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277

Visions for future energy efficient district energy systems

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VTT TECHNOLOGY 277

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Fortum Ltd

ISBN 978-951-38-8478-9 (URL: http://www.vttresearch.com/impact/publications)

VTT Technology 277

ISSN-L 2242-1211
ISSN 2242-122X (Online)
http://urn.fi/URN:ISBN:978-951-38-8478-9

JULKAISIJA – UTGIVARE – PUBLISHER

Teknologian tutkimuskeskus VTT Oy
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Abstract

The future energy system options can be versatile combinations of different energy production technologies including centralized and decentralized systems. Current trends such as decentralization, the end-users starting to produce part of their own energy use as well as offering/selling it to other energy users (prosumers), new technical possibilities in energy production, the increase of the local energy and renewables and improvement of the energy efficiency of buildings will increase the uncertainty of the energy business. The challenge of the energy business lies in the forecasting of the energy business landscape, finding new ways of conducting the energy business in collaboration with customers and other stakeholders and estimating the energy costs and the performance of the selected solutions. The holistic analysis of the energy systems requires the systematic approach and simulation methods and tools.

This report gives the vision of the future district energy systems and describes the state-of-the art of district heating related energy systems in Finland. The challenges and future needs of the energy business and services are described. The approach for scenario analyses is presented using the district heating system of Keski-Uusimaa as a case study.

The scenarios of the energy system selection and energy consumption for the next 20 years (2015–2035) were presented for the case study. The scenarios were based on the assumptions of development scenario of the building stock and energy efficiency of the buildings. The building’s total area will increase 35% over the course of 20 years, but the total heat demand decreases 13% during the period, because of improved building level energy efficiency. Two different types of scenario simulations were done. The first one, system optimization, search for optimal system concept taking into account the investment costs for the energy production system including centralized and decentralized systems. The second one, energy simulation, studied the influence of the decentralized energy production on the energy efficiency, emissions and energy costs. Both the simulation cases had the time frame of 20 years.

The optimization model can be used to study the influence of production unit costs and external conditions on the optimal system typology. The energy system optimization study was based on three main scenarios: the existing bio combine heat and power (CHP) plant and gas boiler would be useable during 2015–2035,

the CHP plant will be stopped in 2025 or there are no existing units in the region. The optimization takes into account costs of the equipment and energy, external conditions (solar, wind) as well as heating and power needs. The study of alternatives showed that it is cost optimal to use the already existing CHP plant. The heat pumps, gas boilers and wind and gas turbines will support the energy system when the CHP is not used anymore.

In the energy simulation study, a set of scenarios for the development of the case area's district heating system have been made. The purpose of the scenarios was not to make a prediction of what the future heating energy systems will be like, but rather to examine what different possible development pathways there are and compare them in terms of technical, environmental and economic criteria. The conservative, extensive and extreme scenarios assumed different amounts of solar energy and ground source heat pumps to be implemented as decentralized systems (1%, 10% or 50% of floor area implemented decentralized renewable energy systems). The industrial heat was used or the consumer acted as an active prosumer selling the excess solar heat back to network.

In the case of simulations, the extreme scenario with ground source heat pumps and a solar thermal system decreased the annual centralized heat production by 34% and, in the case of industrial waste heat by 32% at the end of the scenario timeframe compared to starting year. The non-renewable heat consumption decreased 46% in case of industrial waste. In the case where 20% of the district heating was originating from the industrial waste heat source, the CO_2 emissions decreased by 50%. The energy costs depend strongly on the scenario assumptions. The yearly energy costs of reference case decreased 22% compared to the starting year, and the biggest reduction (34%) was gained in the extreme scenario. In the conservative, extensive and extreme scenarios using heat pumps, the CO_2 emissions increased compared to the reference case, due to the increase in electricity use by heat pumps. The case studies showed that environmental performance depends strongly on the source of emission factors for the primary energy, e.g., if the real factor based on local conditions or average national values will be used. The energy-saving benefits of the prosumer scenario were quite small (<1%) at the district level, because this case only sold solar thermal energy and excess solar heat existed only during summer months.

The results of the scenario analyses depend strongly on the case and assumptions in the background. The weighting of the energy, economic and environmental performance must be decided to be able to select the optimal system. The scenario study with optimization and energy analyses will show the method that can be implemented in real cases.

Tiivistelmä

Tulevaisuuden energiajärjestelmät voivat olla monipuolisia yhdistelmiä erilaisista keskitetyistä ja hajautetuista tuotantoteknologioista, sillä nykyiset trendit lisäävät energialiiketoiminnan epävarmuutta. Näitä trendejä ovat järjestelmien hajauttaminen, kuluttajien oma energiantuotanto (prosumer, kuluttaja tuottajana), uudet energiantuotantotekniikat, paikallisen ja uusiutuvan energian käytön lisääntyminen sekä rakennusten energiatehokkuuden paraneminen. Energialiiketoiminnan haasteina on hahmottaa tulevaa toimintaympäristöä, löytää uusia tapoja tehdä liiketoimintaa yhdessä asiakkaiden ja muiden osapuolten kanssa sekä arvioida valittujen energiajärjestelmien toimivuutta ja energiakustannuksia. Kokonaisvaltainen tarkastelu vaatii systemaattista lähestymistapaa ja simulointimenetelmien ja -työkalujen käyttöä.

Tämä raportti kuvaa tulevaisuuden energiajärjestelmien visioita ja kaukolämpöön liittyvien järjestelmien nykytilaa Suomessa. Raportissa kuvataan tulevaisuuden liiketoimintaan ja palveluihin liittyviä haasteita ja tarpeita. Samoin kuvataan skenaarioanalyysien lähestymistapaa. Keski-Uudenmaan kaukolämpöverkon analyysejä tarkastellaan tapaustutkimuksena.

Skenaariotarkasteluissa esitetään energiajärjestelmän valinnan ja energiankulutuksen vaihtoehtoja tapaustutkimuksen avulla 20 vuoden aikana (2015–2035). Skenaariot perustuivat oletukseen, että rakennuskanta kasvaa ja rakennusten energiatehokkuus paranee tarkastelujakson aikana. Rakennusten kokonaispinta-ala kasvaa 35 % 20 vuoden aikana, mutta alueen kokonaislämmöntarve pienenee samaan aikaan 13 %, koska rakennusten energiatehokkuus paranee jakson aikana. Teimme kahdentyyppisiä skenaariotutkimuksia: Järjestelmäoptimoinnilla etsittiin optimaalista järjestelmävaihtoehtoa ottaen huomioon investointikustannukset. Energiasimuloinnein tutkittiin hajautetun energiantuotannon vaikutuksia energiatehokkuuteen, emissioihin ja energiakustannuksiin. Molemmissa skenaariotutkimuksissa oletettiin 20 vuoden tarkastelujakso.

Optimointimallilla voidaan tutkia tuotannon yksikkökustannusten ja ulkoisten olosuhteiden vaikutuksia optimaaliseen järjestelmäkokoonpanoon. Energiajärjestelmän optimointi perustui kolmeen pääskenaarioon: Nykyinen olemassa oleva bio-CHP-laitos (CHP = yhdistetty lämmön ja sähkön tuotanto) ja kaasukattila voivat olla käytössä vielä tarkastelujakson 2015–2035, CHP-laitos pysäytetään 2025, tai alueella ei ole energiantuotantoyksikköjä. Optimointi ottaa huomioon laitteiden ja energian kustannukset, ulkoiset olosuhteet (aurinko, tuuli) ja lämmön ja tehon tarpeet alueella. Vaihtoehtojen tarkastelut osoittivat, että on kustannusoptimaalista käyttää olemassa olevaa CHP-laitosta. Lämpöpumput, kaasukattila sekä tuuli- ja kaasuturbiinit tukevat energiajärjestelmää, kun CHP ei ole enää käytössä.

Energiasimulointitutkimuksessa muodostettiin skenaarioita tapaustutkimuksen lämmitysjärjestelmävaihtoehdoista. Skenaarioiden tarkoituksena ei ollut tehdä arvioita, millainen tulevaisuuden lämmitysjärjestelmä on, vaan pikemminkin tarkastella, millaisia vaihtoehtoisia kehityspolkuja on, ja arvioida näitä teknisillä, taloudellisilla ja ympäristökriteereillä. Kolme skenaariota – konservatiivinen, laaja ja äärimmäinen

(conservative, extensive, extreme) – kuvasivat aurinkolämmöllä ja maalämpöpumpuilla toteutettavan järjestelmän hajautuksen määrää. Vaihtoehtoina oli, että 1 %, 10 % tai 50 % rakennusten pinta-alasta oli lämmitetty hajautetulla uusiutuvan energian järjestelmällä. Vaihtoehtoina olivat myös teollisuuden ylilämmön käyttö sekä kuluttajan toimiminen lämmön tuottajana (prosumer), joka myy ylimääräisen lämmön takaisin kaukolämpöverkkoon.

Äärimmäisessä (extreme) skenaariossa maalämpöpumppujen ja aurinkolämmön käyttö pienensi keskitetysti tuotetun lämmön tarvetta 34 % ja teollisuuden ylilämmön hyödyntämisen tapauksessa 32 %, kun skenaarion viimeisten viiden vuoden arvoa verrattiin alkutilanteeseen 2015. Ei-uusiutuvan lämmön kulutus pieneni teollisuuden ylilämmön hyödyntämisen tapauksessa 46 %. Kun 20 % kaukolämmöstä tuotettiin teollisuuden ylilämmöllä, CO_2-päästöt pienenivät 50 %. Energiakustannukset riippuvat voimakkaasti tehdyistä oletuksista. Vuotuiset energiakustannukset pienenivät konservatiivisessa tapauksessa 22 % alkutilaan verrattuna, ja suurin alenema saavutettiin äärimmäisen (extreme) skenaarion tapauksessa (34 %). Konservatiivisessa, laajassa ja äärimmäisessä tapauksessa käytettiin lämpöpumppua, jolloin CO_2-päästöt kasvoivat referenssitapaukseen verrattuna, koska näissä tapauksissa käytettiin sähköä lämpöpumppujen toimintaan. Tapaustutkimukset osoittivat, että laskennalliset ympäristövaikutukset riippuvat voimakkaasti käytetyistä primäärienergian päästökertoimista, esimerkiksi siitä, käytetäänkö paikallisia vai kansallisia keskimääräisiä kertoimia. Kuluttaja tuottajana -skenaarion energiansäästövaikutus aluetasolla oli melko pieni (<1 %), koska tässä tapauksessa verkkoon myytiin vain ylimääräinen aurinkolämpö, jota syntyi vain kesäkuukausina.

Skenaariotapausten tulokset riippuvat voimakkaasti tapauksesta ja tehdyistä oletuksista. Energia-, ekologia- ja taloustekijöiden painotus tulee päättää, jotta lopullinen optimaalisen järjestelmän valinta voidaan tehdä. Nyt tehty skenaariotutkimus, joka sisälsi optimointi- ja simulointitarkasteluja, esittää menetelmän, jota voidaan käyttää todellisissa tapauksissa.

Preface

Energy efficiency is a key element in mitigating climate change. International Energy Agency has estimated that almost 40% of the global CO_2 emission reductions required to limit global warming less than 2 °C by 2050, can be achieved by improving end use energy efficiency. Improved efficiency of the building stock together with increasing share of distributed renewable energy production technologies, such as solar panels and ground-source heat pumps, propose new opportunities for improving the efficiency of the whole energy system.

This report outlines a vision for energy efficient district energy system based on the outcomes of the Efficient Energy Use (EFEU) research program. Future energy system is likely to propose changes to the roles of customers and energy providers and may result new types of service businesses that do not exist today. One of the key conclusions of the EFEU program is that for system level energy efficient solutions, all stakeholders are required to participate and to have a joint agenda. This report provides quantified visions of the future energy efficient energy systems might develop. The views of the participants together with the results of the simulated energy scenarios have been described.

This work was carried out in the Efficient Energy Use (EFEU) research program coordinated by CLIC Innovation Ltd. with funding from the Finnish Funding Agency for Technology and Innovation, Tekes.

EFEU program developed system level energy efficient solutions and services for fluid handling systems and regional energy systems. EFEU consortium consisted of 11 industrial partners and 5 research organizations. The industrial partners were ABB Oy, Empower IM Oy, Fortum Oyj, Fortum Power and Heat Oy, Gasum Oy, Helen Oy, Sulzer Pumps Finland Oy, SKF Oy, Valmet Technologies Oy, Wärtsilä Finland Oy and Wellquip Oy. The research partners were Aalto University, Lappeenranta University of Technology, Tampere University of Technology, VTT Technical Research Centre of Finland and Åbo Akademi University. The five-year program was started in 2012 and finished in 2016. The budget of the program was 12 million euros.

Juha Leppävuori
EFEU Program Manager

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Appendix A: Hourly weather conditions of simulations

Abstract
Tiivistelmä

1. Introduction

According to an English dictionary (Longman, n.d.), a district is an area of a country, city, etc. that has official borders, and a region is a large area of a country or of the world, usually without exact limits. Comparisons of building-related energy and other data can be done at different system levels (ADENE, 2013) where a district is a smaller unit than a region (Figure 1). This publication concentrates on the future district-level energy systems in Finland.

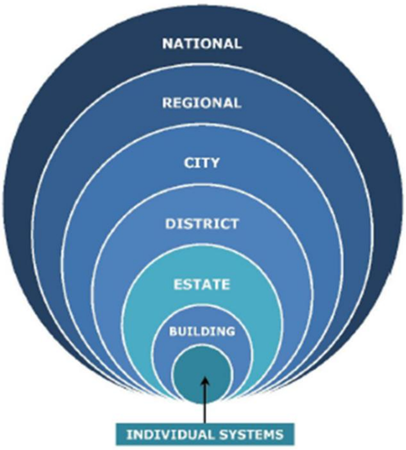

Figure 1. System levels for separate analysis (ADENE, 2013).

The three different scenarios, the Security scenario, the Devices scenario and the Values scenario, were created for the future energy systems within the EFEU project (EFEU, 2015). The aim with the scenarios was to create a common framework for the actors, decision-makers and others stakeholders in the field of energy and to facilitate dialogue. The Security scenario aims for a balance between local and centralized energy supply. The value of local energy production is increasing and as the self-sufficiency rate increases, the energy networks are becoming decentralized. The energy consumers are responsible for their energy production. They are not necessarily producing their energy themselves, but participate in cooperatives that operate power and local heat production plants. In new areas, low-temperature district heating networks are replacing the traditional ones, answering to the lower energy need of new buildings. The Devices scenario focuses on global agreements and a grid-free world. The importance of large-scale power production would decrease and devices would become energy-independent. The energy is locally produced. Smart devices that do not use electricity are used and the devices that need energy are used energy-efficiently and are powered by renewable resources. Ground source heat pumps are being used on an increasingly frequent basis. In the 2020s, a large share of new and renovated buildings in cities are going to use these as their source of heating. In the Values scenario, the energy price is expected to be high and the values to be immaterial. When energy prices are high, the most significant way to respond is with energy efficiency. Energy consumers are the key actors; the lifestyle and daily choices by consumers will have a large impact on the total energy demand (EFEU, 2015).

In order to concretize these scenarios in a shorter time frame, an industry workshop was held with participation of the EFEU partners. Figure 2 summarizes the elements discussed in this workshop. The core of the frame is the energy system components that the industrial partners selected for further analyses as well as the selected user types. The analyses are made within the designated time frame and using the relevant criteria. The scenarios define the variations in different analyses.

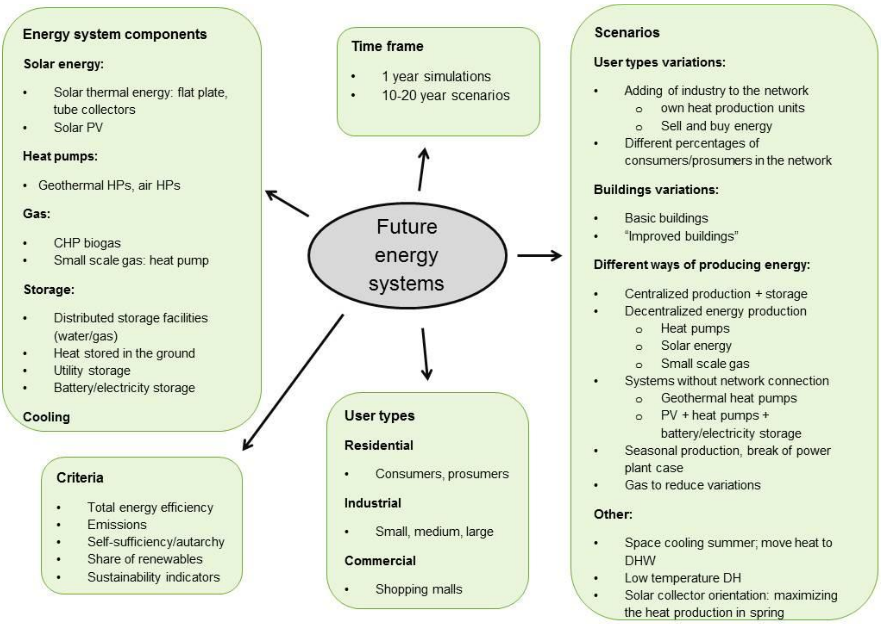

Figure 2. Research frame. CHP = Combined Heat and Power, DHW = Domestic Hot Water, HP = Heat Pump, PV = Photovoltaics, DH = District Heating.

This report strives to summarize the common vision of the EFEU project participants about energy-efficient district energy systems based on the EFEU project results. The report shows opportunities and possibilities for different stakeholders and analyzes effects of selected scenarios. The results could help the industry to anticipate future developments relevant to their business.

1.1 Background from Finland

1.1.1 District heating in Finland

The total heating energy consumption of the Finnish residential building stock was 58,480 GWh in 2012 (Statistics Finland, 2015). The corresponding energy sources are shown in Figure 3 indicating that 33% of the residential buildings are connected to district heating. The average price of district heating was about 74 €/MWh for detached houses (single-family houses) during the whole year 2012, and about 65 €/MWh for apartment buildings. The number of clients connected to district heating has been increasing steadily since the 1970s, but the specific heat consumption in district heated buildings has been decreasing (Figure 4).

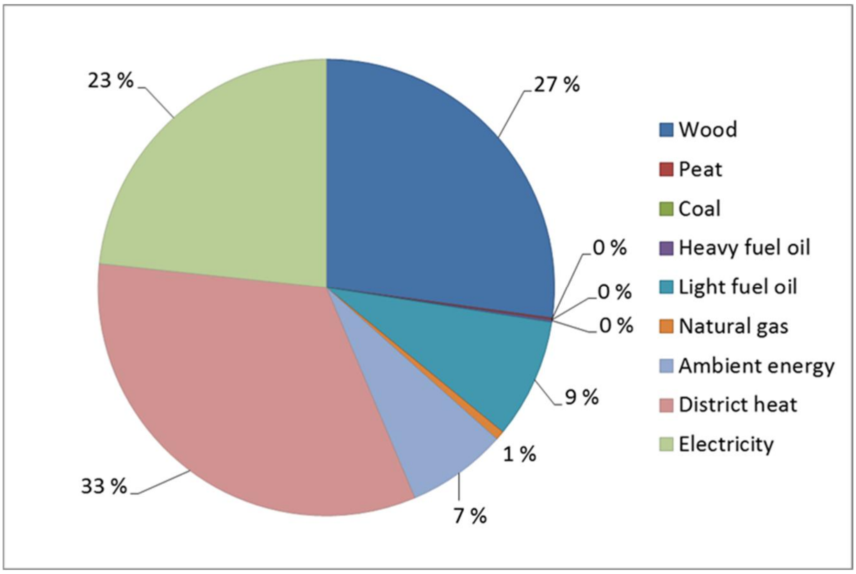

Figure 3. Heating energy sources of Finnish residential buildings in 2012 (Statistics Finland, 2015).

