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Summary

In this paper, we evaluate the viability of a 9.5 kW_e wooden pellet fuelled Stirling engine-based micro-cogeneration plant as a substitute for small-scale district heating. The district heating systems against which the micro-cogeneration plant is compared are based either on a pellet fuelled boiler or a ground-source heat pump. The micro-cogeneration and district heating plants are compared in terms of primary energy consumption, CO_2 emissions, and feasibility of the investment. The comparison also considers an optimally operated individual 0.7 kW_e pellet fuelled Stirling engine micro-cogeneration system with exhaust gas heat recovery. The study is conducted in two different climates and contributes to the knowledge base by addressing: i) hourly changes in the Finnish electricity generation mix; and ii) uncertainty related to what systems are used as reference and the treatment of displaced grid electricity. Our computational results suggest that when operated at constant power, the 9.5 kW_e Stirling engine plant results in reduced annual primary energy use compared with any of the alternative systems. The results are not sensitive to climate or the energy efficiency or number of buildings. In comparison with the pellet fuelled district heating plant, the annual use of primary energy and CO_2 emissions are reduced by a minimum of 25% and 19%, respectively. Due to a significant displacement of grid electricity, the system's net primary energy consumption appears negative when the total built area served by the plant is less than 1200 m^2. On the economic side, the maximum investment cost threshold of a CHP-based district heating system serving ten houses or more can typically be positive when compared with oil and pellet systems, but negative when compared with a corresponding heat pump system.

Keywords: residential buildings, financial analysis, Stirling Engine, micro-CHP

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Acronyms and abbreviations

CDER	Carbon dioxide emission rate
CEF	Carbon dioxide emission factor
CHP	Combined Heat and Power
DHW	Domestic Hot Water
ECBCS	Energy Conservation in Buildings and Community Systems Program
IDA-ICE	Indoor Climate and Energy
IEA	International Energy Agency
LHV	Lower Heating Value
NRPE	Non-Renewable Primary Energy
PER	Primary energy conversion factor
SE	Stirling Engine
TOTPE	Total Primary Energy
UCPTE	Union for the Co-ordination of Production and Transmission of Electricity

1 Introduction

The building sector accounts for approximately 40% of primary energy use and 36% of total CO_2 emissions in most developed countries [1]. Nowadays both research and policy development strongly support improving the efficiency of energy systems and promoting the use of sustainable sources of energy, which, in turn, requires efforts on both the energy supply and demand sides. Traditional energy-saving measures related to building envelopes and fenestration are well-established, whereas much current research focuses on energy management, the integration of building services, and on-site energy generation [2, 3].

Micro-cogeneration, i.e. the local generation of electrical and thermal power simultaneously to satisfy the electrical demands of lighting, appliances, and building services plus the thermal demands of space heating and production of hot water in residential buildings, is an alternative to conventional oil, gas, and biomass boilers, and, to some extent, heat pumps, solar thermal, and photovoltaic systems. Advantages accrue both in terms of improved energy efficiency and reduced environmental burdens, provided that the systems operate in an energy-efficient manner, i.e. the match between electrical and thermal power demand and supply is reached at a local level. [3]

Performance assessment is an approach to the evaluation of the viability of micro-cogeneration systems in comparison with the alternative options for residential energy supply, and thus a way to develop more energy-efficient systems that rise to the challenges of increasing competition on the market. The basic criteria are reductions in life-cycle costs, primary energy, and CO_2 emissions. The basic method for the above task is a computational study leaning on the simulation of a whole building or a local grid. A significant effort was made in terms of Annex 42 of the International Energy Agency's Energy Conservation in Buildings and Community Systems Program (IEA/ECBCS), in which simulation models for the analysis of micro-cogeneration systems were developed, calibrated, and validated [4,5].

One notable advantage offered by Stirling engines in terms of micro-cogeneration is their ability to combust a variety of fuels, such as petroleum and biomass-based fuels. The results of performance assessments conducted to date for the current generation of Stirling engine micro-cogeneration devices suggest that a Stirling engine application may result in a 5% to 24% decrease in non-renewable primary energy use

and in a 20% reduction in CO_2 emissions [3, 6-8]. The outcome of this type of analysis depends on climatic conditions and local building standards, which makes performance assessments country-specific [9-11]. Moreover, issues such as how the primary energy and emission factors for different energy sources are determined may substantially affect the applicability of the results. Specifically, there is a need to incorporate the effect of time-dependent changes in the energy generation mix in these assessments, as well as to examine the function of micro-cogeneration as the energy supply in terms of micro-grids [6].

In this paper, we conduct a performance assessment to evaluate the viability of Stirling engine-based micro-cogeneration systems in comparison with plants based on pellet fuelled boilers and ground-source heat pumps. The study contributes to research by addressing: i) hourly changes in the Finnish electricity generation mix and; ii) uncertainty related to what systems are used as reference and the treatment of displaced grid electricity. The dynamic effects of micro-cogeneration devices, such as warm-ups and shutdowns, are accounted for, as well as the utilization of thermal exhaust through heat recovery. The penetration of micro-cogeneration in the national level is assumed small. Therefore, the electricity grid is considered an infinite storage of electricity. Although the simulation results represent Finnish conditions the methodology is applicable in similar climates.

2 Methodology

2.1 Building simulation

A whole-building simulation program is applied in the computational analysis to determine the instantaneous power demand of an individual building. The simulation platform employed is IDA-ICE (Indoor Climate and Energy), an advanced building

simulation tool, which is widely used in the Nordic Countries for both commercial and research purposes. The program provides dynamic simulation of heat transfer, internal and solar gains, and airflows in buildings and was developed by the Royal Institute of Technology and the Swedish Institute of Applied Mathematics. The details are given in [12] and [13], and test studies are reported for various applications in [14] and [15].

2.2 Annex 42 micro-cogeneration model

The Stirling engine-based micro-cogeneration system model specified by IEA/ECBCS Annex 42 [16] was implemented in the IDA-ICE building simulation program, this to account for the system's dynamic effects and the interaction between the building and the system. This implementation into IDA-ICE was verified through inter-program comparative testing against Energy Plus, ESP-r, and TRNSYS, following the Annex 42 test suite. This suite encompasses nine series of tests including a total of 44 separate cases [17]. Excellent agreement was found between the IDA-ICE implementation and the three above-mentioned tools. This verification process is reported in [18].

