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Future District Energy Systems

Master's Thesis
Department of Energy Technology
School of Engineering, Aalto University

Espoo 23.11.2016
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Abstract of master's thesis

Author Elina Grahn

Title of thesis Future District Energy Systems

Degree programme Degree Programme in Energy and HVAC - Technology

Major Energy Technology **Code** K3007

Thesis supervisor Professor Sanna Syri

Thesis advisor Ismo Heimonen, M. Sc. (Tech.)

Date 23.11.2016 **Number of pages** 73+3 **Language** English

Abstract

In order to mitigate climate change, the energy systems need to change. Fossil fuels need to be replaced by various low carbon energy sources, the energy consumption need to be reduced and the efficiency of the whole system needs to be improved. However, the energy systems are complex and there is not a single right solution for how to meet these requirements. In this thesis, a scenario approach was used to investigate the outcome of different energy system selections.

The thesis is a combination of a literature review and a simulation case study. In the literature review, different development pathways for district energy systems and methods for developing and evaluating scenarios were reviewed. Based on these results, three scenarios for the development of the district energy system in Keski-Uusimaa area were made. The timeframe of the scenarios was 20 years, starting in 2015 and ending in 2035. In the scenarios, a common assumption for the development of the building stock was used while the deployment rates of decentralized heating technologies varied. The heating technologies were restricted to district heating, ground source heat pumps and solar thermal collectors. In order to examine how the heat demand in the area developed over the scenario timeframe, the scenarios were simulated using a dynamic simulation model of the area. The outcomes were compared using different technical, environmental, economic and social criteria.

According to the results of the case study, the scenario with the lowest deployment rate of decentralised heating technologies was ranked best. However, the differences between the scenarios were in general quite small. Only in the case of the investment costs, the outcome of the best-ranked scenario was significantly better than the outcome of the other scenarios, having a huge effect on the scenario ranking. In the process of developing and comparing scenarios, numerous decisions and assumptions were made. As a consequence, the detailed results were strongly dependent on the chosen parameters. Therefore, the main contribution of the thesis lies in the method used to analyse the energy systems.

Keywords district energy systems, energy system transition, scenarios, dynamic simulation, end user engagement, criteria

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Sammandrag av diplomarbetet

Författare Elina Grahn

Titel Framtida lokala energisystem

Utbildningsprogram Utbildningsprogrammet för energi- och VVS-teknik

Huvudämne Energiteknik **Kod** K3007

Övervakare Professor Sanna Syri

Handledare M.Sc. (Tech.) Ismo Heimonen

Datum 23.11.2016 **Sidantal** 73+3 **Språk** Engelska

Sammandrag

För att vi skall lyckas i vår strävan efter att mildra klimatförändringen, måste våra energisystem förändras. Fossila bränslen måste ersättas med bränslen som har låga koldioxidutsläpp, energikonsumtionen måste minska och hela systemets energieffektivitet måste förbättras. Energisystemet är trots allt komplexa och det finns ingen unik lösning för hur man ska kunna uppnå dessa mål. I detta diplomarbete används scenarion som metod för att undersöka följderna av olika val av energisystem.

Arbetet är en kombination av en litteraturunderökning och en fallstudie. I litteraturundersökningen undersöktes olika utvecklingsalternativ för lokala energisystem och olika metoder för utvecklande och utvärdering av scenarion. Baserat på de här resultaten utarbetades tre scenarion för hur det befintliga energisystemet i mellersta Nyland kunde komma att utvecklas. Tidsramen för scenariona var 20 år, med start 2015 och slut 2035. Scenariona var baserade på ett gemensamt antagande för utvecklingen av fastighetsbeståndet i området medan användningsgraden av decentraliserade värmeproduktionsteknologier varierade. De teknologier som togs i beaktande var begränsade till fjärrvärme, bergsvärme och solfångare. För att undersöka hur efterfrågan på värme i området utvecklades över tidsramen för scenariot, simulerades scenariona med hjälp av en dynamisk simuleringsmodell. Resultaten jämfördes med varandra med hjälp av olika tekniska, miljöbetingade, ekonomiska och sociala kriterier.

I fallstudien rankades scenariot med den lägsta användningsgraden av decentraliserade värmeproduktionsteknologier som det bästa alternativet. Hursomhelst, skillnaderna mellan scenariona var i allmänhet mycket små. Endast ifråga om investeringskostnader var resultatet av det bästa scenariot markant bättre än de övriga scenariona, vilket också hade en stor inverkan på den slutgiltiga rankingen. I den process där scenariona utvecklades och jämfördes gjordes många olika beslut och antaganden. Som en följd av detta, var resultaten mycket beroende av de valda parametrarna. Därför ligger värdet i detta arbete huvudsakligen i den metod som utvecklats för att analysera energisystemen.

Nyckelord lokala energisystem, energisystemets övergång, scenarion, dynamisk simulering, engagerande av slutanvändare, kriterier

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Diplomityön tiivistelmä

Tekijä Elina Grahn

Työn nimi Tulevaisuuden alueelliset energiajärjestelmät

Koulutusohjelma Energia- ja LVI-tekniikan koulutusohjelma

Pääaine Energiatekniikka **Koodi** K3007

Työn valvoja Professori Sanna Syri

Työn ohjaaja M. Sc. (Tech.) Ismo Heimonen

Päivämäärä 23.11.2016 **Sivumäärä** 73+3 **Kieli** Englanti

Tiivistelmä

Energiajärjestelmien täytyy muuttua, jotta pystytään hillitsemään ilmastonmuutosta. Fossiiliset polttoaineet on korvattava matalahiilidioksidipäästöisillä polttoaineilla, energiankulutusta täytyy vähentää ja energiajärjestelmien energiatehokkuutta täytyy parantaa. Energiajärjestelmät ovat kuitenkin monimutkaisia ja tavoitteiden saavuttamiseen on olemassa useita eri vaihtoehtoja. Tässä työssä on hyödynnetty skenaariolähestymistapaa eri energiajärjestelmävaihtoehtojen tarkastelussa.

Työ on kirjallisuuskatsauksen ja tapaustutkimuksen yhdistelmä. Kirjallisuuskatsauksessa tarkasteltiin erilaisia kehityssuuntia alueellisille energiajärjestelmille ja erilaisten skenaarioiden kehitys- ja arviointimenetelmiä. Tulosten perusteella kehitettiin kolme vaihtoehtoisia skenaarioita Keski-Uudenmaan energiajärjestelmän kehittämiseen. Skenaariot laskettiin 20 vuoden aikajänteelle alkaen vuodesta 2015 ja päättyen vuoteen 2035. Skenaariotarkastelua varten oletettiin rakennuskannan kehitys vakioiksi ja muuttuvana tekijänä oli hajautettujen energiamuotojen käyttöaste. Lämmöntuotantovaihtoehdot olivat kaukolämpö, maalämpö sekä aurinkokeräimet. Jotta pystyttiin tutkimaan, miten energiantarve kehittyi alueellisesti määrätyllä aikavälillä, skenaarioita simuloitiin alueellisesti dynaamisella simulointiohjelmalla. Tuloksia vertailtiin käyttämällä erilaisia teknisiä, ympäristöllisiä, taloudellisia ja sosiaalisia kriteerejä.

Skenaariotarkastelujen tulosten perusteella, se skenaario missä hajautettujen energiamuotojen käyttöaste oli pienin, arvioitiin parhaaksi vaihtoehdoksi. Skenaarioiden erot olivat kuitenkin aika pieniä. Ainoastaan investointikustannusten tapauksessa, parhaan skenaarion tulos oli huomattavasti parempi kuin muiden skenaarioiden tulokset ja tällä oli suuri vaikutus skenaarioiden loppuluokitukseen. Skenaarioiden kehittämis-, simulointi- ja arviointiprosessin aikana tehtiin lukuisia oletuksia ja päätöksiä. Tästä johtuen lopputulokset ovat vahvasti riippuvaisia valituista parametreista. Näin ollen energiajärjestelmien analysointiin kehitetty menetelmä on tärkeässä roolissa skenaarioiden arvioinnissa.

Avainsanat alueellinen energiajärjestelmä, energiajärjestelmän muutos, loppukäyttäjän käyttäytyminen, skenaariot, dynaaminen simulointi, kriteerit

Acknowledgements

This thesis was made at VTT, as a part of the Efficient Energy Use (EFEU) research programme, funded by Tekes. I am very grateful for the opportunity to participate in the project; it has truly been an interesting and valuable experience.

I would like to thank my instructor Ismo Heimonen for the guidance throughout the project. I would also like to thank my supervisor Sanna Syri for the support in the process of writing this thesis. Furthermore, I would like to thank Lotta Kannari and Rinat Abdurafikov for helping me with the APROS simulation software and Satu Paiho for the advices regarding scientific writing. My gratitude also goes to everyone who have provided comments and encouraged me during the work.

Furthermore, I would like to thank my manager Jari Shemeikka and my other colleagues in the Ecoefficient districts team at VTT. My time at VTT has been delightful and I am very glad for the opportunity to be a part of your team.

Finally, I want to thank my family; thank you for always being there for me, no matter what.

Espoo, November 2016

Elina Grahn

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Appendixes

Nomenclature

S_i	[-]	Weighted sum of the criteria
r_i	[-]	normalized criterion value
x_i	[-]	criterion value
w_i	[-]	criterion weight

Abbreviations

CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
COP	Coefficient of Performance
DHW	Domestic Hot Water
EFEU	Efficient Energy Use research program
EIA	U.S. Energy Information Administration
EPBD	Energy Performance of Buildings Directive
EU	The European Union
GHG	Greenhouse Gas
GSHP	Ground Source Heat Pump
GWh	Gigawatt hour
kWh	Kilowatt hour
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
LCL	Land use and Construction Law
MCDA	Multi-Criteria Decision Analysis
MWh	Megawatt hour
nZEB	nearly Zero Energy Building
OECD	Organization for Economic Co-operation and Development
STC	Solar Thermal Collector
UN	The United Nations
UNFCCC	United Nations Framework Convention on Climate Change
WRI	World Resource Institute

1 Introduction

At the Paris Climate Conference in December 2015, the representatives of 195 countries adopted the first global, legally binding, climate agreement in the history. The aim of the agreement is to strengthen the global response to the threat of climate change by limiting the global warming to well below 2 °C above pre-industrial levels (United Nations 2015). The agreement will enter into force on the 4th of November 2016, in conjunction with the Climate Conference in Marrakech, Morocco.

In order to reach the target of the agreement, the greenhouse gas (GHG) emissions need to be substantially reduced. Since the lion's share of the emissions originate from the energy sector, this will play a key role in the process. The energy systems – all the way from the individual system level up to the global level – need to change. Fossil fuels need to be replaced by various low carbon and renewable energy sources. Furthermore, the energy consumption needs to be reduced and the efficiency of the whole system needs to be improved.

The energy systems are complex and there is not a single right solution for how to meet the future requirements. In order to investigate the outcome of different energy system selections, scenarios can be used as a powerful tool. Scenarios are, in contrast to the common understanding, not predictions of the future, but rather descriptions of the possible future outcomes of different choices and events. By utilizing scenarios, the outcome and consequences of different energy system choices and decisions can be explored, which is very valuable in decision making.

1.1 Objectives

The objective of this thesis is to develop scenarios for future district energy systems and to compare them in terms of their technical, environmental, economic and social viability. The purpose of the scenarios is not to make a prediction of what the future energy systems will be like, but rather to examine what different possibilities there are. The thesis tries to answer the following research questions:

- What different scenarios are there for future energy systems? A selection of possible future energy systems is studied.
- What is the balance between technical, environmental, economic and social aspects when comparing the systems?
- What is the sensitivity of the choice of the system inputs and parameters?

In the scenarios, the focus is set on the demand side of the network and how changes made on this side influences the performance of the whole energy system. Especially the effects of different heating technology selections in buildings are of large interest.

In the study, special emphasis is put on the European and Finnish conditions. The scope of the thesis has been restricted to only include district energy systems that are used to provide heat.

1.2 Research Methods

The thesis has been performed using a combination of a literature review and a simulation case study. The aim of the literature review was to clarify the current situation and the future prospects of district energy systems and the planning of these. Furthermore, the available methods used to develop and evaluate scenarios for future energy systems were also reviewed. The sources of information used included both national and international scientific articles, project reports and roadmaps.

In order to concretize the findings of the literature review, a simulation case study was made. The study was based on a real case; the Keski-Uusimaa area in the south of Finland. The aim was to compare the outcome of different scenarios for the future development of the thermal energy system in the case area. In the scenarios, a common assumption for the development of the building stock in the case area was used while the technologies used to cover the heat demand varied. The technologies were restricted to district heating, ground source heat pumps (GSHP) and solar thermal collectors (STC). A detailed description of the methods used in the case study is given in Chapter 3.2.

1.3 Thesis Structure

The thesis is structured as follows: In Chapter 2, the results of the literature review are presented. First, the state of the art of district energy systems, the transition process and the future prospects for district energy systems are described. Then, different energy system optimization criteria and methods used for developing and evaluating scenarios are reviewed.

Then, in Chapter 3, the case study is presented. First, background information about the case area and the methods and simulation model used are provided. Then, a set of scenarios that are chosen for further investigation are presented. After that, the results of the case study are presented. Finally, the sensitivity of the scenario selections is determined.

In Chapter 4, the outcomes of the literature review and the case study simulations are discussed on a general level and conclusions are made. Furthermore, topics for future research are proposed.

2 Theoretical Background

In this section, the “district energy systems”-concept is clarified. The state of the art of district energy systems are reviewed, targets and strategies for the future energy system are explained and different development pathways for the future systems are presented. Furthermore, the different optimization criteria used for evaluating energy system choices are studied. Finally, different methods for developing scenarios are explained, including methods used for ranking of scenarios, where the optimization criteria are taken into account.

2.1 District Energy Systems

Energy systems have been defined as the energy distribution systems that are used to supply the necessary energy services to the society (Løken 2007). An overview of the energy system components and its inputs and outputs is given in Figure 1.

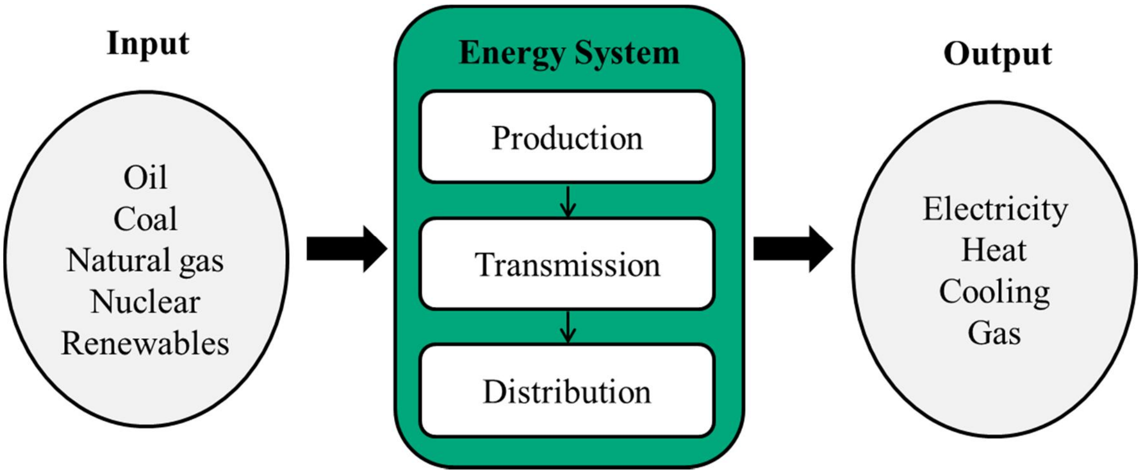

Figure 1. The energy system components and its inputs and outputs.

As can be seen from the figure, energy systems receive inputs in form of resources, extracted from the nature. The inputs include both fossil fuels such as oil and gas and various renewable energy sources. The energy system itself consists of different energy production, transmission and distribution facilities, which are operated as an integrated unit (Catrinu 2006). As an output, energy in form of electricity, heating, cooling and gas is received.

The physical boundaries of the energy system usually coincide with the geographical boarders e.g. of a region, town or community (Catrinu, 2006). In this thesis, the focus is set on district energy systems. The word “district” can be understood in several ways; either as an area of a country or a city. Here, the term “district energy systems” is used to refer to the energy systems in small communities and towns. Usually, these systems are not stand-alone solutions but need imports of electricity or gas (Løken 2007). In the literature, this concept has also been called “local energy systems” and “community energy systems”.

In the following, the state of the art of district energy systems in Finland is examined. First, the current heating technologies and energy sources used to cover the heat demand of buildings are reviewed. Then, the energy system planning process is described. Finally, the actors and stakeholder involved in the process are presented.

2.1.1 Heating Technologies

Heat is used in buildings in order to cover the space heating and domestic hot water (DHW) demands. The demands can be covered in a number of ways, using a variety of technologies. These include e.g. district heating, electricity, heat pumps and heat boilers using oil, pellets or wood as fuel. STCs can also be used, usually in combination with thermal storages. However, these systems are not able to cover the whole building heat demand in Finland. The heating technologies currently used to cover the heat demand of residential and service buildings in Finland are presented in Figure 2.

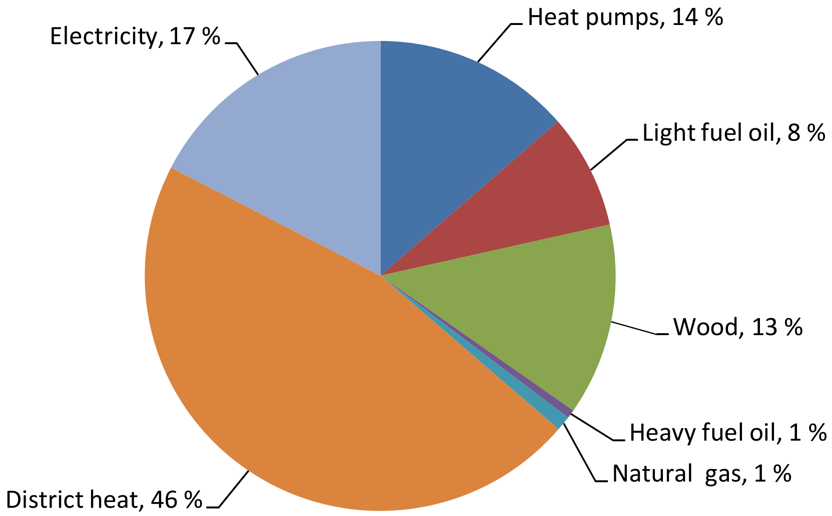

Figure 2. The heating technologies used to cover heat demand in residential and service buildings in Finland in 2014. (Energiateollisuus Ry, 2014)

District heat was by far the most usual way of covering the heat demand in residential and service buildings in 2014. By then, almost half of the buildings used district heat to cover the heat demand. Electricity, wood, heat pumps and light fuel oil were also commonly used while the share of natural gas and heavy fuel oil was negligible.

District heat and electricity differ from the other systems since this energy is usually produced in large, centralized plants and distributed to the customers through district heating and power networks. The other systems are smaller ones, where the heat is produced within or in the immediate surroundings of the buildings. The energy sources used to produce electricity and district heat in Finland in 2014 are shown in Table 1.

Table 1. The energy sources used in electricity and district heat production in 2014. (Energiateollisuus Ry 2015b; Energiateollisuus Ry 2015a)

Electricity production		District heat production	
Energy source	%	Energy source	%
Nuclear	27.2	Wood	31.1
Import	21.5	Coal	24.6
Hydro power	15.9	Natural gas	22.3
Biomass	13.3	Peat	14.0
Coal	9.4	Industrial waste heat & heat	2.5
Natural gas	6.5	pumps	2.1
Peat	3.8	Oil	
Wind	1.3	Other	3.4
Waste	0.9		
Oil	0.2		

In Finland, a wide range of energy sources are used in the electricity and district heat production. In the case of electricity, nuclear power production and electricity imports are important parts of the system. Furthermore, the use of hydro power and biomass is also essential. In the case of district heating, wood is the most commonly used energy source, closely followed by coal and natural gas. The share of industrial waste heat and heat pumps is still very small, even though the potential of these is high (Vainio et al. 2015) (Laitinen et al. 2014).

2.1.2 The Planning Process

Energy system planning is the process, where the sources and technologies used for energy production, transmission and distribution that satisfies the community need are chosen (Catrinu 2006). It can be performed at many different levels and scales; from the individual system level to the national and international level. The lower the level is, the more detailed the planning need to be (Løken 2007a).

At the district level, the purpose of the planning process is to select an energy system that is able to meet the current and future energy demand in the area and to maximize the well-being of the society (Løken 2007a). Thus, the process is not a short term planning task but rather a long term iterative process. In order to reach the goals of sustainability on the urban level, district energy systems needs to be consistently optimized (Jank 2000). Furthermore, since most district energy systems are connected to the main energy system, the planning of these systems needs to be aligned with long-term plans for the national system. (Løken 2007a)

In general, energy system planning at the district level is realized by energy service companies and sometimes also by energy intensive industries. The planning is restricted by the policies and boundary conditions made by the authorities. According to Hedman (2016), energy system planning and urban planning are closely connected and a holistic approach would enable the efficient planning of energy systems. In Finland, the urban planning is based on the Land Use and Construction Law (LCL). The purpose of the law is to ensure that the land use and building support the high quality of living and that it promotes the ecologically, economically, socially and culturally sustainable development (Finlex 1999). At the municipal level, urban planning is defined in a master plan, a town plan and in some cases also in a shore plan. The purpose of the master plan is to steer the development and land use of the municipality as a whole while the town plan regulates the detailed land use and construction in a specific area. (Finlex 1999)

Both the master plan and the town plan provides many possibilities, both direct and indirect, to affect the energy efficiency and the emissions of an area (Rajala et al. 2010). As a part of the master plan, the opportunities to organize energy supply are examined (Finlex 1999). Furthermore, in the town plan, there is a paragraph that treats the duty of new buildings to connect to the district heating network, whenever available. According to that, new buildings can be obliged to connect to the district heating network in case this would promote the efficient and sustainable use of energy in the area. However, in case the building utilizes renewable energy sources with low emissions, it can not be obliged to connect to the district heating system. (Finlex 1999)

2.1.3 Actors and Stakeholders

Traditionally, the planning of district energy systems has been made by local energy companies, owned by the municipality. However, as the energy sector has become liberalized and new business opportunities have risen; new players have been entering the sector (Catrinu 2006). In Finland, the amount of heat entrepreneurs has rapidly increased since the early 1990's. In 2006, there were 330 heat entrepreneurs in Finland with a boiler capacity of 176.6 MW and the future potential is estimated to even 900 entrepreneurs. (Okkonen & Suhonen 2010). As a consequence, the responsibility for the planning of the district energy system has been split between different actors (Catrinu 2006).

The stakeholders of the district energy system include everyone who have a legitimate interest in the system (Løken 2007a). These players can in general be divided into two groups; decision makers and decision receivers (Catrinu 2006). The decision makers are the ones making the actual decisions, while the decision receivers are involved in the decision making process but they do not have the power to make the actual decisions. The main stakeholder groups are presented in Figure 3.