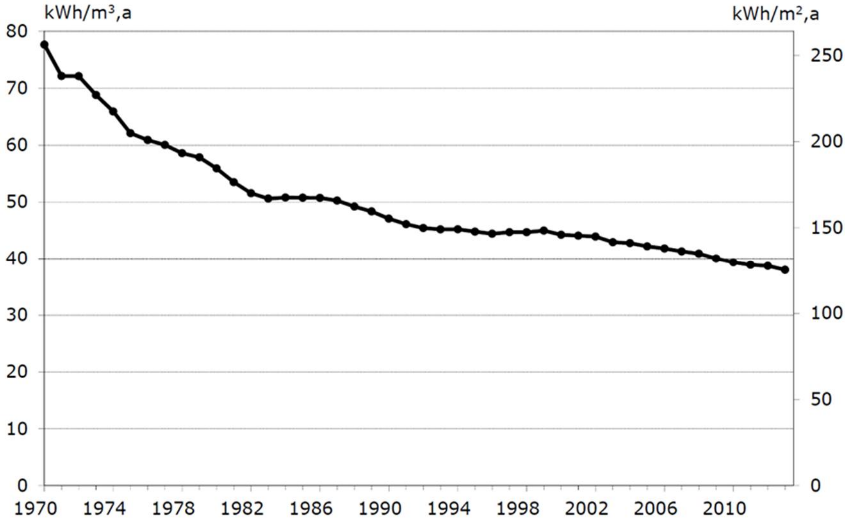

Figure 4. The specific heat consumption in Finnish buildings connected to district heating (Energiateollisuus ry, 2014a).

According to the Energy Year 2012 (Statistics Finland, 2013), the net production of district heat was 38,137 GWh, of which 51% was consumed in residential buildings, 9% in industrial buildings, 32% by other consumers, and 8% accounted for network and metering losses. Interestingly, consumption of district heat in Finland has been growing quite evenly since 1972 (Figure 5) but the shares of different consumer types have remained pretty stable (Figure 6). The total district heat consumption in 2012 was 35,236 GWh. Less than a third of the net production (30.6%) was produced in district heating plants (heat-only boilers) and 69.4% in combined heat and power plants (CHP).

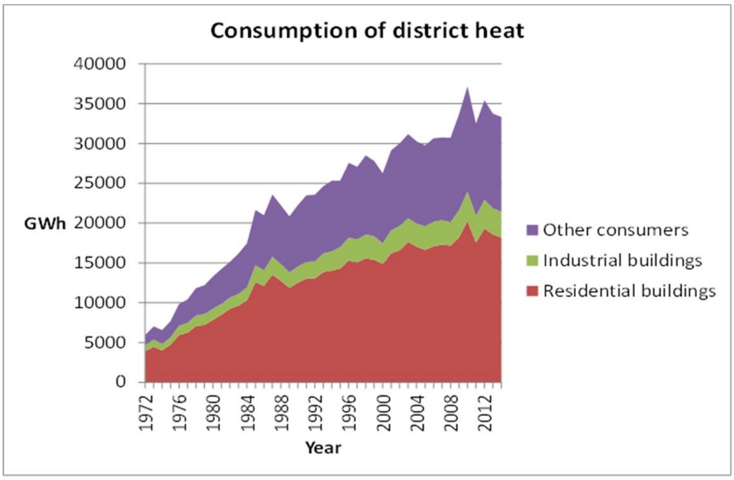

Figure 5. Consumption of district heat in Finland from 1972 to 2014 (Statistics Finland, 2016).

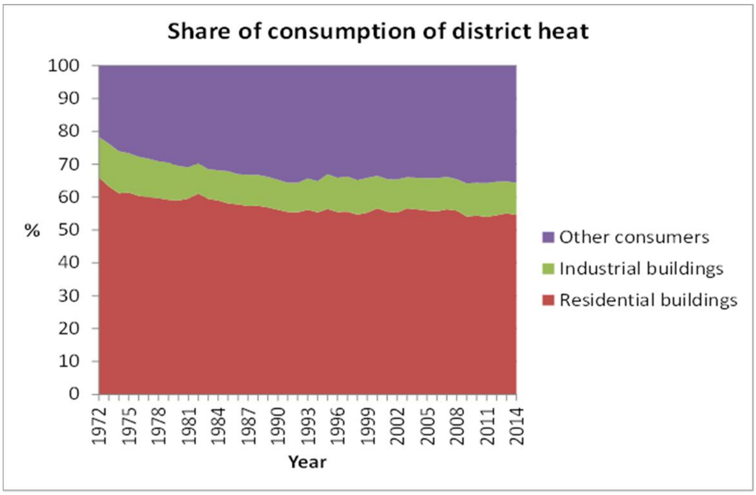

Figure 6. Shares of different consumer types in Finnish district heating networks (Statistics Finland, 2016).

In Finland, a two-pipe district heating system is used. Heat supply to buildings is performed by independent scheme. In every building there is an individual substation (Eliseev, 2011). Each individual substation is equipped with heat exchangers, circulation pumps, automatic regulation fittings, a heat energy counter, and automatic control devices.

1.1.2 Heat pumps in Finland

The utilization of heat pumps is nowadays a common alternative for covering the heat demand of buildings. The interest in heat pumps has rapidly grown over the last decade and especially in small detached houses is the interest in the technology high. The cumulative heat pump installations in Finland are shown in Figure 7.

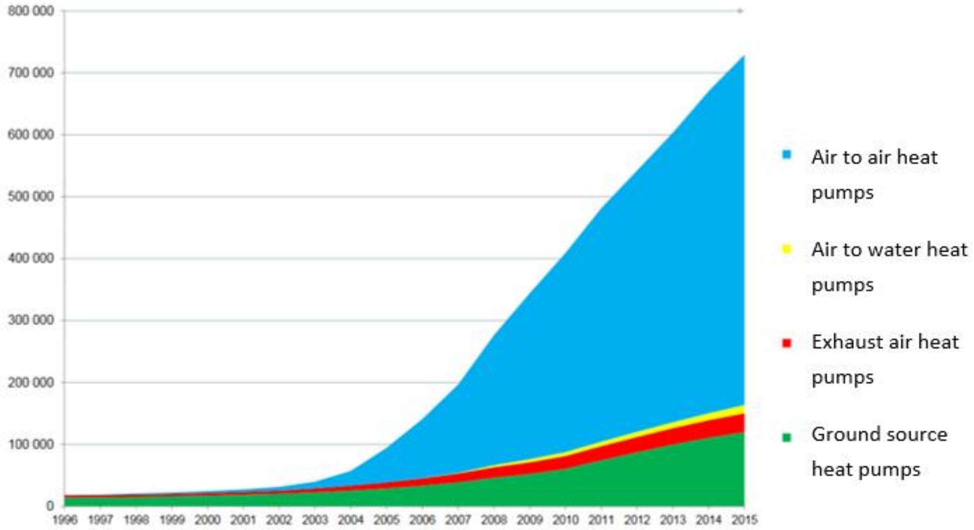

Figure 7. The amount of heat pumps installed in Finland in 2015. Adapted from Sulpu (2016).

In total, 730,000 heat pumps were installed in Finland in 2015. As could be seen from the figure, the market is dominated by air-to-air heat pumps. However, the interest in ground-source heat pumps has also been increasing. The share of exhaust air heat pumps and air-to-water heat pumps on the market is marginal.

In the future, heat pumps are expected to play an important role in both new buildings and retrofitted ones (Laitinen et al., 2014a). According to a forecast made by Laitinen et al. (2014b), the amount of installed heat pumps will increase by 140% by 2020 compared to the situation in 2010. The number of ground source heat pumps is expected to increase the most; by 320% compared to the situation in 2010. By 2030, the number of ground-source heat pumps will be double that of the year 2020 (Gaia, 2014).

1.1.3 Energy storage in Finland

Energy storage technologies can help to better integrate electricity and heat systems and can play a crucial role in energy system decarbonization by (OECD/IEA, 2014):

- improving energy system resource use efficiency
- helping to integrate higher levels of variable renewable resources and end-use sector electrification
- supporting greater production of energy where it is consumed
- increasing energy access
- improving electricity grid stability, flexibility, reliability and resilience.

Short-term thermal energy storage solutions exist in Finnish district heating networks (Fortum, 2015) but large-scale seasonal thermal storage facilities are rare. In addition, water tanks for storing domestic hot water are common.

Electricity storage systems in Finland are mainly experimental ones. But the largest electricity storage facility in the Nordic countries is to be commissioned in Helsinki in 2016 (Helen Ltd., 2016).

1.1.4 Gas in Finland

Natural gas is in Finland is imported from Russia altogether $3.9*10^9$ m^3 or 39 TWh (Finnish gas association, 2012). This is 10% of Finnish primary energy and 13% of Finnish electricity production. Natural gas is especially important in combined heat and electricity production. Additionally, biogas is produced 421 GWh from landfill recovery units, municipal wastewater, industrial wastewater, municipal solid waste and farms (Finnish gas association, 2012). Figure 8 shows natural gas consumption by sector in Finland in 2011.

In the future natural gas will probably also be imported as Liquefied Natural Gas (LNG) to terminals in the Finnish coastal area. This will provide opportunities to increase natural gas consumption in the western parts of the country. The amount of biogas production will steadily grow as can also be seen also in Figure 9 (Finnish gas association, 2012).

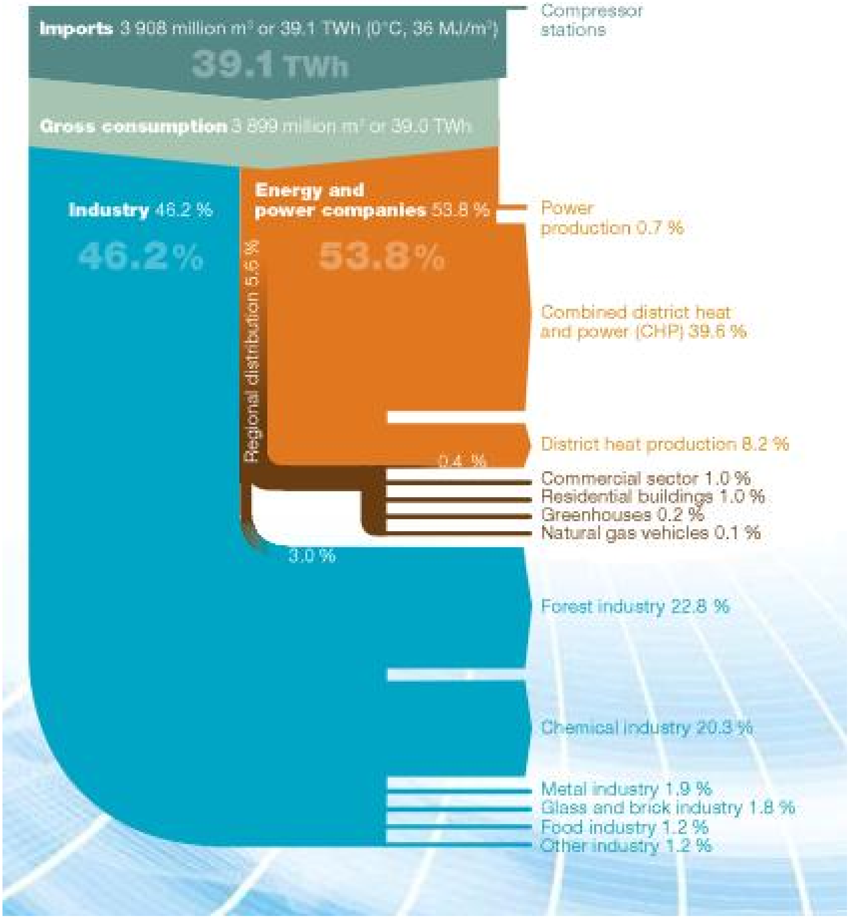

Figure 8. Natural gas consumption by sector in Finland in 2011 (Finnish gas association, 2012).

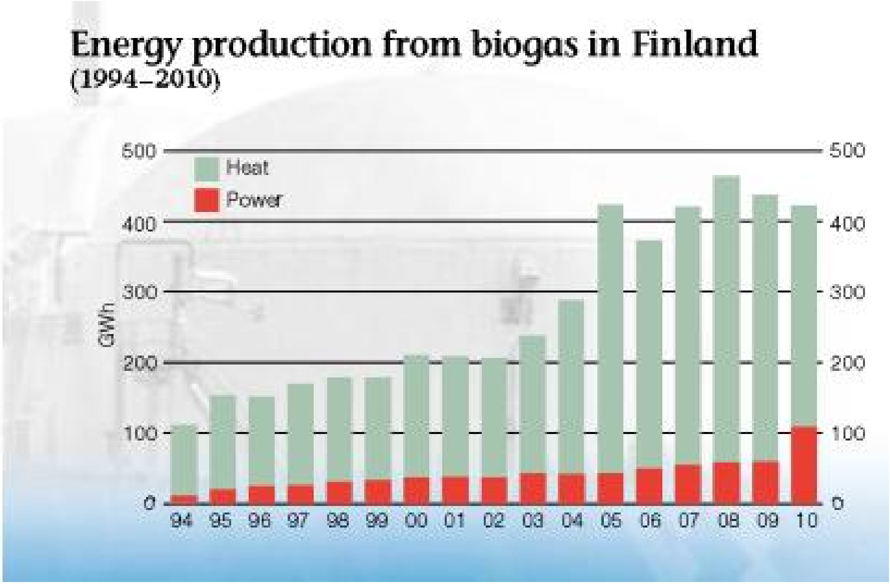

Figure 9. Energy production from biogas in Finland (Finnish gas association, 2012).

1.1.5 Solar potential in Finland

Considering only the European targets for the share of renewable energy in gross final energy consumption in 2020, increasing solar or any other renewable energy would not be needed since Finland has already reached the national target in 2014 (Figure 10). However, there are also longer term targets such as a national goal to switch from coal combustion to renewable energy sources (Rehn, 2015) which also promote increasing solar utilization.

Figure 11 shows the yearly sum of global irradiation in Finland. As can be seen from Figure 12 this potential, especial for solar power, does not vary much from Central European countries, especially for the Southern, more crowded, parts of Finland. Finland is still one of the few countries in the EU that has hardly taken any direct subsidies into use for solar energy (Haukkala, 2015) and where the utilization rate of solar energy is quite low. In 2012, only about 14 GWh of solar heat and about 5.5 GWh of solar power were produced in Finland (Statistics Finland, 2013).

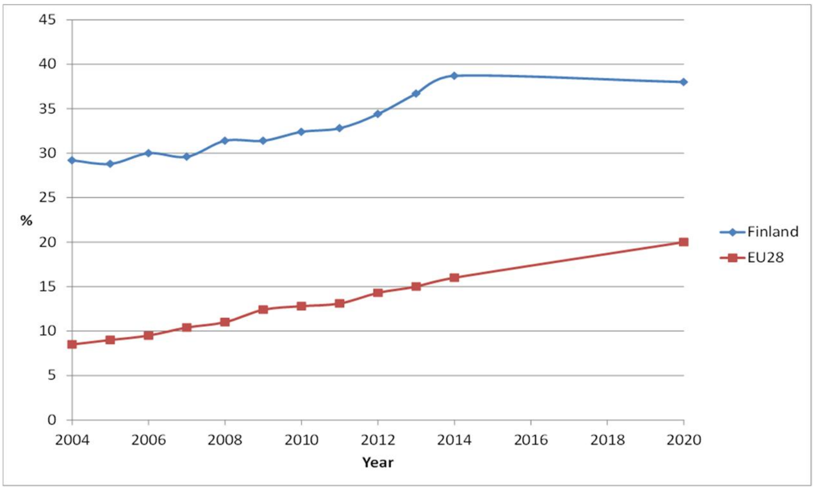

Figure 10. Share of renewable energy in gross final energy consumption (2020 estimate) in Finland and EU-28 (Statistics Finland, 2016).

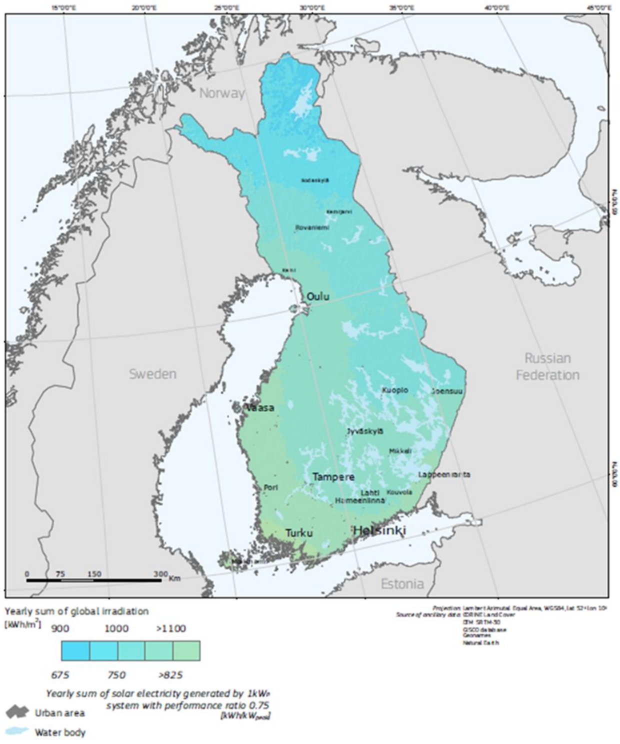

Figure 11. Global irradiation and solar electricity potential for optimally-inclined photovoltaic modules in Finland (Joint Research Centre (JRC), 2012).

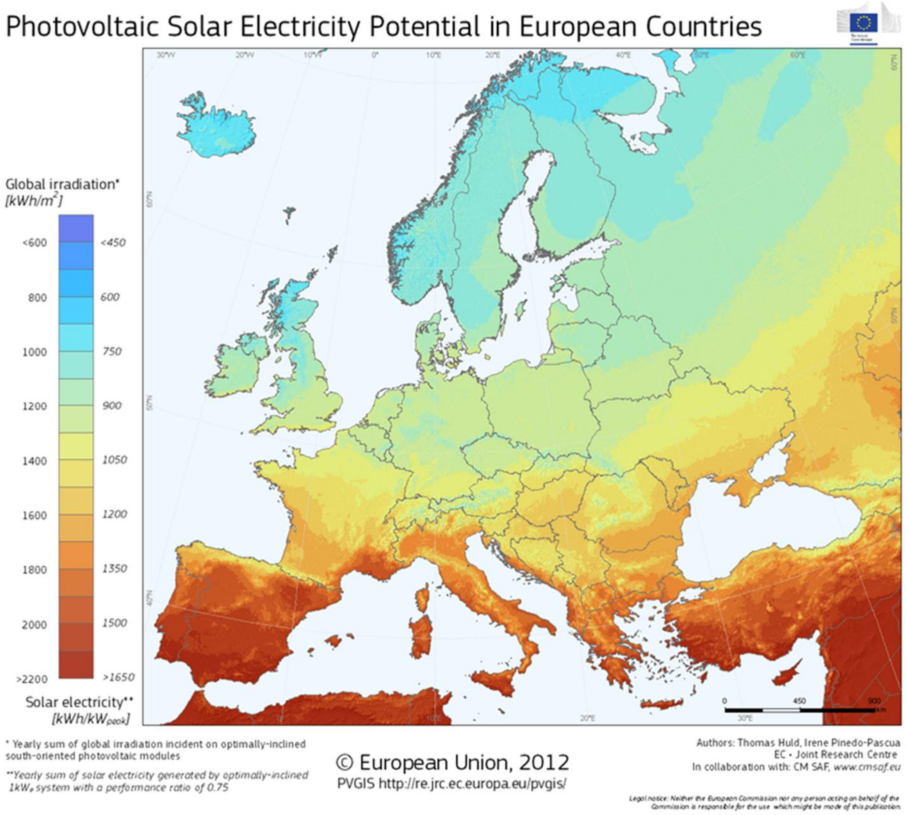

Figure 12. Solar irradiation and photovoltaic electricity potential for Europe (Joint Research Centre (JRC), 2012).

