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Comparative analysis of the life-cycle costs of residential energy supply technologies

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Abstract: *Long-term experiences from the residential use of micro-cogeneration systems are not yet available. The evaluation of the economic viability of these systems therefore calls for feasibility studies and the development of computational models that accommodate uncertainties. In this paper, we review uncertainties related to the life-cycle costs of residential heating systems and present a comparative analysis, in order (i) to determine the impact of uncertainties on the economic viability of micro-cogeneration (which is represented by a natural gas boiler system equipped with a 1* kW_e *Solid Oxide Fuel Cell plant), and (ii) to compare this technology with alternative heating systems based on district heat, oil and electricity. Our results – which are based on the use of confidence intervals in capturing uncertainties about model parameters – suggests that micro-cogeneration seems an attractive alternative to heat pump and oil-based heating systems, while electrical heating still appears the superior alternative. Also, because the cost performance of micro-cogeneration is highly dependent on market conditions, it seems that the economic preconditions for the adoption of this technology should be closely monitored or even enhanced through investment subsidies.*

Keywords: *life-cycle costs, energy supply system, micro-cogeneration, micro-CHP, single-family house, multi-criteria decision analysis.*

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1 Introduction

When making decisions about the adoption of new technologies, customers and technology providers need adequate information on the impacts of new technology during its introduction and the later phases when it is already fully established in the markets. Here, a major complication is that empirical data on the possible impacts of new technology is often scarce, even though one would ideally need information on the construction and operational costs of the new technology for the entire planning horizon. As a result, main sources of data consequently include computer simulations, literature searches in databases and expert judgments, whereby much of this data can be inaccurate. Moreover, uncertainties about individual parameters may accumulate due to various interactions among the parameters.

A timely example of a residential energy supply method with limited operational experiences is small-scale combined heat and power generation (micro-CHP, micro-cogeneration) within a residential building. In this paper, we examine the competitiveness of micro-CHP as an energy source, with close attention to the uncertainties on which its life-cycle costs depend. Earlier research has investigated single-variable effects of related techno-economic parameters by way of sensitivity analyses or break-even analysis (Fuller&Petersen, 1995). Hawkes&Leech (2005a), for instance, considered a Solid Oxide Fuel Cell -based micro-CHP system as a residential energy supply solution and identified energy import prices, electricity export price, stack capital costs, and stack lifetime as driving factors when energy demands were small or average. Similar trends have also been presented by Alanne et al.(2006).

The above studies, however, have not considered how the life-cycle costs of micro-CHP technology may vary due to *multivariate* effects that are caused by simultaneous variations with regard to several model parameters. This notwithstanding, such effects must be accounted for in order to reach reasonably reliable conclusions about the competitiveness of micro-CHP and its competitors. From the methodological point of view, these effects can examined by with multi-criteria decision making approaches that (I) capture uncertainties through intervals that cover the full range of plausible values for each parameter and (II) convey what values the aggregate performance measure (such as life-cycle costs) may assume when the parameters vary over their respective intervals (see, e.g., Salo & Hämäläinen (1992)). The elaboration and interpretation of these multivariate effects is one of the main contributions of this paper, apart from the analysis of uncertainties that bear on the life-cycle costs of CHP.

Finland is one of the potential countries for the introduction of residential micro-CHP due to the long tradition of cogeneration, long distances, and open attitudes towards the adoption of environmentally friendly energy technologies. To-date, there have been no rigorous studies in Finland on the construction economics of residential micro-CHP, which makes it necessary to evaluate how this technology compares with other technologies while recognizing the uncertainties about the parameters of the life-cycle cost model. Towards this end, we (i) give a systematic evaluation of how these uncertainties influence the life-cycle economics of micro-CHP (which is represented by a micro-CHP heating system by a traditional natural gas heating system equipped with a 1 kW_e Solid Oxide Fuel Cell plant), and (ii) present a comparative analysis of life-cycle costs of ten alternative heating systems for a single-family house, including options that are based on district heat, electricity, oil and natural gas, among others.

2 Sources of uncertainty

2.1 Estimation of energy use

In the absence of experimental data, the energy use of a building is commonly estimated with computer simulations. Hensen (1993) and Judcoff et al. (1983) note that simulation errors are caused by (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 energy systems, simulation results may also depend on user-specific sources of error (such as ventilation and the use of electrical appliances), the accuracy of input data, and the user's expertise in the use of the simulation program. Several studies suggest that these uncertainties are less than 10 % on the average. For example, Tuomaala (2002) note that there is a 7 – 10 % difference between the results of heat and mass transfer simulations and actual measurements. Fuehrlein et al. (2000) arrive at an average error of 6 % using the simulation program EnergyGauge.

At times, statistical data can be employed to estimate the energy use of buildings. According to an interview of the representative of a Finnish energy company, for instance, there is a difference of ± 10 % between statistical and measured electricity use in houses without electrical heating in Finland. Over extended periods, the energy consumption may change due to the improvement of energy efficiency through refurbishment, or behavioral changes in user's habits. Reported statistics may supply some estimates about these changes. In Canada, for example, the energy consumption on residential sector increased about 0.55 % per year on average between 2000 and 2004 (Statistics Canada). In view of above percentages, the simulation error appears more significant than the expected statistical change in energy consumption.

To mitigate errors in the evaluation of economic viability of micro-CHP, one also needs to estimate how the system responds to peak energy demands. Hawkes&Leech (2005b) note that coarse temporal precision in heat and power demand data can result in considerable errors, because the difference between 1-h precision and 5-min precision in energy demand data for their micro-CHP system was up to 8 % of life-cycle costs. Alanne et al. (2006) observe a 2.5 % difference between the total use of primary energy in the hourly and monthly evaluation of micro-CHP.

