SUSTAINABLE CITIES' ENERGY DEMAND AND SUPPLY FOR HEATING AND COOLING

Svensk Fjärrvärme

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FJÄRRSYN

SUSTAINABLE CITIES' ENERGY DEMAND AND SUPPLY FOR HEATING AND COOLING

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1. SVENSK SAMMANFATTNING

Resultaten visar att en utbyggnad av fjärrvärme och fjärrkyla, i kombination med energieffektivisering i det byggda beståndet, kan minska utsläppen av koldioxid med upp till 18 procent till år 2020 i flertalet europeiska städer. Undersökningen visar också att den modell för uppvärmning av byggnader som har valts i Linköping leder till cirka 60 procent lägre primär resursanvändning och koldioxidutsläpp än genomsnittet i EU27-ländernas städer om nuvarande teknik används fram till år 2020. Den generella slutsatsen från studien är att insatser måste göras både vad gäller energieffektivisering av byggnaderna och utformningen av städernas energisystem. Varken det ena eller det andra perspektivet är tillräckligt om städerna ska klara att uppfylla målen som finns fram till år 2020 med 20 % lägre utsläpp av växthusgaser, 20 % minskad primärenergianvändning och 20 % mer förnybara energislag.

Hållbara städer i framtiden

Som utgångspunkt för studien har en konceptuell modell utvecklats för hur en framtida hållbar stad kan se ut. Där ska den framtida hållbara staden kunna erbjuda ett gott liv för stadens invånare utan att äventyra resurser, biologisk mångfald och miljö för framtida generationer. En hållbar stads energianvändning kommer att kräva långtgående energieffektivisering tillsammans med tillförsel av mer förnybara energiresurser. Fram till år 2020, som är studiens målår, kommer vi bara att hunnit en bit på väg mot den slutgiltigt hållbara staden. Några olika vägar för hur värme- och kylbehovet kan tillgodoses i framtiden har undersökts där graden av kontroll är en viktig faktor för utvecklingen. Om myndigheterna tex. skulle kräva mer långtgående energieffektiviseringar av bebyggelsen så har vi kallat dessa vägar för ”planering och kontroll”. En mer realistisk väg som antar att utveckling och tillämpning av energieffektivisering sker mer på markandsvillkor har vi kallat ”marknad och policy”. Vi har också tittat på en utveckling som projicerar nuvarande utvecklingstakt utan några större förändringar.

Scenarier

Studien syftar till att undersöka vilken roll fjärrvärme och -kyla har i europeiska städer år 2020 i deras strävan mot att bli mer hållbara. Linköping, Dublin, Tallinn och Madrid har valts som exempel eftersom de skiljer sig åt när det gäller klimat, storlek, befolkningstäthet och nuvarande system för värme och kyla. För varje stad har potentialen för fjärrvärme och -kyla beräknats för år 2020 tillsammans med olika antaganden om energieffektivisering av värme- och kylbehovet i byggnaderna. Effekterna på primärenergianvändning och koldioxidutsläpp av att introducera fjärrvärme och -kyla samt att energieffektivisera bebyggelsen i städerna har beräknats. En modell har utvecklats för beräkningarna, som tar hänsyn till städernas klimat, befolkningsmängd, -täthet, värme- och kylbehov i byggnader och lokalt tillgängliga källor och infrastruktur för fjärrvärme och -kyla. Modellen kan även användas för andra städer i Europa för att undersöka vilken potential till koldioxidreduktion och minskad resursanvändning som introduktion av fjärrvärme eller -kyla samt energieffektivisering av byggnadsbeståndet har. De olika scenarierna som har studerats beskrivs nedan.

Scenario	Description
EU27	Värme och kylbehov antas vara enligt medlet inom EU-27 länderna. Energieffektivisering på 1% årligen antas vilket ger en total ökning av energianvändningen på 15% fram till år 2020.
BAU (Business As Usual)	Värme och kylbehov för städerna antas vara som idag för respektive stad men med 1% energieffekivisering årligen vilket ger en total ökning av energianvändningen på 15% fram till år 2020.
2% energieffektivisering utan fjärrvärme eller frjärrkyla	Inget införande eller uppgradering av fjärrvärme eller fjärrkyla antas. Värme- och kylbehovet är detsamma som i BAU-scenariot oven men med 2% energieffektivisering implementerad årligen, vilket ger totalt 0% ökad energianvändning fram till år 2020.
2% energieffektivsiering med fjärrvärme eller fjärrkyla.	Införande eller uppgradering av fjärrvärme och kyla antas i övrig samma antaganden som ovan.
4% energieffektivsiering utan fjärrvärme eller fjärrkyla	Inget införande eller uppgradering av fjärrvärme eller fjärrkyla antas. Värme- och kylbehovet är detsamma som i BAU-scenariot men med 4% energieffektivisering implementerad årligen, vilket ger totalt 0% ökad energianvändning fram till år 2020.
4% EE with DH or DC	Same as above, but with district heating or cooling implemented or upgraded.

I Linköping antas 100 % av värmebehovet att täckas med fjärrvärme år 2020. Merparten av energin kommer från avfall och fasta biobränslen i kombinerade kraftvärmeverk samt en liten andel fossila bränslen. 26 % i Dublin samt 40 % i Madrid antas kunna komma från fjärrvärme år 2020. Merparten av energin kommer från naturgas och avfall i kombinerade kraftvärmeverk. I Tallinn antas 98 % av värmemarknaden täckas av fjärrvärme med huvuddelen från fasta biobränslen, avfall och naturgas i kraftvärmeverk samt en liten andel naturgasvärmeverk.

50 % av det framtida kylbehovet i städerna antas kunna tillfredställas med fjärrkyla. I Linköping antas olika grad av adsorptionskyla, ”frikyla” och luftkonditioneringsaggregat. Energin till adsorptionskylmaskinerna kommer främst från kraftvärmeverk eldade med fasta biobränslen och avfall. I Madrid och Dublin används främst adsorptionskyla, drivna med kombinerade kraftvärmeverk med avfall och biobränslen, och stora eldrivna luftkonditioneringsaggregat. Tallins fjärrkylanät antas vara liknande som för Linköping men där värmen till adsorptionskylmaskinerna kommer från lika delar avfall och naturgas från kombinerade kraftvärmeanläggningar.

Resultat

Resultaten visare att fjärrvärme och -kyla tillsammans med en snabb energieffektivisering av byggnadsbeståndets värme- och kylbehov leder till både minskat primärenergibehov och minskade utsläpp av växthusgaser. Enskilt leder respektive åtgärd till minskningar men tillsammans blir effekten i de flesta fall större. Primärenergianvändningen minskar för värmesektorn i en stadsdel med mellan 30 % till 87 % och för en hel stads värmesektor med mellan 30 % och 54 % jämfört med om städerna bara fortsätter som hittills utan några särskilda åtgärder. Potentialen för hela stadens primärenergianvändning (el, transporter, värme och kyla) ger en minskning med mellan 7 % och 18 %.

Minskningen av växthusgaser är mellan 77 % och 88 % för en stadsdels värmebehov och för hela stadens värmebehov mellan 40 % och 77 %. Effekten för hela stadens koldioxidutsläpp blir en minskning på mellan 7 % och 18 %.

I de scenarierna med 4 % årlig energieffektivisering av byggnadernas värmebehov står introduktionen av fjärrvärme för ca 1/3 av minskningen i primärenergianvändning och växthusgaser. Dock är introduktionen av fjärrvärme viktigare för minskningen av växthusgaser, eftersom fjärrvärmesystemet underlättar introduktionen av biobränslen i energisystemet för värme.

Primärenergibehovet för en byggnad som energieffektiviseras och ansluter sig till fjärrkyla minskar med mellan 45 % och 71 %, och för hela kylsektorn i en stad är besparingspotentialen mellan 36 % och 51 % jämfört med ett scenario likt dagens system. Besparingspotentialen för hela stadens energianvändning blir mellan 1 % och 3 %. Resultaten vad gäller kylbehovet är betydligt mer osäkra eftersom datatillgången för t.ex. kylbehov i städerna har varit mycket knapphändigt.

Slutsatserna från studien är att introduktionen av fjärrvärme och -kyla är viktigt för att minska den primära resursanvändningen och koldioxidutsläppen. Detta gäller även vid en hög grad av energieffektivisering av de enskilda byggnaderna. Slutsatsen är också att kombinationen av energieffektiviseringsåtgärder med introduktion av fjärrvärme och -kyla ger den snabbaste vägen till en mer hållbar stad.

Förenklingar och känslighetsanalys

Modellering av komplexa system, vilket en stads värme- och kylsystem är, kräver flera förenklingar och en del antaganden. Även metodval för beräkning av t.ex. primärenergianvändning eller allokering av miljöbelastning mellan el och värme påverkar resultatet. Utgångspunkten för metodvalen har varit att beskriva vilka konsekvenser en introduktion eller uppgradering av fjärrvärme och kyla ger upphov till samtidigt som byggnaderna energieffektiviseras. Känslighetsanalysen visar att resultaten är relativt robusta, men om både allokeringsmetod och primärenergifaktorerna ändras samtidigt påverkas resultaten en hel del. Om gränsen sänks för när fjärrvärme och -kyla introduceras i städerna, dvs. vid vilken värme- och kyltäthet (behovet per kvadratkilometer) som bedöms som lönsam, kan potentialen för miljöförbättringar för fjärrvärme- och kyla öka ytterligare. Kostnaden för att minska koldioxidutsläppen genom introduktion av fjärrvärme och -kyla har också beräknats och bör kunna vara lägre i framtiden då redan ett fjärrvärmenät är introducerat.

