LAPPEENRANTA UNIVERSITY OF TECHNOLOGY
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CHOOSING THE OPTIMAL ENERGY SYSTEM FOR BUILDINGS AND DISTRICTS

Examiners: Professor, D. (Tech.) Esa Vakkilainen
Docent, D. (Tech.) Juha Kaikko

ABSTRACT

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Keywords: Energy system, decision method, multi-criteria, renewable energy

The purpose of this master's thesis was to develop a method to be used in the selection of an optimal energy system for buildings and districts. The term optimal energy system was defined as the energy system which best fulfils the requirements of the stakeholder on whose preferences the energy systems are evaluated. The most influential stakeholder in the process of selecting an energy system was considered to be the district developer.

The selection method consisted of several steps: Definition of the district, calculating the energy consumption of the district and buildings within the district, defining suitable energy system alternatives for the district, definition of the comparing criteria, calculating the parameters of the comparing criteria for each energy system alternative and finally using a multi-criteria decision method to rank the alternatives.

For the purposes of the selection method, the factors affecting the energy consumption of buildings and districts and technologies enabling the use of renewable energy were reviewed. The key element of the selection method was a multi-criteria decision making method, PROMETHEE II. In order to compare the energy system alternatives with the developed method, the comparing criteria were defined in the study. The criteria included costs, environmental impacts and technological and technical characteristics of the energy systems. Each criterion was given an importance, based on a questionnaire which was sent for the steering groups of two district development projects.

The selection method was applied in two case study analyses. The results indicate that the selection method provides a viable and easy way to provide the decision makers alternatives and recommendations regarding the selection of an energy system. Since the comparison is carried out by changing the alternatives into numeric form, the presented selection method was found to exclude any unjustified preferences over certain energy systems alternatives which would affect the selection.

TIIVISTELMÄ

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Tämän diplomityön tarkoituksena oli kehittää menetelmä alueiden ja rakennusten optimaalisen energiajärjestelmän valintaan. Optimaalinen energiajärjestelmä määriteltiin siten, että se vastaa parhaiten sen tahon odotuksia, jonka kannalta energiajärjestelmän valintaa tarkastellaan. Vaikutusvaltaisimpana tahona energiajärjestelmän valintaa koskevissa päätöksissä pidettiin alueen kehittäjää.

Valintamenetelmä koostui useasta vaiheesta: Alueen määrittelystä, rakennusten ja alueen energiankulutuksen laskennasta, sopivien energiajärjestelmävaihtoehtojen määrittelystä, vertailussa käytettävien kriteereiden määrittelystä, vertailtavien kriteerien arvojen laskennasta jokaiselle järjestelmävaihtoehdolle ja lopulta vaihtoehtojen vertailusta monimuuttujamallin avulla.

Valintamenetelmän tueksi työssä selvitettiin myös rakennusten ja alueiden energiankulutukseen vaikuttavia tekijöitä. Lisäksi esitettiin erilaisia uusiutuvan energian käytön mahdollistavia teknologioita, ottaen huomioon sekä energian tuotannon että varastoinnin. Valintamenetelmän ydin oli monimuuttuja-päätöksentekomenetelmä PROMETHEE II. Jotta energiajärjestelmä vaihtoehtoja kyettiin vertailemaan kehitetyllä menetelmällä, tarvittavat vertailukriteerit määritettiin työssä. Kriteerit käsittelivät kustannuksia, ympäristövaikutuksia sekä järjestelmien teknisiä ominaisuuksia. Jokaiselle kriteerille määritettiin painoarvot, jotka perustuivat kahden aluekehityshankkeen ohjausryhmille lähetettyyn kyselyyn.

Valintamenetelmää sovellettiin kahdessa tapaustutkimuksessa. Tapaustutkimusten tulosten perusteella valintamenetelmän todettiin antavan käyttökelpoisen ja luontevan tavan tuoda päätöksentekijöille vaihtoehtoja ja suosituksia energiajärjestelmän valintaa koskien. Koska vertailu toteutetaan muuttamalla vaihtoehdot numeeriseen muotoon, esitellyn valintamallin todettiin sulkevan pois mahdolliset valintaan vaikuttavat perusteettomat mieltymykset erilaisten energiajärjestelmien paremmuudesta.

Prologue

This master’s thesis was done at VTT. I would like to thank the organization for the possibility it offered for me to complete my studies and enthusiastically look forward for the interesting challenges in the future. The process of writing has been truly exciting and educating experience, largely thanks to the magnificent and inspiring working environment VTT has.

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List of symbols and abbreviations

Symbols:

a	alternative	[-]
C_a	capital costs per annual energy demand	[€/MWh]
I	investment costs	[€]
E_a	annual energy demand	[MWh/a]
c	criterion	[-]
crf	capital recovery factor	[-]
i	interest rate	[%]
n	operating time	[a]
w	criterion weight	[-]
r	normalized criterion value	[-]
p	preference function	[-]
x	criterion value	[-]
ϕ^+	positive outranking flow	[-]
ϕ^-	negative outranking flow	[-]
π	aggregated preference function	[-]

Abbreviations:

BAT	Best available technology
CH_4	Chemical formula of methane
CHP	Combined heat and power production
CO_2	Chemical formula of carbon dioxide
COP	Coefficient of performance
GEMIS	Global Emissions Model for Integrated Systems
GHG	Greenhouse gas
HAWT	Horizontal-axis wind turbine
MCDM	Multi-Criteria Decision Making
N_2O	Chemical formula of nitrous oxide
SF_6	Chemical formula of sulphur hexafluoride
VAWT	Vertical-axis wind turbine

1 Introduction

One of the major focuses in the development of districts and buildings today is energy efficiency. The base for the energy efficiency of buildings is set by the national building codes of Finland, but even more efficient methods of construction are constantly being developed. The energy efficiency on a district level is defined not only by the energy consumption of the buildings in the district, but also by several other factors. These factors include traffic, efficiency of land use and a numerous of other indicators. One factor which plays a crucially important part in the definition of an energy efficient building or district is the way the energy to meet the demand is supplied.

The European Union has set a target in the RES (Renewable Energy Sources) directive for the share of renewable energy in the final consumption to be increased to 20 % by 2020. The target for Finland is, according to the RES directive, that the share of renewable energy sources should cover 38 % by 2020. (2009/28/EC)

According to the district heat statistics by Energiateollisuus (2010a, 4), the share of fossil fuels in the production of district heat exceeded 80 % in 2009. Although the district heating network is a usual selection for the energy system of buildings in districts it is available, more alternatives should be given for the energy system selection process. Especially alternatives that are focused in renewable energy sources.

Providing the decision makers alternatives for traditional energy systems, such as district heat or electric heating, requires comparison of different alternatives. The results of the comparison of different energy system alternatives depend on the criteria used to compare and the relative importance given for each criterion in the comparison. Thus, by weighting the criterions used in the comparison by the preferences of the decision maker, an optimal energy system alternative can be determined.

This master's thesis is supported by VTT and has been done for an ongoing EU-project, Energy-Hub for residential and commercial districts and transport (E-HUB). The purpose of this master's thesis is to prepare a method for the comparison and selection of an energy system to be used in district development projects.

1.1 Target of the study

The main purpose of this master's thesis is to present a method to be used in the selection of an optimal energy system for buildings and districts. The term optimal energy system is defined as the energy system which best suits the preferences of the stakeholder on whose preferences the energy systems are evaluated. As optimality of an energy system depends on whose point of view the systems are compared and what are the criteria the energy systems are compared with, the study tends to answer the following questions: Who is the most influential stakeholder when decisions concerning energy systems are made and what qualities do they emphasize in the selection? What are the criteria used to compare the energy systems? The case studies are also conducted in order to answer the question: Does the size and structure of the district have effect on the selection of an optimal system?

1.2 Definition of the study

This master's thesis consists of five parts: key elements influencing energy demand of buildings and districts, inventory of enabling renewable energy technologies, theory for decision-making, case studies and discussion. In the beginning the target of the study and basic information about it is introduced. The introduction is followed by background analysis of factors influencing the energy demand in buildings and districts, and inventory of enabling renewable energy technologies for energy supply. Although all of the presented energy conversion and storage technologies are not used in the case studies due to technical feasibility requirements of the compared systems, for example fuel cells might prove out to be an important technology in the future of energy conversion and storage.

The background analysis part is followed by the theory and definition of the energy system selection method. The key stakeholder in the decision making is introduced along with the criteria used to compare the energy systems. Results of a questionnaire made concerning the values affecting the selection of energy system are presented in the definition of the selection method.

The energy system selection method is applied in two case districts. The districts in the case studies are different by their size but also by their structure. The energy consumption of the case districts is calculated and a series of energy system alternatives is selected for the optimization process in both case studies.

The final part of the master’s thesis includes discussions about the assumptions and definitions made during the study and their effects to the results of the case studies. The reliability of the selection method as well as its applicability in future district development projects is also discussed.

1.2.1 Limitations

There are two significant limitations in the study. First limitation is done regarding the energy system alternatives defined for the case districts in the study. The energy systems are assumed to be producing thermal energy and, in some alternatives, electricity only for the buildings within the case districts. The second fundamental limitation in the study and analysis of the energy systems of the case study districts is the assumption that the districts are not self-sufficient in terms of electricity production. Thus, the districts are connected to the national grid in all of the energy system alternatives analysed. This leads to the emphasis of the energy systems being on thermal energy production alternatives.

1.3 Methodology

The case studies are made in order to apply the energy system selection method defined in this master’s thesis in practise. The effect of the difference in the size and structures of case districts on the optimality of different energy system alternatives will be examined in the case studies. Therefore, the case districts selected for the case studies are different in both the size and the structure.

2 Energy demand of buildings and districts

To be able to evaluate the energy systems for buildings and districts, the energy consumption and capacity requirements must be clear. This chapter gives an overview of the major factors affecting the energy efficiency of buildings and districts. The methods to improve the energy efficiency, especially on a building level are also introduced in this chapter.

2.1 Building level energy consumption

The thermal energy consumption of a building is composed of three main factors: the heat losses through the building envelope, ventilation heat losses and the hot water thermal energy consumption. Electricity consumption of the buildings is the consequence of using the electric appliances, lighting and building service systems. (VTT, 2009, 92)

In section D3 of national building code of Finland, a low-energy building is defined as a building which consumes at maximum 85 % of the energy that a reference building does. The reference building represents a building which is designed after the current national building code of Finland. (Kalliomäki P., 2010) The low-energy building concept is currently the only target set by the building code towards energy efficient building. According to VTT definitions of a passive house, the energy consumption target varies depending on the geographic location of the building. In northern Finland, for example, the energy consumption requirements are less strict than in Southern Finland. (Lylykangas and Nieminen) The energy consumption on different energy efficiency levels of buildings is presented in Table 1.

Table 1. Requirement of different building energy efficiency levels (Modified from: Saari M., 2009)

	Building codes	**Low-energy building**	**Passive energy building**
Performance of heating			
Thermal power demand of heating [W/m^2]	50 – 70	20 – 30	10 – 20
Energy consumption [kWh/m^2,a]			
Space heating and cooling	70 – 130	40 – 60	20 – 30
Domestic hot water	25	25	20
Heating system losses	25 - 50	15 – 25	5 – 10
Total thermal energy consumption	130 – 205	80 – 110	45 – 60
Electricity consumption of appliances	50	45	40
Total energy consumption	180 – 260	125 – 155	85 – 100

One of the most important means to improve the energy efficiency of a building is to reduce the heating energy demand. Two of the most important ways to achieve reductions in the heating energy demand are the improvement in the insulation and air-tightness of the structural materials and the improving the efficiency of ventilation heat recovery. (VTT, 2009, 92-93) The reference level of these technical requirements is set by the national building code of Finland, section C3 (Kalliomäki P., 2010). The reference level and the improvements required to improve the energy efficiency of buildings are presented in Table 2. (Saari M., 2009)

Table 2. Methods to improve the energy efficiency of buildings (Saari M., 2009)

	Reference building	Low-energy building	Passive energy building
	U-values [W/m^{2}K]		
Exterior wall	0.24	0.15 – 0.20	0.10 – 0.13
Roof	0.15	0.10 – 0.15	0.06 – 0.08
Base floor	0.15 – 0.24	0.12 – 0.15	0.08 – 0.12
Doors	1.4	0.7	0.4 – 0.7
Windows	1.4	1.0	0.6 – 0.8

The electricity consumption can be affected by using energy efficient appliances. The development of the energy efficiency of electric appliances has been studied by Adato (Adato, 2008). The electric appliances efficiency, especially in low-energy and passive energy buildings can be assumed to be the BAT-level (Best Available Technology) which is introduced in the report.

2.2 District level energy consumption

On a district level, the energy consumption is dependent on the consumption of the buildings in the district as well as from the performance of possible energy distribution networks in centralized energy supply systems. Other factors which consume energy on a district level such as streetlights are not taken into account in the energy consumption calculations of this master’s thesis. The energy consumption of the buildings in the district and the method to affect it are presented in chapter 2.1.

The total energy consumption of the buildings is obtained by combining the energy consumption of all the buildings in the district. If the thermal energy is supplied by a centralized energy system, a heat distribution network is required to deliver the thermal energy to the buildings. The thermal energy losses of a heat distribution network depend on the qualities of the heat distribution piping such as the diameter and insulation. The loss heat flux and thermal energy losses of common heat distribution pipe sizes are presented in Table 3. The thermal energy losses are calculated by multiplying the loss heat flux by the amount of hours per year, 8760 h. (Nuorkivi et al., 2006, 217)

Table 3. Losses of heat distribution network (Nuorkivi et al., 2006, 217)

Pipe size	Loss heat flux [W/m]	Thermal energy loss [kWh/m,a]
DN25	15.8	138
DN40	22.6	198
DN50	24.5	215
DN65	27.3	239

Constantly improving energy efficiency of buildings sets a challenge regarding the construction of heat distribution networks. The costs of constructing the heating network as well as the costs generated from thermal energy losses of the network become more significant. However, with low-temperature district heating network design, the costs of the network can be reduced by 40 % and the thermal losses by 20 %. (Hagström et al., 2009) A low-temperature district heating network requires, for example: optimization of the heat demand, smaller pipe dimensions, larger insulation thickness and optimization of the heating networks length. (Olsen P.K. et al., 2008)

3 Inventory of enabling renewable energy technologies

Renewable energy is derived from constantly replenishing natural processes. The source of renewable energy in its numerous forms is the sun or the heat of the earth's core. (IEA, 2010) There are several methods to utilize renewable energy sources such as direct solar irradiation, wind potential and biomass. The variety of the technologies that can be applied in the energy systems of buildings and districts is wide. However, the market penetration of renewable energy technologies has been slow. The investment costs of renewable energy systems are relatively high when compared to traditional, fossil fuel operated energy generation technologies. The implementation of renewable energy requires the involvement of governments in forms of subsidies, policies and regulations. (Martinot et al., 2005)

This chapter introduces various energy conversion and storage technologies emphasising technologies based on renewable energy sources. Applicability and current status of certain conversion and storage technologies in Finland is also studied in the theory section. Although all of the presented energy conversion and storage technologies are not used in the case studies due to technical feasibility requirements of the compared systems, for example fuel cells might prove out to be an important technology in the future of energy conversion and storage.

3.1 Solar energy

The energy of solar radiation can be exploited in several ways. Active solutions of solar energy usage can be used to generate electricity, heating energy and cooling. Solar energy can also be used passively for space heating in buildings. The passive usage of solar energy is achieved by placement and alignment of buildings but also by making the structures of the building suitable for exploiting the solar energy. (Kara et al., 2004, 268)

The power of the solar radiation which meets earth exceeds the installed power generating capacity by several thousand times. The power of the radiation which meets the upper parts of Earths atmosphere is 1354 W/m^2, varying a bit due to the variation in Earths distance to the sun. In Southern Finland, the annual energy of the solar irradiation is around 1000 kWh/m^2 and in the Central Finland approximately 800 kWh/m^2. (Kara et al., 2004, 268; Erat et al., 2008, 13, 18)

Figure 1 represents the difference between the amounts of solar energy available and the actual energy demand. The demand curve is for thermal energy which makes the curve rather steep. The figure describes the problematic nature of solar energy use in Finland as the need for heating energy is at its peak while the yield of the solar thermal collectors is at its lowest. Electricity demand remains steadier throughout year if electric heating is not taken into account. The yield of a photovoltaic system or a solar thermal collector system is at its highest in the summer time when the demand is low. Therefore, solar energy is usually used as a secondary energy system to reduce the use of the primary system in the summer. The electricity and heat produced in the summer can be used in cooling applications and to heat the domestic hot water.

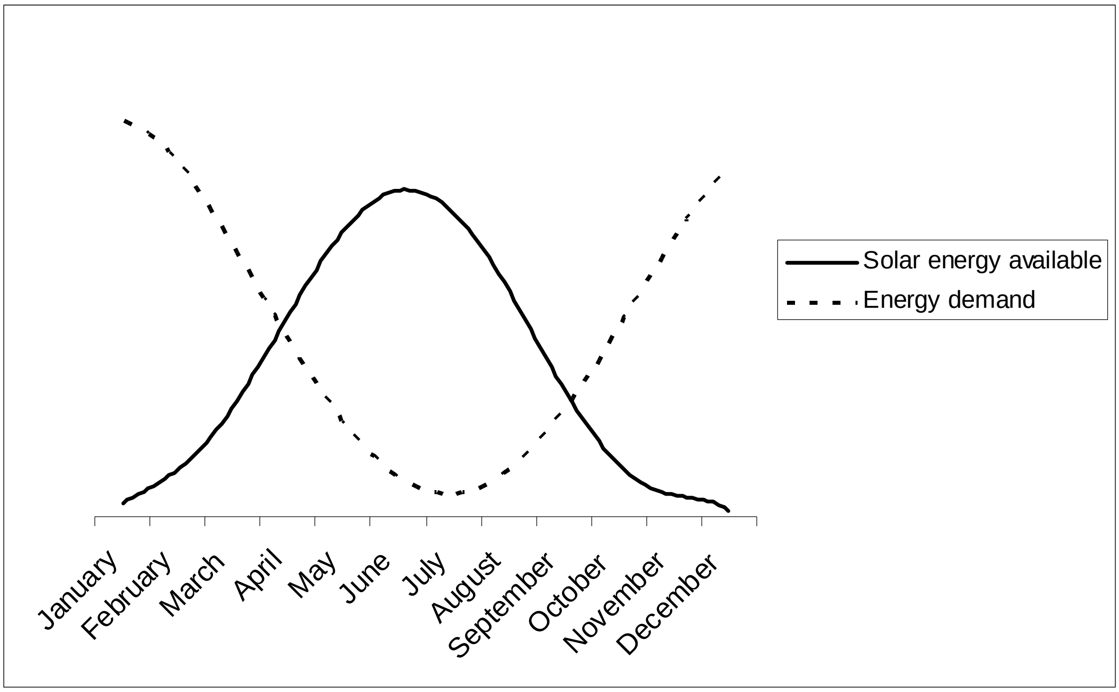

Figure 1. The variation between the demand and supply of solar energy

The location of Finland creates a need for careful planning of the solar energy system especially when the system is supposed to be operated in the wintertime too. The angle of incidence represents the angle between the solar rays and the solar panel. The optimal angle of incidence is zero as the rays then meet the panel in perpendicularly. To maintain the optimal angle of incidence in the wintertime, the panels should be in a nearly vertical position. In summer the situation is opposite and better yield is obtained when the panels are in a horizontal position. Therefore optimization and possible adjustability is required from a system that is supposed to work around the year. (Erat, B. et al., 2001, 15-16)

Although there are several installations of photovoltaic solar panel fields in Europe with electric power output of over 10 MW, such large scale plants are at the moment absent in Finland (Pvresources). Photovoltaic solar panels are commonly used in locations where there is no grid available to provide electricity such as summer cottages. The largest solar energy installations in Finland so far have been made in the Eco-Viikki project which consisted of several sustainable housing cases in the Viikki suburban area of Helsinki. The planning and construction of the area was done under strict ecological criteria. The construction of the area took place between 1999 and 2004 and the area provides housing for over 1 800 people. The area has the largest solar heat production capacity in Finland, with a total of 1 400 m^2 of collector area. The average energy output of the solar collectors was 285 kWh per square meter in 2002. (Hakaste)

In addition to the solar heat production, there are also several photovoltaic installations in the Eco-Viikki area. The Salvia solar-energy house, for example, has a capacity of 24 kW_e which is produced by photovoltaic solar panels integrated in the balcony constructions of the building. The electricity produced by the panels covers 15-20 % of the demand of the building. (Hakaste et al., 2005, 24)

3.1.1 Photovoltaics

Solar energy can be converted to electricity directly with photovoltaic cells or it can be used to heat water into steam which can then be used in a traditional steam turbine to generate electricity. Solar thermal electricity generating is most suitable for centralized generation of electricity from the solar energy whereas photovoltaic cells allow the electricity production to be decentralized and integrated in buildings.

The efficiency of a modern single-junction photovoltaic cell can be as high as 15 %. The theoretical maximum efficiency for single-junction cell is 25 %. This is due to the bandgap which limits the wavelength of the photons that is able to free an electron in the cell material to a certain interval. With multijunction cells with two or more different semiconducting materials stacked one upon another the efficiency can be 50 % higher than single-junction cells and efficiencies as high as 24.7 % have been reported. (Messenger and Goswami, 2007, 23:2)

The average investment costs of a photovoltaic system are presented in Table 4. The costs are calculated for standard test conditions in which the solar irradiation is 1000 W/m^2 and ambient temperature 25 ˚C. Feed-In tariff, which currently is not available in Finland, would reduce the costs as some of the electricity could be sold to the grid at the times of high yield. The effect on the investment costs can be seen in Table 4, where the "Off grid" option is the one without the possibility to feed the electricity produced by photovoltaic panels to the grid. The costs of electricity storage are also taken into account in the comparison table. Operating costs of photovoltaic systems are estimated to be 3 €/MWh (Vartiainen et al., 2002, 13).

Table 4. Investment costs of photovoltaic systems (Pvresources)

	System power [W]	Investment costs [€/W]
Off grid	100 – 500	10 – 15
	1000 – 4000	15 – 30
On grid	1000 – 4000	3.5 – 5
	10 000 – 50 000	3.5 – 5
	50 000 –	3.5 – 5

3.1.2 Solar heating

Solar thermal energy can be used both passively and actively. Passive methods require some pre-construction planning as they deal with the position, direction and constructions of the building.

Active solar heating uses solar thermal collectors to collect the energy of the solar irradiation and convert it into thermal energy. The collectors can be categorized into concentrating and nonconcentrating types. Nonconcentrating collectors make it possible to decentralize the solar heating generation whereas the concentrating collectors are usually related to centralized heat generation.

Passive solar heating

Utilizing the energy of the sun to heat a building by passive means does not require any additional equipment to be installed. The energy is used passively by the methods of construction, placement and alignment of the building. The construction of a building which efficiently utilizes the solar energy needs some careful design and knowledge on local weather data and other relevant information.

To gain the maximum benefit from the solar energy passively, the building should be placed in a position where the sun shines throughout the heating season, preferably as long as possible on a daily basis. The location of the building next to a hill or other higher terrain might also provide some cover from wind. (Erat et al., 2008, 53-54)

In order to receive as much of the energy of solar irradiation, the large masses of the building should be facing south. Large windows on the southern wall also contribute to the passive use of solar energy as they allow the floors and ceilings within the building to heat and store the energy. A crucial part of successful passive solar heating is also sufficient insulation and air tightness of the building. (Erat et al., 2008, 54-55)

To prevent the building from over heating during summer, the passage of solar rays into the building can be blocked by lengthening the overhang of the roof. This method of controlling the heating does not affect the efficiency of the system during winter as the sun is located lower during winter than it is during summer. (Erat et al., 2008, 56)

Concentrating solar collectors

Several advantages can be achieved by concentrating the energy of solar irradiation: the working fluid can be heated to higher temperatures, decreased heat losses and reduced costs. High temperatures allow the energy to be used to generate steam which can then be used to generate mechanical work and electricity in a steam turbine. The heat losses decrease as the aperture size of the receiver or absorber of the collector decreases. Finally, the reduction in the size of the absorber allows lower material costs. (Romero-Alvarez and Zarza, 2007, 21:6)

A parabolic through collector consists of a parabolic through-shaped mirror and a receiver tube. The receiver tube is located in the focal line of the parabola into which the mirrors concentrate the solar radiation. In order to the system to be efficient, the system has to have adjustability. The parabolic through collector mirrors and the receiver tube are connected to a tracking-axis which follows the daily movement of the sun. The alignment of the system is controlled by a control unit which bases its function on either sun sensors or astronomical algorithms. (Romero-Alvarez and Zarza, 2007, 21:18)

Three factors influence the performance of a parabolic through collector which is described as global efficiency. The factors are thermal efficiency, peak optical efficiency and a parameter called the incidence angle modifier which represents the heat, optical and geometrical losses of the collector. (Romero-Alvarez and Zarza, 2007, 21:27) According to Romero-Alvarez and Zarza (2007, 21:16), the parabolic through collector has a peak efficiency of 21 % and demonstrated annual efficiency of 10-12 %.