2.2 Economic parameters

The main economic parameters in the estimation of life-cycle costs include the discount rate and prices of technology, energy, and labor. This paper is related to the pre-design phase of a construction project, where these parameters are obtained from the literature, statistics, databases or expert statements, whereby errors may be caused by the dependence on time and location, general economic situation and varying levels of prices and inflation (Haahtela&Kiiras, 2004).

In life-cycle analysis, the economic impacts over longer planning horizons are highly dependent on the discount rate, which can be computed either on the basis of the nominal interest rate (inflation included) or the real interest rate (inflation subtracted). If the evaluation is based on the real interest rate, the discount rate is the market interest rate minus inflation; but if the annual rise of energy prices exceeds inflation, the discount rate for energy costs is the real interest rate minus the percentage by which the annual rise of energy prices is expected to exceed inflation. In what follows, the real interest rate is applied to all costs except energy.

In the early 2000s, the market interest rates have been low. According to the European Central Bank, the interest rates for long-term loans and deposits in 2003 varied between approximately 2.5 % and 5.6 %. According to the Energy Market Authority, the annual average percentual change in electricity price in Finland in 2003 for residential customers was 2 %. The inflation in Finland was 0.4 % in September 2004 so that the difference between the change in electricity price and the overall inflation was about 0-2 % (Statistics Finland). Recent studies on the life-cycle economics of heating systems have applied a discount rate of 3-6 %. Manczyk (2003), for instance, used a discount rate of 3 % in the evaluation of four heating systems over a 15-year period, but did not mention whether the real or the nominal interest rate was applied. Collins et al. (2001) assessed the life-cycle costs of ground-source heat pump systems using a discount rate of 6 %. They assumed no escalation of electricity prices; nor did they mention whether or not inflation was accounted for.

In liberalized energy markets, the real estate owner may choose the energy supplier. The Finnish electricity market is characterized by a high volatility of electricity prices. According to the Finnish Energy Market Authority, the lowest and highest prices of electricity (including both energy and transfer charges and taxes) in March 2006 were 10.06 snt kWh^{-1} and 11.66 snt kWh^{-1}, respectively, for a residential consumer with an annual consumption of 5,000 kWh and located in Helsinki region. The average price was 10.66 snt kWh^{-1} and the percentual variation to the above extremes was thus - 5.67 %…+ 9.39 %. In most countries, the buyback prices for private electricity producers are not well established, which means that compensation is somewhere between zero and the full price of electricity. Usually, customers do not have several natural gas or district heat options, and the variability of these prices tends to be more moderate than that of electricity. A comparison based on data from 2004 on the two suppliers in the South East region of Finland suggested that the price variation of natural gas is 3.518…3.968 snt kWh^{-1}, with an average at 3.743 snt kWh^{-1} and percentual variation ± 6 %.

Technology-related risks include possible price changes during the construction project as well as the additional costs of further installations later on (Haahtela&Kiiras, 2004). A related problem is also that alternative contractors include different services into their quotations, while prices may also correlate with the size of the contractor. However, averaging several quotations can form reasonably good estimates. For this paper, we requested quotations from three contractors for a ground-source heat pump installation (installation of a ground-source heat pump with all ancillaries plus a bore hole) for a 245 m^2 and 637 m^3 single-family house (2 adults + 2 children) in the Helsinki metropolitan area. The price of installation varied from 17.9 EUR m^{-3} to 22.3 EUR m^{-3}, with an average 20.7 EUR m^{-2} (Value-Added Tax 22 %). The variation in terms of percentages was thus about ± 10 %.

Literature provides useful information for estimating the price of micro-CHP technology. Ellis (2002) concludes that the prices of Polymer Electrolyte Membrane Fuel Cells are about 2,700 – 3,700 EUR per installed electrical kilowatt when the electric power is less than 5 kW$_e$. According to Onovwiona & Ugursal (2004), the total installed cost of a 10 kW$_e$ Polymer Electrolyte Membrane Fuel Cell, a 200 kW$_e$ Polymer Electrolyte Membrane Fuel Cell and 100 kW$_e$ Solid Oxide Fuel Cell was 5,800 EUR kW$_e^{-1}$, 3,800 EUR kW$_e^{-1}$, and 3,700 EUR kW$_e^{-1}$, in 2002 (annual average exchange rate), respectively. Fuelcellstore.com offered a small, 1 kW$_e$ Solid Oxide Fuel Cell plant at 8000 EUR in 2005 (annual average exchange rate). Hence, the price of a small Solid Oxide Fuel Cell system can be reasonably taken to vary between 5,000 and 8,000 EUR kWh$_e^{-1}$. Governmental support can be excepted to vary between 0 % and 50 % of technology price. In Finland, for example, the investment support of 50-60 % may be granted for a back-up electricity system in farms (Ala-Kantti, 2005).

Due to limited operational experiences, data on service and maintenance cycles of fuel cells must be based on rough estimates. Onovwiona & Ugursal (2004) report that the stack must be replaced once within a period of 4-8 years. They give an estimate of 8 ± 1 years of stack life-time for a Solid Oxide Fuel Cell at the price of 0.01 EUR kW$_e^{-1}$; however, these values refer to a 100 kW$_e$ Solid Oxide Fuel Cell and do not include the maintenance of ancillaries. According to the Finnish Energy Agency, the average annual service cost for the heat conversion system (including ancillaries) of a Finnish single-family house is 160 EUR a^{-1}. Because a fuel cell needs modest service only, the service costs of a micro-CHP system can be assumed to vary between 0 and 160 EUR a^{-1}. If the whole the micro-CHP plant is substituted by a new one once or twice during a 30-year period, and its price varies between 5,000 and 8,000 EUR kWh_e^{-1}, the annual cost will vary between 167 EUR a^{-1} and 533 EUR a^{-1}. The interest rate has not been taken into account in these estimates, but it is considered in life-cycle calculations.