2. ABSTRACT

The result from the study show that the introduction of district heating and cooling in combination with energy efficient buildings can decrease the overall green house gases with up to 18% in European cities until the year 2020. The model that the city of Linköping in Sweden uses today, with almost 100% district heating, results in a heating sector that is approximately 60% more energy efficient compared to the EU27-average, using a business as usual scenario until 2020. The overall outcome of the study is that action is needed both on the energy use and on the energy supply side. Neither one of the two perspectives is enough, if the cities' aspiration to achieve the 2020 target with 20% less green house gas emissions and energy use and 20% more renewable resources is to be reached in time.

The sustainable cities of the future

As starting point for the study, a conceptual model of a future sustainable city was drawn up. In a future city, a good life can be offered without jeopardising the resources, the biological diversity and the environment for future generations. A sustainable city's energy use will require far-reaching energy efficiency improvement together with supply of more renewable energy resources. The year of study in this project is 2020, and it is clear that a sustainable state will not be achieved by then. Cities will not be sustainable in 2020, though they might be striving towards sustainability. There are many possible paths towards sustainability. The path depends, among other things, on the degree of control. If authorities require that each retrofit and each new construction apply the most energy-efficient technology, the cities will in theory be dominated by passive houses as quickly as the rate of retrofit and replacement allows. We call this group of paths "Plan & Control". A more realistic group of paths assumes that the development and application of energy-efficient technology depend on a combination of market forces and policy, where policy can influence the market forces. We call this group of paths "Market & Policy".

Scenarios

The pathways representing "Plan and control" and "Market and Policy" are based on the rate of the energy efficiency implemented in the buildings, which is 2% and 4% respectively. Calculations have been made for Linköping, Dublin, Tallinn, and Madrid. They differ in terms of climate, population, structure, and density, and in current heating and cooling systems. For each city the potential for district heating and cooling was calculated in different scenarios for the year 2020, with different assumptions regarding the energy efficiency of buildings. The effect on primary energy resource use and green house gas (GHG) emissions, when introducing or upgrading district-heating and cooling systems, was calculated for each scenario. The different scenarios included were:

Scenario	**Description**
EU27	Average heating and cooling demand per inhabitant in the 27 EU countries with 1% energy efficiency implemented yearly, which gives a total increase in demand of 15% until 2020.
BAU (Business As Usual)	The heating and cooling demand of today in the cities with 1% energy efficiency implemented yearly, which gives a total of 15% increase in demand until 2020.
2% EE without DH or DC	Heating and cooling demand the same as for the BAU-scenario with 2% energy efficiency implemented, which gives about 0% increase in demand until the year 2020, without implementation or upgrade of district heating.
2% EE with DH or DC	Same as above, but with district heating or cooling implemented or upgraded.
4% EE without DH	Heating and cooling demand is the same as for the BAU-scenario with 4% energy efficiency implemented, which gives about 25% decrease in demand until the year 2020, without implementation or upgrade of district heating.
4% EE with DH or DC	Same as above, but with district heating or cooling implemented or upgraded.

EE = Energy efficiency   DH = District heating   DC = District cooling

In Linköping, 100% of the heating demand is assumed to be covered by district heating year 2020. The assumed energy resources for future district heating are combined heat and power (CHP) plants with waste to energy (WTE), solid bio fuels and fossile fuels. For Dublin 26%, and for Madrid 40%, of the heating demand is covered by district heating based on natural gas and waste to energy in combined heat and power plants. For Tallinn, 98% will be covered by district heating with combined heat and power plants supplied with solid biofuels, waste and natural gas, and natural gas boilers.

For all cities, 50% of the projected cooling demand is supplied with district cooling. The assumed upgraded district cooling in Linköping is supplied with 75% absorption cooling from district heating, "free" cooling, and some electric air-condition machines. The heat to the absorption cooling machines is produced with "waste to energy" and solid biofuel combined heat and power plants. In Madrid and Dublin, the district cooling is produced by absorption cooling from district heating and some large scale air-condition machines. The heating to the absorption cooling machines is produced by "waste to energy" and natural gas combined heat and power plants. Tallinn's district cooling system is assumed to be similar to the one in Linköping, but the heat to the absorption cooling machines is produced by 50% "waste to energy" and 50% natural gas combined heat and power plants.

Results

District heating/cooling and a rapid implementation of energy efficiency measures in buildings both serve to reduce primary energy use and green house gas emissions. Individually they will reduce the environmental impact, but together the total effect is larger in most cases. The saving potential of primary energy resources for a district that implements district heating and energy efficiency measures is between 30% and 87%, and for the whole heating sector in the cities it is between 30% and 54% compared to the business as usual (BAU) scenarios. The savings compared to the total use of primary energy resources in the city is 7% to 18%. The reduction of carbon dioxide for a district that implements district heating and energy efficient measures is between 77% and 88%, and for the heating sector in the cities it is between 40% and 77%, and compared to the cities' total carbon dioxide emissions, 7% to 18%.

The heating demand in Linköping in the business as usual scenario is higher than the EU27 average scenario, but the primary energy use and CO_2 emissions are about 50% and 62% lower respectively, mainly due to the extensive use of district heating and the limited use of fossil fuels in the heat production. The primary energy use and CO_2 emissions will decrease further by implementation of energy efficiency measures.

In the scenario with the most rapid increase in energy efficiency (4% per year), the reduction in primary energy use depends to approximately two thirds on the energy efficiency measures and to about one third on the implementation/upgrade of district heating. However, district heating is more important for reducing fossil CO_2 emissions, because district heating systems make it easier to use solid biofuels for heating.

The saving potential of primary energy resources for a building that implement district cooling at the same time as energy efficient measures are taken, is between 45% and 71%, and for the whole cooling sector in the cities, it is between 36% and 51% compared to the business as usual scenarios. The savings compared to the total use of primary energy resources in the city is 1% to 3%. The reduction of carbon dioxide for buildings that implement district cooling and energy efficient measures is between 75% and 100%, and for the cooling sector in the cities it is between 38% and 71%, and compared to the cities' total carbon dioxide emissions, 1% to 3%. However, it should be noted that the calculations for which the results for cooling rely on is of lesser quality then the ones for heating. The accessibility to data is lower for cooling demands, and that affects the quality of the results.

Implementation of district heating and cooling can be important for reducing primary energy use and emissions, even in cities with rapid implementation of measures to increase the energy efficiency of buildings. The combination of energy efficiency improvements and district heating and cooling gives the largest and most rapid reductions in primary energy use and emissions. In this sense, combining these efforts is the quickest route towards the sustainable city.

Simplifications and sensitivity analysis

The model used for the calculations accounts for climate, population density, heating and cooling demand, locally available sources for heating and cooling, existing infrastructure for district heating and cooling, etc. However, modelling complex systems like these require simplifications and assumptions. The methodological choices have been guided by the aim to describe consequences of implementing and upgrading district heating and cooling in the year 2020. The main methodological choices concern allocation and calculation of primary energy factors. Assumptions have been required when the input data are incomplete and data gaps are needed to be filled with approximations and assumptions from other sources. The sensitivity analysis shows that the results are rather robust. However, if the methods for allocation and primary energy factors both are changed, the results would be significantly affected. Lowering the assumed heating-demand threshold for district heat will significantly increase the potential of district heating. The net cost per ton reduced carbon dioxide emissions is also likely to decrease and can even become a net benefit.

3. PREFACE

The study has examined which role district heating and district cooling have in European cities in 2020. The cities Linköping, Dublin, Tallinn and Madrid have been chosen since they vary when it comes to climate, size, population density and current system for heat and cooling.

The project focuses mainly on individual houses, so called zero-energy or plus-energy houses. It shows how district heating can be used in order to reach just as low use of resources and primary energy, as well as equally low emissions of carbon dioxide as zero-energy houses for the system as a whole.

Sustainable cities' energy demand and supply for heating and cooling presents the results from a study within the research program "Fjärrsyn" that is financed by Swedish District Heating Association and Swedish Energy Agency. "Fjärrsyn" will support the competitiveness for district heating and district cooling through increased knowledge about the role of district heating for the sustainable society for example to open for economical feasible solutions and the future's technology.

The project has been implemented by Erik Särnholm, Anna Jarnehammar, Linus Hagberg, Andreas Öman and Tomas Ekvall at the Swedish Environmental Research Institute. A reference group has been connected to the project made up of Ingvar Carlsson Tekniska Verken Linköping (chairman), Johan Brossberg Borlänge Energi, Jörgen Sjödin Swedish Energy Agency, Anne Charlotte Söderlund E.on, Björn Andersson FVB, Ulrika Prytz Lund's Energikoncernen, Tea Alopaeus Naturvårdsverket, Jonas Gräslund Skanska, Jörgen Carlsson Umeå Energi, Martin Blixt Älvstranden Gothenburg, Anna Land and Erik Larsson Swedish District Heating Association.

Gunnar Peters
Chairman "Group of competitive awareness", Swedish District Heating Association

4. AIM AND APPROACH

The aim of this study is to investigate the role of district heating and cooling in European cities on the path towards sustainability in the year 2020. Our focus is on the potential for district heating and cooling systems, and on the effects of these systems on the primary energy use and fossil CO_2 emissions.

We collect data on the current heating and cooling demand and on possible supply sources with a low primary energy factor for four different cities: Linköping, Dublin, Tallinn and Madrid. Based on these data, we project a forecast for the year 2020 for all four cities. The cities have been chosen to represent different shares of district heating and cooling, high and low heating and cooling demand per person, and more or less dense cities. Thus Linköping represents a city with average density and a high degree of district heating. Dublin has a rather high heating demand but a low share of district heating. Tallinn represents a city with quite a high heating demand and district heating share. Finally, Madrid has a lower heating and higher cooling demand, supplied with a low fraction of district heating and cooling, and also represents a city with a high dense structure and population.