The exact analysis of physical and chemical phenomena, including the combustion process, thermodynamic cycles and dynamic characteristics of an engine, has been simplified in the Annex 42 model by applying engine-specific, empirical correlations that rely on measured data. Hence, the model represents the performance characteristics of currently available Stirling engine micro-cogeneration devices. Because the model is already well-documented and applied in several computational studies, the basic principles are not repeated here, instead the reader is referred to [5] and [16] for a detailed treatment.

Rather, some attention is given to the treatment of the exhaust gas recovery, which is our new contribution to the Annex 42 approach in terms of the IDA-ICE implementation. Here, the utilization of waste heat takes place in terms of pre-heating the supply air and/or combustion air. The enthalpy flow of the exhaust outlet is determined from

$$\dot{H}_{exh} = \left(1-\eta_q\right) q_{gross} - P_{net,ss} \qquad (1)$$

where q_{gross} is the gross thermal input to the system, η_q is the net thermal conversion efficiency, i.e. the ratio of gross thermal input that can be converted as utilizable thermal energy into the water circulation and $P_{net,ss}$ is the steady-state electrical output of the system. The gross thermal input to the system q_{gross} is calculated from

$$q_{gross} = \dot{m}_{fuel} \, LHV_{fuel} \qquad (2)$$

where $\dot{m}_{fuel}$ and LHV_{fuel} are the mass flow and the lower heating value of the fuel, respectively.

On the basis of the Shomate equation [19], the enthalpy flow is calculated by

$$\dot{H}_{exh} = \frac{AT_{exh}}{1000} + \frac{B}{2}\left(\frac{T_{exh}}{1000}\right)^2 + \frac{C}{3}\left(\frac{T_{exh}}{1000}\right)^3 + \frac{D}{4}\left(\frac{T_{exh}}{1000}\right)^4 + E\frac{1000}{T_{exh}} \qquad (3)$$

where $A,B,...,E$ are coefficients for each constituent of the exhaust gas. The temperature T_{exh} is now solved from Eq. (3) and applied as an input parameter for the heat recovery model of IDA-ICE.

2.3 Performance assessment

The performance of alternative micro-cogeneration strategies is evaluated in terms of annual primary energy use and CO_2 emissions. Primary energy use is calculated by

multiplying the annual energy consumption of each energy carrier (thermal and electrical energy) by a specific primary energy conversion factor (PER) that indicates the amount of primary energy needed to produce one kilowatt hour of supplied energy at the boundary of the consumption site. Hence, primary energy use represents the real burden related to energy supply, including the fuel's chemical energy plus all the losses caused by the conversion and delivery of each form of energy. The emissions of carbon dioxide are computed equivalently, on the basis of annual energy consumption and a specific carbon dioxide emission factor (CEF). [20]

Primary energy and carbon dioxide methods provide a simple and relatively accurate performance assessment tool, even though the approach is rather inflexible [21]. Both factors depend on the national energy mix, which varies over time as a result of peak demands. Therefore, a method is employed in the present study that addresses the temporal changes in the utilization of various energy sources. Presuming that energy demand and primary energy factors are known for each hour of the year, the annual (8760 h) primary energy demand Q_{pr} can be calculated from

$$Q_{pr} = \sum_{i=1}^{8760} \left(Q_{fuel,i} PER_{fuel,i} \pm W_{grid,i} PER_{grid,i} \right) \quad (4)$$

where $Q_{fuel,i}$ and $W_{grid,i}$ are the fuel consumption of the micro-cogeneration system and the electricity purchased from the grid, respectively, and $PER_{fuel,i}$ and $PER_{grid,i}$ are the primary energy factors for the fuel used by the system and the grid electricity during the i-th hour, respectively. Correspondingly, the carbon dioxide emission rate (CDER) is obtained from

$$CDER = \sum_{i=1}^{8760} \left(Q_{fuel,i} CEF_{fuel,i} \pm W_{grid,i} CEF_{grid,i} \right) \quad (5)$$

where $CEF_{fuel,i}$ and $CEF_{grid,i}$ are the carbon dioxide emission factors for the fuel used by the system and the grid electricity during the i-th hour, respectively.

In the above equations, (Eq.(4) and (5)), $W_{grid,i}$ is assigned a negative value if the micro-cogeneration system feeds electricity into the grid. This represents the situation in which the system displaces the use of grid electricity and thus its primary energy consumption and emissions. If the system displaces electricity to the extent that the primary energy consumption (or emissions) corresponding to the displaced electricity exceeds that caused by the system's fuel consumption, then the primary energy (or emissions) will be negative.

Given that one primary energy and emission factor can be assigned to one source of energy j in an electricity production mix with n energy sources, the total primary energy factor for grid electricity is

$$PER_{grid} = \sum_{j=1}^{n} r_j PER_j \quad (6)$$

and the emission factor is

$$CEF_{grid} = \sum_{j=1}^{n} r_j CEF_j \quad (7)$$

where r_j is the ratio of the energy source j in the energy mix and PER_j and CEF_j are

the individual primary energy and emission factors for the energy source j,

respectively.

The temporal variations in the primary energy and emission factors of individual

fuels are only associated with possible changes in supply chains and their impact on

the absolute value of the factors is relatively small. Hence, it is reasonable to use

average values in the above assessment instead of trying to figure out exact (hourly)

numbers. Average non-renewable primary energy (NRPE) and CO_2 emission factors

for various energy forms are summarized in Table 1.

(Insert Table 1 around here.)

2.4 Economic analysis

A micro-cogeneration system can be considered economically viable if annual

operating savings result due to improvements in energy efficiency, the use of less

expensive fuels as substitutes for expensive grid electricity, and due to revenue

generated through the export of electricity to the grid. In the present study, we first

test the above condition by multiplying the annual amount of energy purchased for

each micro-cogeneration alternative (obtained from the simulations) by the reference

price of a given source of energy (fuel or grid electricity). If an alternative satisfies

the condition at a reasonably high annual saving, a simple payback analysis is

conducted to further evaluate the financial viability of micro-cogeneration.

Here, if the discounted, cumulated savings during an approved period of time

(payback period) give the maximum capital investment threshold of the micro-

cogeneration system. The investment is considered economically viable when the system investment is less than or equal to the threshold. The condition is satisfied if the annuity equation holds:

$$C_{I,CHP} - \frac{(1+r)^n - 1}{r(1+r)^n} S_{a,CHP} = 0 \qquad (8)$$

where $C_{I,CHP}$ is the total capital investment of the micro-cogeneration system, $S_{a,CHP}$ is the annual savings during the given time period n, and r is the real interest rate. In this analysis, a fixed 5 % interest rate and 20-year lifetime have been applied for all the heating system investment estimations. Here the total investment includes the net present value of all possible additional costs that occur during the lifetime of the system, such as maintenance and repairs.