The most distinguishing feature of a central receiver solar thermal power plant is the receiver tower which rises next to a field of heliostats. The heliostats are adjustable reflectors which track the radiation of the sun throughout the day and direct it at the top of the tower. The top of the tower holds a heat exchanger and with the intensity of the solar flux on the tower it is possible to obtain temperatures as high as 1000 ˚C for the working fluid circulating in the heat exchanger. (Romero-Alvarez and Zarza, 2007, 21:50-52)

Non-concentrating solar collectors

Non-concentrating solar collectors can be divided into two categories: flat plate collectors and evacuated tube collectors. These two types have their own subtypes. Although non-concentrating collectors cannot heat the working fluid into the temperature levels that concentrating collectors can, they are suitable for heating domestic hot water or space heating. One of the greatest advantages of non-concentrating collectors is that they are suitable for decentralized heat generation and can be integrated into building constructions, for example roofs. (Erat et al., 2008, 72-75)

The efficiency of a non-concentrating collector depends of its design and the difference between the required temperature and the ambient temperature. As can be seen from Figure 2, the efficiency is highest when the required temperature difference is lowest such as heating the water pool. Evacuated tube collectors also have higher efficiency, but they are also more expensive than flat plate collectors.

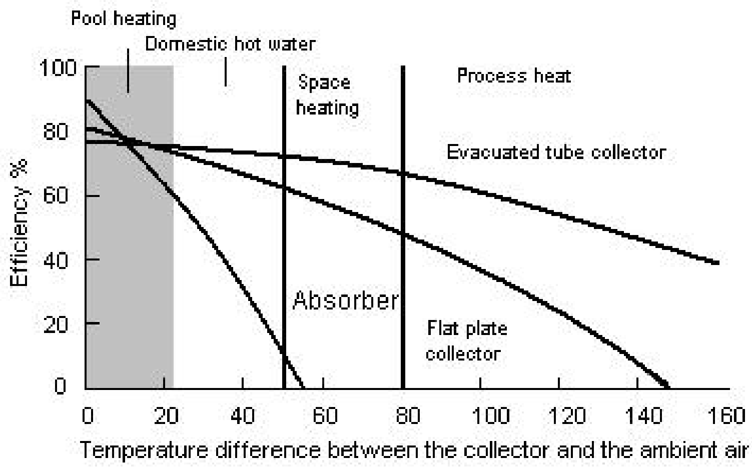

Figure 2. Efficiencies of non-concentrating collectors in different applications. Modified from (Erat et al., 2008, 74)

The investment costs of a non-concentrating solar thermal collector system are estimated to be 500 €/m^2. The value includes the installation of the collector. Operating costs of solar thermal collectors are estimated to be 4 €/MWh. (Vartiainen et al., 2002, 13)

A flat-plate collector is the most commonly used solar collector because of its relative simplicity and economicality. The flat plate collectors are divided into glazed and unglazed types. Flat-plate collectors are suitable for using both air and liquids as their working fluid.

A typical flat-plate collector consists of a frame, which is usually made from aluminium. Some other materials such as plastic may also be used, however the durability of the material under high temperatures must be ensured. The frame is well insulated on the bottom to prevent the heat from conducting through it. The collector tubes in which the working fluid circulates are located on top of the insulation. Depending on the location and the yearly usage time of the collector, the working fluid can be water or some anti-freeze solution. The absorber plate is located on the top of the collector tubes. It is the most varying component in the flat-plate collector when different commercial products are considered. The efficiency of the collector can be increased by adding a selective surface on top of the absorber plate. The selective surface can be found on almost all commercial products on the market today. The box is finally sealed with a transparent cover, which decreases heat losses from the system and also provides cover from weather and other abrasive factors to the parts within the box. (Reddy, 2007, 20:3-4; Erat et al., 2008, 75)

The design of an unglazed flat-plate collector is similar to a glazed flat-plate collector. However, the protective cover is absent in the unglazed type. The glazing adds to the costs of the collector and therefore it is justified to leave it off in some cases, especially when the required temperature difference between input and output does not need to be high, such as heating the swimming pool. The unglazed flat-plate collector does not suit well into the Finnish conditions as the relatively cold climate would decrease the efficiency of the collector through heat losses. (Erat et al., 2001, 77-78)

The heat losses which occur in flat plate collectors due to convection heat transfer from the absorption surface to the glazing and the frames of the collector are minimized in an evacuated tube collector. In evacuated tube collector the working fluid circulates in a collector tube which is located in a vacuum inside another tube. The heat transfer between the working fluid and the tube can be based on direct-flow or heat pipe principle. Due to decreased heat losses, the yield of evacuated tube collector is higher than the yield of flat plate collectors at the times when ambient temperature is low. The differences between the two types are reduced in the summer when the ambient temperature is higher. (Erat et al., 2008, 73; 81-82).

There are several different designs of direct-flow evacuated tube collectors. The working fluid may circulate in the collector tube in one or two layer thus making them single- or double-pass tubes. The tubes can also be straight or u-shaped. A schematic cross-section picture of a single-pass evacuated tube collector is presented in Figure 3.

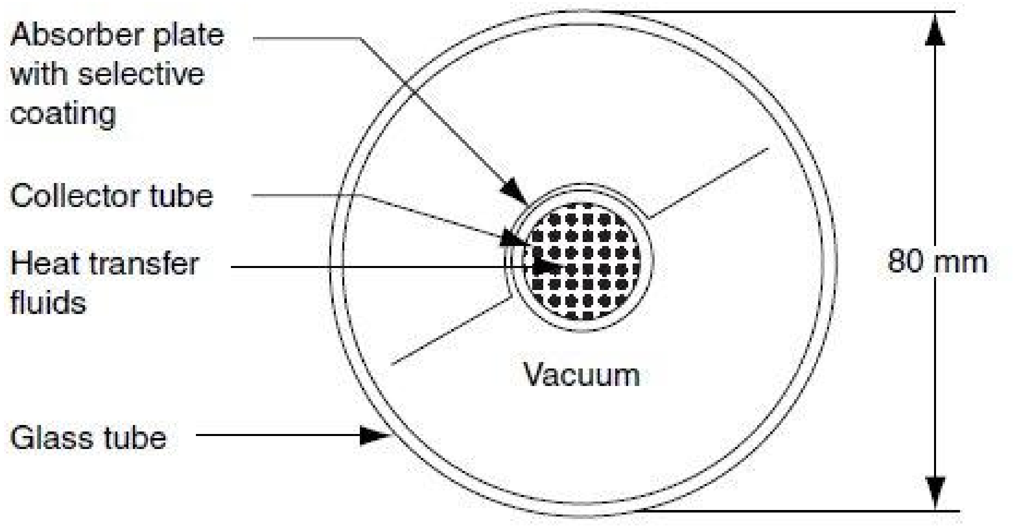

Figure 3. Cross-section of a evacuated-tube collector. (Reddy, 2007, 20:12)

The collector tube is located within another tube. The space between the tubes is under very low pressure, as close to vacuum as possible. The vacuum significantly decreases the convection heat losses from the absorber plate and collector tube to the ambient air. The evacuated tube collector can achieve temperatures above 100 ˚C and is more suitable for the cooler Finnish climate than flat-plate collectors. A typical evacuated tube collector consists of several evacuated tubes which are installed on a rack to form a collector unit.

The operation of a heat pipe evacuated-tube collector is based on the evaporating fluid in the heat collector tube. The vapour rises up in the tube into a heat exchanger where it condensates and transfers heat into the working fluid. The condensed fluid then flows back to the bottom of the collector tube. The operation principle of a heat pipe collector is presented in Figure 4. (Erat et al., 2008, 73)

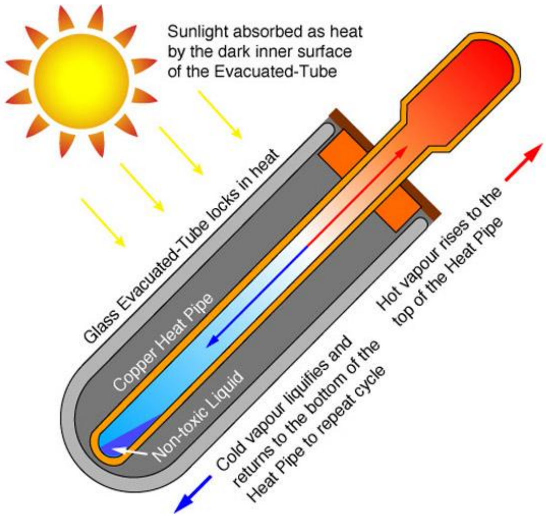

Figure 4. Operation of a heat pipe (SIDITE)

3.1.3 Solar cooling

Solar cooling can be implemented actively or passively. Active methods require harvesting the solar energy in the form of heat or electricity through photovoltaic panels. Some passive methods might also include some degree of activity, but due to their non mechanical design, they are considered passive.

Passive solar cooling

Passive solar cooling solutions include shading and different structures in building, such as tinted windows or sun blinds, which decrease the amount of solar irradiation reaching the windows. The protection which the indoor shades provide is relatively small as the solar rays have already reached the inside of the building. The advantage of adjustable shades is that they make it possible to exploit the solar irradiation for heating when necessary, fixed shades might prevent some of the solar energy reaching the indoor space when heating is required. (Holopainen et al., 2007, 67)

Sun blinds and other fixed methods of protection are rarely used in Finland and most common in office buildings. A window with double framing and three glasses is the most common type of window in Finland. The two inner glasses are usually fixed together and open inwards. Using adjustable shading between the glasses is a functional method for not only preventing excess solar radiation from reaching the indoor space but to act as an extra layer of insulation in the winter. (Holopainen et al., 2007, 69)

Active solar cooling

Solar energy can be used for cooling as well as generating electricity and heat. The most common method of applying solar energy to the generation of cooling energy is a heat pump operating on the vapour compression cycle, where the energy to drive the compressor can be obtained either through producing electricity with photovoltaic panels or solar thermal heat engine. Another widely used method to exploit the solar energy to generate cooling is the absorption-cooling in which the solar energy is utilized as thermal energy. The absorption refrigeration cycle is presented in Figure 5. (Reddy, 2007, 20:121)

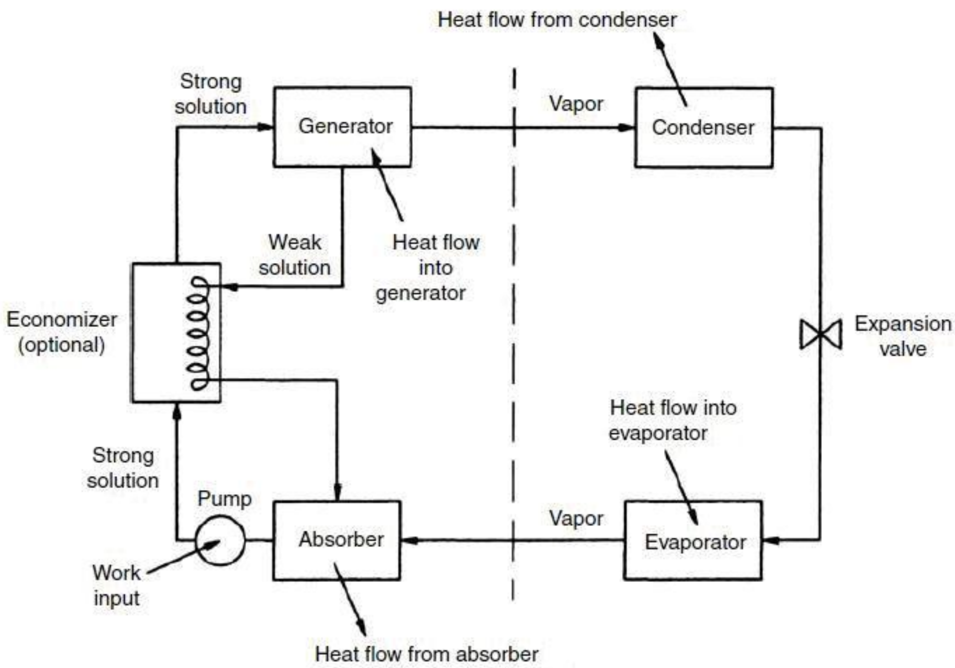

Figure 5. Absorption refrigeration cycle (Modifier from: Reddy, 2007, 20:124)

The efficiency and operation of an absorption refrigeration process is based on the qualities of the materials in the refrigerant-absorbent pair. The refrigerant is dissolved into the absorbent in the absorber. The liquid is then pumped into the generator, increasing the pressure of the liquid. In the generator, the solar thermal energy is used to evaporate the refrigerant from the liquid thus compressing the refrigerant vapour. The vapour is condensed in the condenser while still under high pressure. When the condensate is released into the evaporator through an expansion valve, the pressure drops and the refrigerant begins to boil extracting energy from the air or liquid that is being cooled. (Reddy, 2007, 20:125)

The coefficient of performance or COP of a solar powered absorption refrigeration cycle can be as high as 0.75 in optimal conditions. However, the cooling load usually varies on a daily cycle which leads to continuous on-off cycle of the unit. The cooling unit must be heated up after it is started, significantly lowering the COP of the unit. (ASHRAE, 1999, 32.19)

3.2 Wind power

Electricity generation with wind turbines are a clean and emissionless way to utilize the energy potential of the wind. The effects on the environment are more aesthetic on their nature as the wind turbines shape the landscape and make noise. The wind energy potential on Finnish sea areas is tens of terawatt hours per year. Also the fjelds in the Northern Finland have a great wind power potential. (Motiva)

The wind turbines can be roughly categorized into two types of devices. The more common type is the horizontal-axis wind turbine which is also called HAWT. The more exceptional, but still constructed type is the vertical-axis wind turbine or VAWT. Although the two types have the same basic components, the construction and the conditions affecting the energy generation with the two types of wind turbines differ from each other. The main components and design of both wind turbine types are presented in Figure 6. (Berg, 2007, 22:2-3)

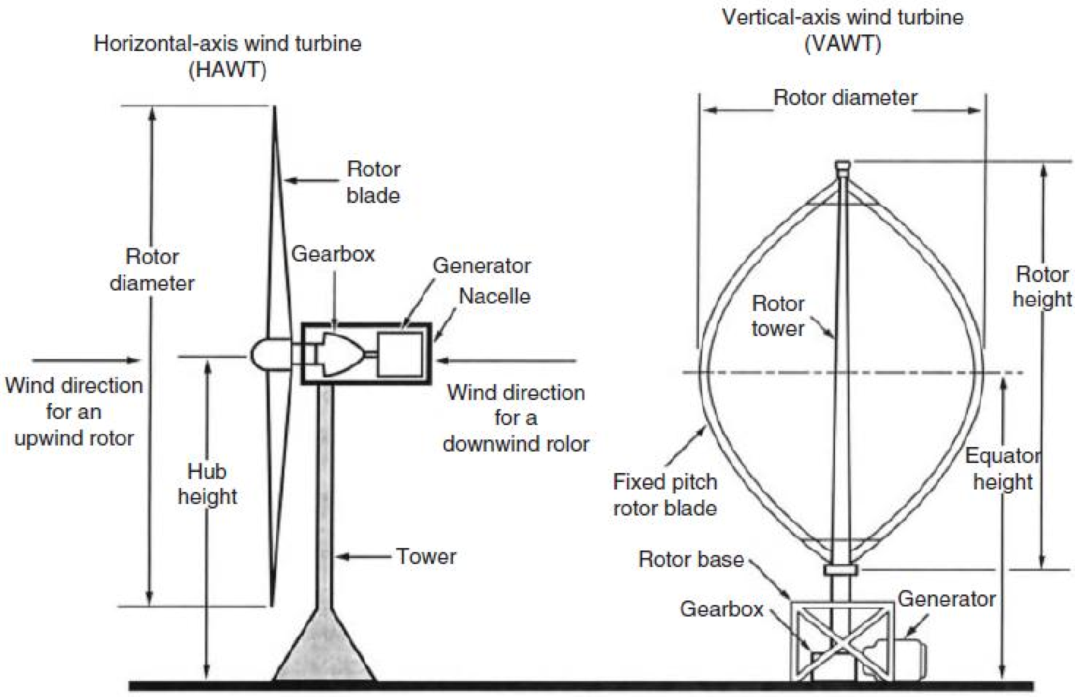

Figure 6. Two types of wind turbines (Berg, 2007, 22:4)

The total amount of electricity produced with wind power worldwide in 2007 was 0.6 % of the total electricity consumption. The amount is however increasing at an average rate of 28 % per year. (Berg, 2007, 22:1) In Finland, the share of wind power was 0.3 % of the total annual electricity consumption in 2009. According to the goals of the climate and energy strategy of the Finnish government, the amount of electricity generated from wind should however be 20 times greater by 2020. (VTT; TEM) For example, in the summer of 2010 Haminan Energia Oy took in use four onshore 3 MW wind turbines in the Summa harbour near the city of Hamina, which is located next to the Gulf of Finland. The total amount of electricity generated with the turbines is 30 GWh annually and the investment costs of the project were 17 M€. (Haminan Energia)

The previously presented values suggest that the specific investment costs of wind power would be approximately 1400 €/kW. For inland applications the investment costs are estimated to be 1300 €/kW. Variable costs of wind power are estimated to be 8 €/MWh. (Vartiainen et al., 2002, 10)

Tuuliatlas is a project executed by the Finnish Meteorological Institute. The output of the project was a wind modelling tool made from wind data that was collected between 1987 and 2007. According to the project, the optimal wind conditions in Finland are on the Gulf of Finland and in the Åland archipelago. However, the modelling tool created within the project suggests that good wind conditions for wind turbines can also be found in the inland when the heights are over 100-150 m. (TEM)

The yield of a wind turbine can be evaluated with the power curves of a specific turbine model. The manufacturers of the turbines provide these curves. An example of the power curves is presented in Figure 7. The turbine in question is a 1 MW turbine by WinWind. The letter-number combination means the diameter of the swept area of the blades. The power curves are presented for a turbine stationed at height 50-70 m. (WinWind)

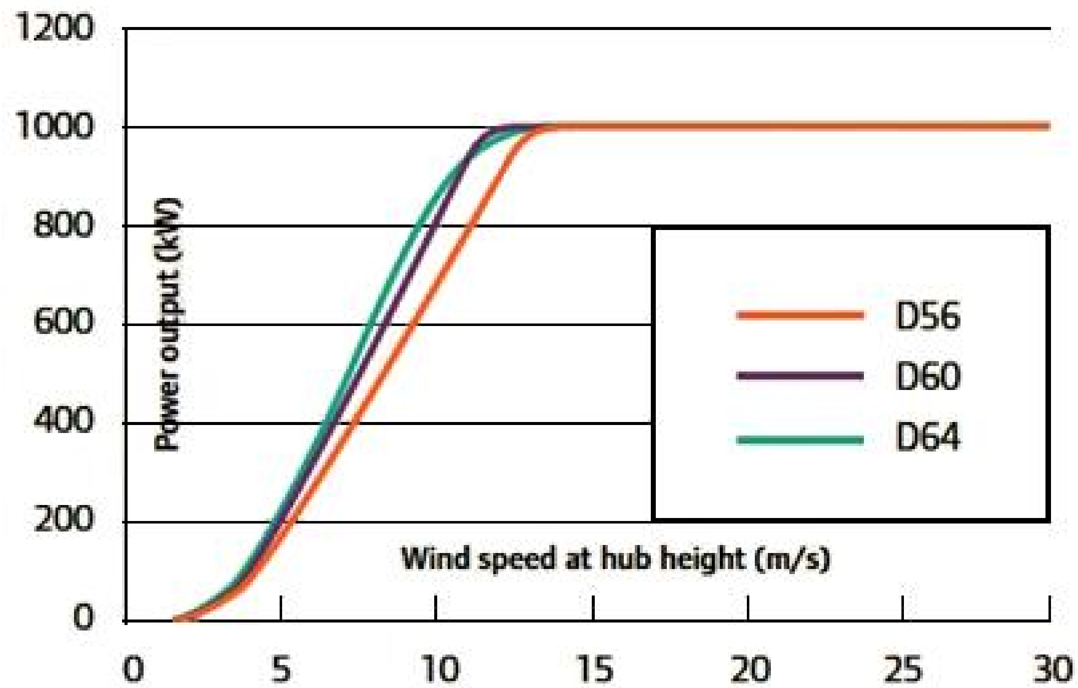

Figure 7. Power curves of a 1 MW wind turbine (Modified from: WinWind)

3.3 Heat pumps

The operation of heat pumps is based on the evaporation and condensing of the working fluid called the refrigerant. When for example the inside air of a house is warmed, the heat required to evaporate the refrigerant is taken from the outside air, ground or water. The pressure of the refrigerant is then raised in a compressor which also raises the temperature of the refrigerant. The thermal energy of the refrigerant is then collected in a condenser where the refrigerant condensates and passes heat to the indoor air. (Aittomäki, 2001, 6) The heat pump operating cycle is presented in Figure 8.

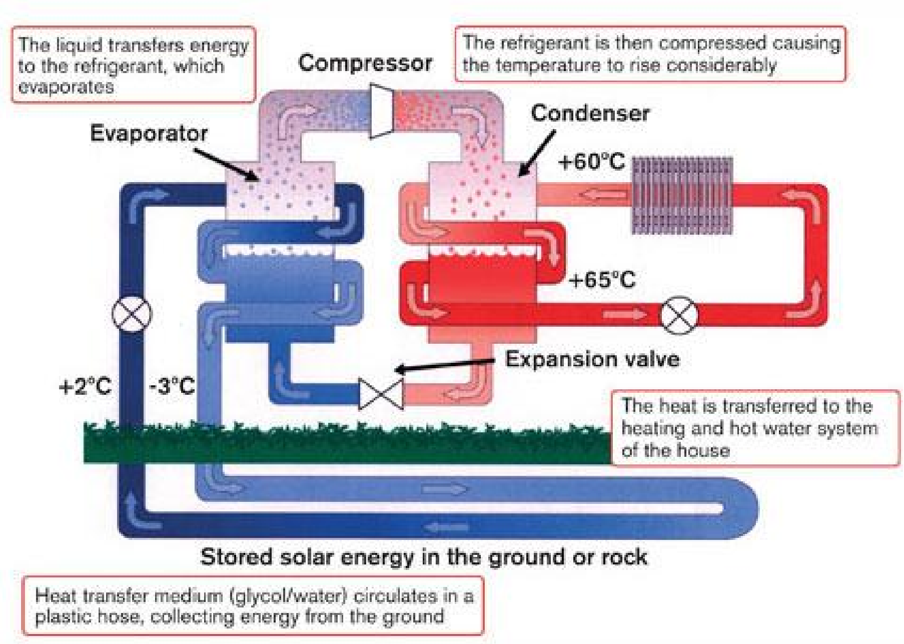

Figure 8. Operating diagram of a ground-source heat pump on certain temperature levels (Heat Exchanger Design)

The efficiency of the heat pump is described with the term coefficient of performance (COP) which describes the thermal energy produced by the pump per a unit of electricity it consumes. For example a heat pump operating with a coefficient of performance of 3 produces three kWh of heat while it consumes one kWh of electricity. The COP is highly dependent of the temperatures of the heat source and the space or substance which is heated. High temperature on the heat source side and low temperature on the side where the heat is used increase the COP of the heat pump. (Aittomäki, 2001, 7)

Investment costs including the devices and installation for ground and water source heat pumps are estimated to be 900-1100 €/kW, depending on the size of the installation. The specific investment costs of larger heat pump systems are considered to be cheaper than for example building-specific heat pump systems. The operating costs of ground source heat pump are approximated to be 3 €/MWh and for the water source heat pump 6 €/MWh. (Vartiainen et al., 2002, 14)

3.3.1 Ground source heat pumps

Ground source heat pumps or geothermal heat pumps are a common type of heat pumps in Finland. There are two methods of inserting the ground pipes into the ground, vertical or horizontal piping. In the horizontal type, the pipes are installed 1-2 meters below the surface in lining with the surface. (Finnish Heat Pump Association)

In the vertical type the pipes are installed into bore holes. The heat transfer between the heat source and the piping is improved as the bore hole fills with water. The costs of vertical type are mostly dependent on the type of the soil where the bore hole is drilled. If there is a layer of loose ground above the rock, the piping needs to be protected from it which brings additional costs. The water from the bore hole cannot be used as domestic water, but it can be used in the garden for example. (Finnish Heat Pump Association)

The yield of the ground source heat pump depends on the material of the soil and the geographic location where the heat collecting pipes are installed. In a clay based soil the annual yield is on average 40-60 kWh/m in Southern- and Central-Finland and in sand based soil around 15-40 kWh/m. The yield decreases the northern the heat pump system is installed. (Finnish Heat Pump Association)

3.3.2 Air-source heat pumps

Air-source heat pumps have rapidly increased their popularity in domestic use. Air-source heat pumps are used to provide heating in the winter and cooling in the summer. In Finnish conditions, the temperature might sometimes drop below -25 ˚C and the air-source heat pump can no longer offer energy saving benefits as the COP drops below 1. The COPs given by the manufacturers of the air-source heat pumps are also much higher than the actual COPs when the outside temperature is low. The average annual COP of air-source heat pumps in Finnish conditions is usually between 1.8 and 2.2. (Finnish Heat Pump Association)

The air-source heat pumps may operate on air-to-air or air-to-water principle. Air-to-air heat pumps heat the indoor air of the building while the air-to-water heat pump is used to heat the heating water or to preheat the domestic hot water. (Finnish Heat Pump Association)

3.3.3 Water source heat pump

The yield of water source heat pumps is better than ground source heat pumps due to better heat transfer between the heating substance and the collector pipes. The water source heat pump system can be implemented in two different ways. The collecting pipes can be installed along the bottom similarly to the horizontal ground source heat pump or the water from the water system can be pumped straight into the evaporator of the heat pump. The posterior method requires accurate monitoring of the system and is rarely used method in water source heat pumps. (Sulpu, 18)

The installation of the heat collector piping into the water sets certain requirements for the conditions of the surroundings of the system. The collector pipes must be anchored into the bottom with concrete weights in order to prevent the ice which forms on the surface of the pipes from resurfacing the pipes. The pipes also need to be buried into the soil near the shore to prevent the ice from breaking them during winter. The heat energy output of a water source heat pump is approximately 40 W per a meter of collecting pipe and the annual yield around 70-80 kWh per a meter of collecting pipe. Maximum length of a single pipe loop is 400 m. Therefore longer pipes need to be divided in several loops. (Sulpu, 18)

3.4 Combustion

Biomass-based fuels are available from several sources such as agricultural and wood residues, slurries from industrial processes and energy crops which are purposely grown to be used as a fuel. (VTT, 2009, 165) Biomass-based fuels can be used in both heat generation and cogeneration, where the power plant produces both electricity and heat. An overview of the qualities of both biomass boilers and cogeneration is presented in this chapter.