Sustainable cities include many different aspects derived from the three pillars social, economical and ecological aspects. All those three aspects must be addressed to fulfill a sustainable development of a city. The overall concept of a sustainable city has been described in the developed conceptual model. However in the analysis and modeling of the four cities only a part of the ecological pillar has been studied, more explicitly the energy supply and demand for heating and cooling of buildings in a city, see Figure 1. Nevertheless, all four kinds of energy carriers (fuel, electricity, heat and cooling) have been included. The energy use and supply of a whole city can also includes transportation and electric appliances, as can bee seen in the figure below, but also energy for food production, waste handling and water treatment, producing products used/consumed in the city, etc.

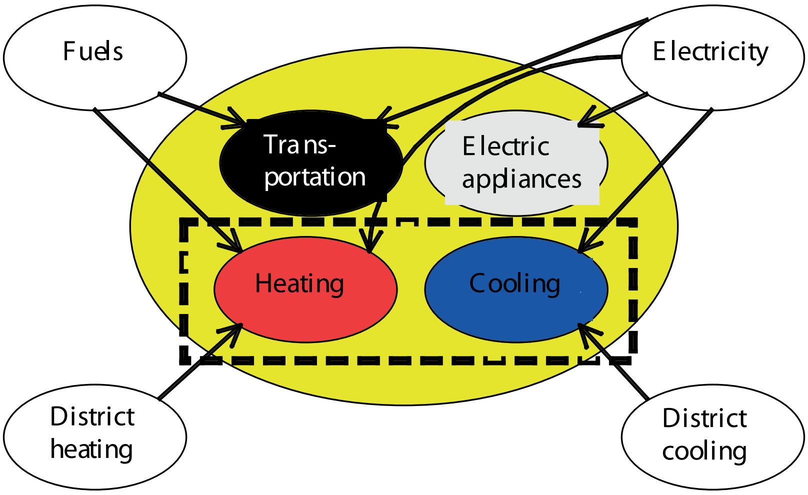

Figure 1. Different energy carriers meet different needs in a city. Note: heating includes space heating, water heating, and cooking. Electricity appliances are, for example, light, computers, machines, etc.

5. CONCEPTUAL MODEL OF SUSTAINABLE CITIES ENERGY USE AND SUPPLY

Sustainability stands for different things in different minds. The probably most authoritative definition of sustainable development stems from the World Commission on Environment and Development: "Sustainable development seeks to meet the needs and aspirations of the present without compromising the ability to meet those of the future" (Bruntland, 1987).

A slightly more operational definition lies in the four socio-ecological principles for a sustainable society (Holmberg, 1995):

(i) Substances extracted from the lithosphere must not systematically accumulate in the ecosphere.
(ii) Society-produced substances must not systematically accumulate in the ecosphere.
(iii) The physical conditions for production and diversity within the ecosphere must not systematically be deteriorated.
(iv) The use of resources must be effective and just with respect to meeting human needs.

These principles where adapted and used as foundation for the activities of The Natural Step (see www.detnaturligasteget.se). A related line of thought was applied in the project Göteborg 2050. Here the description of sustainability was operationalised one step further (see www.goteborg2050.nu). This is also the description of sustainability that we apply in our project:

- Closed material loops: minimised use of non-renewable resources and landfill
- No toxic emissions
- Safeguarded biological diversity
- Eventually: only renewable energy sources
- In 50-100 years: an even distribution of the global wealth
- A good life

Obtaining a good life globally with renewable energy sources only, while safeguarding biological diversity, will require an efficient use of energy resources. In a sustainable future, solid biofuel can be used for co-production of electricity, heat, process steam and/or liquid fuel. Additional electricity can be provided through hydropower, wind power, photovoltaics etc. The sun can also be used for heating of buildings and water.

The combination of these energy sources can generate much more energy than today. However, to obtain a good life on a global level based on these sources, we still probably will have to use exceedingly energy-efficient technologies: the most energy-efficient technologies will have to be applied, and even more advanced technologies need to be developed.

Existing passive-house concepts indicates that buildings can be heated without any external energy through utilizing the heat from inhabitants and household appliances. If appliances become significantly more energy-efficient, passive housing will require even more efficient building shells etc. On the other hand plus-energy houses, such as the ones in Freiburg (PEGE, 2008), demonstrate that current technology allows buildings to be net producers of useful energy: they produce more energy from renewable energy sources than they import from external sources. This is achieved using a combination of micro-generation technology and low-energy building techniques such as passive solar building design, insulation and careful site selection and placement.

Cooling can partly be obtained through passive techniques such as venting, shading, and evaporation. However, these techniques have limited effect, particularly in humid climates. In very warm climates and temperature, active technologies will have to be used for cooling, and it is unclear if sufficient energy can be generated by the house itself.

Making industrial processes and transportation systems independent of external energy sources is a very tough task. Industrial processes require a much higher energy and power intensity in terms of kWh/m^2-yr or kW/m^2, compared to the heating and cooling of buildings. Transportation also requires higher power intensity, for accelerations. The mobility of vehicles is a further constraint on the technologies that can be applied in that sector.

The conclusion is that, in a sustainable society, external energy sources are mainly used for industrial processes, transports, and possibly cooling. Some external energy might still be used for heating of buildings, for example because a good life can require keeping buildings that are part of the cultural heritage. Also, it will probably be cost efficient, in the sustainable society, to utilise waste heat that has no or little alternative use for the heating of buildings. On the other hand, parts of the building stock might be plus-energy houses. For this reason, we assume that the net external energy used for heating of buildings will be close to zero in the sustainable society.

The year of study in this project is 2020. It is clear that a sustainable state, as described by Göteborg 2050 and above, will not be achieved by then. The retrofit and replacement rate of buildings will not allow passive-house technology to dominate the cities until much later. Hence, cities will not be sustainable in 2020, but they might be striving towards sustainability.

There are many possible paths towards sustainability. The path depends, among other things, on the degree of control. If authorities require that each retrofit and each new construction applies the most energy-efficient technology, cities in theory will be dominated by passive houses as quickly as the rate of retrofit and replacement allows. We call this group of paths "Plan & Control".

A more realistic group of paths assumes that the development and application of energy-efficient technology depend on a combination of market forces and policy, where policy can influence market forces (see Figure 2). Market forces and policy are both affected by the environmental awareness and commitment of the public. These, in turn, are subject to various rebound effects and affected by the perceived urgency of environmental threats. In this group of paths, passive-house technology will spread more slowly. There is no guarantee that these paths will actually end in a sustainable society as defined here. We call this group of paths "Market & Policy".

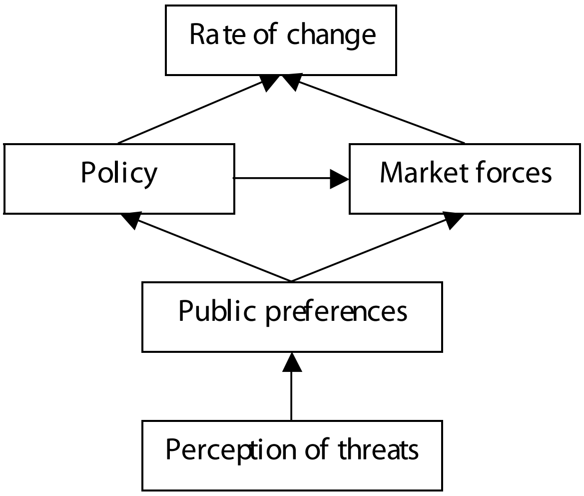

Figure 2. Factors influencing the rate of development and application of energy-efficient technology in a Market & Policy scenario.

Paths towards sustainability can also differ in the role of district heating (DH). While buildings are replaced over a period of many decades, and thorough retrofits of buildings take place with long intervals, DH systems can be established and expanded more quickly. This is environmentally beneficial in the mid-term perspective, for several reasons:

- DH systems allow for the use of low-grade energy sources such as waste heat and heat from waste,
- they allow for efficient conversion of energy through large-scale boilers and, more importantly, combined heat-and-power production, and
- the large-scale DH plants allow for efficient exhaust gas cleaning.

Systems for DH require heavy investments in production plants and grid. However, since the replacement rate of buildings is low, DH systems can be economically viable even when the technology trend is towards passive houses. A Plan & Control scenario that requires a rapid and focused effort on retrofitting old building could change this (Fröling et al., 2007); however, when the path towards sustainability is guided by a more realistic mix of markets forces and policy, near-future investments in DH systems are likely to be economically viable also when retrofits are taken into account.

It is uncertain if new investments in DH systems will be economically viable in the sustainable society; however, DH systems that remain in the sustainable society can be expected to have a value, since they might still serve several purposes:

- distribution of waste heat that has no or little alternative use,
- distribution of heat for tap water and, possibly, for appliances such as washing machines, dishwashers, and dryers,
- distribution of heat from plus-energy houses to houses that require external heating, and/or
- district cooling.

Establishing DH systems might, however, delay the state of sustainable cities, when this rate depends on a mix of market forces and policy (see Figure 3). The high efficiency of the DH systems can be expected to result in low running costs for heat production. It can also contribute to making the perception of environmental threats less urgent. Both of these factors are likely to reduce the demand for passive-house technology. As a result, the rate of application of passive-house technology is likely to be lower.

When considering the DH option, the mid-term environmental gain and the possible long-term environmental loss should both be accounted for.

