buildings—calculation of energy use for space heating; 2004.

Cetiner, I., Özkan, E. 2005. An approach for the evaluation of energy and cost efficiency of glass façades**.** *Energy and Buildings* **37**(6) 673-684.

Citherlet, S. and Defaux, T. 2007. Energy and environmental comparison of three variants of a family house during its whole life span. *Building and Environment* **42**(2) 591-598.

Clemen, R. T. 1996. Making Hard Decisions: An Introduction to Decision Analysis, 2nd ed. Duxbury Press, Belmont, CA.

Collins, T., Parker, S.A., Baxter, V. 2001. Assessment of Hybrid Geothermal Heat Pump Systems, Technology Installation Review. The U.S. Department of Energy (DOE).

Consoli, F., Allen, D., Boustead, I., Fava, J., Franklin, W., Jensen, A.A., de Oude, N., Parris, R., Perriman, R., Postlethwaite, D., Quay, B., Séguin, J. and Vigon, B. (eds.) 1993. Guidelines for life cycle assessment: A = Code of Practice=. Society of Environmental Toxicologicy and Chemistry (SETAC), Brussels.

Canadian Standards Association (CSA). 1999. Standard for Solar Domestic Hot Water Systems, Liquid to Liquid Heat Transfer. CSA f379.1-88 (R-1999).

Dombaycı, Ö.A., Gölcü, M. and Pancar, Y. 2006. Optimization of insulation thickness for external walls using different energy-sources. *Applied Energy* **83** (9) 921-928.

Dorer, V., Weber, R. and Weber, A. 2005. Performance assessment of fuel cell micro-cogeneration systems for residential buildings. *Energy and Buildings* **37** (11) 1132-1146.

Dorre, W.H., Horn, K. and Fiedler, K. 1990. Time budget of young children as a basis fo application to exposure assessment. Ottawa, Ontario, Canada, Canada Mortgage and Housing Corporation (CMHC). *Proceedings of Indoor Air '90 (Toronto)* **2** 525-530.

Dunn S. 2002. Hydrogen futures: toward a sustainable energy system. *International Journal of Hydrogen Energy* **27**(3) 235-264.

Dyer, J.S., Fishburn, P.C., Steuer, R.E., 1992. Multiple criteria decision making, multiattribute utility theory - The next ten years. *Management Science* **38** (5) 645.

Entchev, E., Gusdorf, J., Swinton, M., Bell, M., Szadkowski, F., Kalbfleisch, W. and Marchand, R. 2004. Micro-generation technology assessment for housing technology. *Energy and Buildings,* **36** (9) 925-931.

Ericsson, K., Huttunen, S., Nilsson, L.J. and Svenningsson, P. 2004. Bioenergy policy and market development in Finland and Sweden. *Energy Policy* **32**(15) 1707-1721.

Fanger, P.O. 1970. Thermal comfort: analysis and applications in environmental engineering. Danish Technical Press, Copenhagen, Denmark.

Ferguson, A. and Ugursal, V.I. 2004. Fuel cell modeling for building cogeneration applications. *Journal of Power Sources* **137** (1) 30-42.

Flanagan, R., Norman, G., Meadows, J. and Robinson, G. 1989. Life cycle costing, Theory and practice. Oxford: BSB Professional Books.

Fung, A.S., Aulenback, A., Ferguson, A. and Ugursal, V.I. 2003. Standby power requirements of household appliances in Canada**.** *Energy and Buildings* **35**(2) 217-228.

Granovskii, M., Dincer, I. and Rosen, M.A. 2006. Life cycle assessment of hydrogen fuel cell and gasoline vehicles. *International Journal of Hydrogen Energy* **31** (3) 337-352.

Gustafsson, J., Salo, A. and Gustafsson, T. 2001. PRIME Decisions: An Interactive Tool for Value Tree Analysis. Multiple Criteria Decision-Making in the New Millennium, Lecture Notes in Economics and Mathematical Systems 507. Springer-Verlag, Berlin, pp. 165-176.

Haahtela, Y. and Kiiras, J. 2004. Talonrakennuksen kustannustieto 2004 (Database for Construction Cost Estimation) (in Finnish). Haahtela-kehitys Oy, Tampere.

Hawkes, A.D., Aguiar, P., Hernandez-Aramburo, C.A., Leach, M.A., Brandon, N.P., Green, T.C. and Adjiman, C.S. 2006. Techno-economic modelling of a solid oxide fuel cell stack for micro combined heat and power. *Journal of Power Sources* **156** (2) 321-333.

Hawkes, A. and Leach, M. 2005a. Solid oxide fuel cell systems for residential micro-combined heat and power in the UK: Key economic drivers. *Journal of Power Sources* **149** 72-83.

Hawkes, A. and Leach, M. 2005b. Impacts of temporal precision in optimisation modelling of micro-Combined Heat and Power. *Energy* **30** (10) 1759-1779.

Hawkes, A.D., Aguiar, P., Croxford, P., Leach, M.A., Adjiman, C.S. and Brandon, N.P. 2006. Solid oxide fuel cell micro combined heat and power system operating strategy: Options for provision of residential space and water heating. *Journal of Power Sources* [In Press].

Heijungs, R., Huppes, G., Lankreijer, R. M., Udo De Haes, H. A., Wegener, Sleeswijk, A., Ansems, A. M. M., Eggels, P. G., Van Duin, R. and De Goede, H. P. 1992. Environmental life cycle assessment of products. Guide LCA. CML Leiden, the Netherlands.

Hellgren, J. 2005. Life cycle cost analysis of a car, a city bus and an intercity bus powertrain for year 2005 and 2020. *Energy Policy* In Press (Corrected Proof).

Henninger, R.H., Witte, M.J. and Crawley, D.B. 2004. Analytical and comparative testing of EnergyPlus using IEA HVAC BESTEST E100–E200 test suite. *Energy and Buildings* **36** 855-863.

Hensen, J. 1991. On the thermal interaction of building structure and heating and ventilating systems, Doctoral thesis, Technische Universiteit Eindhoven, Netherlands, 1991.

Hsieh, Ting-Ya, Lu, Shih-Tong and Tzeng, Gwo-Hshiung. 2004. Fuzzy MCDM approach for planning and design tenders selection in public office buildings. *International Journal of Project Management* **22**(7) 573-584.

Huovila, P., Sunikka, M., Leinonen, J. and Nieminen, J. 1999. Multi-Criteria Decision-Making (MCDM) using EcoProP,QFD and MCDM-23. VTT Building Technology, Espoo.

Häkkinen, T., Huovila, P., Tattari, K., Vares, S., Seppälä, J., Koskela, S., Leivonen, J., Pylkkö, T. 2002. Rakennus- ja kiinteistöalan ekotehokkuus (in Finnish). Ministry of the Environment. Helsinki, 2002.

IEA, 2002a. Energy Balances of OECD Countries 1999–2000 (2002 edition). Paris: OECD, International Energy Agency. (Electrical Database)

IPCC, 2001. Climate Change 2001: The Scientific Basis Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, Cambridge University Press.

Isherwood, W., Smith, J.R., Aceves, S.M., Berry, G., Clark, W., Johnson, R., Das, D., Goering, D., and Seifert, R. 2000. Remote power systems with advanced storage technologies for Alaskan villages. *Energy* **25** (10) 1005-1020.

ISO (International Organization for Standardization). 1997. ISO 14040: Environmental management – Life Cycle Assessment – Principles and framework. International Organization for Standardization, Geneva.

Judcoff, R., Wortman, B., O'Doherty, B. and Burch, J. 1983. A methodology for validating building energy analysis simulations, SERI/TR-254-1508, Solar Energy Research Institute, Golden, CO, 1983.

Keefer, D.L., Kirkwood, C.W. and Corner, J.L. 2004. Perspective on Decision Analysis Applications 1990–2001. *Decision Analysis* **1** (1) 4-22.

Keeney, R.L. and Raiffa, H. 1976. Decisions with multiple objectives: Preferences and value trade-offs. John Wiley & Sons, New York.

Keeney, R.L., 1974. Multiplicative utility functions. Operations Research **22** 22-34.

Kelly, N. and Cockroft, J. 2006. A comparative assessment of future heat and power sources for the UK domestic sector. *Energy Conversion and Management* **47** (15-16) 2349-2360.

Kim, S.H. and Han, C.H. 1999. An Interactive Procedure for Multiattribute Group Decision Making with Incomplete Information. *Computers & Operations Research* **26** 755-772.

Kirkwood, C.W. and Sarin, R.K. 1985. Ranking with Partial Information: A Method and an Application. *Operations Research* **33** 38-48.

Kirkwood, C.W. 1997. Strategic Decision Making: Multiobjective Decision Analysis with Spreadsheets. Duxbury Press, Belmont, CA.

Kosonen, R., Laitinen, A., Laine, T., Martiskainen, V. 1999. Huonekohtaisten talotekniikkajärjestelmien elinkaarikustannukset [Life cycle costs of HVAC systems]. VTT Research Notes 1947. VTT Building and Transport, Espoo. (in Finnish)

Leitch, R.A., Davis, K.R. 1992. Accounting Information Systems. Theory and Practice. Prentice-Hall International Inc.

Liesiö, J., Mild, P., Salo, A. 2006. Preference Programming for Robust Portfolio Modeling and Project Selection, *European Journal of Operational Research (to appear).*

Lindstedt, M.R.K., Hämäläinen, R.P. and Mustajoki, J. 2000. Using Intervals for Global Sensitivity Analyses in Multi-attribute Value Trees. Proceedings of the 15th International Conference on Multiple-Criteria Decision-Making.

Lombard, C., Mathews, E.H. and Kleingeld, M. 1999. Demand-Side Management through thermal efficiency in South African houses. *Energy and Buildings* **29**(3) 229-239.

Loutzenhiser, P.G., Manz, H., Felsmann, C., Strachan, P.A., Frank, T. and Maxwell, G.M. 2006. Empirical validation of models to compute solar irradiance on inclined surfaces for building energy simulation. *Solar Energy (in Press).*

Manczyk, H. 2003. Life Cycle Cost Analysis: Selection of Heating Equipment, Manczyk Energy Consulting. Available at: http://www.energy.rochester.edu/efficiency/Life_cycle_cost_analysis.pdf

Ministry of the Environment. 2000. Energy saving potential in residential buildings - preliminary study (in Finnish).

Ministry of the Environment. 2001. National Climate Program - Sectoral Statement (in Finnish).

Ministry of the Environment. 2006. Section D5 of the National Building Code of Finland – Calculation of performance and energy requirement for the heating of buildings (Draft: February17, 2006).

Ministry of Trade and Industry. 2002. Energy Review 1/2002 (in Finnish).