1.1.6 Finnish building typology

At the end of 2013, there were somewhat less than 1.5 million buildings in Finland as (Statistics Finland, 2015). Approximately 1.1 million of them were detached houses, which represented 76% of the number of buildings. However, the detached houses (referring to single-family houses) formed only 34.7% of the total building gross floor area (Table 1). There were approximately 58,000 blocks of flats (referring to multi-family apartment buildings) which represented only 3.9% of the number of buildings, but forming 20.6% of the total building gross floor area. The industrial buildings formed the third biggest share of total gross floor area with a share of 10.6%. More detailed building classification can be found in Table 1.

Table 1. Finland's building stock as of 31.12.2013. Source: (Statistics Finland, 2015).

Building type	**Number of buildings**	**% of number of buildings**	**Gross floor area (m^2)**	**% of gross floor area**	**Avg. gross floor area (m^2)**
Buildings total	**1,483,990**	**100,0**	**455,426,818**	**100.0**	**306.9**
Detached houses	1,128,366	76.0	158,054,032	34.7	140.1
Attached houses	78,751	5.3	33,537,646	7.4	425.9
Blocks of flats	58,430	3.9	93,825,473	20.6	1,605.8
Commercial buildings	42,704	2.9	28,791,780	6.3	674.2
Office buildings	10,881	0.7	19,307,980	4.2	1774.5
Traffic buildings	56,197	3.8	12,521,115	2.7	222.8
Institutional buildings	8,520	0.6	11,910,495	2.6	1,397.9
Buildings for assembly	13,899	0.9	9,396,449	2.1	676.1
Educational buildings	8,888	0.6	18,266,143	4.0	2,055.1
Industrial buildings	42,245	2.8	48,380,771	10.6	1,145.2
Warehouses	29,443	2.0	19,530,693	4.3	663.3
Other buildings	5,666	0.4	1,904,241	0.4	336.1

Figure 13 shows Finnish apartment buildings (buildings including blocks of flats) by year of construction as of 31.12.2013. The number of buildings is shown on the left and the equivalent gross floor area on the right. As can be seen, the majority of the apartment buildings have been built in the 1970s. In 2013, 77.4% of the apartment buildings were connected to district heating (Statistics Finland, 2015).

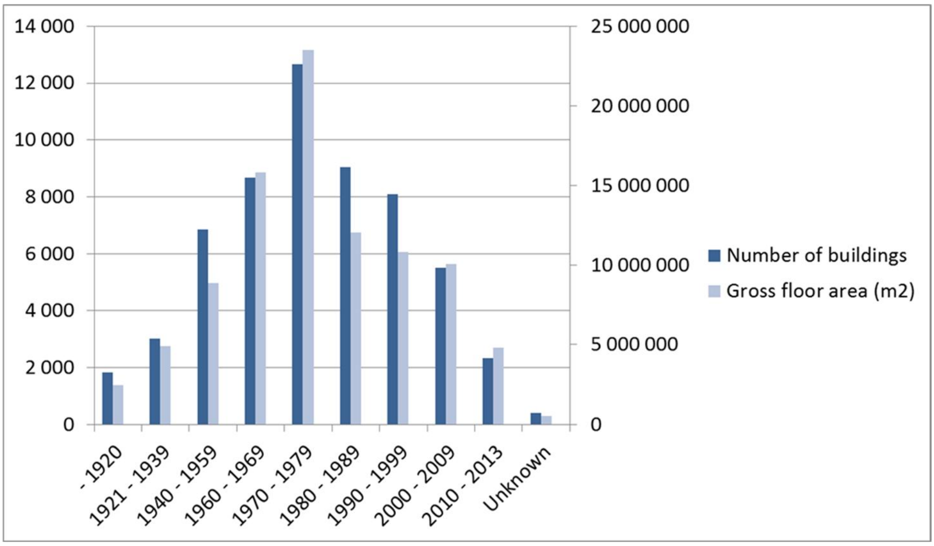

Figure 13. Finnish apartment buildings by year of construction. Source: (Statistics Finland, 2015).

The allowable maximum U-values for the main building components according to the year of updated legislation are given in Table 2. Often the realized values met the maximum at the time of construction. As can be seen in Table 2, over time, the mandatory heat insulation requirements for buildings' envelope have been tightened.

Table 2. The maximum U-values (W/m^{2}K) for the main building components in Finland's building codes (Ministry of the Environment, 2015a, 2015b).

Building component	**1969**	**1976**	**1978**	**1985**	**2003**	**2007**	**2010**
External wall	0.41-0.93	0.4	0.29	0.28	0.25	0.24	0.17
Floor	0.35-0.47	0.4	0.4	0.36	0.25	0.19	0.16
Roof	0.35-0.47	0.35	0.23	0.22	0.16	0.15	0.09
Window	2.44-3.14	2.1	2.1	2.1	1.4	1.4	1.0
External door	-	-	-	-	1.4	1.4	1.0

1.2 Relevant trends

1.2.1 Prospects of district heating

Figure 14 shows the evolution of district heating in terms of temperature, efficiency and best applied available technologies along the time where four generations of district heating can be identified. The inverse relationship between the efficiency and the temperature in Figure 14 stands out. In addition, the efficiency of the 4th generation of district heating is boosted by the adoption of renewable systems.

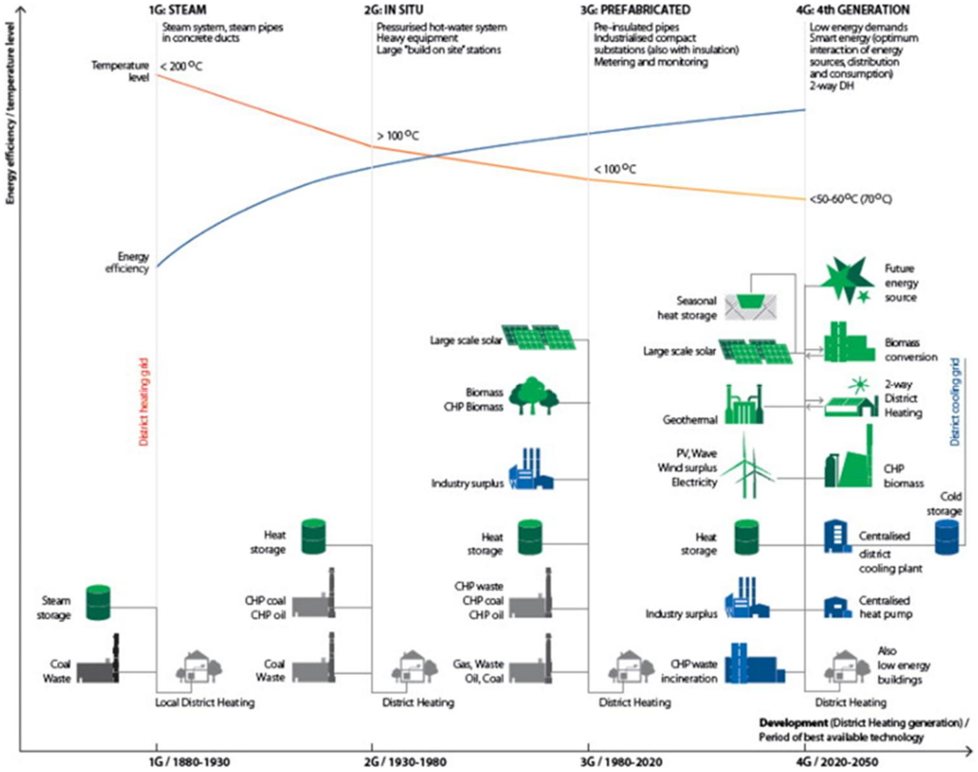

Figure 14. Illustration of the concept of 4th Generation District Heating in comparison to the previous three generation (Lund et al., 2014).

On the other hand, the demand side of district heating consists of buildings built in different periods of time. This means that they have different thermal loads and, in particular, they use different indoor space heating distribution systems, which require diverse inlet temperature set points of the heat carrier fluid. Table 3 shows the inlet/outlet design temperature of the common indoor distribution systems and also the building level of insulation associated with them.

Table 3. Inlet/outlet design temperature of the common indoor distribution systems.

Indoor distribution system typology	**Associated building insulation level**	**Inlet/outlet design temperature**
High temperature radiator (Lauenburg and Wollerstrand, 2014)	Poor	80/60 °C
Radiator (Maivel et al., 2015)	Medium	55/45 °C
Low temperature radiator (Maivel and Kurnitski, 2014)	Good – NZEB (nearly zero energy building)	40/30 °C in apartment buildings. 45/35 °C in detached buildings
Floor heating (Ren et al., 2010)	Good – NZEB (nearly zero energy building)	35 °C / 30 °C
Air heating based (Risberg et al., 2015)	Poor – Medium – Good	40–50 °C / 30–40 °C

In addition to space heating, domestic hot water (DHW) also has to be supplied at a minimum of 55 °C. Therefore, if no additional heating is used in buildings, the heat carrier fluid, usually chemically treated water, of the district heating production-side needs to reach at least the highest inlet design temperature with a certain margin. However, the inlet operating temperatures of the indoor heat distribution system are different from the design ones throughout the year. They vary according to the implemented strategy (Gustafsson et al., 2011), reaching the design values only in the event of severe external cold.

Finnish district heating is facing important challenges, since new European regulations are coming in to play affecting both energy generation methods and building energy efficiency (Paiho and Reda, 2016). Basically, buildings are becoming more efficient and renewable technologies more cost-effective. In addition, the new player, called the 'prosumer' has the dual role of being both an energy producer and a consumer will change the network structure. As Figure 15 shows indicatively, there can be different kinds of prosumers as well as independent heat producers. In the EFEU project, (Paiho and Reda, 2016) identified the key properties of existing and future district heating in Finland. These are listed in Table 4.

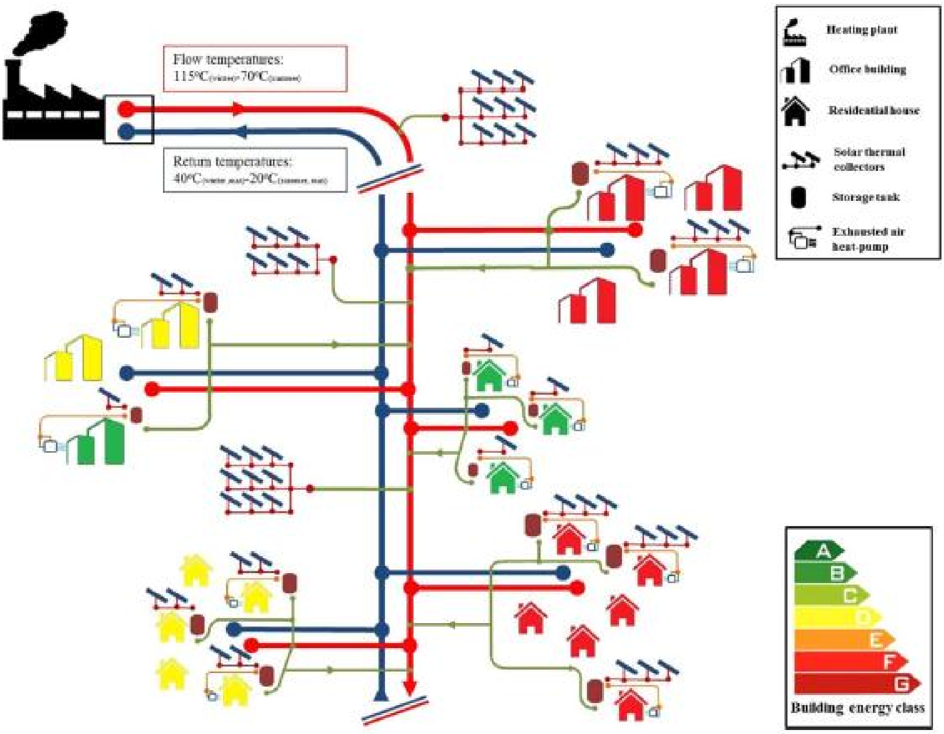

Figure 15. Solar assisted district heating concept with different kinds of prosumers and energy producers. Note: the depicted energy production technologies are only indicative. Note2: Building energy class is only indicative of the different energy consumption of buildings. Source: (Paiho and Reda, 2016).

Table 4. Key properties of existing and future district heating in Finland (Paiho and Reda, 2016).

Existing district heating	**Future district heating**
• Strong role of non-renewable energy sources • Based mainly on centralized production • Typically, municipal production monopolies • Existing stakeholders • Supply water temperature supporting high- or medium- temperature radiators • Buildings with varying energy efficiency connected to district heating • Traditional technologies • Traditional business models	• Increasing share of renewable energy sources • Enabling trigeneration (production of electricity, heating and cooling energy) • Increasing share of distributed and local production • Networks opened for all heat suppliers • Introducing prosumers • Supply water temperature supporting low-temperature heating

	- Increasing share of nearly zero-energy buildings connected to district heating - Utilization of supportive technologies - New business models

1.2.2 EU directive towards nearly zero energy buildings (nZEBs)

The Directive 2010/31/EU (Official Journal of the European Union, 2010) requires that by the year 2020, both European greenhouse gas emissions and energy consumption should be decreased by 20%, and the share of renewable energy sources should be increased by 20%. Moreover, all the new building should be nearly zero-energy buildings (nZEBs). This raises new challenges in the European building sector, which is now going through a delicate transitional phase towards more energy efficient buildings, such as low-energy buildings and passive houses. One of the first measures at the European level, which was responsible for initiating the process of improving the energy efficiency of buildings, was the energy performance of building directive (EPBD) recast (EN 15603). Figure 16 shows the timeline for nZEBs' implementation according to the EPBD recast.

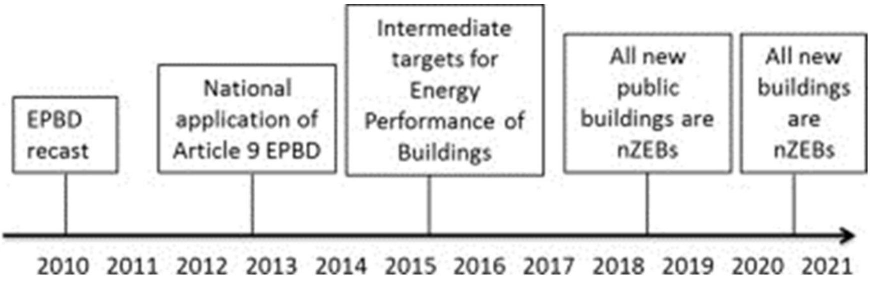

Figure 16. Timeline for nZEBs' implementation according to the EPBD recast (D′Agostino, 2015).

There is no established definition of a zero-energy building (ZEB), e.g., (Marszal et al., 2011; Deng et al., 2014), nor the terms used, such as net zero-energy buildings (nZEBs), e.g., (Kapsalaki and Leal, 2011; Kibert and Fard, 2012). The Directive 2010/31/EU (Official Journal of the European Union, 2010) defines 'nearly zero-energy building' as a building that has a very high-energy performance and that the nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby. In general, it is understood that an nZEB produces as much energy as it consumes throughout the year. Net ZEBs have a dual role of being energy producers and consumers ('prosumers') (Salom et al., 2014). In addition to the terminology used, the energy balance and calculation methods also differ for nZEBs (Marszal et al., 2011).

Adopting the EPBD recast is on process in Finland. In spring 2016, comments on suggested legislation are being asked from different interest groups and stakeholders (Ministry of the Environment, 2016). The proposal quite closely follows the results of the FinZEB project (“FInZEB,” 2015).

2. Stakeholders

This chapter describes some of the main stakeholders involved in future energy systems.

Prosumers
The agents in an energy system who both consume and produce energy are called prosumers. They can also sell and feed in energy to the grid instead of just using it for their own consumption.

Energy companies
An energy company is basically responsible of producing the energy. They have also more and more responsibilities to produce energy environmentally friendly and efficiently. In power production and distribution has been separated but in district heating one company can be responsible of both. Basically an energy company can provide a large portfolio of products and services based on its own business strategy.

An **energy system installation company** can provide services like analysis of the site, design of a system and installation. They can also handle the commissioning of the system with the grid electric service provider.

Energy system or component manufacturers
These companies provide technical solution that can vary from small single components (e.g., valves) to large scale system deliveries (e.g., district heating network) and maintenance based on their product service portfolio.

(Smart) **energy solution providers** have a wider service offering covering the management of customer's power system. These services can also aim to cut energy costs and improve energy savings. Services can include, e.g., measurement, system change planning and management as well as data analysis.

Energy grid operators
An energy grid operator is responsible for moving the energy from a producer to a consumer. This role is becoming more demanding and complex in the distributed energy system. They can also have a role to provide energy storage services on the system level.

Regulators
Regulators have the responsibility to supervise enforcement of legislation and regulations. They also participate in the preparation of a legislative proposal and thus have the important role of being the middleman between the EU/national/municipal level and energy service providers' needs.

Municipality
A municipality is responsible for securing the availability of energy in the area. Many of them have also signed energy efficiency agreements. In an innovation network, they can also take a more active role as an enabler and leader of collaboration activities.

Developers and construction companies
The role of the developers and construction companies is to efficiently implement objectives determined on the market and to produce alternatives based on their own know-how. In a correctly implemented innovation environment, this know-how can be leveraged from the beginning of the planning phase; the competitive negotiated procedure is an example. In a partnership network, the suppliers of building technology and energy systems play an essential role.

Residents
Demand for the area ultimately depends on the residents. Many of which are becoming prosumers, both private property owners and condominiums. They also have the potential to provide energy flexibility capacity. Reacting and responding to the needs of customers requires cooperation between the operators in the area right from the beginning of the area development project.

Architects
The area as a whole must be both pleasant and functionally successful. In the future, energy solutions will have an even bigger role in image creation. With regard to renewable, locally produced energy, the most important task of an architect is to successfully create a symbiosis between technology, visual imagery and practicality in interactive cooperation with the other members of the network and stakeholders.

Providers of energy services
Energy (heat, electricity, cooling) production and distribution in itself comprises only a part of the services required in the area. In addition to energy, customer-targeted communications, planning, maintenance, finance, measurements and monitoring are required, among other things. Other services related to the area's energy solutions include transport and parking, ICT, business support services, municipal services (e.g. schools, day care centers and sports).