In this analysis, the total system investment costs $C_{I,CHP}$ are not calculated as such, but instead the authors evaluate the maximum investment costs threshold that indicates the maximum feasible difference between the investment costs of the compared heating solutions. Thus, the annual savings $S_{a,CHP}$ is here applied as the annual cost difference between two systems.

3 Viability analysis

3.1 Building description

The target building is a two-floor single-family house with a heated area of 145.4 m^2, occupied by four persons following three different profiles that apply on a daily basis

(Table 2). The above model is employed to represent a unit module (one house) in the evaluation of small-scale district heating. The reference location is Helsinki, Finland (60° N, 25° E), and the weather data for 2001 are used, where the annual number of heating degree days is 3871 Kd. The building is equipped with central mechanical supply and exhaust ventilation (constant air volume 53 L s^{-1}, air infiltration rate 2.0 1/h at 50 Pa) with heat recovery (efficiency 60%), and a hydronic heating system.

(Insert Table 2 around here.)

3.2 Energy demand

The heating system has been given a set-point to maintain the room temperature of 21.5º C. The building does not contain a cooling system, so the temperature rises during the summer months. The electrical demand of the lighting and appliances is defined as the sum of the power requirements of single devices (100 W) according to the profiles of occupancy, as well as the use of domestic hot water. Electrical and domestic hot water demand profiles are shown in Figure 1. Energy demands per m^2 of reference area, heat transfer coefficients (*U*-values), and solar heat gain coefficients (*G*-values) are summarized in Table 3.

(Insert Figure 1 around here.)
(Insert Table 3 around here.)

3.3 System description and micro-cogeneration strategies

The reference system is a hydronic heating system connected with district heating network through a heat exchanger for the water circulation through radiators and

another for domestic hot water (DHW). The heat transfer efficiency between district

heat and radiator networks is taken to be 100%.

There are four alternative energy sources for small-scale district heating:

DH1.   light heating oil (total efficiency $\eta = 80\%$ (LHV), including the

distribution losses)

DH2.   wooden pellet (total efficiency $\eta = 80\%$ (LHV), including the

distribution losses)

DH3.   ground-source heat pump (coefficient of performance of the entire

system, distribution losses included, COP = 2.5)

DH4.   wooden pellet-fired Solo Stirling 161 Stirling engine micro-

cogeneration plant (nominal electrical power 9.5 kW_e, thermal power

26 kW_{th}, electrical efficiency $\eta_e = 24\%$ (LHV), thermal efficiency $\eta_{th} =$

66% (LHV), according to the manufacturer's data)

Case DH1 represents a common practice in Finnish small-scale district heating

plants. Therefore it has been considered in this comparison even though it cannot be

fairly evaluated with the alternatives as it uses a non-renewable fuel. In cases DH1-

DH3, all the electricity is purchased from the grid. In case DH4, the micro-

cogeneration system is modeled with the given two constant efficiencies and operated

at nominal power throughout the year. The excess electricity is fed into the grid and

the thermal surplus is dumped to the environment.

The individual micro-cogeneration plant (WhisperGen SE 0.7 kW_e, constant

electrical efficiency $\eta_e = 9.3\%$, constant net thermal conversion efficiency $\eta_q = 97\%$,

both determined on the basis of lower heating value (LHV) of the natural gas; LHV =

12.9 kWh kg^{-1} = 46.4 MJ kg^{-1}, as reported in detail in [4] and [5]), is connected to a

hydronic heating system via a buffer storage that allows the parallel application of more than one thermal source and can be set to operate at constant power or to follow the electrical or thermal load or both provided that the system can be controlled ideally. In practice, the system only allows ON/OFF operation, where the threshold values for temperatures and electrical/thermal power are given as set points to determine whether the device is activated or deactivated. In the event of a thermal surplus or thermal shortage, the device is either deactivated or an auxiliary burner is started to ensure sufficient heat generation. The excess electricity is fed into a battery if possible; otherwise, the system is shut down. The skin losses are released to the room surrounding the plant, which allows them to be utilized in heating up neighboring rooms and preheating the combustion air. The integration of the Stirling engine micro-cogeneration system into the building's heat distribution system is illustrated in Figure 2.

(Insert Figure 2 around here.)

As a part of the work reported in detail by Söderholm [26], the dynamic Stirling engine model implemented into IDA-ICE was used to find out the threshold values for both electrical and thermal power, optimal sizes for storage tanks, and the effect of heat recovery from the exhaust gases with the aim at avoiding the annual use of grid electricity and thermal dumping. In comparison with a reference system, including a standard low temperature natural gas boiler (efficiency $\eta = 90\%$), at best a 3-5% decrease in primary energy consumption and CO_2 emissions, were obtained for a natural gas-fuelled SE micro-cogeneration system.

On the basis of the above research, the following system was identified here as the most promising in the sense of individual micro-cogeneration:

IND1. threshold values 200 W and 3500 W, electrical and thermal, respectively / thermal storage 500 L / heat recovery from exhaust gases (buffer storage of 500 L) / mandatory operation of 2.5 h during peak demand hours between April 1 and October 31

Furthermore, we assume that the performance characteristics of a pellet fuelled Whispergen Stirling engine micro-cogeneration plant do not differ significantly from that of a natural gas fuelled plant.

3.4 Primary energy and emission profiles

The primary energy and emission factors for each hour were calculated by way of a spreadsheet application, following the principles in Subsection 2.4. The Finnish electricity production mix for the year 2006 was determined using measured hourly electricity generation data in Finland (coverage: 99% of the plants), plus imports and exports inside the Nordic electricity market. The source of these data is Finnish Energy Industries (ET). The profiles derived from these data are shown in Figure 3.

(Insert Figure 3 around here.)

3.5 Energy prices

To assess the economic value of the savings, the typical Finnish price for a small natural gas user is applied as a reference, i.e. €0.04 per kilowatt-hour[1]. The reference retail prices for other energy sources are € 0.10 kWh^{-1} for electricity, 0.05 € kWh^{1}

for wood pellets, and € 0.06 kWh[1] for heating oil[2]. An additional electricity-to-grid

price has been defined as € 0.04 kWh[1].