Nilsson, L.J., Pisarek, M., Buriak, J. Oniszk-Popławska, A., Bućko, P., Ericsson, K. and Jaworski, L. 2006. Energy policy and the role of bioenergy in Poland. *Energy Policy* **34** (15) 2263-2278.

Ossebaard, M.E., Van Wijk, Ad J. M. and Van Wees, M.T. 1997. Heat supply in the netherlands: A systems analysis of costs, exergy efficiency, CO_2 and NO_x emissions. *Energy* **22** (11) 1087-1098.

Paatero, J.V. and Lund, P.D. 2007. Effects of large-scale photovoltaic power integration on electricity distribution networks.

Papamichael, K. 1999. Application of information technologies in building design decisions. *Building research and information* **27** (1) 20-34.

Pavlovas, V. 2004. Demand controlled ventilation A case study for existing Swedish multifamily buildings. *Energy and Buildings* **36** (10) 1029-1034.

Peacock, A.D. and Newborough, M. 2005. Impact of micro-CHP systems on domestic sector CO_2 emissions. *Applied Thermal Engineering* **25** (17-18), 2653-2676.

Prek, M. 2004. Environmental impact and life cycle assessment of heating and air conditioning systems, a simplified case study. *Energy and Buildings* **36** (10) 1021-1027.

Raab, S., Mangold, D., Müller-Steinhagen, H. 2005. Validation of a computer model for solar assisted district heating systems with seasonal hot water heat store. *Solar Energy* **79** 531-543.

Riihimäki, M. and Mikkola, K. 2001. The willingness of a builder of a detached house to ecological ways of building (in Finnish). VTT Building and Transport, Tampere.

Saaty, T.L. 1980. The analytical hierarchy process. McGraw Hill, New York.

Salo, A. and Hämäläinen, R.P. 1992. Preference Assessment by Imprecise Ratio Statements. *Operations Research* **40** 1053-1061.

Salo, A. and Hämäläinen, R.P. 2001. Preference Ratios in Multiattribute Evaluation (PRIME) - Elicitation and Decision Procedures under Incomplete Information. *IEEE Transactions on Systems, Man, and Cybernetics* **31** (6) 533-545.

Schmidt-Bleek, F. 1998. Das MIPS-Konzept: weniger Naturverbrauch-mehr Lebensqualität durch Faktor 10 (The MIPS-concept: Factor 10 for less nature consumption and more quality of life). München: Droemersche Verlaganstalt.

Seppälä, J. 2003. Life cycle impact assessment based on decision analysis (Doctoral Thesis). Finnish Environment Institute, Helsinki.

Seppänen, O. 1996. Ilmastointitekniikka ja sisäilmasto [Air conditioning technology and indoor air]. Kirjapaino Kiitorata Oy, Helsinki [in Finnish].

Sharplin, A. 1985. Strategic management, McGraw-Hill.

Sidler, O. 2002. Demand side management. End-use metering campaign in 400 households of the European Community. SAVE Programme, Project EURECO France: Commission of the European Communities.

Singhal, S.C. and Kendall, K. 2003. High Temperature Solid Oxide Fuel Cells – Fundamentals, Design and Applications. Elsevier.

Sinivuori, P. and Saari, A. 2006. MIPS analysis of natural resource consumption in two university buildings. *Building and Environment* **41** (5) 657-668.

Soebarto, V.I. and Williamson, T.J. 2001. Multi-criteria assessment of building performance: theory and implementation. *Building and Environment* **36** (6) 681-690.

Statistics Finland. 2004. Production of electricity and heat in 2004. Available at: http://www.stat.fi/til/salatuo/2004/salatuo_2004_2006-06-16_kat_001_en.html

Statistics Finland. 2006. Final energy consumption by sector 2005. Available at: http://www.stat.fi/til/ekul/2005/ekul_2005_2006-12-08_kuv_003_en.html

Tanimoto, J., Chimklai, P., Balcomb, D., Andresen, I., Aggerholm, S. 2001. Multi-criteria Decision-making MCDM-23, A Method for specifying and prioritising criteria and goals in design (Draft). International Energy Agency Solar Heating and Cooling.

Tuomaala, P. 2002. Implementation and evaluation of air flow and heat transfer routines for building simulation tools. Doctoral thesis. VTT Building and Transport, Espoo, Finland.

Valkiainen, M., Klobut, K., Leppäniemi, S., Vanhanen, J. and Varila, R. 2002. Micro CHP Systems based on PEM fuel cell. Status report (in Finnish). VTT Tiedotteita-Meddelanden-Research Notes:2055, Finland: VTT Chemical Technology, Espoo. ISBN 951-38-5804-9

Vanhanen, J. and Loimaranta, O. 1999. Micro and Mini CHP. Technology and market review. Final Report (in Finnish). Otaniemi Consulting Group Oy, Helsinki.

von Winterfeldt, D., Edwards, W. 1986. *Decision Analysis and Behavioral Research*, Cambridge University Press, Cambridge, UK.

Väyrynen E., Kivisaari S., Lovio R. 2002. Societal embedding of innovations related to renewable energies and energy saving. An article in "Technology and climate change CLIMTECH 1999-2002, Final report". Technology programme report 14/2002. Soimakallio, Sampo & Savolainen, Ilkka (eds.). Tekes, the National Technology Agency . Helsinki. 235 – 244.

Watson, H. and Hatchman, J.C. 1997. Design of a prototype fuel cells/composite cycle power station. *Proceedings of the I MECH E Part A Journal of Power and Energy* **23** 171-180.

Weber, M. 1985. A Method of Multiattribute Decision Making with Incomplete Information. Management Science **34** 431-445.

White III, C.C., Sage, A.P. and Dozono, S. 1984. A Model of Multiattribute Decision-Making and Trade-Off Determination Under Uncertainty. *IEEE Transactions on Systems, Man, and Cybernetics* **14** (2) 223-229.

Yao, R., Steemers, K. 2005. A method of formulating energy load profile for domestic buildings in the UK. *Energy and Buildings* **37**(6) 663-671.

Yongson, O., Badruddin, I.A., Zainal, Z.A., Aswatha Narayana P.A. 2007. Airflow analysis in an air conditioning room**.** *Building and Environment* **42**(3) 1531-1537.

Zhang, H.-F., Ge, X.-S. and Ye, H. 2007. Modeling of a space heating and cooling system with seasonal energy storage. *Energy* **32**(1) 51-58.

Zimmermann M., Althaus, H.-J. and Haas, A. 2005. Benchmarks for sustainable construction: A contribution to develop a standard**.** *Energy and Buildings* **37**(11) 1147-1157.

APPENDIX I: The estimation of energy consumption of a building according to D5

Heat loss of spaces through envelope

The heat loss through envelope (Q_{env}) is

$$Q_{env} = 0.001 \cdot \sum_j U_j A_j \left(T_i - T_o\right) \Delta t \qquad (1)$$

where U_j is the thermal conductance for the *j-th* building component (W mK^{-2}), A_j is the area of the *j-th* building component (m^2), T_i is the indoor temperature (ºC), T_o is the average outdoor temperature (ºC), Δt is the length of time period (h), and 0.001 is the conversion factor that is used to convert watts (W) to kilowatts (kW).

If the *j-th* building component is not bounded directly by outdoor air, T_i -T_o in Eq. (1) is substituted by a reduced temperature difference. This can be taken, for example, 20 % less than T_i -T_o, if the *j-th* building component is represented by a ventilated floor structure with ventilation openings representing maximum 8 % of the area of the floor.

Heat loss of spaces through ventilation and air leakages

Both the heat losses through air leakages (Q_{leak}) and ventilation (Q_{vent}) can be calculated from

$$Q = 0.001 \cdot \rho_a c_{pa} q_V \theta \left(1 - \eta_{hr}\right)\left(T_i - T_o\right) \Delta t \qquad (2)$$

where ρ_a is the density of air (1.2 kg m^{-3}), c_{pa} is the specific heat capacity of air in constant pressure (1006 Ws kg^{-1}K^{-1}), q_V is the air flow (m^3 s^{-1}), T_i is the indoor temperature (ºC), T_o is the average outdoor temperature (ºC), Δt is the length of time period (h), 0.001 is the conversion factor that is used to convert watts (W) to kilowatts (kW), η_{hr} is the (annual) efficiency of heat recovery, and θ is a factor that takes into account the effect of operation hours of the ventilation system.

Here, the (annual) efficiency of heat recovery (η_{hr}) is defined as

$$\eta_{hr} = \frac{\sum\left(\left(T_i - T_{exh}\right)\Delta t\right)}{\sum\left(\left(T_i - T_o\right)\Delta t\right)} \qquad (3)$$

where T_{exh} is the exhaust air temperature after heat recovery (ºC).

For the estimation of the heat loss through air leaks (Q_{leak}), q_V equals to the leak air flow ($q_{V,leak}$) that is given by

$$q_{V,leak} = \frac{n_{leak} V}{3600} \qquad (4)$$

where n_{leak} is the air leak factor (1/h, expresses how many times per hour the total air volume of a building is substituted by fresh air), and V is the volume of a building (m^3). If the actual air leak factor n_{leak} is not known, the default value of 0.2 1/h can be used according to D5. Moreover, $\eta_{hr} = 0$ and $\theta = 1$.

In the estimation of heat losses through ventilation (Q_{vent}) q_V equals to the exhaust airflow. If the ventilation operates continuously *and* the outdoor temperature remains constant throughout a day, then $\theta = 1$. Otherwise, θ is calculated from

$$\theta = \theta_w \theta_d \theta_r \qquad (5)$$

where θ_w is the number of weekly operation hours of the ventilation system (d/week), θ_d is the number of diurnal operation hours of the ventilation system (h/d), and θ_r is the factor that takes into account the diurnal variations of outdoor temperatures.

θ_r is calculated by means of the table of "reduced hours". Here, the effect of the diurnal variations of outdoor temperatures on the heat demand are taken into account by conceiving that an "hour" is kind of "longer" during night than it is during day. The table of reduced hours for Helsinki, based on the statistics of year 1979 and the indoor temperature of 21 ºC is illustrated below.

Table1. Reduced hours for Helsinki (1979) for the estimation of θ_r.