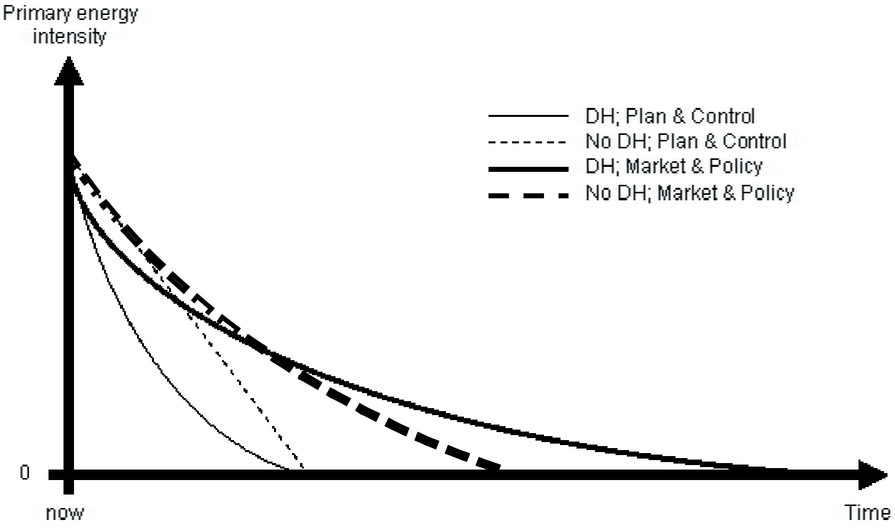

Figure 3: Different paths towards the sustainability target of zero net external energy for heating. The Market & Policy paths described here are optimistic in the sense that they both reach this target.

The cost-effective energy saving potential by 2020 is significant according to EU (2008): 30% less energy use within the sector is feasible. In the study the different paths towards sustainability have been established by assuming 2% energy efficiency per year for the Market & Policy and 4% for the Plan & Control pathway. The ratio 2 and 4% energy efficiency per year for the buildings are assumed values. The 2% assumption gives an energy saving of 25% year 2020 (2006 is the base year) which corresponds well with the calculations done by EU where 30% less energy can be reached with cost-effective measures. The 4% energy saving ratio per year gives 45% energy savings until the year 2020 and will require stricter legislative actions if it is going to be achieved and thus represent the Plan & Control path in a realistic way.

6. THE CITY MODEL

– SYSTEM BOUNDARIES, PRIMARY ENERGY FACTORS, CO_2 EMISSIONS AND ALLOCATION

System boundaries

In this study the aim is to examine the consequences of introducing different energy supply options for the heating and cooling demand of the cities. The system studied is the one represented in Figure 4 below where the primary energy factors for the different fuels and energy carriers that passes the system boundary is determined by valuating the likely alternative use of each fuel in the year of 2020. The extraction and refining of fuels, energy transformation processes and the processes for heating and cooling the cities different buildings are thus included. The scope has however some limitations since the energy used for constructing the energy facilities that transform the fuel into e.g. electricity and heat has not been included. The construction or the demolition of the buildings has not been included either since the goal is not to compare the energy performance of different buildings. In the analysis of the cities' heating and cooling demand, different scenarios for energy efficiency in the future has been studied, the energy used for production of for example insulation material, heat recovery systems etc. is not included either, since energy efficiency actions is assumed to take place anyway as a part of the overall goal in EU for the construction sector. The background for the choice of system boundaries can be read in Appendix A.

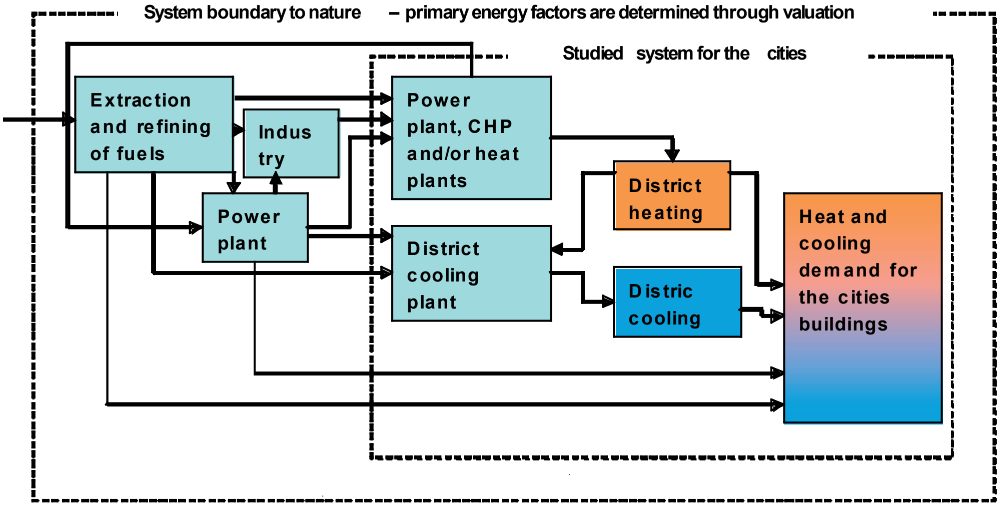

Figure 4. The figure presents the energy flows of the system studied. For each energy carrier that pass the system border "Studied system for the cities", the primary energy factors are determined by valuating the marginal production or likely alternative use of each energy carrier in the year of 2020.

Primary energy and CO_2 emission factors

The study examines the consequences of introducing a change to the energy system in the four cities. Therefore an approach is used where the primary energy factor of each energy carrier is determined by considering if the use of this energy carrier in the district-heating/cooling system is likely to affect the production of the energy carrier, or if it is likely to affect the use of the energy carrier in other systems. The primary energy factor is then calculated based on the estimated effect of the marginal production or the likely alternative use in the year 2020.

Fossil fuels and electricity will be produced to the extent that they are demanded by district-heating systems and other user. For solid biofuel, the production and alternative use of the fuel might both be affected. In all cases, these fuels and electricity have a primary energy factors above unity. In the case of waste the alternative to use it in waste-to-energy (WTE) plants is to deposit it at landfills. At most European landfills, methane is recovered from the waste. This alternative use is assumed to recover 15% of the energy in the waste, and this is the basis for our primary energy factor for waste. Waste heat from industries and solar heat is only used for heating purposes. Since they have no other likely use, the primary energy factor is close to zero.

Primary energy factors of fuels could differ between use in large-scale and small-scale energy facilities. This depends on the differences in transport distances and efficiency in transportation system for large-scale and small-scale quantities. However, these small differences are neglected. The underlying rational for the defined primary energy factors for the energy carriers can be studied more in detail in Appendix A. The primary energy factors and CO_2 emission factors used in the study can be found in Table 1.

Table 1. In the table the primary energy factors and CO_2 emissions used in the study are presented along with the values for the sensitivity analysis.

	Primary energy (kWh/kWh)			**CO_2 gr/kWh**		
Fuels	**Normal value (NV)**	**Sencitivity analysis 1 (SA1)**	**SA2**	**Normal value (NV)**	**Sencitivity analysis 1 (SA1)**	**SA2**
Solid biofuels (e.g. wood)	1.08	Not changed	Not changed	11	Not changed	Not changed
Waste	0.31	1.16	Not changed	88	Not changed	Not changed
Surplus heat	0.05	Not changed	Not changed	0	Not changed	Not changed
Natural Gas	1.16	Not changed	Not changed	225	Not changed	Not changed
Oil	1.18	Not changed	Not changed	295	Not changed	Not changed
Coal	1.04	Not changed	Not changed	339	Not changed	Not changed
Electricity production	1.93	1.00	2.97	374	0	969
Electricity used	2.10	1.09	3.23	407	0	1053

Source for primary energy factors: See Appendix A
Source for emission factors for carbon dioxide: Uppenberg et al (2001)

Allocation

In most countries in Europe, for example Spain and Ireland, the electricity is the main product when building large energy plants. If the heat from these power plants should be used for district heating, the plants' electricity production will decrease. This reduction in electricity production has to be considered when calculating the environmental impact of using the heat for district heating. The consequence of using heat from power plants is calculated by using the "decreased electricity production method" (DEPM).

In some countries, for example Sweden and Estonia, the use of heat in district heating systems determine how much the CHP plants is used and therefore the use of heat determine the electricity production in the CHP plants. The consequence of using heat from CHP plants is in these cases totally different from above and the so called "primary energy method" (PEM) is used for calculating these consequences.

The allocation methods is further described in Appendix A and discussed in the discussion chapter.

7. THE CITY MODEL – CITY SPECIFIC MODEL PARAMETERS

The model consists of the parameters; population/area, climate, heating/cooling demand, heating/cooling production, total energy use and implementation level for district heating/cooling. In this section, limitations, definitions, need for input data, data collection and assumptions for the 2020 scenario are described for each model parameter. Some underlying assumptions in the model were made part due to limited data accessibility while others were made simply because the model is a simplification of reality. As will be seen in this chapter the data availability varies considerably between the cities.

7.1 Population and area

7.1.1 Need for input data

The most central parameter in the model is the heating demand density for different parts of the examined cities. This parameter is used to decide if district heating is implemented or not in the model scenarios (see Chapter 7.8 for more information). To be able to calculate the heating demand density for different parts of the city information about number of inhabitants, number of employees, area size, and share of green area have to be collected at city district level.

The cities have been divided into as many city district levels as possible depending on the available statistics to get a as good understanding as possible the differences in heating demand densities between different parts of the city. The number of inhabitants and employees are needed to distribute the heating demand over the city in the case heating demand for each city district could not be found (see section 7.3.4 for more information). The total area and the exploited area of each city district are needed to calculate the heating demand and the population densities.

7.1.2 Data collection

Statistics of inhabitants per city district have been accessible for all cities. Statistics for employees per city district have been found for all cities except Tallinn. The number of city districts in each city differs depending on data accessibility. The exploited area has been calculated from the city territory with information about green areas. The inhabitants and employees for 2020 as presented in Table 2 has been calculated from the latest statistics and with an assumption of 1% growth per year[1].