3.4.1 Combined heat and power generation

Combined heat and power generation (CHP) or cogeneration, is a term used to describe the production of heat and power from the same process. The efficiency of CHP plants is higher than conventional plants as the surplus heat from the power generation process can be used for heating or cooling. Cogeneration can decrease the fuel consumption by 25-35 % when comparing to a conventional plants, which produce the same amount of power and heat in separate processes. (Sipilä et al., 2005, 11)

The total efficiencies of 1- 20 MW_e biomass-fuelled CHP plants constructed in Finland between 1990 and 2004 vary around 90 %. The electric efficiency of these plants ranges between 8 and 31 %. The electricity production remains low, however, as the back-pressure needs to be taken in at a higher pressure than in a regular condensing power plant. The term describing the rate of electricity and heat production is called power-to-heat ratio. Power-to-heat ratio is quite dependent on the size of the plant and it is usually around 0.15 for plants that have electric capacity of less than 2 MW_e. (Sipilä et al., 2005)

The investment costs of a CHP plant are highly dependent on the size of the plant. The estimated investment costs for CHP-plants with an electric capacity under 700 kW_e is 5000 €/kW_e and with a thermal capacity over 800 kW_e, 3000 €/kW_e. Variable costs of CHP-plants are estimated to be 14 €/MWh_{th}. (Vartiainen et al., 2002, 18; Sipilä et al., 2005, 34)

3.4.2 Biomass boilers

The boilers can be used for both decentralized and centralized heat generation, as the scale of boiler capacities varies from few kilowatts to several megawatts. The efficiency of the boilers is usually around 80-90 %. The efficiency of the boiler depends on, for example, the moisture content of the fuel. (Pellettienergia)

The investment costs of biomass boilers range from 100 to 250 €/kW, depending on size of the boiler. A smaller boiler is usually more expensive as the share of the additional systems, for example fuel feeding system, is larger when compared to the size of the boiler. The operating costs of biomass boilers are estimated to be 2-3 €/MWh. For large installations such as centralized heat plants, an efficient fuel delivery system is also required to maintain the plant operational. This generates additional investment costs which in this master's thesis are assumed to range from 100 to 300 €/kW. (Vartiainen et al., 2002, 15-16)

3.5 Fuel cells

Fuel cells are a crucial part of the hydrogen economy which is a candidate to replace the fossil fuels in the future. Hydrogen chain offers clean and environmental friendly energy production and storage from the point that hydrogen is produced till the point it is used as the fuel of a fuel cell. Especially producing hydrogen with renewable energy sources such as solar energy provides a way to store, transfer and produce energy with very low emissions. As can be seen from Table 5, certain fuel cell types operate at a temperature over 600 ˚C and can be used in combined heat and power production. The heat released in fuel cells which operate at lower temperatures could also be utilized, for example, in domestic hot water heating. (Kara et al., 2004, 277-279**;** Xianguo, 2007, 28:31)

Fuel cell is a device that converts the chemical energy of the fuel and the oxidant directly into electricity. Most fuel cell designs require hydrogen as their fuel. Therefore the fuel cell system consists of the fuel cell itself, a fuel processor and several other devices such as oxidant conditioner and devices to control the power and current of the fuel cell. The fuel processor allows for example natural gas to be fed into the fuel cell system and be used as the fuel. Modern fuel cells can also operate using carbon monoxide or methane as their fuel. (Xianguo, 2007, 28.1-2; Kara et al., 2004, 275-276)

Several different types of fuel cell concepts are available. The first commercial fuel cell was the alkaline fuel cell or AFC but due to it expensiveness it has been widely replaced by other types. The properties of different types of fuel cells vary greatly. There properties include operating temperature, fuel efficiency, usable fuel, power levels and costs. Power density affects the applications where the specific type of fuel cell can be used. The properties of different types of fuel cells are presented in Table 5.

Table 5. Properties of different fuel cell types. (Xianguo, 2007, 28:31)

Fuel cell type	Operating temperature [˚C]	Power density [mW/cm^2] Present	Power density [mW/cm^2] Projected	Power level [kW]	Fuel efficiency [%]	Lifetime [h]	Fuel
AFC	60-90	100-200	>300	10-100	40-60	>10 000	H_2
PEMFC	50-80	350	250	0.01 - 1000	45-60	>40 000	H_2
PAFC	160-220	200	>600	100-5000	55	>40 000	H_2
MCFC	600-700	100	>200	1000-100 000	60-65	>40 000	H_2, CO, CH_4
SOFC	800-1000	240	300	100-100 000	55-65	>40 000	H_2, CO, CH_4
DMFC	90	230		0.001 - 100	34	>10 000	CH_3OH

The investment costs of different types of fuel cells vary from 200 €/kW to over 3000 €/kW. Phosphoric acid fuel cells (PAFC) are the most expensive fuel cell technology available. The investment costs of polymer-electrolyte-membrane fuel cells (PEMFC) and direct methanol fuel cells (DMFC) begin from 200 €/kW, according to Xianguo (2007, 28.2).

The basic parts of a fuel cell are two opposite charged electrodes, cathode and anode and an electrolyte between them. The electrolyte usually permits positive ions to pass through. In hydrogen fuelled fuel cell the fuel is lead to the negative electrode. The hydrogen atoms are then ionized and the positive hydrogen ions pass through the electrolyte. Oxygen is lead to the positive electrode where the hydrogen ions and oxygen form water. A schematic picture of a fuel cell is presented in Figure 9. (Sørensen, 2005, 118-119)

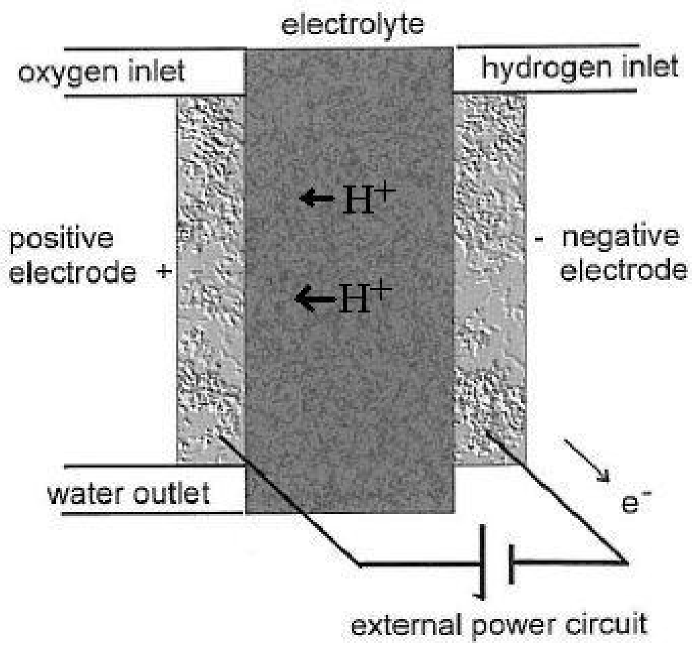

Figure 9. Main fuel cell components and operation. Modified from (Sørensen, 2005, 13)

The products of a hydrogen fuelled fuel cell are water, electricity and heat. The absence of greenhouse gases in the exhaust of the fuel cell makes it one of the cleanest methods to produce and store energy. Fuel cells also have a great modularity as they can be used in both power plant scale applications and to power a portable device such as mobile phone. The greatest drawback of the fuel cell technology today is the rather limited lifespan of the cells. The investment costs of the fuel cells per unit of electricity are also rather high when compared to a diesel generator, for example. (Xianguo, 2007, 28:1-2)

3.6 Energy storage

In this chapter different types of thermal energy are presented from sensible heat storages to latent heat storages. Different methods of storing electricity are also reviewed.

3.6.1 Thermal energy storage

The energy storages have been used mainly to control the demand in district heating networks in Finland. With thermal storages in combined heat and power production it is possible to maximize electricity production, while decreasing the need for oil-fuelled boilers which are used to adjust the consumption peaks. Thermal storages can also be used to compensate the variation of fuel quality when biofuels are used. (Kara et al., 2004, 299)

Sensible heat storages

Storing thermal energy as sensible heat is the most common method of storing energy used in Finland. The storage of sensible heat is based on the increase of the temperature of the storing substance. In short-term storages the storing substance is usually water but it may also be materials in the soil such as rock or clay. Common sensible heat storages in households are hot-water tanks and fireplaces which can store heat.

The best profit from large thermal storages is received when they are located next to district heat production plants, especially when the plant is suitable for the cogeneration of electricity and heat. In Finland, the biggest thermal storages are located next to district heat systems where they are used to control the demand of district heat by means that are presented in (Alanen et al., 2003, 30-31) and (Kara et al., 2004, 299):

- Maximizes the electricity production of CHP plants
- Increases the utilization rate of the district heat production plant
- Decreases the need to use oil-fuelled boilers to compensate demand peaks
- Acts as a power reserve in case of production failures

- Acts as a water reserve in case of pipe breakages
- Serves as a part of the pressure control system of the district heating network

Thermal storages also help to compensate the variation of fuel quality and the thermal stress of the boiler in bio-fuelled plants. Several sensible heat storages are in use in Finland with volumes between few hundred cubic meters to several tens of thousand cubic meters (Table 6). The district heating network is also used for short-term heat storage in roughly half of Finnish district heat plants.

Table 6. Sensible heat storages in Finland (Kara et al., 2004, 300)

Location	Volume [m^3]	Capacity [MWh]	Maximum power [MW]	Year of commissioning
Otaniemi	500	20	10	1974
Oulu	15 000	800	80	1985
Oulu	190 000	10 000	8	1996
Lahti	10 000	450	40	1985
Lahti	200	9	1	1989
Naantali	15 000	690	82	1985
Helsinki, Salmisaari	20 000	1 000	130	1987
Helsinki, Vuosaari	26 000	1 400	130	1997
Saarijärvi	350	21	3	1988
Kouvola	10 000	420	72	1988
Hämeenlinna	10 000	320	50	1988
Hyvinkää	10 000	350	50	1988
Vantaa	20 000	900	50	1990
Rovaniemi	10 000	450	30	1998
Kokkola	3 200	185	50	2001
Turku	6 000	300	60	2003

Underground sensible heat storages can be categorized into three types of systems: natural water storages, underground containers and heat exchangers installed into the soil. There is a difference between the types in costs, environmental effects and the capacity of the storages. (Paalanen and Siren, 1997, 2)

The ground water reserves in Finland are vast and they are the most suitable option for storing heat and cold underground. A typical ground water pool in Finland is fast flowing, which limits the efficient storing of thermal energy on the low temperature difference range. (Paalanen and Siren, 1997, 7)

Groundwater storages can be of one or two well type. The one well type requires that the ground water deposit is composed of two layers which are separated by a layer which insulated water efficiently. This type of ground water deposits are rare in Finland, thus the two well type is the most suitable option for Finnish conditions. The hot and cold wells, also called the loading and unloading wells, of the two well type storage are located in the same ground water pool. The unloading well is located down stream in the deposit. (Paalanen and Siren, 1997, 5-6)

Several factors affect the efficiency of the ground water thermal storage such as the dimensions of the ground water deposit, the difference between the storage temperature and the natural temperature of the ground water and also the qualities of the ground water flow. The efficiency of the ground water storages is lower when storing heat than it is in the case of storing cold, because of the heat losses. (Paalanen and Siren, 1997, 8)

The size and storage temperature of aboveground sensible heat storage vary depending on their application. Small hot water storages are typically used in households for short term thermal storage. Their usage is usually related to the fact that electricity is cheaper at night when the storage is charged. Small storages are also suitable to be used along with solar thermal collectors and other forms of renewable heat generation. Thermal storages are rarely used with district heating networks as the cost of district heat is fixed on a daily interval. (Alanen et al., 2003, 20-22)

Larger aboveground storages are suitable for centralized heat generation, for example connected with a district heating plant. Except a few exceptions, the large aboveground storages in Finland are steel tanks. (Alanen et al., 2003, 30-31)

Latent heat storage

Latent heat storages use phase change of materials to store the energy. The used phase changes are liquid-gas and solid-liquid or evaporation and melting, respectively. Solid-solid phase change may as well be used and it has similar characteristics to the solid-liquid phase change. (Mehling and Cabeza, 2005, 258-259)

The most well-known and used phase change material is water which has a specific melting heat of 333 kJ/kg at a melting temperature of 0 ˚C. Other PCM-materials include liquid water-salt solutions, salt hydrates and organic materials such as paraffins and fatty acids. PCM-materials can be used for short-term thermal storage and they are applicable to the constructions of a building. By adding PCM-materials to the hot water tank the size of the tank can be reduced. (Alanen et al., 2003, 14-15; Mehling and Cabeza, 2005, 261-263)

Properties of different PCM-materials are presented in Figure 10. An overview of the commercialization level of different PCM-materials is also included in the figure.

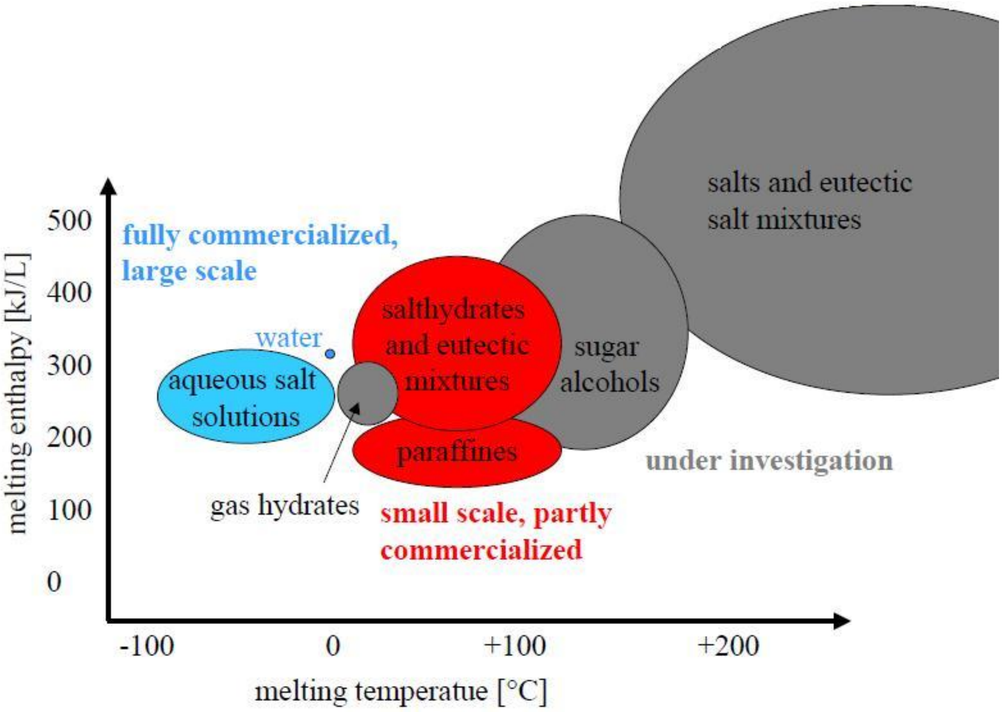

Figure 10. Properties and commercialization level of different PCM materials (Zae Bayern)

3.6.2 Electricity storage

The functionality of electricity storage is measured with three factors. The first factor is the efficiency of the system which can in some cases compromise of several partial systems including the devices needed to operate the storage. Second factor is the energy density or specific energy of the storage and is expressed as amount of energy per a unit of volume or mass. The third factor is the amount of load-unload cycles the storage device can perform before the efficiency and energy density begin to decrease.

Several different methods to store electricity will be presented in this chapter. Different battery technologies will be explained shortly and the properties of them compared. Mechanical storage methods such as compressed air storage and flywheels will also be briefly introduced as well as electrochemical capacitors.

Batteries

A battery consists of three basic parts: negative and positive electrodes and an electrolyte. When the battery is being unloaded the negative electrode gives electrons to the external load. The battery is charged when the positive electrode receives electrons from the load. The electrolyte enables chemical reaction between the positive electrode and the electrolyte to remove electron from the positive electrode and a passageway for the electrons from positive to negative electrode where the electrons are stored. The function principle of a battery is presented in Figure 11. (Hammerschlag et al., 2007, 18:8)

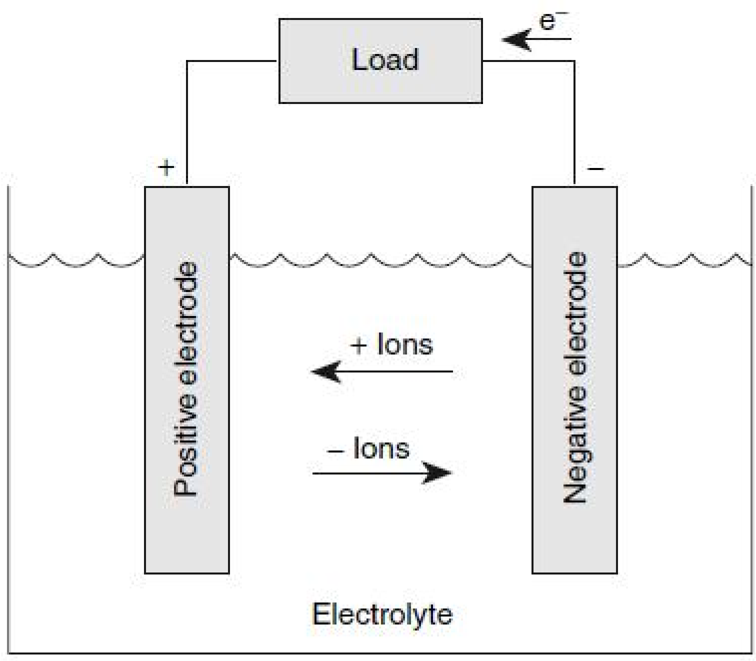

Figure 11. The main components and the electron and ion flows of a battery (Hammerschlag et al., 2007, 18:8)

Lead-acid battery is the most traditional battery technology. The components of a typical lead-acid battery are a lead negative electrode, lead dioxide positive electrode and a separator which electrically isolates the electrodes. Diluted sulphuric acid is used as the electrolyte. Three main types of lead-acid batteries are the flooded cell, gel cell and absorbed glass mat (AGM) battery. Gel and AGM batteries are sealed. The electrolyte of the flooded cell type lead-acid battery must be occasionally refilled as some of the oxygen and hydrogen evaporates during the charging. The sealed types do not need to be refilled, however their charging rate is lower. (Hammerschlag et al., 2007, 18:8-9)

The advantages of lead-acid batteries include low costs but the low cyclic lifetime of 200 – 1500 cycles and the rather low energy density of 0.25 MJ/l reduce the applicability of lead-acid batteries. (Hammerschlag et al, 2007, 18:9; ESA)

Sodium-sulphur (NaS) battery has a liquid state, molten sulphur positive electrode and a molten sodium negative electrode. A solid ceramic beta-alumina membrane acts as the electrolyte of the sodium-sulphur battery. When the NaS-battery is discharged, positive sodium ions pass through the electrolyte and form sodium polysulphides with the sulphur. The reaction is reversed when the battery is charged and the sodium polysulphides release sodium ions which pass through the electrolyte and form elemental sodium. (Hammerschlag et al., 2007, 18:10)

Sodium-sulphur battery has a high energy density and specific energy. The corresponding values are approximately 0.65 MJ/l and 0.86 MJ/kg. The efficiency can also be as high as 90 %. However, the NaS-battery has a rather high operating temperature of 300 ˚C which reduces its usability in some applications. (Hammerschlag et al., 2007, 18:10)

Lithium-ion or Li-ion and lithium polymer batteries are common energy storage method in portable devices such as mobile telephones and portable computers. The negative electrode of a Li-ion battery is lithiated metal and the positive electrode is made from layer structured graphite. Lithium salts dissolved in organic carbonates act as the electrolyte of Li-ion battery. In a lithium polymer battery the electrolyte is replaced with a plastic film which allows ions to pass through but does not conduct electricity. When Li-ion battery is charged, the lithium atoms in the negative electrode are ionized and the ions pass through the electrolyte to combine with the electrons from the charging current to form lithium atoms on the positive electrode. The process is reversed when the battery is discharged. (Hammerschlag et al., 2007, 18:9)

Lithium-ion and lithium polymer batteries have high efficiency, exceeding 90 %. The energy density of the batteries is also high, over 0.70 MJ/l. (Hammerschlag et al., 2007, 18:9; ESA)

Flow batteries store the electric energy in electrolyte instead of electrodes as most batteries do. The charging and discharging of flow batteries is accomplished trough reversible chemical reactions in two liquid electrolytes. The battery cell has compartments for both liquid electrolytes and an ion exchange membrane between them to separate the liquids but allow ions to pass through. (Hammerschlag et al., 2007, 18:11)

The capacity of most batteries is limited by the size of the electrodes. In flow battery the only limiting factor is the amount of the electrolyte solution and by increasing it the capacity of the flow battery can be increased. The major disadvantage of flow battery is the rather low specific energy of around 0.05 MJ/kg. (Hammerschlag et al., 2007, 18:11; Kara et al., 2004, 303)

The use of nickel-cadmium (NiCd) batteries in domestic applications has been widely denied due to the toxic nature of the heavy metal cadmium used in the NiCd-batteries. Although NiCd-batteries may suffer from the memory effect in which the battery can only be fully charged after several complete discharges, it has major advantages such as high resistivity to cold. (Hammerschlag et al., 2007, 18:9)

Compressed air storage

Compressed air energy storage, or CAES, utilizes the three key components of a conventional gas turbine power plant: compressor, combustion chamber and expansion turbine. However, instead of the turbine, the power to compress the air is taken from the grid at the times of low electricity demand. The combustion stage is necessary as otherwise the temperature of the exhaust air would drop and cause icing and degradation in brittle materials. To improve the sustainability of the CAES, biofuels can be used as the combustion fuel. (Hammerschlag et al., 2007, 18:13-14)

According to Kara et. al (2004), this triples the yield of the turbine when comparing to a traditional gas turbine plant. The compressed air can be stored in large underground cavers, mines or aquifers. First commercial CAES plant was constructed in Germany, with a capacity of 290 MW in 1978. A CAES facility has been also planned to be located into an abandoned mine in Finland, but the project was not seen as economically feasible.(Kara et al., 2004, 304; Hammerschlag et al., 2007, 18:14)

Flywheel

In flywheel energy storages the energy is stored as kinetic energy of the flywheel. Charged flywheel storages are a considerable option for short-term energy source, for example to act as a bumper before the main secondary power source becomes functional. The main factors affecting the maximum capacity of the flywheel storage are the speed of rotation of the flywheel and the mass of inertia. (Hammerschlag et al., 2007, 18:14)

The energy storage capacity of a flywheel is proportional to the mass of the flywheel and to the square of the velocity. Therefore, the maximum capacity is usually increased by increasing the velocity of the flywheel rather than making the flywheel heavier. Additionally, heavier constructions do not allow high speeds as the centrifugal forces would cause damage to the construction. The flywheel energy storages require very little maintenance and the cyclic lifetime of them is relatively long, over 10 000 cycles. The long lifetime is achieved by a magnetically levitated bearing design, which eliminates bearing wear. (Hammerschlag et al., 2007, 18:14)

Electrochemical capacitor

Electrochemical capacitor differs from a conventional capacitor in that the dielectric is replaced with a thin film of electrolyte. The electrolyte film increases the energy density of the electrochemical capacitor and can be water based or organic material. The properties of the electrochemical capacitor vary depending on the choice of the electrolyte material. The water based electrolyte allows higher temperature range than an electrolyte based on organic materials which on the contrary has a higher energy density. (Hammerschlag et al., 2007, 18:6-7)

Electrochemical capacitors may serve as an energy reserve to cope with demand peaks. The self-discharge rate of almost 10 % per day however rules out the use of electrochemical capacitors as long-term energy storage. The advantages of the technology are the over 500 000 cycles lifetime, maintenance free use and quick discharge. (Kara et al., 2004, 302; Hammerschlag et al., 2007, 18:6-7)

Summary of electricity storage methods

Different electricity storage methods are compared in Figure 12. The comparing qualities in this figure are lifetime and efficiency; however energy density would be a good property to be compared as well. As can be seen from the figure, the two technologies in the upper right corner, electrochemical capacitors and flywheels, have the longest lifetime and also good efficiency. However, these two technologies do not suit long-term storage well and the most efficient technology for long term storage is the lithium ion battery which stands out from other battery technologies in the figure.