	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Jan	0.00	1.03	2.06	3.09	4.12	5.15	6.18	7.20	8.22	9.22	10.22	11.21	12.20
Feb	0.00	1.02	2.05	3.09	4.13	5.18	6.23	7.29	8.35	9.39	10.42	11.43	12.41
Mar	0.00	1.02	2.05	3.08	4.12	5.16	6.21	7.25	8.29	9.31	10.32	11.31	12.29
Apr	0.00	1.11	2.24	3.37	4.52	5.68	6.81	7.91	8.97	9.98	10.95	11.88	12.78
May	0.00	1.34	2.73	4.14	5.58	7.04	8.39	9.62	10.73	11.73	12.62	13.39	14.10
Jun	0.00	1.71	3.58	5.46	7.34	9.22	10.87	12.28	13.44	14.41	15.17	15.74	16.19
Jul	0.00	1.36	2.76	4.17	5.58	6.99	8.28	9.44	10.47	11.40	12.22	12.94	13.64
Aug	0.00	1.50	3.08	4.67	6.29	7.92	9.38	10.67	11.78	12.70	13.43	13.98	14.46
Sep	0.00	1.17	2.37	3.59	4.83	6.10	7.31	8.46	9.56	10.56	11.48	12.30	13.09
Oct	0.00	1.05	2.11	3.18	4.25	5.33	6.40	7.47	8.54	9.56	10.54	11.47	12.38
Nov	0.00	1.01	2.02	3.04	4.05	5.06	6.07	7.09	8.12	9.13	10.14	11.14	12.12
Dec	0.00	1.02	2.03	3.05	4.05	5.06	6.06	7.06	8.06	9.06	10.06	11.05	12.03
	12	13	14	15	16	17	18	19	20	21	22	23	24
Jan	12.20	13.17	14.14	15.11	16.08	17.05	18.02	19.00	19.99	20.98	21.98	22.99	24.00
Feb	12.41	13.36	14.29	15.22	16.15	17.09	18.04	19.01	20.00	20.99	21.99	22.99	24.00
Mar	12.29	13.25	14.19	15.14	16.08	17.02	17.98	18.96	19.95	20.95	21.96	22.98	24.00
Apr	12.78	13.65	14.50	15.34	16.18	17.02	17.90	18.83	19.80	20.80	21.84	22.91	24.00
May	14.10	14.75	15.35	15.95	16.55	17.15	17.84	18.62	19.50	20.47	21.56	22.75	24.00
Jun	16.19	16.55	16.80	17.05	17.30	17.56	17.93	18.40	18.99	19.86	21.00	22.41	24.00
Jul	13.64	14.30	14.93	15.57	16.24	16.92	17.68	18.50	19.40	20.40	21.51	22.73	24.00
Aug	14.46	14.87	15.22	15.60	16.01	16.46	17.06	17.82	18.74	19.83	21.08	22.51	24.00
Sep	13.09	13.85	14.58	15.32	16.07	16.84	17.68	18.61	19.61	20.65	21.73	22.85	24.00
Oct	12.38	13.28	14.15	15.04	15.94	16.86	17.81	18.79	19.79	20.82	21.87	22.93	24.00
Nov	12.12	13.10	14.06	15.03	16.00	16.99	17.97	18.97	19.97	20.98	21.98	22.99	24.00
Dec	12.03	13.00	13.96	14.94	15.93	16.93	17.93	18.94	19.95	20.96	21.97	22.99	24.00

For example, if the ventilation operates between "real" hours 6 and 18 in April, the real number of operational hours is 18 - 6 = 12. As seen in Table 1, the reduced hours are 6.81 and 17.9 and the reduced number of operational hours is 17.9 - 6.81 = 11.09 h. Now, $\theta_r = 11.09/12 = 0.924$.

Heat demand of domestic hot water system

The net heat demand (without losses) for the domestic hot water system (Q_{DHW}) is

$$Q_{DHW} = \frac{1}{3600} \cdot \rho_w c_{pw} V_{hw,spec} n \left(T_{hw} - T_{cw} \right) \Delta t = \frac{1}{3600} \cdot \rho_w c_{pw} V_{hw,spec} A_{gr} \left(T_{hw} - T_{cw} \right) \Delta t \qquad (6)$$

where ρ_w is the density of water (1000 kg m^{-3}), c_{pw} is the specific heat capacity of water in constant pressure (4.2 kJ kg^{-1}K^{-1}), $V_{hw,spec}$ is the specific hot water demand (m^3 m^{-2},a or m^3 person^{-1}, d), n is the number of persons in the building (if known), A_{gr} is the gross area of the building (m^2, applied if number of persons is not known), T_{hw} is the hot water temperature (55 ºC), T_{cw} is the cold water temperature (5 ºC), Δt is length of time period (d), and 3600 is the conversion factor that is used to convert hours (h) to seconds (s). Specific hot water demands for different building types are summarized in Table 2.

Table2. Specific hot water demands.

Building type	**dm^3 person^{-1}, d**	**m^3 m^{-2},a**
Residential buildings	50	600
Office	-	100
Hospital	-	520
Nursery	-	460
Library	-	120
Swimming hall	-	1200
School	-	180
Shop	-	65

Heat loss of heating system

If the heating system is known in detail, the heat loss of space heating ($Q_{l,hd}$) can be estimated by modelling the heat transfer for each component to the ambience, regarding the total heat loss as the sum of generation losses, distribution losses, transfer losses, and control losses. Otherwise, specific annual loss factors (kWh per gross m^2 of the building) can be used for each type of losses, as summarized in Table 3.

Table 3. Specific annual loss factors for space heating.

Heat distribution system	**Specific loss factor (kWh per gross m^2)**				
	Generation	Distribution	Transfer	Control	Total
Radiators (water circulation), 70/40	2	20	4	2	28
Floor heating (water circulation), 40/35	2	5	10	4	21
Electric baseboards	0	0	4	1	5
Electrical floor heating	0	0	10	4	14

Specific annual losses are distributed throughout a year, assuming that 15 % of annual losses is directed to November, December, January and February, 10 % to October, March, April, and 5 % to May, September. In June, July and August the losses are 0 %.

The heat loss of DHW heating ($Q_{l,DHW}$) is the sum of generation losses, storage losses, and circulation losses. Generation losses are generally included into the generation losses of space heating and they are not estimated separately for the DHW system. Storage and circulation losses are calculated using specific annual loss factors (kWh per gross m^2 of the building) that are assumed equal and constant for each month. Specific heat loss factors for DHW in residential buildings are presented in Table 4.

Table 4. Specific heat loss factors for DHW heating (Temperature drop 5 ºC (55 ºC -> 50 ºC)).

	kWh per gross m^2	**kWh a^{-1}**
Circulation loss, circulation takes DHW's heat to equipment (radiators etc.)	30	-
Circulation loss, circulation does not take DHW's heat to equipment	15	-
Only distribution (no circulation)	2	-
Specific tank loss, 50 dm^3 tank	-	440
Specific tank loss, 300 dm^3 tank	-	1300
Specific tank loss, 750 dm^3 tank	-	1900

Electricity consumption

If the lighting and ventilation systems and appliances are known in detail,

- the electricity consumption of lighting (W_l) can be estimated on the basis of the room-specific requirement of lighting
- the electricity consumption of ventilation (W_{vent}) can be estimated for each ventilation fan on the basis of their specific curves
- the electricity consumption of appliances (W_{app}) can be estimated for each application on the basis of their specific data.

Otherwise, the above electricity consumptions are calculated using specific electricity consumptions (kWh per gross m^2 of the building). The specific electricity consumptions for lighting, ventilation and appliances classified according to different building types, are given in Table 5.

Table 5. Specific electricity consumptions for lighting, ventilation, and appliances.

Building type	**Lighting kWh per gross m^2**	**Ventilation kWh per gross m^2**	**Appliances kWh per gross m^2**	**Total kWh per gross m^2**
Single-family dwelling	7	6	37	50
School	23	12	25	60
Office	30	11	29	70
Rowhouse	7	6	57	70
Apartment building	7	6	67	80
Hospital	60	28	12	100
Hotel	60	17	33	110
Restaurant	42	36	32	110

Heat loads

If the number of persons and the time they spend in a building are known in detail, the heat load released by persons (Q_{pers}) can be estimated assuming that the specific heat released by one person is 70 W on average. Otherwise, the specific heat released by persons (kWh per gross m^2 of the building) is used. Specific heat loads released by persons are presented in Table 6.

Table 6. Specific heat loads of persons in different building types.

Building type	**kWh per gross m^2**
Single-family dwelling	8
Office	10
Rowhouse	11
Apartment building	17
Hotel	18
Restaurant	38
School	58
Hospital	70

The estimation of heat load caused by the heating system ($Q_{l,DHW,hl}$ + $Q_{l,hd,hl}$) is based on the assumption that the proportion of heat loads is 70 % of the heat losses of space heating ($Q_{l,hd}$), 30 % of the net heat demand for DHW (Q_{DHW}) and 50 % of the heat losses of DHW heating ($Q_{l,DHW}$).

If the characteristics of electrical appliances are known in detail, the heat load from electrical appliances ($Q_{l,ele,hl}$) can be defined by modelling the heat transfer from applications to the environment. Otherwise, the specific heat load of electrical appliances (kWh per gross m^2 of the building) is used. Specific heat loads from lighting, ventilation and electrical appliances are summarized in Table 7.

Table 7. Specific heat loads of electrical appliances in different building types.

Building type	**kWh per gross m^2**
Single-family dwelling	32
Rowhouse	44
School	44
Apartment building	50
Office	53
Restaurant	79
Hospital	81
Hotel	88

The heat load caused by solar radiation through windows (Q_{sol}) is calculated from

$$Q_{sol} = G_{rad} \sum_i F_{ori,i} F_{pene,i} A_i g_i \qquad (7)$$

where G_{rad} is the solar radiation to horizontal surface (kWh m^{-2} $month^{-1}$), $F_{ori,i}$ is the conversion factor that takes into account the conversion from horizontal to vertical surface, $F_{pene,i}$ and g_i are the penetration factors, and A_i is the area of the i-th window (m^2).

Numerical values for G_{rad} and $F_{ori,i}$ (three different window orientations) are presented in Table 8. Here, the solar radiation to horizontal surface represents the weather information of Helsinki (1979).

Table 8. Numerical values for G_{rad} and $F_{ori,i}$.

Month	G_{rad}	$F_{ori,i}$		
		North	East and West	South
Jan	7.1	0.29	0.57	3.14
Feb	27.9	0.29	0.79	2.14
Mar	55.2	0.29	0.71	1.29
Apr	103.7	0.29	0.57	0.93
May	167.8	0.29	0.57	0.64
Jun	195.2	0.29	0.57	0.57
Jul	131.7	0.29	0.64	0.57
Aug	130.6	0.29	0.71	0.79
Sep	72.1	0.29	0.64	1.14
Oct	33.2	0.29	0.57	2.00
Nov	6.9	0.29	0.50	3.43
Dec	4.7	0.29	0.43	3.57

Furthermore, the heat load caused by solar radiation through windows depends on

- window frames
- features of the glass
- curtains
- shadowings (trees, other buildings)

The penetration factor (g_i) illustrates the relation between radiation penetration and the type of the window. Table 9 presents g-values for selected windows.