Research and development networks
Research in locally produced energy solutions is very active, both in Finland and internationally. Comparisons between areas and solutions (benchmarking) are possible in research projects. Examination of the subjects can also continue over their life cycle through active participation, with key projects being sought out for each stage.

3. Industry views

Several discussions and workshops were organized with the companies participating in an EFEU project to incorporate the industry's views. In this chapter, the main topics discussed are presented to emphasize some of the concerns and future prospects that industry has about the future of district energy and the related efficiency discussion.

3.1 Forecasting the business landscape

The forecasting of the evolution of the energy business ecosystem is probably the most important topic brought up by companies. A big challenge is the unpredictability of national and EU policies on subventions like feed-in-tariffs as well as evaluation rules for CO_2 emissions. The impact that policies have, both at the stimulus side (incentives, e.g., subsidies and investment support) and the regulation side (e.g. taxation), on investment planning is especially crucial. The shorter the foreseeable future the shorter the economically acceptable payback time for an investment is. This drives financing away from the riskier long term investments. The worst-case scenario is that the post-investment change of rules makes the already realized investments unprofitable.

In the future, companies see decentralization of energy systems, but the impact will not be the same for all districts or types of energy: In distributed energy systems, energy efficiency is mainly determined by locally available renewable or excess energy resources. Solar and wind power production are generally considered to gain a great share of electricity production while, when available, local biomass and waste streams may as well be used as primary electricity and heat sources via CHP production.

For future decisions, a key question pertains to the definition of a 'district' or another boundary of a system to be optimized and how this will guide calculation rules set by authorities both for energy efficiency and emissions. The framework of any future business case will then be heavily impacted by this and the weight of local renewable energy sources and storage capacity will then be optimized accordingly. A district is not only the geographical but also a systemic definition that includes the actors, types of energy and time.

However, only the selection of a geographical district already has a formidable impact on the final results. Basically it can be a block, a district, a city or the whole country. Shall we do partial optimization or also go for the EU-level 'smart grid' in district heating? The best technologies, e.g., for energy storage are quite different on one block versus on a city level. The big challenge here is the increasing complexity as the system grows bigger. Already on the district level, energy efficiency is much harder to grasp than on the building and technological level.

3.2 Customer orientation

Co-innovation with the customers is seen as an important means of building the new technology-based solutions and product service system (PSS)-oriented business models. New opportunities are constantly forming in the ecosystem of business and they need to be made visible for exploitation. These opportunities appear in different parts of the ecosystem with different actors and their individual timing, thus making the understanding of the system-level connections and processes viable for value capture. The forecasting of the customer needs is based on customer understanding that requires active cooperation. The co-creation and value capture takes place in the legislative framework of public procurement that has to enable long-term energy efficiency-driven planning and execution.

The awareness of municipalities about energy efficiency and its systemic nature and new procurement models like ’competitive bidding’ is growing and the role of municipalities as a district’s enabling manager is becoming more and more important.

3.3 The impact of renewable energy technologies to energy system characteristics

As the use of renewable energy technologies (e.g., solar, wind) expand, it creates a challenge for managing the total energy system and steady electricity supply. This is due to their weather-dependent fluctuating electricity output. There are two major approaches to manage this fluctuation, storage and responsive ‘traditional fuel’ electricity production. Gas is often considered a potential back-up energy source due to swiftly responding gas motors and gas power plants while gas is also suitable for traffic use and process industry. Locally, gas can be produced in biogas plants or by storing electricity via Power-to-Gas technology to hydrogen or electro-synthetic natural gas, but LNG or LBG imports could also be feasible.

3.4 Energy efficiency as a business

Economical reasoning and rational planning must be the foundation for all decisions. In decision-making, there are common drivers and goals for all actors, but also exclusive ones for each partner. The drivers of the main partners have more weight in decision-making but all of the partners have to be notified to make the system work.

From the point of view of the companies, the solutions and investments have to be economically feasible and profitable. Various know-how, capabilities and investments are required from the actors providing different solutions in type and size with different product and service requirements. If optimization is driven by the business interests of the individual actors, a component provider has quite different motivations than one with the responsibility to provide the total service with years of maintenance for the customer. Here the providers' business collaboration and customers' procurement expertise is the key to long term success.

The companies see energy efficiency as a tool that guides rational planning. In the long run this is also true for the consumers, municipalities and nation: It is not possible to run an unprofitable business for a long time (the pilots/trials can be unprofitable). Undoubtedly the discussion about an enterprise's value in society and economy has to determine the relationship between economic and non-economic values and their importance. This discussion will then directly subsidize and compensate, e.g., through taxation and investment aids. However, within the economy, the business has to be profitable. A kind of a 'base line' for this will be set by the primary energies selected since the importance of energy efficiency is proportional to the environmental impact of the primary energy used.

The new business ecosystem spills value that will benefit the local economy in general. Tore solutions are based on local technology the more value is captured locally. The local product and service suppliers gain competitive advantage in international tendering through customer references. In each customer case in Finland and abroad, it should be discussed how to get the most out of each as a customer reference to support future tenders and offerings.

4. Regional collaboration and service business perspective

4.1 Collaborative approach required

Traditionally, different stakeholders within a region manage and develop their energy use or production independently. Utilization of, e.g., excess energy of other stakeholders in the region has been rather sporadic. Regulatory policies driven by increasing energy costs and sustainability needs, related to, e.g., the use of renewable energy sources and energy efficiency have also directed attention towards the opportunities for regional energy collaboration. This requires a new kind of innovative cooperation between the stakeholders.

Regarding the development of energy efficiency in a region, our conceptual idea is to utilize the existing and new energy production technologies within the region more efficiently by matching the regional energy demand and supply more intelligently. The two major challenges are typically that the different stakeholders within the region manage and develop their energy use/production independently and the regional energy efficiency viewpoint is typically not included in the processes of decision-making and planning. To improve the situation, collaborative decision processes between stakeholders are required, e.g., relating to the management of energy resources, investing in the required technologies and managing the energy's delivery (Figure 17).

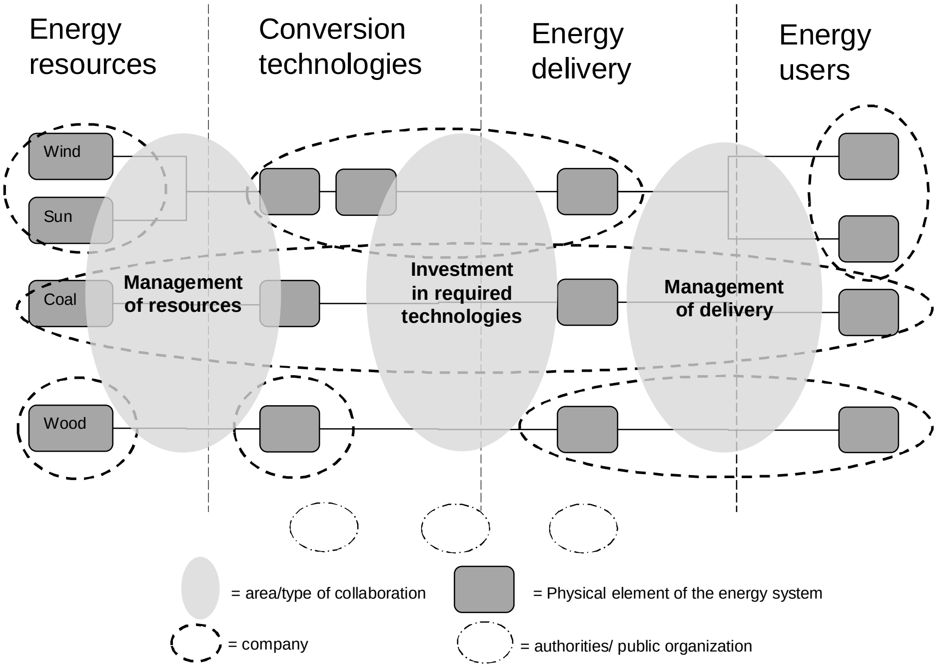

Figure 17. Regional energy collaboration context (Jussila et al., 2014).

Figure 18 illustrates one approach to building regional collaboration. The approach has three main phases and it is extremely important that all key stakeholders are included in the process from the very beginning: 1) joint analysis of the current situation, identification of development opportunities and setting of mutual targets, 2) joint planning and experimentation of solutions to achieve the targets, 3) establishing workable solutions in everyday practice.

In order to achieve a common understanding of the development opportunities, basic information and data are required to lay out the necessary joint development and discussions to bring about feasible solutions and opportunities. Utilizing third-party expert organizations to gather and analyze the base data is a viable solution to obtain this kind of unbiased base information. On this foundation, joint master agenda and development scenarios can be built. As an example, a workshop carried out in one EFEU case region concluded that there is a need to reach a mutual understanding of the following factors affecting regional energy efficiency:

- Energy use patterns (residents, public sector and industrial users)
- Energy technologies (e.g., geothermal heat) and fuel selection (e.g., optimal mix between bio and fossil)
- Market conditions such as energy price, subsidy policies and taxation issues
- Waste energy reduction/utilization
- Current regional infrastructure and future city planning

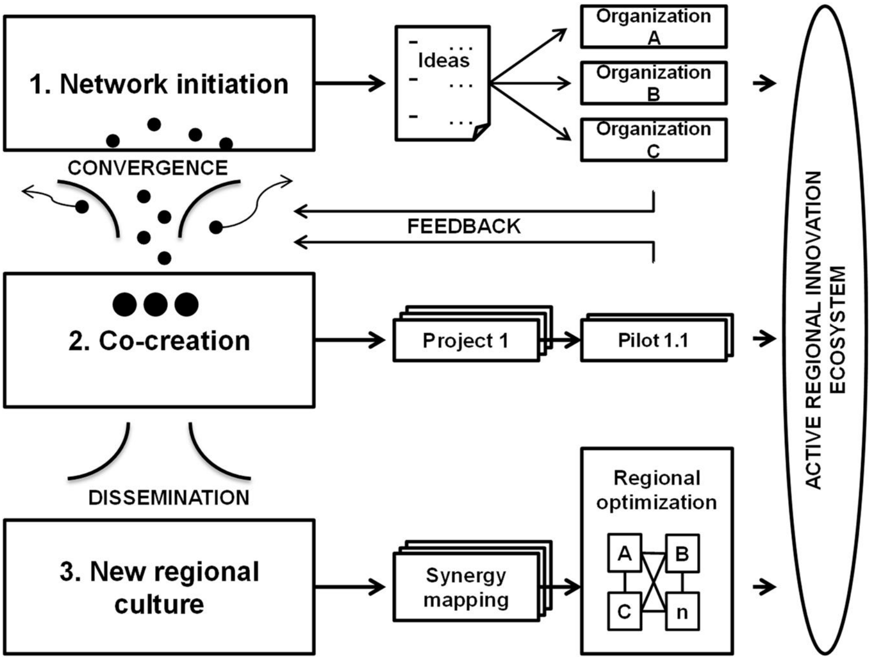

Figure 18. Developing a collaborative approach to regional energy system development (Jussila et al., 2014).

Starting the broader collaboration from zero requires time and several meetings to reach the first joint conclusions on collaborative energy efficiency activities. This calls for an actor who is able to facilitate the process in the long-term. Our current understanding is that the most suitable actor would be some municipal organization that naturally has a long-term interest in developing the region.

As mentioned earlier, reaching a common understanding of the development opportunities and creating a joint agenda for it is a challenging task when the stakeholders' businesses and strategies vary significantly. Table 1 presents a comparison of the key findings of two EFEU case studies regarding the case-specific and common factors that either support or hinder collaboration in regional energy efficiency development. Some interesting findings can be highlighted.

First, good personal-level relationships were brought up in both cases. It appears that people working in a specific region and in a specific domain can form a grassroots-level foundation on which to build organizational collaboration. However, there is a lack of resources to be allocated for the collaboration from the organization's perspective.

Second, it is very challenging for individual organizations to commit themselves to long-term joint energy system solutions due to the varying time spans in their business planning.

Third, the collaboration activities require continuous coordination and guidance. Our studies suggest that there should be a leading organization which has a long-term interest in the region. In the case of Finland, one potential source of leading organizations are the development companies of the municipalities.

Considering the potential differences in regional energy-efficiency development solutions, we can identify some background factors. First, rather obviously, if the region crosses the boundaries of many municipalities, it requires a higher level of collaboration than in the case of a region situated within a single municipality. Thus, a corresponding management level for the collaboration must be introduced. Second, if the region has heavy energy users, it may be possible for the region to reach its energy efficiency development targets if a single large user makes an improvement investment to its operations independently.

Table 5. Common and specific supporting and barrier factors for collaborative regional energy-efficiency development.

	Case A	Case B
Case-specific supporting factors	• Bilateral development of energy systems between stakeholders exists	• Collaboration activities exist in other areas between municipalities
Case-specific barrier factors	• Size difference of the different stakeholders (in energy use) • Different planning horizons of the different stakeholders	• Municipalities often focus on the efficiency of energy utilization, whereas energy producers would like to extend the focus to the production side as well (i.e., the whole energy system) • Competition between municipalities • Stakeholders' energy consumption relatively low, not enough potential savings appeal
Common supporting factors	• Energy efficiency is a common goal for all stakeholders • Good relationships between personnel in different organizations	
Common barrier factors	• Limited resources to initiate and maintain active collaboration • Internal energy efficiency development activities dominate external activities • Energy efficiency is only one of many goals • Lack of leader organization for the collaboration • Competing long-term commitments • Lack of commitment to joint long-term initiatives	

4.2 Service business opportunities

The future energy system is characterized by being more open, decentralized, inclusive of several different technologies and for its engagement of new stakeholders. Figure 19 illustrates this in the context of a district heating and cooling network.

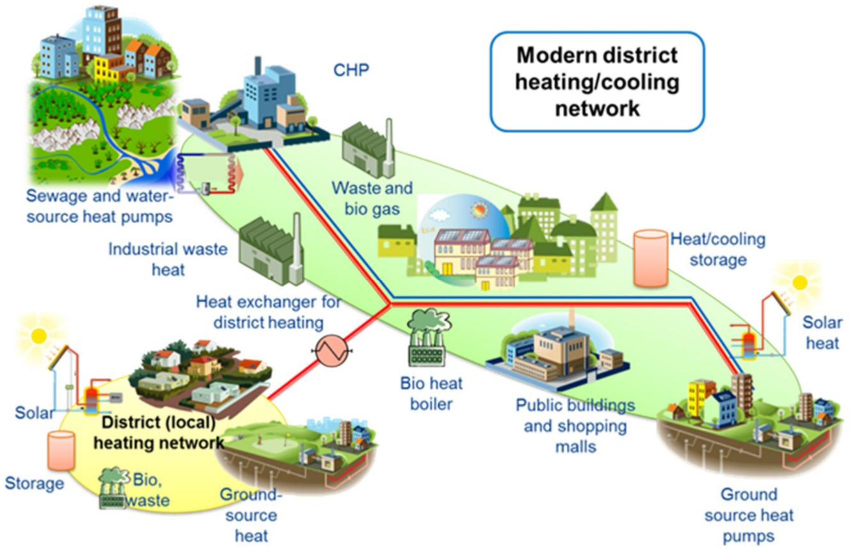

Figure 19. Future energy system consists of a broader range of technology solutions and stakeholders. (Source: Fortum 2015.)

This also creates new service business opportunities. Here, these opportunities are considered from two perspectives: the implementation of regional collaboration perspective and the support of the adoption of new energy technologies perspective.

Regarding the implementation of regional collaboration, the following services are required:

- Initiation phase:
  - Regional energy analyses (energy balances, flows, etc.)
  - Identification and engagement of relevant stakeholders
- Operational phase
  - Knowledge provision for decision-making (continuous)
    - Measurement and analysis services
    - IT-system services
  - Continuous facilitation of collaboration
  - Separate analysis concerning specific energy investments

The most relevant stakeholder types to provide these kinds of services are energy consultants, data analytics providers and municipal development companies.

Adoption of new technology solutions always creates need for supporting services. When energy systems become more open and new stakeholders become more closely engaged with the operation of the system, the following general service needs can be identified:

- Training and education: Is required to promote awareness about the new technology and the opportunities it enables. Also, basic knowledge is required by the new stakeholders with relatively low understanding of the energy system and technologies (e.g., prosumers)
- Planning and engineering: new competences are required to design the new energy systems.
- Funding: to implement the novel solutions with varying stakeholder constellations making the investments may require new kinds of funding models as well.
- Operation and maintenance: Some stakeholders who don’t consider themselves sufficiently competent to operate the new solutions may opt for outsourcing the operation and maintenance activities to a service provider.

The above activities provide new service opportunities for a broad range of companies such as educational organizations, technology providers, engineering companies, funding agencies and system operators.

Some examples of the service business opportunities are presented in Table 6 below.

Table 6. Examples of service business opportunities.

Service	**Description**
Energy storage	If local producer / prosumer has no interest or economically feasible solution to handle heat or power storage locally a storage service on the network level could sell this as a service. This requires metering and billing solutions able to determine prices for trading.
Platform as a Service (PaaS)	Defined by Wikipedia as “a cloud computing service that provides a platform allowing customers to develop, run, and manage applications without the complexity of building and maintaining the infrastructure typically associated with developing and launching an app” PaaS could open the market for prosumers but also for smaller companies and start-ups to provide easier new and innovative services.
Grid flexibility	Benefitting from the advanced smart metering and building systems, the service provider would manage and control your energy consumption, e.g., by turning compatible electric devices or district heating-based floor heating off for a short time during a high-price period. This flexibility potential can then be sold.
Big Data analytics and optimization	Services that take an advantage of big data accumulation. B2C energy use optimization services or B2B-embedded services.
Local energy solution as a service	If the consumer (or other type of customer) is not willing to set up or invest in their own local energy equipment, a service provider could carry out a feasibility study and provide equipment as well as run the system for the customer for a fee.
Renting production space	This could be feasible especially in the areas of compact construction where energy production space is scarce. The company could rent your rooftop for solar heat or power production and pay rent, e.g., in discounted energy.

5. Criteria

In this chapter, different criteria for evaluating different energy system options are presented. The findings, expect from Section 3.1, are based on a literature review made by Grahn (in press). Traditionally, energy system planning has aimed at minimizing the costs and maximizing the benefits (Pohekar and Ramachandran, 2004). However, as the need for a more efficient and sustainable energy system has become evident, other criteria have also been used more frequently. The criteria currently used for energy system decision-making can be divided into four categories: technical, economic, environmental and social (Wang et al., 2009; Ghafghazi et al., 2010a). Each category incorporates a large number of indicators. The most frequently used ones have been summarized by Wang et al. (Wang et al., 2009) and these are listed in Table 7.

Table 7. Frequently used criteria for energy system 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 for each category are efficiency, CO_2 emissions, investment costs and job creation. Other criteria often used are operation and maintenance costs, fuel costs, and land use. Furthermore, in addition to the criteria presented in Table 7, the primary energy consumption per fuel use and renewable energy shares are also used as system evaluation criteria for energy systems where large shares of renewable energy sources with fluctuating energy production are being used (Østergaard, 2009).

In the EFEU workshop discussed in Chapter 1, the following energy system criteria were seen as interesting: total energy efficiency, emissions, self-sufficiency, the share of renewables and sustainability. Thus, the results of the workshop correspond quite well to the literature findings. In the following, different energy system criteria are reviewed. The emphasis is put on energy efficiency criteria, but the most important sustainability criteria are also reviewed.