4 Results

4.1 Annual energy balance

Annual energy demands, fuel consumptions, thermal dump and electrical shortage or

surplus for the micro-cogeneration systems were ascertained for two different

climates (Helsinki (60° N, 25° E, 3871 Kd) and Jyväskylä (62° N, 26° E, 4800 Kd))

and two house constructions (standard house and passive house) and they are

summarized in Table 4. The values are given as the function of the number of

buildings in the set (N) in megawatt-hours per year [MWh a^{-1}].

(Insert Table 4 around here.)

The annual electrical demand is the same for all of the houses and it does not depend

on the location or whether the house is of passive or standard construction. Therefore,

a conclusion can be drawn on the basis of Table 4, that the regional system DH4 is

not dependent on the grid electricity if the number of houses does not exceed three

(3). On the other hand, the system is not capable of generating excess electricity if the

number of houses exceeds 20. The individual micro-cogeneration system (IND1)

always requires both grid electricity and auxiliary heat. Due to its control, based on

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[1] Vattenfall, representing a large company providing gas for private customers, charges
0.0423 € kWh[1] , while Valkeakaasu, a corresponding small-sized company, charges 0.0449 € kWh[1]
[2] The other energy prices are adapted with slight simplifications from a well established online
household heating systems planning tool, that uses Finnish energy prices from spring 2009
(http://www.motiva.fi/rakentaminen/lammitysjarjestelman_valinta/vertaile_lammitysjarjestelmia/pient
alon_lammitysjarjestelmien_vertailupalvelu/kaytetyt_energianhinnat).

threshold values, the annual degree of operation remains less than 100% and therefore more grid electricity is required. The need to employ auxiliary heat in the system DH4 starts from the number of houses (4-7) depending on the construction and climate. To eliminate thermal dump entirely, the building group served by the system DH4 should contain 132 passive houses or 123 standard houses in the Helsinki location, or 126 standard houses in Jyväskylä.

The percentage of micro-cogenerated (DH4) electricity of the total annual electricity demand and that of micro-cogenerated heat of the total annual thermal demand as the function of the size of the group of buildings is shown in Figure 4.

(Insert Figure 4 around here.)

As seen in Figure 4, more than 70 % of thermal and electrical energy demand can be supplied by micro-cogeneration only when the number of houses is ten (10) or less. After that the percentage first reduces quickly and becomes nearly steady, being 10-20% when the number of houses reaches 100.

4.2 Primary energy demand and emissions

Figure 5 summarizes the annual primary energy use and CO_2 emissions of the systems DH1 through DH4 and IND1. The values are given in kilowatt hours and kilograms per each built square meter and year to make use of a general expression that deals with a "mass" of buildings of a certain type rather than with single buildings. The primary energy use and CO_2 emissions of the alternatives DH1 through DH3 and IND1 remain constant because the energy supply is "scalable"

according to the demand, whereas the performance of the system DH4 (local micro-cogeneration with pellet-burning Solo Stirling 161) is represented by a curve.

(Insert Figure 5 around here.)

The data in Figure 5 indicate that micro-cogeneration is a top option among its competitors in terms of primary energy consumption and CO_2 emissions when the built area (the total area of buildings served by a cogeneration plant) varies between 727 m^2 (5 houses) and 5089 m^2 (35 houses).

The curves representing the performance of the system DH4 have negative values due to the displacement effect, as was anticipated in Section 2.3. Even though some thermal dumping is inevitable when the number of buildings is small (and the total thermal demand low), the values remain negative, i.e. the undesirable effect of the thermal dumping is compensated by the electricity displacement. The most obvious reason for this is that the primary energy and emission factors for electricity are substantially higher than those for fuel (wooden pellets). Therefore, a crucial matter is to which extent the system DH4 is able to displace electricity purchased from the grid. The more electricity is generated vis-à-vis the electrical demand, the stronger the displacement effect will be.

When compared to small-scale district heating based on oil-boiler (DH1), the system DH4 comes out distinctly better, but a comparison just with the system DH1 is not fair without investigating plant constructions based on renewable energy sources (DH2). On the other hand, the individual system (IND1) is not necessarily an approvable alternative if an entry to a district heating network exists and is available.

Finally, it can be inferred from Figure 5 that the viability of micro-cogeneration is not sensitive to location (climate) and the type of construction (passive or standard construction).

4.3 Economic viability

Annual energy costs for the systems DH1 through DH4 and IND1 are solved using the energy consumption data from Table 4 and the energy prices discussed in Subsection 3.5. An example of such costs is given in Table 5. With Eq. (8), the differences in these costs can be transferred into the maximum investment cost threshold between the two systems like demonstrated in Table 6. These thresholds have significant variations depending on the systems compared and the type of buildings being heated. Among systems DH1 and DH2, the pellet based DH2 system has the lowest energy costs. However, the investment intensive heat pump system DH3 has even lower running costs, and the micro-CHP system DH4 can compete with it only in very limited size ranges. For standard houses in Helsinki and Jyväskylä, DH4 has (around 30 houses) about € 1000 maximum investment cost threshold in comparison to DH3. Similar maximum thresholds exists around 40 houses when passive houses in Helsinki are considered. However, with the passive house heating load DH4 performed best against DH3. When compared with DH1 and DH2, the DH4 system seems to have a clearly higher total investment cost, and the larger the system the larger the difference. For example, for 50 households the maximum investment cost threshold between DH2 and DH4 is € 22 000-26 000 for the standard houses and € 15 000 for the passive house. In small system sizes, DH4 cannot compete, and the point of zero investment cost threshold for DH2 and DH4 is

about 8 households for the standard houses and between 10 and 15 for the passive
ones.

(Insert Table 5 around here.)

(Insert Table 6 around here.)

The individual CHP-system IND1 exhibited different behaviour with constant per
household investment cost thresholds. With the applied assumptions, IND1 should
always have a smaller total investment than DH3. The difference is about € 258 per
household. Correspondingly, when compared with DH1 and DH2 the CHP-based
IND1 has always a positive maximum investment cost threshold. For example, with
standard Helsinki house DH2 systems the threshold is € 183 per household. The
corresponding figures with passive houses are smaller by more than a half.

4.4 On the errors and uncertainties

The above results apply only to certain equipment and system configurations.
However, one of the most important uncertainties is related to the sensitivity of the
result to the plant efficiency. In practice, the electrical and overall efficiencies of a
Stirling engine micro-cogeneration plant vary in the range of 10 to 30% and 75 to
90%, respectively [27].

The impacts of electrical (η_e) and overall (η_{tot}) efficiencies on the annual primary
energy use and emissions in the present analysis are shown in Table 7. Both results
apply to a group of ten standard houses (corresponding to minimum CO_2 emissions)
located in Helsinki.