2.3 Features of micro-CHP technology

For a given size and the operational strategy, the electrical and overall efficiencies of a residential micro-CHP system are the key technological parameters its economic life-cycle analysis. Several review articles report results on the fuel cell based residential micro-CHP technologies. Ellis (2002) and Valkiainen et al. (2002) note that the electrical efficiency of a Polymer Electrolyte Membrane Fuel Cell system is 40 %. According to Onovwiona & Ugursal (2004), the electrical efficiency varies from 30 % of Polymer Electrolyte Membrane Fuel Cell to 45 % of Solid Oxide Fuel Cell and 46 % of Molten Carbonate Fuel Cell. In their evaluation of the performance of a Solid Oxide Fuel Cell and combined heat and power (CHP) system configurations for application in residential dwellings, Braun et al. (2005) demonstrate an electrical efficiency of 40%. Ellis (2002) reports that the half load electrical efficiency of Polymer Electrolyte Membrane Fuel Cells is close to their full load efficiency. For a 5 kW_e Solid Oxide Fuel Cell by Fuel Cell Technologies, electrical efficiency varies between 38 and 45 % when the load changes between 20 % and 100 % (Alanne et al.,2006). All these efficiencies are given on the basis of Higher Heating Value; for of Lower Heating Value, the efficiency is higher (e.g. 45 % for a Solid Oxide Fuel Cell) (Braun et al., 2005).

Ellis (2002) reports that the overall efficiency of a micro-CHP plant based on a Polymer Electrolyte Membrane Fuel Cell varies between 75 – 85 %. Onovwiona et al. (2004) arrive at an efficiency value of 70 % (Higher Heating Value). Braun et al. (2005) estimate the overall efficiency of a Solid Oxide Fuel Cell plant at 79% (88% Lower Heating Value) and present a sensitivity analysis which suggests that the overall efficiency of methane-fueled Solid Oxide Fuel Cell systems can be up to 6% higher than that of hydrogen-fueled ones. Alanne et al. (2006) employ an overall efficiency of 82 % in a study of a micro-CHP plant based on the Solid Oxide Fuel Cell of Fuel Cell Technologies. If there is no certainty about how the electrical or overall efficiency is defined, an error of ± 5 % is possible.

2.4 Summary of uncertainties

Proper life-cycle analysis of residential energy supply systems requires that the data is as consistent and comparable as possible. This means, among others, that the location, size and operational strategy for using the system should be unambiguously defined. Building on the results in the preceding Section, Table 1 presents the estimated confidence intervals for the key parameters and their associated intervals through which uncertainties can be captured.

***Table 1**. Confidence intervals for techno economic parameters*[1].

	Parameter	Abbreviation	MIN	MAX
Energy use	Electricity demand, error-%	P1	-10	+10
	Primary energy demand, error-%	P2	-10	+10
Economic parameters	Discount rate, %	P3	2	6
	Price of district heat, error-%	P4	-5	+5
	Price of natural gas, error-%	P5	-5	+5
	Price of electricity, error-%	P6	-10	+10
	Price of oil, error-%	P7	-10	+10
	The buyback price of electricity, %*	P8	0	100
	Investment support, %**	P9	0	50
	The unit price of a micro-CHP plant, EUR	P10	5,000	8,000
	Micro-CHP service costs, EUR a^{-1}	P11	0	160
	Micro-CHP maintenance costs, EUR a^{-1}	P12	200	500
Technological parameters	Micro-CHP total efficiency, %	P13	75	85

* Expressed as the ratio of the buyback price and retail price of electricity
** The percentage of the capital costs of a micro-CHP plant

In Table 1, the lower bound for life-cycle costs is attained when the energy demand and the price of energy are at their lower bound, while the discount rate is at its upper bound. Furthermore, the unit price of a micro-CHP plant, micro-CHP service and maintenance costs must be at their lower bound at the same time when the parameters for the buyback price of electricity, investment support and overall efficiency are at their upper bounds. The competitiveness of micro-CHP also improves when the price of other energy sources increases. This would be the case, for example, if a natural disaster blocks the import of electricity and oil, but the import of natural gas remains unaffected.

Future prices and technological capabilities may be influenced by technological development and mass production. The high price of catalysts, for instance, has motivated research into more economic alternatives (e.g. Wang, 2005). Yet, a significant price decline of fuel cells is not expected within the prevailing technological framework. Political and strategic decisions may nevertheless influence important parameters, such as the buyback price of electricity and the amount of investment support.

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[1] The data in Table 1 has been collected from the Finnish Energy Agency (http://www.motiva.fi) and through consultations with various suppliers of energy systems, life cycle experts, designers and contractors. The capital costs refer to Helsinki region in 2004. A sensitivity analysis for life-cycle calculations (see: Section 4.3) was carried out to omit irrelevant parameters.

3 Life-cycle cost analysis

3.1 General frame

According to Flanagan et al. (1989), “life-cycle costs are the costs of ownership of an item, taking into account all the costs of acquisition, operation, maintenance, modification and disposal, for the purpose of making decision, and Life Cycle Cost Analysis is the analysis of buildings or systems in use”. Here, we are concerned with a single family house whose energy supply system consists of the relevant structures, as well as the mechanical, electrical and information services on the building lot that are related to the supply of heat and electricity to the building. The real estate owner’s decision to invest in the system is the starting point of the construction project that includes the design and construction of the system, too. Regular service, maintenance and refurbishment works are performed during operational use.

Table 2 lists the main systems and subsystems associated with the construction project of a single-family house and summarizes the percentage of different cost components.

***Table 2**. Percentage of cost components in a construction project [12].*

Main system	Subsystem	Costs, %
Structures	Site structures	4.5
	Building structures	31.5
	Infill structures	19.9
Mechanical, electrical and information services	Heating, water and sewer	7.7
	systems	2.1
	Air conditioning systems	3.6
	Electrical systems	0.7
	Information systems	
	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

We consider all subsystems that influence the total project costs, such as the costs of energy supply, installation, and transportation. The costs are mainly caused by (i) spaces required to locate a system into the building, structures required on the building site, such as fuel storages, bore holes etc., (ii) energy conversion plant and its instrumentation, heat distribution etc., (iii) electrical services, interconnection to gas distribution network etc., and (iv) system design.