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[1] In the case of Madrid the population growth is assumed to be 1.23% per year because that is the resent statistical growth rate. In Madrid different population growth in the different city districts has been used since statistics where available. For the other cities the same population growth is assumed for all city districts.

Table 2. Overview of the cities population, area and districts division in 2020

	Population (thousands)	Employees (thousands)	City territory (km²)	Exploited area (km²)	District division (#)
Linköping	112	62	59	21	26
Dublin	1 178	519	295	209	34 / 1131*
Madrid	3 695	1 707	604	551	128
Tallinn	460	244**	160	95	8 / 101***

* The 34 city districts is used in the Model. Statistics of inhabitants and area were found for a division of 1131 city districts in Dublin. However, because of confidentiality reasons it was only possible to get employees for the aggregated 34 city districts. Green areas were also only possible to calculate for the 34 areas. Codema[2] has collected the disaggregated information about inhabitants and employees in Dublin

** Only aggregated statistics of employees was found for Tallinn.

*** The 8 city districts is used in the model. Area information was found for the 101 city districts. However, no other data were found on this disaggregated level within the time frame of this project.

Statistical information about size of the districts and about the part that is green area/ open area has been collected from the authorities in each city respectively or calculated from the European Corine land cover database (EEA, 2009).

7.2 Climate

7.2.1 Need for input data

Data of temperatures in the cities is needed to understand the shifting heating demand over the year, to calculate Heating Degree Days (HDD), and to calculate Cooling Degree Days (CDD) for each city respectively. The HDD is used to compare the performance of the heating system in each city with the EU27 average. The CDD is used to calculate the cooling demand in each city.

7.2.2 Data collection

Data on monthly average temperatures for each city has been collected from World-climate (2009). As shown in Figure 5 the climate is almost identical in Linköping and Tallinn while Madrid is much warmer all year around. The climate in Dublin is similar of those of Tallinn and Linköping during summer and Madrid in the middle of the winter. The temperature in Dublin is more even than in the other cities.

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[2] An agency for energy and sustainability in Dublin

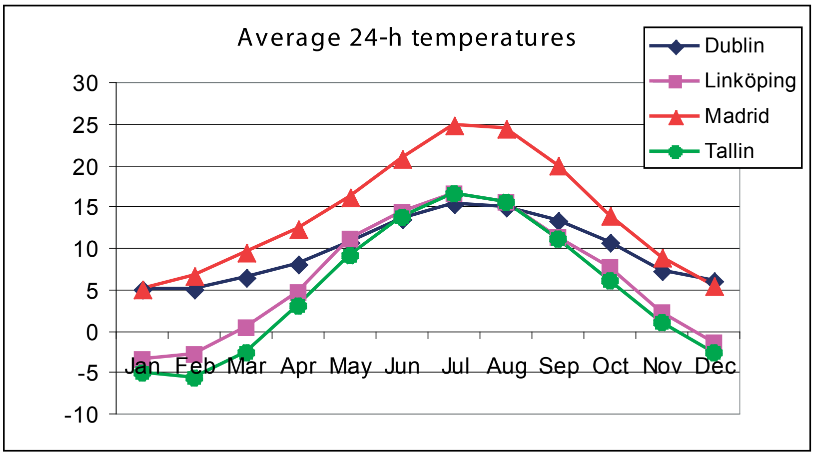

Figure 5. The monthly average 24h temperatures for the cities (Worldclimate, 2009).

The mean temperature has been the basis for calculating HDD and CDD respectively.

Table 3. Mean temperature, Heat Degree Days respectively Cooling Degree Days for each city.

	Mean temp (°C)	HDD[3]	CDD[4]
Linköping	6.5	4 292	560
Dublin	9.6	3 060	548
Madrid	13.9	2 032	1 877
Tallinn	4.8	4 775	505

7.3 Heating demand

7.3.1 Definitions and limitations

Heating demand is in this study defined as demand that could be fulfilled with the use of heat from a district heating system. Mainly this involves space heating and hot water.

7.3.2 Need of input data

The heating demand is necessary to calculate the heating demand densities. When it is not possible to obtain heating demand on city district level the total heating demand have been calculated and then distributed according to the number of inhabitants and employees in each city district (see below for further information).

Statistics of heating demand is complicated to obtain for the consumers that are not covered by district heating. The main reason for the complexity is that statistics usually is divided according to which fuels that is used for example in residential and service

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[3] Heat Degree Days with "breaking temperature" of 18 degrees C. The "breaking temperature" is in the case of HDD-calculation the temperature below which heating is needed.

[4] Cooling Degree Days with "breaking temperature" of 10 degrees C. The "breaking temperature" is the case of CDD-calculation the temperature above which cooling is needed.

sectors. However, it is not told what the fuels are used for. Not all energy in residential and service sectors is used for heating purposes. Because of the different characteristics and the different quality of the statistics the heating demand calculations have in some cases been done separately and with different methodologies for the residential and the service sectors respectively.

The mix of fuels for heating is needed to calculate the benefit of energy efficiency implementation and introduction of district heating. The mix of fuels is also complicated to calculate because of the same reasons as mentioned above.

To be able to understand the results in a European context it is important to compare the results with the EU27 average[5]. The heating demand and mix of fuels for producing the heating is therefore also needed for EU27 average.

7.3.3 Data collection

Linköping city has provided the most complete set of data including heating demand for each city district divided in different user groups. District heating is assumed to supply 100% of the heating used in Linköping city. The energy company in Linköping approximate the market share in Linköping city to 90-95% (Gustavsson, 2008). However, it has been difficulty to determine which other fuels that is used and in which city district these are used. Therefore the simplification of assuming 100% market share for district heating is made.

Unfortunately, heating demand at city district level has not been found for other cities than Linköping. Instead the heating demand for the whole city has been calculated and then distributed to the different city districts.

The total heating demand and its energy carriers in **Dublin** was calculated with help from Codema[6] that provided the background data used for the Energy Plan for Dublin city (Wardell et al, 2008). The information from Codema made it possible to calculate the heating demand for the residential sector and approximate the mix of fuels used. For the service sector they could provide energy use for different fuels. However, they were not able to estimate how much that was used for heating. The methodology based on data from Ecoheatcool WP1 (Werner, 2006) and Odyssee (2009) described in Appendix B was used for estimating the heating demand and the mix of fuels in the service sector. The energy data from Codema only include Dublin city. These data were scaled to the parts of Dublin that is included in the study by considering the difference in inhabitants and employees between Dublin city and the whole Dublin. It was assumed that the industry do not have any heating demand because Codema claimed that there is very few heavy industries in Dublin.

The use of final energy is in the energy statistics for **Madrid** presented per fuel for the residential and service sectors together (Rodríguez et al, 2008). Final energy use for different purposes in a typical Spanish household was presented in Ayuntamiento de

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[5] The average in the countries included in EU.

[6] An agency for energy and sustainability in Dublin

Madrid (2008). Assumptions had to be made on which fuels that was used for different purpose. Corresponding numbers for the service sector was not found. The methodology based on data from Ecoheatcool WP1 (Werner, 2006) and Odyssee (2009) described in Appendix B was used for estimating the different size of the residential sector and the service sector as well as estimating the heating demand and the mix of fuels in the service sector. Energy used for heating in the industry sector is assumed to be 10% of the total energy use in the sector, of which 5% from electricity, 10% from petroleum products and 85% from natural gas.

The district heating system in **Tallinn** has a market share of 68% and the rest of the market consist of local heating networks and to a lesser extent direct heating in houses/apartments (Petrova, 2009). The complexity surrounding data collection for the local heating netwotks and the direct heating has made us assume (based on discussions with Dalkia) that all heat is produced with natural gas (Petrova, 2009). The geographical distribution of the delivered heat from the district heating system did not correspond to the division of the 8 city areas selected for Tallinn. Thus the total heating demand, calculated based on the 68% market share, where distributed between the city districts by the statistics of inhabitants.

The heating demand for 2020 depend on population growth, behavior change and energy efficiency measure implementation in the buildings. The energy efficiency measure implementation in the buildings will change between the scenarios. (See Chapter 5 and Chapter 8 for further information).

In Table 4, a summary of the cities' total heating demand in the business as usual (BAU) scenarios for 2020 is presented. In addition to this, comparable indicators between the cities are presented. These could be used to understand for example the differences in climate, population density, and the share of green area in the different cities.

Table 4. Heating demand in the different cities, including some relevant indicators for comparison of the conditions in the cities. The values represent the business as usual (BAU) scenario 2020 for each city.

	Total heating demand (GWh)	Heating demand/inhabitant (kWh/inh.)	Heating demand per inhabitant + employee (kWh/(inh.+emp.))	Average heating demand density (GWh/km$_2$ exploited area)
Linköping	1 257	11 252	7 237	60.2
Dublin	10 634	9 028	6 269	50.9
Madrid	11 850	3 207	2 194	21.5
Tallinn	2 800	6 091	n.a.	31.5

The EU27 average heating demand and mix of fuels are calculated from data in the Ecoheatcool report WP1 (Werner, 2006) combined with data from Odyssee (2009) according to the method described above. When the data for EU27 average is compared to the city specific data the EU27 average data have been adjusted according to the climate in each city by using HDD and by adjust the data to the number of inhabitants in each city respectively.

7.3.4 Geographical distribution of heating demand

As described in Section 6.3.2, it is of interest to know the heat demand in different parts of the cities. In the case of Linköping, it has been possible to obtain heat consumption data at city district level. For the other cities we had to find a methodology to distribute the heat demand between the city districts in each city. By using the Linköping data it was found that the heating demand divided by the inhabitants plus employees was the best methodology when statistics of heating demand is not available at city district level[7]. In the cities (Tallinn) where only statistics of inhabitants was found at city district level the heating demand per inhabitant were used as the distribution tool.