(Insert Table 7 around here.)

As seen in Table 7, the reference case ($\eta_e = 24\%$, $\eta_{tot} = 90\%$) represents a good performance in comparison with the "optimum" case ($\eta_e = 30\%$, $\eta_{tot} = 90\%$). Because the generated electrical power is kept constant, varying the electrical efficiency does not affect electrical shortages and surpluses, but rather the amount of fuel demanded by the plant and thus the primary energy and emission profiles. On the other hand, increasing the amount of heat recovered from the plant to the water circulation (increasing the overall efficiency) provides benefits only if the heat can be utilized in terms of heating spaces or producing domestic hot water.

In the economic analysis, the calculations were based on a fixed interest rate and system lifetime. By increasing the interest rate, the break-even points in comparing the systems remain the same, but the resulting quantities change. For example, using 8% interest rate results in about 20% lower maximum investment cost thresholds. Shortening the system lifetimes has a similar effect, setting it to 14 years results also in 20% lower thresholds. If fuel prices are varied, increasing any fuel cost will correspondingly limit the success of the technology using it. Increased electricity prices always benefit the CHP-systems, but particularly it makes them more competitive with the heat pump system DH3.

In general, the price of fuel has so far been lower than that of electricity, and there is a correlation between the prices. These statistical effects were not examined in detail.

Simulation errors cause an additional source of uncertainty in this type of study. The variation between actual energy demand and energy demand estimated on the basis of

dynamic, whole-building simulations may be up to $\pm$ 10%, but the best agreements lay within $\pm$ 3% [28, 29]. Hence, a separate uncertainty analysis was not included in this study.

5 Conclusions

In this paper, a 9.5 kW_e wooden pellet fuelled Stirling engine-based micro-cogeneration plant was considered a substitute for small-scale district heating based on oil or pellet fuelled boiler, a ground-source heat pump and an optimally operated, 0.7 kW_e individual micro-cogeneration system encompassing heat recovery and appropriate thermal storage. Our results pointed out that the use of a district Stirling engine micro-cogeneration system reduced primary energy use and CO_2 emissions in comparison with any of the reference systems. The result was not sensitive to climate or the energy efficiency or number of buildings. The annual primary energy demand and CO_2 emissions were found to be 25% and 19% lower, respectively, relative to the pellet fuelled district heating plant. Due to a significant displacement of grid electricity, the plant's primary energy consumption can be negative when the total built area served by the plant is less than 1200 m^2.

It was demonstrated that when the whole lifetime of the investment is considered the maximum investment cost threshold of a CHP-based district heating system serving ten houses or more can typically be positive when compared with oil and pellet systems, but negative when compared with corresponding heat pump system.

The above results apply to given types of buildings located in a cold climate. The computational method is generic in terms of application.

In the future, electricity supply for buildings will play a more important role than the production of thermal energy, even in cold climates. Firstly, the latter can be produced in easy and cheap ways from renewable resources such as biomass. Secondly, the ratio of electrical demand to thermal demand will increase drastically due to construction standards that aim at the lowest possible thermal loss. Thirdly, the construction practices based on so called zero energy standards are being developed. They aim at making the net energy flow across the building boundary zero. Local electricity production is a necessity in this sense, but thermal energy becomes a liability rather than an asset. Since a Stirling engine-based micro-cogeneration plant generates electricity at low efficiency, its application in the future will be limited should these thermal advances be realised.

There are several avenues for further research. The research on micro-cogeneration will have to address the effects of the large-scale penetration of micro-cogeneration into the national energy grids. The concept of micro-cogeneration will also be extended to hybrid systems where solar and micro-wind power is integrated into one system, and the simultaneous production of more than two "forms" of energy, the so-called polygeneration.