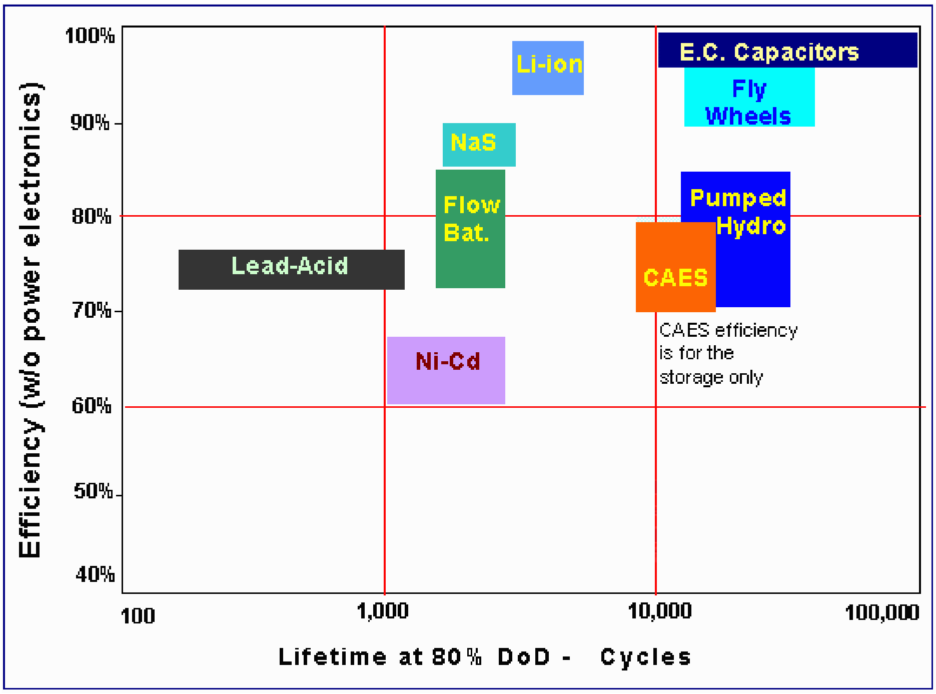

Figure 12. Efficiency comparison of different electricity storage methods at 80 % degree of discharge (Modified from: ESA)

4 Selection method of energy system

A step by step method for selecting the optimal energy system will be presented in this chapter. The most influential stakeholder regarding the selection of the energy system is assumed to be the district developer. Depending on the scale and location, the district may be a block of buildings, neighbourhood or even a city. In this master's thesis, a district is defined to be a system consisting of several buildings bound together as a district by a district land-use plan, for example. The development of a district can be greatly influenced through district planning and it is assumed that trough regulations in the district plan, the energy system and its selection can be affected at least on a district level. Thus, the selection whether the energy system will be district level or building level is made by the district developer or district planner.

As the district planning stakeholder is considered the most important factor in the process of selecting the energy system, a questionnaire was conducted for the members of the steering groups of two on-going Tekes projects at VTT: EcoDistrict (Asukaslähtöiset energiatehokkaat asuinalueratkaisut – Ekotaajama) and EcoDrive (Ekotehokkaasti uudistuva yhdyskunta). The members of these steering groups represent the community level decision makers as well as the district developers. The case districts presented in chapter 5 are part of these projects. The results and brief analysis of the questionnaire are presented in chapter 4.6.

4.1 Selection process

The energy system selection process, presented in Figure 13, is considered to begin by obtaining the basic information about the district the energy system is going to be selected for. The information can be obtained from the client who has ordered the case study in form of district plan proposals or other sort of information. Some key information regarding the district is location of the district, number, type and size of buildings. The type of a building can be residential or industrial, for example. Furthermore, residential buildings can be detached houses, row houses or apartment buildings.

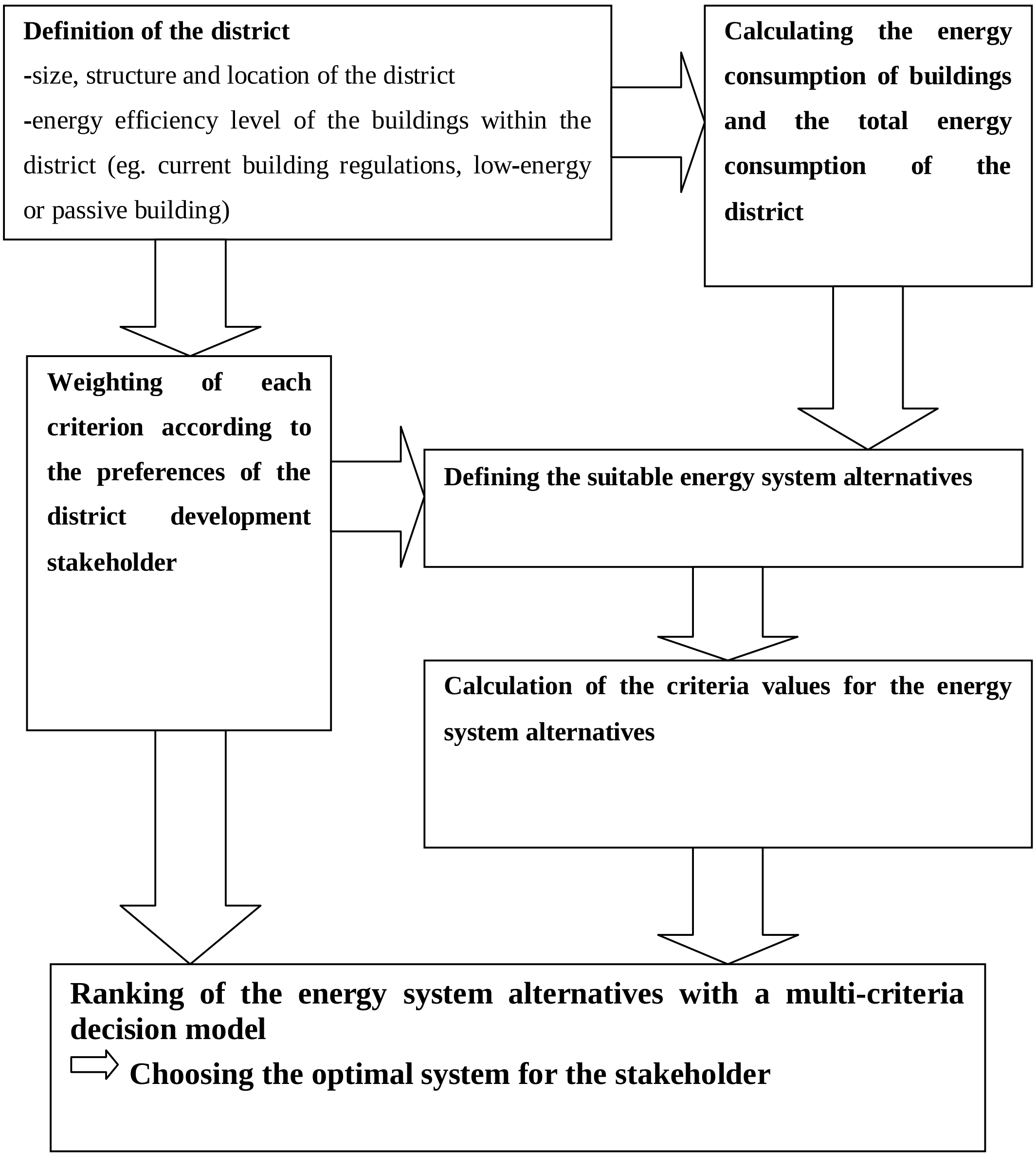

Figure 13. Energy system selection method

Next step is to calculate the energy consumption of the buildings and district. The method used in this master's thesis to calculate the energy consumption in the case study districts is presented in chapter 4.2. The buildings in the case study districts are assumed to be low-energy buildings and the energy consumption calculation is based on the low-energy building definitions in chapter 2.

A parallel process with the energy consumption is to determine the preferences of the developers regarding the energy systems that should be considered for the district. Energy system alternatives are defined according to the wishes of the decision making stakeholder but also taking into account the limits set by the location of the district and possibly the size and energy demand of the district. The list of energy systems taken into consideration when defining the energy system alternatives in this master's thesis is presented in chapter 4.3.

When the possible energy systems are determined, the parameters used in the multi-criteria decision model are calculated for each system. A model for each energy system alternative, based on the energy consumption and capacity requirements of the district, is presented in both case study and the models are used to determine the parameter values for each energy system. The criteria used for evaluating the energy systems are presented in chapter 4.5 along with summaries of the specific values that are used in the calculation of the parameter values of the energy system alternatives.

When the comparison parameters for each energy system alternative are defined, the alternatives are taken into multi-criteria decision model, which is presented in chapter 4.4. The decision model is used to rank the energy system alternatives in respect with the calculated parameters and the weighting of the criteria used. The weights of the criteria that are used in this master's thesis are based on the questionnaire carried out for the steering groups of the two projects and are presented in chapter 4.6.

4.2 Energy consumption of buildings and district

The energy consumption calculation begins by calculating the energy consumption of the buildings within the district. The accuracy of the energy consumption calculations depend on the scope of the initial information required of the district. For example, if there are no clear dimensions for the buildings, type houses must be defined for the different building types within the district.

Several simulation tools exist for the calculation of energy consumption of buildings, such as IDA ICE, TRNSYS or EnergyPlus. The level of detail in both input and output between the simulation tools varies. (Manfren M. et al., 2010) In this master's thesis, the energy consumption calculations of buildings are determined by a simulation tool created by VTT, WinEtana.

WinEtana is a simulation tool which can calculate the energy consumption of a building with very limited input data. A rough estimate can be calculated by simply inserting the building’s dimensions, location, construction year and the type of the building. For a more accurate simulation, several variables can be changed to correspond the specific building that is to be calculated. The user interface of WinEtana is presented in Figure 14. The main window is on the left and on the right a window where the areas and overall heat transfer coefficients of the buildings structures can be modified. The main output is visible in the main window and more throughout output can be obtained from the report the program generates.

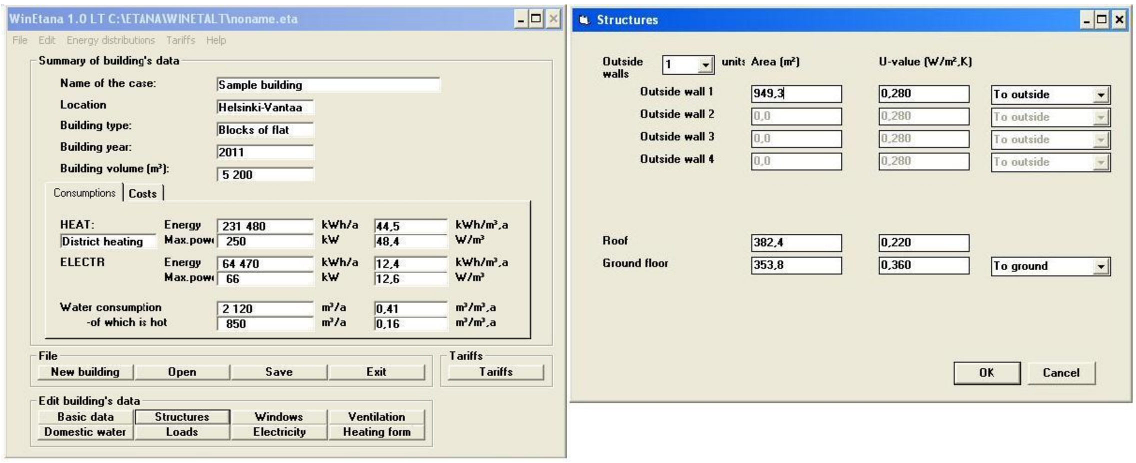

Figure 14. The user interface of WinEtana

The heating system can be chosen, the overall heat transfer coefficients and areas of roof, floor and exterior walls as well as windows can be modified. The base floor can also be chosen to be a ‘crawl space’, a ‘slab floor’ or a ‘towards outdoor’ type. The type of the windows used and their alignment as well as shading angles can also be modified. WinEtana also allows choosing the type of the ventilation to be natural or mechanical and the parameters of the ventilation process such as yearly heat recovery efficiency, air flow rates, air tightness of the building envelope. As an output, WinEtana provides monthly thermal energy consumption. Peak thermal and electric power requirements and electricity consumption is given on a yearly time step.

The energy consumption of the district is calculated by adding up the energy consumption values of the buildings within the district. Depending on the level of centralisation of the energy supply system, possible thermal energy losses of the distribution network will also be incorporated into the total energy consumption of the district.

4.3 Defining the suitable energy systems

The selection process of the optimal energy system begins with the definition of suitable energy systems for the case study district in question. The objective of this step is to eliminate the technically or otherwise unfeasible energy system alternatives from a closer analysis on the basis of the initial information of the case. One of the most important outranking factors is the limits set by the customer who has ordered the comparison. The weather conditions are proportional to the location of the district, which is also taken into consideration while studying the adequacy of solar and wind energy for the district.

The energy system alternatives can be categorized into building, building group or district level energy systems depending on the level of centralisation of the suggested energy system. The energy system alternatives which are taken into account in the definition of the suitable energy systems are presented in Table 7. The final energy system alternatives in the more throughout comparison can be one of the systems presented in Table 7 or a combination of two or more.

Table 7. List of energy systems

Energy system	Building	Building group	District
Electric heating	X		
District heat			X
Wood pellet boiler	X		
Biomass heat plant			X
Ground source heat pump	X	X	X
Water source heat pump			X
CHP			X
Wind energy			X
Solar thermal collector	X	X	X
Photovoltaic panels	X		

Although the electricity used with electric heating is not necessarily produced by with renewable energy sources, which are the focus of this master’s thesis, it was selected because it is common method to provide heating in Finnish buildings. Electric heating also provides a comparison system for the rest of the energy system alternatives in the optimization process. In the district heat alternative, the existing capacity of the district heating network is assumed to be able to cover the energy demand of the district in total without installing additional district heat generation equipment.

4.4 Multi-criteria decision method

In order to achieve a more profound evaluation of the energy system alternatives that were selected as suitable for the district, a multi-criteria decision making (MCDM) approach is used to rank the energy system alternatives. The multi-criteria method selected for the evaluation in this master's thesis is PROMETHEE II, which is an outranking method developed by J-P Brans in the 1980's. The PROMETHEE II method has been used in several fields of applications, such as determining the industry locations, investments and medicine. Reasons for its wide range of utilization are the user-friendly calculation procedures and mathematical qualities. (Brans J-P. and Mareschal B., 2005) PROMETHEE II has also been used in a study conducted by Ghafghazi et al. (2009) where the method was used to evaluate and rank the available energy sources for a district heating system located in Canada. The calculation procedure of PROMETHEE II method is presented in chapter 4.4.1.

Multi-criteria decision making begins by defining the criteria to be used in the evaluation. Depending on the subject the method is applied to, the criteria can include costs, environmental effects, social effects and other sort of measurable criterions. The decision makers usually weight these criterions depending on their preferences, for example, some might considerer costs more important than emissions. (Brans J-P. and Mareschal B., 2005) In this master's thesis, the criteria selected to rank the energy system alternatives are: investment costs, annual costs of energy, greenhouse gas emissions, particulate emissions, locality of the energy source and maturity of technology of the energy system alternative. The criterions and the specific values with which the total criterion value for each energy system alternative will be calculated in the case studies are presented in chapter 4.5.

The weighting of the criteria that used in the multi-criteria evaluation in this master's thesis are presented in chapter 4.6. The weighting is done after the results of a questionnaire that was conducted for the steering groups of the two projects from which the case districts of this master's study are.

4.4.1 Calculation procedure

The calculation procedure of the multi-criteria decision method is explained in this chapter. In order to make the explanation of the calculation procedure more comprehensive, an example scenario is set with three alternatives: a_1, a_2 and a_3. Three criterions will also be used: c_1, c_2 and c_3. The criteria weights in the calculation procedure explanation will be w_1, w_2 and w_3 for c_1, c_2 and c_3, respectively.

The first step is to compose a value matrix including the chosen alternatives and their values for each criterion (Brans J-P. and Mareschal B., 2005, 168). In the example tables or matrixes, the value for each alternative on a certain criterion is denoted by x_{ij}, where i is the number of the alternative in question and j the criterion. For example the value of alternative a_2 on criterion c_3 is x_{23}. The example of the value matrix is presented in Table 8.

Table 8. An example of a value matrix

	c_1	c_2	c_3
a_1	x_{11}	x_{12}	x_{13}
a_2	x_{21}	x_{22}	x_{23}
a_3	x_{31}	x_{32}	x_{33}

The scale of the numerical values between the values of different criterions may vary greatly. For example, while costs such as investment costs are measured in several thousand or even more, locality of energy source is measured with a binary value of 0 or 1. However, PROMETHEE II method is based on pairwise comparison (Brans J-P. and Mareschal B., 2005). In order to get the different values of different criteria into a more comparable form, the criterion values are normalized to an interval of [0, 1]. The normalization of the values is done with Equations (1) or (2) depending on the nature of the criterion. For example, criterions where lower value is considered to be beneficial such as emissions, the values are normalized using Equation (1). (Athawale & Chakraborty, 2010, 2)

$$r_{ij} = \frac{\left[\max(x_{ij}) - x_{ij}\right]}{\left[\max(x_{ij}) - \min(x_{ij})\right]} \qquad (1)$$

, where r_{ij} is the normalized value of value alternative i on criterion j.

The criterions where a higher value is considered to be beneficial are normalized using Equation (2). (Athawale & Chakraborty, 2010, 2)

$$r_{ij} = \frac{\lfloor x_{ij} - \min(x_{ij}) \rfloor}{\lfloor \max(x_{ij}) - \min(x_{ij}) \rfloor} \tag{2}$$

When the criterion values of all alternatives are normalized, next step is to calculate preference functions for each pair of alternatives. Brans and Mareschal (2005, 169-170) offer several preference functions to compare how preferred the value of a certain alternative is over the value of an other alternative on the same criterion. According to Athawale & Chakraborty (2010), with the use of the most simple preference function several problems considering the choosing of the correct function can be avoided. As presented in Equation (3), alternative *i* is not preferred over alternative *i'* on criterion *j*, if the normalized value of alternative *i* is smaller or equal to the normalized value of alternative *i'* on criterion *j*, thus giving the preference value of 0. (Athawale & Chakraborty, 2010, 2)

$$p_j(i,i') = 0 \; if \;\; r_{ij} \leq r_{i'j} \tag{3}$$

, where *p*(*i*, *i'*) is the preference of alternative *i* over alternative *i'* on criterion *j*.

If the normalized value of alternative *i* is larger than the normalized value of alternative *i'* on criterion *j*, the preference function is as presented in Equation (4). (Athawale & Chakraborty, 2010, 2)

$$p_j(i,i') = (r_{ij} - r_{i'j}) \; if \;\; r_{ij} > r_{i'j} \tag{4}$$

The results of the preference function calculations can be presented in preference function matrix where each alternative is compared pairwise for each criterion. The matrix of three alternatives and three criterions is presented in Table 9.

Table 9. An example of the preference function matrix

	c_1	c_2	c_3
(a_1,a_2)	$p_1(a_1,a_2)$	$p_2(a_1,a_2)$	$p_3(a_1,a_2)$
(a_1,a_3)	$p_1(a_1,a_3)$	$p_2(a_1,a_3)$	$p_3(a_1,a_3)$
(a_2,a_1)	$p_1(a_2,a_1)$	$p_2(a_2,a_1)$	$p_3(a_2,a_1)$
(a_2,a_3)	$p_1(a_2,a_3)$	$p_2(a_2,a_3)$	$p_3(a_2,a_3)$
(a_3,a_1)	$p_1(a_3,a_1)$	$p_2(a_3,a_1)$	$p_3(a_3,a_1)$
(a_3,a_2)	$p_1(a_3,a_2)$	$p_2(a_3,a_2)$	$p_3(a_3,a_2)$

When the preferences of the alternatives over other alternatives are calculated, an aggregated preference function is used to calculate the combined preference of the alternatives over other alternatives on all of the criteria. (Brans J-P. and Mareschal B., 2005, 171) The criteria weights used to mark the importance of a certain criterion are introduced to the calculation procedure in the aggregated preference function. The aggregated preference function is calculated according to Equation (5) (Athawale & Chakraborty, 2010, 2).

$$\pi(i,i') = \frac{\left[\sum_{j=1}^{m} w_j p_j(i,i')\right]}{\sum_{j=1}^{m} w_j} \qquad (5)$$

where m is the number of criteria

w is the weight of the criterion *j*

The aggregated preference function is calculated for each pair of alternatives in both direction, for example, $\pi(a_1, a_2)$ and $\pi(a_2, a_1)$. As a result of the aggregated preference calculations, an aggregated preference function matrix can be written. The aggregated preference function matrix of the example set of alternatives used in the calculation procedure explanation is presented in Table 10.

Table 10. An example of aggregated preference function matrix

	a_1	a_2	a_3
a_1	-	$\pi(a_1,a_2)$	$\pi(a_1,a_3)$
a_2	$\pi(a_2,a_1)$	-	$\pi(a_2,a_3)$
a_3	$\pi(a_3,a_1)$	$\pi(a_3,a_2)$	-

In order to rank the alternatives, the positive and negative flows of each alternative in contrast to other alternatives must be calculated (see also Figure 15). The positive flow $\phi^{+}(a_1)$ of alternative a_1, for example, is the sum of $\pi(a_1,a_2)$ and $\pi(a_1,a_3)$. The sum represents the ability of alternative a_1 to outrank the other alternatives, a_2 and a_3, in the comparison of the alternatives. On the other hand, negative flows $\phi^{+}(a_i)$ of the alternatives represent how the alternative is outranked by the other alternatives. The positive flows of different alternatives can be also referred to as leaving flows and the negative flows can be referred to as the entering flows, as presented in Figure 15. (Brans J-P. and Mareschal B., 2005, 171)

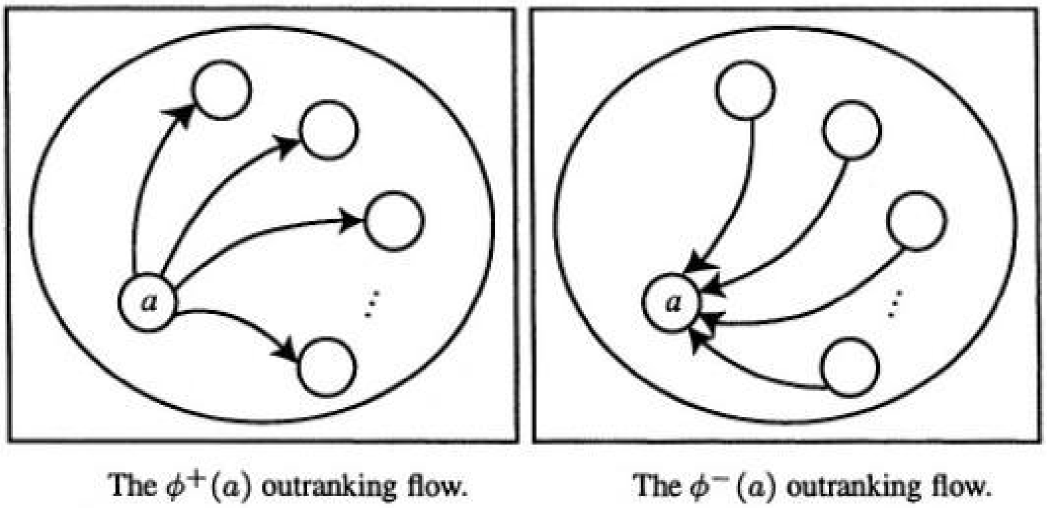

Figure 15. Leaving and entering outranking flows of alternative *a* (Brans J-P. and Mareschal B., 2005, 171)

The positive or leaving flows of the alternative are calculated according to Equation (6). (Athawale & Chakraborty, 2010, 3).

$$\phi^{+}(i) = \frac{1}{n-1}\sum_{i'=1}^{n}\pi(i,i') \qquad (i \neq i') \qquad (6)$$

The negative or entering flows are calculated with Equation (7). (Athawale & Chakraborty, 2010, 3).

$$\phi^{-}(i) = \frac{1}{n-1}\sum_{i'=1}^{n}\pi(i',i) \qquad (i \neq i') \qquad (7)$$

The results of the calculations of positive and negative flows according to the example scenario set up in the beginning of this chapter are presented in Table 11.