5.1 Energy efficiency criteria

In engineering, the ways to evaluate the efficiency of power conversion are quite established. One measure of efficiency is thermal efficiency (TE). That is the ratio between work, heat or work and heat output and the heat input in a heat-engine cycle. More generally, the TE can be defined as the ratio between the useful output and energy input of the process. This approach that is based on calculating the conversion efficiencies can be applied to traditional energy conversion systems, like heat-only boilers. However, in more complex systems having many types of energy inputs and outputs, it becomes important to widen the system boundaries and, in particular, include more upstream processes into the analysis as it is routinely done e.g., in life-cycle assessment.

Primary energy (PE) analysis is another method that is used to evaluate energy efficiency of energy conversion systems. It considers all the PE input into a production system that is required for yielding a certain product at the system boundary. It is the sum of all of the PE inputs into the system divided by the useful energy delivered at the system border, thus yielding a primary energy factor (the reciprocal of that being called primary energy efficiency). PE is a general concept, but such analysis can be made, e.g., based on EN 15603 (European Committee for Standardisation (CEN), 2008) The PE analysis according to this standard is an integral part of the Energy Performance of Buildings Directive, EPBD (Official Journal of the European Union, 2010). PE analysis based on EN 15603 has been used for evaluation of biomass (BM) pre-treatment systems (European Committee for Standardisation (CEN), 2008; Kohl et al., 2013) and in a more general way in different fields of process engineering ranging from evaluation of carbon capture and storage (Saygin et al., 2013), over power, heat and cooling generation (Gustavsson et al., 2011; Wu et al., 2013; Eicker et al., 2012; Caresana et al., 2011) to vehicle powertrains (Åhman, 2001) and cement plants (Khurana et al., 2002), respectively.

Exergy, by definition, is the maximum useful work that can be obtained from a system in a given state in a given environment. Exergy analysis (EXE) is a method based on the second law of thermo-dynamics. Exergy is a combination property of a system and its environment, because unlike energy, it depends on the state of both, the system and the environment. Exergy is a state property for a fixed environment and the exergy of a system in equilibrium with the environment is zero. Exergy analysis is used to compare, improve and optimize processes. It provides efficiencies that measure how far the process studied is from ideal and in which parts of the process exergy losses occur. Exergy losses are additive meaning that exergy loss of a system is the sum of the exergy losses of the system's components. Thus exergy analysis provides the true metric for energy efficiency. Exergy analysis has been applied in many fields. An introduction to these can be found in the book from Dincer and Rosen (2012).

In order to find a criteria that is able to combine the benefits of EXE and PEE, so that the whole energy chain needs not to be modeled, but still the effect of an energy improvement can be analyzed with respect to the whole energy chain, in the EFEU program a method called Primary Exergy Analysis (PeXa) was developed

(Laukkanen et al., 2015). It is generally a basic exergy analysis method where losses outside the studied process are calculated with factors obtained from PEE. This way the exergy of a product that is made up of many production routes depending on the portions of these routes used to make up the product. In some cases, it is possible that basic exergy analysis of the process can lead to increased primary energy use of society as a whole. PeXa is able to handle such instances.

The drawback of the TE analysis is that it does not take energy quality issues into account. The challenge in the use of primary energy efficiency (PEE) is calculating all energy inputs as PE. The use of exergy methods (EXE and PeXa) is often considered too complex to be used in practical engineering problems. The drawback of all the methods is that they cannot directly recommend how the process could be improved. A standard accounting framework would help to ensure consistency and transparency. This is far from the current case.

5.2 Environmental criteria

Most energy technologies cause some negative form of environmental impact and therefore, it is important that different environmental criteria are taken into account when comparing different energy systems (Løken, 2007). 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 greenhouse gas emissions and are mainly emitted from energy systems through the combustion of fossil energy sources such as coal, lignite, oil and natural gases. Thus, the emissions are of significant importance in the energy sector.

CO_2 emissions criteria can be measured in different ways. For example, these can be calculated as the CO_2 emissions per floor area (Forsström et al., 2011). Then, it is used as a measure of the energy efficiency of the system. Another way of measuring the CO_2 emissions criteria is by determining the absolute amount of CO_2 emissions in an area. In the ideal case, the emissions during the whole life cycle are taken into account: the construction phase, normal operation and accidental emissions (Løken, 2007). 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 of CO_2 equivalent (CO_2e). 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, as the absolute amount of emissions in a specific area.

The share of renewable energy sources is another environmental criterion that may be interesting to examine. As the name indicates, the criterion is used to measure what the share is of renewable energy sources in the energy production process. It can either be calculated as the ratio of renewable energy sources consumed to primary energy consumption, or as the ratio of renewable energy sources consumed to final energy consumption. The second alternative will generally give higher shares of renewables than the first one. The criterion is, like the energy efficiency and CO_2 emission indicators, very sensitive to the chosen system boundaries. (Østergaard, 2009)

5.3 Economic criteria

The economic and technical criteria are closely interconnected and it is not always even possible to separately handle them (Østergaard, 2009). In general, investment decisions are based on profitability calculations. Since most companies are aiming at maximizing the investment profits and minimizing the costs related to investment, no investments will be made if no economic benefits are offered (Løken, 2007). Thus, the economics are an important aspect of energy system planning.

The frequently used economic criteria include investment costs, operation and maintenance costs and fuel costs (Wang et al., 2009). The 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 energy, products and services for energy system operation. The maintenance costs are the costs of measures to preserve and restore the quality of the energy system, with the aim of avoiding failures and prolonging the lifetime of the energy system (inspections, adjustments, small repairs, replacements of consumables, cleaning, etc.). Fuel costs are the costs of the raw material used for operating the energy system. The costs can include extraction and mining, transportation and fuel processing. The costs vary depending on time and place. (Wang et al., 2009)

5.4 Social criteria

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., on a scale of 1–10 (Ghafghazi et al., 2010b).

In order for a specific energy technology to be implemented and used, it must be accepted by the public (Santoyo-Castelazo and 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 costs of the technology (E. 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 E. 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.

6. Technical case analyses

In the EFEU project, a numbers of cases were studied using simulation. All of the studies focused on a selected case area located in Southern Finland. In the study, a set of scenarios for the future development of the heat demand and supply in the case area were made. The scenarios are partly based on the work by Grahn (in press). Selected future energy production alternatives were studied with the aim of determining the most efficient composition of energy production for the case area. The scenario time frame was 20 years, starting in 2015 and ending in 2035.

6.1 Case study description

The selected case area closely represents an operational area of the district heating system of Tuusula and Järvenpää – two municipalities in the Uusimaa region, about 30 km north of Helsinki. The number of inhabitants in these municipalities has been growing continuously over the last 35 years and in 2015, the total number of inhabitants was 78,600. Residential buildings constitute the main segment of the building stock in the area, but there are also a number of public and office buildings and some light industry (Aluesarjat, 2016).

6.1.1 Case area: state of the art

In the case area, about a third of the buildings use district heat to cover their heat demand (Aluesarjat, 2016). The district heating network is 210 km long and 400 GWh of heat is annually produced and supplied through 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 plants mainly use natural gas and fuel oil. The fuel mix used for district heat production in 2014 is shown in Figure 20 (Energiateollisuus ry, 2014b).

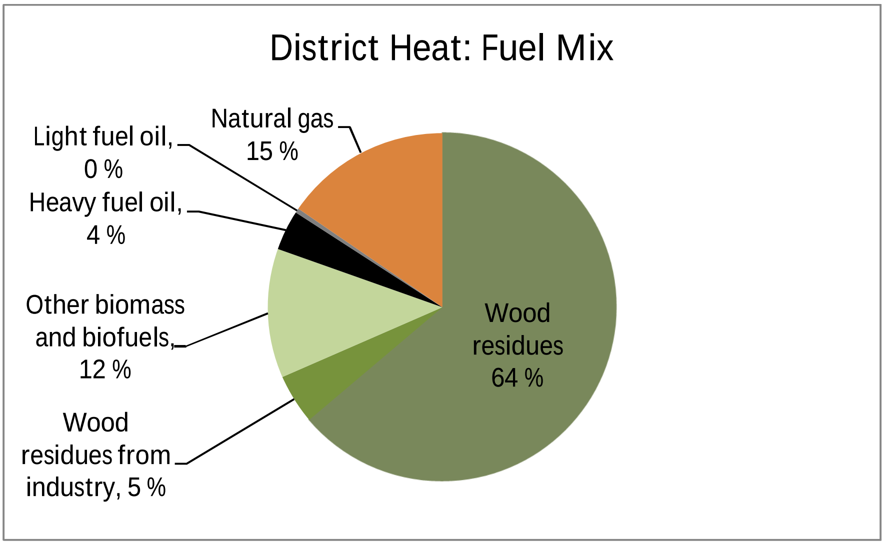

Figure 20. The fuel mix used for district heat production in the Keski-Uusimaa area in 2014 (Energiateollisuus ry, 2014b).

Thus, 81% of the fuel used for district heating production is biomass-based, 15% is natural gas and 4% is heavy fuel oil.

6.1.2 Building stock assumptions

In the scenarios, a time step of five years was used, i.e. for the following years: 2015, 2020, 2025, 2030 and 2035. A forecast for the development of the building stock in the area formed a common basis for the scenarios studied in both the simulation cases. The forecast was based on the historical development of the building stock in the area. As a result, the following annual changes to the building stock were used: new buildings 2.0%, demolished buildings 0.2% and renovated buildings 3.2%. The development of the building stock is visualized in Figure 21.

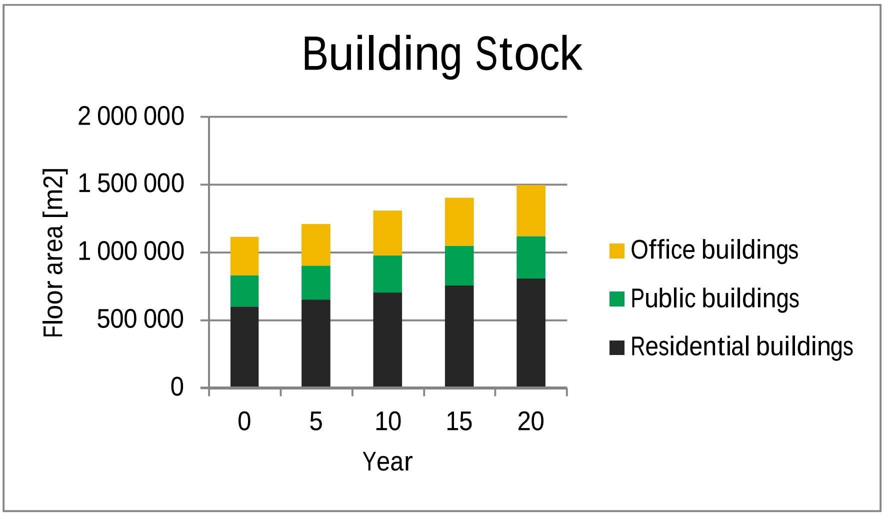

Figure 21. The estimated development of the building stock in the case area.

Thus, the built floor area in the case study was increased by 35% over the scenario time frame. All of the buildings in the initial phase were assumed to follow the building standards from 1985. Renovated buildings were assumed to reach the building standards from the year 2007. New buildings were assumed to develop according to the pattern shown in Table 8. The building standards for the different years are listed in Table 9.

Table 8. Efficiency levels of new buildings in terms of the year they were built and the type of building. Note that in 2015, no new buildings were added.

Building types	**2015**	**2020**	**2025**	**2030**	**2035**
Residential	(1985)	2010	Low	Low	Passive
Office	(1985)	2010	Low	Low	Passive
Public	(1985)	Low	Passive	Passive	Passive

Table 9. Parameters of the defined efficiency levels for new buildings in the reference scenario (Aalto, 2009; Kouhia et al., 2010).

Efficiency level	**Unit**	**1985**	**2007**	**2010**	**Low**	**Passive**
U-value: floor	W/m^2K	0.36	0.24	0.16	0.16	0.16
U-value: roof	W/m^2K	0.22	0.15	0.09	0.09	0.09
U-value: wall	W/m^2K	0.28	0.24	0.17	0.17	0.17
U-value: window	W/m^2K	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 g factor	–	0.75	0.75	0.70	0.70	0.70

6.2 Heat and power production alternatives

The objective was to study what kind of an energy system, especially from the heat and power production side, would look like in the studied case over the next 20 years. For this, an optimization model (MILP = Mixed Integer Linear Programming) was built and solved. The objective function was the total annual cost, meaning that both operational costs and the investment costs of heat and power-producing units are considered. The main decision was to decide which of the units will be installed, what the size of these installed units are and how these units should be operated. The hourly heat demand was estimated by calculations using the simulation model of the reference scenario, as described in section 6.3.2, and the same hourly weather conditions (outside air temperature, radiation from sun and wind speed) were used. These are given in the Appendix A. Table 10 gives the heat and/or power-producing technologies used in the optimization model and in Table 11, the constant efficiencies of some of these technologies are given.

Table 10. Chosen technologies.

Bio-CHP
Wind turbines
Solar panels
Gas engines
Compressed air energy storage (CAES)
Vanadium redox battery (VRB)
Heat pumps
Gas boilers
Solar collectors

Table 11. Efficiencies of some of the technologies.

Efficiencies	
Bio-CHP P	0.29
Q	0.77
Gas engines	0.45
Gas boilers	0.9
Gas elec.	0.6
Heat pump COP	1.6–4.5

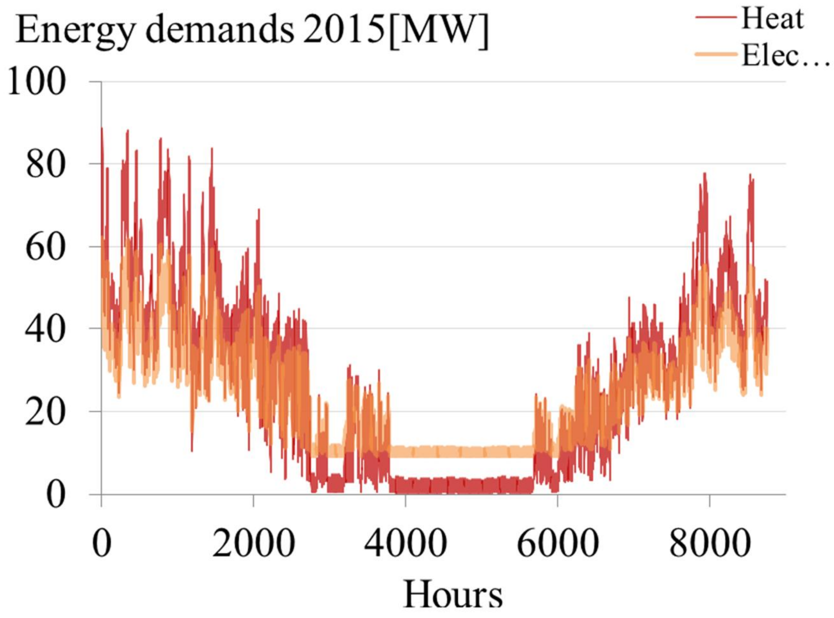

Figure 22. The hourly energy demand.

In the model, new investments were allowed every five years and the effect of heat consumption and equipment prizes were taken into account. Table 12 shows the annual change in these parameters and Table 13 the investment and operation costs of the utilized technologies.

Table 12. Annual development of energy consumption and costs of some technologies.

Demand	
Electricity	+ 0.5 %
Heat	- 0.7 %
Costs	
Wind turbines	- 2 %
Solar panels	- 2 %
VRB	- 2 %
Heat pumps	- 1.5 %
Solar collectors	- 2.5 %

Table 13. Investment (Inv) and operation (Op) cost of the technologies.

Coal		€/MWh	40
Turbines	Inv	€	6500000
	Op	€/a	90000
Solar panels	Inv	€/m^2	200
	Op	€/m^2/a	3
Gas engines	5 MW	€	4000000
	8 MW	€	5500000
	10 MW	€	6500000
Natural gas		€/MWh	46
CAES	Inv	€/MW	600000
	Inv	€/MWh	40000
	Op	€/MWh	3
VRB	Inv	€/MW	500000
	Inv	€/MWh	500000
	Op	€/MWh	0.9
Heat pumps	Inv	€/MW	400000
Gas boilers	Inv	€/MW	100000
Solar collectors	Inv	€/m^2	330
	Op	€/m^2/a	3

6.2.1 Results

In total, three cases were calculated using the model and assumptions presented in the previous chapter. In the first case, there is an existing bio-based CHP plant and existing gas boilers meaning that the investment for these are not needed. This closely resembles the current situation in the Keski-Uusimaa case study. Table 14 shows the installed capacity of the units. Figure 23 shows the results of produced heat and electricity in this case.

Table 14. Installed capacity in Case 1 (existing bio-based CHP plant and existing gas boilers).

Period		0	1	2	3	4
Years		0	1 - 5	6 - 10	11 - 15	16-20
Bio-CHP	P MW	23	23	23	23	23
	Q MW	45	45	45	45	45
Wind turbines	à 3.1 MW	0	0	0	0	5
Solar panels	m^2	0	0	0	0	0
Gas engines		0	0	0	0	0
CAES	MW	0	0	0	0	0
	MWh	0	0	0	0	0
VRB	MW	0	0	0	0	0
	MWh	0	0	0	0	0
Heat pumps	MW	0	31.8	32.9	33.4	33.6
Gas boilers	MW	0	0	0	0	0
Solar collectors	m^2	0	0	0	0	0

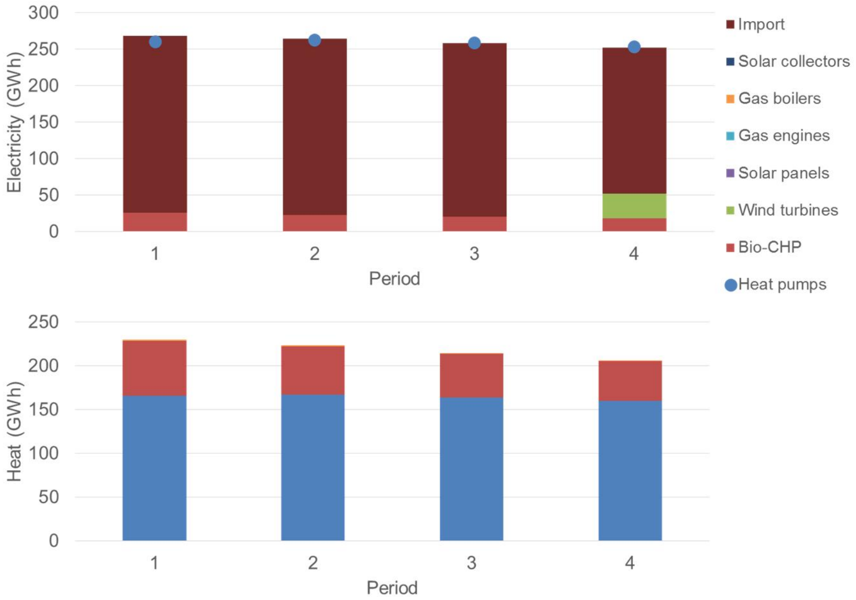

Figure 23. Heat and electricity produced in each unit annually in Case 1 (existing bio-based CHP plant and existing gas boilers).