7.4 Cooling demand

7.4.1 Definitions and limitations

The study include both cooling demand needed for comfort cooling that change with the outdoor temperature and cooling demand needed for cooling, for example in computer rooms, that do not change with the outdoor temperature. The cooling demand in the BAU scenario for 2020 is the amount of cooling that is assumed to be used without any further policy implementations. The potential demand would, according to Ecoheatcool WP2 (Dalin et al, 2006), be about twice as high if all areas in residential and service sectors had access to cooling.

7.4.2 Need of input data

The total cooling demand in each city in the business as usual (BAU) scenarios in 2020 are needed to calculate the impact of the scenarios. The mix of cooling production to meet this demand in 2020 is also needed. To be able to compare the results with the EU27 average the corresponding numbers for EU27 average has to be found as well. To calculate the total cooling demand in each city according to the selected method the cooling demand per inhabitant in Linköping and the CDD for each city is needed.

7.4.3 Data collection

It is difficult to estimate the cooling demand where district cooling is not used. The reason is that when electricity is used for cooling instead of district cooling the cooling demand cannot be separated from the overall electricity figures, since the electricity is used for many purposes.

The estimations of cooling in the cities have all been based on the delivered cooling in the district cooling network in Linköping. The market share of district cooling in Linköping is assumed to be 30% in discussion with the district cooling company in Linköping (Fornander, 2009). The cooling demand can be divided in comfort cooling, which represent cooling depending on the outside temperature, and other cooling, representing cooling demand not depending on the outside temperature. The share of

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[7] The heating demand divided with the inhabitants and employees where calculated for each city district in Linköping. The variance between the results for the different city districts were lower than for other possible options as dividing the heating demand with inhabitans or inhabitants plus students for each city district. The low variance indicate that dividing with the inhabitans and employees was the best distributing tool.

cooling demand that do not change with outdoor temperature has been calculated by examining the district cooling consumption in January which is the month with lowest cooling demand. This type of cooling demand is 50% of the consumption in the district cooling system. The other 50% represents comfort cooling.

The 70% of the cooling demand that is not covered by district cooling in Linköping is assumed to be produced by electricity with an average Seasonal System Energy Efficiency Ratio (EER) of 2.5[8] which represent a mix of small scale and large scale cooling machines. 70% of this cooling demand is assumed to be comfort cooling and 30% is cooling demand that do not depend on outdoor temperature. The reason for the higher share of comfort cooling in the cooling that is not delivered by district cooling, is that the competiveness for district cooling is assumed to be lower for comfort cooling then for other types of cooling demand.

The estimations of the cooling demand in the other cities are based on the situation in Linköping. The cooling demand per inhabitant that is not dependent on the outdoor temperature is assumed to be constant in all cities. The cooling demand per inhabitant that is dependent on temperature has been scaled from Linköping to the other cities by using the square root of the CDD[9].

The calculation of the cooling demand for the EU27 average has been performed in the same way as the calculations for the cities. The EU27 average scenario is therefore identical with the BAU scenarios for all cities except for Linköping where the use of district cooling makes a difference.

The cooling demand 2020 depend on population growth, behavior change and energy efficiency measure implementation in the buildings. Behavior change result in a larger increase for cooling demand than for heating demand, partly because of increased installation of cooling machines. The energy efficiency measure implementation in the buildings will change between the scenarios. (See Chapter 5 and Chapter 8 for further information)

Table 5. Cooling demand in business as usual (BAU) scenarios for 2020 and some comparable indicators for the cities.

	Total cooling demand (GWh)	Cooling demand per inhabitant (kWh/inh.)	Average cooling demand density (GWh/ km_2 exploited area)
Linköping	133	1 188	5.1
Dublin	1 403	1 191	5.3
Madrid	6 775	1 834	9.6
Tallinn	534	1 161	4.7

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[8] In the European context small scale cooling machines differs between 1.5 and 3.5 (Dalin et al, 2006). Large scale cooling machines usually have an EER above 5 (Dalin et al, 2006). A mix of large and small scale elcectric cooling machines give an average of 2.5 (Rubenhag, pers comm 2009).

[9] The CDD has been calculated with a "breaking temperature" of 10 degrees. The reason to select this low temperature is to get enough CDD for Linköping to be able to compare this number with e.g. Madrid. The reason is also that there is cooling demand even with very low temperatures.

7.5 District heating production

7.5.1 Definitions and limitations

In this section the production of heat to the district heating system is described. Other forms of heating are included in chapters above.

7.5.2 Need of input data

How the district heating is produced determine the performance of the district heating system and therefore affect the reduction potentials for implementation of district heating. For example the benefit with district heating is that it has the possibility to utilise energy that cannot be used elsewhere. The best potentials for improving the environmental impact from heating in a city with district heating is reached when the district heating is produced with as low environmental impact as possible.

In the cities with district heating, information about realistic options to improve the production is needed. In cities without district heating, information about future realistic heating production possibilities is needed.

The ambition has been to find heating production with low use of primary energy resources and carbon dioxide emissions, e.g. industrial waste heat, power plants that could deliver heat, new production of WTE and solid biofuel CHP plants.

To construct a realistic combination of different heating production units in the district heating system the differences of heating demand over the year is needed.

7.5.3 Data collection

In Linköping they have hade district heating for a long time and they are working with minimizing the environmental impact from heating production and have e.g. recently built a new WTE CHP plant. However, they still use some coal and oil that they plan (at least to 2020) to reduce by converting one of the plants to a solid biofuel CHP plant (Nordenstam, 2009). According to there projections this will also increase the electricity production. Further improvements have not been considered realistic.

In Dublin the first steps towards building a district heating system has been taken. For example, Dublin is building a waste-to-energy (WTE) power plant that is obligated to be built for the option to use it as a CHP plant. This will according to the plan be in operation in 2012 (Gaillot et al, 2008). Relatively close to the city centre in Dublin there is large scale electricity production from natural gas. It is assumed that some of these power plants, including new built power plants that will replace others that are closing down, are converted so they can be used as CHP plants when there is a district heating demand. The heating peak load during the winter is assumed to be covered by natural gas boilers.

In Madrid there is no plan to build a district heating system at the moment. In the Madrid county they plan to build 2800 MW of electricity production from natural gas to 2012 (Comunidad de Madrid, 2004). A future district heating production system is assumed to consist of WTE power plants that can be used as CHP plants and the 2800 MW electricity power production used as CHP plants when there is a heating demand. The heating peak load during the winter is assumed to be covered by natural gas boilers.

Tallinn has district heating systems with relatively ineffective heat production. It consists of a rather old natural gas CHP plant and several large natural gas boilers (Eesti Energia, 2009; Tallinna Küte, 2009). A new solid biofuel CHP plants will start its operation during 2009 and there are plans to build a WTE CHP plant (Petrova, 2009; Eesti Energia, 2009). There is also a plan to upgrade the transmission lines between the different parts of the district heating system to increase the usage of the new plants. On top of this it is assumed that the existing natural gas CHP plant will be replaced before 2020. The existing natural gas boilers will continue their operation, but as peak load units.

A lot of effort has been put into finding industrial waste heat possibilities for the cities. However, the lack of statistics has made it impossible to find information for estimating this potential. The potential probably exist even if it was not possible to quantify it within this project.

The heating demand variation over the year affect how much each of the different heating producing units is used during the year. How heating demand variation has been considered can be found in Appendix C

Table 6. Use of district heating and performance of the district heating production.

	Using DH	Market share	PEF	CO_2/MWh	Effect of heat use on CHP
Linköping	Yes	100%	0.68	101	Increased utilisation
Dublin	No	0%	n.a.	n.a.	
Madrid	No	0%	n.a.	n.a.	
Tallinn	Yes	68%	1.12	217	Increased utilisation

Table 7. The performance of the district cooling production in the scenarios where district cooling is introduced/upgraded.

	Market share / heating demand density level	PEF	CO_2/MWh	Effect of heat use on CHP
Linköping	100%	0.69	34	Increased utilisation
Dublin	60 GWh / km² exploited area or above	0.31	60	Reduced electricity efficiency
Madrid	60 GWh / km² exploited area or above	0.44	86	Reduced electricity efficiency
Tallinn	60 GWh / km² exploited area or above	0.60	74	Increased utilisation

7.6 District cooling production

7.6.1 Definitions and limitations

In this section only data for the district cooling production is found. The data about other cooling production is found in Section 6.4 above.

Only absorption cooling that use district heating has been examined for the main production of district cooling, except for free cooling in the air where this option exist. Free cooling in sea water or in underground aquifers, and large scale electric cooling production has not been included.

7.6.2 Need of input data

How the district cooling is produced determine the performance of the district cooling system and therefore affect the reduction potentials for implementation of district cooling. Mainly absorption cooling has been examined, except for peak load production. The performance of absorption cooling depends on the environmental impact of the heat produced in the district heating system when absorption cooling is produced. Data for the district heating system during the time of the year when absorption cooling is used is therefore of large importance.

7.6.3 Data collection

In 2008 absorption cooling from heating produced 65% of the district cooling production in Linköping. 19% was produced by free cooling in cooling towers (used during winter when the air temperature is low), and 16% was produced by electric cooling machines. Linköping claim that they will have 75% of the district cooling from adsorption machines, 22% from free cooling and 3% from electric cooling machines (Fornander, 2009). The heat to the absorption machines is assumed to be produced by WTE CHP (75%) and solid biofuel (25%) both for 2008 and 2020[10].