Table 11. Positive and negative flows of different alternatives in the example

Positive flow	Negative flow
$\phi^+(a_1)$	$\phi^-(a_1)$
$\phi^+(a_2)$	$\phi^-(a_2)$
$\phi^+(a_3)$	$\phi^-(a_3)$

In order to achieve he final ranking of the alternatives, PROMETHEE II introduces calculation of the net outranking flow $\phi(a_i)$ for each alternative. The net outranking flow is calculated with Equation (8). (Athawale & Chakraborty, 2010, 3) In the case studies of this master's thesis, the energy system with the highest net outranking flow is considered to be the optimal energy system for the case district in question, with the criteria weights defined in chapter 4.6.

$$\phi(i) = \phi^+(i) - \phi^-(i) \tag{8}$$

4.5 Criterion values

The criteria used to rank the energy systems include investment costs of the energy system, annual costs of energy, greenhouse gas emissions, particulate emissions, locality of the energy source and technological maturity of the energy production technology. The criterions and the method to obtain their values for the multi-criteria analysis are explained in this chapter.

4.5.1 Investment costs

The first criterion in the multi-criteria analysis is the investment cost of the energy system. Investment costs are generated from the actual energy production system but also from the heat distribution systems in the buildings and from the construction of a possible heat distribution network. In the multi-criteria comparison of the energy system alternatives, the investment costs of the end-user are regarded as comparable costs. However, in district level energy systems, the investment costs of the energy supply system are also calculated in order to determine the amount of capital costs which are added to the cost of energy.

Decentralized energy systems, that are building or building group-specific, are considered to be invested by a single customer or group of customers. The investments in these systems consist of the energy production system itself, heat distribution system in the buildings and the possible small scale heat distribution networks within the building groups. In district level energy systems, the investor is assumed to be a separate operator and the investment costs in these energy systems consist of the energy production system and the district level heat distribution network. The customer related investment costs in the district level energy system alternatives are generated from the installation of heat distribution system in the buildings and the connection fee to the district heating network.

With the exception of electric heating, the heat distribution in the buildings is assumed to be based on water circulation. The investment costs of the heat distribution system is estimated to be 600 €/kW for the water circulation based systems. The investment costs of an electric heating system are estimated to be 500 €/kW. The values include the heating devices, installation and domestic hot water heater and distribution in the building. (Klobut et al., 2009, 47; Motiva, 2009)

The specific investment costs of different energy systems are presented in Table 12. For the investment cost of the heat distribution network in all of the alternatives where it is required, an average price of 130 €/m will be used. (Klobut et al., 2009). The investment cost of energy system in the case of an existing district heating network is an average value calculated from the connection fees to the district heating network in the Tampere region. (Tampereen Kaukolämpö)

The investment costs of the energy supply systems are estimations based on a reports by Gaia Consulting (Vartiainen et al., 2002) and GreenStream Network (GreenStream Network, 2007). The values have also been compared to the appropriate extent with current market prices.

Table 12. Summary of investment costs for building-specific energy system alternatives

	Energy supply system [€/kW]	Heat distribution in building [€/kW]	Heat distribution network [€/kW]
Electric heating	-	500	-
District heat	118	600	130
Wood pellet boiler	250	600	130
Biomass heat plant	350	600	130
Ground source heat pump (Small)	1100	600	130
Ground source heat pump (Large)	900	600	130
Water source heat pump	900	600	130
CHP			
< 700 kW_e	5000	600	130
800 – 7000 kW_e	3000	600	130
Wind energy	1300		
Solar thermal collector [€/m^2]	500	600	130
Photovoltaic panels	5000		

4.5.2 Cost of energy

The cost of thermal energy produced by a certain energy system alternative depends on the cost of resource used to generate the heat and the operation and maintenance costs of the energy system. For example, electric heating devices require electricity as a resource to provide thermal energy. The costs of resources used to evaluate the energy systems in this master's thesis are presented in Table 13.

The cost of electricity is an average price for the time interval 1.1.2011 and 18.3.2011 including both the transmission cost and the cost of energy itself. The cost of electricity also depends on the consumption of the user, being cheaper for customers with electric heating. (Sähkönhinta) The costs of wood chips and pellets are estimated on the basis of Bio energy-magazine (Bioenergia, 2011).

Table 13. Costs of resources used by the energy systems

	Resource cost [€/MWh]
Electricity	
Electric heating	127
Other	153
Wood chip	22
Wood pellet	43

The operating and maintenance costs are also added into the total costs of energy produced by a certain system alternative. The operating and maintenance costs for different energy systems are presented in Table 14. The operating costs of the energy supply systems are estimations based on a reports by Gaia Consulting (Vartiainen et al., 2002) and GreenStream Network (GreenStream Network, 2007).

Table 14. Operating and maintenance costs

	Operating costs [€/MWh]
Electric heating	1
District heat	1
Wood pellet boiler	2
Biomass heat plant	3
Ground source heat pump	3
Water source heat pump	6
CHP	14
Wind energy	8
Solar thermal collector	4
Photovoltaic panels	4

When the energy system alternative being compared is a centralized, district level energy system, the investor of the system is assumed to redeem the investment costs of the system as capital costs added in the price of energy the customer has to pay. The calculation method of capital cost is presented in Equations (9) and (10). First, the investment costs will be divided for the annual energy demand with Equation (9)

$$C_{\mathrm{a}} = \frac{I}{E_a} \qquad (9)$$

, where C_{a} = capital costs per annually sold energy [€/MWh]

I = total investment costs [€]

E_a = annual energy demand of the district [MWh/a]

The capital costs per annual energy production C_{a} represents the addition to the cost of energy produced by the energy system, if the investment costs would be divided for the production of one year. However, the operating time of energy systems is considerably longer than one year. The capital costs will therefore be multiplied with capital, which takes into account the operation time of the system as well as the interest rate. Capital recovery factor *crf* which is calculated with Equation (10) (Knuutila H., 2005)

$$crf = \frac{i(1+i)^n}{(1+i)^n - 1} \qquad (10)$$

, where *crf* = capital recovery factor

i = interest rate

n = operation time

In the district level energy systems evaluated in this master's thesis, the operating time is assumed to be 30 years and the interest rate 5 %, thus Equation (10) gives a value of 0.065 for the capital recovery factor *crf*. The capital costs C_a for the energy produced by different alternatives are calculated separately for each case as there is variation between the investment costs of the energy systems as well as annual energy demand.

4.5.3 Greenhouse gas emissions

The greenhouse gas emissions (GHG-emissions) or CO_2-equivalent emissions represent the global warming potential of gaseous emissions produced by a certain energy system. The CO_2-equivalent emissions for the produced energy are calculated for the entire lifecycle of the energy system in this master's thesis. The lifecycle of the energy system includes the construction and the materials, the production of energy and the disposal of the energy system. The emission for different energy systems are calculated with GEMIS (Global Emission Model for Integrated Systems). The greenhouse gases included in the CO_2-equivalent emissions are CO_2, CH_4, N_2O, HCF, PCF and SF_6. (Fritsche and Schmidt, 2008, 29)

GEMIS is software developed by Ökö-Institut and Gesamthochschule Kassel (GhK) in the late 1980s' and has been since updated and upgraded constantly. The current version is 4.6 which was published in August 2010. GEMIS is a life-cycle analysis program and database for energy, material, and transport systems. The database consists of information about various fuels such as fossil fuels, renewable energy, and hydrogen but also generating processes for electricity and heat, construction materials and transportation. The database for the processes is extensive, including efficiency, power, capacity factor, lifetime direct air pollutants, greenhouse-gas, solid wastes, liquid pollutants and land use. The software is available for download on the internet page of Ökö-Institute. (Öko-Institut, 2011)

The CO_2-equivalent emissions of different energy system alternatives are presented in Table 15. The emissions of district heat are calculated separately for each case as the production method as well as the fuel used for the energy production varies between district heating energy providers.

Table 15. CO_2-equivalent emissions

	CO_2-equivalent emissions [kg_{CO2}/MWh]
Thermal energy	
District heat	*
Wood pellet boiler	11
Biomass heat plant	24
Ground source heat pump	9
Water source heat pump	10
CHP	79
Solar thermal collector	24
Electricity	
Average Finnish electricity	330
Wind energy	58
Photovoltaic panels	110

The emissions of average Finnish electricity were calculated according to the statistics provided by IEA (IEA, 2008). It must also be noted that the emissions of the heat pump technologies presented in Table 15 do not include the emissions of the electricity needed to operate the heat pumps. The additional emissions will therefore be calculated according to the electricity consumption of the heat pump.

4.5.4 Particulate emissions

On the contrary to the CO_2-equivalent emissions, the effect of the particulates in the air is more local than global. As well as the CO_2-equivalent emissions, the particulate emissions per a produced energy are calculated for the entire lifecycle of the energy system. The calculation is done with GEMIS and the particulate emissions of different energy systems are presented in Table 16. The particulate emissions of district heating need to be calculated for each case separately as the energy production method and fuels used to produce the district heat vary. The particulate emissions of heat pumps do not include the emissions of the electricity they require to operate and these additional emissions must therefore be calculated when the electricity consumption is known.

Table 16. Particulate emissions

	Particulate emissions [kg/MWh]
Thermal energy	
District heat	*
Wood pellet boiler	0.148
Biomass heat plant	0.165
Ground source heat pump	0.005
Water source heat pump	0.007
CHP	0.204
Solar thermal collector	0.009
Electricity	
Average Finnish electricity	0.114
Wind energy	0.026
Photovoltaic panels	0.011

4.5.5 Maturity of technology

The criterion represents the maturity of the technology, which in this master's thesis is assessed by how widespread the use of a certain technology is and the certainty of energy production with the technology. The maturity of the technology is given by a value 1, 2 or 3. The estimated values for the technological maturity of the energy system alternatives are presented in Table 17.

Table 17. Maturity of technology

	Maturity of technology
Electric heating	3
District heat	3
Wood pellet boiler	3
Biomass heat plant	3
Ground source heat pump	3
Water source heat pump	2
CHP	3
Wind energy	1
Solar thermal collector	1
Photovoltaic panels	1

Electric heating and district heat are considered to be well known and widely used technologies with a high level certainty of energy delivery, thus receiving a value of 3. Heat pump technology is well known, although the yield of water source heat pumps might vary some depending on the qualities of the water system such as the depth of the water and composition of the sediment. Therefore the ground source heat receives 3 and water source heat 2. Boiler and CHP technology is widespread and the availability of wood based fuels in Finland is good, therefore all three combustion based energy systems receive maturity value of 3. Solar and wind energy systems and their certainty of production is highly dependent of weather and wind conditions, thus the maturity rate of these technologies through is assumed to be 1.

4.5.6 Locality of energy

The locality of the energy source is criterion which can be expressed as a binary criterion, 0 or 1. The criterion receives the value 0 when the energy source is not local and 1 when it is. The values used for the locality criterion in this master's theses for different energy system alternatives are presented in Table 18.

Table 18. Locality of energy

	Locality of energy
Electric heating	0
District heat	0
Wood pellet boiler	1
Biomass heat plant	1
Ground source heat pump	1
Water source heat pump	1
CHP	1
Wind energy	1
Solar thermal collector	1
Photovoltaic panels	1

The only energy systems receiving value 0 are electric heating and district heat. Almost 50 % of Finnish electricity is produced by resources imported from abroad such as uranium, oil or natural gas. Also 12 % of the electricity consumed in Finland is directly imported from abroad. (Energiateollisuus, 2010b) District heat is produced, especially in larger district heating networks, with CHP-plants operating on natural gas for example and can therefore not be considered as local energy.

Although heat pumps require electricity to operate, majority of the energy is produced from a local source. The energy systems based on combustion technologies are considered to be operated by wood based fuels which are considered as local resources. The resources of solar and wind energy technologies are naturally considered as local.

4.6 Weights of criteria

The weights of different types of criteria depend on the preferences and expectations of the party who is considered. For example an energy company who is the developer of the energy system, might consider the overall costs of the system more important than the locality of the energy source. The end-user of the energy then again probably expects the energy system to be as environmentally friendly and ineffective on the landscape as possible, depending on his personal values.

The most important stakeholder influencing on the selection of the energy system is considered to be the community level decision maker, developer of the district, district planner or whoever can make decisions regarding the district plan and the regulations in it regarding the energy system of the district.

An enquiry (Appendix 5) was sent to the steering groups of the two projects from which the case studies in this master's thesis are selected from. The target group of the questionnaire was rather limited and 12 persons who can be considered as a part of the most influential group regarding the district plan answered the enquiry. The contents of the questionnaire dealt with the criteria introduced in the previous chapter regarding the selection of an energy system. The respondents were asked to give the importance of the selection criteria by setting the criterions in order. The answers were processed by giving the six most important criteria an importance from 1 to 6. The relative importance of each criterion based on the results of the questionnaire is presented in Figure 16.

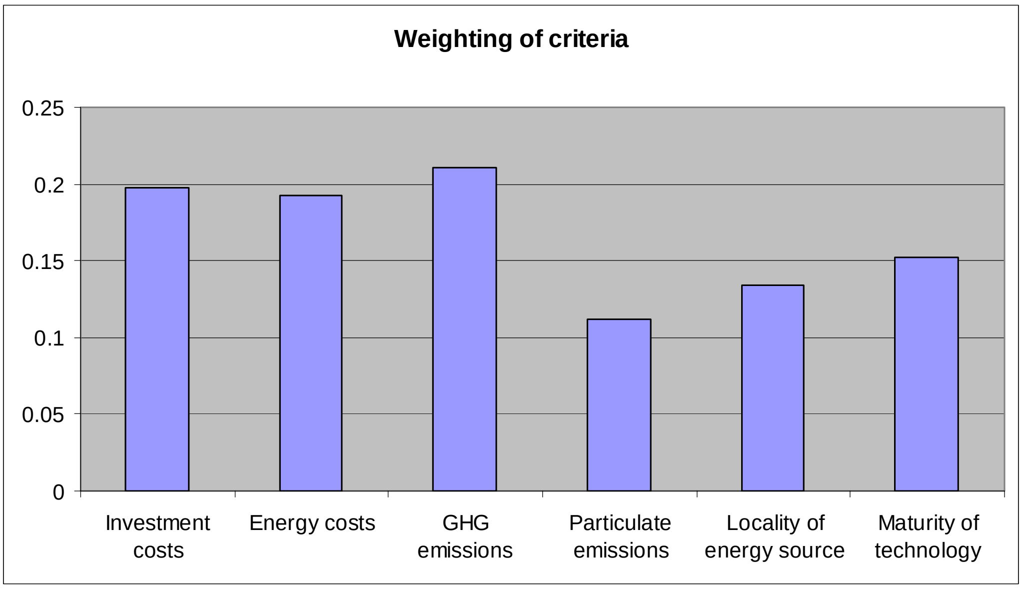

Figure 16. The relative weights of the criteria for each criterion in the enquiry

As can be seen from Figure 16, the first three criteria from the left are clearly considered as the most important criterions by a majority of the district developers. The questionnaire allowed same importance to be given for multiple criterions. Most important criterion on the basis of the questionnaire is the greenhouse gas emissions of the energy system. Interestingly, the particulate emissions received the lowest importance of all in the questionnaire. On the basis of the questionnaire, the criterions can be arranged in following order:

$$\text{GHG emissions} > \text{Investment costs} > \text{Energy costs} > \text{Maturity of technology} > \text{Locality of energy source} > \text{Particulate emissions} \tag{11}$$

, where the greater than sign denotes the importance of certain criterion to the other criterions.

When the relative order of the criterions is defined, the numerical weights for each criterion can be defined in several ways. In this master's thesis the criteria weights are determined by the expected value method which is also used by Ghafghazi et al. (2010). Using the expected value method the criteria weights can then be calculated as in Equation (11) (Ghafghazi et al., 2010).

$$\begin{aligned}
w_1 &= \frac{1}{k^2} \\
w_2 &= \frac{1}{k^2} + \frac{1}{k(k-1)} \\
w_3 &= \frac{1}{k^2} + \frac{1}{k(k-1)} + \frac{1}{k(k-2)} \\
&\vdots \\
w_{k-1} &= \frac{1}{k^2} + \frac{1}{k(k-1)} + \frac{1}{k(k-2)} + \cdots + \frac{1}{2k} \\
w_k &= \frac{1}{k^2} + \frac{1}{k(k-1)} + \frac{1}{k(k-2)} + \cdots + \frac{1}{2k} + \frac{1}{k}
\end{aligned} \tag{12}$$

, where

w_k= the weight of the most important criterion described by Equation (11)

k = the number of criteria

The weights of the criteria used in the multi-criteria analysis are presented in Table 19. The values have been calculated with Equation (12) taking into account the relative importance of each criterion presented in Equation (11).

Table 19. Criteria weights

Investment costs	Energy costs	GHG emissions	Particulate emissions	Locality of energy source	Maturity of technology
0.24	0.16	0.41	0.03	0.06	0.10

5 Application of the selection method

The energy system selection method presented in chapter 4 is applied in two case districts. The districts are different by their size but also by their structure. The smaller case district is located in Central-Finland, in the city of Jämsä. The larger case district is located in the city of Tampere, Finland.

In this chapter, type buildings for both case districts will be defined according to the information obtained from the district plans and the developers of these districts. The energy consumption of the type buildings is calculated and the energy consumption of the case districts is evaluated on the basis of the type building energy consumption. The energy efficiency level of the buildings within the case district is assumed to be based on the definitions of a low-energy building which are presented in chapter 2. A number of energy system alternatives are defined for both case districts taking into account the limits and requirements set by the developers of the case districts, location of the districts and other factors affecting the feasibility of the energy system alternatives.

The parameters for each energy system alternative are calculated and the parameters are used, together with the specific values for each criterion presented in chapter 4.5, to determine the criterion values for the multi-criteria decision model. The multi-criteria decision model is then used to compare and rank the energy system alternatives according to the weights of criteria set by the district developers. A summary of the case district studies is presented in chapter 5.3.

5.1 Small case district – Jämsä

The district of this case study is located in the city of Jämsä in the Central-Finland. The district belongs to a series of case districts in the EcoDistrict project. According to the current district plan proposition 45 single-family houses are going to be built to the district. The district plan proposition is presented in Figure 17. There are three plots on the district which are already built on and will not be taken into account in these calculations as the energy systems in the buildings are already determined.

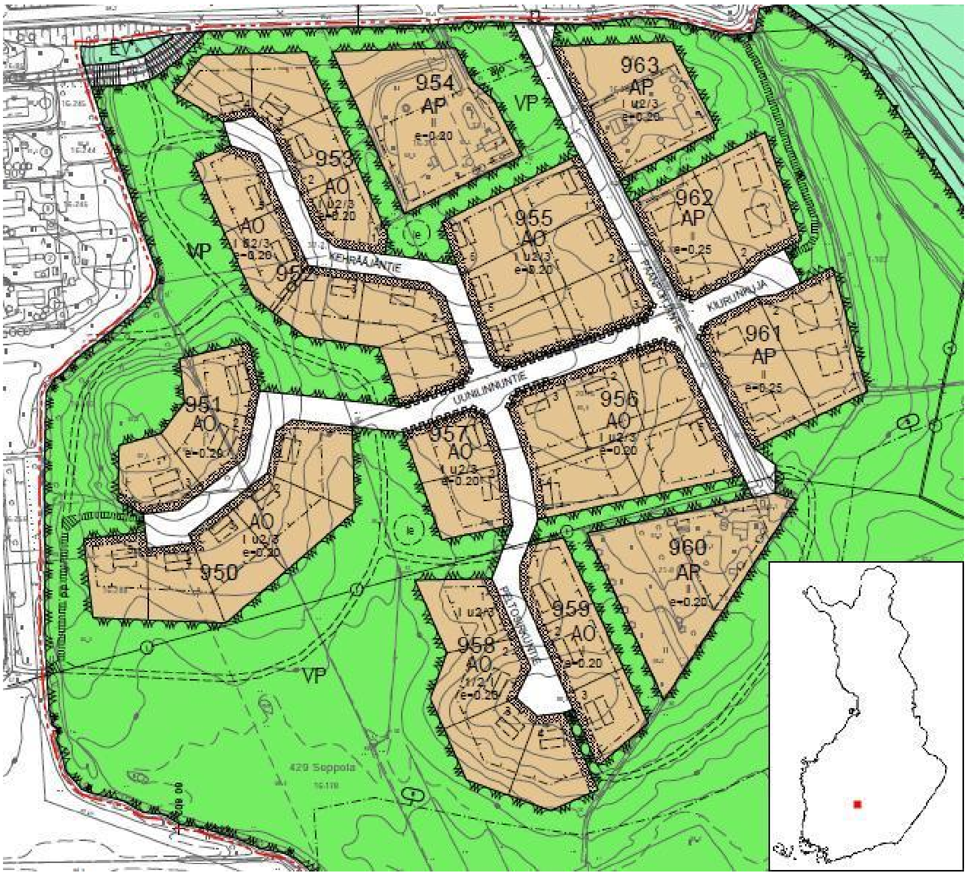

Figure 17. Proposed district plan of the case district (Modified from: City of Jämsä)

5.1.1 Energy consumption calculations

The energy consumption of two type buildings with different sizes was calculated for the case district. The energy consumption calculations were done with WinEtana using the values presented in Table 20. The estimates regarding the number and size of the buildings have been approved by the city of Jämsä.

Table 20. Size and number of type buildings

Building type	Size of building [m^2]	Number of buildings [-]
Detached house, large	220	6
Detached house, small	125	39

The heating energy and the domestic hot water energy consumptions are presented separately in Table 21 as well as the electricity consumption of the type buildings. The energy consumption values are the energy consumption of the total number of each two type buildings.

Table 21. Energy consumption of the buildings in the case district

Building type	Heating [MWh/a]	Domestic hot water [MWh/a]	Electricity [MWh/a]
Detached house, large	57	18	36
Detached house, small	199	55	185
Total	256	73	221

The thermal power demand of the type buildings was also calculated with WinEtana. Total thermal power demands for both heating and domestic hot water are presented in Table 22. The values represent the total amount for the number of each type building.

Table 22. Power demand of the district

Building type	Heating [kW]	Domestic hot water [kW]
Detached house, large	30	26
Detached house, small	117	98
Total	147	124

A district heat distribution network is required for district level energy systems. The length of the distribution network was estimated on the basis of the district plan proposal. According to the requirements of a low-temperature district heating network, a significant factor in the design is reducing the pipe diameter (Hagström et al., 2009, 7). Thus, the heat distribution network is assumed to be constructed from a pipe size of DN25. The length of the distribution network, annual thermal energy losses and the loss heat flux of the heat distribution network is presented in Table 23.

Table 23. Heat distribution network

Pipe size	Length [m]	Total thermal energy loss [MWh/a]	Total loss heat flux [kW]
DN25	2050	211	32

5.1.2 Energy system alternatives

The energy system alternatives selected for the multi-criteria comparison in the Jämsä case are presented in Table 24. The information received of the district and wishes of the client have been taken into account while defining the alternatives. It is unclear, if a district heating network will be constructed for the district. Thus, the existing district heating network is not considered as an alternative for the energy system comparison.

The alternatives include energy systems for building, building group and district level system. Alternatives 1, 2 and 3 are the building-specific energy systems. Ground source heat pumps are also considered as a building group-specific energy system in alternative 4. The district level energy systems are alternatives 5 and 6.

Table 24. Energy system alternatives

	Energy system
Alternative 1	Electric heating
Alternative 2	Pellet boilers
Alternative 3	Ground source heat pump, building
Alternative 4	Ground source heat pump, building group
Alternative 5	District heat plant
Alternative 6	Solar thermal, seasonal storage

The key values for each energy system alternative are presented in the paragraphs below. More detailed calculation tables regarding the definition of the multi-criteria decision method parameters are presented in Appendix 1.

Alternative 1 – Electric heating

For the first alternative, electric heating, the total heat distribution capacity in buildings is 271 kW. Total thermal energy consumption of the buildings is 329 MWh/a and household electricity consumption 221 MWh/a. Total electricity consumption with electric heating is then the sum of the electricity required by the heating system and the household consumption, 550 MWh/a.

Alternative 2 – Pellet boilers

The combined thermal power demand of heating and domestic hot water is 271 kW. Pellet boiler is assumed to operate on an efficiency of 0.9. The total thermal capacity required by the boilers is then 301 kW. The thermal energy demand of the buildings is 329 MWh/a, which means that with the selected boiler efficiency 366 MWh/a of energy from pellets is required. Electricity consumption is 221 MWh/a.

Alternative 3 – Ground source heat pump, building

Total thermal power required from the ground source heat pumps is 271 kW. The heat pumps are assumed to be operating on a COP of 3. The thermal energy demand by the buildings is 329 MWh/a for which the heat pumps require a total of 110 MWh/a electricity to produce. The total electricity consumption with this alternative is 331 MWh/a.