The project costs do not usually occur at the moment when the decision is made. Because the construction project usually lasts less than a year, construction costs are assumed to occur at the outset. In energy supply systems, most life-cycle costs occur during the operation, while possibilities for influencing life-cycle costs are best at the start of the construction project.

To determine the life-cycle costs of different systems, the costs of construction can be estimated using reliable databases (e.g., the Finnish Construction Cost Database of Haahtela&Kiiras (2004)). If a database is not available, quotations can be asked from multiple contractors. The energy consumption of a single-family building can be evaluated through computer simulations, and empirical data on the costs of maintenance, service and retrofit can be estimated through literature searches and interviews. Below, we present a mathematical model for the evaluation of life-cycle costs and then give an illustrative application.

3.2 Initial costs

The initial costs are

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

where C_I is the total initial costs, 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 subsystem i, $N_{c,I}$ is the number of installed units assigned to subsystem i, C_j is the connection fee of interconnection j, and S is the amount of governmental support.

3.3 Energy costs

The total energy costs of a micro-CHP heating system during a certain period of

$$C_E = \left[\left(C_{fa,e} + c_{e,p} E_{e,p} - c_{e,del} E_{e,del}\right) + \left(C_{fa,pr} + c_{pr}\left(E_{pr,CHP} + E_{pr,f}\right)\right)\right] \sum_{n=1}^{N} \frac{1}{\left(1+r\right)^n}$$

(2)

where $C_{fa,e}$ is the fixed annual electricity costs, $c_{e,p}$ is the retail price of electricity, $E_{e,p}$ is the annual electricity purchased from the grid, $E_{e,del}$ is the annual electricity delivered to the grid, $c_{e,del}$ is the buyback price of electricity, $C_{fa,pr}$ is the fixed annual primary energy costs, c_{pr} is the price of primary energy (e.g.fuel), $E_{pr,CHP}$ is the annual primary energy consumed by micro-CHP plant, and $E_{pr,f}$ is the annual primary energy demand of the backup heating system, N is the total number of years of the time period, and r is the real interest rate.

Equation (2) assumes that the same form of primary energy is employed in a micro-CHP plant and in a backup heating system. When all the required electricity is purchased from the grid and all required heat comes from a single source, equation (2) can be used by setting the terms $E_{e,del}$, $c_{e,del}$, and $E_{pr,CHP}$ to zero. Alanne et al. (2006) describes the simulation model and the assumptions concerning the annual amount of electricity that is purchased from the grid, plus the annual primary energy consumption of a micro-CHP plant.

3.4 Service and maintenance costs

Service costs of residential energy supply include a wide range of activities (e.g., janitorial services due to the delivery of solid or liquid fuel to the building lot). The different subsystems have different service needs, wherefore an annual service cost is assigned to each. The accumulated service costs over the planning horizon are

$$C_S = \left(c_{rm} t_{rm} + \sum_i c_{s,i} t_{s,i} \right) \sum_{n=1}^{N} \frac{1}{(1+r)^n} \qquad (3)$$

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 subsystem i, and $t_{s,I}$ the required annual service time for subsystem i.

The supply system is maintained through equipment upgrading or replacement. The costs consist of purchasing a new subsystem and the demolition of an obsolete one, whereby the obsolete subsystem may have value upon depreciation. Because the different subsystems may have different operational lifetime, a constant annual maintenance cost is needed for each subsystem. The accumulated costs are

$$C_M = \sum_i C_{m,i} \sum_{n=1}^{N} \frac{1}{(1+r)^n} \qquad (4)$$

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

Now, the total life-cycle costs of an energy supply system for the planning horizon can be aggregated from the initial investment, energy costs, service provision and maintenance activities, i.e.,

$$C_{LC} = C_I + C_E + C_S + C_M \qquad (5)$$

4 Comparative analysis

4.1 Alternatives

For our comparative analysis, we make use of the data for a low-energy-single-family house that has been provided by the Finnish Energy Agency. This house represents the forthcoming standard of buildings with decreased energy consumption due to energy saving measures (such as additional insulation and low-energy appliances), based on weather and cost data from the Helsinki region. Table 3 gives the specific characteristics of the house.

***Table 3**. Characteristics of the single- family house.*

Feature	Low energy house
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

More specifically, we compare the economic viability of the following heating systems:

1. District heating with floor heating (S1)
2. Geothermal heating (with heat pump and bore hole) with floor heating (S2)
3. Electrical floor heating (S3)
4. Electric baseboards (S4)
5. Electric baseboards + fireplace (heating 1-2 times per week) (S5)
6. Electric baseboards + fireplace (heating 1-2 times per week) + solar heating + air heat pump (S6)
7. Oil heating with floor heating (S7)

8. Solar oil heating with floor heating (S8)
9. Natural gas heating with floor heating (S9)
10. Natural gas heating with 1 kW_e Solid Oxide Fuel Cell and floor heating (S10)

All systems are connected to the municipal electricity grid. In Systems S1-S9, all the electricity is purchased from the grid, while in System 10 (CHP) the base load of electricity and heat is generated with solar oil heating technology. In System S10, a Solid Oxide Fuel Cell plant, i.e. a power unit (Fuel Cell Technologies Ltd) plus a seasonal heat storage tank, is added to the gas heating system; however, there are no other modifications. The Solid Oxide Fuel Cell system is run at full power throughout a year so that all heat is led to the heat distribution and the domestic hot water system via the heat storage tank. If the amount of excess heat is more than the capacity of heat storage, a heat dump valve is used. The gas boiler is used as a backup heat source. The system is connected to the electricity grid through an interface that makes it possible to feed the excess electricity into the grid. Any shortage of electricity can be bought from the grid while any excess electricity can be fed into the grid.