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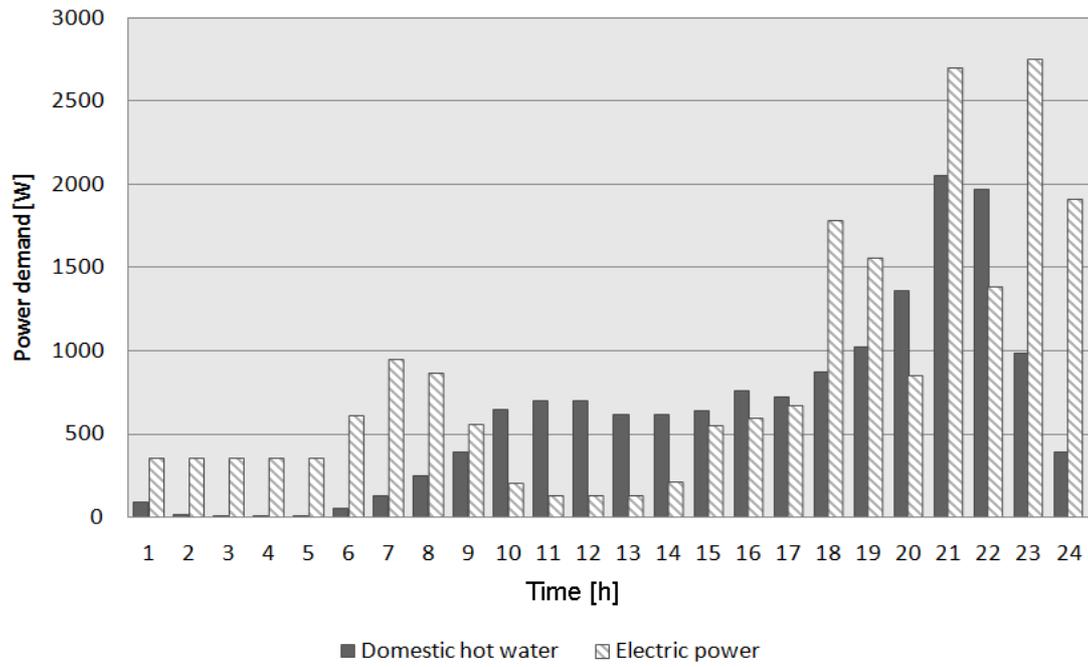
Figure 1. Hourly power consumption schedules for domestic hot water and electric power demand [25].
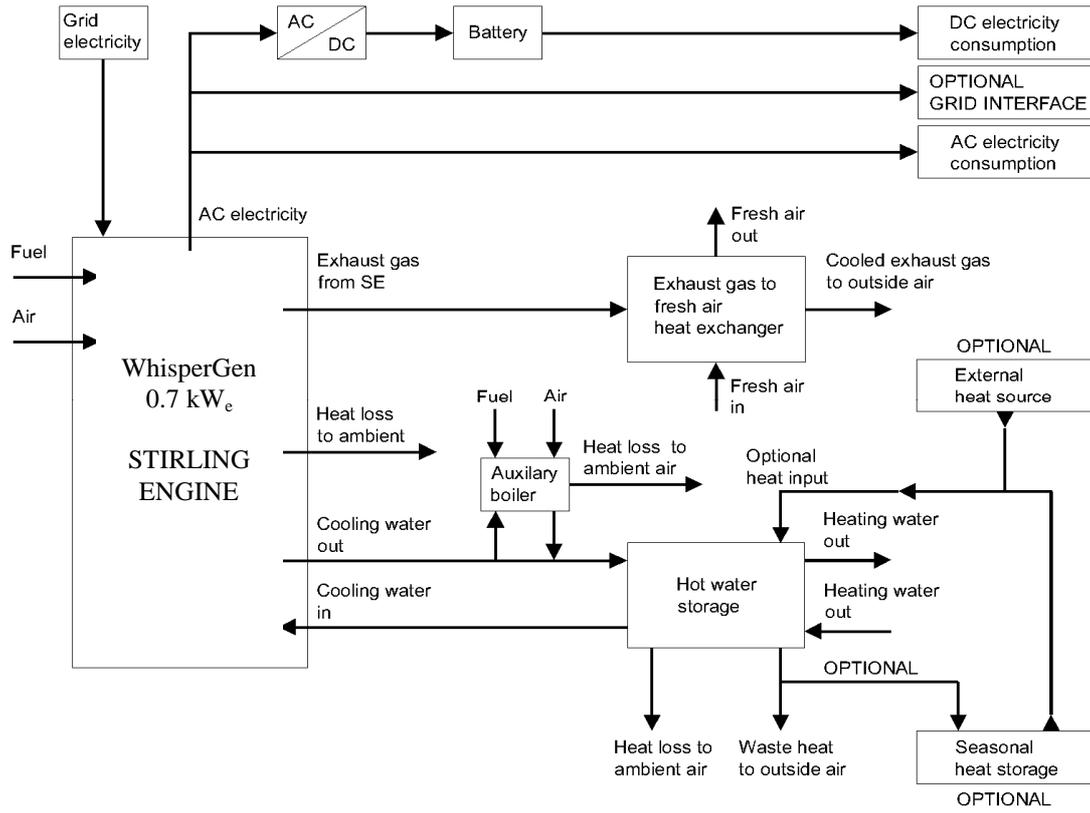
Figure 2. Integration of the individual micro-cogeneration plant [26].