Table 9. Numerical values for g_i.

Window type	g_i
Single-glass window	0.77
Double-glass window	0.68
Triple-glass window	0.63
Triple-glass window with low-emissivity surface	0.45
Solar-protecting window	0.18

If detailed information on window frames, shadowings and curtains is available, the penetration factor of the i-th window ($F_{pene,i}$) is calculated from

$$F_{pene,i} = F_{frame} F_{curtain} F_{shadow} \qquad (8)$$

where F_{frame} is the ratio of the area of window opening to the area of window opening and frame, $F_{curtain}$ is a factor ($\in$ [0,1]) that takes into account the effect of curtains assigned to the i-th window, and F_{shadow} is a factor ($\in$ [0,1]) that depends on shadowing angles and orientations of the i-th window. If detailed information is not available and there are no significant shadowings and permanent curtains, the penetration factor can be taken $F_{pene,i} = 0.75$.

Total heat load is now

$$Q_{hl} = Q_{pers} + Q_{l,DHW,hl} + Q_{l,hd,hl} + Q_{ele,hl} + Q_{sol} \qquad (9)$$

where Q_{pers} is the heat load released by persons, $Q_{l,DHW,hl}$ is the heat load caused by DHW heating system (30 % of the net heat demand for DHW plus 50 % of the heat losses of DHW heating), $Q_{l,hd,hl}$ is the heat load caused by space heating system (70 % the heat losses of space heating), $Q_{l,ele,hl}$) is the heat load from electrical appliances, and Q_{sol} is the solar radiation energy through windows.

Utilizable heat loads

The first presumption for the utilization of heat loads is that heat demand exists, i.e. the sum of heat losses exceeds the sum of heat loads. Secondly, the heating system must be operated so that the effect of heat loads is taken into account. The utilizable heat load ($Q_{hl,\ util}$) is calculated from

$$Q_{hl,util} = \eta_{hl} Q_{hl} \qquad (10)$$

where Q_{hl} is the total heat load and η_{hl} is the degree of heat load utilization. The theoretical maximum is that all the heat loads can be utilized, i.e. $Q_{hl,\ util} = Q_{hl}$ and $\eta_{hl} = 1$. The degree of heat load utilization depends on both the ratio of heat loads to heat losses and heat capacity of the building. The following expression has been given for the degree of heat load utilization in D5:

$$\eta_{hl} = \frac{1 - \left(\dfrac{Q_{hl}}{Q_{loss}} \right)^{\left(1+\frac{\tau}{15}\right)}}{1 - \left(\dfrac{Q_{hl}}{Q_{loss}} \right)^{\left(1+\frac{\tau}{15}\right)+1}} \qquad (11)$$

where Q_{loss} is the total heat loss, i.e. the sum of heat losses of envelope, air leaks and ventilation reduced by the heat released by the air heater of the ventilation system and τ is a time constant that takes into account the heat capacity of the building.

The sum of heat losses through envelope, air leaks and ventilation reduced by the heat released by the air heater of the ventilation system is calculated from

$$Q_{loss} = Q_{env} + Q_{vent} + Q_{leak} - Q_{h,vent} \qquad (12)$$

where Q_{env} is the heat loss through envelope, Q_{leak} is the heat loss caused by air leaks, Q_{vent} is the heat loss caused by ventilation, and $Q_{h,vent}$ is the heat released by air heater. The heat demand of the air heater of ventilation ($Q_{h,vent}$) can be estimated by applying the expression (2), where q_V is now substituted by supply air flow ($q_{V,sup}$), T_i by the supply air temperature (T_{sup}), and T_o by the temperature after heat recovery (T_{hr}).

The time constant is defined as

$$\tau = \frac{0.001 \cdot C_{bui} \left(T_i - T_o \right) \Delta t}{Q_{loss}} \qquad (13)$$

where C_{bui} is the effective indoor heat capacity of the building (Wh K^{-1}) and Δt is the length of time period (h). Effective indoor heat capacities for various building types are given in Table 10.

Table 10. Effective indoor heat capacities for various building types.

Building type	**Effective indoor heat capacity (Wh m^{-3}K^{-1})**
Single-family dwellings	30
Rowhouses	30
Apartment buildings	50
Hospitals	40
Other buildings	40

APPENDIX II: Source information for the Canadian study.

The case building is a two-floor, four-bedroom single-family house with the heated area of 240 m^2, including the basement, as built for the test houses of the Canadian Centre for Housing Technology (CCHT) in Ottawa. The house has been designed following the requirements of the R-2000 energy efficiency standard[1]. The building is equipped with a high-efficiency gas furnace (efficiency 93 %[2]) and a forced air heating system plus an SOFC plant with 3000 L heat storage tank. Monthly thermal demands have been estimated using HOT2000 software[3].

Table 1. Energy prices in Ottawa and Vancouver.

	Ottawa	**Vancouver**
Electricity, C$ kWh^{-1}	0.110	0.069
Gas, C$ kWh^{-1}	0.053	0.049
Oil, C$ kWh^{-1}	0.061	0.061

Table 2. Energy consumption of the building estimated by the HOT2000 software.

	Gas furnace	**Oil furnace**	**Electric furnace**
Space heating (kWh a^{-1})	15421	15589	15319
DHW heating (kWh a^{-1})	4474	4474	4474
Total input energy (kWh a^{-1})	24207	26317	20476
Total electricity* (kWh a^{-1})	10779	10760	10808

* The work of Clement (1991)[4] suggests that the error between HOT2000 estimates and measured energy consumptions would be –18.6 % (underestimates energy consumption).
** Does not include electricity used to heating in the case of electric furnace.

Table 3. Energy profiles estimated using the HOT2000 tool and a separate SOFC analysis.

	1 kW_e	**2 kW_e**	**3 kW_e**	**4 kW_e**	**5 kW_e**
SOFC electrical output (kWh a^{-1})	8760	17520	26280	35040	43800
SOFC thermal output (kWh a^{-1})	11180	22359	33539	44719	55898
SOFC input energy (kWh a^{-1})	24172	48344	72517	96689	120861
Backup thermal output (kWh a^{-1})	13943	8467	4253	1616	349
Backup input energy (kWh a^{-1})	15031	9127	4585	1742	376
Total input energy (kWh a^{-1})	39203	57472	77101	98431	121237
Total electrical input (kWh a^{-1})	11276	11679	12143	12618	13120
Electrical shortage (kWh a^{-1})	3140	714	51	0	0
Electrical excess (kWh a^{-1})	624	6536	14188	22422	30680
NET electricity (kWh a^{-1})	-2516	5823	14137	22422	30680

[1] R-2000 is a series of technical requirements for new home performance to improve the energy efficiency and the reduction of greenhouse gas emissions in Canada's new housing stock.

[2] Condensing furnace, the efficiency is defined as the ratio of the thermal output to the chemical energy content of the fuel, expressed by its higher heating value (HHV).

[3] Available at: http://www.buildingsgroup.nrcan.gc.ca/software/hot2000 e.html.

[4] Clement, Y.S. Li. 1991. Model[l]ing and evaluation of the energy consumption of R-2000 houses. Master's Thesis. Technical university of Nova Scotia, Halifax, Canada.

APPENDIX III: Source information for the Finnish study.

Table 1. Characteristics of the single-family house investigated in the Finnish study[5].

Feature	Value
Location	Helsinki
Gross volume, m^3	514
Heated volume, m^3	327
Habitable area, m^2	131
Gross area, m^2	153
Inhabitants	2 adults + 2 children
U-value, envelope, $W\ m^{-2}K^{-1}$	0.14
U-value, roof, $W\ m^{-2}K^{-1}$	0.1
U-value, floor, $W\ m^{-2}K^{-1}$	0.15
U-value, windows, $W\ m^{-2}K^{-1}$	1
U-value, doors, $W\ m^{-2}K^{-1}$	0.5

Table 2. Reference energy prices (January, 2006)[1].

Energy price	EUR kWh^{-1}	Fixed, EUR a^{-1}
District heat	0.038	250
Natural Gas	0.025	340
Pellet	0.031	0
Wooden fuel	0.039	0
Electricity (baseboard heating)	0.075	125
Electricity (floor heating)	0.068	125
Electricity (lighting, appliances)	0.096	55
Oil	0.056	0

Table 3. Weight factors for the calculation of CO_2 and SO_2 equivalents.

GWP (CO_2 equivalent)	RTS[6]	IPCC[7]
CO_2	1.00	1.00
CH_4	24.50	23.00
N_20	320.00	296.00
AP (SO2 equivalent)		
SO_2	1.00	
NO	1.07	
NO_2	0.70	
NO_x	0.70	
NH_3	1.88	
HCl	0.88	
HF	1.60	

[5] The data is provided by the Finnish Energy Agency: http://www.motiva.fi
[6] The data is provided by the Building Information Foundation (RTS)
[7] The data is provided by the Intergovernmental Panel on Climate Change (IPCC)

Table 4. MI factors for construction materials and energy[8].

Material	Abiotic (kg kg^{-1})	Biotic (kg kg^{-1})	Water (kg kg^{-1})	Air (kg kg^{-1})
Copper	348.47	0.00	367.20	1.6
Steel	7.63	0.00	56.00	0.41
Aluminium	18.98	0.00	539.20	5.91
Class Wool	4.66	0.00	46.00	1.8
Rock Wool	4.00	0.00	39.70	1.69
Polyethylene (PE)	2.49	0.00	122.20	1.62
Polyurethane (PUR)	6.31	0.00	505.10	3.56
Polypropylene (PP)	4.24	0.00	205.50	3.37
Polycarbonate (PC)	6.94	0.00	212.20	4.70
ABS	3.97	0.00	206.90	3.75
Brick	2.11	0.00	5.70	0.047
Cement	2.22	0.00	21.30	0.25
Concrete	1.33	0.00	3.40	0.04
Gravel (fillings)[a]	1.00	0.00	0.03	0.00
Polystyrene	2.51	0.00	164.00	2.80
Wood	0.86	5.51	10.00	0.13
Gypsum	1.83	0.00	10.30	0.06
Energy	**Abiotic (kg kWh^{-1})**	**Biotic (kg kWh^{-1})**	**Water (kg kWh^{-}**	**Air (kg kWh^{-1})**
Oil	0.11	0.00	0.79	0.27
District heat[b]	0.65	0.00	1.06	0.40
Electricity[b]	0.50	0.00	186.04	0.21
Natural gas	0.11	0.00	0.04	0.32
Hydrogen[c]	0.08	0.00	2.83	0.02
Methanol[c]	0.30	0.00	0.81	0.70

a Transport 10 km
b Finnish energy system
c The production and delivery of hydrogen and methanol not included

Table 5. Carbon and sulphur dioxide equivalents for construction materials and energy[8].