In the second case, the assumption is that the CHP plant has to be shut down after 10 years. An additional assumption is that the electricity consumption in the region needs to be satisfied with the power-producing units installed in the region, so no electricity imports or export is allowed. Table 15 shows the installed capacity of the units. Figure 24 shows the results of produced heat and electricity in this case.

Table 15: Installed capacity in Case 2 (CHP plant ceases after 10 years and no electricity import/export).

Period		0	1	2	3	4
Years		0	1 - 5	6 - 10	11 - 15	16-20
Bio-CHP	P MW	23	23	23	0	0
	Q MW	45	45	45	0	0
Wind turbines	à 3.1 MW	0	0	0	3	4
Solar panels	m^2	0	0	0	32985.9	44956.6
Gas engines		0	6 x 10 MW	6 x 10 MW	8 x 10 MW	8 x 10 MW
CAES	MW	0	0	0	0	0
	MWh	0	0	0	0	0
VRB	MW	0	0	0	0	0
	MWh	0	0	0	0	0
Heat pumps	MW	0	2.1	2.3	9.5	10.1
Gas boilers	MW	0	21.8	21.8	65.9	65.9
Solar collectors	m^2	0	0	0	0	0

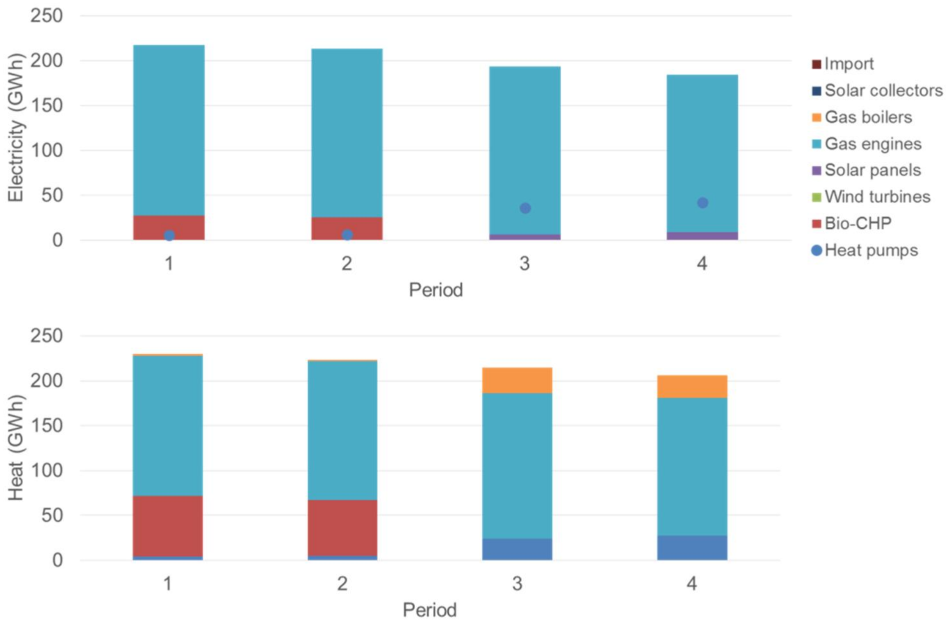

Figure 24. Heat and electricity produced in each unit annually in Case 2 (CHP plant ceases after 10 years and no electricity import/export).

In the third case, the assumption is that there are no existing units in the region. Additionally, the electricity consumption in the region needs to be satisfied with the power-producing units installed in the region, so no electricity imports or export is allowed. Table 16 shows the installed capacity of the units. Figure 1 shows the results of produced heat and electricity in this case.

Table 16. Installed capacity in Case 3 (No existing capacity and no electricity import/export).

Period		0	1	2	3	4
Years		0	1 - 5	6 - 10	11 - 15	16-20
Bio-CHP	P MW	0	0	0	0	0
	Q MW	0	0	0	0	0
Wind turbines	à 3.1 MW	0	0	0	2	4
Solar panels	m^2	0	0	0	46720.9	46720.9
Gas engines		0	8 x 10 MW	8 x 10 MW	8 x 10 MW	8 x 10 MW
CAES	MW	0	0	0	0	0
	MWh	0	0	0	0	0
VRB	MW	0	0	0	0	0
	MWh	0	0	0	0	0
Heat pumps	MW	0	5.9	5.9	7.4	10.1
Gas boilers	MW	0	68.6	68.6	68.6	68.6
Solar collectors	m^2	0	0	0	0	0

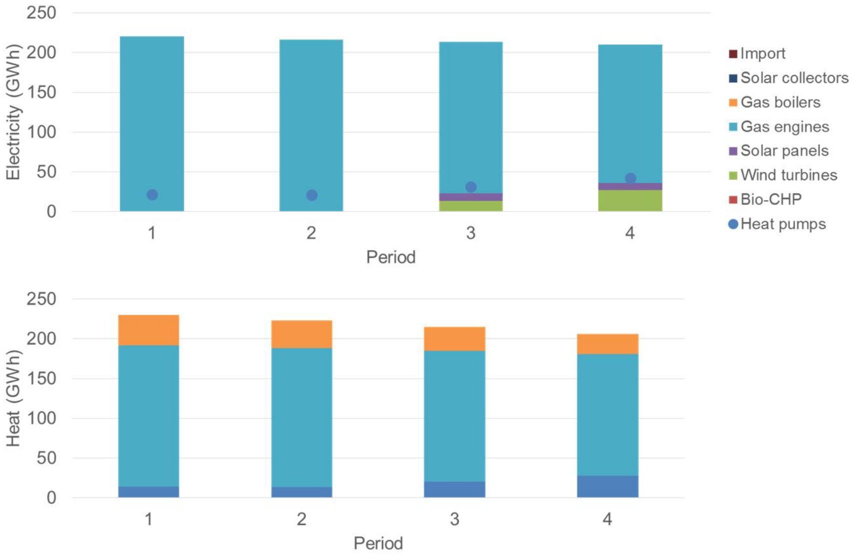

Figure 25. Heat and electricity produced in each unit annually in Case 3 (No existing capacity and no electricity import/export).

6.2.2 Analysis of results

First, the study of heat and power production alternatives confirmed that it is cost-optimal to use the already existing CHP plant, which is the actual situation in the

Keski-Uusimaa case. Approximately 30 GW of heat pumps are built immediately, which covers most of the heat demand. No electricity generating plants are built until after 15 years, when 5 MW wind turbines are commissioned. Most of the consumed electricity is imported.

Results indicate that existing CHP can and should be utilized. However, the CHP plant is only used for 1300 peak load hours in the first period, declining to 940 peak load hours in the fourth period. The heat pumps, however, are used for 5200 to 4800 peak load hours, at an average 3.2 coefficient of performance.

The second and third case highlight the economic benefit of electrical grid connection: in these cases, local electricity demand must be fulfilled with local electricity production. A number of gas engines are built, and after an existing CHP plant is decommissioned after 10 years in the second case, more gas engines and also heat pumps and gas boilers are built. In the third case these are built already in the beginning. Compared to first case, where mean energy cost is 21 EUR/MWh produced, in these cases energy costs are 65 and 60 EUR/MWh.

6.3 Heat demand and scenarios for heat supply

A set of scenarios for the development of the case area's district heating system have been made. The purpose of the scenarios was not to make a prediction of what future heating energy systems will be like, but rather to examine what different possible development pathways there are and to compare them in terms of technical, environmental and economic criteria. In the scenarios, the focus has been set on the demand side of the district heating network and the actions and choices made by the end users of energy. The competitiveness of district heat versus decentralized energy production methods especially has been of key interest.

The scenarios were simulated using the APROS software, which is a dynamic simulation software developed by Fortum and VTT. By simulating the scenarios, a deeper understanding about the physical energy system behavior was reached. The simulation model comprised a district heating network in the case area and the buildings connected to it as points of aggregated consumption. In addition to district heating, the model also provided the opportunity to use either ground-source heat pumps (GSHP) or solar thermal collectors (STC) to cover the building's heat demand. The simulation output was a set of data, describing the energy consumption in the area and the energy technologies used to cover the heat demand.

The simulation results were used to compare the scenarios against each other and to examine how the scenarios influenced the overall performance of the system. However, 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 26. The analysis included only the energy flows used to cover the heat demand of the building stock in the case area.

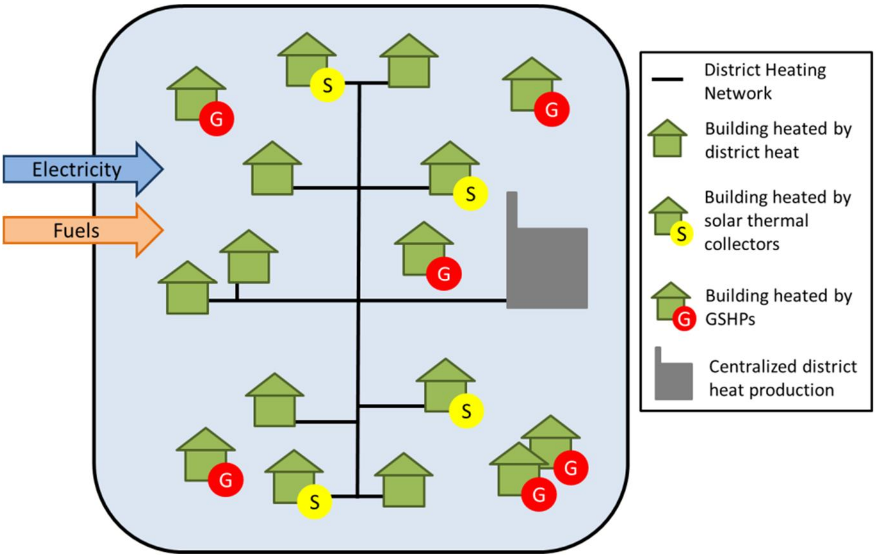

Figure 26. The energy system boundaries.

As could be seen from the figure, electricity and fuels were imported to the area. The electricity was used to run the ground-source heat pumps and the fuel was used for district heat production. There were no energy exports from the system. In the scenarios, 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. The details of the heat production processes were not modelled. 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 the following section, the studied set of scenarios for the future development of the demand side of the network is presented.

6.3.1 Scenarios

There are three scenarios for the adoption rate of decentralized heating technologies that replace district heating in buildings: a conservative, an extensive and an extreme scenario. Furthermore, there is one scenario where industrial waste heat is introduced to the district heating system and there is one scenario where the end users of heat turn into heat prosumers, i.e., being both consumers and producers of heat. The scenarios, characteristics are described in the analysis below.

Conservative scenario

In the conservative scenario, no large changes to the current situation 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 is shown in Figure 27.

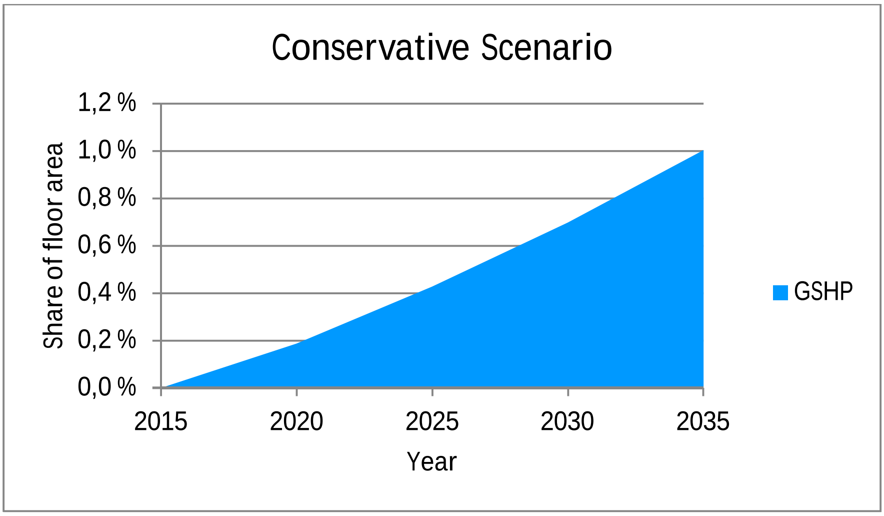

Figure 27. The share of floor area of buildings using GSHPs in the area in conservative scenario.

As could be seen from the figure, it is assumed that for the buildings situated in the area served by the district heating network, the share of them switching to GSHPs reaches only 1% of the buildings' floor area by 2035. The development is calculated from the expected development of the building stock and the assumption that in 2035, 10% of the new residential buildings will choose GSHP technology over district heating.

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 of those in residential buildings. Solar thermal collectors are also installed into new, residential buildings in the area. Even though the interest in decentralized energy sources is considerably higher than in the conservative scenario, district heating still holds a significant position. The development of GSHP and STC installations is shown in Figure 28.

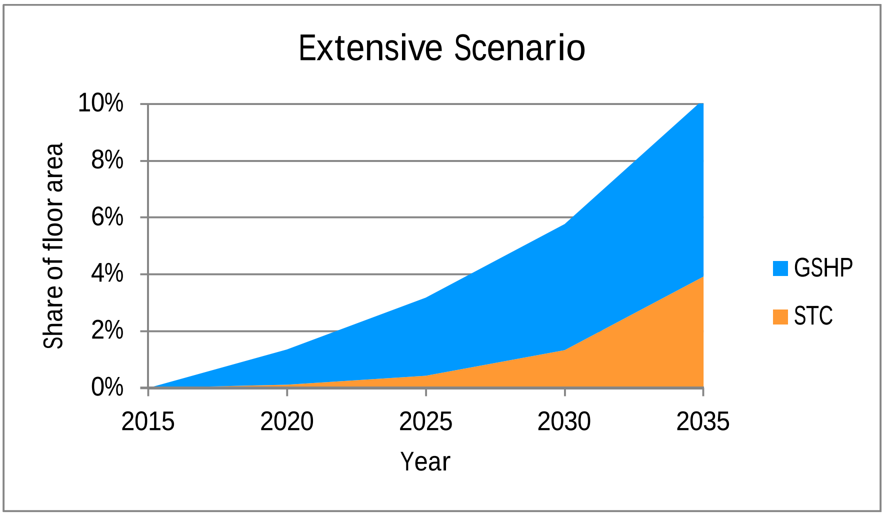

Figure 28. The share of floor area of buildings using GSHPs and STCs in the area in the extensive scenario.

In this scenario, 10% of all buildings in the case area use either GSHPs or solar thermal collectors by 2035: 6% of the buildings use GSHPs and 4% of the buildings use solar thermal collectors.

Extreme scenario

In the extreme scenario, energy system development is driven by high interest in decentralized and local energy production technologies. GSHPs and STCs are installed in 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 solar thermal collector installations in the area are shown in Figure 29.

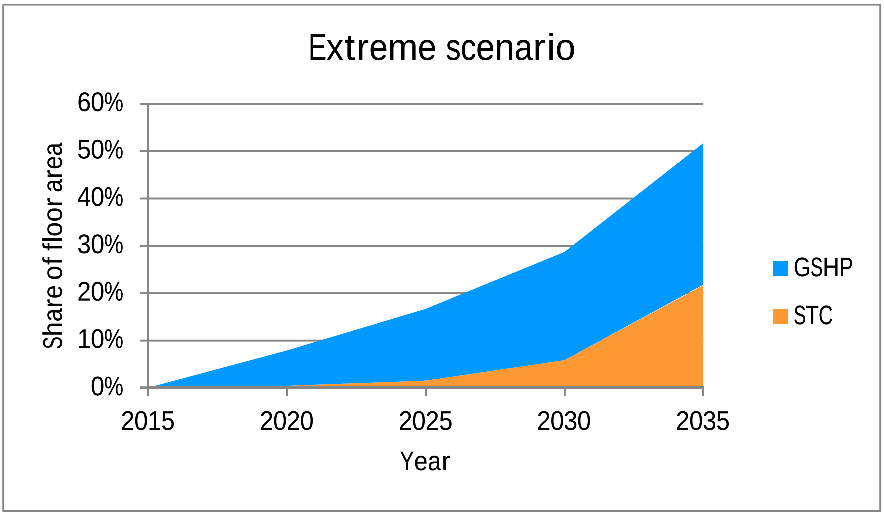

Figure 29. The share of floor area of buildings using GSHPs and STCs in the area in the extreme scenario.

In this scenario, almost half of the buildings use GSHPs or solar thermal collectors by year 2035. The share of buildings using GSHPs is 30% and the share of buildings using solar thermal collectors is 22%.

Industrial waste heat

In the industrial waste heat scenario, heat from a waste heat source is introduced to the district heating network. The heat source is introduced in 2025, and it continues to produce heat for the district heating network until the end of the scenario time frame. The source in question is a data centre, where the heat in the ventilation air is recovered. The recovered waste heat was used to reheat the fluid that was recirculated after returning to the supply line of the district heating network.

Heat prosumer

Another simulation experiment was set up to simulate feeding excess solar heat into a district heating network. The scenario assumptions were the same as in the conservative scenario with one difference: one of the prosumers had a solar collector field of 1000 m^2 – almost eight times larger than the total area of solar collectors installed in the case area. The excess solar heat was being injected into the supply line of the district heating network. The amounts of the energy fed to the network were modest, about 1% of the prosumer's own annual consumption and feeding to the network was set up to take place only during the warm period of the year.

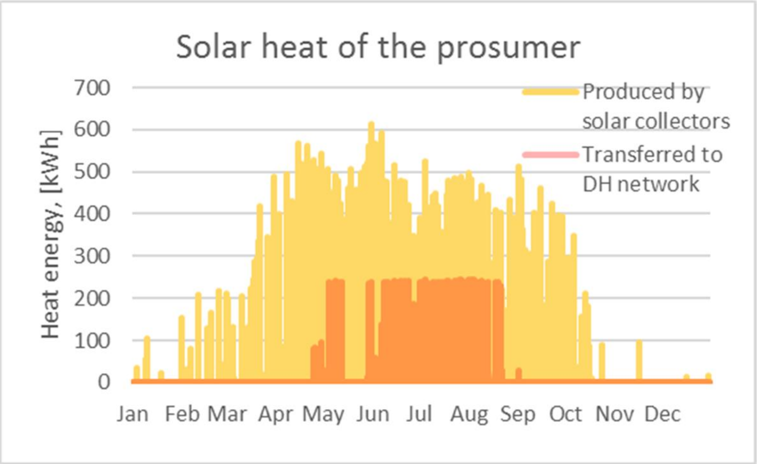

Figure 30. Output of excess heat into a district heating network from a prosumer with 1000 m^2 of solar collectors.

It was found that excess heat at the temperatures exceeding the district heating network supply temperature was only available in warm periods of the year. In other periods, solar heat production covered the prosumer's own heat loads.

6.3.2 Results

In this section, the main results of the simulation and analyses are presented. The main results include the estimate of the future development of the heat demand in the area over the scenario time frame, the technologies used to cover this demand and the amount of heat annually produced and supplied into the district heating network. The criteria used to compare the scenarios included specific non-renewable heat consumption, the carbon dioxide equivalent (CO_2e) and particulate emissions and the energy costs paid by the energy consumers.

Heat is used in the case area to cover the space heating and DHW demand of the building stock. Since the development of the building stock is the same in all scenarios, the heat demand will also be the same. The development of the total annual heat demand in the area was established by simulation and is depicted in Figure 31.