Alternative 4 – Ground source heat pump, building group

In this alternative the buildings of the case district are divided into building groups. The groups are presented in Figure 18. Each building group gain the thermal energy from a group-specific ground source heat pump system, forming a small scale heat network.

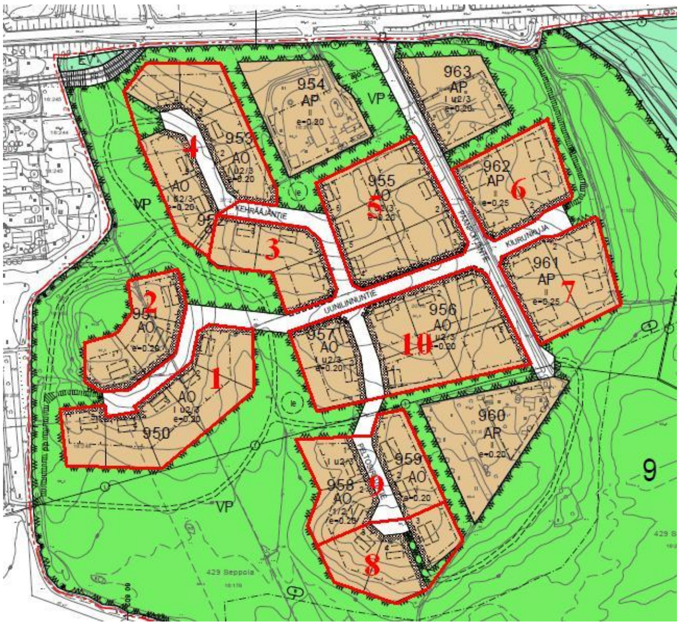

Figure 18. Case district divided to building groups

The lengths of the distribution network piping are estimated on the basis of the building groups and the district plan proposal. The distribution pipe size in the building group-specific energy systems is assumed to be DN25. The estimated distribution network lengths for each building group and the distribution network losses are presented in Table 25.

Table 25. Building group-specific heat distribution systems

Building group	Number of buildings		Thermal energy demand in buildings	Pipe length	Energy loss	Loss heat flux	Total thermal energy
	Large	Small	[MWh/a]	[m]	[MWh/a]	[kW]	[MWh/a]
1		5	32.6	125	17	2.0	50
2	3		37.6	75	10	1.2	48
3		3	19.5	75	10	1.2	30
4, 5		6	78.1	600	83	9.5	161
6, 7		4	52.1	200	28	3.2	80
8	1	2	25.6	50	7	0.8	32
9	2	2	38.1	100	14	1.6	52
10		7	45.6	300	42	4.7	87
Total	6	39		1525	211	24.1	540

The thermal power demand of the buildings is 271 kW. The combined loss heat flux of the distribution systems must be added to the value to obtain the required heat pump thermal capacity, which is 295 kW. Thermal energy produced with the heat pumps is 540 MWh/a which at COP of 3 means a heat pump electricity consumption of 180 MWh/a. The total electricity consumption of the district with this alternative is 410 MWh/a.

Alternative 5 – Heat plant

Fifth alternative is a district level heat plant which operated by wood chip. As the thermal power demand of the buildings is 271 kW and the loss heat flux of the heat distribution network 32 kW, the heat plant must be designed to a capacity of 356 kW taking into account the efficiency of the heat plant, which is assumed to be 0.85. Thermal energy demand of the district is 329 MWh/a and the distribution losses are 280 MWh/a, thus the heat plant must produce 609 MWh of heat annually. Total electricity consumption of the buildings is 221 MWh/a and the length of the heat distribution network 2025 m.

Alternative 6 – Solar thermal

In alternative 6 the thermal energy for the buildings is produced with solar thermal collectors. Due to the variation in the yield of solar thermal collectors throughout the year, a seasonal thermal storage must be added in the energy system to store the thermal energy produced during summer.

More specific information about the thermal energy consumption of the buildings is required to be able to design the solar thermal collectors and the thermal storage at an appropriate size. The thermal energy consumption of the district on a monthly interval was calculated with WinEtana and is presented in Table 26.

Table 26. Monthly thermal energy demand of the district

	Heating [kWh]	Domestic hot water [kWh]	Distribution losses [kWh]	Total [MWh]
January	50976	6201	23804	81.0
February	42918	5601	21501	70.0
March	29190	6201	23804	59.2
April	19248	6001	23036	48.3
May	7008	6201	23804	37.0
June	510	6001	23036	29.5
July	510	6201	23804	30.5
August	510	6201	23804	30.5
September	9198	6001	23036	38.2
October	21948	6201	23804	52.0
November	29280	6001	23036	58.3
December	44793	6201	23804	74.8
Total	256089	73008	360693	609.4

The yield of solar collectors was estimated with SolarTool, an excel-based tool created at VTT for estimating the yield of solar collectors in heating and domestic hot water applications. The calculation procedure of SolarTool is based on part 4-3 of EN standard 15316. (SFS-EN 15316-4-3) Yield per 1 m^2 of collector area in the location of the case district is 595 kWh. According to section D5 of the national building code of Finland, the energy of solar irradiation on a horizontal plane is 839 kWh/m^2 in Jämsä region (Kalliomäki P., 2007). The figures suggest the annual efficiency of 0.71 for the solar thermal collectors. The total required solar thermal collector area is 1024 m^2. The yield of the solar collectors in respect to the thermal energy consumption is presented in Table 27.

Table 27. Thermal energy consumption and the yield of solar collectors

	Energy consumption [kWh]	Yield of collectors [kWh]	Total [kWh]
January	80981	0	-80981
February	70019	8798	-61222
March	59195	47768	-11427
April	48285	82731	34446
May	37013	102715	65702
June	29547	98161	68614
July	30515	111867	81352
August	30515	84535	54020
September	38235	59994	21759
October	51953	12805	-39148
November	58317	0	-58317
December	74798	0	-74798

The negative values in the rightmost column represent the amount of thermal energy consumption per month which the solar thermal collectors are unable to cover. The total amount of thermal energy that must be stored in the seasonal storage is 325 893 kWh. According to Alanen et al. (2003, 107-108), an above ground steel tank thermal storage costs approximately 200 €/m^3 and can store 57 kWh/m^3 with an efficiency of 0.9. With the storage efficiency of 0.9, the total thermal capacity of the storage must be 362 103 kWh or 6353 m^3. This means that an additional thermal energy of 36 210 kWh must be produced by solar thermal collectors. With the annual yield of 595 kWh/m^2, the additional solar thermal collector area is 61 m^2 making the total collector area 1085 m^2. Electricity consumption of the district in this alternative is 221 MWh/a and the total length of the heat distribution network 2025 m.

5.1.3 Applying the multi-criteria decision method

The criterion values for each alternative were calculated according to the energy system alternatives presented in chapter 5.1.2 and the specific information for each energy system presented in chapter 4.5. The values with which the systems will be evaluated in the multi-criteria analysis are presented in Table 28.

Table 28. Initial data for the multi-criteria comparison

	Investment costs [€]	Energy costs [€/a]	GHG emissions [t/a]	Particulate emissions [kg/a]	Locality of energy source [-]	Maturity of technology [-]
Alternative 1	135500	69850	182	63	0	3
Alternative 2	237878	50190	77	74	1	3
Alternative 3	433600	51579	112	39	1	3
Alternative 4	596850	62973	137	48	1	3
Alternative 5	162600	80423	86	114	1	3
Alternative 6	162600	171352	88	31	1	1

The positive and negative flows for each alternative are presented in Table 29. The multi-criteria analysis was made with the criteria weighting presented in chapter 4.6. The normalized decision matrix, preference function matrix and aggregated preference function matrix are presented in Appendix 2. The net outranking flow of different energy system alternatives is also presented in Table 29 along with the rank the alternative reached in the multi-criteria analysis.

Table 29. The outranking flows and ranks of the energy system alternatives

	Positive flow ϕ^+	Negative flow ϕ^-	Net flow ϕ	**Rank**
Alternative 1 **-** Electric heating	0.1500	0.3944	**-0.2444**	**6**
Alternative 2 **-** Pellet boilers	0.3150	0.0341	**0.2809**	**1**
Alternative 3 **-** Ground source heat pump, building	0.1795	0.1759	**0.0037**	**3**
Alternative 4 **-** Ground source heat pump, building group	0.1090	0.3467	**-0.2377**	**5**
Alternative 5 **-** District heat plant	0.2750	0.0540	**0.2210**	**2**
Alternative 6 **-** Solar thermal, seasonal storage	0.2350	0.2584	**-0.0234**	**4**

With the weights of the criteria presented in chapter 4.6 the most optimal energy system for the case district from the point of view of the district developer is building-specific pellet boilers. The wood chip operated district heat plant ranked second in the comparison, suggesting that a centralized energy system with low investment costs could also be taken into consideration while selecting the energy system for the district.

5.2 Large case district – Tampere

The second and larger case district, Vuores-Koukkujärvi, is located in the city of Tampere in Finland. The district belongs to a series of case districts in the EcoDrive project. The gross floor area on the district will be approximately 48 000 m2, consisting of detached houses, row houses and apartment blocks. The proposed district plan for the district is presented in Figure 19.

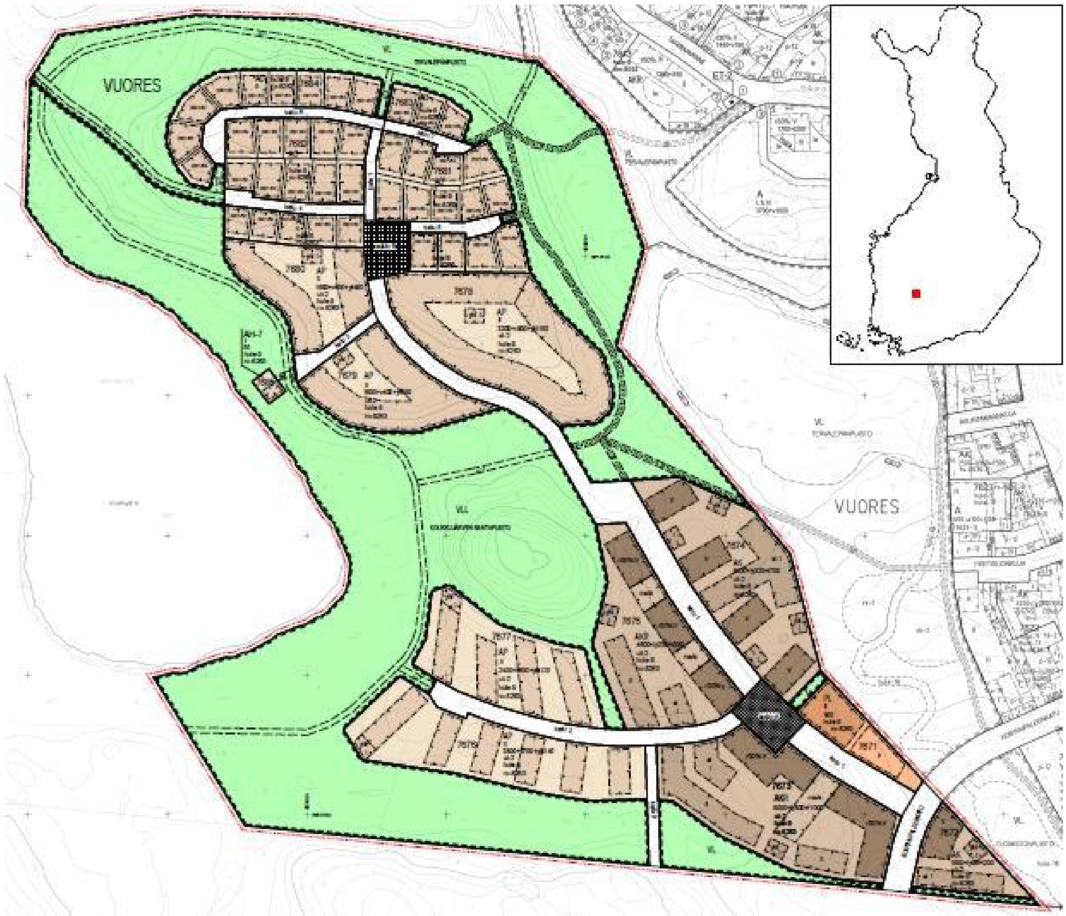

Figure 19. Proposed district plan for the case district (Modified from: City of Tampere, 2010)

The district is divided into two sections. The northern part of the case district is composed of small, detached and semi-detached buildings. The southern part of the district has large apartment buildings, lower apartment buildings and row houses. The services in the district are also located in the southern part.

5.2.1 Energy consumption calculations

The energy consumption of the buildings in this case district was calculated with WinEtana by creating separate type buildings for three different building types. The type buildings were assumed to be built after the low-energy building requirements presented in Table 2. The energy consumption calculations were done with following type buildings:

- Apartment building
- Row house
- Detached building

The gross floor areas for each block were evaluated from the district plan proposal. The floor areas on a city block level are presented in Table 30. The southern part of the district consists of blocks 7671-7677. Blocks 7678-7685 belong to the northern part of the district.

Table 30. Gross floor areas per a block and the building types

	Block	Building type	Floor area [m^2]
South part	7671	Apartment building	500
	7672	Apartment building	2090
	7673	Apartment building	9800
	7674	Apartment building	7420
	7675	Apartment building	5330
	7676	Row house	3640
	7677	Row house	3120
North part	7678	Row house	4160
	7679	Row house	2080
	7680	Row house	2080
	7681	Detached building	2600
	7682	Detached building	3000
	7683	Detached building	600
	7684	Detached building	1800
	7685	Detached building	50

As the number of the buildings and their size cannot be determined from the district plan, the energy consumption of the district was calculated by creating a type building for each building type. The type buildings included a 250 m^2 type building for the detached house, a 600 m^2 type building for the row house and a 1 500 m^2 type building for the apartment building. The floor area of the detached building was assumed to be 250 m^2 as it is the maximum floor area allowed by the district plan. The created type buildings were then used to determine the specific heating and domestic hot water energy consumptions and electricity consumption for each building type. The specific energy consumption values for the type buildings are presented in Table 31.

Table 31. Specific energy consumption values of the type buildings

Building type	Heating [kWh/m^2]	Domestic hot water [kWh/m^2]	Electricity [kWh/m^2]
Apartment building	37	21	29
Row house	47	16	32
Detached house	52	16	17

The specific energy consumption values were then used to evaluate the total energy consumption of the district. The energy consumption of the district on a block level is presented in Table 32.

Table 32. Energy consumption of the case district

Block	Heating [MWh/a]	Domestic hot water [MWh/a]	Electricity [MWh/a]
7671	18.5	10.5	14.5
7672	77.3	43.9	60.6
7673	362.6	205.8	284.2
7674	274.5	155.8	215.2
7675	197.2	111.9	154.6
7676	171.1	58.2	116.5
7677	146.6	49.9	99.8
7678	195.5	66.6	133.1
7679	97.8	33.3	66.6
7680	97.8	33.3	66.6
7681	135.2	41.6	44.2
7682	156.0	48.0	51.0
7683	31.2	9.6	10.2
7684	93.6	28.8	30.6
7685	2.6	0.8	0.9
Total	**2058**	**898**	**1349**

The thermal power requirement of heating and the domestic hot water were also calculated with WinEtana. The specific thermal power values for the type buildings are presented in Table 33.

Table 33. Specific thermal power demand of type buildings

Building type	Heating [W/m^2]	Domestic hot water [W/m^2]
Apartment building	22	23
Row house	23	27
Detached building	24	20

The thermal power demands of the district on a block level are presented in Table 34. The values in Table 34 are calculated with the type building-specific thermal power demands presented in Table 33 and the type building floor areas presented in Table 30.

Table 34. Thermal power of the case district

Block	Heating [kW]	Domestic hot water [kW]
7671	11.0	11.5
7672	46.0	48.1
7673	215.6	225.4
7674	163.2	170.7
7675	117.3	122.6
7676	83.7	98.3
7677	71.8	84.2
7678	95.7	112.3
7679	47.8	56.2
7680	47.8	56.2
7681	62.4	52.0
7682	72.0	60.0
7683	14.4	12.0
7684	43.2	36.0
7685	1.2	1.0
Total	**1093**	**1146**

The distribution losses of the heat distribution network are calculated for the northern and southern part separately. The lengths of the distribution pipes are estimated on the basis of the district plan presented in Figure 19. The estimates on the pipe size are based on the types of buildings the pipes are used to deliver heat. The distribution losses and loss heat flux were calculated according to the values presented in Table 3. The results are presented in Table 35.

Table 35. Heat distribution network losses

	Pipe size	Length [m]	Thermal energy loss [MWh/a]	Loss heat flux [kW]
South	DN25	1 035	143	16
	DN40	225	45	5
	DN65	285	68	8
	Total	1 545	256	29
North	DN25	1 685	233	27
Total		4 775	489	56

5.2.2 Energy system alternatives

The energy system alternatives selected for comparison in the Tampere case are presented in Table 36. The information received of the case district and wishes of the client have been taken into account while defining the alternatives. A district heating network is being planned at least for the southern part of the case district, but in the definition of the energy system alternatives it is also assumed that in one alternative the network would reach out to the northern part of the district too.

Alternatives 1, 2 and 3 are the building-specific energy systems chosen for this case study. Alternatives 4 and 5 are a combination of district heating network in the southern part of the case district and building group-specific ground source heat pumps in the northern part. In alternative 5, solar energy is also utilized in the northern part along with the ground source heat pumps. Finally, alternatives 6, 7 and 8 are district level energy systems, where the energy production system and the district heat distribution network is assumed to be invested by an energy operator.

Table 36. Energy system alternatives

	Energy system
Alternative 1	Electric heating
Alternative 2	District heating network
Alternative 3	Pellet boilers
Alternative 4	Building group ground source heat (North part) District heating network (South part)
Alternative 5	Building group ground source heat north and solar energy (North part) District heating network (South part)
Alternative 6	Water source heat pump
Alternative 7	Water source heat pump and wind energy
Alternative 8	CHP

The key values for each energy system alternative are presented in the paragraphs below. More detailed information about the values that were used while defining the parameters for the multi-criteria analysis is presented in Appendix 3.

<u>Alternative 1 – Electric heating</u>

The comparison details the electric heating alternative can be calculated from the consumption values presented in chapter 5.2.1. Total thermal energy consumption 2956 MWh/a and electricity consumption 1348 MWh/a. Thus, the total electricity consumption per year is 4304 MWh. Required thermal power is 2240 kW, including heating and domestic hot water.

<u>Alternative 2 – District heating network</u>

In alternative 2 the district heat energy consumption is 2956 MWh/a and electricity consumption 1348 MWh/a. Required heat distribution system capacity in buildings is

2240 kW. For the emission calculations, the distribution losses of the district heat network must be added to the thermal energy consumption. Total thermal energy demand of the district is 3445 MWh/a.

For the calculation of costs regarding the district heating network alternative, the case specific information had to be obtained. The connection fee to the district heating network is on average 118 €/kW. The district heating network also has an average yearly fee of 28 €/kW and the cost of heat is assumed to be 57 €/MWh. (Tampereen Kaukolämpö)

Alternative 3 – Pellet boilers

Required heat distribution capacity in buildings is 2240 kW. Thermal energy production required by the pellet boilers is 2956 MWh/a. The boiler efficiency is assumed to be 90 %, thus the total wood pellet consumption is 3284 MWh/a. The total electricity consumption is 1348 MWh/a.

Alternative 4 – Ground source heat and district heat

Thermal energy consumption of the southern part of the case district is 1884 MWh/a. For emission calculations, the distribution losses 256 MWh/a, as presented in Table 35 must be added to the value. The total district heat consumption in this alternative is therefore 2140 MWh/a. District heat capacity needed in the southern part is 1469 kW and the length of the distribution network 1545 m.

The ground source heat pump systems in the northern part of the district are considered as building group specific systems. The building groups in this alternative are formed by the city blocks presented in the district plan. Each building group requires an individual heat distribution network. The details of the building group heat distribution networks are presented in Table 37.

Table 37. Heat distribution within building groups

Block	Pipe length (DN25) [m]	Thermal energy loss [MWh/a]	Loss heat flux [kW]
7678	320	44.3	5.1
7679	240	33.2	3.8
7680	140	19.4	2.2
7681	160	22.1	2.5
7682	240	33.2	3.8
7683	60	8.3	0.9
7684	180	24.9	2.8

The total length of heat distribution pipes in the northern part is 1340 m. The energy consumption and thermal power demand of each city block is calculated separately. The results of the calculations, which are used to determine the required ground source heat pump capacity, are presented in Table 38.

Table 38. Ground source heat pump requirements

Block	Consumption [MWh/a]	Losses [MWh/a]	Total [MWh/a]	Thermal power [kW]	Loss heat flux [kW]	Total [kW]
7678	262	44	**306**	208	5.1	**213**
7679	131	33	**164**	104	3.8	**108**
7680	131	19	**150**	104	2.2	**106**
7681	177	22	**199**	114	2.5	**117**
7682	204	33	**237**	132	3.8	**136**
7683	41	8	**49**	26	0.9	**27**
7684	122	25	**147**	79	2.8	**82**
Total			**1254**	**768**		**789**

The total thermal capacity required from the ground source heat pumps is 789 kW and the total thermal power demand in the buildings is 768 kW. Total thermal energy production by the heat pumps is 1254 MWh/a. The COP of the ground source heat pumps is assumed to be 3, thus 418 MWh/a electricity is required to operate the heat pumps. The total electricity consumption in this alternative is therefore 1766 MWh/a.

Alternative 5 – Ground source heat, solar energy and district heat

The calculation of the southern part is identical to alternative 4. The yield of solar collectors was estimated with SolarTool, a tool created at VTT for estimating the yield of solar collectors. The calculation procedure of SolarTool is based on part 4-3 of EN standard 15316. (SFS-EN 15316-4-3) According to the district plan presented in Figure 19, there are two types of buildings in the northern part: detached houses and row houses. In this alternative, it is assumed that the solar thermal collector area for detached houses is 6 m^2 and for row houses 15 m^2. The collectors are used to heat the domestic hot water in the buildings. The domestic hot water consumption of the 600 m^2 row house type building is 9.6 MWh/a and 4 MWh/a for the 250 m^2 detached house type building.

Domestic hot water consumption is assumed to remain steady throughout the year. Monthly energy demand can then be calculated by dividing the annual consumption by the total number of days per year and multiplying the result with the number of days per the specific month. The monthly domestic hot water energy demand of the type buildings and the thermal energy produced by the selected collector areas are presented in Table 39.

Table 39. Solar collector yields in type buildings

	Row house (600 m^2) [kWh/month]	Collector (15 m^2) yield [kWh/month]	Detached building (250 m^2) [kWh/month]	Collector (6 m^2) yield [kWh/month]
January	815	0	340	0
February	736	171	307	73
March	815	553	340	228
April	789	782	329	323
May	815	815	340	340
June	789	789	329	329
July	815	815	340	340
August	815	815	340	338
September	789	649	329	266
October	815	210	340	88
November	789	0	329	0
December	815	0	340	0
Total	**9600**	**5600**	**4000**	**2324**

The gross floor area of row houses in northern part of the case district is 8320 m^2 and the gross floor area of detached houses 8000 m^2. Approximately 14 row house type buildings and 32 detached house type buildings can be built on the district. The total thermal energy produced by solar thermal collectors is then 78 MWh/a.

Alternative 5 also includes photovoltaic panels. The calculations were done with an assumption, that each row house has a 8 kW_p photovoltaic panel module and each detached house a 2 kW_p module. Total photovoltaic capacity is then 175 kW_p. The yield of the photovoltaic panels was estimated at the location of the case district with a utility provided by Joint Research Centre of European Commission (EU JRC). The total electricity yield of the photovoltaic panels is presented in Table 40.

Table 40. Photovoltaic yield

	Total yield [kWh]
January	2 729
February	8 589
March	13 820
April	19 068
May	22 391
June	20 642
July	21 342
August	16 584
September	11 633
October	6 630
November	2 572
December	1 503
Total	147 502

The utilization of solar energy in the northern part of the district does not however affect the total capacity required from the ground source heat pumps as they need to be able to meet the demand at times when the consumption is at highest and the solar energy production is at lowest. The thermal energy produced by the solar thermal collectors does reduce the energy production by the ground source heat pumps though and the total thermal energy production of the ground source heat pumps is obtained by deducting the yield of the collectors from the annual thermal energy demand. Thus, the total thermal energy produced by the ground source heat pumps in this alternative is 1176 MWh/a which at a COP of 3 means 392 MWh/a electricity consumption.

The electricity produced by the photovoltaic panels, approximately 148 MWh/a, is deducted from the total electricity consumption, resulting in 1593 MWh/a of electricity to be obtained from the grid by the whole district.

Alternative 6 – Water source heat pump

Alternative 6 is a district level energy system where the thermal energy is produced by water source heat pump. The calculations of distribution network losses presented for the district heating network will be used to calculate the total energy production and the capacity requirement of the water source heat pump system.