Material	CO_2 equivalent (kg CO_2 kg^{-1})	SO_2 equivalent (g SO_2 kg^{-1})
Copper	2.8	9.9
Steel	0.9	1.6
Aluminium	4.5	26.5
Class Wool	0.8	3.3
Rock Wool	1.4	2.1
Polyethylene (PE)	2.4	27.1
Polyurethane (PUR)	4.2	30.6
Polypropylene (PP)	4.5	45.9
Polycarbonate (PC)	5.4	25.3
ABS	3.3	17.7
Brick	0.2	0.6
Brickwork Mortar	0.1	0.4
Concrete	0.3	1.1
Gravel (fillings)[a]	0.0025	0.026
Polystyrene	-	-
Wood	0.6	0.0
Gypsum	4.9	0.8
Energy	**CO_2 equivalent (kg CO_2 kWh^{-}**	**SO_2 equivalent (g SO_2 kWh^{-}**
Residential Heating Oil[b]	0.264	0.257
District heat[c]	0.269	0.875
Electricity[c]	0.247	0.811
Natural gas[b]	0.236	0.600
Methanol[b,d]	0.248	-

a Transport 10 km
b kWh of fuel
c Finnish energy system
d Only the emissions released in the chemical reaction included

[8] The data is provided by the Wuppertal Institute.

Table 6. Estimated composition for the components of a heat distribution system[9].

	Weight (kg)	Steel (kg)	PE (kg)	ABS (kg)	Other (kg)
Radiators					
Pressure vessel	6	6			
Piping	308	308			
Radiators	557	557			
Floor heating					
Pressure vessel	6	6			
Piping	84	1	70	3	10
Electric baseboard heating					
Electric baseboards	393	393			

Table 7. Estimated life-cycle information for the components of a heating system[10].

Energy conversion	Life span, a	Service, h a^{-1}	Capital cost, EUR $(unit)^{-1}$
Oil reservoir	40 – 50	0.4	430 (A)
Oil (or gas) boiler	25 – 30	4	7.6 (B)
Ground source heat pump	20 – 25	4	12.5 (B)
Seasonal heat storage tank	30 – 40	0.25	-
DHW tank	30 – 40	0.25	-
Piping	50	-	-
Pump	15 – 20	0.25	-
Solar Collectors	30	-	-
District heating heat exchanger	30 – 40	0.5	5.0 (B)
SOFC power module	15 – 20	2 – 4	25 (C)
Heat Distribution			
Pressure vessel	20	0.1	-
Pump	15 – 20	0.25	-
Piping (radiator heating)	50	-	-
Piping (floor heating)	40 – 50	-	30 (D)
Radiators	50	0.5	-
Electrical baseboards	25 – 30	0.5	-
Structures			
Fire Place	100	-	-
Chimney	100	1	-

A the unit is the volume of the reservoir, m^3
B the unit is the volume of the building, m^3
C the unit is the volume of the building, m^3 (1 kW_e system, 8000 EUR)
D the unit is the floor heating area, m^2 (includes piping plus auxiliaries)

[9] The data is provided by the Technical Research Centre of Finland (VTT).
[10] The information in Table 7 has been collected through consultations with various suppliers of energy systems, life cycle experts, designers and contractors. The capital costs refer to Helsinki region in 2004.

Table 8. Reference input parameters for the Finnish study[11].

Parameter	MIN
Electricity demand, error-%	0
Primary energy demand, error-%	0
Discount rate, %	3
Price of district heat, error-%	0
Price of natural gas, error-%	0
Price of electricity, error-%	0
Price of oil, error-%	0
The buyback price of electricity, %[A]	0
Investment support, %[B]	0
The unit price of a SOFC plant, EUR	5000
SOFC service costs, EUR a^{-1}	0
SOFC maintenance costs, EUR a^{-1}	250
SOFC total efficiency, %	80
Life span error, a	0
Material use, error-%	0
Abiotic material input factor, error-%	0
Biotic material input factor, error-%	0
Material input factor of water, error-%	0
Material input factor of air, error-%	0
Global Warming Potential, error-%	0
Acidification Potential, error-%	0

Table 9. Intervals for input parameters for the Finnish study.

	Parameter	MIN	MAX
Energy Use [A]	Electricity demand, error-% [B]	-10	+10
	Input energy demand, error-%	-10	+10
Economic parameters	Discount rate, % [C]	2	6
	Price of district heat, error-%	-5	+5
	Price of natural gas, error-%	-5	+5
	Price of electricity, error-%	-10	+10
	Price of oil, error-%	-10	+10
	The buyback price of electricity, %[D]	0	100
	Investment support, %[E]	0	50
	The unit price of a SOFC plant, EUR	5000	8000
	SOFC service costs, EUR a^{-1}	0	160[F]
	SOFC maintenance costs, EUR a^{-1}	200	500
Technological parameters	SOFC total efficiency, %	75	85
	Life span error, a	-5	5
Material use	Material use, error-%	-5	+5
	Abiotic material input factor, error-%	-20	+20
	Biotic material input factor, error-%	0	0
	Material input factor of water, error-%	-30	+30
	Material input factor of air, error-%	-15	+15
Emissions	Global Warming Potential, error-%	-10	+10
	Acidification Potential, error-%	-10	+10

A The estimation of energy consumption is based on the existing version of D5.

B This percentage indicates how much the "probable" energy consumptions, prices and environmental parameters deviate from the reference values in Table 8.

C Only one discount, based on real interest rate, is applied to all prices to avoid the use of many discount rates. It is implicitly assumed, however, that the annual rise of energy prices exceeds overall inflation by 1 % at the most.

D expressed as the ratio of the buyback price and retail price of electricity

E the percentage of the capital costs of a micro-CHP plant

F the estimate of Finnish Energy Agency for the annual service cost of a heat conversion system in a Finnish single-family house.

[11] The information in Tables 8 and 9 presumes that the location, size, and operational strategy of a SOFC plant are fixed.

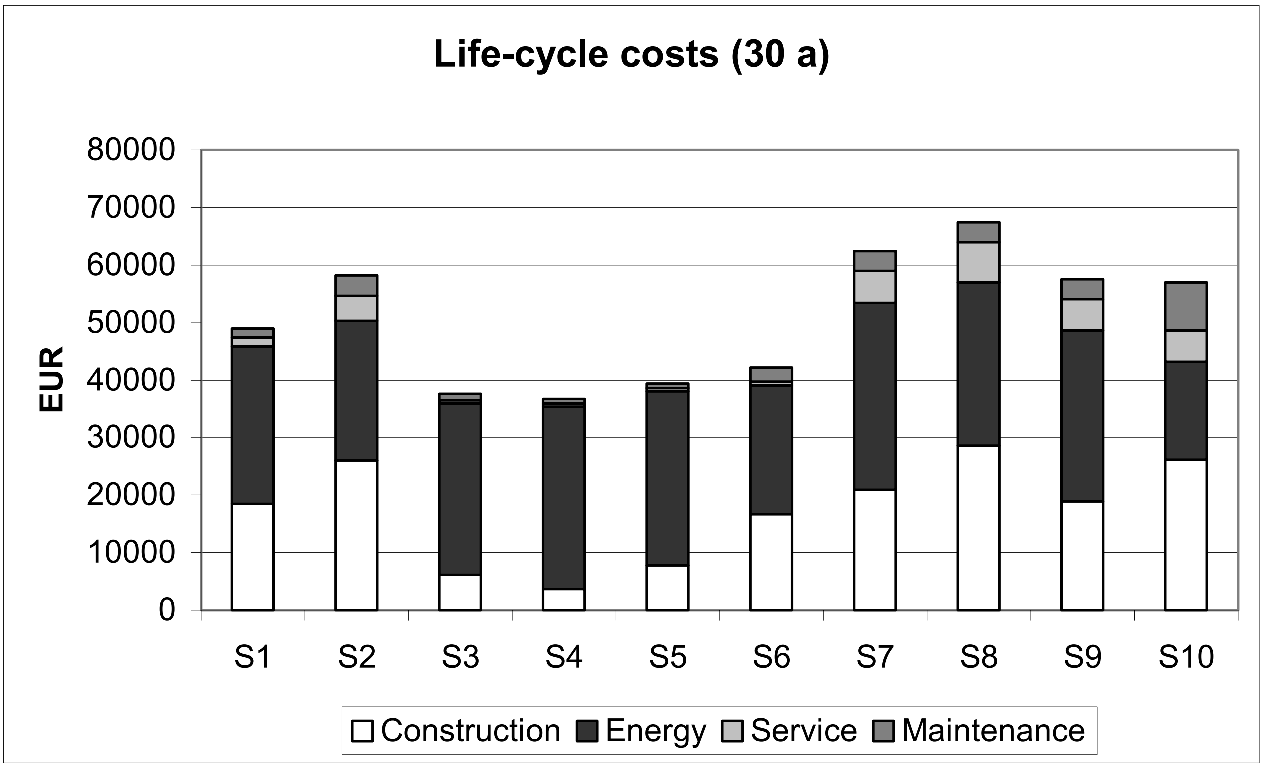

Figure 1. Distribution of life-cycle cost components (reference output).