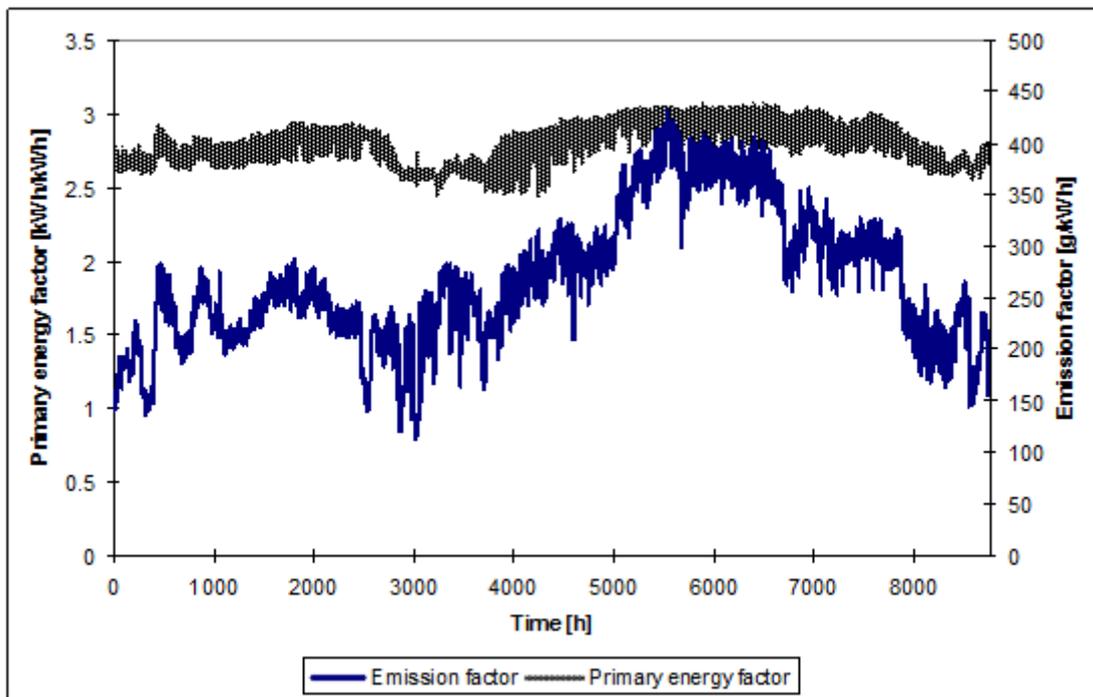
Figure 3. Hourly primary energy and emission factors of Finnish electricity mix in 2006.
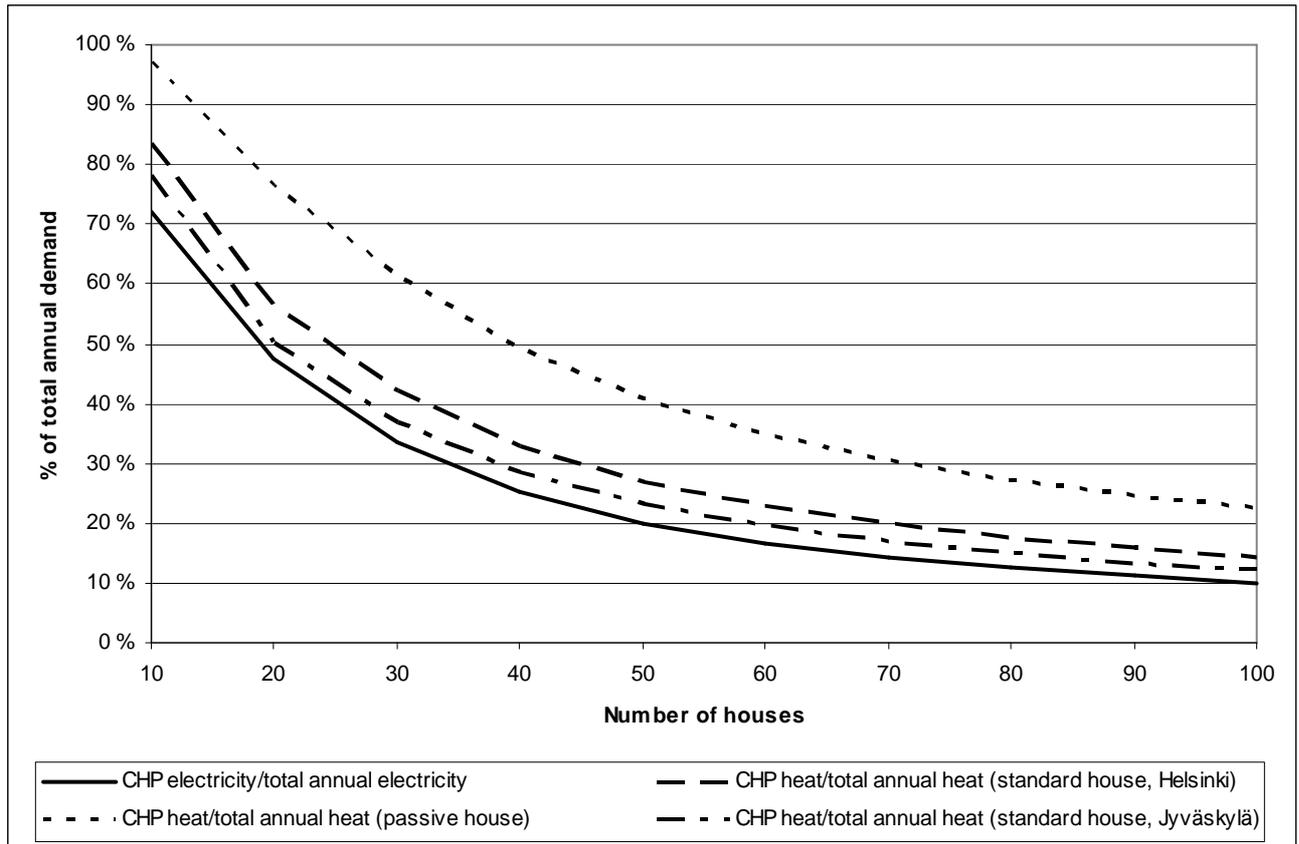
Figure 4. Percentage of micro-cogenerated electricity and heat.
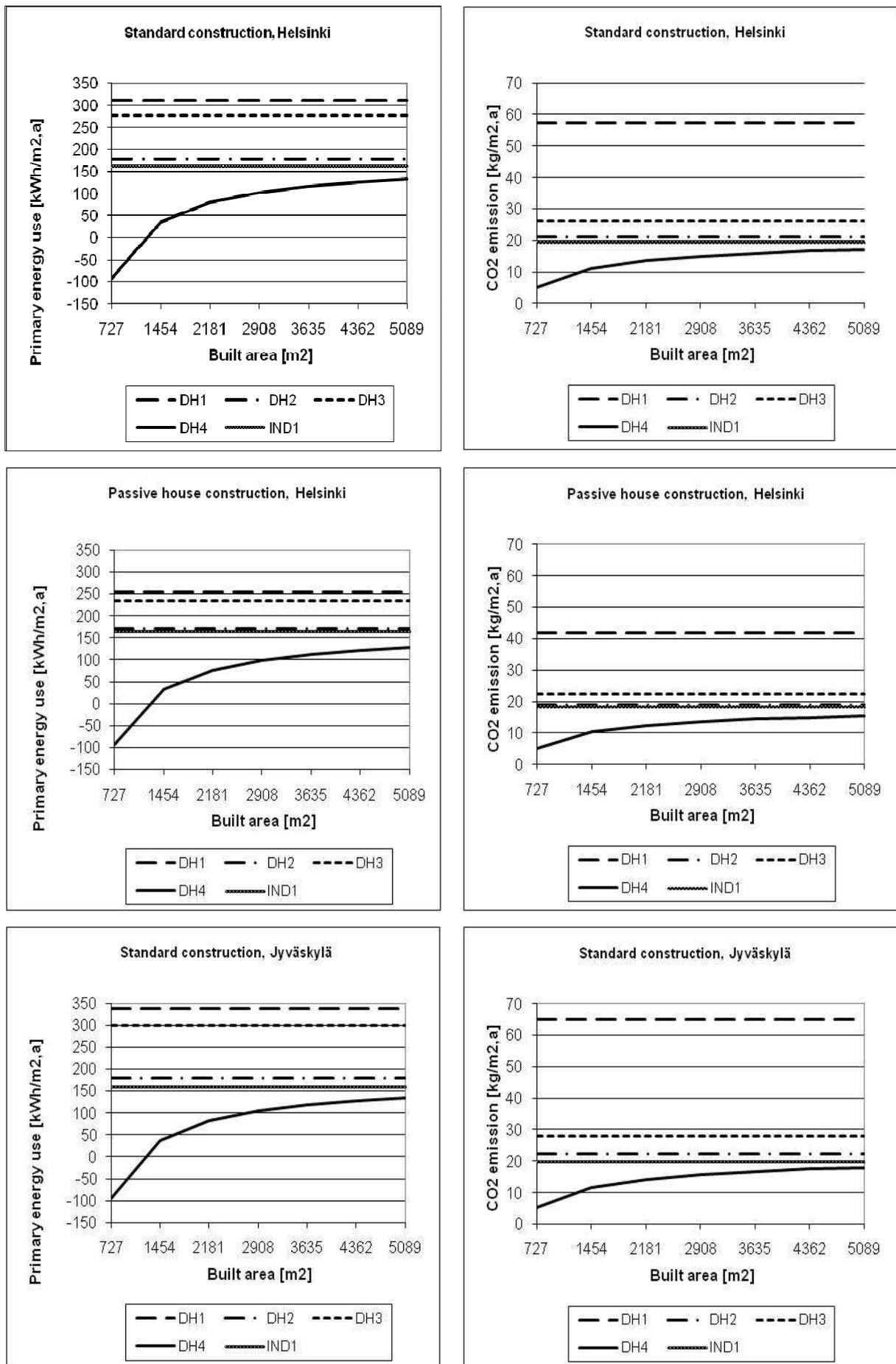
Figure 5. Primary energy use and CO_2 emissions.