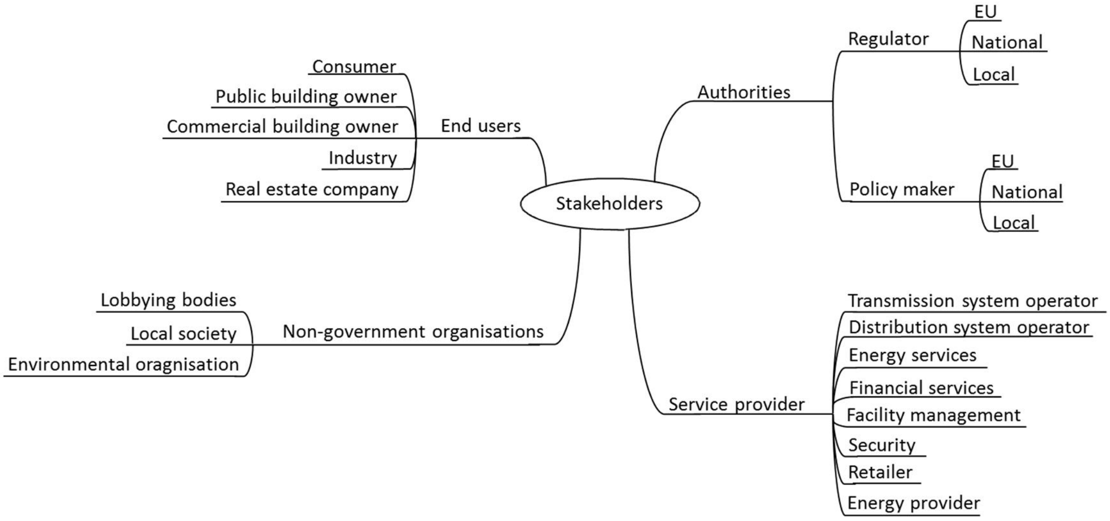

Figure 3. The stakeholders of district energy system planning. Adapted from Sepponen & Heimonen (2015)

As can be seen from the figure, there are four stakeholder groups: authorities, service providers, non-governmental organizations and end users of energy. In the following are the roles and objectives of each of these groups discussed.

Authorities consist of regulators and policy makers on different levels: the EU, national and local level. The EU and the national authorities provide policies and legislation, which must be followed when planning the energy system. Furthermore, local authorities can formulate plans and make decisions that directly affect the planning of the systems. For example, they can formulate the master plan so that it is not sufficient to use a specific heating technology. Thus, the authorities have many possibilities to influence on district energy system planning. Moreover, since it is common that local authorities own at least a part of the energy distribution companies, these are also active decision makers in energy system planning. (Catrinu 2006; Løken 2007a)

Service providers include companies that own and operate local generation units, companies that own and operate the distribution networks and companies supplying energy and related services to the end users of energy. In many cases, the same company may provide several energy services. In general, this stakeholder group is the main decision maker in district energy planning. (Catrinu 2006; Løken 2007a)

Non-government organizations such as lobbying bodies, the local society and environmental organizations may also give an opinion on what alternatives for energy supply that they prefer. However, this stakeholder group does not usually have any decision power. (Catrinu 2006)

End users of energy are a crucial stakeholder group in the energy planning since these are the consumers of the services delivered by the system. There are many different end users types: private energy users, public building owners, commercial building owners, industries and real estate companies. The system needs to be designed so that it fulfills needs of all these consumer types. The different end user types may not have the same power to influence the major decisions. Especially large consumers will have a large effect on the design of the network and if these customers decide to change their energy consumption pattern, the district energy system will be greatly affected. Therefore, these end users may participate in the planning of the energy system. (Catrinu 2006; Løken 2007a)

Different stakeholder groups have different objectives and sometimes, the objectives within a stakeholder group may differ, depending on which perspective is taken. The owners of energy companies generally aim to maximize the profits of the investments while the employees may wish that the company take decisions that project their jobs and create interesting tasks. The end users of energy might also have different objectives. For example, some users might be interested in minimizing the investment costs while others are more interested in minimizing the long-term costs. The objectives of the local authorities are in general to improve the conditions for the people that live and work in the area. In the planning of energy systems, it is important that the stakeholders are involved in the planning process already from the beginning. In that way, it is more likely that the stakeholders are willing to cooperate. (Løken 2007)

2.2 The System Transition

In order to mitigate climate change, a transition towards low carbon energy systems is needed. There are several ways of decarbonizing the energy sector. These include e.g. improving the energy efficiency, increasing the share of renewables in the energy production, the implementation of carbon capture and storage technologies and utilization of nuclear energy (European Commission 2012).

Thus, in the future, the use of energy production technologies with low emissions will be an essential part of the energy system. However, significant energy savings throughout the whole system are also required. According to IPCC (2014), GHG emissions reductions pose substantial technological, economic, social and institutional challenges. For example, in order to achieve the full potential of renewable resources, technological innovations are needed but in addition, the economic and policies also need to be aligned (Verbruggen et al. 2010). The key enablers of the energy system transition process include rethinking of the energy markets, the public engagement and incentives to behavior change and a great political ambition (European Commission 2012).

Achieving radical system changes is hard since the current systems acts as a barrier to the new ones (Könnölä et al. 2008). The main challenges of the transformation process include the efficient financing of low carbon energy production, updating of markets and business models to encourage efficient investing in the flexibility of the system and changing the role of energy customers (Growth Analysis 2014). Usually, system transitions are achieved by gradual adoption. In order to generate favorable conditions for the transition, short and medium term strategies need to be linked to long term visions. (Könnölä et al. 2008)

Accordingly, the adoption of efficient energy technologies with low emissions and energy savings is important in climate change mitigation. However, in the development of such systems, economics, policies and end user behavior are also essential. When planning the future energy system, a holistic view must be taken. In the following, the international and national targets that need to be taken into account when planning energy systems are summarized. This is followed by a review of the targets for future buildings. Finally, the role of end user engagement in the transition process is clarified. The transition and different development pathways for future energy systems are explained from the technology point of view in Section 2.3.

2.2.1 Energy System Targets

Both national and international agreements have been made in order to mitigate climate change. In this section is a selection of the targets and strategies that will influence the development of the energy system presented. Both international and country specific targets for Finland are considered.

The first international agreement with legally binding targets for reducing the GHG emissions was the Kyoto Protocol. In the first commitment period of the protocol, 2008-2012, the member parties agreed to reduce the global GHG emissions by 5 % below 1990's levels (United Nations, 1998). In the second commitment period, 2013-2020, the aim is to reduce the GHG emissions by 18 % below 1990's levels (UNFCCC 2012). At the Paris Climate Conference in 2015, a new agreement was made aiming at "holding the increase in global average temperature to well below 2 ºC above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 ºC above pre-industrial levels" (UNFCCC 2015).

The European Union (EU) and its member countries have for a long time been committed to the international actions for climate change mitigation. In order to reach the targets, EU has made its own directives and strategies. Before the year 2020, the EU has committed to reach the following targets (European Commission 2016):

- Reduce the GHG emissions by 20 %, compared with the 1990 levels
- Produce 20 % of the energy by renewables
- Improve the energy efficiency by 20 %

Furthermore, by 2030 these targets are sharpened; GHG emissions need to be cut by 40 %, the energy efficiency improved by 27 % and share of renewables should reach 27 %. In the long term, the EU target is to cut the emissions by 80% by 2050. (European Commission, 2016)

However, different countries have different prerequisites to reach these targets and therefore, national targets have been made. By 2020, the Finnish national targets are to reduce the GHG by 16 % compared with 1990's levels, to produce 38 % of the energy by renewables and to increase the energy efficiency by 20 % (European Commission, 2010).

The long term Finnish national target is to become a carbon neutral society (Ministry of Employment and the Economy, 2013). In order to reach this target, actions in all sectors and at all levels are need. The main actions are related to energy efficiency, renewable energy and clean tech solutions. The efficient use of energy includes both measures related to the technologies used, such as the efficiency of electric appliances, and consumer actions. Renewable energy should be used to replace the fossil fuels in power and district heating production. Especially forest biomass has huge potential but also other renewable energy sources such as hydroelectric power, wind power, small scale electricity production, solar power, solar heat and heat pumps could be used. (Ministry of Employment and the Economy, 2014)

2.2.2 Building Targets

Globally, a fifth of the energy delivered is consumed in the building sector (EIA 2016). Thus, by improving the energy performance of buildings, huge energy savings can be obtained. There are three ways of reducing the energy consumption within the building stock: by building new, energy efficient buildings, by renovating existing buildings or by reducing the heat consumption within the buildings (Pesola et al. 2011).

In 2010, EU announced the energy performance of buildings directive (EPBD) recast, aiming to reduce the GHG emissions by improving the building efficiency (European Parlament, 2010). According to the directive, all new public buildings should be nearly zero energy buildings (nZEB) by the end of 2018 and all other new buildings by the end of 2020. In the directive, nZEB buildings are defined as a "building that has a very high energy performance", where a significant part of the energy need is covered by renewable energy sources. However, there is no more detailed definition of the nZEB concept available. It is the responsibility of the member countries to set national and regional minimum requirements for the nZEBs before the directive comes to power.

In Finland, the preparations for adapting to the EPBD recast are proceeding and at the beginning of 2017, the final regulations will be published. Within the FinZEB project, suggestions for how to define the nZEB concept, targets and guidelines on a national level have been made (FinZEB 2015). In Figure 4 below, the suggested boundaries of nZEB buildings are shown.

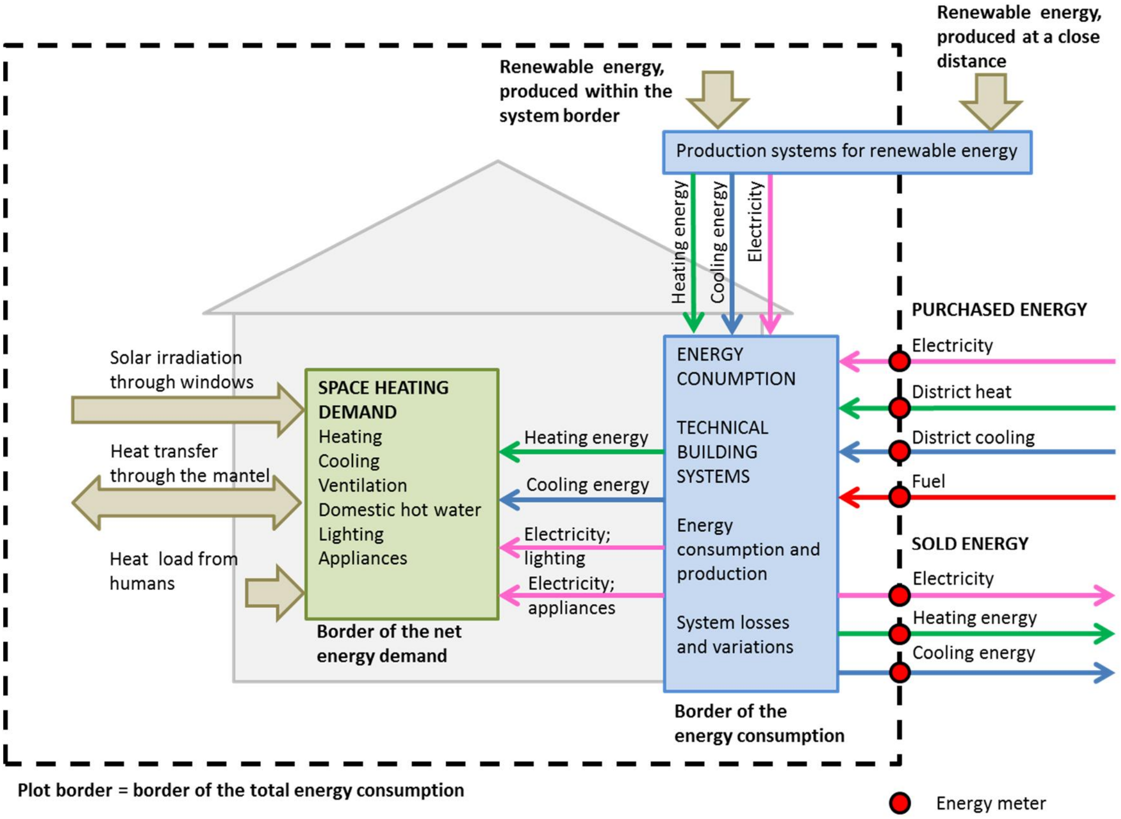

Figure 4. The energy flows and borders of nZEBs. Adapted from FinZEB (2015).

According to the FinZEB suggestions, the unnecessary energy demands are to be minimized and the energy systems are to be efficiently used in nZEBs. The successful implementation of nZEBs requires careful planning and the full engagement by all parties throughout the whole building construction process. Due to the tight time schedule, it is suggested that the future regulation for nZEBs is based on the current construction practices and available technologies. The largest improvements in nZEBs compared with the current buildings are expected to be reached by the appropriate use and control of technical systems within the buildings. No improvements of the building envelopes are expected. However, voluntarily implementations of the passive house requirements could be a way of further improving the physics of the buildings. (FinZEB 2015)

Within the FinZEB project, no recommendations have been given for how to produce the necessary energy. One option is to use decentralized energy production units, such as solar photovoltaics or heat pumps, another is to use energy produced in centralized units with increasing shares of renewable resources. Furthermore, it is established that new business opportunities will appear e.g. when bidirectional energy sales become more common. (FinZEB 2015)

2.2.3 End User Engagement

As already established, the transition towards a low carbon energy system requires significant energy savings throughout the whole energy system. However, in order to reach such savings, the current measures to increase the energy efficiency are not enough. The energy consumption and the economic growth need to be decoupled (European Commission 2012). Furthermore, lifestyle changes, followed by cultural changes and socio-technological changes are needed (O'Rourke & Lollo 2015).

Achieving large system changes is not easy since consumption is deeply ingrained in behaviors, cultures and institutions (O'Rourke & Lollo 2015). Thus, it is not only shaped by individual factors but also by the context. According to Owens and Driffill (2008), the factors affecting the energy behavior include prices, awareness, the sense of moral obligation, cultural norms, routine habits and practices, and comfort. Furthermore, energy behaviors are not static; they change along with experiences and they are often inconsistent (Lopes et al. 2012).

Ever since it became obvious that the energy consumption has a negative effect on the climate, there have been many attempts to make people aware of these effects and to help them make rational and well-informed energy related decisions. The methods used include regulations, economic instruments and the provision of information (Owens & Driffill 2008). Out of these methods, especially the provision of information has frequently been used. For example, both municipalities and energy companies have for a long time been providing information for households on how to reduce their energy consumption. According to a study made by Gyberg & Palm (2009), the provided information often focus on technological improvements rather than behavioral changes. Furthermore, the proposed actions are often motivated by lower energy costs, reduced environmental impacts and sometimes also by better health (Gyberg & Palm 2009).

However, information is not likely to be effective if is runs counter to other important factors such as norms and prices (Owens & Driffill 2008). According to a study by Heimonen, et al. (2012), the end users of energy are interested in how energy is produced. However, they are typically not willing to pay much extra for energy that is produced using environmental friendly energy technologies. Moreover, another of the main barriers to end user engagement is that individual consumers may perceive that they do not have the prime responsibility to take actions or that their actions do not have much effect. Instead, governments are seen as responsible for addressing environmental problems. (Owens & Driffill 2008). According to Johnson and Nemet (2010), the end users of energy need to be shown that their choices really make a difference in order for them to participate. Furthermore, if the users have the possibility to benefit from the decisions themselves, the incentives for them to participate are stronger.

2.3 Future Energy Systems

In the literature, there are different views on how the building heat demand could be satisfied in the future, avoiding the use of fossil fuels. According to Lund et al. (2010), one alternative pathway would be to completely remove the external heat demands in future low-energy buildings. The heat demands could instead be covered by local renewable energy sources such as solar thermal energy. Another alternative would be to utilize heating sources such as excess heat from industries, waste heat incineration, geothermal energy, large scale solar thermal energy and large scale heat pumps. In the first case, district heating systems will have a minor role but in the second case, the district heating network is a key enabler. (Lund et al. 2010)

Different heat production alternatives have also been discussed in the context of the EU's target to reach 80 % reductions in GHG emissions by 2050 compared with the levels in the year 1990. In the "Energy Roadmap 2050" by the European Commission, (2012) it is emphasized that electricity will play a great role in the decarbonization of the heating sector. Likewise, in the "Roadmap 2050" by the European Climate Foundation, (2010), it is stated that electricity needs to be increasingly used in the heating sector in the future. In these roadmaps, heat pumps are seen as the key technology of the future heat generation. One of the main advantages of heat pumps is that they add flexibility to the energy system as a whole, as they are able to transform excess electricity into heat.

However, according to Connolly et al. (2014), it would also be possible to reach the 80 % reduction in GHG emissions by a large scale implementation of district heating. An increased use of district heating systems could improve the efficiency of the overall energy system and allow for the efficient use of local renewable resources and recycling of heat that is currently wasted (Connolly et al. 2014). Moreover, according to Rezaie and Rosen, (2012), the large scale implementation of district heating could facilitate the integration of the energy systems and increase the share of renewables in heat production.

In the case of Finland, the current district heating system is seen as an important, emission saving part of the future energy system (The Finnish Climate Panel 2013). In the future, the following elements are expected to contribute to energy systems with low emissions: low temperature district heating networks, short term storage of heat in buildings and storage tanks, long term storage of heat in the ground, utilization of renewable energy sources and possibly also the opening of the energy systems for small scale heat production. (The Finnish Climate Panel 2013)

Thus, there are different options for how to satisfy the heat demand in future buildings. The options are presented in Figure 5.

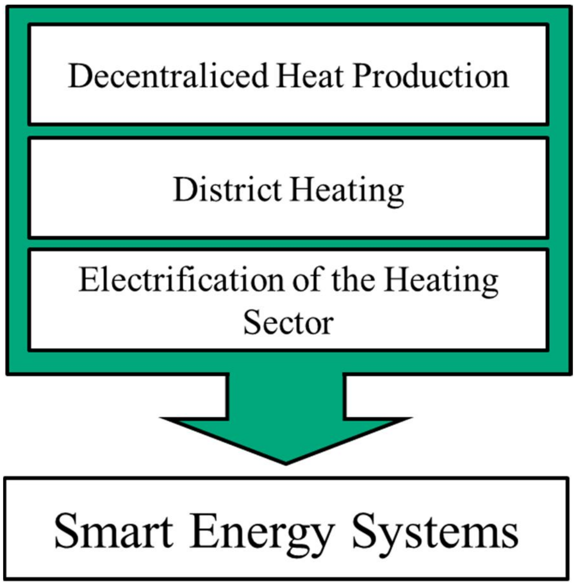

Figure 5. The different options for how to satisfy the heat demand in future buildings.

Both decentralized heat production and district heating are seen as interesting technologies of the future. Furthermore, the electrification of the heating sector is seen as a way of improving the flexibility of the whole energy system. The implementation of one of these alternatives does not necessarily mean that the other options are omitted. A combination of different systems is also possible. As a result, a smart energy system, where a holistic approach to the energy system is taken, is reached.

In the following, the different development pathways are examined more closely. First, decentralized heat production alternatives are presented. Then, development pathways for district heating are examined. Finally, the smart energy system concept is explained.

2.3.1 Decentralized Heat Production

Within the last few years, the interest in decentralized, or distributed, energy generation technologies has grown. In the public debate, a shift from centralized energy generation towards decentralized generation is seen as an alternative to covering the heat demand in energy efficient buildings and to increase the share of renewables in the energy production. Decentralized energy production has indeed many advantages. For example, it is a flexible alternative to matching the local electricity and heat demands. Furthermore, it could bring a greater awareness of energy issues among the end users of energy than community based energy systems can. The disadvantages on the other hand comprise long payback periods for the investments and that some of the technologies are not mature yet. (UK Gouvernment's Business Taskorce on Sustainable Consumption and Production 2011)

In the literature, many attempts have been made to define the concept of decentralized generation. For example, within the electricity sector, decentralized generation has been defined as the electric power generation within the distribution networks or on the customer side of the network (Ackermann et al. 2001). According to Pesola et al. (2010), decentralized energy, electricity, heating or cooling is energy that is generated close to where it is consumed. This definition is visualized in Figure 6.

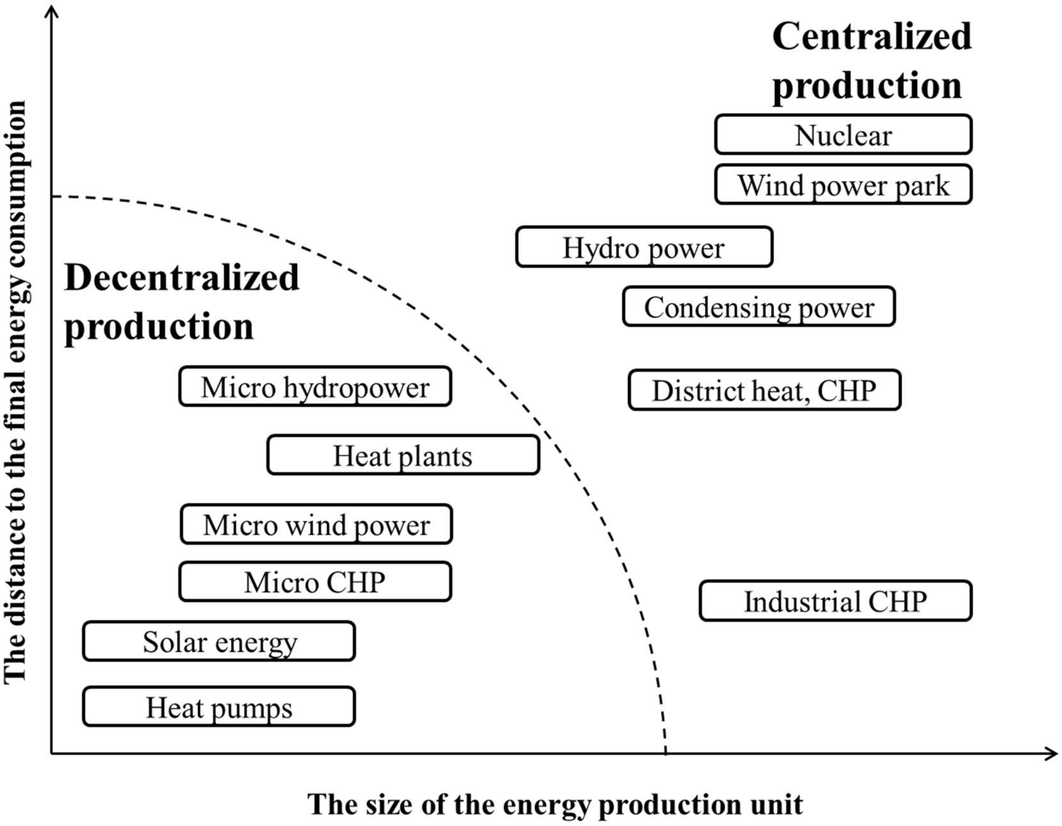

Figure 6. A definition of decentralized energy production. Adapted from Pesola et al. (2010)

In the case of decentralized heat generation, the scope of the decentralized heat technologies is often restricted to the systems used to provide heat for single buildings. However, according to Koikkalainen (2015), the concept also includes energy generation used in regional energy systems. The maximum size of decentralized heat production units varies in different studies. A nominal power of 10 MW has been set as the limit by Vartiainen et al. (2002) while Koikkalainen (2015) uses 20 MW as the limit.

Thus, decentralized heat production is energy that is locally produced in a small scale close to the end consumers. The technologies that could be used for heating and cooling in energy efficient buildings include e.g. micro combined heat and power (CHP) technologies, heat pumps, STCs and thermal energy storages (IEA 2014). The applicability of the technologies is affected by many different factors such as the local conditions, the resources to be used, the existing energy infrastructure and the local energy sources (Pesola et al. 2010). In the case of Finland, the following technologies have high potential: GSHPs, air-water heat pumps, air-air heat pumps and STCs (Koikkalainen 2015). Furthermore, the utilization of thermal storages contributes to an improved system efficiency since partial load generation can be avoided, demand shifting for reducing peak loads and facilitation of the increased use of renewables (IEA 2014).

Heat pumps are one of the most interesting heat production technologies at the moment. According to a study by Häkämies et al. (2015), Finnish nZEB are achieved in the most cost efficient way by utilizing heat pumps. In the study, heat pumps turned out to be a cheaper option than district heating and in addition to the provided heating, the pumps were also able to provide buildings with cooling, almost without any extra investment costs (Häkämies et al. 2015). Furthermore, as, discussed earlier, heat pumps add flexibility to the whole energy system.

2.3.2 District Heating

District heating is a heating alternative that is widely used especially in countries with cold climate. The heat is usually produced in large centralized plants and distributed to the customers through a district heating network. The main advantages of district heating compared with individual heating systems include high energy efficiency, low emissions and high fuel flexibility (Ericsson et al. 2004). Especially the cogeneration of district heat is more efficient and has lower emissions than small scale heating systems (Gustavsson & Karlsson 2002). Furthermore, from the users' perspective, district heating is reliable and easy to use since it does not require any actions during the operation phase by the user; the heat is automatically supplied whenever it is needed.