4.3 Assumptions and realization of the study

For Systems S1-S8, estimates about annual energy consumption and life cycle costs were obtained from the Finnish Energy Agency, and energy demand was estimated through a simulation approach in the Finnish Standard D5. The energy demand of a Solid Oxide Fuel Cell heating system was determined by the principles in Alanne et al. (2006). The most important simplifications were that the electrical power demanded by ancillaries (pumps, fans etc.) of a cogeneration plant is about 6 % of the electrical output power of the plant (Watson, 1997) and the thermal losses are constant. The life-cycle costs were estimated as described in Chapter 3 by applying the intervals in Table 1 for parameters instead of fixed values. The planning horizon was 30 years, and sales taxes were included. Energy prices are summarized in Table 4.

Table 4. *Assumptions about energy prices.*

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

Because the costs of additional room and fireplaces, or the costs of design and service were not included in the data of the Finnish Energy Agency, these costs were estimated using Finnish Construction Cost database. According to Haahtela&Kiiras (2004), the space requirement of residential heating, ventilation and air-conditioning equipment is about 2-3 % of the habitable area. For a house with the habitable area of 131 m^2, the space requirement of a ground-source heat pump, a district heating system, and a gas heating system is approximately 4 m^2. For a micro-CHP heating system and an oil heating system, the estimated space requirement is 5 m^2 due to additional instrumentation and fuel processing (oil reservoir, micro-CHP plant). If electric baseboards are used, no additional space is needed. According to experiences, the costs of heating, ventilation and air-conditioning design for a residential building are approximately 12 % and those electrical design are about 8 % of the construction price. Annual service costs for each system were estimated on the basis of practical knowledge, as well.

All systems were taken to have the same electrical interface (3X25 A). It was assumed that the utility company builds and maintains the connections to the point where consumption is measured. The installed and service costs as well as the efficiencies of oil and gas boilers were considered equal. The size of a gas boiler does not depend on a micro-CHP plant, because the specific heat flow of the boiler must be sufficient for the boiler to operate as a “backup” heat source during possible shutdowns of a micro-CHP plant. The price of a natural gas interface of an energy company located in the South East Finland was applied as a reference.

4.4 Results

4.4.1 Energy demand

Using the intervals of techno-economic parameters of Table 1, the energy demand of alternative heating systems may vary as shown in Table 5.

***Table 5**. Intervals of energy consumption for alternative systems.*

System	Annual electricity from the grid (kWh a^{-1})	Annual electricity to the grid (kWh a^{-1})	Annual primary energy demand (kWh a^{-1})
S1	5,500…6,800	0	11,800…14,400[a]
S2	7,500...9,200	0	4,300...5,200[c]
S3	5,500...6,800	0	11,300...13,800[c]
S4	5,500...6,800	0	10,800...13,200[c]
S5	5,500...6,800	0	9,900…12,100[c]
S6	5,600…6,900	0	5,100…6,200[c]
S7	6,700…8,200	0	14,400…17,600[b]
S8	5,600…6,900	0	12,800…15,600[c]
S9	6,700…8,200	0	14,400…17,600[d]
S10 (CHP)	0…100	100…1,500	28,000…37,500[d]

a	district heat
b	oil
c	electricity
d	natural gas

In CHP, the interval of energy demand depends on the interval of overall efficiency of a Solid Oxide Fuel Cell plant (75-85 %) and the simulation error (± 10 %). In Table 5, the term “primary energy” refers to the chemical energy content of the fuel that is consumed at the building site or the amount of electricity used for heating in electrical heating. The primary energy use of S10 includes the fuel (natural gas) consumed by both a Solid Oxide Fuel Cell plant (base load) and backup boiler (peak load). The electricity consumption represents the annual electricity flow through an electricity service to and from the house. Hence, it is not a net amount of electricity. Increased electricity consumption (Column 1) for water-based heat distribution systems can be explained by the electricity consumption of ancillaries such as circulation pumps.

Table 5 suggests that CHP can be self-sufficient in terms of electricity supply, if the electricity demand is less than expected. With a one-kilowatt micro-CHP plant, purchasing electricity from the grid must fulfill peak electricity demands, but yet at least some electricity will be fed into the grid. Overall, the annual primary energy demand of CHP exceeds that of traditional heating systems, because it includes both the production of heat and electricity.

Because the average efficiency of electricity production (grid electricity) is approximately 20-30 %, CHP is an efficient energy source.

4.4.2 Life-cycle costs

For most systems, upper and lower bounds for life-cycle costs can be determined based on the intervals in Table 1. Table 6 presents the intervals of life-cycle costs for each heating system as well as combinations of parameter that result in the lower and upper bounds of life-cycle costs. Empty cells indicate that the parameter has no influence on the life-cycle costs of the corresponding heating system.

(Insert Table 6 around here.)

For CHP, the life-cycle costs are minimized when the demand of electricity is less than expected, in which case the system can be self-sufficient with respect to electricity. Thanks to this self-sufficiency, the retail price of electricity on the life-cycle costs of CHP does not have major impacts. On the other hand, if the price of electricity is higher, then the compensation for the electricity that is fed into the grid may be higher, too.

Table 7 presents the percentual initial, energy, and service and maintenance costs of the total life cycle for each system. Each interval refers to the upper and lower bound of life-cycle costs of the corresponding system.

***Table** 7. Components of total life-cycle costs.*

Cost component	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
Initial, %	32…49	39…57	13…25	8…16	16…29	33…52	28…46	36…55	28…44	35…52
Energy, %	45…62	31…48	71…83	80…89	67…81	42…60	41…59	31…49	42…57	28…36
Service, %	3	7	1…2	1…2	1…2	1	8	9…10	9	9…11
Maintenance, %	3	5…6	3	2	2	6	5	5	6	12…18

The main costs of electrical heating systems are energy costs, because the initial and upgrade investments are small. In the case of CHP, initial and energy costs play an important role, but also maintenance costs are considerable. This is due to the large uncertainties over the life span, as well as the costs that accrue when a micro-CHP plant be repaired or substituted by a new one.