Table 1. Primary energy factors and CO_2 emission factors [22-24].

	NRPE [kWh kWh^{-1}]	CEF [g kWh^{-1}]
Fuel oil	1.13	311
Gas	1.36	277
Natural gas	1.14	247
Wood shavings	0.06	4
Wooden pellet	0.14	43
Log	0.09	14
Nuclear electricity	2.8	16
Coal electricity	4.05	1340
UCPTE electricity mix	3.14	617
EU-17 grid electricity	2.35	430

Table 2. Occupancy patterns.

	The building is occupied between:
Profile 1	6:00…8:00 A.M and 3:00…23:00 P.M.
Profile 2	22:00 P.M…8:00 A.M.
Profile 3	5:00…22:00 P.M.

Table 3. Energy demands, heat loss coefficients, and solar heat gain coefficients.

	Standard house	Passive house
Space heat demand [kWh $m^{-2}a^{-1}$] [b]	67.9 (244.4)	32.2 (115.9)
Electricity demand [kWh $m^{-2}a^{-1}$] [b]	32.2 (115.9)	32.2 (115.9)
U-value exterior wall [W $m^{-2}K^{-1}$]	0.21	0.07[a]
U-value roof [W $m^{-2}K^{-1}$]	0.11	0.06
U-value ground floor [W $m^{-2}K^{-1}$]	0.16	0.08
U-value door [W $m^{-2}K^{-2}$]	1.10	0.40
U-value windows [W $m^{-2}K^{-2}$] [b]	1.0	0.7
G-value glazing [-]	0.56	0.46

[a] Insulation thickness 600 mm

[b] The values in SI units (MJ) are given in parentheses. The conversion factor is 1 kWh = 3.6 MJ.

[c] The frame is included in the U-value; The standard house is fit with triple-glazed windows, the passive house entails triple-glazed windows with two low-emissive selective layers and krypton gas fill.

Table 4. Annual energy balance in MWh $^{a-1}$.

Standard house, Helsinki

N	Electricity	Heat	Electricity DH3[a]	Electrical shortage DH4	Electrical surplus DH4	Electrical shortage IND1	Fuel DH1(2)	Fuel DH4	Fuel IND1
1	8	16	15	0	75	8	20	347	18
2	17	31	29	0	67	15	39	347	36
3	25	47	44	0	58	23	59	347	54
4	33	63	58	1	51	30	79	347	73
5	41	79	73	3	45	38	98	347	91
6	50	94	87	6	39	45	118	350	109
7	58	110	102	10	35	53	138	354	127
8	66	126	117	14	31	61	157	360	145
9	75	142	131	18	27	68	177	367	163
10	83	157	146	23	23	76	197	376	181
15	124	236	219	52	11	114	295	431	272
20	166	315	292	87	4	151	393	499	363
30	248	472	437	165	0	227	590	650	544
40	331	629	583	248	0	303	787	816	726
50	414	787	729	331	0	379	983	985	907

Passive house, Helsinki

N	Electricity	Heat	Electricity DH3[a]	Electrical shortage DH4	Electrical surplus DH4	Electrical shortage IND1	Fuel DH1(2)	Fuel DH4	Fuel IND1
1	8	10	12	0	75	8	12	347	12
2	17	20	25	0	67	16	25	347	23
3	25	30	37	0	58	24	37	347	35
4	33	40	49	1	51	32	50	347	46
5	41	50	61	3	45	40	62	347	58
6	50	60	74	6	39	48	74	347	69
7	58	70	86	10	35	56	87	347	81
8	66	79	98	14	31	65	99	348	92
9	75	89	110	18	27	73	112	349	104
10	83	99	123	23	23	81	124	350	115
15	124	149	184	52	11	121	186	367	173
20	166	199	245	87	4	161	248	399	230
30	248	298	368	165	0	242	372	475	345
40	331	397	490	248	0	323	497	572	460
50	414	497	613	331	0	403	621	674	575

Standard house, Jyväskylä

N	Electricity	Heat	Electricity DH3[a]	Electrical shortage DH4	Electrical surplus DH4	Electrical shortage IND1	Fuel DH1(2)	Fuel DH4	Fuel IND1
1	8	19	16	0	75	7	23	347	21
2	16	37	31	0	67	15	46	347	42
3	25	56	47	0	58	22	70	347	63
4	33	74	63	1	51	29	93	347	85
5	41	93	78	3	45	36	116	349	106
6	49	111	94	6	40	44	139	353	127
7	58	130	110	10	35	51	163	360	148
8	66	149	125	14	31	58	186	369	169
9	74	167	141	18	27	65	209	380	190
10	82	186	157	23	23	73	232	392	211
15	124	279	235	52	11	109	348	466	317
20	165	372	314	86	4	145	465	552	423
30	247	557	470	164	0	218	697	738	634
40	330	743	627	247	0	290	929	937	845
50	412	929	784	329	0	363	1,161	1,139	1,056

a   includes electricity used for heating

Table 5. Annual energy costs for Helsinki standard house energy systems with 1, 5 and 15 households.

Number of households	DH1	DH2	DH3	DH4	IND1
1	201	181	146	1,012	166
5	1,004	906	729	1,195	832
15	3,012	2,717	2,186	2,189	2,497

Number of households	DH1	DH2	DH3	DH4	IND1
1	201	181	146	1,012	166
5	1,004	906	729	1,195	832
15	3,012	2,717	2,186	2,189	2,497

Table 6. Differences in total system investment costs for Helsinki standard house energy systems with 1, 5, and 15 households.

Number of households	DH1	DH2	DH3	DH4	DH4+[a]	IND1
1	-14,784	-15,029	-15,471	428	183	-258
5	-5,152	-6,377	-8,583	2,141	916	-1,290
15	9,574	5,897	-720	6,424	2,747	-3,870

a   The system DH4+ equals DH4 except 0.05€/kWh compensation is expected from excess electricity generated by the system.

Table 7. The impact of electrical and thermal efficiencies on the primary energy use, emissions and annual energy balance (a group of 10 houses located in Helsinki).

η_e/η_{tot}	PE^a [kWh m^{-2},a^{-1}]	CO_2^a [kg m^{-2},a^{-1}]	Electrical shortage [MWh,a^{-1}]	Thermal dump [MWh,a^{-1}]	Electrical surplus [MWh,a^{-1}]	Fuel [MWh,a^{-1}]
30% / 90%	30.63 (58.06)	9.68 (10.76)	23	54	23	327
24% / 90%	35.30 (61.66)	11.11 (11.86)	23	98	23	375
10% / 75%	79.28 (95.49)	22.25 (24.62)	23	384	23	832

a   The number in parentheses indicates the case where the electricity displacement is omitted.