Traditionally, fossil fuels have been used to generate district heat (Lund et al. 2010). However, it is possible to utilize a number of different energy sources and production technologies. Currently, mixed systems where different energy sources are used is also an economically feasible alternative to fossil fuels; e.g. the combined use of natural gas, wood waste, municipal solid waste and industrial waste heat (Rezaie & Rosen 2012). Other energy sources that can be used include e.g. waste-to-energy plants, direct use of biomass fuels and geothermal heat (Persson & Werner 2011).

In order for district heating to be a competitive alternative also in the future, the current technology and the business concept need to be developed. In the future, the district heating system must be able to handle a reduced heat demand due to an increasing amount of low-energy buildings connected the systems. Furthermore, in the development of future sustainable energy systems with a high share of renewables, the whole energy system needs to be taken into account so that the available energy sources are used in the best possible way, keeping the costs as low as possible (Lund et al. 2010).

The competitiveness of district heating is affected by three major factors: the current use of district heat, the future competition on the market and the future heat density in cities. The future competitiveness of district heating depends on the difference between centralized and decentralized heat supply and the cost of heat distribution. If the heat density decreases, the distribution cost increases and district heat can lose its competitiveness. In low heat density areas, local heating alternatives are expected to be favored while in large heat density areas, district heating is expected to remain a good option even if the heat demand of buildings decreases. (Persson & Werner 2011)

The investment in district heating networks is very high and once it is made, the network will be used for a long time. An extension of an existing district heating network is an option if the heat density is high and if there is excess heat generated in the area. In that case, district heating could contribute with redistributing the available energy in the area. (Finney et al. 2012) In areas with low heat density, district heating is a feasible alternative only when the investment costs in the distribution network and the marginal costs of heat production are low (Reidhav & Werner 2008).

The current district heating trends include increasing shares of renewables in heat production, lower supply temperatures, the utilization of excess heat e.g. from industry and to some extent also from small suppliers and utilization of surplus electricity production from renewable energy sources (Sayegh M. A. et al. 2015; Lund et al. 2010). In Sweden, the transition towards high shares of renewable energy sources has already been going on for a while. There, the district heating sector has gone from being heavily dependent on fossil fuels to a system that mainly uses biomass and other renewable sources (Di Lucia & Ericsson 2014).

According to the Finnish strategy for the district heating sector, the vision is to provide diverse energy solutions and services to the customers and to reach carbon neutrality. In order to reach the vision, the following strategic goals have been set: increased flexibility and integration, development of new business from services and partnerships and committing to a carbon neutral future. Increased flexibility includes the utilization of customers' surplus heat in the district heating networks and adapting the business to changes in energy consumption and output requirements. New business areas include offering district cooling solutions and services linked to the products. (Finnish Energy Industries 2013)

2.3.3 Smart Energy Systems

The "Smart energy systems" concept has gained much attention recently. Smart energy systems are systems where the electricity, heating and transportation sector interact in order to balance large amounts of fluctuating renewable energy in the system (Mathiesen et al. 2015). In the Low Carbon Finland 2050 vision, such systems are pointed out as key enablers of the future low carbon energy system (Koljonen et al. 2012).

Thus, in smart energy systems, an integrated approach to the supply of electricity, heating and cooling is taken. The heating part of such systems is referred to as the 4th Generation District Heating (4GDH) or smart thermal grids. According to Lund et al., (2014), smart thermal grids are "a network of pipes connecting the buildings in a neighborhood, town center or a whole city, so that they can be served from centralized plants as well as from a number of distributed heating and cooling producing units including individual contributions from the connected buildings". In Figure 7 below, the development of district heating networks towards smart thermal grids can be seen.

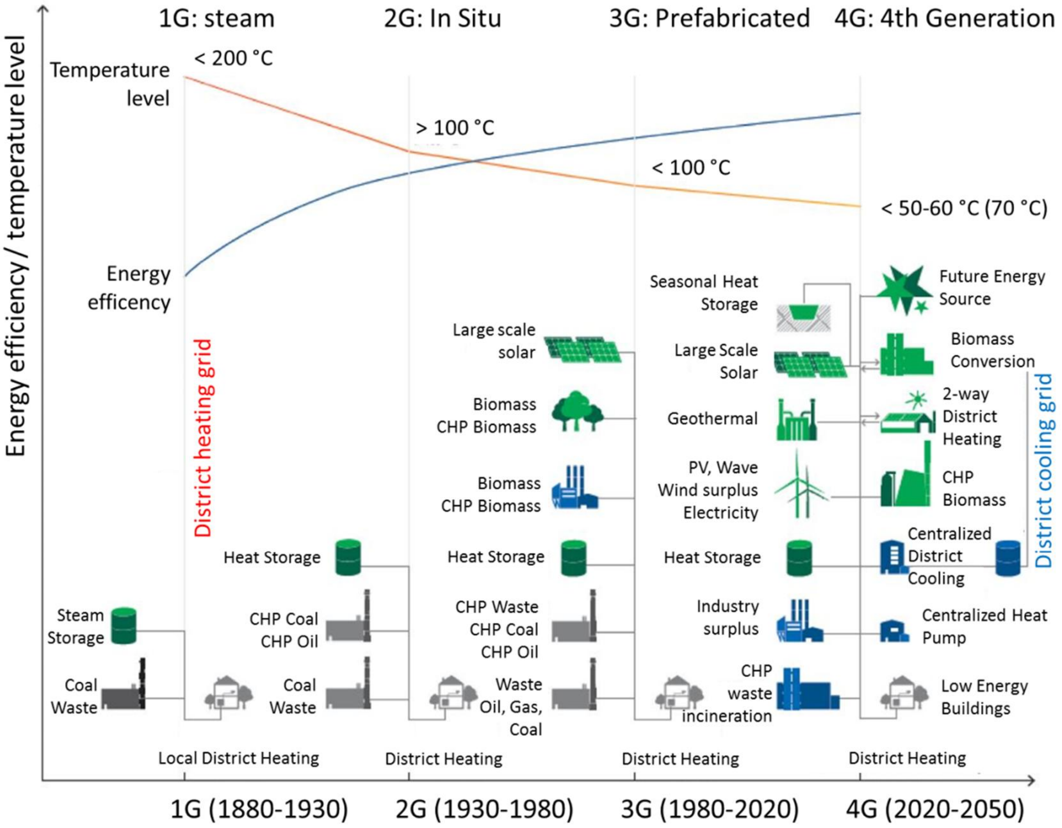

Figure 7. The development of district heating systems to smart thermal grids. Adapted from Lund et al. (2014)

As can be seen from the figure, the temperature level of district heat has decreased throughout the different development phases while the energy efficiency has increased. In smart thermal grids, the temperatures are expected to decrease even more, perhaps to 50 ºC in the supply pipe and 20 ºC in the return pipe (Lund et al., 2014). Low temperature district heating network would provide a number of benefits compared to the current heating networks. The advantages include high fuel flexibility, the possibility to use renewable energy sources directly or in combination with heat storages and a great potential for using waste heat from different sources. (Olsen et al. 2008). Furthermore, a lower feeding temperature would result in lower heat losses from the network (Lund et al., 2014). However, the problem of temperature levels below 55-58 °C needs to be solved before low temperature networks are implemented in large scale.

In smart energy systems, decentralized heat production is essential. By combining decentralized heat production and district heating, synergies can be reached and the full potential of decentralized heat generation can be utilized (Koikkalainen 2015). The lower the district heating temperature is, the easier it is to utilize heat that is produced by energy technologies such as solar thermal, ground heat and excess heat from buildings (Koikkalainen 2015). Energy consumers that both consume and produce district heat are called heat prosumers (Brange et al., 2016). Thus, future buildings with high energy efficiency and decentralized heat production units will be an important part of smart energy systems.

At the same time as the energy systems are becoming more versatile and complex, the importance of control and management is becoming more important. In order to operate energy system in an efficient and intelligent way, smart meters are needed. The meters can be used to optimize the energy system both at the building level but also at the system level. They can be used to manage the devices in homes and maximize the user savings. Furthermore, if they are interconnected to the grid, they can also be used for reducing the peaks in demand on the grid level. (Ramchurn et al. 2011)

2.4 Optimization Criteria

Traditionally, the energy system planning has aimed at minimizing the costs and maximizing the benefits (Pohekar & Ramachandran 2004). However, as the need for a more efficient and sustainable energy system has become evident, also other criteria have been increasingly used. Currently, a multi-criteria decision analysis (MCDA) approach is often taken in energy system decision making. The method provides solutions for problems where several parameters need to be optimized, which is often the case in energy system planning (Pohekar & Ramachandran 2004). Furthermore, MCDA contribute to creating a formalized and well-informed decision making process (Løken 2007).

In practice, the MCDA method is used to analyze different energy system options by using a set of evaluation criteria and based on these, the options are ranked. When evaluating the sustainability of an energy system, a set of economic, environmental and social criteria are usually considered (Santoyo-Castelazo & Azapagic 2014). In addition to these, technical criteria are also used when comparing different energy supply systems (Ghafghazi et al. 2010; Wang et al. 2009).

Thus, the criteria used for energy system decision making can be divided into four categories: technical, environmental, economic and social. Each category incorporates a large number of criteria that can be used for evaluating the performance of different energy systems. Different criteria used for energy decision making have been reviewed by Wang et al. (2009). The results are shown in Table 2.

Table 2. A review of criteria used for energy decision making. (Wang et al. 2009)

Technical	Environmental	Economic	Social
Efficiency Exergy efficiency Primary energy ratio Safety Reliability Maturity	NO_x emissions CO_2 emissions CO emissions SO_2 emissions Particulate emissions Non-methane volatile organic compounds Land use Noise	Investment cost Operation & Maintenance cost Fuel cost Electric cost Net present value Payback period Service life Equivalent annual cost	Social acceptability Job creation Social benefits

According to the review results, the most frequent criteria used in each category were efficiency, carbon dioxide (CO_2) emissions, investment costs and job creation. Other criteria frequently used included the operation and maintenance costs, fuel costs, and land use.

Many of these criteria are sensitive to the chosen system boundaries. Clear boarders enable a consistent analysis and a clear view of which inputs and outputs that are considered and at which stage of the energy chain (Forsström et al. 2011). However, even though the system boundaries are clearly defined, it may be difficult to decide e.g. which emissions should be taken into account when analyzing different systems. This is due to the fact that the energy solution choices within the system could possibly lead to emissions not only inside the system but also on the outside. There are different approaches for how to address this boundary problem: one alternative is to only take into account local emissions. Alternatively, the emissions of imported/exported energy carriers could also be considered. (Løken 2007a)

In the following, a more comprehensive description of the following criteria is given: energy efficiency, CO_2 emissions, particulate emissions, investment costs, energy costs and employment effects. These criteria are also used to compare the different scenarios in the case study in Chapter 3. The different methods that can be used for criteria weighting and ranking are described in detail in Section 2.5.3.

2.4.1 Technical Criteria

Efficiency is one of the most popular technical criteria used to compare different energy systems. In general, energy efficiency is understood as the ratio of an energy output to the energy input. However, even though this definition seems simple, measuring the energy efficiency is a complex task; it can be done in many different ways, using different indicators and different system boundaries. Several attempts have recently been made in order to create a general approach to the problem. For example Forsström et al. (2011) has investigated how to measure the energy efficiency and the energy potential of buildings, communities and energy systems. Tuomaala et al. (2011) have also made a similar study but they use a slightly different area division; communities, buildings, transportation and logistics, process industry and energy production (Tuomaala et al. 2011).

In this thesis, different ways of measuring the energy efficiency at the community level are of main interest. According to Tuomaala et al. (2011), the energy efficiency in communities is determined as the final, non-renewable, energy consumption relative to the services produced by the community. The consumption includes the total end use of non-renewable energy, taking the whole life cycle into account. The services refer e.g. to the total building floor area or the number of inhabitants and workplaces within the community. In practice, the primary energy consumption per floor area or the final, non-renewable, energy consumption per floor area can be used as a measure of the energy efficiency in a community. (Tuomaala et al. 2011)

2.4.2 Environmental Criteria

Most energy technologies have some negative environmental impacts and therefore, it is important that different environmental criteria are taken into account when comparing different energy systems (Løken 2007a). The environmental indicator that has been most frequently used when comparing energy systems is CO_2 emissions. CO_2 emissions constitute the largest share of the anthropogenic GHG emissions and are mainly emitted from energy systems through the combustion of fossil energy sources such as coal, oil and natural gases. Thus, the emissions are of significant importance in the energy sector.

The CO_2 emissions can be measured as the CO_2 emissions relative to the building floor area. However, when comparing different energy systems for a specific area, the absolute CO_2 emissions can also be compared. In the ideal case, the emissions during the whole life cycle are taken into account: construction phase, normal operation and accidental emissions (Løken 2007a). There are several types of emissions that contribute to the greenhouse effect, and for this reason the CO_2 emission criteria are often measured in terms carbon dioxide equivalent (CO_2e) emissions. The CO_2e emissions are used as a measure to compare the emissions from different GHG emissions, based on their global warming potential (OECD 2013).

Particulate emissions are another environmental indicator that can be used to compare different energy systems. Particulate emissions consist of small particles and liquid droplets that are released into the air e.g. in the combustion processes in power plants and motor vehicles. These particulate emissions are determined in the same way as the CO_2 emissions; either as the particulate emissions relative to the building floor area or as the absolute amount of particulate emissions in the area.

2.4.3 Economic Criteria

Economic criteria are also an important aspect in energy system planning. Investment decisions are based on profitability calculations which include e.g. investment costs, operation and maintenance costs and fuel costs (Tuomaala et al. 2011). Since most companies are aiming at maximizing the investment profits and minimizing the costs related to the investment, no investments will be made if no economic benefits are offered (Løken 2007a).

The economic criteria that are generally used for evaluating energy system options include investment costs, operation and maintenance costs and fuel costs. Investment costs include all costs related to the purchase of mechanical equipment, technological installations, construction of the infrastructure needed, engineering services and other incidental work. The size of the investment cost depends on the technology chosen. Operation costs include employees' wages, funds spent for the energy and the products and services for the energy system operation. The maintenance costs are the costs related to maintain the energy system. The aim is to avoid failures and prolong the lifetime of the energy system. Fuel costs are the costs of the raw material used for operating the energy system. The costs can include fuel extraction and mining, transportation and fuel processing. The costs vary depending on time and place. (Wang et al. 2009)

2.4.4 Social Criteria

The technical, environmental and economic aspects of different energy systems are of huge importance. However, these are not enough. Over the last few years, the social aspects have been the most important criteria for people's acceptance of energy systems (Wang et al. 2009). Social criteria include e.g. social acceptability, job creation and social benefits (Wang et al. 2009). For many of these, it is not possible to use quantitative measures. Instead, qualitative measures are used, e.g. by a scale of 1-10. (Ghafghazi et al. 2010)

In order for a specific energy technology to be implemented and used, it must be accepted by the public (Santoyo-Castelazo & Azapagic 2014). The acceptance is affected by many different factors; socio-economic background, age group, political beliefs, attitudes and behavior but also the perceived usefulness, intention to use and the costs of the technology (Moula et al. 2013). In order to determine the public acceptability of different energy technologies, questionnaires and interviews have frequently been used. For example, the social acceptability of renewable energy technologies in Finland was investigated by Moula et al. (2013) using a multiple choice questionnaire. A corresponding investigation has also been performed in Germany by Zoellner et al. (2008), using a combination of a questionnaire and interviews.

Employment effects, or the employment factor, is a key for the development of a region since these have an effect on the development in many different areas: social, environmental, economic, technological and territorial (Llera Sastresa et al. 2010). Therefore is the employment effects frequently used in energy system decision making. There are a number of metrics that can be used to determine the employment effects of different energy technologies: jobs per annual MW installed, jobs per cumulative MW installed, manufacturing jobs per MW, person years per MW etc. (Lambert & Silva 2012). Different metrics are used at different stages of the technology life cycle. When calculating the employment effects, the stages of the technology life cycle are usually divided into the two following groups: construction, installation and manufacturing and operations, maintenance and fuel processing. The first group is measured as job-years per MW installed while the second group is measured as jobs per peak MW over the lifetime of the plant. (Wei et al. 2010)

2.5 Scenarios

In the literature, the scenario concept has been defined in a number of ways. One of the first definitions was given by Kahn and Wiener (1967) and according to them, scenarios are a “set of hypothetical events set in the future constructed to clarify a possible chain of casual events as well as their decision points”. Later on, Durance and Godet (2010) have defined scenarios as a mean to represent the future, aiming for clarifying the current situation by using possible and desirable futures. Furthermore, it has also been stated that scenarios can be used as a tool for analyzing how different events could influence the future (IPCC 2000).

The range of applications that scenarios are used for have been developed over time. The first modern scenarios were used to develop military strategies in the middle of the 20th century (Rounsevell and Metzger 2010). Later on, the use of scenarios was adapted also by companies in order to improve their business strategies. One of the first companies to make advantage of long term forecasts in their business was Royal Dutch Shell. In the late 1960’s, Shell started to develop long term scenarios for the oil price development (Wilkinson and Kupers 2013). The application of these scenarios in their business strategies turned out to be extremely successful. After that, the popularity of scenarios has grown and today, scenarios are used in many different fields and for many different purposes.

Thus, scenarios are not forecasts of the future but rather descriptions of possible future outcomes. The application areas include especially the analysis of different choices and decisions, which is valuable information in decision making. In the context of energy systems, scenarios have been increasingly used ever since the early 1990’s when the use of energy models became much more common. At the global level, such scenarios have e.g. been made to investigate the future potential of different energy technologies and the development of GHG emissions and their effects on the climate change. At the district energy system level, scenarios have mostly been used to compare the outcome of different energy system choices.

In the following, the scenario concept is explained in detail. First, different ways of classifying scenarios are presented. Then, the most common methods used to develop scenarios are reviewed. Finally, different ways of evaluating the scenario outcomes are assessed.

2.5.1 Scenario Classification

Scenarios can be classified in different ways. One of the most common ways of classifying them is according to their purpose. Börjeson et al. (2006) suggests the use of the following categories: predictive scenarios, explorative scenarios and normative scenarios. An overview of these categories and their subcategories is given in Figure 8.

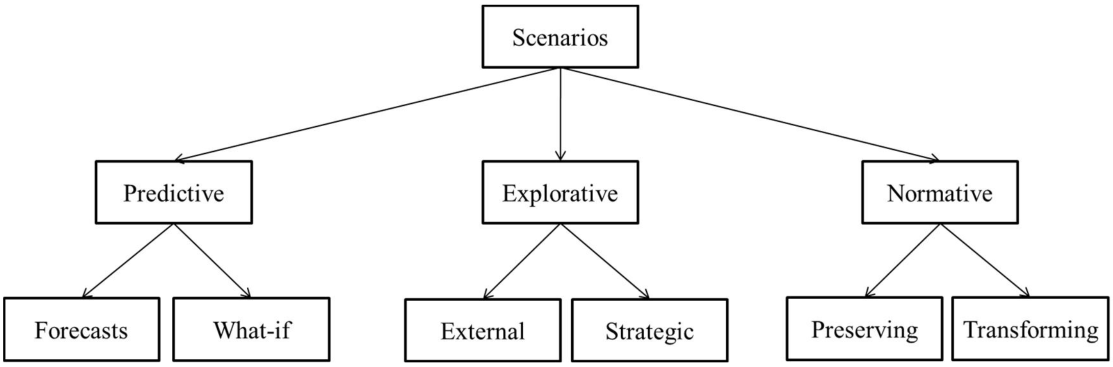

Figure 8. Scenario classification according to their purpose. Adapted from Börjeson et al. (2006)

Predictive scenarios answer the question "What will happen?" and can be further divided into forecasts and what-if scenarios. Forecasts are used to investigate what the result of the most likely development is, while what-if scenarios are used to investigate the consequences of some specific development. This scenario type is usually used in order to be able to adapt to future situations. (Börjeson et al. 2006)

The second scenario category, explorative scenarios, answers the question "What can happen?" and is divided into external and strategic scenarios. External scenarios explore what the effects on future situations that factors out of the control of the scenario actors can have. Strategic scenarios examine the possible outcome of some certain actions that can be affected by the scenario actors. These scenarios aim to explore a wide range of possible situations from many different perspectives. (Börjeson et al. 2006)

The last type, normative scenarios, answer the question "How can a specific target be reached?". Normative scenarios are divided into preserving scenarios and transforming scenarios. Preserving scenarios explore how the specific target can be reached by changes made to the current situation while transforming scenarios examine how the specific target can be reached when the necessary changes seem to be blocked by the current situation. These scenarios focus on how a certain future situation or objective can be reached. (Börjeson et al. 2006)

Another way of classifying scenarios is by dividing them into qualitative and quantitative scenarios, depending on the type of data that is utilized. Qualitative scenarios make use of visual symbols or storylines to describe the future while quantitative scenarios use numerical figures instead. (Fortes et al. 2015)

Qualitative scenarios are usually created in stakeholder workshops or by other participatory methods and they are important especially when the uncertainty is high or when the information can not be quantified (van Notten et al. 2003). Quantitative scenarios on the other hand are usually obtained by the use of mathematical models. In order to obtain such scenarios, assumptions and simplifications are required. Therefore, this type of scenarios highlight the expertise of the one's that has created them (Varho & Tapio 2013). It is also possible to create a combination of quantitative and qualitative scenarios. The integrated uses of qualitative and quantitative scenarios include benefits such as an increased robustness of the scenario development (Fortes et al. 2015).

2.5.2 Scenario Development Methods

Since scenarios are used in many different fields and for many different purposes, a variety of scenario development methods have evolved. The methods mainly vary depending on the type of data that is utilized. In the following, scenario development methods used for developing qualitative scenarios, quantitative scenarios and a combination of qualitative and quantitative scenarios are described.

For the development of qualitative scenarios, the following method is suggested by Rounsevell and Metzger (2010). First, the focal question, i.e. the aim of the study needs to be identified. Then, the key drivers are to be recognized and the scenario logic to be determined. After that, the scenario assumptions need to be described. Finally, the scenario outcomes and their potential impacts should be assessed. In order to broaden the knowledge sources, participatory approaches are often used. Furthermore, in the scenarios analysis, expert judgements are often used. (Rounsevell and Metzger, 2010)

For quantitative scenarios, there are different approaches that can be used. One approach is to form a scenario matrix from key uncertainty factors. These factors are then used in a mathematical model to generate a set of different scenarios. Another approach is to use a predefined energy system with a fixed outcome. Different conditions and decisions that are needed for reaching the predefined outcome are then used to create different scenarios by running the model. The selection of uncertainty factors is often reflected by subjective judgements of the relevance of the scenarios. (Trutnevyte et al. 2016)

Combined qualitative and quantitative scenarios can be developed using a three-step method. First, qualitative scenarios are developed e.g. in stakeholder workshops. Then, these scenarios and their key indicators are transformed into comprehensible numerical modelling assumptions. Finally, quantitative scenarios are developed by using the quantified indicators and scenarios in a modelling tool. (Fortes et al. 2015)

Even though there are different approaches for how to develop scenarios, there are some common pathways. In order to create scenarios, ideas need to be generated. In order to generate ideas, different techniques can be used such as workshops, surveys and interviews. (Börjeson et al. 2006). The techniques used for the integrating of elements are based on mathematical modelling; time-series analysis, explanatory modelling and optimizing modelling. These approaches facilitate the collection of data and can be used to ensure that all parts of the system are consistently described. The techniques used for checking on consistency are e.g. cross impact analysis and morphological field analysis. However, in practice, consistency checking is often carried out through using expert panels and their suggestions for improvement. (Börjeson et al. 2006)

2.5.3 Ranking of Scenarios

The criteria usually used for optimizing the energy systems were presented in Chapter 2.4. These criteria can also be used to compare the outcome of different scenarios with each other. However, even though there are a wide range of criteria that can be used for evaluating energy systems, it is to be remembered that the best energy system choice is not necessarily made by using as many criteria as possible. Instead, a careful selection could facilitate the comparison of different energy systems. The following principles can be used to select the major criteria (Wang et al. 2009):

- *Systemic principle*: The chosen criteria should reflect the crucial characteristics and the performance of the whole energy system.
- *Consistency principle*: The chosen criteria should be consistent with the objective of the decision making.
- *Independency principle*: The chosen criteria should measure different aspects of the system.
- *Measurability principle*: The chosen criteria should be measurable; either as quantitative values or as qualitative expressions
- *Comparability principle*: The chosen criteria should have an obvious comparability. Through the normalization of the criteria, their direct comparison is facilitated. Usually, a scale with performances between 0 and 1 is used.