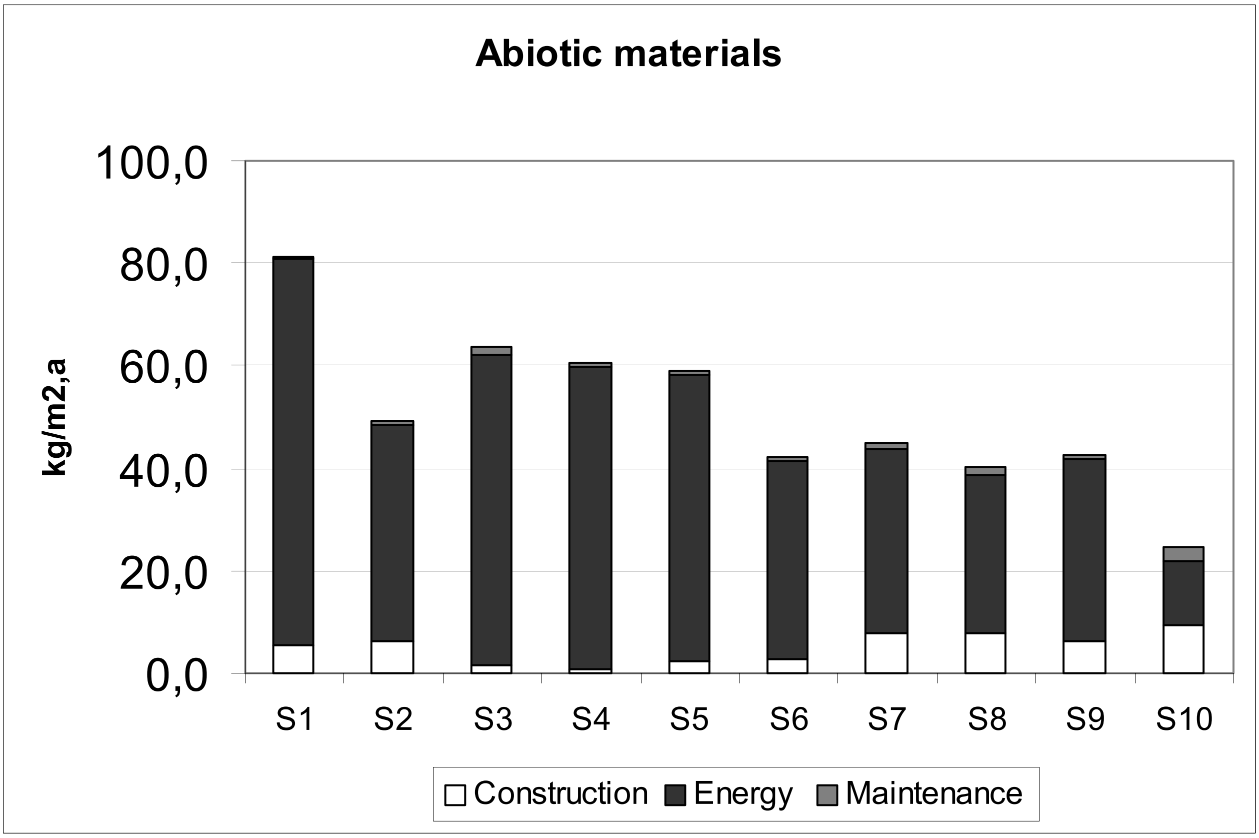

Figure 2. Distribution of MIPS of abiotic materials (reference output).

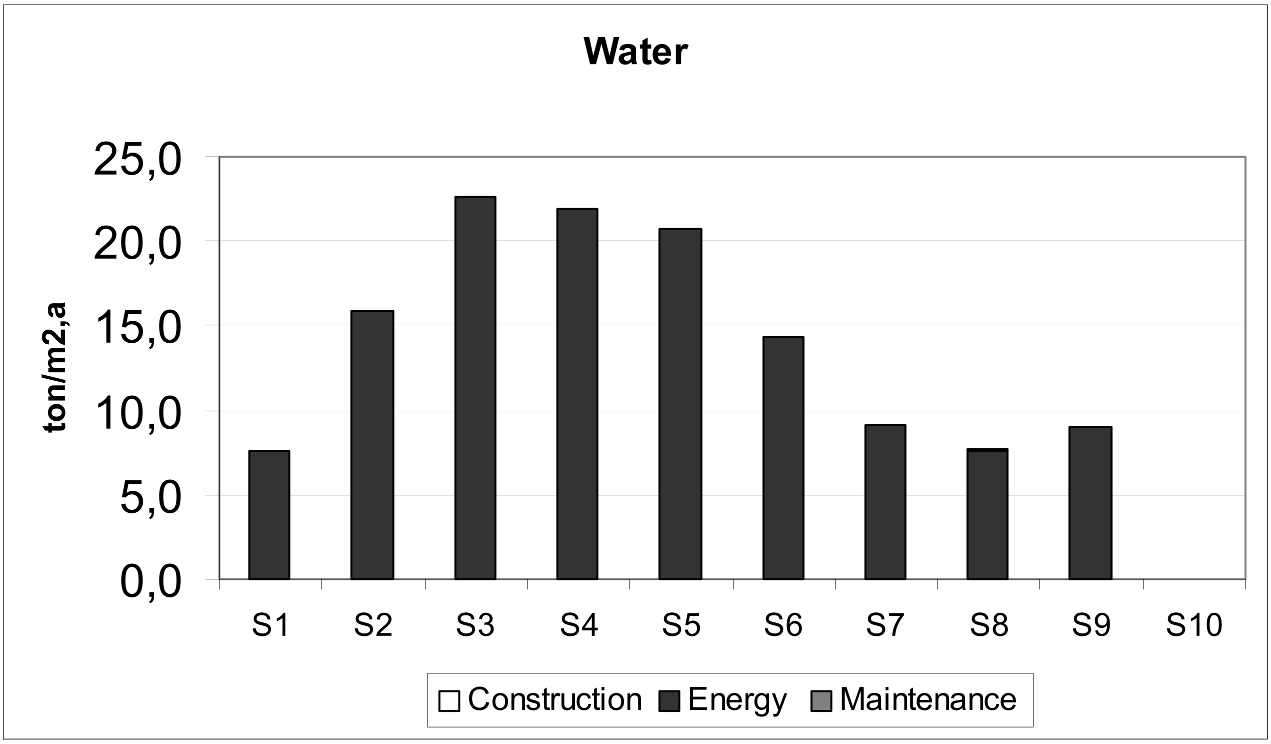

Figure 3. Distribution of MIPS of water (reference output).

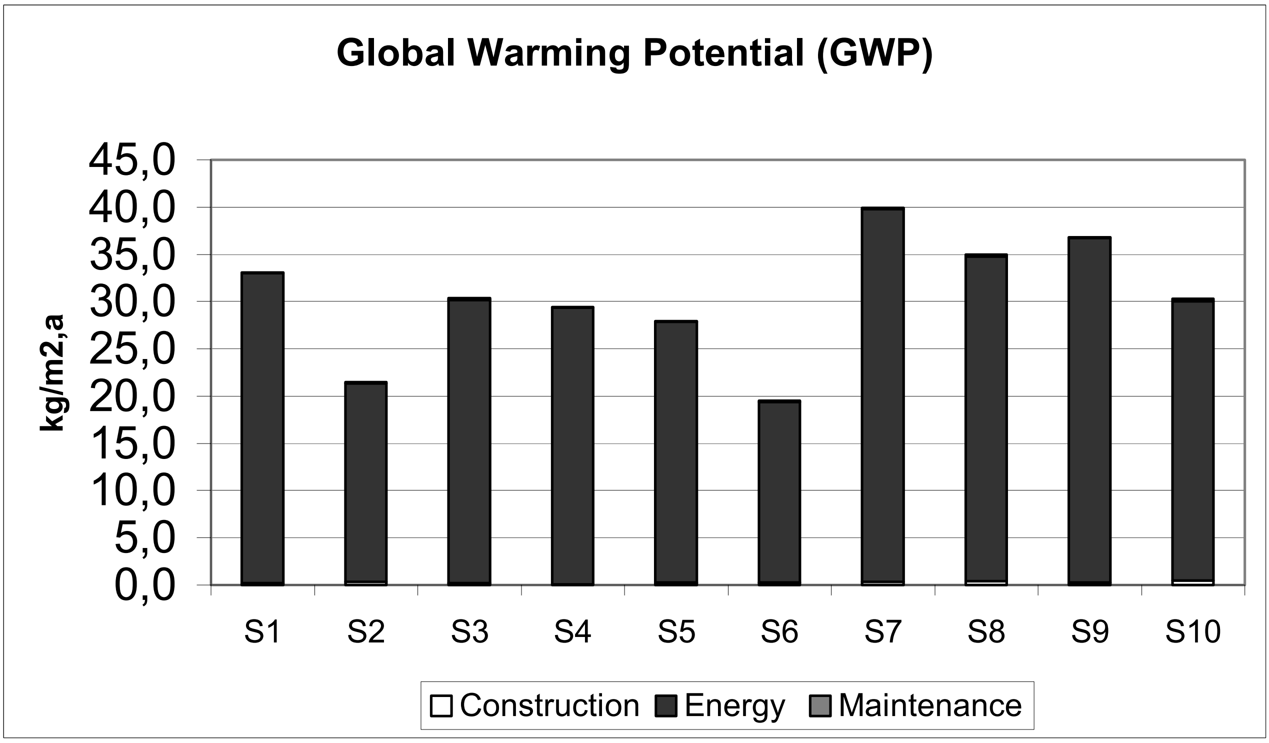

Figure 4. Distribution of GWP (reference output).

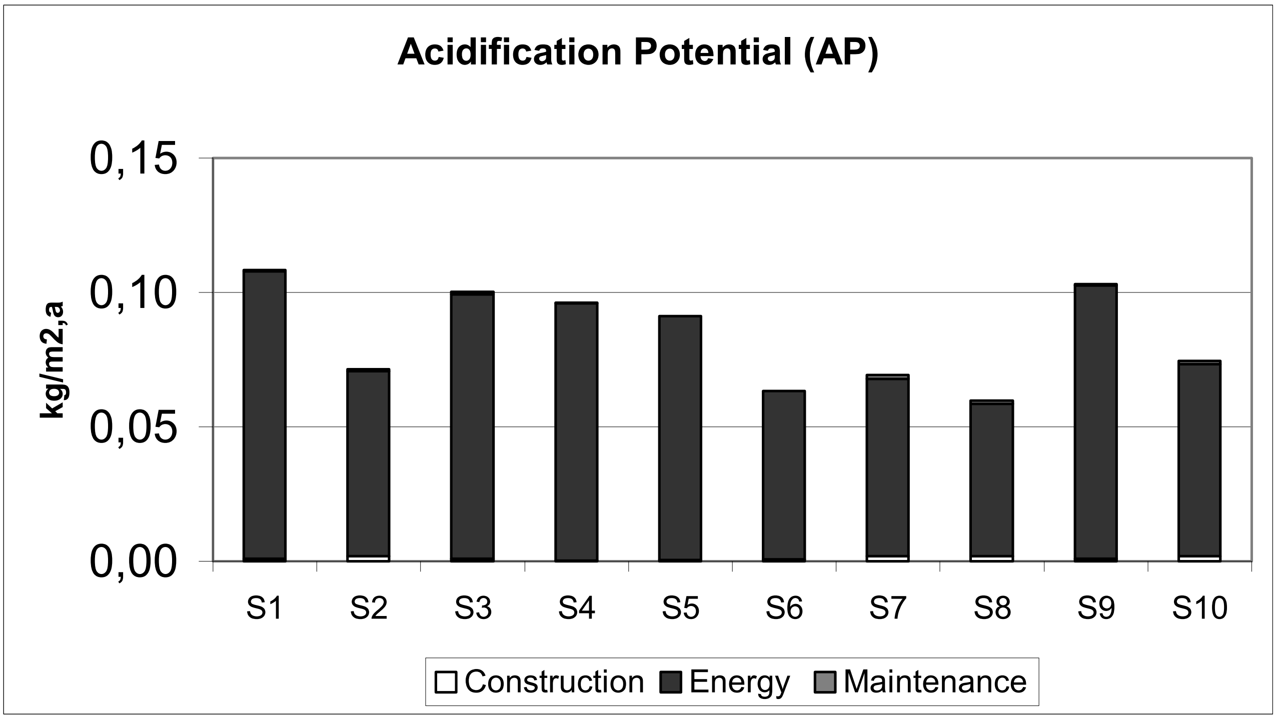

Figure 5. Distribution of AP (reference output).