The thermal power demand of the buildings is 2240 kW. The loss heat flux of the distribution network is 56 kW. Total capacity required from the water source heat pump system is then 2295 kW. Heat consumption of the buildings is 2956 MWh/a and the distribution network losses 489 MWh/a, thus the total thermal energy production by the water source heat pump is 3445 MWh/a. With COP of 3, the heat pump system requires 1148 MWh/a of electricity to operate. The total electricity consumption of the district is then 2497 MWh/a. Length of the distribution network is 3230 m.

Alternative 7 – Water source heat pump and wind energy

Alternative 7 is similar to alternative 6 with the exception that the heat pump electricity demand is assumed to be produced by a wind turbine. The yield of a 1 MW wind turbine in the location of the case district, at the height of 50 m, is approximately 1000 MWh/a (Tuuliatlas). As the electricity consumption of the heat pump is 1148 MWh/a, a total capacity of 1.15 MW is required from the wind turbine to produce the electricity for operating the heat pump. The rest of the electricity, 1348 MWh/a, is obtained from the grid.

Alternative 8 - CHP

The thermal capacity required from the CHP-plant is 2295 kW. The value includes both the thermal power demand of the buildings and the distribution network loss. The power to heat ratio of the CHP-plant is assumed to be 0.2 thus the electric capacity is 459 kW_e. The annual thermal energy produced by the plant is 3445 MWh/a, including the buildings' thermal energy demand and the distribution losses. The maximum utilization period of the plant is calculated by dividing the total annual thermal energy production with the thermal capacity of the power plant. The maximum utilization period of the CHP-plant in this alternative is 1500 h. The plant generates 689 MWh of electricity annually. Electricity demand in this alternative is 1348 MWh/a and total distribution network length 3230 m.

5.2.3 Applying the multi-criteria decision method

The criterion parameters for each alternative were calculated according to the energy system alternatives presented in chapter 5.2.2 and the specific information for each energy system presented in chapter 4.5. More detailed information about the calculations of parameters for each alternative is presented in appendix 3. The values with which the systems will be evaluated in the multi-criteria analysis are presented in Table 41.

Table 41. Initial data for the multi-criteria comparison

	Investment costs [€]	Energy costs [€/a]	GHG emissions [t/a]	Particulate emissions [kg/a]	Locality of energy source [-]	Maturity of technology [-]
Alternative 1	1 120 000	546 608	1420	491	0	3
Alternative 2	1 608 320	415 056	1 096	178	0	3
Alternative 3	1 966 222	353 387	477	591	1	3
Alternative 4	2 400 212	407 847	999	223	1	3
Alternative 5	3 474 879	378 268	952	204	1	2
Alternative 6	1 344 000	564 219	858	309	1	2
Alternative 7	1 344 000	494 744	546	190	1	1
Alternative 8	1 344 000	384 890	544	918	1	3

The positive and negative flows for each alternative are presented in Table 42. The multi-criteria analysis was made with the criteria weighting presented in chapter 4.6. The normalized decision matrix, preference function matrix and aggregated preference function matrix for the Tampere case are presented in Appendix 4. The net outranking flow of different energy system alternatives is calculated with Equation (8) presented in chapter 4.4.1. Net outranking flows of different energy systems alternatives as well as their ranks are also presented in Table 42.

Table 42. The outranking flows and ranks of the energy system alternatives

		Positive flow ϕ^+	Negative flow ϕ^-	Net flow ϕ	**Rank**
Alternative 1	Electric heating	0.1168	0.4269	**-0.3101**	**8**
Alternative 2	District heating network	0.1413	0.2218	**-0.0805**	**6**
Alternative 3	Pellet boilers	0.3442	0.0555	**0.2887**	**1**
Alternative 4	Building group ground source heat (North) District heating network (South part)	0.1440	0.1952	**-0.0511**	**4**
Alternative 5	Building group ground source heat and solar energy (North part) District heating network (South part)	0.1320	0.3185	**-0.1865**	**7**
Alternative 6	Water source heat pump	0.1542	0.2086	**-0.0544**	**5**
Alternative 7	Water source heat pump and wind energy	0.2593	0.1531	**0.1062**	**3**
Alternative 8	CHP	0.3219	0.0342	**0.2876**	**2**

The multi-criteria analysis was carried out with the criteria weights presented in chapter 4.6. The weights used represent the preferences of the district developer. The numerical values for each criterion weight were calculated with estimated value method, also presented in chapter 4.6. With the used criteria weights, the most optimal energy system from the district developers' point of view is alternative 3, building specific wood pellet boilers.

A district level alternative based on CHP is ranked second in the comparison and water source heat pump combined with wind energy ranked third. The results suggest that with a denser building pattern such as in the Tampere case district, a centralized solution could also be taken into consideration when selecting the energy system.

5.3 Summary of case studies

The results of both case studies suggest that the most optimal energy system for the districts would be building-specific wood pellet boilers. The results can be justified by the rather low specific investment costs of the boilers and low GHG-emissions of the process. Although particulate emissions are relatively high in the pellet boiler alternative, the weight given for the particulate emission criterion is low. Thus, the particulate emissions have little effect on the outcome of the comparison.

A centralized alternative based on CHP is ranked second in the comparison of the Tampere case study. The results suggest that with a denser building pattern a centralized solution could also be taken into consideration when selecting the energy system. The district heat plant alternative ranked second in the Jämsä case which also indicates that with low investment costs and low costs of energy, a centralized energy system is a reasonable alternative even in low density residential districts. Therefore, the size and structure of the district does not seem to have any particular effect on the optimality of building-specific energy systems over district level energy systems or vice versa. However, the actual difference between these two case districts is relatively small as the district could consist of several hundreds of buildings. The optimal energy system in much larger districts than the two studied in this master’s thesis could very well be centralized.

An interesting notice can be made in both case studies regarding the electric heating alternative. Although the investment costs of such energy system are the lowest of all alternatives, the alternative ranked bottom in the list in both case study. The GHG-emissions of Finnish electricity and the high costs of electricity are key factors affecting the low rank of electric heating. If the increase in the costs of energy over a certain time step would have been taken into account in the cost calculations, the rank of electricity would have probably been even lower, if possible.

If the alternatives are examined on a single criterion, for example investment costs, it can be seen from Tables 28 and 41 that the electric heating alternative would be most suitable alternative. However, by selecting the single criterion to be energy costs of GHG-emissions, the most suitable energy system would once again be pellet boiler.

6 Discussion

The reliability and applicability of the presented selection method in case studies is discussed in this chapter. A sensitivity analysis of the selection method will also be done, regarding the weighting of the criteria used in the multi-criteria comparison. The applicability of the selection method is evaluated in chapter 6.2. Finally, questions which remained open during the master's thesis and possible future research topics are discussed in chapter 6.3.

6.1 Reliability analysis of the developed method

The most fundamental definitions and assumptions affecting the reliability of the energy system selection method and the case studies where it was applied are discussed in this chapter.

6.1.1 Definitions, assumptions and their effect to the selection method

The first major definition was made regarding the most important stakeholder in the energy system selection process. The district developer was defined as the most important stakeholder as the information and requirements concerning the district plan, energy efficiency of buildings, possible existing district heating networks and desired energy systems came from the district developers in the case studies. It can be discussed, how far up into the process of selecting an energy system the district developer is actually able to affect. The actual influence might very well remain at the level, where the district developer sets targets or regulations on whether the energy system is a district level or a smaller scale energy system such as building or building group level.

Second major definition was made regarding the electric resources of the case districts. Both of the districts were assumed to be connected to the national electric grid. The assumption on availability of electricity simplified the comparison of energy system alternatives to focus mainly on heating systems.

Last major definition was that the energy system alternatives and the design of them only took into account the energy and thermal power demands of the case districts.

Thus, the energy system alternatives were designed to meet the maximum demand of the districts. In Tampere case study, for example, the CHP-plant was designed according to the peak thermal power requirements of the district. The annual peak utilization of the CHP-plant remains low, at approximately 1500 h/a. This is due to the rather large peak thermal power requirement of the district in contrast to the thermal energy demand of the district. The same issue affects a majority of the energy system alternatives compared in the case studies. With higher accuracy energy consumption simulation, the peak thermal power requirements could have been identified more precisely and the dimensioning of the energy supply system could have been optimized.

The cost calculations in the case studies were done with the specific costs presented in chapter 4.5.The specific costs presented in this master’s thesis for the energy supply systems as well as for the heat distribution systems in buildings and districts should be considered indicative as the size of the energy systems or heat distribution systems was largely left unaccounted for while defining the specific costs.

The emissions calculated in this master’s thesis are for the entire life cycle of the energy production system. The life cycle emissions were selected as they give a more profound picture of the actual environmental impact of the energy systems than the emissions of the production of energy alone. The locality of the life cycle particulate emissions of different energy systems can, however, be questioned. Majority of the lifecycle particulate emissions of energy systems which are not based on combustion technologies are generated from the production and transportation of the energy system components, thus the locality of the emissions depend on the site of manufacturing. However, as the results of the questionnaire show, the community level decision makers considered the particulate emissions as the least important criterion when selecting the energy system. Thus, the effect of this assumption to the final outcome of the ranking remains low.

The cooling energy consumption was not calculated in this master’s thesis as according to Holopainen et al. (2007, 67), the mechanical cooling of buildings can not be justified in the sense of energy economics. Thus, the cooling of the buildings was assumed to be accomplished by passive methods. The energy consumption level of the buildings in the case studies was assumed to be low-energy level, which was assumed to include also passive solar heating and cooling methods.

The results of the questionnaire were used to define the criteria weights for the multi-criteria decision method. The criterion weights were given a numerical value according to the estimated value method. The actual accuracy of the obtained weights is arguable, as the results of the questionnaire imply no large differences between weights of any particular criteria, especially among the three criteria with the highest importance and additionally the sample of the questionnaire was small. The target group included community level decision makers, district developers and district planners. In practice the weights of the criteria are set by the actor in charge of the district developing.

6.1.2 Sensitivity analysis of the selection method

The sensitivity of the multi-criteria decision method was studied by assuming the criterions which ranked second and third, investment costs and energy costs, equally important. The weights of these criteria were obtained by their average, which is calculated by Equation (13) as suggested by Ghafghazi et al. (2010).

$$w_a = \frac{w_1 + w_2}{2} \tag{13}$$

, where w_a = the weight of criterions w_1 and w_2 if they are considered equally important

w_1 = weight of criterion obtained by the expected value method

w_2 = weight of criterion obtained by the expected value method

The weights of the criteria were presented in Table 19. With Equation (13), the weight for both of the criterions in the sensitivity analysis is 0.20. When the multi-criteria comparison in done with the new criterion weights, the results of top three energy system alternatives remain the same as presented in both case study analyses. In the larger case study, whole ranking remains the same.

6.1.3 The reliability of the case study analyses

The reliability of the results in the case studies were evaluated by comparing the results acquired to previous studies where energy systems have been compared. Because studies with such wide range of different energy systems and several indicators used to compare the energy systems has not been done in Finnish conditions, the reliability is evaluated with studies concentrating on fewer energy system options. The results of a study by Holopainen et al. (2010) indicate, that ground source heat pumps is a cost effective solution when compared to district heat. The results of the Tampere case study are similar to this, as the energy system alternative with ground source heat pumps in the northern part of the district outranks the alternative where the whole district is connected to district heating network. Moreover, the previous studies do not take into account the emissions, which also favour ground source heat pumps over district heat.

All of the energy system alternatives in the case study analyses of this master's thesis were designed to meet the peak thermal power demand in total. By utilizing thermal storages, however, a part load design is also possible on some energy systems. Klobut et al. (2009) propose a district heating solution for very low-energy house which reduces the heating load of the building by 30 %. The reduction is made possible by a domestic hot water storage tank, which allows to cut the peak thermal power demands and therefore reduces the heat load to the district heating network. Holopainen et al. (2010) also studied the optimal design of a ground source heat pump in their study. According to the results, the most cost-effective ground source heat pump solution is designed to meet 50 % of the peak thermal power demand. The rest of the thermal energy demand is covered by additional electric heating.

6.2 Applicability of the selection method

The energy system selection method is most applicable in the preselection phase of a districts energy system. In case the weights of the criteria are known, the selection method can be used to point out the optimal energy system. The energy system can then be optimized more precisely to meet the requirements of the building or district. In addition, additional energy supply systems such as solar thermal collectors could be implemented to the energy system. The new versions of the initially selected energy system could be compared again with the multi-criteria method.

The strength of the selection method and especially the multi-criteria comparison is the transparency of it as the selection process is converted into a numerical form. This reduces the effects of favouring certain energy systems. Energy system alternatives which might on a first thought appear the best choice, might not receive such a high rank in the results of the comparison. For example, the alternative 6 in the Jämsä case study, the solar thermal alternative, received rather low rank in the comparison although it otherwise might have appeared to be an innovative and attractive alternative.

6.3 Open questions and further research topics

This master's thesis held the district planning stakeholder as the most influential stakeholder when it comes to selecting the energy system. The other stakeholders and their preferences should also be studies for a more profound evaluation of the energy systems. The interaction between different stakeholders such as end-users, real estate owners, energy providers, facility management service providers, politicians, authorities, investors and the district planners could be modelled and studied by the means of system dynamics, for example. Therefore, modelling and simulation of decision-making processes in complex networks of stakeholders (understanding key factors influencing paradigm shift of business operations foreseen in the near future) is very important topic of further research.

One approach to get a wider view of the values and preferences of the different stakeholders could be a questionnaire, similar one as conducted for the community level decision makers for the purposes of this master's thesis, carried out for the other stakeholders as well.

The energy system alternatives defined for the case studies were relatively simple and the systems were designed to meet the peak thermal power demand in total. Studying the district energy systems in dynamic conditions in order to obtain the optimal match of supply and demand and studying the effects of different energy storage methods with more sophisticated simulation tools could have led to different outcomes in the ranking of the energy system alternatives. Thus, there is clear need to develop district level simulation tools which include both efficient use of energy (building system models) and energy production including energy storage.

In general, there is a lot of research need for multi-energy source energy systems on district level. The energy-efficiency of buildings will be improving and renewable energy production technologies will be increasingly integrated into buildings. These building integrated energy production systems will be integrated to district level energy systems. This will also require development and implementation of smart heat and power grids to the energy systems. Fundamental question from business perspective is: who in the near future have real interest to invest to building integrated energy production and energy storage solutions? Another fundamental question from the technical perspective is: What is the locally optimal configuration of multi-energy source energy system with those specific business interests?

7 Conclusions

This master’s thesis presents a method for the selection of an optimal energy system in district development projects. The optimality of the energy system alternatives is evaluated through a series of criterions and the importance the stakeholder who makes the decisions regarding the energy system gives for the different criterions. The selection method includes the definition of the district, calculating the energy consumption, creating models for energy system alternatives and finally comparing different energy systems from the point of view of the most important stakeholder regarding the selection of the energy system.

The most influential stakeholder involved in the selection of an energy system is recognized to be the decision maker who is in charge of the district planning. It is assumed that the development of the district can be directed through district plan regulations, recommendations or instructions. The question of how far into the selection process the stakeholder responsible for district planning can influence remains open, however. The criteria which the community level decision makers appreciate in energy system selection were studied by a questionnaire sent to the steering groups of two district development projects. These districts were used as case districts in this master’s thesis.

The results of both case studies suggest that the most optimal energy system for the districts would be building-specific wood pellet boilers. The results can be justified by the rather low specific investment and fuel costs of the boilers and low GHG-emissions of the process. A centralized alternative ranked second in both case study districts. In the smaller case study district, located in Jämsä, the centralized alternative consisted of a district heat plant operated by wood chip. In the Tampere case district, the centralized alternative was a CHP-plant, also operated by wood chip. The high ranking of the CHP-plant can be justified by the assumption that the revenue generated from selling the electricity the plant produces is directly decreased from the cost of thermal energy.

On the basis of the two case study analyses, it seems that the size and structure of the district has relatively small effect on the optimality of certain energy system. However, the actual difference between these two case districts is relatively small as a district could consist of several hundreds of buildings. The most optimal energy system in much larger districts than the two studied in this master’s thesis could very well be centralized.

The energy system selection method is most applicable in the preselection phase of a districts energy system. When the energy system is selected, more precise optimization could be carried out. In addition, additional energy supply systems such as solar thermal collectors could be implemented to the energy system. If a new series of alternatives, based on the energy system obtained from the first selection round would emerge, the multi-criteria method could be applied again.

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Appendix 1: Energy system alternatives, Case Jämsä

Alternative 1 - Electric heating		
Thermal capacity required	271	kW
Thermal energy consumption	329	MWh/a
Electricity consumption	221	MWh/a
Total electricity consumption	550	MWh/a
Electric heating investment costs	500	€/kW
Cost of electricity	127	€/MWh
CO_2-equivalent emissions of electricity	330	kg/MWh
Particulate emissions of electricity	0.114	kg/MWh
Total investment costs	**135 500**	**€**
Annual energy costs	**69 850**	**€/a**
Annual CO_2-eqv. emissions	**182**	**t/a**
Annual particulate emissions	**63**	**kg/a**

Alternative 2 - Pellet boilers		
Thermal capacity required	271	kW
Boiler efficiency	90	%
Boiler capacity	301	kW
Thermal energy demand	329	MWh/a
Wood pellet consumption	366	MWh/a
Electricity consumption	221	MWh/a
Pellet boiler investment costs	250	€/kW
Heat distribution investment costs	600	€/kW
Cost of pellets	43	€/MWh
Cost of electricity	153	€/MWh
Operation and maintenance costs	2	€/MWh
CO_2-equivalent emissions of pellet boiler	11	kg/MWh
Particulate emissions of pellet boiler	0.148	kg/MWh
CO_2-equivalent emissions of electricity	330	kg/MWh
Particulate emissions of electricity	0.114	kg/MWh
Total investment costs	**237 878**	**€**
Annual energy costs	**50 190**	**€/a**
Annual CO_2-eqv. emissions	**77**	**t/a**
Annual particulate emissions	**74**	**kg/a**

Alternative 3 - Building-specific ground source heat pump			
Thermal capacity required	271	kW	
Thermal energy consumption	329	MWh/a	
Thermal energy from ground	219	MWh/a	(COP = 3)
Thermal energy from electricity	110	MWh/a	
Electricity consumption	221	MWh/a	
Total electricity consumption	331	MWh/a	
Ground source heat pump investment costs	1 100	€/kW	
Heat distribution investment costs	600	€/kW	
Cost of electricity	153	€/MWh	
Operation and maintenance costs	3	€/MWh	
CO_2-equivalent emissions of ground source heat pump	9	kg/MWh	
Particulate emissions of ground source heat pump	0.005	kg/MWh	
CO_2-equivalent emissions of electricity	330	kg/MWh	
Particulate emissions of electricity	0.114	kg/MWh	
Total investment costs	**460 700**	**€**	
Annual energy costs	**51 579**	**€/a**	
Annual CO_2-eqv. emissions	**112**	**t/a**	
Annual particulate emissions	**39**	**kg/a**	

Alternative 4 - Building group-specific ground source heat pump			
Thermal capacity required	271	kW	
Loss heat flux of heat distribution networks	24	kW	
Total heat pump capacity	295	kW	
Thermal energy consumption	329	MWh/a	
Distribution losses	211	MWh/a	
Thermal energy produced by heat pumps	540	MWh/a	
Thermal energy from ground	360	MWh	(COP = 3)
Thermal energy from electricity	180	MWh	
Electricity consumption	221	MWh/a	
Total electricity consumption	401	MWh/a	
Total length of heat distribution pipes	1 525	m	
Ground source heat pump investment costs	900	€/kW	
Heat distribution investment costs	600	€/kW	
Heat distribution network construction costs	130	€/m	
Cost of electricity	153	€/MWh	
Operation and maintenance costs	3	€/MWh	
CO_2-equivalent emissions of ground source heat pump	9	kg/MWh	
Particulate emissions of ground source heat pump	0.005	kg/MWh	
CO_2-equivalent emissions of electricity	330	kg/MWh	
Particulate emissions of electricity	0.114	kg/MWh	

Total investment costs	**626 350 €**
Annual energy costs	**62 973 €/a**
Annual CO_2-eqv. emissions	**137 t/a**
Annual particulate emissions	**48 kg/a**

Alternative 5 - District level heat plant	
Thermal capacity required	271 kW
Loss heat flux of heat distribution networks	32 kW
Capacity demand	303 kW
Boiler efficiency	85 %
Boiler capacity	356 kW
Thermal energy consumption	329 MWh/a
Distribution losses	211 MWh/a
Thermal energy produced by heat plant	540 MWh/a
Wood chip consumption	635 MWh/a
Electricity consumption	221 MWh/a
Total length of heat distribution network	2 025 m
Heat plant investment costs	350 €/kW
Heat distribution investment costs	600 €/kW
Heat distribution network construction costs	130 €/m
Cost of wood chips	22 €/MWh
Cost of electricity	153 €/MWh
Operation and maintenance costs	3 €/MWh
CO_2-equivalent emissions of wood chip heat plant	24 kg/MWh
Particulate emissions of wood chip heat plant	0.165 kg/MWh
CO_2-equivalent emissions of electricity	330 kg/MWh
Particulate emissions of electricity	0.114 kg/MWh
Investment costs of production and distribution	**388 015 €**
Capital costs for annual energy sale	1 179 €/MWh
Capital recovery factor	0.065
Capital costs	77 €/MWh
Customer investment costs	**162 600 €**
Annual energy costs	**74 630 €/a**
Annual CO_2-eqv. emissions	**86 t/a**
Annual particulate emissions	**114 kg/a**

Alternative 6 - Solar thermal

Thermal capacity required	271 kW
Thermal energy consumption	329 MWh/a

Monthly thermal energy consumption and collector yield

	Heating [kWh]	Domestic hot water [kWh]	Distribution losses [kWh]	Total [MWh]	Yield / 1m² [kWh]
January	50 976	6 201	23 804	81.0	0.0
February	42 918	5 601	21 501	70.0	8.6
March	29 190	6 201	23 804	59.2	46.6
April	19 248	6 001	23 036	48.3	80.8
May	7 008	6 201	23 804	37.0	100.3
June	510	6 001	23 036	29.5	95.9
July	510	6 201	23 804	30.5	109.2
August	510	6 201	23 804	30.5	82.5
September	9 198	6 001	23 036	38.2	58.6
October	21 948	6 201	23 804	52.0	12.5
November	29 280	6 001	23 036	58.3	0.0
December	44 793	6 201	23 804	74.8	0.0
				609.4	595.0

Needed collector area 1 024 m²

Energy produced with obtained collector area compared to consumption

	Energy consumption [kWh]	Collector yield [kWh]	Total [kWh]
January	80 981	0	-80 981
February	70 019	8 798	-61 222
March	59 195	47 768	-11 427
April	48 285	82 731	34 446
May	37 013	102 715	65 702
June	29 547	98 161	68 614
July	30 515	111 867	81 352
August	30 515	84 535	54 020
September	38 235	59 994	21 759
October	51 953	12 805	-39 148
November	58 317	0	-58 317
December	74 798	0	-74 798

Stored thermal energy needed	325 893 kWh
Storage effiency	90 %
Total thermal energy required to storage	362 103 kWh
Over production in higher yield season	325 893 kWh
Extra collector production required	36 210 kWh
Collector area for extra production	61 m²
Total collector area	1 085 m²
Storage conversion factor	57 kWh/m³
Needed storage volume	6 353 m³
Total thermal energy produced	646 MWh/a
Electricity consumption	221 MWh/a
Total length of distribution network	2 025 m

Solar thermal collector investment cost	500	€/m^2
Heat distribution investment costs	600	€/kW
Heat distribution network construction costs	130	€/m
Operation and maintenance costs	4	€/MWh
Cost of electricity	153	€/MWh
Storage investment cost	200	€/m^3
CO_2-equivalent emissions of solar thermal collectors	24	kg/MWh
Particulate emissions of solar thermal collectors	0.009	kg/MWh
CO_2-equivalent emissions of electricity	330	kg/MWh
Particulate emissions of electricity	0.114	kg/MWh
Investment costs of production, storage and distribution	**2 076 258**	**€**
Capital costs for annual energy sale	6 311	€/MWh
Capital recovery factor	0.065	
Capital costs	410	€/MWh
Customer investment costs	**162 600**	**€**
Annual energy costs	**171 352**	**€/a**
Annual CO_2-eqv. emissions	**88**	**t/a**
Annual particulate emissions	**31**	**kg/a**

Appendix 2: Multi-criteria analysis matrixes of Jämsä case district

The normalized decision matrix of Jämsä case study is presented in Table A2-1.

Table A2-1. Normalized decision matrix, Case Jämsä

	Investment costs	Energy costs	GHG emissions	Particulate emissions	Locality of energy source	Maturity of technology
Alternative 1	1.000	0.838	0.000	0.620	0.000	1.000
Alternative 2	0.778	1.000	1.000	0.485	1.000	1.000
Alternative 3	0.354	0.989	0.662	0.900	1.000	1.000
Alternative 4	0.000	0.895	0.422	0.791	1.000	1.000
Alternative 5	0.941	0.751	0.911	0.000	1.000	1.000
Alternative 6	0.941	0.000	0.887	1.000	1.000	0.000

Preference function matrix of Jämsä case study is presented in Table A2-2.