In order to compare the criteria with each other, the chosen criteria need to be summed up and the relative importance of each criterion compared with the other ones need to be determined. The choice of method mainly depends on the preferences of the decision makers and analysts. Most probably, different methods will end up in different results. (Løken 2007)

There are in general two alternatives for criteria weighting: the equal weight method and the rank order weight method. The equal weight method is the most popular weighting method and using it requires no or little knowledge about decision makers' priorities. As the name implies, in this method, all criteria are given the same importance. The rank order weighting method can be further divided into three subgroups: subjective weighting method, objective weighting method and combination weighting method. In the subjective weighting method, the criteria are ranked according to the preference of decision makers. In the objective weighting method, the weighting of the criteria is obtained by mathematical methods. In the combination weighting method, the criteria weight is reached by combining the subjective and objective methods. (Wang et al. 2009)

When the weight of each criterion is determined, the results are ranked. The methods used for MCDA can be divided into three categories: elementary, unique synthesizing criteria and outranking methods. Each category contains a large number of methods that can be used for the ranking. The most commonly used method for ranking of sustainable energy systems is the weighted sum method. In this method, each alternative is scored and the alternative that gets the highest scores is ranked as the best alternative. Other commonly used methods used are the ELECTRE and PROMOTHEE methods. (Wang et al. 2009)

3 Simulation Case Study

This simulation case study examines a set of scenarios for the development of the thermal energy system in the Keski-Uusimaa area. The scenario timeframe is 20 years, starting in 2015 and ending in 2035. The purpose of the scenarios is not to make a prediction of what the future energy systems will be like, but rather to examine what different possibilities there are and to compare them in terms of technical, environmental, economic and social criteria. In the scenarios, the focus has been set on the demand side of the network and how changes made on this side affect the performance of the whole energy system. Especially the future competitiveness of district heat versus decentralized heat production has been of key interest. In the study, the heating alternatives were restricted to district heating, GSHPs and STCs.

The scenarios were developed as a part of the EFEU research program. In the program, industrial partners and research organizations have worked together, aiming for developing methods and tools for the step-wise improvement of energy efficiency in energy systems. One of the project outcomes was the APROS simulation model of the Keski-Uusimaa area that has been used in this thesis to simulate the scenarios. Furthermore, the scenarios made in this thesis are based on the development of the building stock and solar deployment as defined in the EFEU research program. This thesis has additionally defined estimates for the deployment of GSHPs in the case area.

3.1 Case Area Description

The case area, Keski-Uusimaa, is the joint area of Tuusula and Järvenpää, two municipalities in the Uusimaa region, about 30 km north of Helsinki. The number of inhabitants in the area has been growing continuously over the last 35 years and in 2015, the total number of inhabitants was 78 600. The main part of the buildings in the area is residential buildings, but there are also a number of public and office buildings and some light industry. The heating alternatives currently used to cover the heat demand of the building stock are shown in Figure 9. The electricity used to run heat pumps is included in the electricity section. (Aluesarjat 2016a)

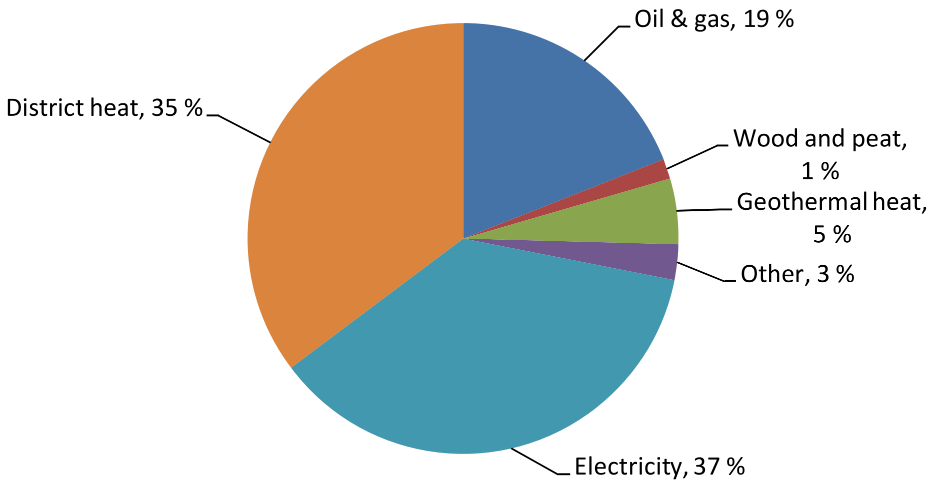

Figure 9. The heating sources used in the Keski-Uusimaa area in 2014. (Aluesarjat 2016a).

As can be seen from the figure, electricity and district heat are the most common heating alternatives used in the area. Oil and gas also hold a remarkable market share while the use of wood, peat and geothermal heat is small.

The district heating system was originally built as two separate ones, but in 2012, the systems were united through an eight km long connecting pipe (Fortum 2014). Today, the district heating network is 210 km long and 400 GWh of district heat is annually produced within the network. The heat is produced within different plants in the area; there is one CHP plant, several stationary heat plants and a couple of transferable heat plants. The CHP plant was built in 2013 and has a thermal output of 45 MW and a power output of 22 MW. The CHP plant uses biomass as the main fuel while the heat only plants are mainly using natural gas and fuel oil. The fuel mix used for district heat production in 2014 is shown in Figure 10. (Energiateollisuus Ry 2014)

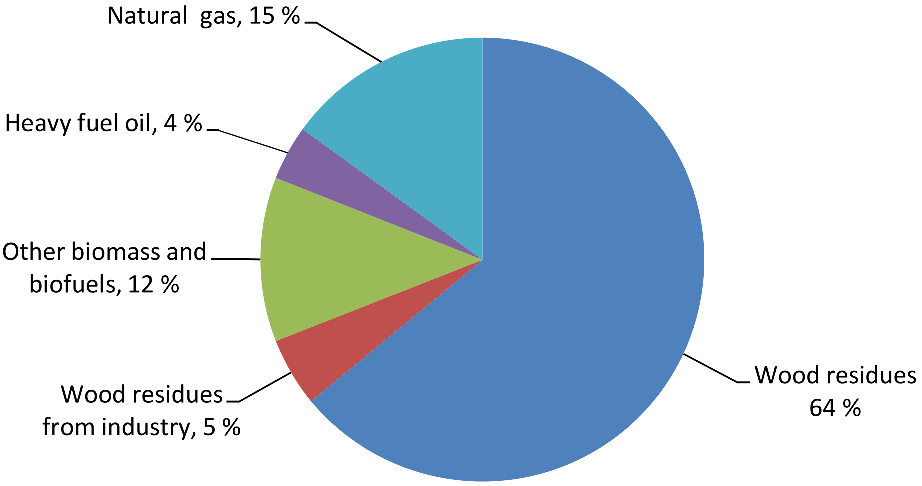

Figure 10. The fuel mix used for district heat production in the Keski-Uusimaa area in 2014 (Energiateollisuus Ry 2014).

In 2014, 81 % of the district heating fuel was based on biomass. Wood residues constituted the main part of this. In addition, natural gas and heavy fuel oil was also used.

3.2 Methods

This section describes the methods used in the case study for developing, simulating and comparing scenarios for the future energy system. The chosen methods are based on the findings of the literature review in Chapter 2.5. The method is visualized in Figure 11.

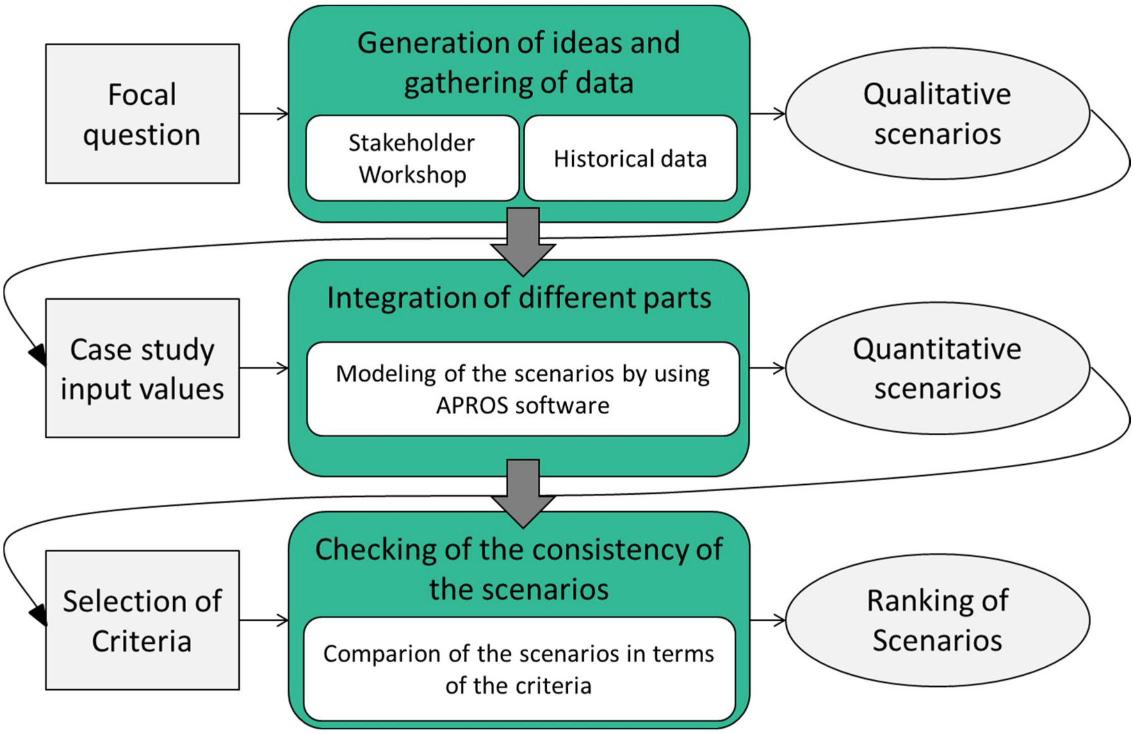

Figure 11. The method used to develop, simulate and compare the scenarios.

As the figure implies, the process of developing, simulating and comparing scenarios was divided into three steps. First, once the focal questions were selected, ideas for how to design the scenarios were generated. In order to support these, historical data about the case area was gathered. Based on these results, qualitative scenarios were generated, where scenarios were formulated as narrative storylines. In the second step of the process, the input values of the case study were chosen and the scenarios were simulated using the APROS software. As a result, quantitative scenarios were got, where the key simulation results were expressed in terms of time series. Finally, in the third step, the scenarios were compared against each other in terms of selected criteria. Based on the results of the comparison, the scenarios were ranked.

A comprehensive description of each step in the process is given below. First, the methods used for developing the scenarios are described. Then, the methods and models used for simulating the scenarios are specified. Finally, the criteria are defined and the methods used to compare the different scenarios are determined.

3.2.1 Scenario Development

In Chapter 2.5, it was established that scenarios can be used for many different reasons and with different purposes. Thus, when developing scenarios it is of main importance to decide what the purpose of the scenarios is. In this case study, an explorative approach was taken in the scenario development process. The focal question chosen was: "What different scenarios are there for future energy systems?". The scope of the examined scenarios was narrowed down to only include scenarios for the demand side of the network and the influence of choices made by the end users of energy.

In order to generate ideas about what the possible future district energy systems could be like, a stakeholder workshop was organized. The participants included energy providers, industry representatives and research organizations. First, the participants were divided into small groups and asked to discuss their own views on what the future energy systems could be like, what their own interests were and what kind of scenarios they found interesting. After that, each group presented the outcomes of their discussion to the other participants. Finally, the participants had the chance to comment on and further elaborate on the findings. The outcome of the workshop is presented in Appendix1.

In order to be able to form realistic scenarios for the future development of the thermal energy system in the case area, historical data on the development of the building stock and the heating technologies in the area was gathered and analyzed. Furthermore, forecasts and views on the future potential of GSHPs and STCs in Finland were also collected. This information was used to make an estimate for the adoption rate of GSHPs and STCs in the case area. The resulting estimates are presented in Appendix 2.

Based on the ideas and the data collected, qualitative scenarios for the future development of the thermal heating system in the case area were formed. The scenarios are presented in Section 3.4.

3.2.2 Simulations

In order to obtain quantitative scenarios, the qualitative scenarios were simulated. The simulations were made using the APROS software, allowing for the complex dynamic modelling of the heat production, distribution and consumption in the case area (Fortum & VTT 2016). A model of the Keski-Uusimaa area formed the foundation for the simulations. The model comprised the district heating network in the case area and the buildings connected to it. In addition to district heating, the model also provided the opportunity to use GSHPs and STCs to cover the heat demand of the buildings. The model of the case area used for the simulations is further described in Chapter 3.3.

The qualitative scenarios created in the former step of the scenario development process were used to tune the simulation model. Then, each one of the qualitative scenarios was simulated. The simulations were made for every fifth year of the scenario timeframe; i.e. for the following years: 2015, 2020, 2025, 2030 and 2035. It was assumed that the yearly results were the same for the following five years.

The simulation output was got as a set of quantitative scenarios, where selected model variables were collected as time series to describe the performance of the energy system in the case area. The model variables collected included e.g. the heat demand of the buildings in the area, the technologies used to cover this heat demand and the amount of district heat produced in the area.

3.2.3 Scenario Comparison

In order to be able to compare the scenarios, the energy system boundaries need to be clearly defined. The chosen boundaries of the case study are visualized in Figure 12. Only the energy flows used to cover the heating needs of the building stock in the case area were included in the analysis.

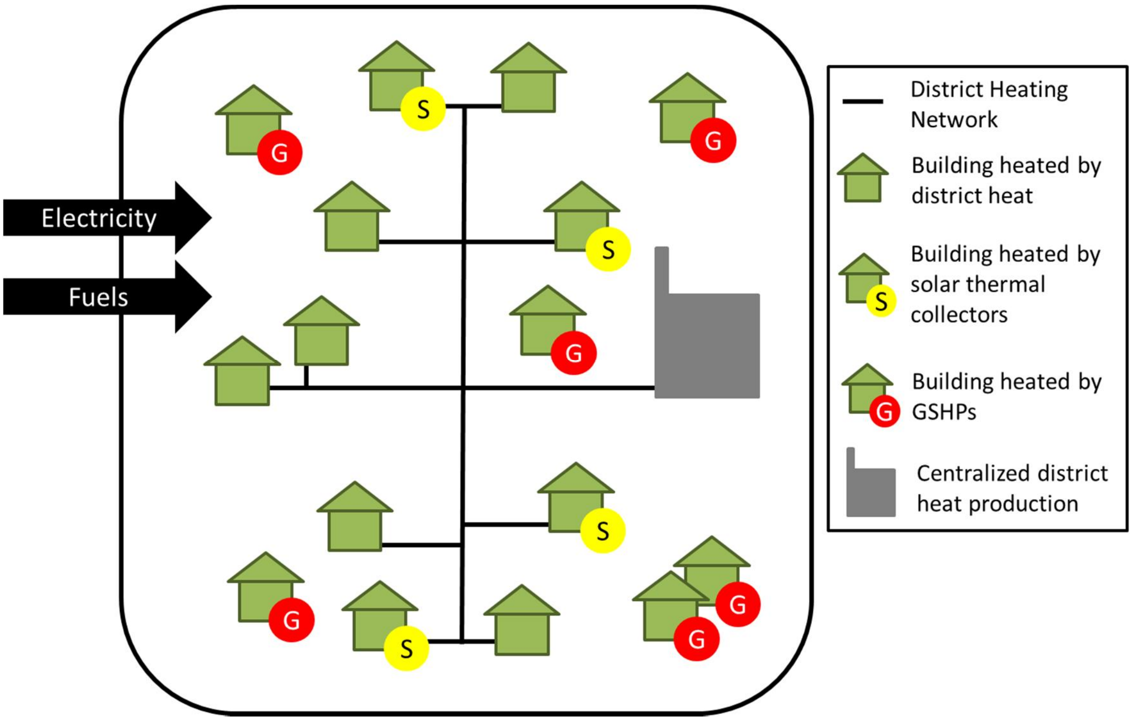

Figure 12. The energy systems boundaries of the case area.

As can be seen from the figure, electricity and fuels were imported to the area. The electricity was used to run the GSHPs and the fuel was used for district heat production. There were no energy exports from the system. In the study, it was assumed that all district heat was fed to the district heating network at the location of the CHP plant and that the fuel mix used for district heating production corresponded to the real fuel mix used in the area in 2014. Furthermore, the origin of the imported electricity was assumed to correspond to the Finnish average in 2014. Both the electricity and fuel mix were assumed to remain constant throughout the scenarios.

In order to compare the scenarios against each other, a set of criteria was used. In this study, the following selection was chosen: energy efficiency, CO_2e emissions, particulate emissions, investment costs, energy costs and employment effects. The selection was made based on the literature review and the workshop result. The methods used for calculating each of the criteria are described below.

The energy efficiency was calculated as the final, non-renewable, energy consumption of the building stock per unit of floor area. Heat produced by STCs was regarded as 100 % renewable energy. In the case of GSHPs, the share of non-renewable heat was determined by multiplying the amount of electricity used to run the heat pumps, with the share of the electricity that was produced by non-renewable fuels. In the case of district heating, the share of non-renewable district heat consumption was assumed to be equal to the share of non-renewable fuels used to produce the district heat.

The CO_2e emissions and the particulate emissions were calculated as the total amount of emissions originating from the final heat consumption of the building stock per unit of floor area. In the calculations, the emissions originating from the electricity used to run the heat pumps were also taken into account. The CO_2 emission factors and the particulate emission factors used in the calculations are shown in Table 3. The emission factors were formed using the GEMIS database, which is a public domain, global emissions model and database, provided by IINAS (IINAS 2016). The district heat emissions corresponded to the local conditions in the case area, while the electricity emissions corresponded to the average for the Finnish electricity network. Only the direct emissions that originated from the energy production were taken into account in the calculations.

Table 3. The CO_2e and particulate emission factors for the different heating alternatives. (IINAS 2016)

Energy form	CO_2e emissions [$kgCO_2$/MWh]	Particulate emissions [kg/MWh]
District heat	49	0.024
Electricity	345	0.05

The total sum of the investments made by the end users of energy in the area over the scenario timeframe was calculated based on the investment costs for the different heating technologies listed in Table 4. These costs included the purchase of equipment, the costs of the technical installations, the connection fees and the taxes. In the calculations, it was assumed that the average size of a district heat connection or a heat pump was 10 kW. As GSHPs and STCs are quite new heating technologies and the technology used is still being developed, the price of these is expected to decrease in the future. This has been taken into account in the calculations by assuming that the investment costs for GSHPs and STCs are decreasing by 1 % annually over the scenario timeframe. The district heating investment costs were assumed to remain constant throughout the scenario.

Table 4.The investment costs of the different heating technology alternatives.

Technology	Investment cost	Unit	Source
District Heat	580	€/kW	(Energiateollisuus Ry 2015c)
GSHP	1 520	€/kW	(Satosalmi 2012)
STC	750	€/m^2 of installed STCs	(FinSolar 2014)

The energy costs paid by the end users of energy were calculated using the cost estimates listed in Table 5. The costs include the costs of the purchased electricity and district heat and the annual operation and maintenance costs of the decentralized heat production technologies that were installed into the buildings. Taxes, demand charge and the distribution costs of electricity were also included in the prices. In the calculations, the costs for electricity and district heating were assumed to increase by 1 % annually over the scenario timeframe.

Table 5. The energy costs of the different heating technology alternatives.

Technology	Energy cost	Unit	Source
Electricity	154	€/MWh	(Eurostat 2016)
District Heat	92.11	€/MWh	(Energiateollisuus Ry 2015c)
GSHP	11	€/kW/year	(Satosalmi 2012)
STC	2.5	€/m^2/year	(FinSolar 2014)

The employment effects of the scenarios, or the numbers of jobs related to the energy supply, were calculated as the sum of the jobs in the operation, maintenance and heat supply of district heat and the jobs in construction and manufacturing of GSHPs and STCs. In the calculations, it was assumed that the centralized heat production units used to produce district heat were already available in the beginning of the scenarios and therefore, no jobs related to the construction and installation of these were taken into account. The employment factors used in the calculations are listed in Table 6. The factors include only direct employment effects.

Table 6. The employment factors for the different heating technology alternatives. (Rutovitz & Harris 2012)

Energy Technology	Construction & Installation [Job years/MW]	Manufacturing [Job years/MW]	Operation & maintenance [Jobs/MW]
District heat (average)	-	-	1.15
GSHP	3.0 jobs/MW (construction and manufacturing)		
STC	7.4 jobs/ MW (construction and manufacturing)		

All criteria were measured by using different units. In order to be able to easily compare the outcomes, the results were normalized. Depending on the nature of the criterion, two different equations were used for the normalization. For criterion where high values were considered beneficial, Equation (1) was used. This was for example the case for employment effects. For criterion where low values were considered beneficial, Equation (2) was used. This was e.g. the case for particulate emissions. (Ishizaka & Nemery 2013)

$$r_i = \frac{x_i - \min(x_i)}{\max(x_i) - \min(x_i)} \qquad (1)$$

$$r_i = \frac{\max(x_i) - x_i}{\max(x_i) - \min(x_i)} \qquad (2)$$

r_i is the value of the normalized criteria , x_i is the criteria outcome, $min(x_i)$ is the lowest possible criteria outcome and $max(x_i)$ is the highest possible criteria outcome.

The criteria were then weighted using the equal weight method, thus giving all the criteria the same importance. The criteria weight was defined as:

$$\boldsymbol{w_i = \frac{1}{n}, i = 1, \dots, n} \qquad (3)$$

w_i is the weight of one criterion and n is the total number of criteria.

Finally, the normalized criteria were summed up using the weighted sum method:

$$S_i = \sum_{i-1}^{n} w_i r_i, i = 1,2, \dots, n \qquad (4)$$

S_i is the weighted sum of the criteria.

The criteria were then ranked based on the outcome of the weighted sum. The scenario that got the highest weighted sum was ranked as the most beneficial one.

3.3 Simulation Model

The APROS model of the case area that was used for simulating the scenarios was developed as a part of the EFEU research program. The purpose of the model was to provide a means for investigating how the heat demand in the area is affected by changes made on the demand side of the network and how these changes affects the physical behavior of the system. In the following sections, the characteristics of the model are described. First, the main model components are presented. Then, the operation principle of the building blocks is defined and finally, the inputs and outputs of the model are specified.

3.3.1 Model Components

In the model, it was assumed that heat was used to cover the space heat and DHW demand of the building blocks. In order to cover the demand, district heating was principally used. However, there was also the possibility to cover the heat demand of the building blocks by utilizing GSHPs and STCs. A schematic picture of a part of the APROS model is shown in Figure 13.