No district cooling systems exist today in Dublin, Madrid and Tallinn. The district cooling in Dublin and Madrid is in a future district cooling system assumed to be produced by 90% absorption cooling and 10% electricity. The absorption cooling will cover the base load and electricity cover the peak load when the capacity of absorption cooling is not enough. The heat to the absorption cooling machines is assumed to be produced by WTE power plants converted to CHP plants (50%) and natural gas power plants converted to CHP plants (50%)[11].

The district cooling in Tallinn is in a future district cooling system assumed to be produced in the same way as in Linköping in 2020. The heat to the absorption cooling machines is assumed to be produced by WTE CHP plant (50%) and solid biofuel CHP (50%)[12].

In all the cities it is assumed that the district cooling may reach a 50% market share. The level was in the case of Linköping considered realistic in discussion with the energy company in Linköping (Fornander, 2009). The same share has been assumed for the other cities. This is optimistic, but gives an indication of the potential reductions.

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[10] The difference from the average heating production in the district heating system is explained by the time of the year the heat to the absorption machines is produced. During summer with highest demand of heat to the absorption machines the heat is produced by the WTE CHP plant and during autumns with some demand of heat to the absorption machines the heat is produced by the solid biofuel CHP plant.

[11] The same is valid as for Linköping with the exception that a larger part of the cooling demand is during autumns and that absorption cooling is used during winter as well (no free cooling). It is assumed that absorption cooling is not used when the natural gas boilers is used for heat production.

[12] The same is valid for Tallinn as for Linköping with the exception that WTE CHP plant has a smaller share of the heating production in Tallinn then in Linköping. Therefore the WTE CHP share of heat to the absorption cooling is lower as well.

Table 8. Use of district cooling and performance of the district cooling production in the business as usual (BAU) scenarios 2020 for each city.

	Using DC	Market share	PEF	CO_2/MWh
Linköping	Yes	30%[13]	0.55	69
Dublin	No	0%	n.a.	n.a.
Madrid	No	0%	n.a.	n.a.
Tallinn[14]	No	0%	n.a.	n.a.

Table 9. The performance of the district cooling production in the 2020 scenarios where district cooling is introduced/upgraded.

	Market share	PEF	CO_2/MWh
Linköping	50%	0.51	57
Dublin	50%	0.67	130
Madrid	50%	0.67	130
Tallinn	50%	0.35	-24

7.7 Total energy use

This section provides an overview of total energy use in each of the included cities. In addition to this, the need of primary energy to supply the energy demand and the corresponding CO_2-emissions that the primary energy causes is presented.

7.7.1 Definitions and limitations

The total energy use includes the fuels and electricity used in the city. The primary energy resources use and the carbon dioxide emissions related to the use of electricity is calculated according to the alternative production of electricity (see Chapter 6 for further information).

Energy use and emissions caused by producing products consumed in the city is not included.

7.7.2 Need of input data

The total energy use in the cities has been determined to relate the effect of energy efficient measures in buildings and introduction of district heating in the city districts on the overall energy performance of the cities.

The aim has been to collect information about the use of fuel and electricity in the industry, transport, residential, and service sectors for the same parts of the cities that are included in this study.

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[13] Assumption based on discussions with "Tekniska verken i Linköping" (pers comm Jimmy Fornander, 2009)

[14] A sum of the three main district heating systems and the smaller local district heating systems within Tallinn.

7.7.3 Data collection

Statistics of the cities' energy use has been collected in collaboration with city councils, national statistics and heat producers/distributors. However, the data collection has not always been straightforward.

Total primary energy resources and carbon dioxide emissions have been calculated based on total energy use using primary energy factors and emission factors from Chapter 5.

Table 10. Overview of total use of primary energy resources and the corresponding carbon dioxide emissions in each city respectively.

	Total use of primary energy resources (GWh)	Total emissions of CO_2 (kton)
Linköping	3 215	632
Dublin	39 420	8 427
Madrid	63 368	13 512
Tallinn	12 676	2 778

7.8 Heating demand density level for implementing district heating

7.8.1 Definitions and limitations

The heating demand density level is the heating demand in a city district divided by the exploited area in that city district. The ambition of the definition of the heating demand density is to judge where district heating is most interesting. The higher heating demand density the larger interest to introduce district heating.

7.8.2 Need of input data

In the model the level of heating demand density determine where it is interesting to introduce district heating. Information about which heating demand density levels that is reasonable for district heating introduction is needed for each city respectively.

7.8.3 Data collection and assumptions

In cities such as Linköping and Tallinn, where the district heating has been implemented over long time, areas with low heating demand is also covered by district heating. In Linköping city districts with heating demand densities down to 10 GWh / km^2 exploited area is covered by district heating.

In Tallinn the district heating has a lower market share then in Linköping. It is assumed that the district heating can expand to city districts with an average heating density of 10 GWh / km^2 exploited area to 2020.

It is not realistic that city districts with that low heating demand density will be covered in 2020 in cities such as Dublin and Madrid since district heating is not implemented at all today. In these cities a heating demand density level of 60 GWh / km^2 exploited area for introduction of district heating has been selected. Implementation of district heating is assumed to be more interesting in the areas with the highest heating demand density and it is not probable that areas with less than 60 GWh / km^2 will implement district heating until 2020. However, lower heating demand density will probably be interesting for district heating in a longer time perspective.

A rough cost estimation of implementation of a full-scale district heating system has been done for Madrid and is presented in Appendix D. The calculations for Madrid indicate that the net cost (costs minus savings) can vary between 0 and 17 Euro/ton saved CO_2, if district heating is implemented in districts with a heating demand density level of 60 GWh / km^2. The higher cost includes implementation also in apartments that are lacking water based radiator systems, and the lower when implementation is restricted to apartments and premises that have such system installed. An implementation level of 30 GWh / km^2 (district heating is introduced in less densely populated areas) could lead to either a somewhat higher net cost or a gain depending on if the most costly apartments are included or not.

8. RESULTS OF THE SCENARIO CALCULATIONS 2020

This chapter presents the main results of the calculations according to the city model for Linköping, Dublin, Madrid and Tallinn. The scenarios are compared to the EU27 average as projected for 2020 (adjusted to the climate conditions in each city). The EU27 average is used as a baseline to understand if the performance of the heating system in the city is above or under the average in EU27. Heating/cooling demand, primary energy use and CO_2 emissions of the scenarios are the key factors presented in this Chapter. The characteristics of the six base scenarios that have been analysed for the heating and the cooling system in each city are summarized and explained below in Table 11 and Table 15 respectively. More detailed description of the basic underlying model parameters are found in Chapter 6. In the sensitivity analysis in Chapter 8 the impact on the result of some determining parameters such as allocation method, valuation of electricity, use of primary energy factors and assumed limit for district heating implementation is illustrated and discussed.

8.1 Heating

Table 11. Important characteristics of the main scenarios analysed with the city model. All scenarios are for 2020, based on an annual 1% population growth in the cities and 1% energy use increase per person and year because of behavior changes. Abbreviations in the footnote [15]

Scenario	Heating demand	Mix of energy sources	DH production
EU27	- 6 671 kWh per inhabitant in average in EU27 calculated based on information from Ecoheatcool WP1 and Odyssee database. The heating demand is temperature correlated to the conditions in each city by using the HDD. - 1% energy efficiency implementation in the buildings (about 15% heating demand increase in the city to 2020).	8% DH, 32% electricity, 35% natural gas, 2% coal, 6% solid biofuels, 17% oil, 1% other. These numbers are calculated based on information from Ecoheatcool WP1 and Odyssee database.	The small share of DH is assumed to have the same performance as natural gas.
BAU	- Heating demand today calculated from statistics for each city. - 1% energy efficiency implementation in the buildings (about 15% heating demand increase in the city to 2020).	Calculated from statistics for each city. In some cases information from Ecoheatcool WP1 and Odyssee database have been used.	The performance of the DH systems has been calculated from city specific statistics. For Madrid and Dublin no DH is used.
2% EE without DH impl/DH upgrade	- Heating demand today is the same as for BAU - 2% energy efficiency implementation in the buildings (about 0% heating demand increase in the city to 2020).	The same as for BAU	The same as for BAU
2% EE with DH impl/DH upgrade	- Heating demand today is the same as for BAU - 2% energy efficiency implementation in the buildings (about 0% heating demand increase in the city to 2020).	City districts where the heating demand density is high enough will in the model implement DH. The other city districts will use the same mix as in the BAU scenario.	- Existing DH production is upgraded according to their own plans plus reasonable improvements. - New DH production is based on WTE, natural gas CHP, and natural gas boilers in a city specific combination.
4% EE without DH impl/DH upgrade	- Heating demand today is the same as for BAU - 4% energy efficiency implementation in the buildings (about 25% heating demand decrease in the city to 2020).	The same as for BAU	The same as for BAU
4% EE with DH impl/DH upgrade	- Heating demand today is the same as for BAU - 4% energy efficiency implementation in the buildings (about 25% heating demand decrease in the city to 2020).	City districts where the heating demand density is high enough will in the model implement DH. The other city districts will use the same mix as in the BAU scenario.	- Existing DH production is upgraded according to their own plans plus reasonable improvements. - New DH production is based on WTE, natural gas CHP, and natural gas boilers in a city specific combination.

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[15] Business As Usual (BAU), District Heating (DH), Heating Degree Days (HDD), Waste-to-Energy Plant (WTE), Combined Heat and Power (CHP).

A comparison of the performance of the district heating systems for each city in the 2020 scenarios is summarized in Table 12. For Linköping and Tallinn, which already have district heating, the performance also of the district heating systems without district heating upgrading (business-as-usual) are presented.