The intervals of total life-cycle costs are illustrated in Figure 1 using a bar chart representation.

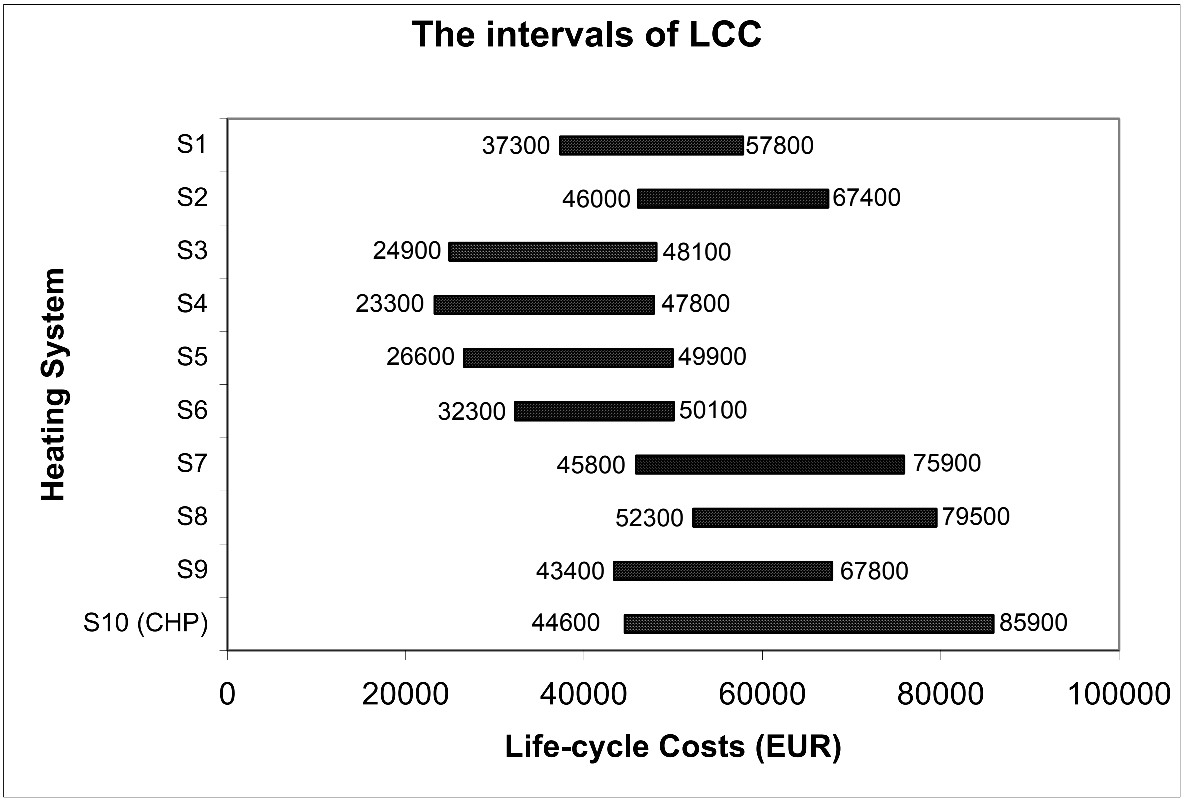


Figure 1. *Intervals of life-cycle costs for Systems S1-S10.*

In Table 6 and Figure 1, the interval of life-cycle costs is large when the current framework of techno-economic parameters is applied. The largest interval (44,600-85,900 EUR) is associated with CHP, whose interval overlaps with those for the life-cycle costs of most alternative technologies. The comparison of economic costs of these heating systems calls for further analyses.

4.4.3 General comparison

In the PAIRS method of Salo&Hämäläinen (1992), alternative A outperforms 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. However, because we are concerned with costs (rather than benefits), this concept must be adapted by noting that alternative A is preferred to alternative B in the sense of absolute dominance if the largest possible cost of A is *less* than the smallest possible cost of B. Thus, for example, because the highest life-cycle costs of electrical heating systems (Systems S3-S6) (50,100 EUR) are less than the least life-cycle costs of solar oil heating system (52,300 EUR), there is absolute dominance between the life-cycle costs of these systems. Also, the electrical systems are unambiguously better than a solar-oil system.

The intervals in Figure 1 do not indicate for which parameter values the lower and upper bounds of the corresponding energy systems are attained. Thus, while intervals may overlap, it is possible that for all permissible combinations of parameter values, one system has lower total life-cycle costs than another. It is therefore necessary to examine if the possible superiority of one system can be concluded on the basis of *pairwise dominance* which checks for simultaneous variations in multiple parameters. For decision contexts where pairwise dominance cannot be established, additional guidance about which alternatives seem better than others can be based on decision rules Salo&Hämäläinen (2001). In the present context, relevant decision rules are (I) *minimin* (which refers to the alternative with least possible life-cycle costs), (II) *maximin* (the alternative with the largest possible costs), and (III) *central value* (alternative for which the midpoint of the cost interval thus defined is smallest).