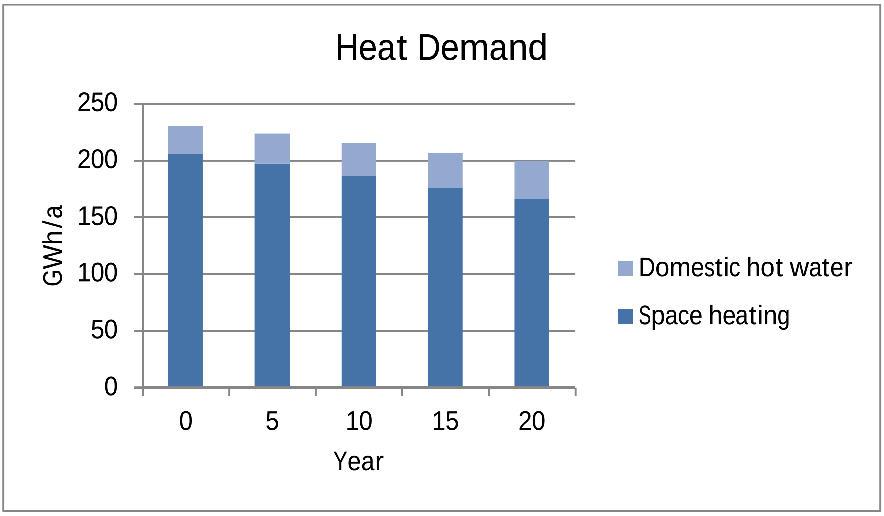

Figure 31. The development of the total annual heat demand in the case area.

The simulation results indicate that the total heat demand in the area will decrease even though the amount of buildings and their total floor area in the area increases. In 2015, the total heat demand is 230 GWh but by 2035, the heat demand is reduced by 13%, reaching 200 GWh. The decreasing heat demand in the area is a consequence of the energy efficiency improvements in renovated buildings and the high efficiency level of new buildings. When the efficiency level is improved, the space heating demand is decreased. The domestic hot water demands, on the other hand, are not affected by energy efficiency levels. Thus, when the amount of buildings in the area increases, the total domestic hot water demand is also increased.

The development of the specific heat consumption of the buildings in the area, i.e., the final heat consumption per built floor area is presented in Table 17.

Table 17. Demand-side energy efficiency improvements

	Unit	**2015**	**2020**	**2025**	**2030**	**2035**
Specific heat demand	kWh/m2	207	185	165	147	133
Share	%	100 %	89 %	80 %	71 %	64 %

In the first year of the scenario, the estimated specific heat consumption was 207 kWh/m^2, but by 2035 the corresponding number was 133 kWh/m^2. Thus, the assumed development of the building stock in the area on average results in 36% improvement of demand-side energy efficiency.

In the scenarios, the three different heating technologies were 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 by 2035 are presented in Table 18.

Table 18. The shares of the heat consumption covered by the different heating technologies.

	District heat (%)	**GSHP (%)**	**STC (%)**
Reference	100.0	0.0	0.0
Conservative	99.2	0.8	0.0
Extensive	94.6	5.1	0.3
Extreme	74.5	24.2	1.3
Industrial waste heat	100.0	0.0	0.0
Prosumers	99.9	0.0	0.1

In the reference and industrial waste heat scenario, 100% or of the heat consumption is covered by district heating. In the prosumer scenario, almost 100% of the heat demand is also covered by the district heating network. In the conservative scenario, about 1% of the heat demand is covered by GSHPs and the rest is covered by district heat. The corresponding shares of GSHPs in the extensive and extreme scenario are 5% and 24% respectively. The annual shares of solar thermal heat in both the extensive and extreme scenario are small.

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 ground-source heat pumps in the area. 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 solar collectors mainly produce heat during the summer, but in the winter, when the heat demands are the highest, almost no heat is produced.

The use of decentralized heat production technologies and industrial waste heat will affect the amount of district heat that will need to be produced by CHP and heat-only boilers. The annual amount of heat that is produced by centralized heat production units is shown in Figure 32.

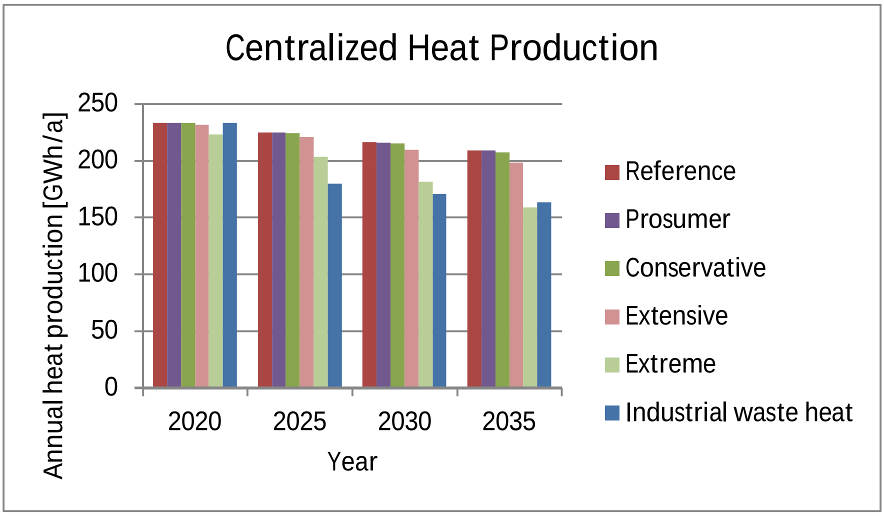

Figure 32. Centralized heat production in the case area during the years in the scenarios.

In the first year (2015), 240 GWh of heat is produced annually in the area. As could be seen from the figure, centralized heat production is decreasing in all scenarios over the scenario timeframe. In the reference scenario, the production is 13% lower in 2035, compared with the situation in 2015. In this scenario, the decrease in centralized heat production is completely due to the decreasing heat demand in the area. In the other scenarios, the installed amounts of decentralized heating technologies and the introduction of industrial waste heat and surplus solar heat further decrease the centralized heat production. In the extreme scenario, the production is decreased the most, closely followed by the industrial waste heat scenario. In the extreme scenario, the production is reduced by 34% and in the industrial waste heat scenario, it is reduced by 32%.

In the first year, approximately 9.7 GWh or 4% of the district heat is lost due to transmission losses. The shares of district heating losses in the scenarios are shown in Figure 33.

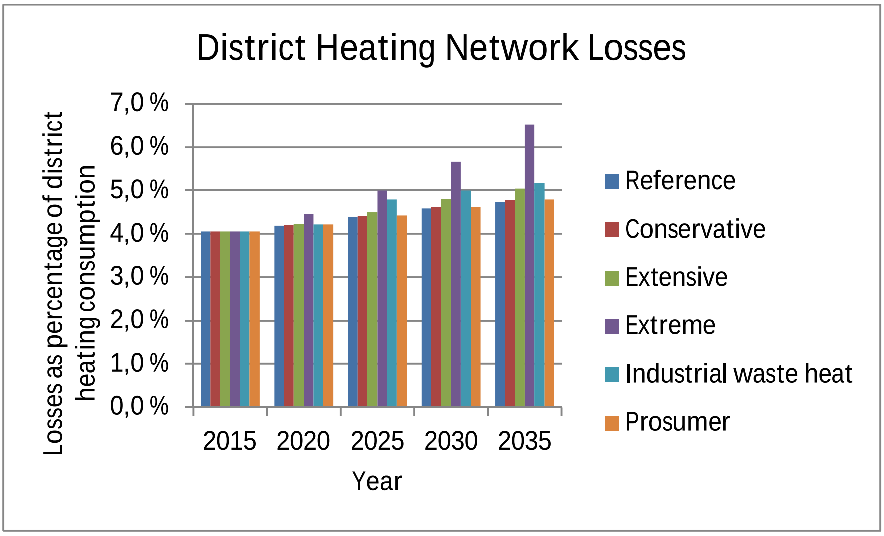

Figure 33. The district heating network losses as percentage of supplied district heating energy during the years of the scenarios.

As the district heat demand decreases, the share of losses is increasing. In the reference case, the losses reach 9.9 GWh or 4.7% by 2035 while in the extreme case, they reach 10.3 GWh or 6.5%. In the industrial waste heat scenario, the losses are the highest, 10.8 GWh but their share of the heat supplied to the network are lower than in the extreme case, 5.2%.

The decrease in centralized heat production in the scenarios also affects the peak heat output. In 2015, the peak heat output needed is 91.2 MW. The peak outputs of the different scenarios by 2035 are listed in Table 19.

Table 19. The peak heat output in 2035.

Scenario	**Peak heat output [MW]**	**Decrease [%]**
Reference	84.4	93%
Conservative	83.8	92%
Extensive	80.4	88%
Extreme	64.3	70%
Industrial waste heat	80.9	89%
Prosumers	84.4	93%

In all scenarios, the peak heat output of the centralized heat production is reduced. In the reference scenario, the output is decreased the least; by 7%, reaching 84.4 MW by 2035. In the extensive scenario, the output is reduced the most, by 30%, reaching 64.3 MW by 2035. In the Industrial waste heat scenario, the peak heat demand is reduced by 11%, reaching 80.9 MW by 2035. Thus, the peak heat output in the different scenarios is also decreased but not as much as the annual centralized heat production. Especially in the industrial waste heat scenario, the difference between the decrease in the peak heat output is much smaller than the reduction of the annual heat production. In addition, from Figure 33 it can be seen that as the total heat demand decreases, the share of heat losses in the network grows.

While the specific heat consumption of the building stock is the same in all scenarios, the specific, *non-renewable* heat consumption is developed in different manners, depending on the heating technologies used. The development of the non-renewable heat consumption for the different scenarios is presented in Figure 34.

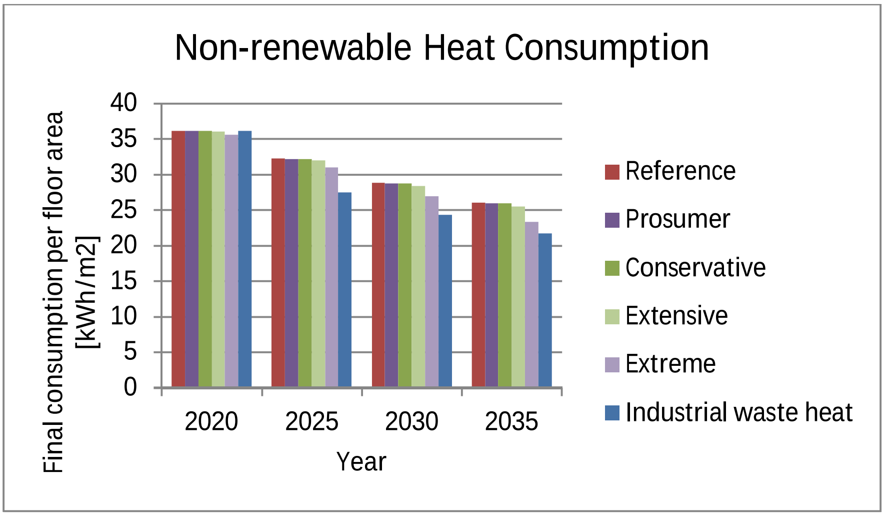

Figure 34. A comparison of specifically the non-renewable heat consumption in the different scenarios.

In 2015, the specific non-renewable heat consumption for all scenarios is 40.5 kWh/m^2. However, as could be seen from the figure, the consumption is decreasing over the scenario time frame. The main reason is the total decrease in heat consumption in the case area, but there are also differences between the scenarios depending on the choice of heating technology and how the district heat is produced. The usefulness of using non-renewable specific heat consumption is that despite the end-consumption of heat being the same in all of the scenarios, it helps identify improvements in how the demand is being covered. In the reference scenario, where district heating covered the whole heat demand, the specific non-renewable heat consumption trajectory changes in the same pattern as specific heat demand (Table 17). In the industrial waste heat scenario, the specific non-renewable heat consumption is decreased the most: by 46% compared to the year 2015. In this scenario, about 20% of the district heat was produced by the industrial waste heat source, which was assumed to be renewable.

The environmental effects of the scenarios are evaluated using two criteria: CO_2e emissions and particulate emissions. Both criteria were calculated as the emissions per unit of floor area. The CO_2e emissions are presented in Figure 35 and the particulate emissions are presented in Figure 36.

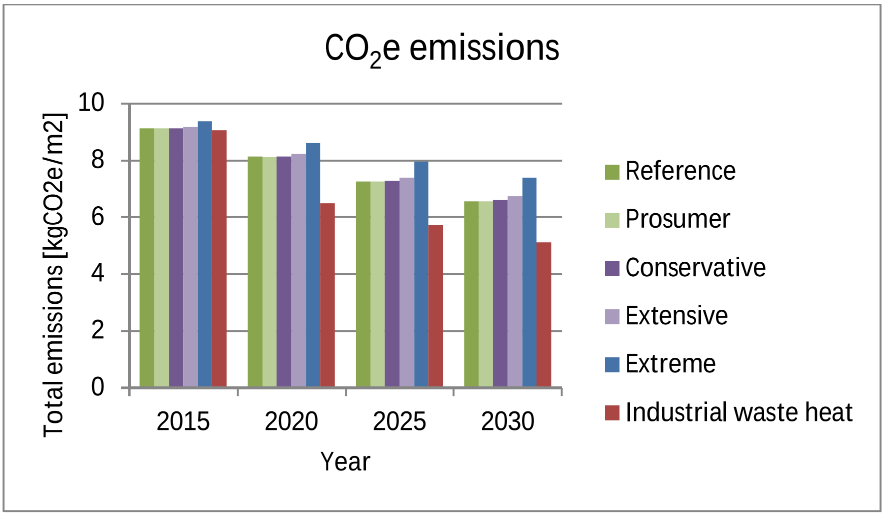

Figure 35. A comparison of the CO_2e emissions in the different scenarios.

In 2015, the annual CO_2e emissions of the scenarios are 10.21 $kgCO_2e/m^2$. As seen in the figure, the absolute amounts of the emissions are reduced over the scenario timeframe in all of the scenarios. In the reference case, the CO_2e emissions decrease by 36%, reaching 6.25 $kgCO_2e/m^2$ by 2035. Thus, in this case, the emissions decrease in proportion to the decrease in total heat consumption. In the industrial waste heat scenario, the CO_2e emissions are reduced the most. By 2035, the emissions are reduced by 50%, compared to the situation in 2015. In the conservative, extensive and extreme scenarios, the absolute amount of emissions decrease over the time frame of the scenario, but the decrease is smaller than in the reference case. In these scenarios, there are heat pumps installed and as the amount of heat pumps increases, electricity consumption also increases. The results indicate that the emissions originating from the electricity consumption of heat pumps are higher than the emissions originating from district heat consumption.

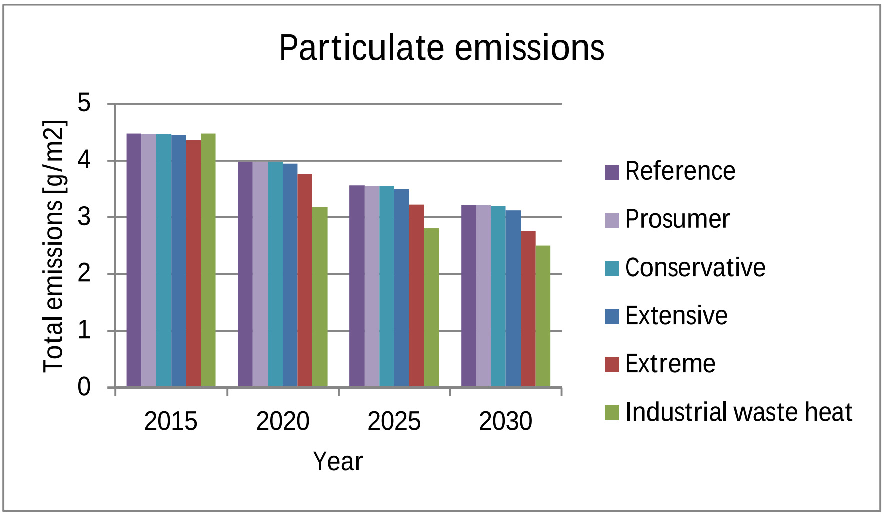

Figure 36. A comparison of the particulate emissions in the different scenarios.

In 2015, the annual particulate emissions are 5 g/m^2 in all of the scenarios. As could be seen in the figure, the emissions decrease over the time frame of the scenario. In the reference case, the emissions are once again decreasing in proportion to the decrease in heat demand, reaching 3.2 g/m^2 by 2035. In the industrial waste heat scenario, the emissions are reduced the most. By 2035, the emissions are reduced by 50%, reaching 2.5 g/m^2 by 2035.

The heating costs are used as a criterion for investigating the economic effects of the scenarios. The costs are examined from the point of view of the energy consumers. In the calculations, it was assumed that the electricity price and the district heating price increase annually by 1% and that the introduction of industrial waste heat does not affect consumer prices. The heating costs are shown in Figure 37.

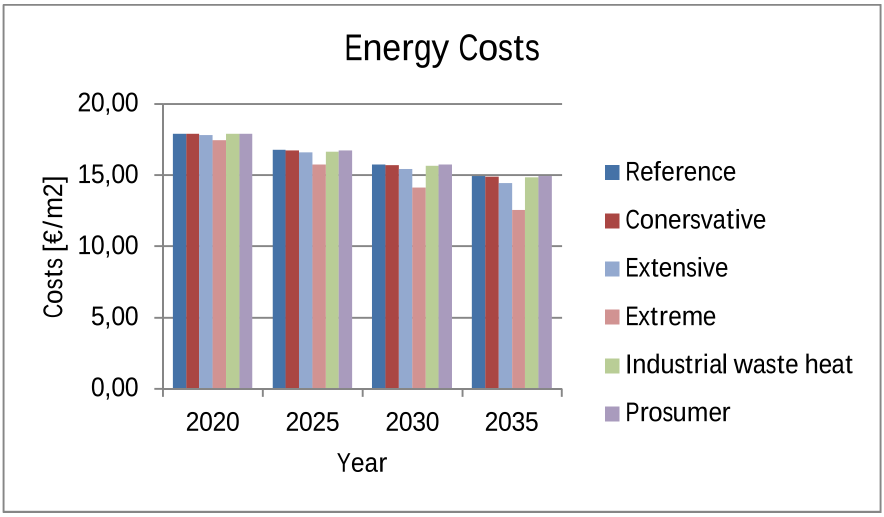

Figure 37. The heating costs.

In 2015, the average heating costs in the area are approximately 19 €/m^2. The costs decrease throughout the time frame of the scenario, mainly due to the decreasing heat demand in the area. In the reference case, the costs decrease by 22%, reaching 15 €/m^2 in 2035. In the extreme case, the energy costs decrease the most; 34% by 2035, reaching 12.5 €/m^2.

7. Discussion and conclusions

This report summarizes the main results of the EFEU project dealing with energy-efficient district energy systems. After giving an introduction to background data from Finland and relevant trends, the report concluded that the collected industry views and discussed regional collaboration and service business opportunities. After defining criteria for energy system analyses, a summary of the technical case analyses was given.

Based on the selected case area in southern Finland, two types of simulation studies were carried out. Both of the studies used the same assumptions regarding the future development of the building stock, which resulted in a common estimate of the heat demand over the time frame of 20 years.