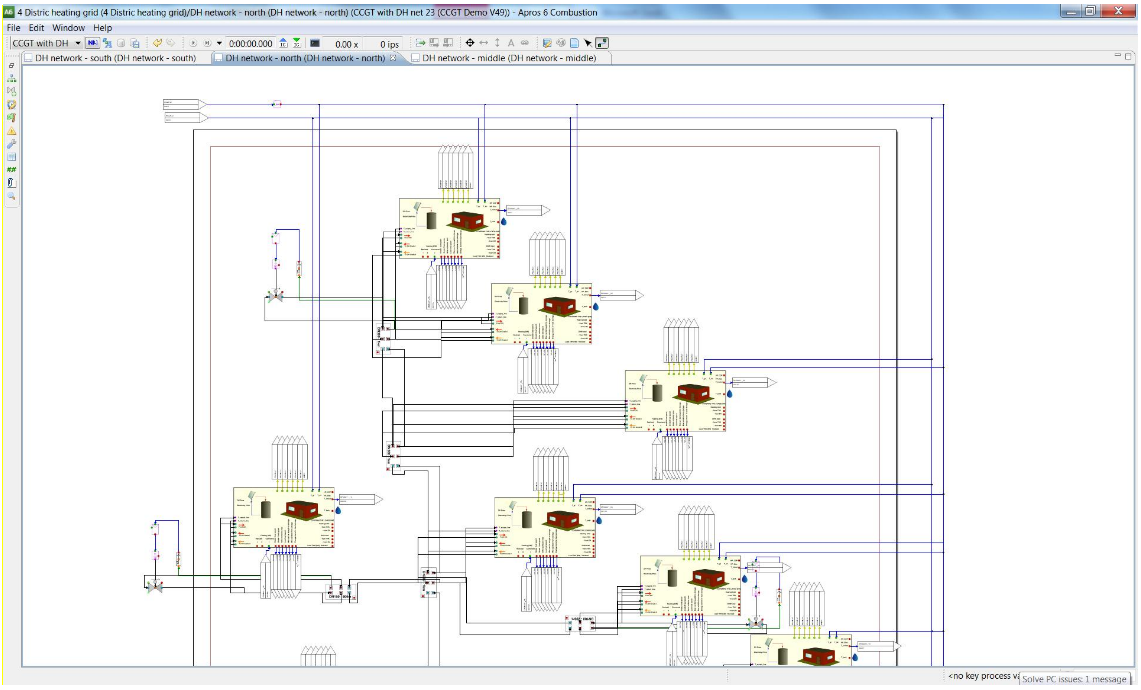

Figure 13. The northern part of the district heating network in APROS.

A district heating network and 25 building blocks constituted the main components of the model. The district heating network was a simplified, downscaled, version of the real district heating network in the case area. However, the blocks have the same heat consumption profiles as the buildings in the real case area. The network consisted of two lines; one supply line and one return line. The building blocks were connected to the network through heat exchangers. The details of the heat production processes were not modelled. It was assumed that all the heat was fed to the network from the same location and that the network is always able to cover the heat demand of the customers.

In order to model the heat demand in the area, a set of 25 building blocks were used. Each building block consisted of a specific amount of buildings of a certain energy consumer type. In the model, a great freedom was given to the APROS user to modify building block parameters that affected the heat demand of the building blocks. The following parameters of the blocks were adjustable: the number of buildings in the block, their energy efficiency level, the consumer type and the heating technology used.

Each building block consisted of a specific amount of buildings of one consumer type. The number of buildings in the building block was chosen so that the peak consumption of the blocks was either 1, 2 or 5 MW. The consumer types available in the model included residential, public and office buildings. The energy efficiency level of the blocks was chosen by adjusting the U-values for the floor, roof, wall and windows. Furthermore, the air leakage rate, heat recovery efficiency and the window transmission coefficient were also adjustable according to the preferences of the user. The building blocks had three alternative heating configurations: the utilization of district heating, GSHPs or STCs. The STCs were used in combination with a hot water storage tank.

3.3.2 The Operation Principle of the Buildings Blocks

In the model, the heat demand of the buildings was calculated taking into account the ambient temperature, the ground temperature, solar irradiation and internal gains. These influence the heat flows through the envelope, the ventilation, the heat recovery and the air leakage. In order to keep the indoor temperature of the buildings as close as 21 ºC as possible, a PI-controller was used. Based on the temperature, heat was requested. If the indoor temperature was lower than 21 ºC, the heat request was raised for the next simulation step. If the temperature was higher than 21 ºC, the heat request was decreased.

The heat demand of the buildings was covered by using either district heating, GSHPs or STCs. In order to determine which demands should be covered by which heat source, a controller was used. The controller collected heat requests from all the buildings in the same building block. Then, it decided how much energy that should be produced with which technology. The different technologies then tried to supply the requested heat to the buildings.

In the case where district heat is used to cover the heat demand of all buildings in a building block, the operation principle of the controller is easy. Then, the controller simply requests the required amount of energy from the district heating network. However, in the case where heat pumps or solar energy is used to cover the heat demand, the operation principle is somewhat more complicated. In the model, heat pumps could be used to cover the heat demand in either a part of the buildings in a building block or all the buildings in the blocks. If only a part of the buildings in the building block were using heat pumps, the heat demand of the rest of the buildings was covered by district heating. The operation principle of the controller in building blocks where heat pumps were used is visualized in Figure 14.

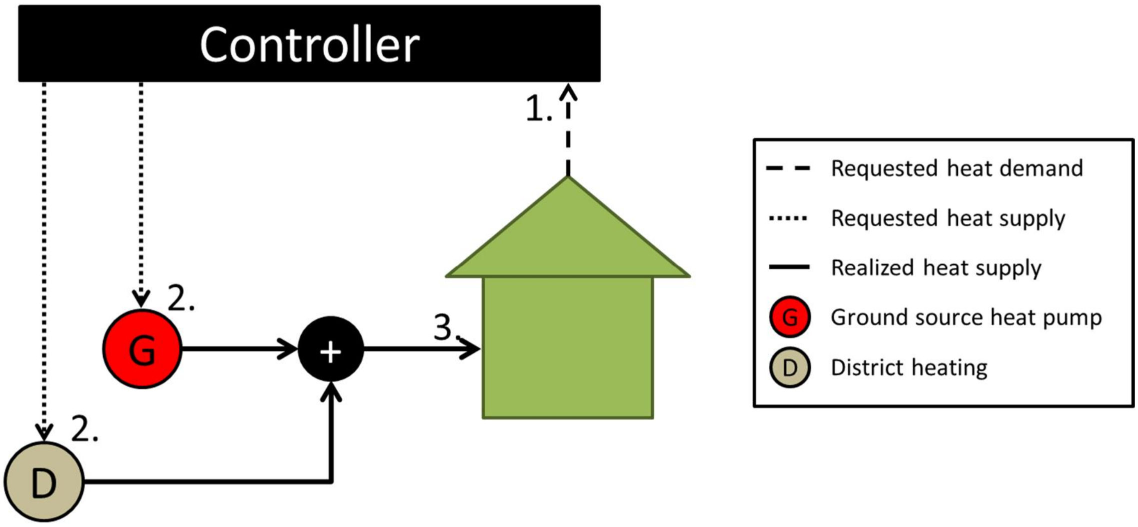

Figure 14. The operation principle of the controller in building blocks where GSHPs were used.

The operation principle of the controller in building where GSHPs were used was the following:

1. The controller collected the heat demand requests from the buildings.
2. Based on these requests and information about the share of the buildings using heat pumps in the building block, it decided how much heat to request from the heat pumps and how much to request from the district heating network.
3. The heat pumps and the district heating network then supplied the requested heat to the buildings.

Two separate heat pumps were used to produce the requested heat; one produced space heat and the other one produced DHW. In order to determine the ratio between the amounts of electricity needed to produce a certain amount of heat, the coefficient of performance (COP) is used. In the model, the COP of the heat pumps was calculated based on the source and sink temperatures using the method of fixed exergetic efficiency. The source temperature for both heat pumps was the ground temperature, which was assumed to be approximately 6 °C, the whole year around. The sink temperature of the heat pump used for space heating varied between 25 °C and 60 °C, depending on the ambient temperature. The sink temperature of the heat pump producing DHW was 58 °C.

In the case solar energy was chosen as heat source of the building block, the controller tried to optimize the use of this energy. In order to do this, a hot water energy storage tank was always used in combination with solar collectors. Whenever heat was produced by the collectors, this was used to increase the temperature of the tank. If the solar heat production was not enough to cover the heat demand of the building block, district heating was used to cover the rest of the demand. The operation principle of the controller in building blocks where STCs are used is visualized in Figure 15.

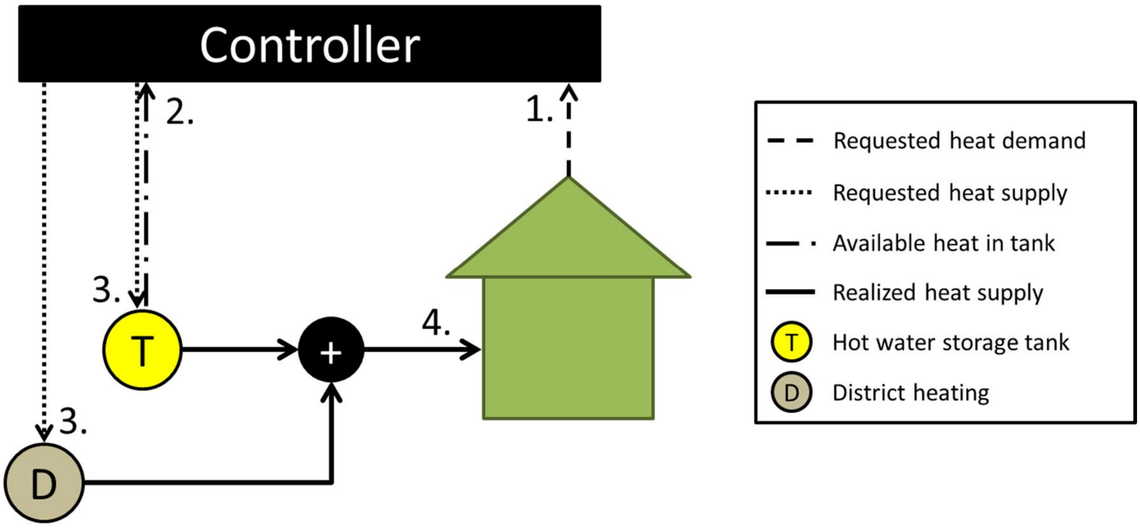

Figure 15. The operation principle the controller in building blocks where STCs were used.

The operation principle of the controller in building where STCs were used was the following:

1. The controller collected heat demand requests from the buildings.
2. The controller collected information about the energy contents of the tank.
3. If the energy contents of the tank were higher or of equal to the heat request, the controller requested the tank to supply the required heat to the buildings. If the energy contents of the tank were smaller than the request, the controller requested the district heating network to supply the rest of the heat.
4. The tank and the district heating network then supplied the requested heat to the buildings.

3.3.3 Input and Output Data

The model received input data in form of text files with time series of both the ambient temperature and the solar irradiation. The same time series were used for all the simulations. The data was got from Ilmatieteen laitos (2016) and consisted of a collection of weather data from different years that corresponded to the typical weather in the South of Finland for one year. The ambient temperature is shown in Figure 16.

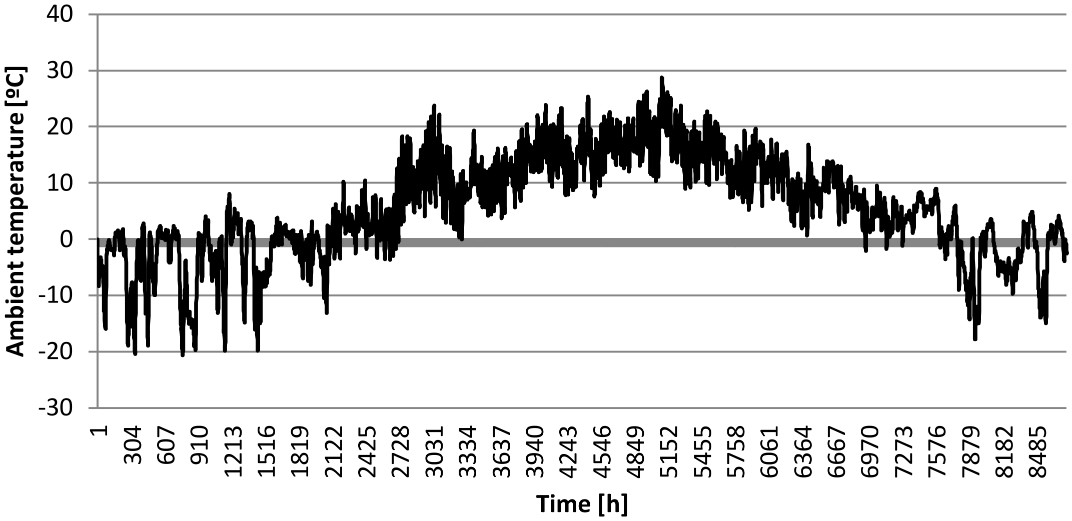

Figure 16. The ambient temperature during a typical year in the South of Finland (Ilmatieteen laitos 2016).

Furthermore, estimates for the internal gains from people, electricity usage and DHW usage in the buildings was also given to the model. The internal gains from people, electricity usage and DHW were used in the buildings in form of repeated daily profiles. In the profiles, the difference between weekdays and weekends was taken into account. Furthermore, the reduced lighting needs due to bright seasons was taken into account by using annual correction for the electricity profiles. The reduced DHW usage in offices and public building during summer holidays was also taken into account by using annual correction factors for the DHW usage profiles.

The simulation results were exported from the model in form of text files. The model parameters from where history data was collected are listed in Table 7.

Table 7. Model values from where simulation data is collected.

Model component	Measured value	Unit
District Heating Network	District heat supplied to the network	kWh
	DH supply line temperature at plant	°C
	DH return line temperature at plant	°C
Building blocks	Indoor temperature	°C
	Space heating temperature	°C
	Heat demand; space heating and DHW	kWh
	DH supply; space heating and DHW	kWh
	GSHP supply; space heating and DHW	kWh
	STC/tank supply; space heating and DHW	kWh
	Electricity consumption of GSHP	kWh
	COP of GSHP	-
	Solar collector output	kWh

The values that are collected from the district heating network included the amount of district heat supplied to the network and the temperature of the district heating supply and return lines at the location where district heat is fed to the network. In the case of the building blocks, the same values have been collected from each one of them. These values included the indoor temperatures, the heat demand of space heating and DHW and the amount of heat supplied by each one of the available technologies in order to cover the heat demand.

3.4 Scenario Descriptions

This thesis has developed three scenarios for the adoption of decentralized heating technologies in the case area: a conservative, an extensive and an extreme scenario. The scenarios are based on the development of the building stock and deployment of STCs in the case area as defined in the EFEU research program. This thesis has additionally defined estimates for the deployment of GSHPs. In the following, the scenarios are presented. First, the common scenarios assumptions are presented, and then each one of the scenarios is described.

3.4.1 The Building Stock Development

All of the scenarios rely on a common assumption for the development of the building stock in the case area. This assumption formed the foundation of the scenarios. The future development of the building stock in the case area is estimated by using historical data from the Järvenpää area (Aluesarjat 2016b) and the historical development of the

Finnish building stock (Tuominen, 2015). As a result, the following annual changes to the building stock are used in the scenarios: new buildings 2.0 %, demolished buildings 0.2 % and renovated buildings 3.2 % of the buildings stock.

Furthermore, the division between different building types is also the same in all scenarios; 45.9 % residential buildings, 26.6 % public buildings and 27.5 % offices. The division was based on real data about the buildings connected to the DH network in the case area. The estimated development of the building stock used in the scenarios is shown in Figure A2-2..

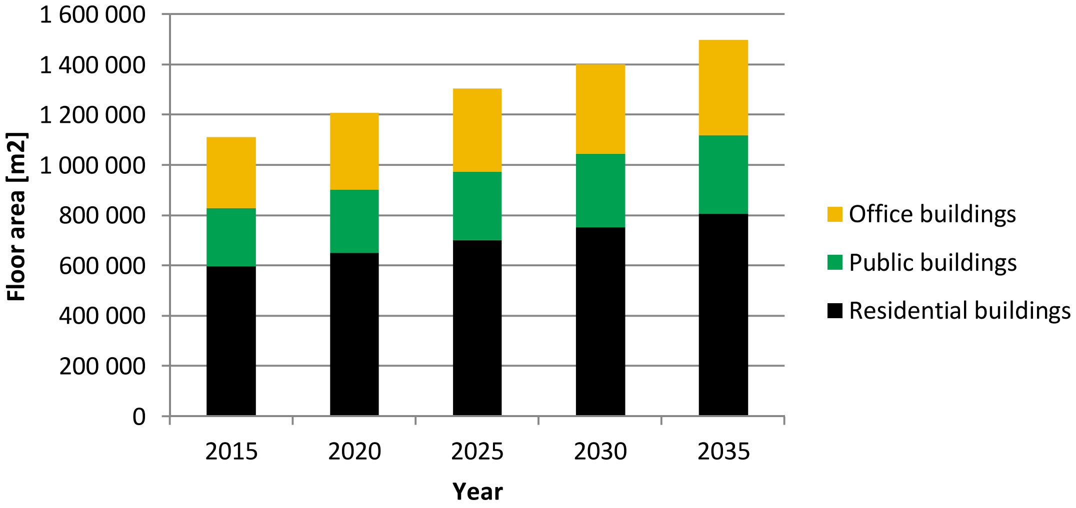

Figure 17. The estimated development of the building stock in the Keski-Uusimaa area.

All the buildings in the initial phase of the scenarios were assumed to follow the building standards from 1985. Renovated buildings were assumed to reach building standards from the year 2007. New buildings were assumed to be developed according to the pattern shown in Table 8. The building standards for the different years are listed in Table 9.

Table 8. The energy efficiency of new buildings.

Building types	2015	2020	2025	2030	2035
Residential	(1985)	2012	nZEB	nZEB	nZEB*
Office	(1985)	2012	nZEB	nZEB	nZEB*
Public	(1985)	nZEB	nZEB*	nZEB*	nZEB*

The current building regulations came to power in 2012. However, according to the EU Directive 2010/31, new public buildings need to follow nZEB building standards by the end of 2018 and all the other new buildings by the end of 2020. In the scenarios, it is assumed that this directive will be followed.

Table 9. The efficiency levels for old, new and renovated buildings. (Aalto 2009; Kouhia et al. 2010)

Efficiency level	Unit	1985	2007	2012	nZEB	nZEB*
U-value: floor	W/m^{2}K	0.36	0.24	0.16	0.16	0.16
U-value: roof	W/m^{2}K	0.22	0.15	0.09	0.09	0.09
U-value: wall	W/m^{2}K	0.28	0.24	0.17	0.17	0.17
U-value: window	W/m^{2}K	2.10	1.40	1.00	1.00	1.00
Air leakage rate	1/h	0.24	0.16	0.08	0.08	0.024
Heat rec. eff.	–	0.00	0.30	0.45	0. 70	0.80
Window transmission factor	–	0.75	0.75	0.70	0.70	0.70

Between 1985 and 2012, the buildings regulations became much stricter. However, the limits for how much the building envelope still can be improved with the current materials used are soon to be reached. Therefore, the building envelopes of nZEB buildings were assumed to be equal to the levels in 2012. The air leakage rate and the heat recovery efficiency on the other hand are assumed to be slightly improved within the scenario timeframe. From 2025 and onwards, an air leakage value of 0.024 and a heat recovery efficiency of 0.8 were used for public buildings. In the rest of the buildings, these values were used from 2035 and onwards.

3.4.2 Conservative Scenario

In the conservative scenario, no large changes to the current situation in the case area are realized. The importance of the district heating network in the case area remains high and the interest in decentralized energy sources is low. Thus, district heating is used in almost all the buildings to cover the heat demand. However, in some of the new residential buildings, GSHPs are installed. The assumed development of GSHP installations in the area are shown in Figure 18.

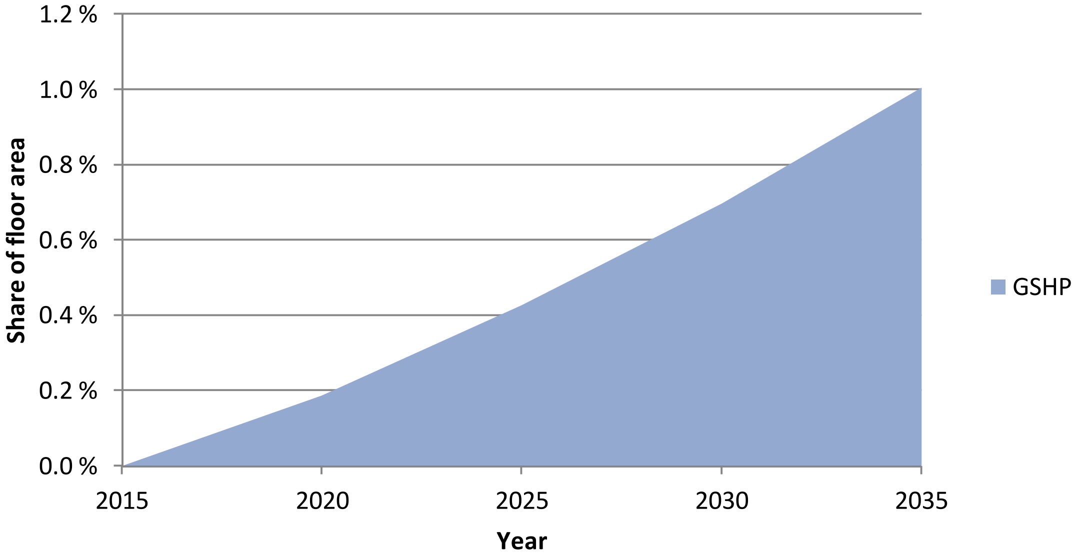

Figure 18. The share of floor area of buildings using GSHPs in the area in the conservative scenario.

As can be seen from the figure, 1 % of the built floor area is heated by GSHPs by 2035. This corresponds to the situation where 10 % of the new residential buildings in the area choose GSHPs instead of district heating. The development of GSHP installations in the area is shown in Table 10.

Table 10. The development of GSHP installations in the area. The ratio is calculated as the ratio of the built floor area heated by GSHPs to the total built floor area.

	2015	2020	2025	2030	2035
GSHP, new residential buildings	0.0 %	4.4 %	6.4 %	8.2 %	10.1 %
GSHP, all buildings	0.0 %	0.2 %	0.4 %	0.7 %	1.0 %

3.4.3 Extensive Scenario

In the extensive scenario, the interest in local, decentralized energy production units is increasing. GSHPs are installed into all new building types; residential, public and offices. However, in public buildings and offices, the installation ratios are half the one in residential buildings. STCs are also installed into new, residential buildings in the area. Even though the interest in decentralized energy sources is considerable higher than in the conservative scenario, district heating still holds a significant position. The development of GSHP and STCs installations is shown in Figure 19.

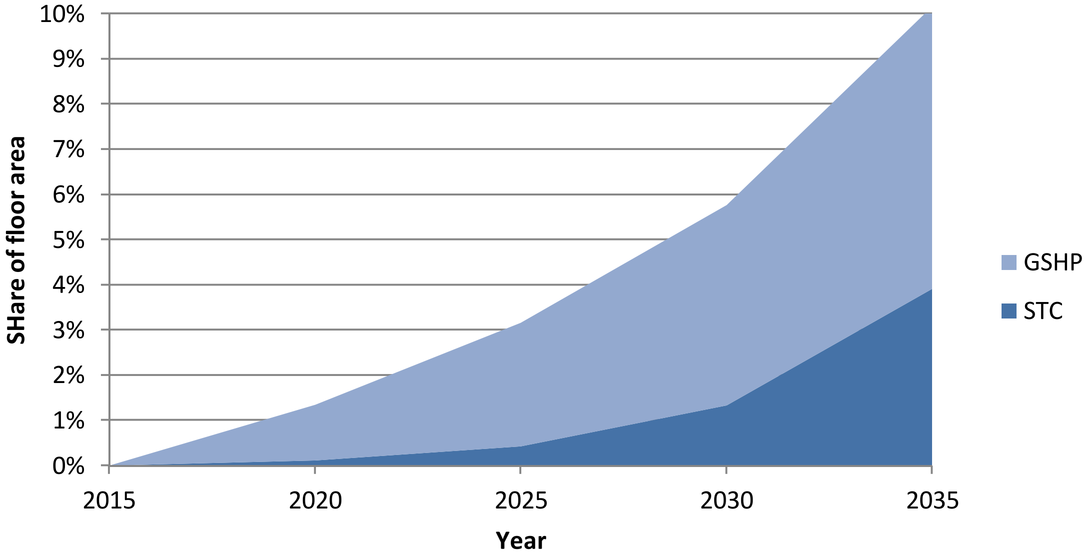

Figure 19. The share of floor area of buildings using GSHPs and STCs in the area in the extensive scenario.