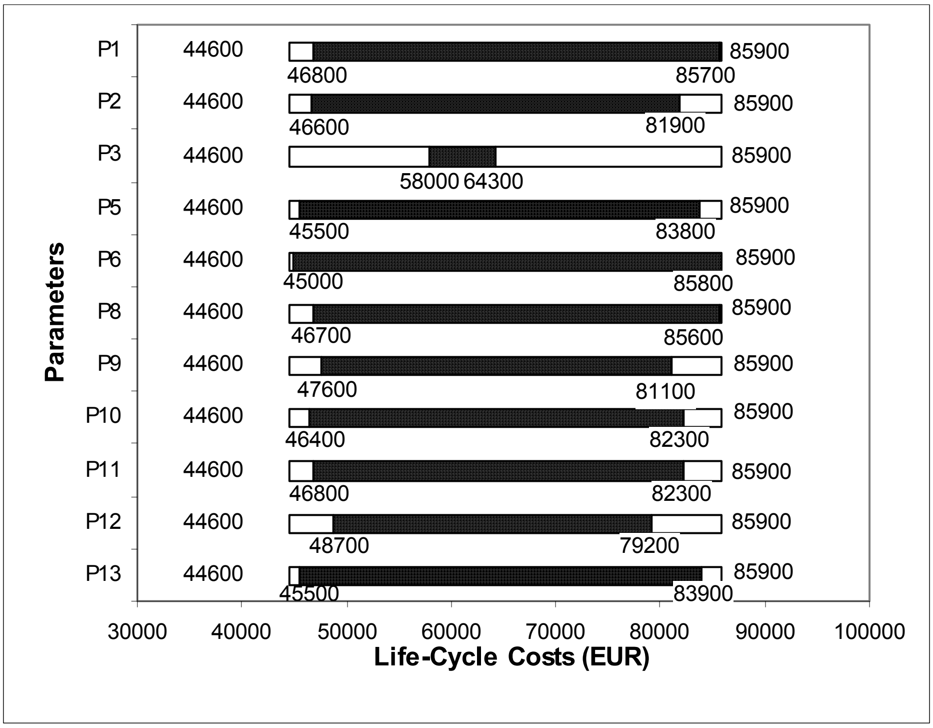
4.4.4 Pairwise comparison

The life-cycle costs of micro-CHP are minimized when the price of electricity is at its upper bound and the price of fuel is at its lower bound. Under these same assumptions, the life-cycle costs of heating systems based on electricity are also maximized. Similarly, the viability of CHP may improve if the customer fully utilizes possibilities in the liberalized energy market. Table 8 presents the life-cycle costs of competing heating systems, subject to the assumption that the parameters in the computation of the *life-cycle costs of a micro-CHP heating system are at their minimum or maximum*. Even though this analysis does not correspond to thorough comparison on the basis of the pairwise dominance, it offers additional insights about how well CHP compares with the other systems, which involve smaller uncertainties.

Table 8. *Life cycle costs for Systems S1-S10 corresponding the minimum and maximum life cycle costs of CHP.*

	$C_{LC,\,min}$	$C_{LC,\,max}$
S1	39,100	57,200
S2	48,500	67,400
S3	28,100	48,100
S4	26,700	47,800
S5	29,800	49,900
S6	34,500	50,100
S7	48,700	73,700
S8	54,700	77,600
S9	45,200	67,800
S10 (CHP)	44,600	85,900

Specifically, Table 8 shows that when the life cycle costs of CHP are minimized, CHP is less costly than oil heating and geothermal heating; however, it does not improve its status with respect to other alternative systems. The parameters explaining the variations of the life-cycle costs of CHP were analyzed one by one as shown in Figure 2.



Abbreviations:

P1:	Electricity demand
P2:	Primary energy demand
P3:	Real interest rate
P4:	Price of district heat
P5:	Price of natural gas
P6:	Price of electricity
P7:	Price of oil
P8:	The buyback price of electricity
P9:	Investment support
P10:	The unit price of a micro-CHP plant
P11:	Micro-CHP service costs
P12:	Micro-CHP maintenance costs
P13:	Micro-CHP overall efficiency

***Figure 2**. Effect of uncertainties in parameters P1-P13 on the life-cycle costs of CHP.*

The values between the lower (44,600 EUR) and upper (85,900 EUR) bounds in Figure 2 represent the life cycle costs of CHP when the corresponding parameter varies over its corresponding interval in Table 1. For example, if the interest rate associated with minimum life-cycle costs (6 %) changes 6 % to 2 %, then life-cycle costs vary between 44,600 EUR to 58,000 EUR. Thus, Figure 2 also shows that the most influential parameters are the interest rate (P3), investment support (P9) and maintenance costs (P12). Conversely, the life-cycle costs are not sensitive to electricity price (P6). This is not surprising, because micro-CHP is rather self-sufficient with respect to electricity.

Because interest rate influences the life-cycle costs of all alternatives, its impact depends on the relative timing of their respective costs, wherefore straightforward conclusions cannot be give. As for the other parameters, Table 8 and Figure 2 indicate that the changes in them do not change the status of micro-CHP with respect to district heat or electrical heating systems. Rather, growing maintenance costs make CHP less attractive in comparison with geothermal heating and natural gas heating. Decreased investment support makes CHP unattractive in comparison with natural gas heating. Thus, the competitiveness of CHP depends on investment support and maintenance, which suggests that these issues should be recognized when developing markets for micro-CHP technology.

4.4.5 Decision rules

In view of Figure 1, electric baseboards seem best on the basis of *minimax* decision rule, because its maximum life-cycle costs 47,800 EUR are lower than those of others. Also, it is also recommended by *minimin* and *central value* decision rules, because the smallest (23,300 EUR) and mid-point (35,500 EUR) life-cycle costs are also the lowest among all heating systems.

The electrical heating systems are competitive with other alternatives in terms of their life-cycle costs. Among the other systems, the least costly one on the basis of the three decision rules is district heating, on condition that there is a connection to the district heating network, while solar-oil heating with floor heating is the most costly alternative. Based on the *minimin* decision rule, CHP outperforms geothermal heating, oil heating, and solar oil heating (all with floor heating); but if an attempt is made to minimize risks (as captured by the *minimax* decision rule), the other systems seem a better choice. Only solar oil heating with floor heating has lower life-cycle costs than CHP (65,200 EUR) when the *central values* decision criterion is applied. Hence, CHP is not the recommended alternative if this decision rule is adopted.