APPENDIX IV: Background information on the portfolio study.

The case building is an apartment building located in Kirkkonummi (Finland) and constructed in 1983. The building has 29 dwellings in 3 stairways and 3 floors. The building is equipped with a district heating system and exhaust air fans (without heat recovery). The set-point of room temperature is 21°C. The electricity consumption of electrified car parking spaces is approximately 5 % of total electricity consumption. The energy consumptions are estimated applying the WinEtana Simulation tool, using input values in Table 1. The theoretical annual heating energy and electricity consumptions of the building are 313 MWh (44.2 kWh/m^3) and 103 MWh (14.5 kWh/m^3), respectively.

Table 1. Characteristics of the case building.

Feature	Value
Location	Kirkkonummi
Gross volume, m^3	7080
Floor area, m^2	2045.10
Inhabitants	55
U-value, envelope, W $m^{-2}K^{-1}$	0.28
U-value, roof, W $m^{-2}K^{-1}$	0.22
U-value, windows, W $m^{-2}K^{-1}$	2.2

Alternative retrofit actions (N = 27):

1. Decrease and Adjustment of Indoor Temperatures: -1 C
2. Decrease and Adjustment of Indoor Temperatures: -2 C
3. Decrease and Adjustment of Indoor Temperatures: -3 C
4. Decrease and Adjustment of Indoor Temperatures: -4 C
5. Adding Heat Recovery to Ventilation
6. Installation of New Windows: 3x Glass
7. Installation of New Windows: 3x Glass Selective
8. Installation of New Windows: 3x Glass Selective + Argon
9. Additional Insulation to Roof: 50 mm
10. Additional Insulation to Roof: 100 mm
11. Additional Insulation to Roof: 150 mm
12. Additional Insulation to Roof: 200 mm
13. Additional Insulation to Walls: 50 mm
14. Additional Insulation to Walls: 100 mm
15. Additional Insulation to Walls: 150 mm
16. Additional Insulation to Walls: 200 mm
17. Flow Rate Adjustment of Water Fittings
18. Installation of Economizer Jets into Water Fittings
19. Installation of New Water Fittings
20. Installation of Pressure Reducer into Water Distribution System
21. Water Consumption Measurement into Apartment Level
22. Energy Consumption Measurement into Apartment Level
23. Radiator Network Adjustment, Installation of Thermostatic Valves
24. Installation of New Light Fittings
25. Improvement of Lighting Control
26. Improvement of Control of Electrified Parking Space
27. Installation of Peak Power Limit

Table 2. Source data for alternative retrofit actions.

N	Saving Potential*	Costs*** [€/m2]	Decr. CO2 [%]	Environmental value	Functionality **
1	4 % heat	0.2	3.81	1.90	0
2	8 % heat	0.2	7.61	3.81	-4
3	12 % heat	0.2	11.42	5.71	-6
4	16 % heat	0.2	15.23	7.61	-8
5	15-20 % heat	10	14.27	7.14	2
6	4 % heat *	11.58	3.81	1.90	2
7	6 % heat *	12.41	5.71	2.85	4
8	9 % heat *	14.06	8.56	4.28	5
9	1 % heat *	0.15	0.95	0.48	-4
10	2 % heat *	0.3	1.90	0.95	-5
11	3 % heat *	0.45	2.85	1.43	-7
12	3 % heat *	0.6	2.85	1.43	-8
13	1 % heat *	0.15	0.95	0.48	-4
14	2 % heat *	0.3	1.90	0.95	-5
15	3 % heat *	0.45	2.85	1.43	-7
16	5 % heat *	0.6	4.76	2.38	-8
17	5 - 7 % heat	0.3	4.76	2.38	-4
18	5 % heat	5	4.76	2.38	2
19	5 - 10 % heat	15	4.76	2.38	3
20	0 - 10 % heat	1	4.76	2.38	-4
21	0 - 10 % heat	15	4.76	2.38	-2
22	10 - 15 % heat	15	9.52	4.76	-4
23	5 - 10 % heat	0.3	9.52	4.76	1
24	5 - 10 % electricity	8	0.48	0.24	4
25	5 - 10 % electricity	5	0.48	0.24	4
26	2 % of electricity *	5	0.10	0.05	5
27	1 % of electricity **	1	0.05	0.02	2

* achieved through calculations by WinEtana software (based on the existing version of D5)
** approximated value (initial expert estimate)
*** based on VTT's cost database for residential buildings

APPENDIX V: Screenshots from System Selection Tool[12]

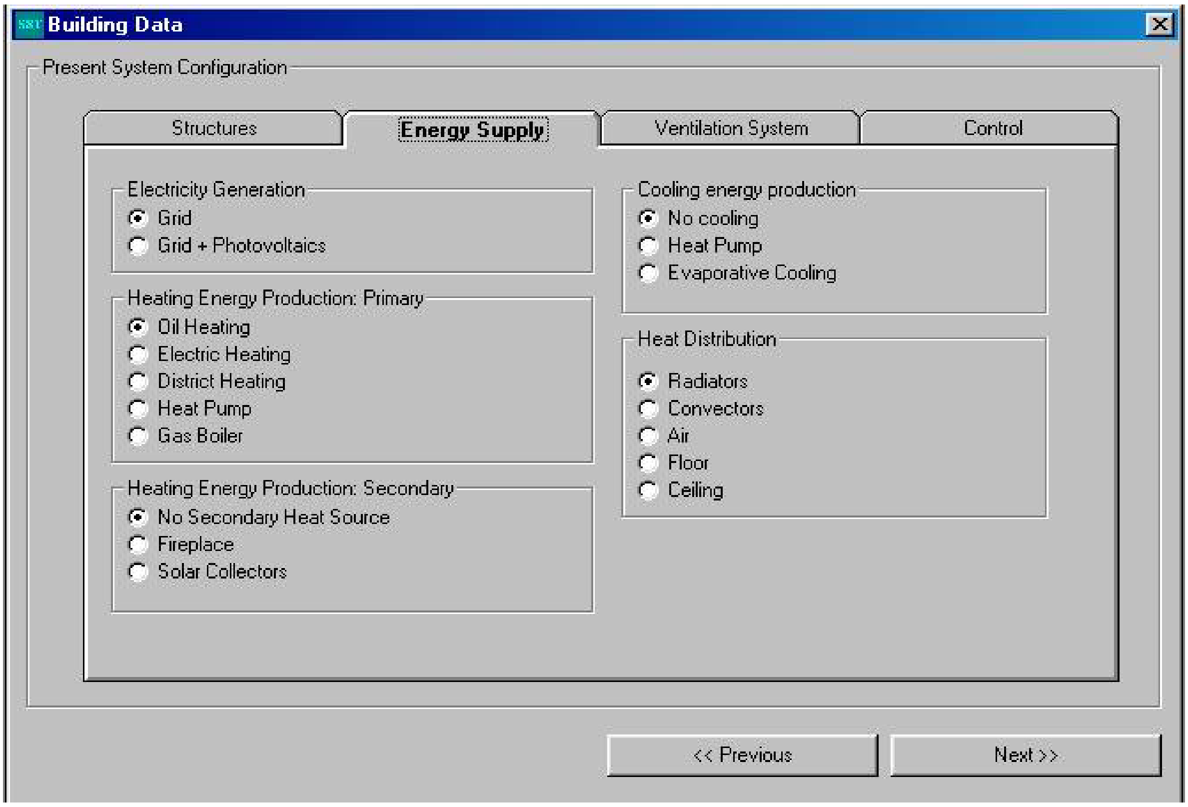

Figure 1. Describing the existing system.

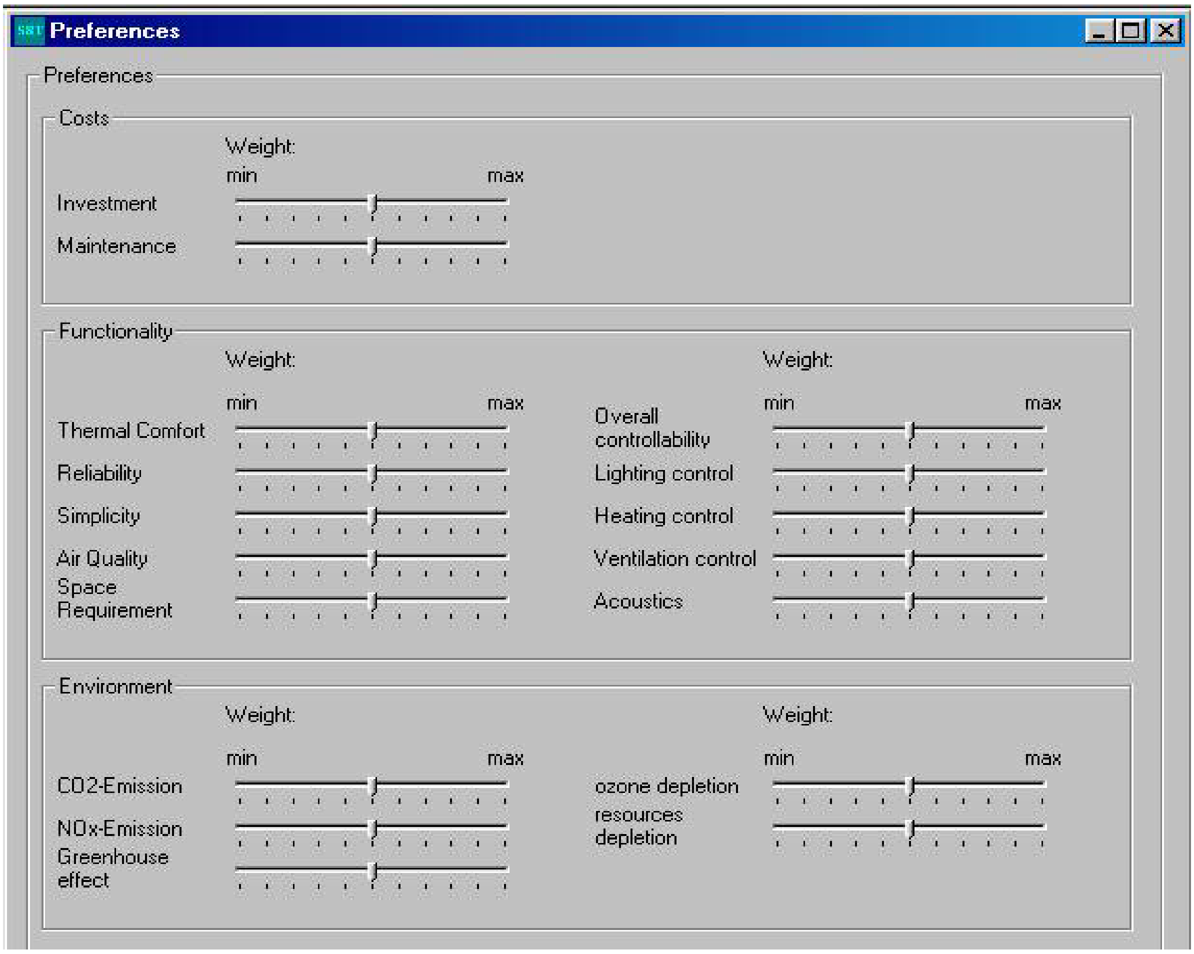

Figure 2. Eliciting criteria weights.