In this scenario, 10 % of the built floor area is heated either by GSHPs or STCs by 2035; 6 % of the floor area is heated by GSHPs and 4 % of the floor area is heated by STCs. The annual growth rate of STCs is 25 %. The development of GSHP and STC installations in the area are shown in Table 11.

Table 11. The development of GSHP and STC installations in the area. The ratio is calculated as the ratio of the built floor area heated by the respective heating technologies to the total built floor area.

	2015	2020	2025	2030	2035
GSHP, new buildings	0.0 %	15.4 %	21.5 %	27.4 %	32.6 %
GSHP, all buildings	0.0 %	1.2 %	2.7 %	4.4 %	6.3 %
STC, new and renovated residential buildings	0.0 %	0.8 %	2.7 %	11.9 %	26.0 %
STC, all buildings	0.0 %	0.1 %	0.4 %	1.3 %	3.9 %

3.4.4 Extreme Scenario

In the extreme scenario, the energy system development is driven by a high interest in decentralized and local energy production technologies. GSHPs and STCs are installed into all building types; residential, public and offices. The GSHP installations are made both in new and renovated buildings, while solar collectors are also installed into old buildings. The development of GSHP and STC installations in the area are shown in Figure 20.

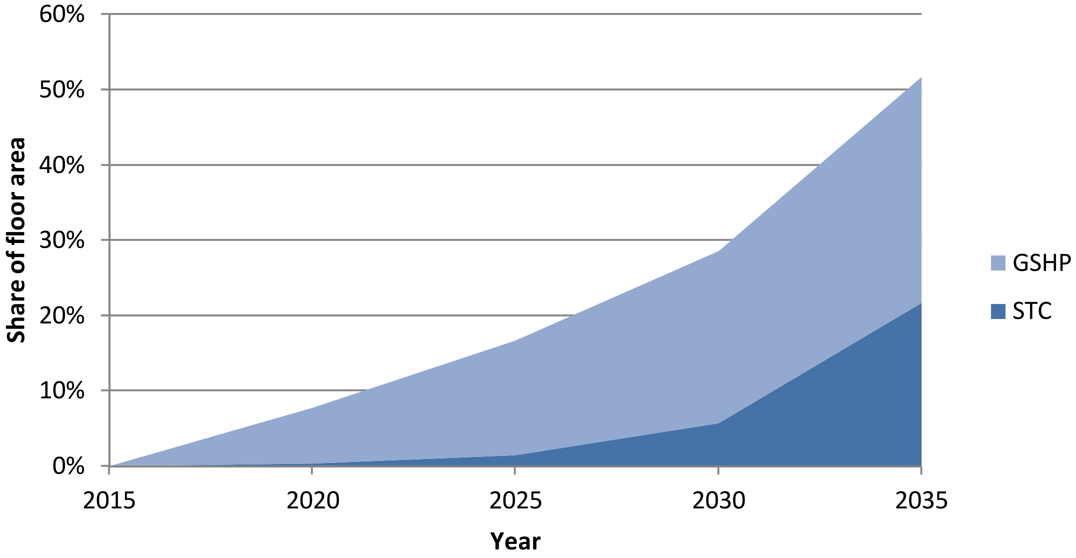

Figure 20. The share of floor area of buildings using GSHPs and STCs in the area in the extreme scenario.

In this scenario, almost half of built floor area is heated by using GSHPs or STCs by year 2035. The share of the floor area heated by using GSHPs is 30 % and the corresponding share of STCs is 22 %. The an annual growth rate of the STCs is 32 %. The development of GSHP and STC installations in the area are shown in Table 12.

Table 12. The development of GSHP and STC installations in the area. The ratio is calculated as the ratio of the built floor area heated by the respective heating technologies to the total built floor area.

	2015	2020	2025	2030	2035
GSHP, new and renovated buildings	0.0 %	31.2 %	37.7 %	44.4 %	49.5 %
GSHP, all buildings	0.0 %	7.4 %	15.2 %	22.9 %	30.0 %
STC, all buildings	0.0 %	0.3 %	1.5 %	5.7 %	21.7 %

3.5 Scenario Outcomes and Evaluation

In this chapter, the outcome of the scenarios is presented. First, the simulation results are presented. These include the annual heat demand of the three building types, the development of the total heat demand in the case area within the scenario timeframe and the technologies used to provide the necessary heat. Then, the energy efficiency, CO_2e emissions, particulate emissions, investment costs, energy costs and employment effects of the scenarios are presented. Finally, based on the criteria outcome, the scenarios are ranked using the method described in Section 3.2.3.

3.5.1 Simulation Results

Heat is used to cover the space heat and DHW demand of the buildings in the case area. Since the development of the building stock is the same for all the scenarios, the heat demand will also be developed in the same way. The annual heat demand of the three building block types; residential, public and office (with the size 1 MW) in 2015 is presented in Figure 21. The annual ambient temperature is also shown in the figure.

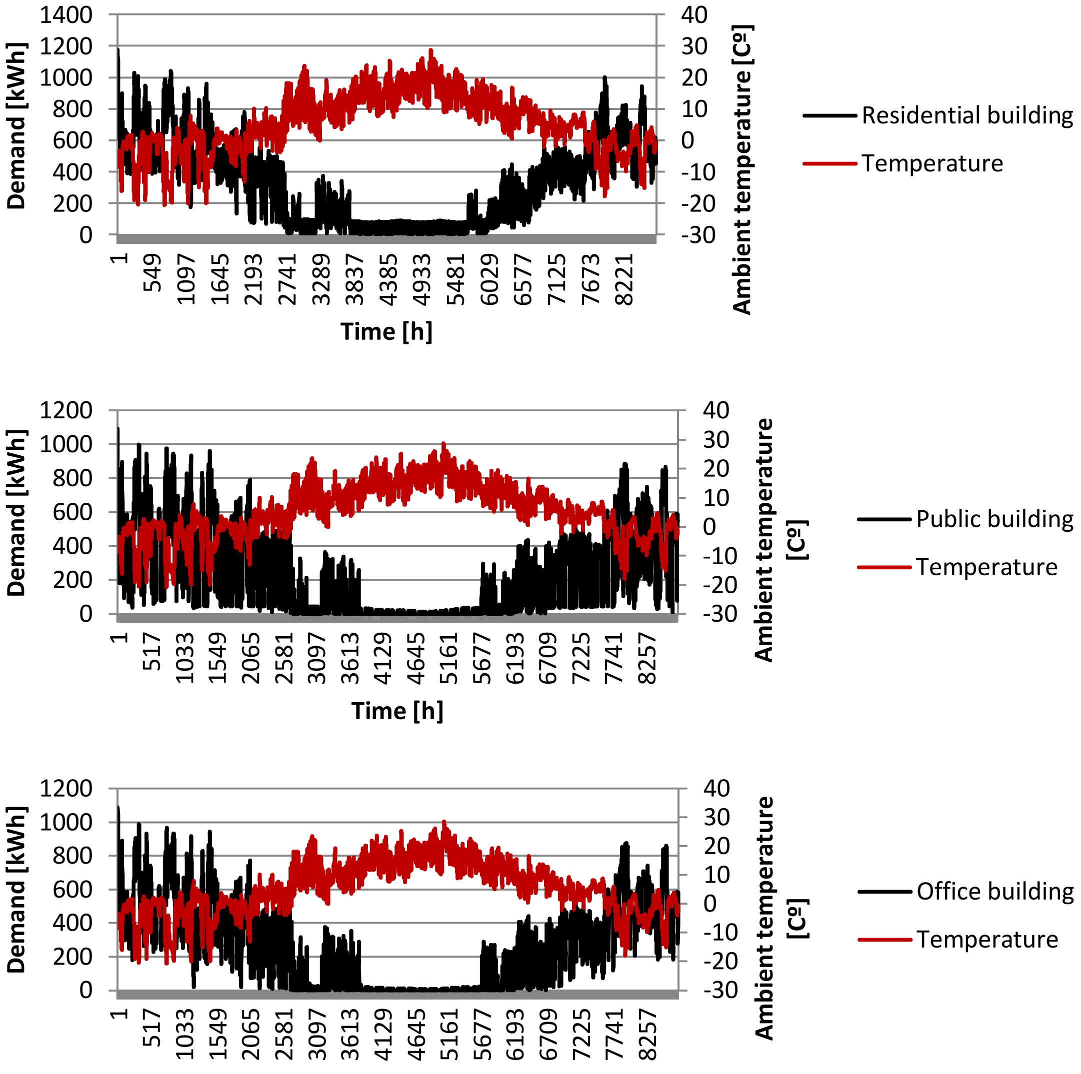

Figure 21. The annual heat demand of the different building types.

As can be seen from the figure, the heat demand of all building types correlates with the ambient temperature. During the coldest winter days, the heat demand is at its highest and when the ambient temperature increases, the heat demand decreases. During the summer, there is no space heating demand at all. Then, heat is only needed to cover the DHW demand. The DHW profile is approximately the same throughout the year.

As the building stock in the area is changed, the total heat demand in the area is also changed. The development of the total annual heat demand in the area is presented in Figure 22.

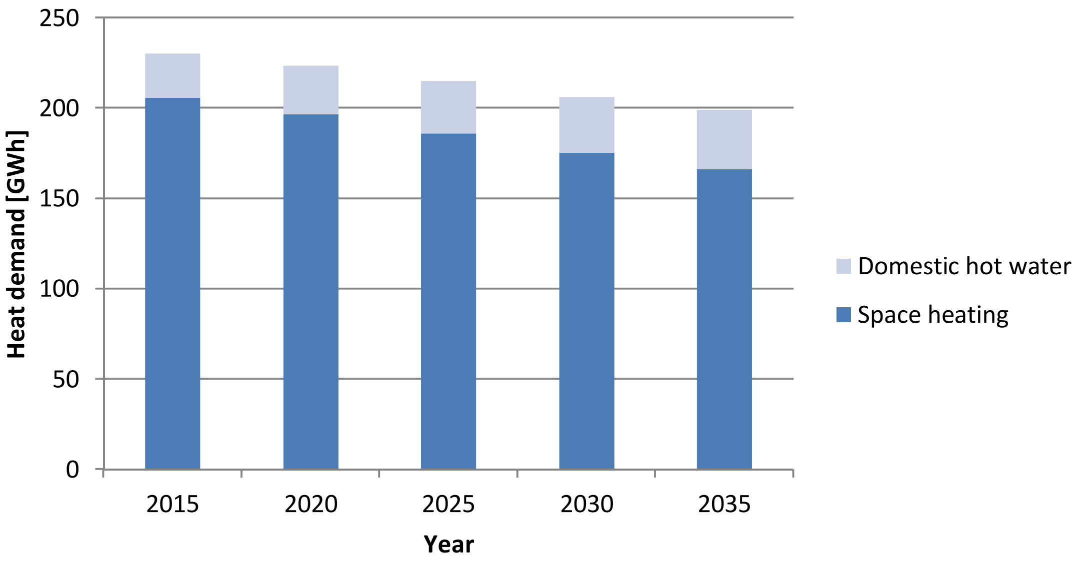

Figure 22. The development of the annual heat demand in the area over the scenario timeframe.

The simulation results indicate that the total heat demand in the area will decrease over the scenario timeframe even though the built floor area increases. In 2015, the total heat demand in the area is 230 GWh but by 2035, the heat demand is reduced by 13 %, reaching 200 GWh. The decrease in heat demand in the area is due to the energy efficiency improvements made in renovated buildings and the high efficiency level of new buildings. When the efficiency level is improved, the space heating demand is decreased. The DHW demand on the other hand is not affected by the energy efficiency improvements. In 2015, the DHW in the area is 24.6 GWh. However, by 2035, the DHW is increased by 35 % reaching 33.1 GWh. Thus, the DHW demand increases in proportion to the increase in built floor area.

The development of the specific heat demand of the buildings in the area, i.e. the final heat consumption per built floor area, is presented in Table 13.

Table 13. Demand side energy efficiency improvements

	2015	2020	2025	2030	2035
kWh/m^2	207.0	184.8	164.6	147.2	132.9
%	100.0%	89.3 %	79.6 %	71.1 %	64.2 %

In 2015, the specific heat demand in the area is 207 kWh/m^2 but by 2035, the corresponding number is 133 kWh/m^2. Thus, the energy efficiency improvements made to the building stock result in an on average 36 % improvement of the demand side energy efficiency.

In the scenarios, there are three different heating technologies used to cover the heat demand of the buildings: GSHPs, STCs and district heat. The shares of the heat consumption provided by the different technologies in the scenarios are visualized in Figure 23.

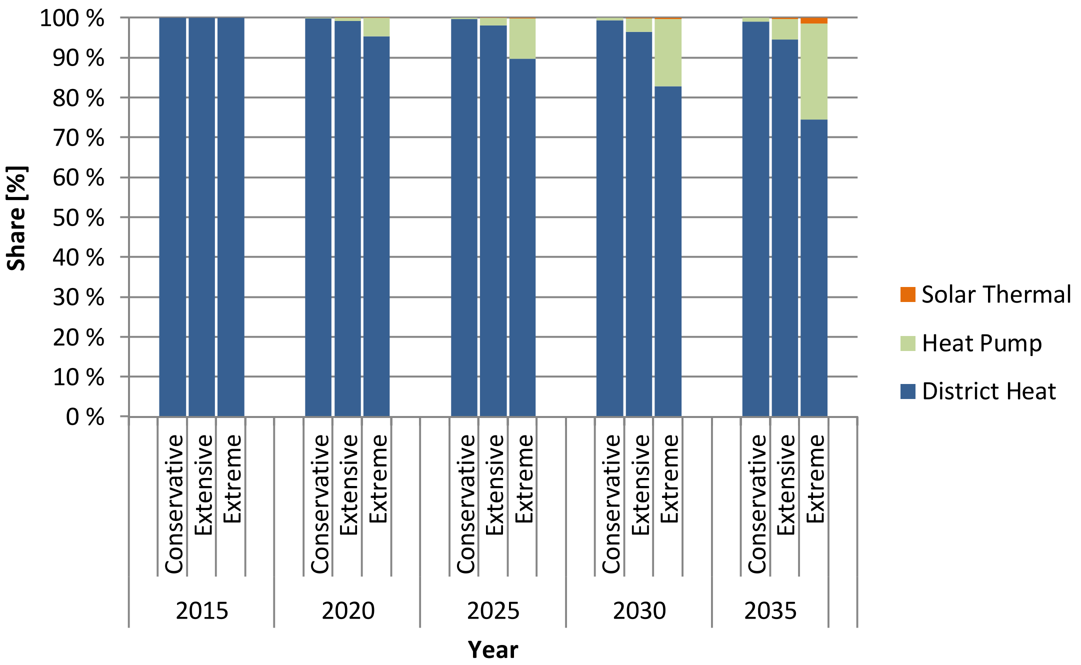

Figure 23. The development of the annual shares of heat used to provide the necessary heat to the area.

As can be seen from the figure, the share of the heat supplied by decentralized heat production technologies is less than 1 % in the conservative scenario, roughly 5 % in the extensive scenario and about 25 % in the extreme scenario.

In the scenarios, the heat pumps are only installed into new and renovated buildings, with lower heat demand than the old buildings. Therefore, the share of the heat consumption covered by the heat pumps is slightly smaller than the share of floor area of buildings using GSHPs. The annual amount of electricity used to run all heat pumps in the case area is shown in Figure 24.

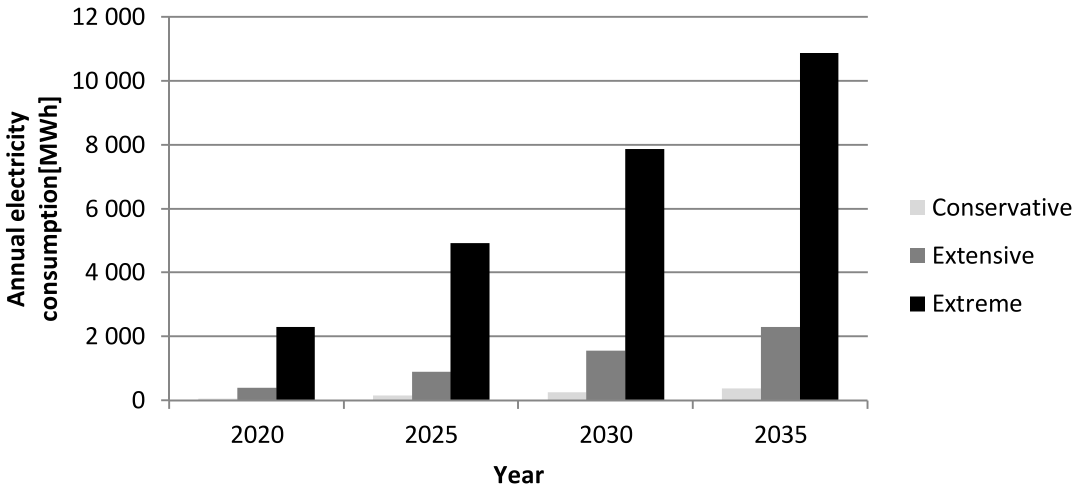

Figure 24. The total annual amounts of electricity used to run the heat pumps in the case area.

In the conservative scenario, the total amount of electricity used in 2035 is 385 MWh. In the extensive and extreme scenario, the corresponding numbers are 2 308 MWh and

10 883 MWh. Thus, as the amount of heat pumps increases, the electricity consumption also increases.

The share of the heat demand covered by solar heat remains very low even though there is a remarkable increase in solar thermal collector installations. The total hourly solar heat production in the case area in the year 2035 is visualized in Figure 25. In the conservative scenario, no STCs are installed.

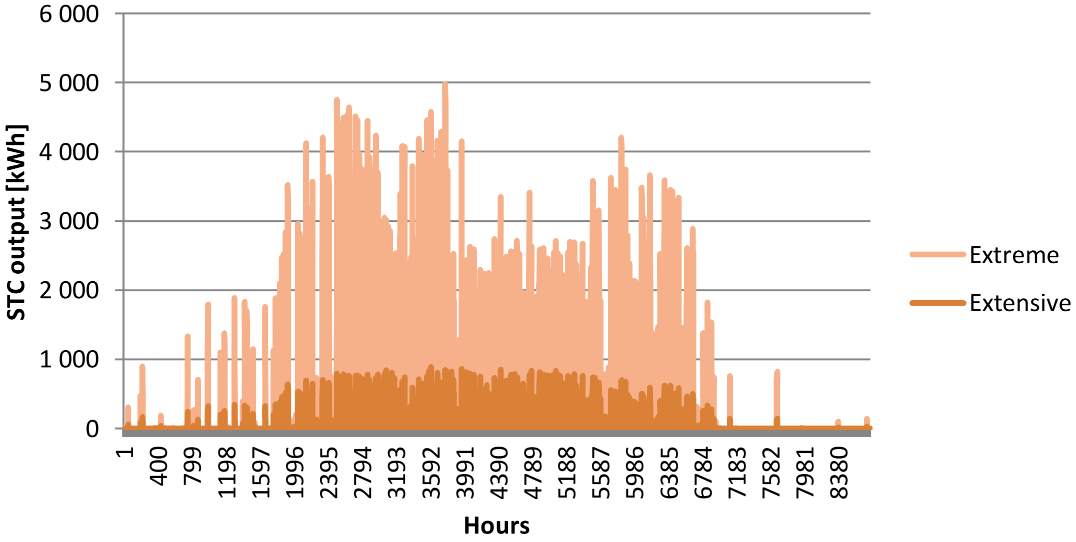

Figure 25. The hourly solar heat production in 2035.

The solar heat production varies much depending on the time of the year and the time of the day. In the extensive scenario, almost 900 kWh of solar heat is produced during summer days with the most favorable conditions. The corresponding number in the extreme scenario is 5 000 kWh. During the summer, the heat demand of the buildings using STCs is completely covered by solar heat. However, in the winter, when the heat demand is at its highest, the solar heat production is marginal. In the extreme scenario, the annual share of the heat covered by solar energy in the buildings using STCs is only 3 %. The rest of the heat is covered by district heating.

The use of decentralized heat production technologies and particularly the use of GSHPs will affect the amount of district heat that need to be produced within the area. The annual amount of heat produced by centralized heat production units within the area is shown in Figure 26.

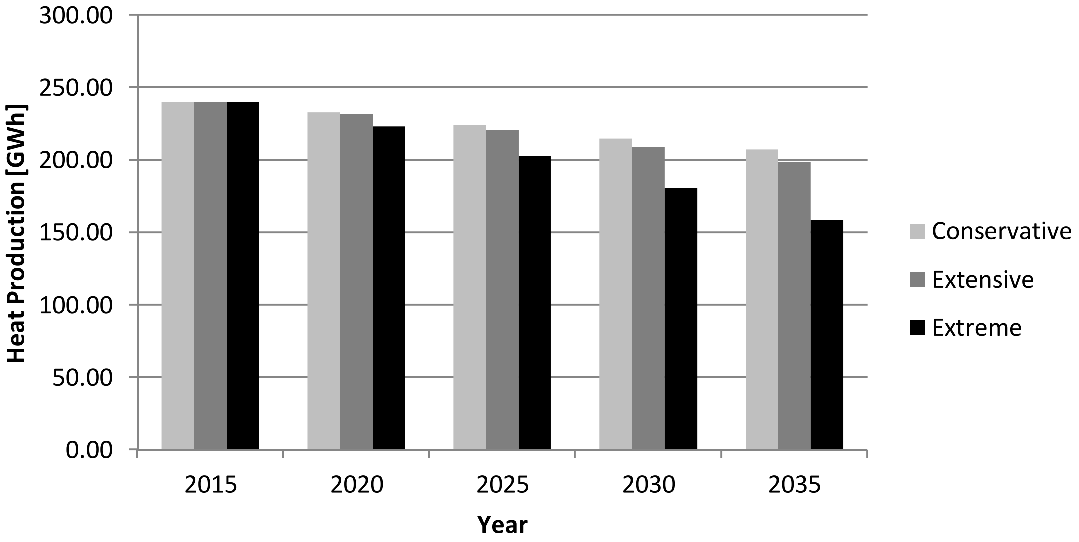

Figure 26. The annual district heat production in the case area.

As the heat demand in the area decreases and decentralized heating technologies are installed, the district heating demand decreases. In 2015, 240 GWh of district heat is produced. 9.7 GWh (4 %) of the heat is lost due to transmission losses and the rest of the heat is delivered to the district heating customers. By 2035, the annual demand is reduced by 14 % in the conservative scenario, reaching 207 GWh. In the extensive scenario, the demand is reduced by 17 %, reaching 198 GWh and in the extreme scenario, it is reduced by 34 %, reaching 159 GWh. In the conservative case, the transmission losses account for 4.8 % of the demand. In the extensive and extreme scenario, the corresponding numbers are 5.0 % and 6.5 % respectively. Thus, as the heat production decreases, the transmission losses are slightly increased.

The decreasing heat demand and the choice of energy technologies also affect the peak heat output. In 2015, the peak heat output is 91.2 MW. The peak outputs of the different scenarios by 2035 are listed in Table 14.

Table 14. The peak heat demand.

	Conservative	Extensive	Extreme
MW	83.8	80.4	64.3
%	92 %	88 %	70 %

In all scenarios, the peak heat output of the centralized heat production is reduced. In the conservative scenario, the peak output is decreased the least; by 8 % reaching 83.8 MW by 2035. In the extensive scenario, it is decreased by 12 % reaching 80.4 MW and in the extreme scenario, it is decreased by 30 % reaching 64.3 MW. Thus, the peak heat demand does not decrease as fast as the annual heat demand decreases. The reduction of the peak heat demand is mainly due to the decrease in heat demand in the area and the installed heat pumps. The peak occurs in the winter, when the ambient temperature is at its lowest. Thus, the installation of STCs does not affect the size of the peak since, no solar heat is produced by then.

3.5.2 Criteria Results

In order to evaluate the energy efficiency of the demand side, the final non-renewable heat consumption per floor area is used as an indicator. The development of the energy efficiency of the scenarios over the scenario timeframe is presented in Figure 27.