The main advantage of using an optimization model for designing the heat and power production of a studied region (Keski-Uusimaa in this case) lies in the possibility to study the sensitivity of the parameters of the final design. These parameters include the costs of equipment and energy, the amount of irradiation and wind in the case region, and the variation in heat and power consumption in the region. With this type of model, these issues can be easily analyzed to see, for example, how much less solar collectors should cost, or how much more irradiation there should be or how much more efficient the solar collectors should be to be viable for investment.

The model could be improved to be more realistic. Now the model is linear and thus provides globally optimal solutions, which naturally is very beneficial. However, in some cases, the linearity simplifies issues too much, including, for example, the fact that the efficiency of units varies depending on the load. Including aspects like that would probably make the model more realistic, but at the same time make it non-linear and non-convex, thus causing the guarantee to find globally optimal solutions to disappear. Additionally, the fact that now only the annual costs of the model are the sole concern should be challenged. More objectives, including the criteria found in Chapter 4, should be included.

Despite the anticipated increase of the buildings' total floor area by about 35%, the total heat demand of buildings was estimated to drop by 13%, due to improvements in the overall energy efficiency level of buildings. In specific terms, when expressed in terms of combined heating and domestic hot water demand per unit of floor area, the estimated drop was approximately 36%. The drop in heat demand is due to improvement of building insulation and more efficient use of energy for space heating - this means that in the future, the share of the domestic hot water component in the total supplied heat may be expected to grow in the energy balances of both buildings and district heating systems.

In addition to reduction of heating losses and space heating demand, the anticipated adoption of heating technologies and sources, such as solar collectors, ground-source heat pumps and industrial waste heat were studied using the scenario approach. The scenarios that envisage extrapolation of the current trend in adoption of solar collectors and ground-source heat pumps resulted in almost no reduction of centralized heat production (conservative and prosumer scenarios). At the same time, more rapid transition to using solar collectors and heat pumps in new and renovated buildings reduces consumption of heat from the district heating network, however, even in the case when half of the newly built and renovated buildings start using solar collectors and heat pumps, centralized heat production drops by only 34%. This could be explained by greater energy efficiency and lower heat demand of new and renovated buildings.

The use of such a criterion as the specific non-renewable final heat consumption proved useful in describing the origin of the energy covering the same heat demands in different heat production scenarios. In particular, it was useful to incorporate the information about the electricity consumption of heat pumps. At the same time, it was observed that the conclusions may be sensitive to the fuel mix of the centralized heat production units of the district heating network as well as to treatment of the origin of electricity - whether it is considered fully non-renewable or, as it was done in this case, represented the national electricity production fuel mix. A similar effect can be observed from the Figure 35, where the adoption of heat pumps in the extensive and extreme scenarios lead to an increase of CO_2e emissions. This increase is largely due to values of the applied emission factors in the situation when the central heat production of district heating (mainly based on biomass) was substituted with buildings' own heat pumps consuming electricity. In the case of particulate emissions, the results are contrary to those of CO_2e, because the emission factors favor electricity over biomass.

The adoption of heat pumps in the extensive and extreme scenario leads to decrease of average energy costs in the area. This conclusion is highly sensitive to the price development of the electricity and district heat. It needs to be noted that the scenario with utilization of waste heat improves the situation in almost all cases: it reduces emissions and non-renewable heat consumption and it also replaces centralized heat production and thus saves fuel at the centralized production units of the district heating network. In this study, the utilization of industrial waste heat did not result in significant reduction of peak output of other centralized heat production units. This can be explained by the type of the waste heat source, which was heat recovery from exhaust air of a data center and reduced output during the peak demand period in the case area. The reduction is mainly due to a high supply line temperature in the district heating network.

The high requirements to supply temperature limit the possibilities of using locally produced excess heat. In the prosumer scenario, the excess heat for feeding district heating was available only during warm periods of the year, when the heat demand was rather low and mainly made up of usage of domestic hot water, and when the required temperature of feeding the network was the lowest (75°C). In the simulation process, the prosumer's position was in the beginning of a branch line, which is probably favorable in terms of feeding the heat as there would be other heat consumers downstream. The topics related to optimal sizing and use of solar systems in conventional district heating systems deserves further study, especially because the existing district heating systems in Finland already operate in the most densely built areas and in the future, the new networks are expected to be primarily extensions of the existing ones to the new areas (Pöyry Management Consulting Oy, 2016).

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Appendix A: Hourly weather conditions of simulations

The same hourly weather conditions (outside air temperature, radiation from sun and wind speed) were used in all technical analyses. This are shown in the following figures.

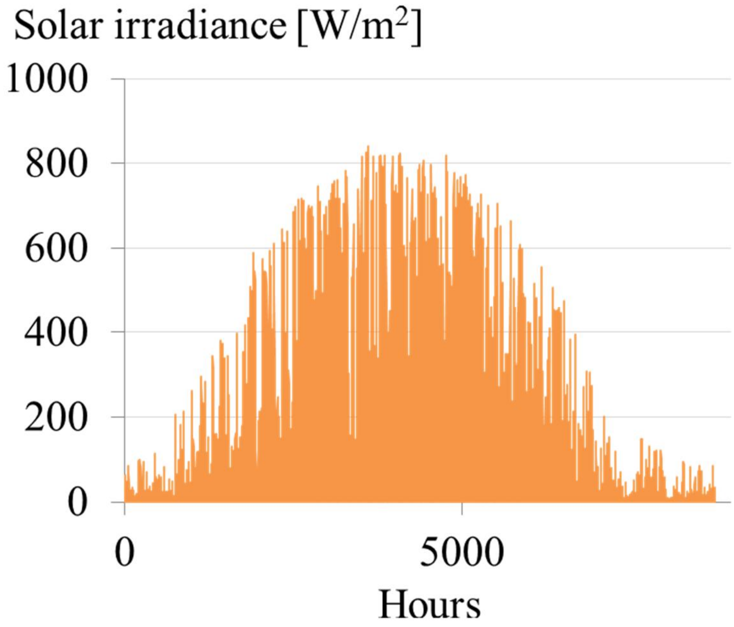

Figure A1. The hourly irradiation.

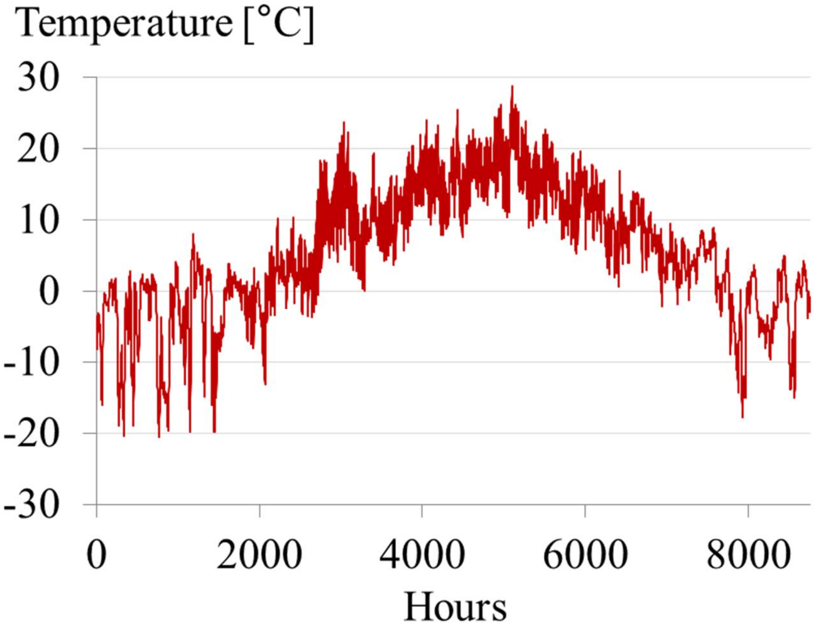

Figure A2. The hourly outside temperatures.

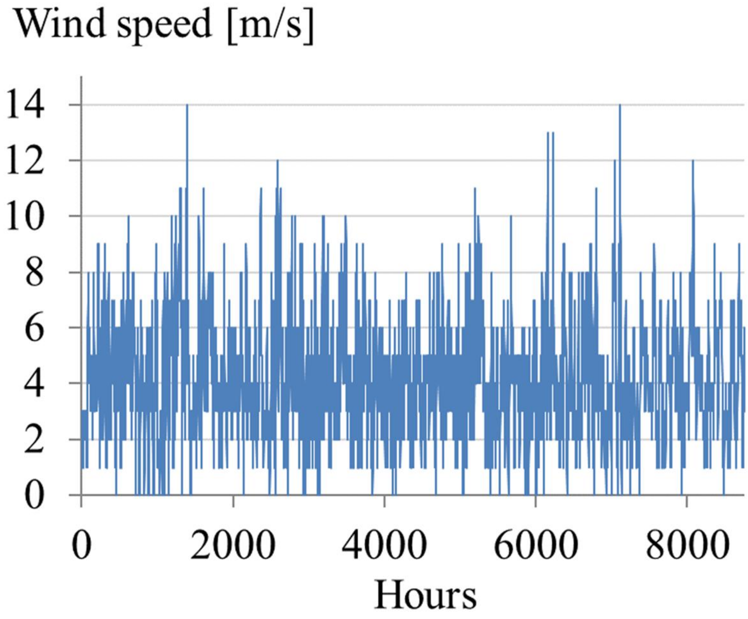

Figure A3. The hourly wind speeds.

Series title and number

VTT Technology 277

Title	**Visions for future energy efficient district energy systems**
Author(s)	Satu Paiho, Ismo Heimonen, Elina Grahn, Rinat Abdurafikov, Lotta Kannari, Markku Mikkola, Tapani Ryynänen, Timo Laukkanen, Joel Ypyä & Sampo Kaukonen
Abstract	This report gives the vision of the future district energy systems and describes the state-of-the art of district heating related energy systems in Finland. The challenges and future needs of the energy business and services are described. The approach for scenario analyses is presented using the district heating system of Keski-Uusimaa as a case study. The scenarios of the energy system selection and energy consumption for the next 20 years (2015–2035) were presented for the case study. The scenarios were based on the assumptions of development scenario of the building stock and energy efficiency of the buildings. Two different types of scenario simulations were done. The first one, system optimization, search for optimal system concept taking into account the investment costs for the energy production system including centralized and decentralized systems. The second one, energy simulation, studied the influence of the decentralized energy production on the energy efficiency, emissions and energy costs. Both the simulation cases had the time frame of 20 years. The optimization model can be used to study the influence of production unit costs and external conditions on the optimal system typology. The energy system optimization study was based on three main scenarios: the existing bio CHP plant and gas boiler would be useable during 2015–2035, the CHP plant will be stopped in 2025 or there are no existing units in the region. The optimization takes into account costs of the equipment and energy, external conditions (solar, wind) as well as heating and power needs. The study of alternatives showed that it is cost optimal to use the already existing CHP plant. The heat pumps, gas boilers and wind and gas turbines will support the energy system when the CHP is not used anymore. In the energy simulation study, a set of scenarios for the development of the case area's district heating system have been made. The purpose of the scenarios was not to make a prediction of what the future heating energy systems will be like, but rather to examine what different possible development pathways there are and compare them in terms of technical, environmental and economic criteria. The conservative, extensive and extreme scenarios assumed different amounts of solar energy and ground source heat pumps to be implemented as decentralized systems (1%, 10% or 50% of floor area implemented decentralized RES). The industrial heat was used or the consumer acted as an active prosumer selling the excess solar heat back to network. In the case of simulations, the extreme scenario with ground source heat pumps and a solar thermal system decreased the annual centralized heat production by 34% and, in the case of industrial waste heat by 32% at the end of the scenario timeframe compared to starting year. The non-renewable heat consumption decreased 46% in case of industrial waste. In the case where 20% of the district heating was originating from the industrial waste heat source, the CO_2 emissions decreased by 50%. The energy costs depend strongly on the scenario assumptions. The yearly energy costs of reference case decreased 22% compared to the starting year, and the biggest reduction (34 %) was gained in the extreme scenario. In the conservative, extensive and extreme scenarios using heat pumps, the CO_2 emissions increased compared to the reference case, due to the increase in electricity use by heat pumps. The case studies showed that environmental performance depends strongly on the source of emission factors for the primary energy, e.g., if the real factor based on local conditions or average national values will be used. The energy-saving benefits of the prosumer scenario were quite small (<1%) at the district level, because this case only sold
ISBN, ISSN, URN	ISBN 978-951-38-8478-9 (URL: http://www.vttresearch.com/impact/publications) ISSN-L 2242-1211 ISSN 2242-122X (Online) http://urn.fi/URN:ISBN:978-951-38-8478-9
Date	November 2016
Language	English, Finnish abstract
Pages	77 p. + app. 2 p.
Name of the project	EFEU
Commissioned by	
Keywords	district energy systems, future, energy efficiency
Publisher	VTT Technical Research Centre of Finland Ltd P.O. Box 1000, FI-02044 VTT, Finland, Tel. 020 722 111

Julkaisun sarja ja numero

VTT Technology 277

Nimeke	**Tulevaisuuden energiatehokkaiden alueellisten energiajärjestelmien näkymiä**
Tekijä(t)	Satu Paiho, Ismo Heimonen, Elina Grahn, Rinat Abdurafikov, Lotta Kannari, Markku Mikkola, Tapani Ryynänen, Timo Laukkanen, Joel Ypyä & Sampo Kaukonen
Tiivistelmä	Tämä raportti kuvaa tulevaisuuden energiajärjestelmien visioita ja kaukolämpöön liittyvien järjestelmien nykytilaa Suomessa. Raportissa kuvataan tulevaisuuden liiketoimintaan ja palveluihin liittyviä haasteita ja tarpeita. Samoin kuvataan skenaarioanalyysien lähestymistapaa. Keski-Uudenmaan kaukolämpöverkon analyysejä tarkastellaan tapaustutkimuksena. Skenaariotarkasteluissa esitetään energiajärjestelmän valinnan ja energiankulutuksen vaihtoehtoja tapaustutkimuksen avulla 20 vuoden aikana (2015–2035). Skenaariot perustuivat oletukseen, että rakennuskanta kasvaa ja rakennusten energiatehokkuus paranee tarkastelujakson aikana. Teimme kahdentyyppisiä skenaariotutkimuksia: Järjestelmäoptimoinnilla etsittiin optimaalista järjestelmävaihtoehtoa ottaen huomioon investointikustannukset. Energiasimuloinnein tutkittiin hajautetun energiantuotannon vaikutuksia energiatehokkuuteen, emissioihin ja energiakustannuksiin. Molemmissa skenaariotutkimuksissa oletettiin 20 vuoden tarkastelujakso. Optimointimallilla voidaan tutkia tuotannon yksikkökustannusten ja ulkoisten olosuhteiden vaikutuksia optimaaliseen järjestelmäkokoonpanoon. Energiajärjestelmän optimointi perustui kolmeen pääskenaarioon: Nykyinen olemassa oleva bio-CHP-laitos ja kaasukattila voivat olla käytössä vielä tarkastelujakson 2015–2035, CHP-laitos pysäytetään 2025, tai alueella ei ole energiantuotantoyksikköjä. Optimointi ottaa huomioon laitteiden ja energian kustannukset, ulkoiset olosuhteet (aurinko, tuuli) ja lämmön ja tehon tarpeet alueella. Vaihtoehtojen tarkastelut osoittivat, että on kustannusoptimaalista käyttää olemassa olevaa CHP-laitosta. Lämpöpumput, kaasukattila sekä tuuli- ja kaasuturbiinit tukevat energiajärjestelmää, kun CHP ei ole enää käytössä. Energiasimulointitutkimuksessa muodostettiin skenaarioita tapaustutkimuksen lämmitysjärjestelmävaihtoehdoista. Skenaarioiden tarkoituksena ei ollut tehdä arvioita, millainen tulevaisuuden lämmitysjärjestelmä on, vaan pikemminkin tarkastella, millaisia vaihtoehtoisia kehityspolkuja on, ja arvioida näitä teknisillä, taloudellisilla ja ympäristökriteereillä. Kolme skenaariota – konservatiivinen, laaja ja äärimmäinen (conservative, extensive, extreme) – kuvasivat aurinkolämmöllä ja maalämpöpumpuilla toteutettavan järjestelmän hajautuksen määrää. Vaihtoehtoina oli, että 1 %, 10 % tai 50 % rakennusten pinta-alasta oli lämmitetty hajautetulla uusiutuvan energian järjestelmällä. Vaihtoehtoina olivat myös teollisuuden ylilämmön käyttö sekä kuluttajan toimiminen lämmön tuottajana (prosumer), joka myy ylimääräisen lämmön takaisin kaukolämpöverkkoon. Äärimmäisessä (extreme) skenaariossa maalämpöpumppujen ja aurinkolämmön käyttö pienensi keskitetysti tuotetun lämmön tarvetta 34 % ja teollisuuden ylilämmön hyödyntämisen tapauksessa 32 % , kun skenaarion viimeisten viiden vuoden arvoa verrattiin alkutilanteeseen 2015. Ei-uusiutuvan lämmön kulutus pieneni teollisuuden ylilämmön hyödyntämisen tapauksessa 46 %. Kun 20 % kaukolämmöstä tuotettiin teollisuuden ylilämmöllä, CO2-päästöt pienenivät 50 %. Vuotuiset energiakustannukset pienenivät konservatiivisessa tapauksessa 22 % alkutilaan verrattuna, ja suurin alenema saavutettiin äärimmäisen (extreme) skenaarion tapauksessa (34 %). Konservatiivisessa, laajassa ja äärimmäisessä tapauksessa käytettiin lämpöpumppua, jolloin CO2-päästöt kasvoivat referenssitapaukseen verrattuna, koska näissä tapauksissa käytettiin sähköä lämpöpumppujen toimintaan. Kuluttaja tuottajana -skenaarion energiansäästövaikutus aluetasolla oli melko pieni (<1 %), koska tässä tapauksessa verkkoon myytiin vain ylimääräinen aurinkolämpö, jota syntyi vain kesäkuukausina.
ISBN, ISSN, URN	ISBN 978-951-38-8478-9 (URL: http://www.vtt.fi/julkaisut) ISSN-L 2242-1211 ISSN 2242-122X (Verkkojulkaisu) http://urn.fi/URN:ISBN:978-951-38-8478-9
Julkaisuaika	Marraskuu 2016
Kieli	Englanti, suomenkielinen tiivistelmä
Sivumäärä	77 s. + liitt. 2 s.
Projektin nimi	EFEU
Rahoittajat	
Avainsanat	alueelliset energiajärjestelmät, energiatehokkuus, tulevaisuus
Julkaisija	Teknologian tutkimuskeskus VTT Oy PL 1000, 02044 VTT, puh. 020 722 111

VTT TECHNOLOGY 277 Visions for future energy efficient district...

Visions for future energy efficient district energy systems

The future energy system options can be versatile combinations of different energy production technologies including centralized and decentralized systems. Current trends such as decentralization, the end-users starting to produce part of their own energy use as well as offering/selling it to other energy users (prosumers), new technical possibilities in energy production, the increase of the local energy and renewables and improvement of the energy efficiency of buildings will increase the uncertainty of the energy business.

This report gives the vision of the future district energy systems and describes the state-of-the art of district heating related energy systems in Finland. The challenges and future needs of the energy business and services are described. The approach for scenario analyses is presented using the district heating system of Keski-Uusimaa as a case study.

ISBN 978-951-38-8478-9 (URL: http://www.vttresearch.com/impact/publications)
ISSN-L 2242-1211
ISSN 2242-122X (Online)
http://urn.fi/URN:ISBN:978-951-38-8478-9