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[12] System Selection Tool was programmed by Kari Alanne applying Visual Basic.

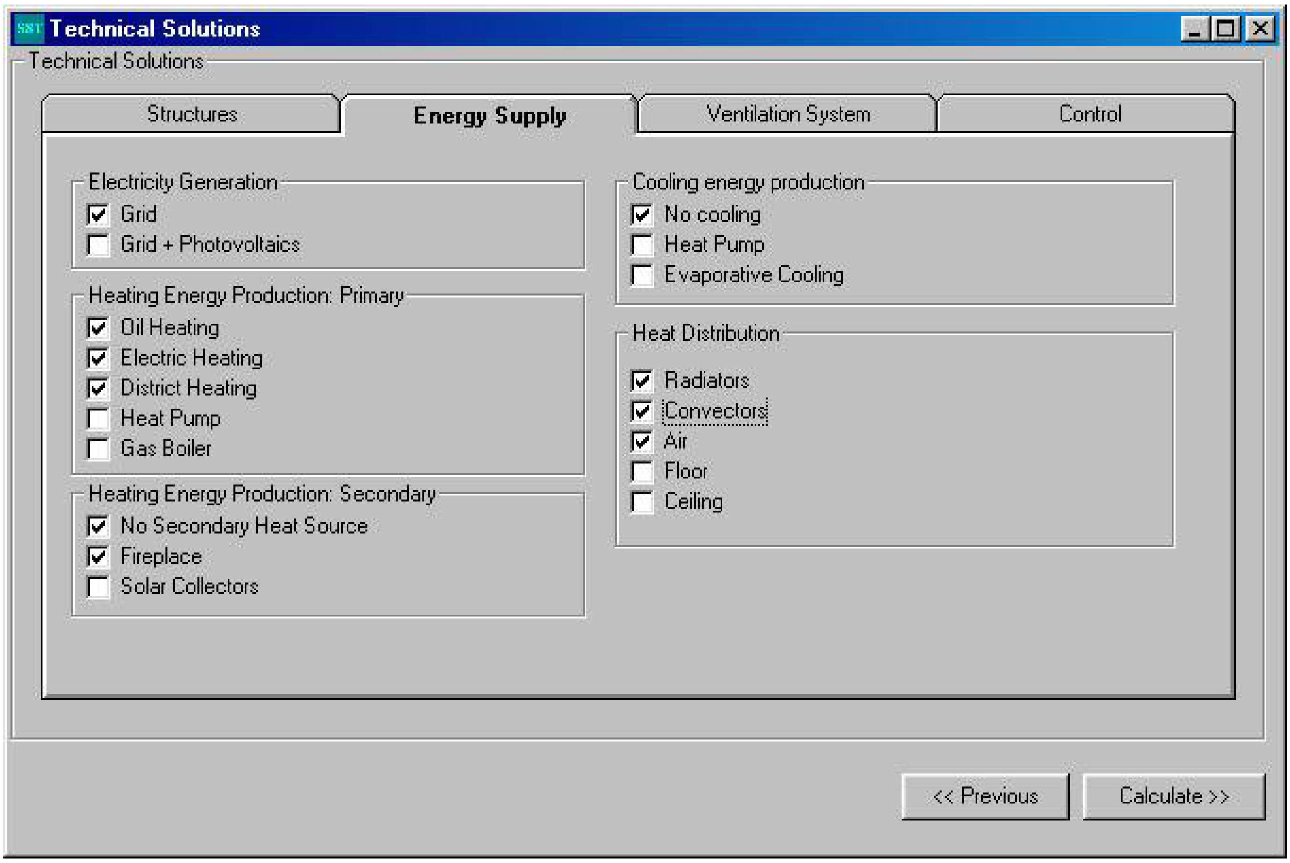

Figure 3. Defining alternatives.

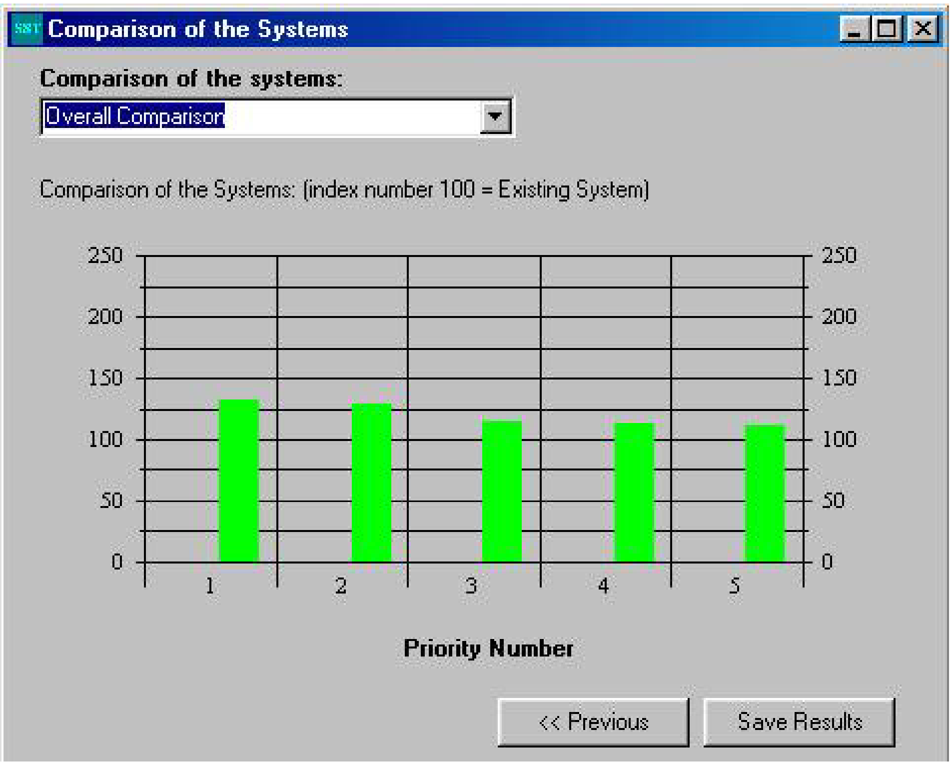

Figure 4. Comparison of alternative retrofit scenarios.

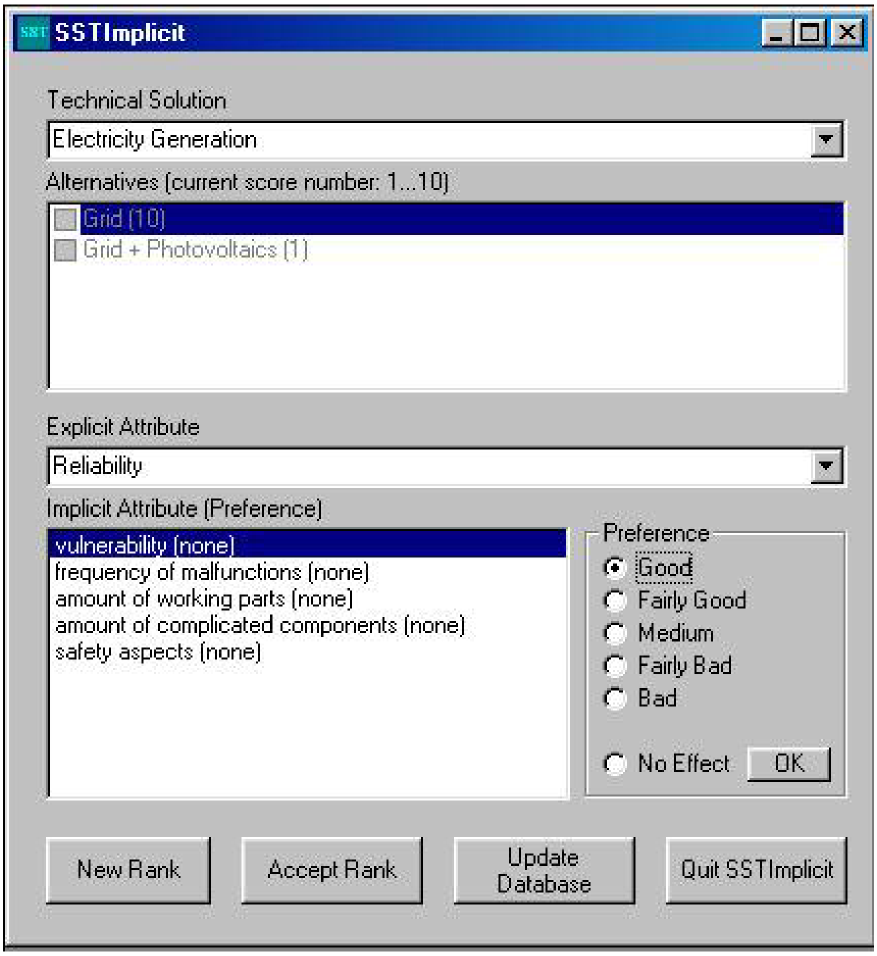

Figure 5. Updating tool for the expert database[13].

[13] Explicit attributes have been selected as the twig-level attributes in the System Selection Tool. Implicit attributes form a *checklist* of "sub-attributes below twig-level" that helps expert users to identify and estimate the performance of an alternative with respect to an explicit attribute *without the use of numerical indicators*.

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