5 Summary and conclusions

In this paper, we have reviewed the uncertainties that pertain to the life-cycle costs of residential heating systems, mostly by citing empirical and computational results from the literature. We have also presented a comparative analysis that captures multivariate effects due to the uncertain parameters on which the economic viability of micro-CHP depends. These uncertainties were captured through confidence intervals, in the realization that the location, time frame and system configuration should be fixed in life cycle cost analyses to ensure comparability. Specifically, we have considered ten heating systems based on district heat, oil and electricity for a single-family house located in Finland.

Our numerical results suggest that the level of energy use, technological parameters and prices of energy, technology and workmanship are among the key parameters. They also suggest that electrical heating appears superior to the other heating methods on the basis of its life-cycle costs. Micro-CHP appears a viable alternative in comparison with a traditional gas heating system, ground-source heat pump and heating systems utilizing oil. In our study, dominance structures and decision rules provided a useful way to reveal the risks involved in the evaluation of alternative heating systems. We emphasize, however, that the above results are strongly affected by the case building and its location. Therefore, these conclusions cannot be generalized.

The life-cycle costs may change considerably when the relevant parameters vary within their respective confidence intervals. Here, the discount rate, investment support and maintenance costs are essential, in the sense that the reduction of uncertainties about these results in much narrower intervals for life cycle costs. The attractiveness of micro-CHP is sensitive to market conditions, which suggests that possibilities for stimulating investments in residential micro-CHP systems are worth considering. There is also a need for research that helps lengthen the life span of micro-CHP plants through the development of improved materials and other technical advances, for example.

From the viewpoint of a real-estate owner, micro-CHP entails risks, but may offer significant benefits if the techno-economic environment is utilized effectively. Also, because environmentally friendly energy supply systems may offer enhanced possibilities, we believe there is a need for research that pays attention to environmental issues in residential cogeneration. Decision support for extensive investment planning, in turn, calls for the formulation of multi-objective optimization problems that allow the real-estate owner to make optimal choices among alternative combinations of micro-CHP technology and traditional heating methods. Such analyses help evaluate the competitiveness of micro-CHP heating systems in recognition of a variety of long-term costs and environmental burdens.

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Acronyms

CHP	Combined Heat and Power (cogeneration)

Nomenclature

$c_{e,del}$	electricity buyback price (EUR kWh^{-1})
$c_{e,p}$	electricity retail price (EUR kWh^{-1})
c_i	installed unit cost assigned to subsystem *i* (EUR m^{-2} or EUR kW^{-2})
c_{pr}	price of primary energy (e.g.fuel) (EUR kWh_{pr}^{-1})
c_{rm}	estimated price for an hour of janitorial work (EUR h^{-1})
$c_{s,i}$	price for a hour of service work for subsystem *i* (EUR h^{-1})
$C_{fa,e}$	fixed annual electricity costs (EUR a^{-1})
$C_{fa,pr}$	fixed annual primary energy costs (EUR a^{-1})
C_I	total initial costs (EUR)
C_j	connection fee for interconnection *j* (EUR)
$C_{m,i}$	annual maintenance cost for subsystem *i* (EUR a^{-1})
$E_{e,del}$	annual electricity delivered to the grid (kWh_e a^{-1})
$E_{e,p}$	annual electricity purchased from the grid (kWh_e a^{-1})
$E_{pr,CHP}$	annual primary energy consumed by micro-CHP plant (kWh_{pr} a^{-1})
$E_{pr,f}$	annual primary energy (fuel) consumption of the boiler (kWh_{th} a^{-1})
N	total number of years of the life cycle period
$N_{c,i}$	number of installed units assigned to subsystem *i*
p_{ps}	the fraction of the construction costs assigned to project services
r	real interest rate
S	amount of governmental support (EUR)
t_{rm}	estimated annual time required to energy supply management (h a^{-1})
$t_{s,i}$	annual service time for subsystem *i* (h a^{-1})

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Table 6. Combinations of parameters resulting in the lower and upper bounds of life-cycle costs for Systems 1-10.

	S1		S2		S3		S4		S5		S6		S7		S8		S9		S10 (CHP)	
Par.	min	max	min	max	min	max	min	max	min	max	min	max	min	max	min	max	min	max	min	max
P1	-10	10	-10	10	-10	10	-10	10	-10	10	-10	10	-10	10	-10	10	-10	10	-10	10
P2	-10	10	-10	10	-10	10	-10	10	-10	10	-10	10	-10	10	-10	10	-10	10	-10	10
P3	6	2	6	2	6	2	6	2	6	2	6	2	6	2	6	2	6	2	6	2
P4	-5	5																		
P5																	-5	5	-5	5
P6	-10	10	-10	10	-10	10	-10	10	-10	10	-10	10	-10	10	-10	10	-10	10	10	10
P7													-10	10	-10	10				
P8																			100	0
P9																			50	0
P10																			5,000	8,000
P11																			0	160
P12																			200	500
P13																			85	75
LCC	37,300	57,800	46,000	67,400	24,900	48,100	23,300	47,800	26,600	49,900	32,300	50,100	45,800	75,900	52,300	79,500	43,400	67,800	44,600	85,900

Abbreviations:

P1:	Electricity demand, error-%
P2:	Primary energy demand, error-%
P3:	Real interest rate, %
P4:	Price of district heat, error-%
P5:	Price of natural gas, error-%
P6:	Price of electricity, error-%
P7:	Price of oil, error-%
P8:	The buyback price of electricity, %
P9:	Investment support, %
P10:	The unit price of a micro-CHP plant, EUR
P11:	Micro-CHP service costs, EUR a^{-1}
P12:	Micro-CHP maintenance costs, EUR a^{-1}
P13:	Micro-CHP overall efficiency, %