Table A2-2. Prefence function matrix, Case Jämsä

	Investment costs	Energy costs	GHG emissions	Particulate emissions	Locality of energy source	Maturity of technology
A1,A2	0.222	0.000	0.000	0.134	0.000	0.000
A1,A3	0.646	0.000	0.000	0.000	0.000	0.000
A1,A4	1.000	0.000	0.000	0.000	0.000	0.000
A1,A5	0.059	0.087	0.000	0.620	0.000	0.000
A1,A6	0.059	0.838	0.000	0.000	0.000	1.000
A2,A1	0.000	0.162	1.000	0.000	1.000	0.000
A2,A3	0.424	0.011	0.339	0.000	0.000	0.000
A2,A4	0.778	0.106	0.578	0.000	0.000	0.000
A2,A5	0.000	0.250	0.089	0.485	0.000	0.000
A2,A6	0.000	1.000	0.113	0.000	0.000	1.000
A3,A1	0.000	0.151	0.662	0.281	1.000	0.000
A3,A2	0.000	0.000	0.000	0.415	0.000	0.000
A3,A4	0.354	0.094	0.239	0.109	0.000	0.000
A3,A5	0.000	0.238	0.000	0.900	0.000	0.000
A3,A6	0.000	0.989	0.000	0.000	0.000	1.000
A4,A1	0.000	0.057	0.422	0.172	1.000	0.000
A4,A2	0.000	0.000	0.000	0.306	0.000	0.000
A4,A3	0.000	0.000	0.000	0.000	0.000	0.000
A4,A5	0.000	0.144	0.000	0.791	0.000	0.000
A4,A6	0.000	0.895	0.000	0.000	0.000	1.000
A5,A1	0.000	0.000	0.911	0.000	1.000	0.000
A5,A2	0.163	0.000	0.000	0.000	0.000	0.000
A5,A3	0.587	0.000	0.250	0.000	0.000	0.000
A5,A4	0.941	0.000	0.489	0.000	0.000	0.000
A5,A6	0.000	0.751	0.024	0.000	0.000	1.000
A6,A1	0.000	0.000	0.887	0.381	1.000	0.000
A6,A2	0.163	0.000	0.000	0.515	0.000	0.000
A6,A3	0.587	0.000	0.225	0.100	0.000	0.000
A6,A4	0.941	0.000	0.465	0.209	0.000	0.000
A6,A5	0.000	0.000	0.000	1.000	0.000	0.000

Aggregated preference function matrix of Jämsä case study is presented in Table A2-3.

Table A2-3. Aggregated prefence function matrix, Case Jämsä

	A1	A2	A3	A4	A5	A6
A1	-	0.0574	0.1561	0.2417	0.0452	0.2496
A2	0.4951	-	0.2425	0.4407	0.0893	0.3073
A3	0.3629	0.0115	-	0.2012	0.0627	0.2593
A4	0.2473	0.0085	0.0000	-	0.0448	0.2444
A5	0.4331	0.0394	0.2438	0.4271	-	0.2314
A6	0.4338	0.0537	0.2368	0.4230	0.0278	-

Appendix 3: Energy system alternatives, Case Tampere

Alternative 1 - Electric heating		
Thermal capacity required	2 240	kW
Thermal energy consumption	2 956	MWh/a
Electricity consumption	1 348	MWh/a
Total electricity consumption	4 304	MWh/a
Electric heating investment costs	500	€/kW
Cost of electricity	127	€/MWh
CO_2-equivalent emissions of electricity	330	kg/MWh
Particulate emissions of electricity	0.114	kg/MWh
Total investment costs	**1 120 000**	**€**
Annual energy costs	**546 608**	**€/a**
Annual CO_2-eqv. emissions	**1420**	**t/a**
Annual particulate emissions	**491**	**kg/a**

Alternative 2 - District heating network		
Thermal capacity required	2 240	kW
Thermal energy consumption	2 956	MWh/a
Distribution network losses	489	MWh/a
Total thermal energy consumption	3 445	MWh/a
Electricity consumption	1 348	MWh/a
Heat distribution investment costs	600	€/kW
Connection fee	118	€/kW
Cost of thermal energy	57	€/MWh
Annual energy fee	18	€/kW
Cost of electricity	153	€/MWh
CO_2-equivalent emissions of district heat	189	kg/MWh
Particulate emissions of district heat	0.007	kg/MWh
CO_2-equivalent emissions of electricity	330	kg/MWh
Particulate emissions of electricity	0.114	kg/MWh
Total investment costs	**1 608 320**	**€**
Annual energy costs	**415 056**	**€/a**
Annual CO_2-eqv. emissions	**1 096**	**t/a**
Annual particulate emissions	**178**	**kg/a**

Alternative 3 - Pellet boilers

Thermal capacity required	2240 kW
Boiler efficiency	90 %
Boiler capacity	2489 kW
Thermal energy demand	2956 MWh/a
Wood pellet consumption	3284 MWh/a
Electricity consumption	1348 MWh/a
Pellet boiler investment costs	250 €/kW
Heat distribution investment costs	600 €/kW
Cost of pellets	43 €/MWh
Cost of electricity	153 €/MWh
Operation and maintenance costs	2 €/MWh
CO_2-equivalent emissions of pellet boiler	11 kg/MWh
Particulate emissions of pellet boiler	0.148 kg/MWh
CO_2-equivalent emissions of electricity	330 kg/MWh
Particulate emissions of electricity	0.114 kg/MWh
Total investment costs	**1 966 222 €**
Annual energy costs	**353 387 €/a**
Annual CO_2-eqv. emissions	**477 t/a**
Annual particulate emissions	**591 kg/a**

Alternative 4 - Building group ground heat pumps (North), District heat (South)

North part

Block	Energy MWh/a	Losses MWh/a	**Total MWh/a**	Power kW	Loss kW	**Total kW**
7678	262	44	**306**	208	5.1	**213**
7679	131	33	**164**	104	3.8	**108**
7680	131	19	**150**	104	2.2	**106**
7681	177	22	**199**	114	2.5	**117**
7682	204	33	**237**	132	3.8	**136**
7683	41	8	**49**	26	0.9	**27**
7684	122	25	**147**	79	2.8	**82**
Total			**1254**	**768**		**789**

Thermal energy demand	1 068 MWh/a	
Distribution losses	185 MWh/a	
Total thermal energy production by heat pumps	1 254	
Heat from ground	836 MWh/a	(COP = 3)
Heat pump electricity demand	418 MWh/a	
Electricity demand (North + South part of the case area)	1 348 MWh/a	
Total electricity demand	1 766 MWh/a	
Total length of distribution networks	1 340 m	
Heat pump capacity	789 kW	

Ground source heat pump investment costs	900	€/kW
Heat distribution investment costs	600	€/kW
Heat distribution network construction costs	130	€/m
Cost of electricity	153	€/MWh
Operation and maintenance costs	3	€/MWh

South part

Thermal energy demand	1 884	MWh/a
Distribution losses	256	MWh/a
Thermal capacity required	1 469	kW
Heat distribution investment costs	600	€/kW
Connection fee	118	€/kW
Cost of thermal energy	57	€/MWh
Annual energy fee	18	€/kW
CO_2-equivalent emissions of ground source heat pump	9	kg/MWh
Particulate emissions of ground source heat pump	0.005	kg/MWh
CO_2-equivalent emissions of district heat	189	kg/MWh
Particulate emissions of district heat	0.007	kg/MWh
CO_2-equivalent emissions of electricity	330	kg/MWh
Particulate emissions of electricity	0.114	kg/MWh
Total investment costs	**2 400 212**	**€**
Annual energy costs	**407 847**	**€/a**
Annual CO_2-eqv. emissions	**999**	**t/a**
Annual particulate emissions	**223**	**kg/a**

Alternative 5 - Building group ground heat pumps + solar (North), DH (South)

North part

Thermal energy demand	1 068	MWh/a
Distribution losses	185	MWh/a
Total thermal energy production by heat pump	1 254	

Type building domestic hot water energy demand		
Row house (600 m^2)	9.6	MWh/a
Detached building (250 m^2)	4	MWh/a

	Days/month	Row house (600 m^2) [kWh/month]	Solar collector yield (15 m^2) [kWh/month]	Detached building (250 m^2) [kWh/month]	Solar collector yield (6 m^2) [kWh/month]
January	31	815	0	340	0
February	28	736	171	307	73
March	31	815	553	340	228
April	30	789	782	329	323
May	31	815	815	340	340
June	30	789	789	329	329
July	31	815	815	340	340
August	31	815	815	340	338
September	30	789	649	329	266
October	31	815	210	340	88
November	30	789	0	329	0
December	31	815	0	340	0
Total		9600	5600	4000	2324

Total floor area of row houses in north part	8320	m^2
Total number of row house type buildings (600 m^2) in north pa	14	
Total floor area of detached houses in north part	8000	m^2
Number of detached house type buildings (250 m^2) in north	32	
Total solar thermal collector area	400	m^2
Thermal energy production with solar thermal collectors	152	MWh/a
Thermal energy produced with heat pumps	1 102	MWh/a
Heat from ground	734	MWh/a
Heat pump electricity demand	367	MWh/a
Total length of distribution networks	1 340	m
Heat pump capacity	789	kW

Yield of 1 kW photovoltaic system

	Yield (kWh/kWp) [kWh/month]
January	16
February	49
March	79
April	109
May	128
June	118
July	122
August	95
September	67
October	38
November	15
December	9
Total	843

2 kW photovoltaic system in detached houses		
8 kW photovoltaic system in row houses		
Total photovoltaic capacity	175	kW
Total photovoltaic electricity production	148	MWh/a
Electricity demand (North + South part of the case area)	1 348	MWh/a
Heat pump electricity demand	367	MWh/a
Total electricity demand (from the grid)	1 568	MWh/a

Ground source heat pump investment costs	900 €/kW
Heat distribution investment costs	600 €/kW
Heat distribution network construction costs	130 €/m
Cost of electricity	153 €/MWh
Solar thermal collector investment cost	500 €/m^2
Photovoltaic investment cost	5000 €/kW
Operation and maintenance costs (Heat pumps)	3 €/MWh
Operation and maintenance costs (Solar thermal collector)	4 €/MWh
Operation and maintenance costs (Photovoltaics)	4 €/MWh

South part

Thermal energy demand	1 884	MWh/a
Distribution losses	256	MWh/a
Thermal capacity required	1 469	kW

Heat distribution investment costs	600 €/kW
Connection fee	118 €/kW
Cost of thermal energy	57 €/MWh
Annual energy fee	18 €/kW

CO_2-equivalent emissions of ground source heat pump	9	kg/MWh
Particulate emissions of ground source heat pump	0.005	kg/MWh
CO_2-equivalent emissions of solar thermal collector	24	kg/MWh
Particulate emissions of solar thermal collector	0.009	kg/MWh
CO_2-equivalent emissions of photovoltaic panels	110	kg/MWh
Particulate emissions of photovoltaic panels	0.026	kg/MWh
CO_2-equivalent emissions of district heat	189	kg/MWh
Particulate emissions of district heat	0.007	kg/MWh
CO_2-equivalent emissions of electricity	330	kg/MWh
Particulate emissions of electricity	0.114	kg/MWh
Total investment	**3 675 729**	**€**
Annual energy costs	**378 268**	**€/a**
Annual CO_2-eqv. emissions	**952**	**t/a**
Annual particulate emissions	**204**	**kg/a**

Alternative 6 - Water source heat pump (District level)			
Thermal capacity demand of buildings	2240	kW	
Distribution network loss heat flux	56	kW	
Water source heat pump capacity	2296	kW	
Thermal energy consumption	2 956	MWh/a	
Distribution network losses	489	MWh/a	
Total thermal energy production	3 445	MWh/a	
Thermal energy from water	2 297	MWh/a	(COP = 3)
Thermal energy from electricity	1 148	MWh/a	
Electricity consumption	1348	MWh/a	
Total electricity consumption	2 496	MWh/a	
Total length of distribution network	3230	m	
Water source heat pump investment costs	900	€/kW	
Heat distribution investment costs	600	€/kW	
Heat distribution network construction costs	130	€/m	
Cost of electricity	153	€/MWh	
Operation and maintenance costs	6	€/MWh	
CO_2-equivalent emissions of water source heat pump	10	kg/MWh	
Particulate emissions of water source heat pump	0.007	kg/MWh	
CO_2-equivalent emissions of electricity	330	kg/MWh	
Particulate emissions of electricity	0.114	kg/MWh	
Investment costs of production and distribution	2 486 300	€	
Capital costs for annual energy sale	841	€/MWh	
Capital recovery factor	0.065		
Capital costs	55	€/MWh	
Customer invesments	**1 344 000**	**€**	
Annual energy costs	**564 219**	**€/a**	
Annual CO_2-eqv. emissions	**858**	**t/a**	
Annual particulate emissions	**309**	**kg/a**	

Alternative 7 - Water source heat pump and wind energy (District level)

Thermal capacity demand of buildings	2240	kW
Distribution network loss heat flux	56	kW
Water source heat pump capacity	2296	kW
Thermal energy consumption	2 956	MWh/a
Distribution network losses	489	MWh/a
Total thermal energy production	3 445	MWh/a
Thermal energy from water	2 297	MWh/a (COP = 3)
Thermal energy from electricity	1 148	MWh/a
Yield of wind turbine	1 000	MWh/MW
Required wind capacity	1148	kW
Electricity consumption (from the grid)	1348	MWh/a
Total length of distribution network	3230	m
Water source heat pump investment costs	900	€/kW
Heat distribution investment costs	600	€/kW
Heat distribution network construction costs	130	€/m
Cost of electricity	153	€/MWh
Operation and maintenance costs (heat pump)	6	€/MWh
Wind turbine investment cost	1300	€/kW
Operation and maintenance costs (wind turbine)	8	€/MWh
CO_2-equivalent emissions of water source heat pump	10	kg/MWh
Particulate emissions of water source heat pump	0.007	kg/MWh
CO_2-equivalent emissions of wind energy	58	kg/MWh
Particulate emissions of wind energy	0.011	kg/MWh
CO_2-equivalent emissions of electricity	330	kg/MWh
Particulate emissions of electricity	0.114	kg/MWh
Investment costs of production and distribution	3 979 133	€
Capital costs for annual energy sale	1 346	€/MWh
Capital recovery factor	0.065	
Capital costs	87	€/MWh
Customer invesments	**1 344 000**	**€**
Annual energy costs	**494 744**	**€/a**
Annual CO_2-eqv. emissions	**546**	**t/a**
Annual particulate emissions	**190**	**kg/a**

Alternative 8 - District level CHP

Thermal capacity demand of buildings	2240	kW
Distribution network loss heat flux	56	kW
CHP thermal capacity	2296	kW
Thermal energy consumption	2 956	MWh/a
Distribution network losses	489	MWh/a
Total thermal energy production	3 445	MWh/a
Efficiency of CHP-plant	80	%
Power to heat ratio	0.2	
Electric capacity	459	kW
Generated electricity	689	MWh/a
Fuel consumption	5167.5	MWh/a
Electricity consumption	1348	MWh/a
From CHP	689	MWh/a
From grid	659	MWh/a
Total length of distribution network	3230	m
CHP investment costs	5000	€/kWe
Heat distribution investment costs	600	€/kW
Heat distribution network construction costs	130	€/m
Cost of electricity (from grid)	153	€/MWh
Cost of electricity (without transmission)	79	€/MWh
Operation and maintenance costs	14	€/MWh
Cost of wood chips	22	€/MWh
CO_2-equivalent emissions of CHP	79	kg/MWh
Particulate emissions of CHP	0.204	kg/MWh
CO_2-equivalent emissions of electricity	330	kg/MWh
Particulate emissions of electricity	0.114	kg/MWh
Investment costs of production and distribution	2 715 900	€
Capital costs for annual energy sale	919	€/MWh
Capital recovery factor	0.065	
Capital costs	60	€/MWh

Electricity assumed as a benefit product--> profit removen from the cost of thermal energy

Customer invesments	**1 344 000**	**€**
Annual energy costs	**384 890**	**€/a**
Annual CO_2-eqv. emissions	**544**	**t/a**
Annual particulate emissions	**918**	**kg/a**

Appendix 4: Multi-criteria analysis matrixes of Tampere case district

The normalized decision matrix of Tampere case study is presented in Table A4-1.

Table A4-1. Normalized decision matrix, Case Tampere

	Investment costs	Energy costs	GHG emissions	Particulate emissions	Locality of energy source	Maturity of technology
Alternative 1	1.000	0.084	0.000	0.578	0.000	1.000
Alternative 2	0.793	0.708	0.344	1.000	0.000	1.000
Alternative 3	0.641	1.000	1.000	0.442	1.000	1.000
Alternative 4	0.456	0.742	0.447	0.940	1.000	1.000
Alternative 5	0.000	0.882	0.497	0.964	1.000	0.500
Alternative 6	0.905	0.000	0.596	0.823	1.000	0.500
Alternative 7	0.905	0.330	0.927	0.983	1.000	0.000
Alternative 8	0.905	0.851	0.929	0.000	1.000	1.000

The normalized decision matrix of Tampere case study is presented in Table A4-2.

Table A4-2. Preference function matrix, Case Tampere

	Investment costs	Energy costs	GHG emissions	Particulate emissions	Locality of energy source	Maturity of technology
P1,P2	0.207	0.000	0.000	0.000	0.000	0.000
P1,P3	0.359	0.000	0.000	0.136	0.000	0.000
P1,P4	0.544	0.000	0.000	0.000	0.000	0.000
P1,P5	1.000	0.000	0.000	0.000	0.000	0.500
P1,P6	0.095	0.084	0.000	0.000	0.000	0.500
P1,P7	0.095	0.000	0.000	0.000	0.000	1.000
P1,P8	0.095	0.000	0.000	0.578	0.000	0.000
P2,P1	0.000	0.624	0.344	0.422	0.000	0.000
P2,P3	0.152	0.000	0.000	0.558	0.000	0.000
P2,P4	0.336	0.000	0.000	0.061	0.000	0.000
P2,P5	0.793	0.000	0.000	0.036	0.000	0.500
P2,P6	0.000	0.708	0.000	0.177	0.000	0.500
P2,P7	0.000	0.378	0.000	0.017	0.000	1.000
P2,P8	0.000	0.000	0.000	1.000	0.000	0.000
P3,P1	0.000	0.916	1.000	0.000	1.000	0.000
P3,P2	0.000	0.293	0.656	0.000	1.000	0.000
P3,P4	0.184	0.258	0.553	0.000	0.000	0.000
P3,P5	0.641	0.118	0.503	0.000	0.000	0.500
P3,P6	0.000	1.000	0.404	0.000	0.000	0.500
P3,P7	0.000	0.670	0.073	0.000	0.000	1.000
P3,P8	0.000	0.149	0.071	0.442	0.000	0.000
P4,P1	0.000	0.658	0.447	0.362	1.000	0.000
P4,P2	0.000	0.034	0.103	0.000	1.000	0.000
P4,P3	0.000	0.000	0.000	0.498	0.000	0.000
P4,P5	0.456	0.000	0.000	0.000	0.000	0.500
P4,P6	0.000	0.742	0.000	0.116	0.000	0.500
P4,P7	0.000	0.412	0.000	0.000	0.000	1.000
P4,P8	0.000	0.000	0.000	0.940	0.000	0.000
P5,P1	0.000	0.798	0.497	0.386	1.000	0.000
P5,P2	0.000	0.175	0.153	0.000	1.000	0.000
P5,P3	0.000	0.000	0.000	0.522	0.000	0.000
P5,P4	0.000	0.140	0.050	0.025	0.000	0.000
P5,P6	0.000	0.882	0.000	0.141	0.000	0.000
P5,P7	0.000	0.552	0.000	0.000	0.000	0.500
P5,P8	0.000	0.031	0.000	0.964	0.000	0.000
P6,P1	0.000	0.000	0.596	0.246	1.000	0.000
P6,P2	0.112	0.000	0.252	0.000	1.000	0.000
P6,P3	0.264	0.000	0.000	0.381	0.000	0.000
P6,P4	0.449	0.000	0.149	0.000	0.000	0.000
P6,P5	0.905	0.000	0.099	0.000	0.000	0.000
P6,P7	0.000	0.000	0.000	0.000	0.000	0.500
P6,P8	0.000	0.000	0.000	0.823	0.000	0.000
P7,P1	0.000	0.246	0.927	0.405	1.000	0.000
P7,P2	0.112	0.000	0.583	0.000	1.000	0.000
P7,P3	0.264	0.000	0.000	0.541	0.000	0.000
P7,P4	0.449	0.000	0.480	0.044	0.000	0.000
P7,P5	0.905	0.000	0.430	0.019	0.000	0.000
P7,P6	0.000	0.330	0.331	0.160	0.000	0.000
P7,P8	0.000	0.000	0.000	0.983	0.000	0.000
P8,P1	0.000	0.767	0.929	0.000	1.000	0.000
P8,P2	0.112	0.143	0.585	0.000	1.000	0.000
P8,P3	0.264	0.000	0.000	0.000	0.000	0.000
P8,P4	0.449	0.109	0.482	0.000	0.000	0.000
P8,P5	0.905	0.000	0.432	0.000	0.000	0.500
P8,P6	0.000	0.851	0.333	0.000	0.000	0.500
P8,P7	0.000	0.521	0.002	0.000	0.000	1.000

Aggregated preference function matrix of Tampere case study is presented in Table A4-3.

Table A4-3. Aggregated preference function matrix, Case Tampere

	A1	A2	A3	A4	A5	A6	A7	A8
A1	-	0.0501	0.0906	0.1314	0.2931	0.0876	0.1258	0.0390
A2	0.2510	-	0.0522	0.0830	0.2440	0.1683	0.1631	0.0278
A3	0.6145	0.3753	-	0.3112	0.4303	0.3746	0.2386	0.0648
A4	0.3580	0.1087	0.0138	-	0.1617	0.1721	0.1680	0.0261
A5	0.4012	0.1512	0.0145	0.0432	-	0.1436	0.1389	0.0317
A6	0.3113	0.1912	0.0744	0.1692	0.2592	-	0.0514	0.0229
A7	0.4900	0.3264	0.0789	0.3057	0.3950	0.1919	-	0.0273
A8	0.5620	0.3499	0.0638	0.3225	0.4466	0.3221	0.1860	-

Appendix 5: The questionnaire study used to determine the weighting of criteria

Alueellisen energiajärjestelmän valinnan päätöksenteko ja arvovalinnat

VTT selvittää projektiinsa liittyen alueellisen energiantuotantojärjestelmän valintaan osallistuvaa toimijakenttää sekä päätösten taustalla vaikuttavia valintakriteerejä.

Tietojen hankkimiseksi on rakennettu webpohjainen kysely, johon vastaamiseen menee 2-5 minuuttia.

Tervetuloa vastaamaan kyselyyn!

Mikä on roolisi energiajärjestelmästä päätettäessä?

- ☐ Kuntapäättäjä
- ☐ Kaavoittaja
- ☐ Alueen kehittäjä
- ☐ Energian toimittaja
- ☐ Alueellisen järjestelmän omistaja
- ☐ Energian loppukäyttäjä/asiakas
- ☐ Tekniikkaratkaisun toimittaja
- ☐ Jokin muu, mikä? ______________________

Paikkakunta ______________________

Kohdealueen talotyyppi

- ☐ pientalo
- ☐ rivi/paritalo
- ☐ pienkerrostalo
- ☐ kerrostalo
- ☐ teollisuus
- ☐ palvelurakennus
- ☐ Jokin muu, mikä ______________________

Asukkaiden ja työpaikkojen määrä alueella

- ☐ alle 100
- ☐ 100-1 000
- ☐ 1 000-10 000
- ☐ yli 10 000

Kuinka tärkeänä koet kunkin kriteerin uuden energiajärjestelmän valinnassa ja kuinka jaat 100 pistettä painottaen kriteerin tärkeyttä (esim kriteeri Y saa sijaluvun 1 ja 50 pistettä, ...)

	Tärkeys, sijaluku 1=tärkein, 2=seuraavaksi tärkein jne										Jaa 100 pistettä kriteerien kesken tärkeyttä painottaen (tärkeimmälle eniten pisteitä; jos kriteeri ei vaikuta päätöksentekoosi, anna 0 p)
	1	2	3	4	5	6	7	8	9	10	
Järjestelmän investointikustannus	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	________
Energian hinta	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	________

Kasvihuonekaasujen päästöt (ilmastonmuutos)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	________
Hiukkasmaiset päästöt (paikallinen ilmanlaatu)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	________
Paikallinen energianlähde	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	________
Teknologian tunnettuus (sis. käytön helppous, toimintavarmuus & tasalaatuisuus)	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	________
Huolto- ja ylläpitokustannukset	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	________
Jokin muu, mikä	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	________
Jokin muu, mikä	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	________
Jokin muu, mikä	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	________

Olen kiinnostunut tulosten yhteenvedosta ja tietoa tuloksista saa lähettää sähköpostiosoitteeseen (jos et halua tietoa, jätä kenttä tyhjäksi) ________________