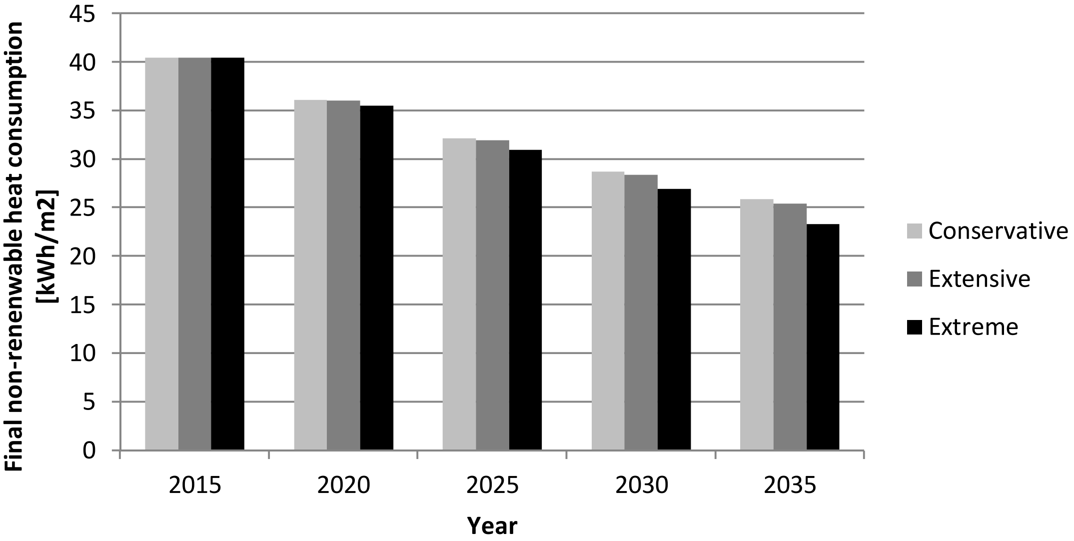

Figure 27. The energy efficiency in the case area as final, non-renewable heat consumption per square metre.

In 2015, the specific non-renewable heat consumption in all scenarios is 40.5 kWh/m^2. In the conservative scenario, the consumption is reduced by 36 %, reaching 25.9 kWh/m^2 by 2035. In the extensive scenario, it is reduced by 37 % reaching 25.4 kWh/m^2 and in the extreme scenario, it is reduced by 42 % reaching 23.4 kWh/m^2. Thus, the efficiency is clearly improved in all the scenarios. However, the differences between the scenarios are small; in 2035, the energy efficiency of the extensive scenario is 1.2 % better than the conservative scenario and the extreme scenario is 10 % better. The main improvement of the energy efficiency is due to the heat demand reductions in the area. The differences between the scenarios are due by the different choices of heating technologies.

The environmental effects of the scenarios are evaluated using two criteria: CO_2e emissions and particulate emissions. Both criteria are calculated as the amount of direct emissions per unit of floor area. The CO_2e emissions are presented in Figure 28 and the particulate emissions are presented in Figure 29.

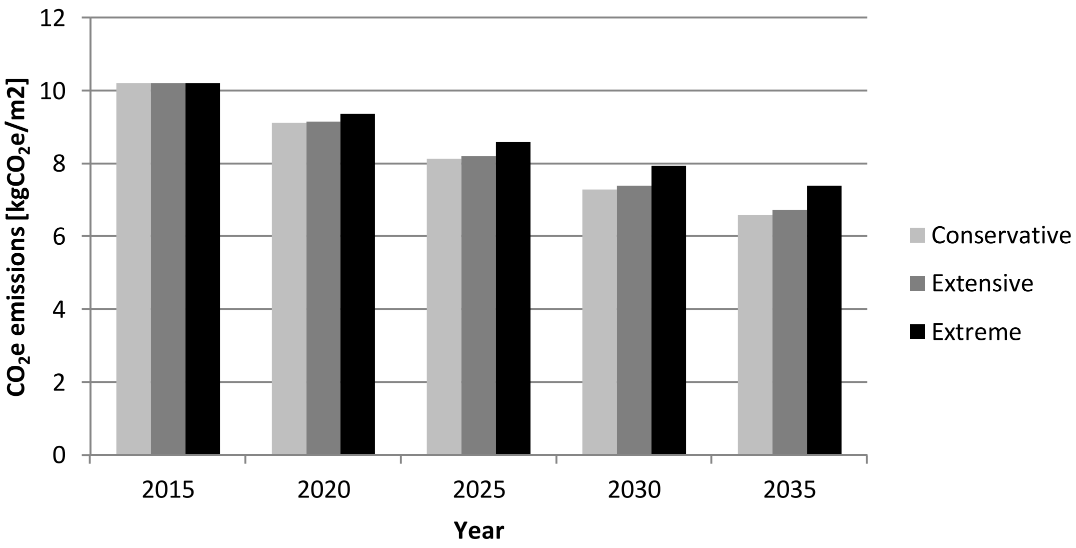

Figure 28. The annual CO_2e emissions in the case area.

In 2015, the CO_2e emissions are 10.2 $kgCO_2e/m^2$. In the conservative scenario, the emissions are decreased by 35 % by 2035, reaching 6.6 $kgCO_2e/m^2$. In the extensive scenario, the decrease is 34 %, reaching 6.7 $kgCO_2e/m^2$ and in the extreme scenario the decrease is 28 %, reaching 7.4 $kgCO_2e/m^2$. Thus, the CO_2e emissions are decreased in all scenarios and in the conservative scenario, they are decreased the most. The differences between the scenarios are moderate. By 2035, the emissions are 2 % higher in the extensive scenario than in the conservative scenario and in the extreme scenario, the emissions are 12 % higher. The differences in emissions between the scenarios are due to the electricity consumption by the heat pumps. In the extensive and extreme scenarios, there are more heat pumps installed than in the conservative scenarios. The electricity consumed by these heat pumps causes more emissions than the district heat production causes in the conservative scenario.

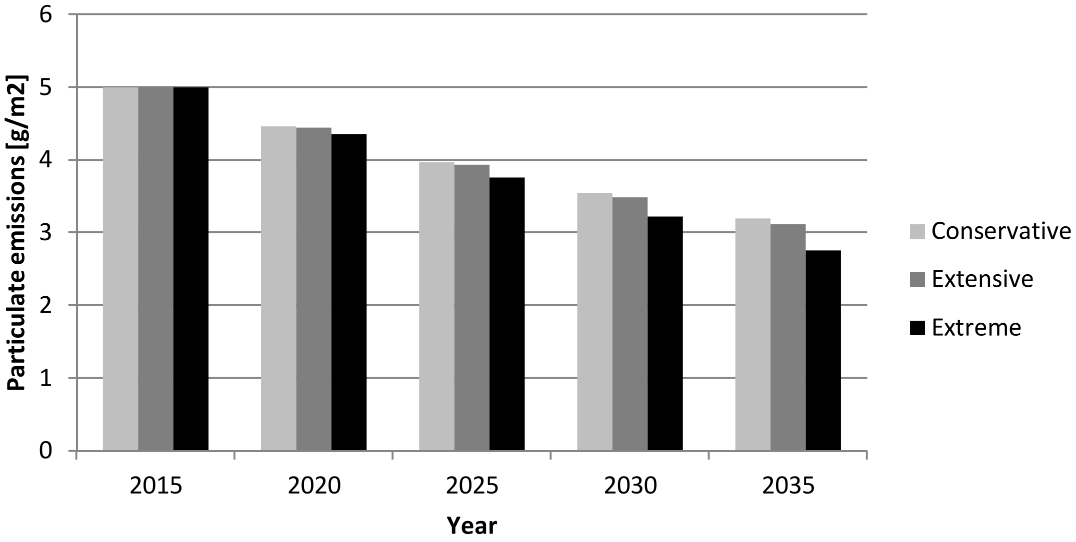

Figure 29. The annual particulate emissions in the case area.

In 2015, the particulate emissions are 5.9 g/m^2. By 2035 are the emissions decreased by 36 % reaching 3.2 g/m^2 in the conservative scenario, 38 % reaching 3.11 g/m^2 in the extensive scenario and 45 % reaching 2.75 g/m^2 in the extreme scenario. Thus, the particulate emissions are decreased in all scenarios but in the extreme scenarios, they are decreased the most. By 2035, the particulate emissions are 16 % higher in the conservative scenario than in the extreme one and in the extensive scenario, the emissions are 13 % higher. The differences between the scenarios are due to the differences in the amount of emissions originating from the electricity and district heat production. It is known that the utilization of biomass in combustion processes is creating high particulate emissions. The fuel mix used for electricity production contains less biomass and accordingly, the particulate emissions are lower.

The economic effects of the scenarios are also evaluated using two indicators: the investment costs and the energy costs. Both indicators are examined from point of view of the energy consumer. Only the costs that rose during the scenario time frame are taken into account. The investment costs are presented in Figure 30 and the energy costs are presented in Figure 31.

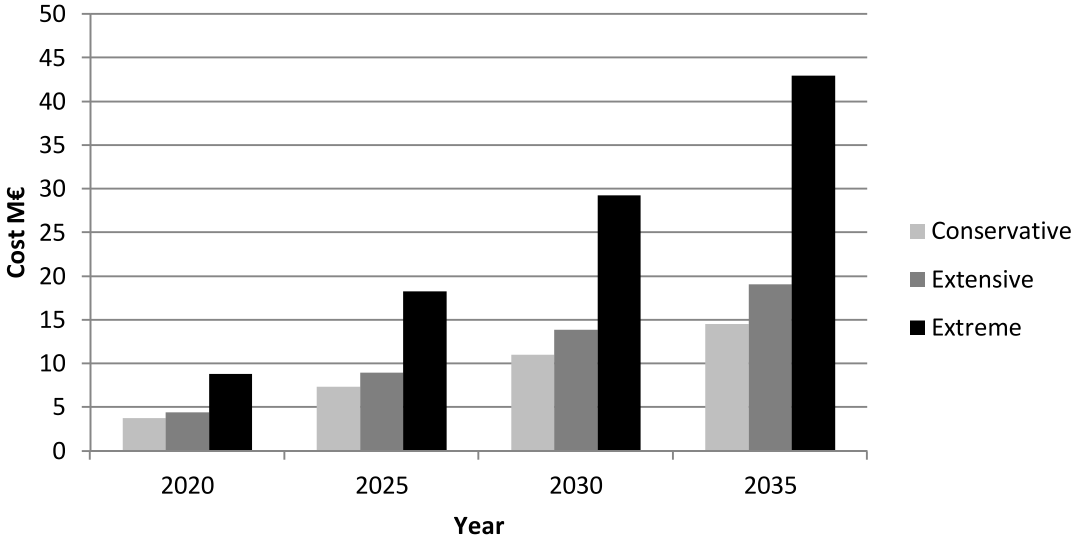

Figure 30. The cumulative investment costs in the case area.

In the case of the investment costs, the scenarios are compared in terms of the total investment costs over the whole scenario timeframe. In the conservative scenario, the total costs are 14.57 M€. The main part of the costs, over 90 %, is due to district heating installations. In the extensive scenario, the costs reach 19.13 M€. In this scenario, over half of the investment costs are due to GSHP installations and 42 % due to district heating installations. The rest of the costs are used to install STCs. In the extreme scenario, the total investment costs are 42.95 M€. In this scenario, there are almost no investments made in district heating connections. The main part of the costs, 87 %, are due to GSHP installations and the rest is used to install STCs.

Thus, the investment costs are by far the highest in the extreme scenario. In the calculations, it was assumed that the costs of GSHPs and STCs will decrease by 1 % annually over the scenario timeframe. Thus, by 2035, the investment costs for these technologies were decreased by 18 % compared with the situation in 2015. However, the decrease was not enough for GSHPs to reach the prices of district heat. In 2035, the investment costs for GSHPs were still twice as high as for district heat.

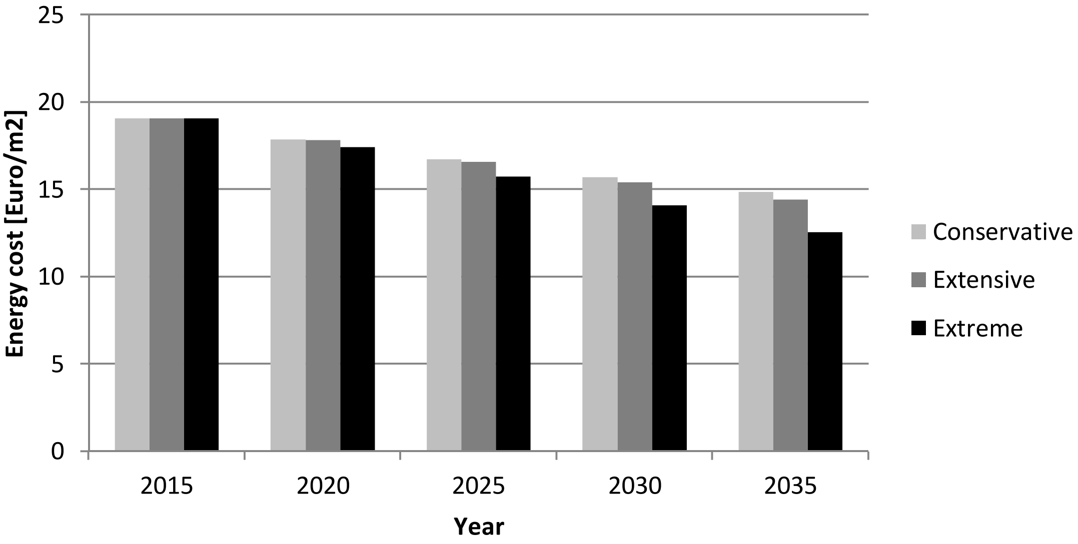

Figure 31. The annual energy costs in the case area.

In 2015, the average energy costs in the area are approximately 19 €/m^2. However, as could be seen from the figure, these costs are decreased throughout the scenario timeframe in all scenarios, even though the energy prices are increased. By 2035, the energy costs are decreased by 22 %, reaching 14.7 €/m^2 in the conservative scenario, by 24 %, reaching 14.4 €/m^2 in the extensive scenario and by 34 %, reaching 12.6 €/m^2 in the extreme scenario. Thus, in the extreme scenario, the energy costs are decreased the most. The differences between the scenarios are moderate; in the conservative scenario, the costs are 16 % higher than in the extreme scenario and in the extensive scenario, the costs are 14 % higher.

Thus, the decrease in energy consumption in the area is, in percentage terms, larger than the increase in energy costs. In the extreme case, heat pumps are used in a large extent to cover heat demands. According to the results, the electricity used to run these heat pumps is cheaper than the corresponding amount of district heat used in the conservative and extensive scenarios.

The employment effects or, the number of jobs related to energy supply, is used as an indicator for comparing the social benefits of the scenarios. The cumulative number of jobs related to the maintenance and operation of centralized district heat production and the construction and manufacture of GSHPs and STCs is shown in Figure 32.

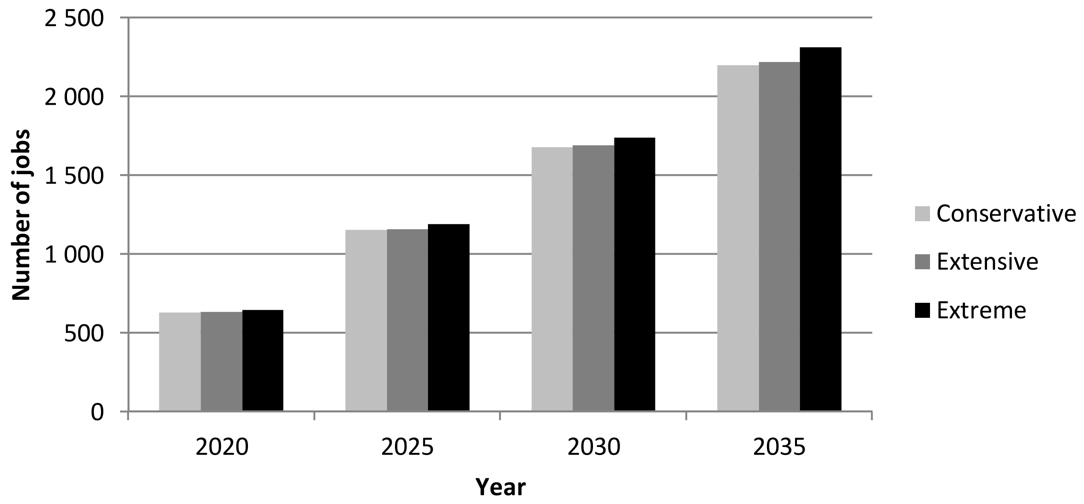

Figure 32. The cumulative number of jobs related to energy supply activities in the case area.

As in the case for the investment costs, the scenarios are compared in terms of the total number of jobs related to energy supply in each scenario over the whole scenario timeframe. In the conservative case, there are in total 2201 jobs related to energy supply. Of these, 3 are related to the construction and manufacture of GSHPs while the rest are related to the operation and maintenance of centralized district heat production. In the extensive scenario, there are in total 2222 jobs related to the energy supply and of these, 25 are related to the construction and manufacturing of GSHPs and STCs. In the extreme scenario, the total number of jobs related to energy supply is 2315 and in this scenario, 128 are related to the manufacturing and construction of GSHPs and STCs.

Thus, the extreme scenario gives rise to the highest number of jobs. In this scenario, there are 5% more jobs than in the conservative scenario and 4 % more jobs than in the extensive scenario. In the scenarios, the number of jobs related to the operation and maintenance of centralized district heating plants is almost the same. Thus, the difference between the scenarios is mainly due to the adoption of decentralized heating technologies.

3.5.3 Ranking of Scenarios

The scenarios are ranked based on the criteria outcome. In the ranking, the average criteria values of the energy efficiency, CO_2e emissions, particulate emissions and energy costs over the scenario timeframe are used. In the case of the investment costs and the employment effects, the cumulative outcomes of the criteria over the scenario timeframe are used. A summary of the criteria outcome is given in Table 15. In the table, the scenario with the most beneficial criteria outcome is marked with grey color.

Table 15. Summary of the criteria outcome. For each criteria, the most beneficial criteria outcome is market with green colour.

Criterion	Unit	Conservative	Extensive	Extreme
Energy efficiency	kWh/m^2	35.67	35.50	34.65
CO_2e emissions	kgCO_2e/m^2	9.02	9.08	9.40
Particulate emissions	g/m^2	4.40	4.37	4.22
Investment costs	M€	14.57	19.13	42.95
Energy costs	€/m^2	18.08	17.93	17.21
Employment effects	person years	2201	2222	2315

As can be seen from the table, the most beneficial outcome for two of the criteria; CO_2e emissions and the investment costs, is obtained in the conservative scenario. The rest of the criteria; energy efficiency, particulate emissions, energy costs and the employment effects, reach the best outcome in the extreme scenario. Since the criteria are measured by different units, they can not be directly compared with each other. In order to be able to compare them, the criteria outcomes need to be normalized. The approach used is described in Section 3.2.3. The estimates used for the minimum and maximum values of the criteria in the normalization are listed in Table 16. The outcome of the normalization is shown in Figure 33.

Table 16. The minimum and maximum values of the criteria used in the normalization.

Criterion	Unit	Minimum	Maximum
Energy efficiency	kWh/m^2	0.00	217.00
CO_2e emissions	$kgCO_2e/m^2$	0.00	58.93
Particulate emissions	g/m^2	0.00	5.21
Investment costs	M€	12.34	50.00
Energy costs	$€/m^2$	15.00	25.00
Employment effects	-	154	2400

The minimum and maximum values of the energy efficiency, CO_2e emissions and particulate emissions correspond to two extreme situations; the situation when all heat in the area is produced by renewable, emission free energy sources and the situation where the heat is produced by non-renewable energy sources with the highest possible emissions. The minimum value of the investment costs and the employment effects also correspond to two extreme situations; the situation when all new buildings choose the heating technology with the lowest installation costs and the situation where all heat in the area is produced in the least labor intense way. The maximum values of the investment cost and the employment effects and both the maximum and minimum value of the energy costs could in principle reach any value. However, in order to reach a realistic outcome, restrictions are given to these values.

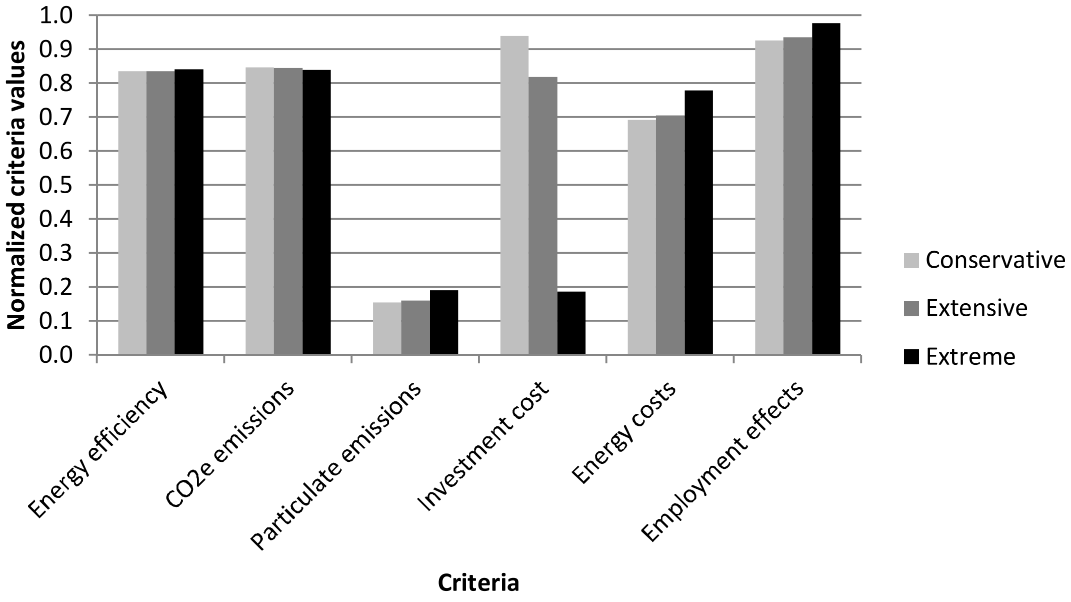

Figure 33. The normalized criteria outcomes.

The normalized criteria outcomes reach values between 0 and 1, where 0 is the worst possible outcome and 1 is the best possible outcome. As could be seen from the figure, many of the normalized criteria values are close to or even higher than 0.8. The only criterion, whose normalized value is closer 0 than 1 is the particulate emissions. In the scenarios, it was assumed that the district heat was produced by using a large share of biomass in the fuel mix. Biomass has, compared to many other fuels, high particulate emissions and therefore are the particulate emissions quite high in all the scenarios. On the other hand, the use of biomass in the district heat production contributes to that the energy efficiency of the scenarios is high and that the CO_2e emissions are low.

The outcome of the normalized values also shows that the differences between the scenarios are very small. Only in the case of the investment costs, the differences between the scenarios are large. In the conservative scenario, the investments are mainly made into district heat installations, whose costs are the lowest ones. In the extreme case, the main parts of the investments are made into GSHPs, whose investment costs are much more expensive than the ones for district heating. Thus, the outcome of the extreme scenario is close to the maximum limit while the outcome of the conservative scenario is close to the minimum limit.

In order to rank the criteria, the weighted sum method was used. In the ranking, all criteria were considered to be equally important. The results of the ranking are shown in Table 17.

Table 17. The results of the scenario ranking.

Ranking	Scenario	Scenario weight
1	Conservative	0.73
2	Extensive	0.72
3	Extreme	0.63

As could be seen from the table, the conservative scenario was ranked as the best one, closely followed by the extensive scenario. The extreme scenario was ranked as the worst scenario. Thus, even though the outcome of four of six criteria was the most beneficial ones for the extreme scenario, the conservative scenario was in total regarded as the best one. The result is mainly a following of the differences in investment costs between the scenarios. Since the differences between the scenarios were otherwise very small, the investment costs had a huge influence on the result.

3.6 Sensitivity of the Scenario Selections

In the process of developing and comparing scenarios for future district energy systems, numerous decisions and assumptions have been made. The scenarios themselves were focused on investigating the demand side of the energy network and how the choices of the end users of energy affected the performance of the whole energy system. However, in order to be able to do this, assumptions about the energy supply and the price development in the area were made. In this chapter is the sensitivity of these scenario selections examined. First is the sensitivity of the chosen energy supply examined and then is the influence of the price development on the scenario outcomes examined.

3.6.1 Energy Supply

The criteria were calculated based on the assumption that the fuel mix used for district heat production in the area was 81 % biomass, 15 % natural gas and 4 % heavy fuel oil. However, this assumption directly affects the outcome of the energy efficiency, CO_2e emissions and particulate emissions. Furthermore, the fuel mix will also have an effect on the district heating costs but these aspects are not taken into account in this thesis.

In the following are the criteria outcomes of the case study compared to two cases:

- Case I: The fuel mix consists of 71 % biomass, 25 % natural gas and 4 % heavy fuel oil
- Case II: The fuel mix contain 91 % biomass, 5 % natural gas and 4 % heavy fuel oil

The influence of the fuel mixes on the energy efficiency is shown in Table 18, on the CO_2e emissions in Table 19 and the influence on the particulate emissions in Table 20.

Table 18. The sensitivity of the energy efficiency. For each criteria, the most beneficial criteria outcome is market with green colour.

Case	Unit	Conservative	Extensive	Extreme
Reference	kWh/m^2	36.67	35.50	34.65
Case I (less biomass)	kWh/m^2	53.88	53.48	51.47
Case II (more biomass)	kWh/m^2	17.46	17.52	17.83

As could be seen from the table, the absolute amount of non-renewable energy consumption in the area is highly affected by the fuel mix used for district heat production. In Case I, where the share of biomass in the fuel mix is the lowest, the final, non-renewable heat consumption is the highest. In this case, the non-renewable energy consumption is almost 50 % higher than in the reference case. In Case II, where the share of biomass in the fuel mix is the highest, the non-renewable heat consumption is the lowest. In this case, the non-renewable energy consumption is over 50 % smaller than in the reference case.

Furthermore, the internal ranking of the scenarios is also affected by the fuel mix. In the reference case and in Case I, the extreme scenario is the best scenario from the energy efficiency point of view. However, in Case II, the conservative case is the most efficient one. In Case II, the electricity consumed by the heat pumps in the extensive and extreme case exceeds the amount of non-renewable heat used for producing district heat. However, the differences in energy efficiency between the best and worst scenarios are low, below 6 %.

Table 19. The sensitivity of the CO_2e emissions. For each criteria, the most beneficial criteria outcome is market with green colour.

Case	Unit	Conservative	Extensive	Extreme
Reference	kWh/m^2	9.02	9.08	9.40
Case I (less biomass)	kWh/m^2	13.17	13.18	13.23
Case II (more biomass)	kWh/m^2	4.03	4.16	4.79

The absolute amount of CO_2e emissions are also heavily depending on the fuel mix used for district heat production. In Case I, the total amounts of CO_2e emissions are the highest. In this case, the emissions are about 40 % higher than in the reference case. In

Case II, the total CO2e emissions are the lowest. In this case, the emissions are about 50 % lower than in the reference case.

For this criterion, the internal ranking of the scenarios for the different cases is not affected by the fuel mixes in the comparison. In all case, the conservative scenario has the lowest CO_2e emissions. In Case I, the CO_2e emissions are almost of equal size; the difference between the conservative and extreme scenario is less than 1 %. In Case II, the CO_2e emissions are 19 % higher in the extreme scenario than in the conservative scenario.

Table 20. The sensitivity of the particulate emissions. For each criteria, the most beneficial criteria outcome is market with green colour.

Case	Unit	Conservative	Extensive	Extreme
Reference	kWh/m^2	4.40	4.37	4.22
Case I	kWh/m^2	3.86	3.84	3.72
Case II	kWh/m^2	4.95	4.91	4.72

The differences between the absolute amounts of particulate emissions in the different cases are not as high as the differences between the energy efficiency and CO_2e emissions. In Case I, where the particulate emissions are the lowest, they are 12 % lower than in the reference case. In Case II, where the emissions are the highest, they are 12 % higher than in the reference case.

Neither for this criterion, the internal ranking of the scenarios are affected by the fuel mix used to produce district heat. In all cases, the emissions are lowest in the extreme scenario and highest in the conservative scenario. In all the cases, the differences between the best and worst scenario is less than 5 %.

3.6.2 Price Development

In order to determine the investment and energy costs, assumptions for the future development of energy prices were made. In this section is the sensitivity of these assumptions examined. First, the sensitivity of the investment costs is examined and then, the sensitivity of energy costs is examined.

GSHPs and STCs are heating technologies that are still being developed and whose investments costs are expected to be reduced. In the thesis, the investment costs were calculated based on the assumption that the costs for both technologies are reduced by 1 % annually throughout the scenario timeframe. However, this is only an estimate; it is not possible to make a perfect foresight for how the costs will be developed. In the following, the outcome of the assumption is compared with four different cases:

- Case 1: The investment costs are not reduced at all
- Case 2: The investment costs are reduced by 2.5 % annually
- Case 3: The investment costs for GSHPs are reduced by 1% annually and investment costs for STCs are reduced by 2.5 % annually
- Case 4: The investment costs for GSHPs are reduced by 2.5 % annually and investment costs for STCs are reduced by 1 % annually

The results of the comparison are presented in Table 21.

Table 21. The sensitivity of the investment costs. The best case for each scenario is marked with green colour.

Criterion	Unit	Conservative	Extensive	Extreme
Reference	M€	14.57	19.13	42.95
Case 1	M€	14.74	20.41	49.16
Case 2	M€	14.37	17.56	35.38
Case 3	M€	14.57	18.90	41.68
Case 4	M€	14.37	17.79	36.65

In all cases, the investment costs are the lowest in the conservative scenario. In the extensive scenario, the investment costs are between 20 and 40 % higher than in this scenario and in the extreme scenario, the investment costs are between 150 and 240 % higher. In the conservative scenario, the cost differences between the different cases are quite small. In the best cases, case 2 and 4, the investment costs are only 2.5 % lower than in the worst case, Case 1. In the extreme scenario on the other hand, the differences in investment costs between the different cases are rather big. In the best case, Case 2, are the investment costs 28 % lower than in the worst case, Case 1.

Thus, in the scenarios where there are a large amount of decentralized heating technologies installed, the final investment costs are highly dependent on the price development of the heating technologies. The more the investment costs of the GSHP and STC technologies are reduced, the lower are the final investment costs. The development of the GSHP installation costs affects the final costs more than the development of the STC installation costs.

The energy costs were calculated based on the assumption that both the electricity and district heating consumer prices were increased by 1 % annually throughout the scenario timeframe. However, it is not possible to know how the energy costs will develop in the long term. In the following, the assumption is compared with four alternative cases:

- Case A: The energy costs are increased by 2 % annually
- Case B: The energy costs are increased by 5 % annually
- Case C: The district heating costs are increased by 1 % annually and the electricity costs are increased by 5 % annually
- Case D: The district heating costs are increased by 5 % annually and the electricity costs are increased by 1 % annually.

The results of the comparison are presented in Table 22.

Table 22. The sensitivity of the energy costs. The best case for each scenario is marked with green colour.

Alternative	Unit	Conservative	Extensive	Extreme
Reference	€/m^2	18.08	17.93	17.21
Case A	€/m^2	19.53	19.36	18.53
Case B	€/m^2	25.00	24.74	23.51
Case C	€/m^2	24.98	24.67	23.14
Case D	€/m^2	18.09	18.01	17.58

In all the cases, the energy costs are the lowest in the extreme scenario and highest in the conservative scenario. In the extensive scenario, the energy costs are between 2 and 7 % more expensive than in the extreme scenario and in the conservative scenario, the energy costs are between 3 and 8 % more expensive. Thus, the differences between the scenarios are quite small. The absolute energy costs on the other hand, are lowest in the Reference case, closely followed by Case D. In Case B and C, the costs are the highest, almost 40 % higher than in the reference case.

Thus, high electricity costs result in high energy costs for the consumers. The increase in district heating prices does not affect the final energy costs as much as the increase in electricity prices.

4 Discussion and Conclusions

In this chapter, the thesis results are discussed at a general level and conclusions are made. In Chapter 4.1, the future prospects for district energy systems and the use of scenarios as a tool for evaluating the different options are discussed in the light of the theories presented in the literature review. In Chapter 4.2, the case study findings are examined. Finally, in Chapter 0, relevant topics for future research are proposed.

4.1 Literature Review Findings

In order to succeed in climate change mitigation, the energy sector needs to undergo radical changes. The main actions needed include substantial GHG emission reductions, the increased use of renewable energy sources and the improved energy efficiency of the system. However, achieving large system changes is hard since the current systems acts as a barrier to the new ones. The renewal of the building stock is slow and the existing energy infrastructure will have an effect on the energy choices for a long time ahead. Therefore, the existing systems need to be used as the starting point in energy system planning.

The realization of the energy system transition and the development pathway chosen is affected by many different factors such as the available technologies, economics, policies and regulations. Furthermore, incentives for behavioural changes and the end user engagement in the transition process are crucial. However, since the energy consumption patterns are not only affected by policies and prices but also by cultures and institutions, it will be challenging to make changes to these. In order for end users to participate, they need to be shown that their choices really make a difference. Furthermore, if the users have the possibility to benefit from the decisions themselves, the incentives for them to participate are stronger.

In the literature, it was found that there are several development pathways for how the heat demand of buildings could be covered in the future. These include the increased utilization of renewable, decentralized heat production technologies, the large scale implementation of district heating and the electrification of the heating sector. Furthermore, the combined use of these alternatives is also a possible pathway. The result is then a smart energy system where a holistic approach to the whole energy system is taken. In such systems, the opening of the energy system for small scale heat production is essential.

In the planning of energy systems, a holistic view needs to be taken where the short term actions are aligned with the long term targets. In order to compare the outcome of different energy system choices, scenarios can be used as a powerful tool. Furthermore, the utilization of the Multi-Criteria Decision Analysis approach in the planning process contributes to a more balanced result.

The result of the analysis is heavily dependent on which criteria are chosen and what the relative importance of the criteria is. Since there are many different stakeholders with different interests involved in the energy planning process, the result may be different depending on whose perspective is taken. In the future, the cooperation between different stakeholders will be of great importance in order to develop the energy systems in the best possible way.

4.2 Case Study Findings

In the simulation case study, a scenario approach was used to examine how changes made on the demand side of the network affected the overall performance of the system. Three scenarios were made; a conservative, an extensive and an extreme scenario. In the scenarios, a common assumption for the building stock development was used while the choice of heating technologies varied. In the conservative scenario, the adoption of decentralized heating technologies instead of district heating was small while in the extensive and extreme cases, the adoption rates were high.

The simulation results indicate that by improving the energy efficiency of existing buildings and setting strict energy targets for new buildings, the heat consumption can be considerably reduced. In the study, these actions resulted in a 13 % large reduction of the total heat demand in the case area even though the built floor area was increased by 35 % over the scenario timeframe. The specific heat demand was reduced by even 36 %. Furthermore, as a direct consequence of the reduction of the heat demand, the energy efficiency of the system was improved and the emissions were reduced.

The results also showed that different heating technology selections affect the performance of the energy system in different ways. As the amount of installed decentralized heat production technologies in the area was increased, the district heating demand was reduced. In the conservative scenario, the share of heat supplied by decentralized heat production technologies was less than 1 %. In the extensive scenario, the share was 5 % and in the extreme scenario, it was 25 %. The main part of the reduction of the district heating demand was due to the amounts of installed ground source heat pumps in the area. The heat produced by the heat pumps was proportional to the heat pump installations while the heat produced by solar collectors remained small in all scenarios.

In order to compare the scenario outcomes to each other, the following criteria were used: energy efficiency, CO_2e emissions, particulate emissions, investment costs, energy costs and employment effects. In the case of the CO_2e emissions and the investment costs, the conservative scenario gave the most beneficial results. For the other criteria, the extreme scenario gave the best results. However, even though the outcome of four out of six criteria resulted in the best results for the extreme scenario, the conservative scenario was ranked as the best scenario. In general, the differences between the scenarios were small. Only in the case of the investment costs, the differences between the scenarios were large, which determined the outcome of the comparison to the advantage of the conservative scenario.

In the study, a sensitivity analysis was done to investigate how sensitive the results were, with respect to the energy supply mix in the case area and the assumed price development. The results of the analysis showed that the choice of district heating fuel had a large impact on the criteria outcome. By changing the fuel mix a little, large differences in especially the energy efficiency and the CO_2e emissions were got. The particulate emissions on the other hand were not as dependent of the fuel mix. The results also showed that both the investment and energy costs were sensitive to the price development assumptions made. By making changes to the assumptions, large changes in the absolute costs were reached. However, the scenario ranking was not affected by the changes. In order to reach changes in the ranking, radical assumptions for the price development would have been needed.

In the process of developing and comparing scenarios, hundreds of decisions and assumptions were made. These decisions had a large impact on the final result. In the study, some simplifications were made in order to save time and make the calculations simpler. For example, the emission calculated took only into account direct emissions created in the case area. Furthermore, the employment effects were based on general employment factors, picturing the European situation. The results give an estimate for what the employment effects of the different scenarios could be. However, in order to get more detailed results, the employment factors for at the country or even regional level of the case area would be needed.

The method used to evaluate the scenarios relied on the multi criteria decision analysis approach. Thus, in the evaluation process, several criteria were taken into account. When ranking the scenarios, all the criteria were given the same importance. However, this does not properly reflect the real situation. In order to develop the method further, the different perspectives of different stakeholders should be reflected in the weighting of the criteria. Criteria that are considered important should be given a higher weight than criteria considered less important. This way, it could be ensured that the chosen system fulfil the needs of the stakeholders.

It must be emphasized that the case study results should not be interpreted as forecasts of the future. As already established, the results are highly dependent of the assumptions and choices made. Furthermore, the accuracy of the simulation model and also the objectives and backgrounds of those who have made the study affect the results. The main outcome of the study lies instead in the method developed for creating and evaluating different energy system scenarios. The method provides solutions for how to develop energy systems taking both technical and economic criteria but also environmental and social criteria into account.

4.3 Future Research

In this study, the effects of changes made on the demand side of the system were investigated. These included both the improved energy efficiency of buildings and different heating technology selections. Thus, the selections were such that could be easily affected by the end users of energy. In order to extend the results, the effects of different supply side measures should also be taken into account.

In the study, the scenarios were ranked using criteria of equal weight. However, this is not the most realistic case. Different stakeholders have different objectives and depending on the view taken, the relative importance of the criteria will vary. Therefore, it would also be useful to study how more realistic weights of the criteria could affect the energy system performance.

The effects of demand side management and behavioral changes were left beyond the scope of the thesis. However, these aspects also need to be examined in order to be able to fully understand the influence of end user behavior on the energy system. Knowledge of energy related behavior is important especially when smart energy systems are becoming available since the end user actions and acceptance are a key to the success in the implementation of such systems. In the study, the same weight was given to all the criteria.

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List of Appendixes

Appendix 1. Workshop Result

The outcome of the stakeholder workshop is presented in Figure A1-1.

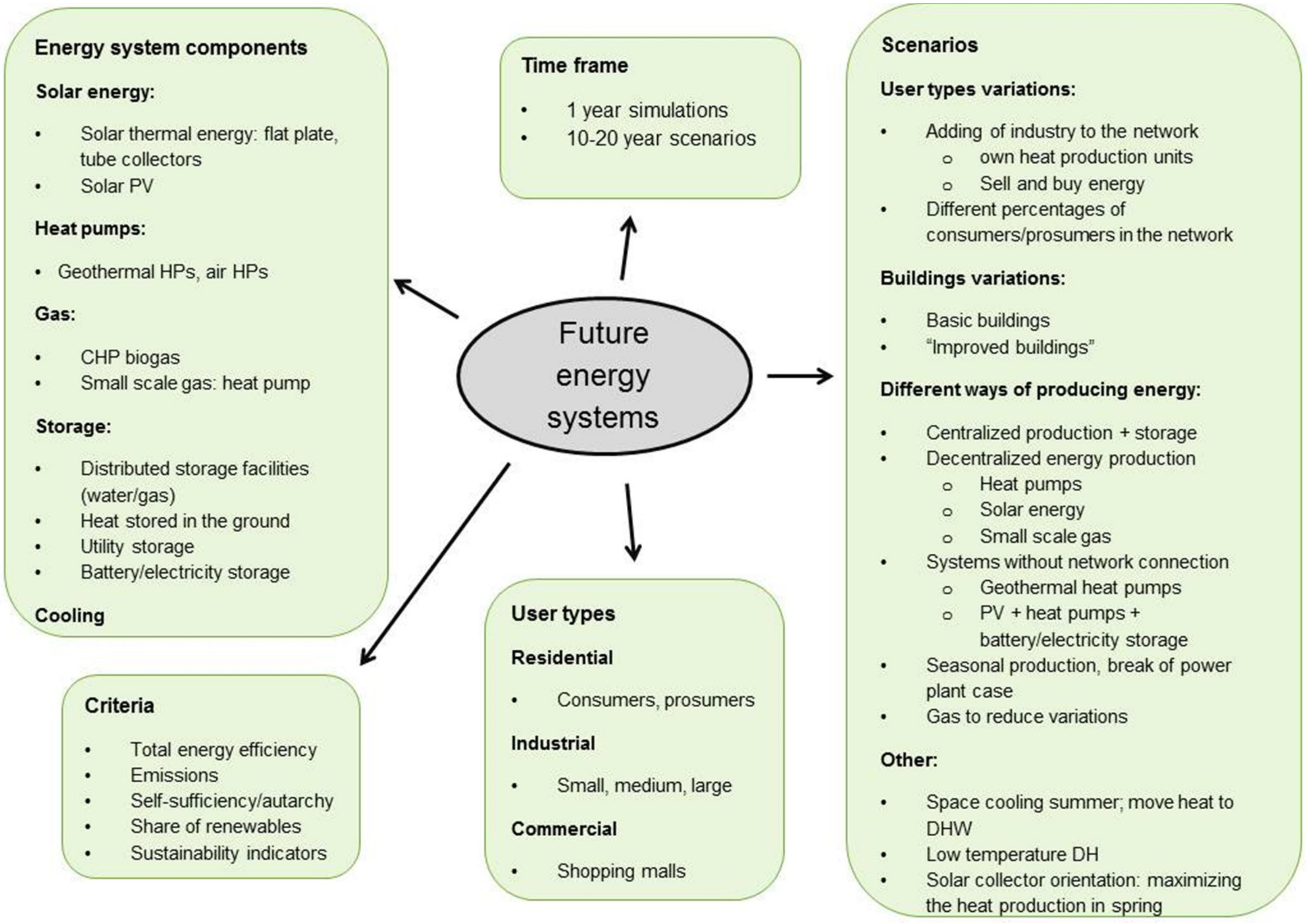

Figure A1-1. An overview of the stakeholder outcome.

Appendix 2. Decentralized Heating Technology Installations

The forecast for the adoption of GSHPs in the case area was based on historical data of the GSHP installations in residential buildings in Järvenpää and forecasts for the adoption of GSHPs in residential buildings in Finland. The statistics show that the amount of GSHPs in Järvenpää has grown over the last ten years and by 2014, there were 54 000 heat pumps installed in the area (Aluesarjat 2016b). According to Laitinen et al. (2014), the amount of GSHPs in Finland will increase by 170 % by 2016 and by 320 % by 2020 with respect to the cumulative installations in 2010. By 2030, the number of GSHPs will double with respect to year 2020 (Gaia 2014). The forecast for the GSHP installations in the case area is visualized in Figure A2-1.

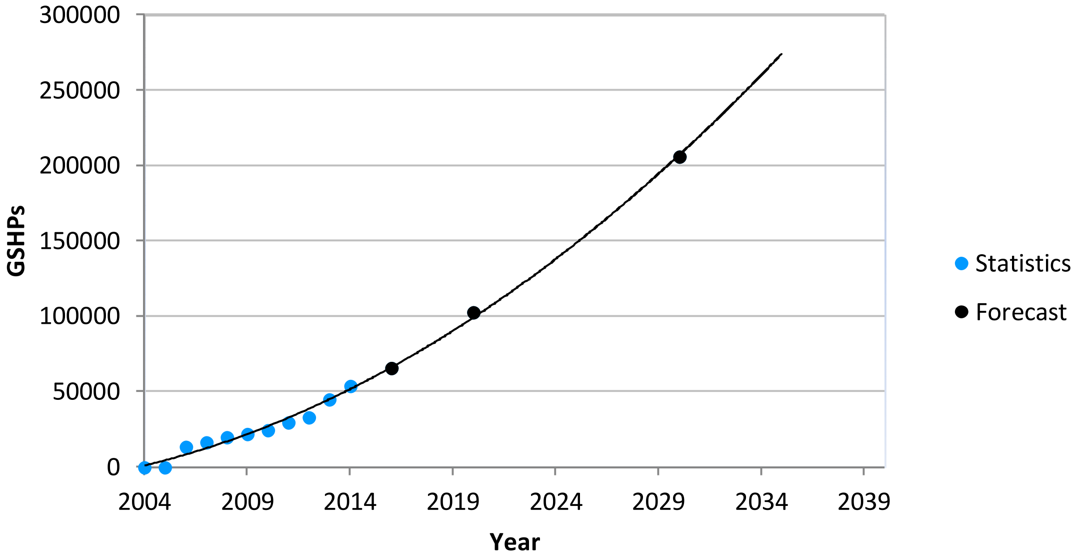

Figure A2-1. The historical development and the forecasts for GSHP installation in residential buildings in the case area.

As could be seen from the figure, the GSHP installations are expected to increase quite fast in the area. However, the forecasted GSHP installations cover the installations in the whole area and this amount is not equal to the amount of heat pumps installed into buildings within the district heating network area.

Historical data of STC installations in Finland constitutes the foundation of the adoption rate of STCs used in the scenarios. The historical development of installed solar collector area is shown in Figure A2-2.

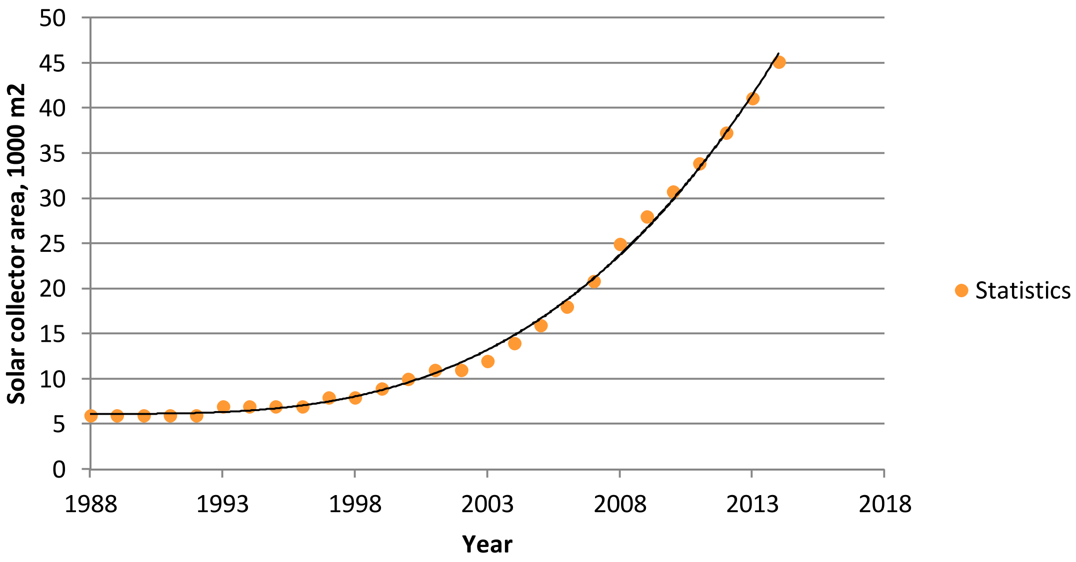

Figure A2-2. The historical development of STC installations in residential buildings in Finland.

The statistics show that the growth rate of solar thermal systems has been 10 % between 2009 and 2013 (Tilastokeskus 2016). By increasing and decreasing the growth rates of the forecasts, different scenarios for the adoption of the STC and GSHPs in the case area were formed.