8.1.1 Linköping

Figure 6. Map of Linköping. The city borders of Linköping is indicated by the green areas, which also show the districts covered by district heating in the 2020 scenarios. In the 2020 scenarios, 100% of the total heating demand is covered by district heating.

Since district heating covers practically all parts of Linköping, no expansion of the district heating is possible. As shown in Figure 8, 100% of the heating demand in Linköping is assumed to be covered by district heating in all scenarios. In the EU27 average scenario the heating supply consist of a mix of energy sources: district heating, electricity, natural gas, biofuels, oil and others. The mix fuels for heating production in the scenarios with and without upgrade of the district heating production in the district heating network in Linköping is shown in Figure 7.

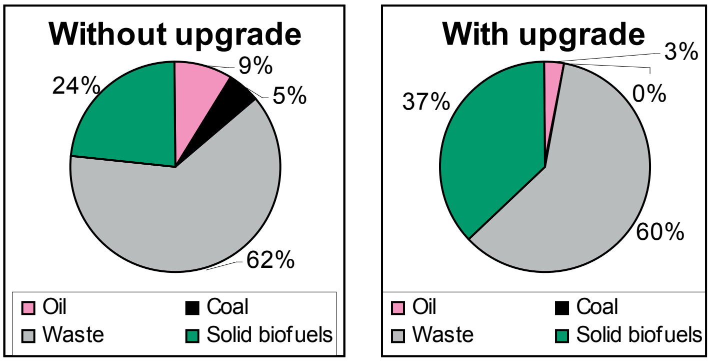


Figure 7. The figure shows heat production from different kind of fuels in the scenarios with and without district heating upgrading in 2020. The fuels for the electricity production in the CHP plants at the district heating system is not included in this picture.

As shown in Figure 9, the heating demand in Linköping in the business-as-usual scenario (BAU) is higher than the EU27 average scenario but the primary energy use and CO_2 emissions are about 50% and 62% lower respectively, mainly due to the extensive use of district heating and the limited use of fossil fuels in the heat production. The primary energy use and CO_2 emissions will decrease further by implementation of energy efficiency measures. According to the results, district heating upgrading does not affect the primary energy use but leads to large reductions of CO_2 emissions. The explanation is that in the scenarios where the district heating system is upgraded, some of the heat produced from coal, oil and waste is replaced by heat produced in a CHP converted to solid biofuel, with rather high primary energy factor but low CO_2 emission factor (see Figure 7). With the highest energy efficiency rate and with conversion of the district heating system the primary energy use will be 65% lower than EU27 average and CO_2 emissions almost 90% lower. It can be concluded that energy efficiency measures in the building stock has the largest effect on reducing the primary energy use in Linköping since the district heating is implemented everywhere and already has a good production performance, whereas upgrading of the district heating system gives the highest reductions of CO_2 emissions.

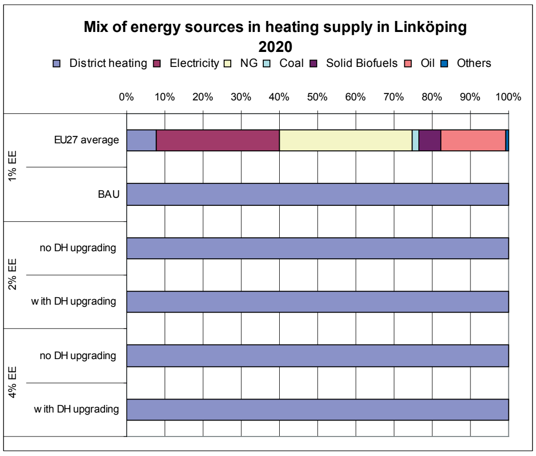


Figure 8. Mix of energy sources in heating supply in Linköping 2020 in the different scenarios

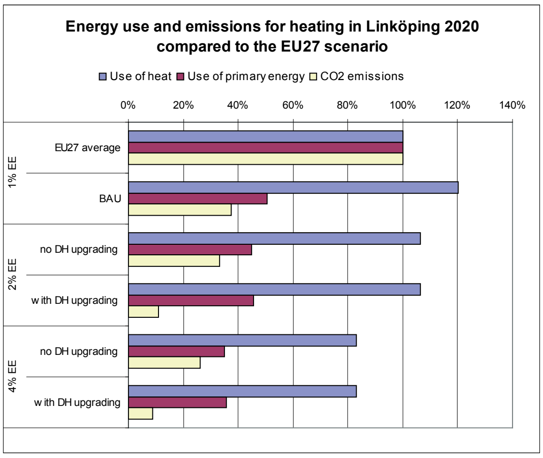
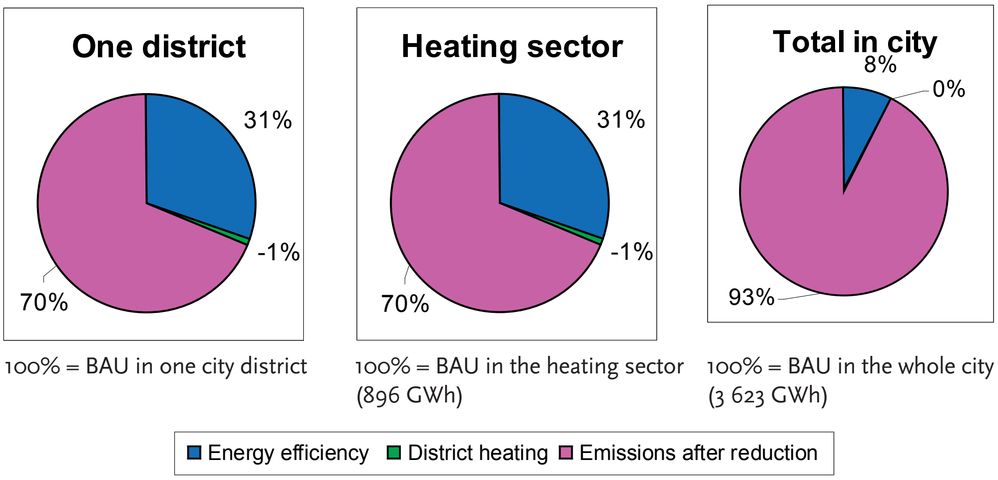


Figure 9. Resulting heating demand, primary energy use and CO2 emissions in Linköping 2020 compared to the EU27 average 2020.

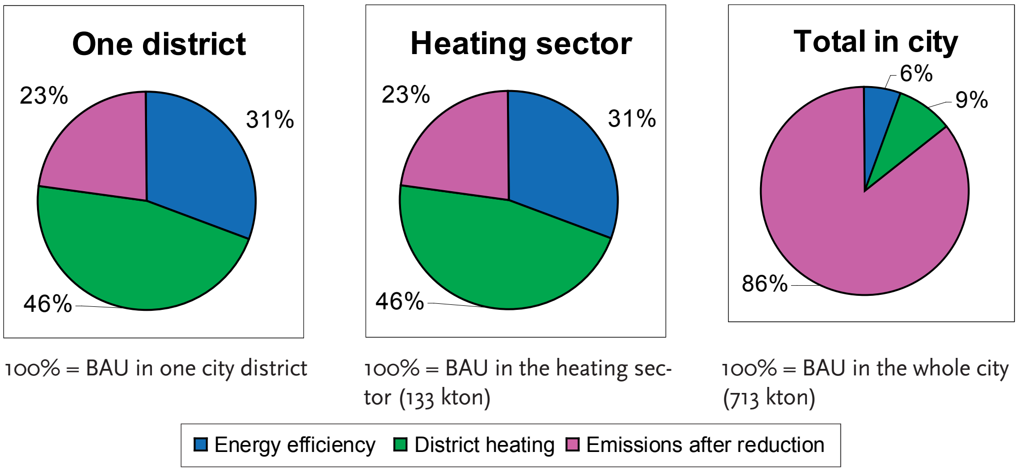


100% = BAU in one city district

100% = BAU in the heating sector (896 GWh)

100% = BAU in the whole city (3 623 GWh)

Figure 10.The figures show reduced use of primary energy resources where the energy efficiency measures (4% per year level) is introduced first and then the district heating upgrade is implemented. The impact of the measures is presented for one district, for the heating sector, and as a comparison for the whole city.



100% = BAU in one city district

100% = BAU in the heating sector (133 kton)

100% = BAU in the whole city (713 kton)

Figure 11. The figures show reduced emissions of carbon dioxide where the energy efficiency measures (4% per year level) is introduced first and then the district heating upgrade is implemented. The impact of the measures is presented for one district, for the heating sector, and as a comparison for the whole city.

8.1.2 Dublin

Figure 12. Map of Dublin. The city borders of Dublin are indicated by the yellow and green areas. The green coloured districts (3 out of 34 districts in the city) show the districts that are covered by district heating 2020 in the scenario with 4% energy efficiency per year. This corresponds to 23% of the total heating demand. District heating is implemented in districts where the heating demand is greater than 60 GWh/km2. Since there is no district heating system in Dublin today, a conservative implementation limit is used.

The resulting mix of energy sources in the heating supply in the scenarios for Dublin 2020 is presented in Figure 14. No district heating exists in Dublin today, which is illustrated in the business-as-usual (BAU) scenario. Heating is produced from natural gas, oil and electricity. For the scenarios with district heating up to 26% of the total heating demand is covered by district heating.

As shown in Figure 15, the heating demand in Dublin (BAU) is 35% higher than the climate adjusted EU27 average scenario. Also primary energy use and CO_2 emissions from heating are 30-35% higher in Dublin. Energy efficiency measures in the building stock reduce the heating demand, primary energy use and carbon dioxide emissions equally, from approximately 30-35% higher than EU27 with no measures (BAU) to 12-15% lower than EU27 with 4% energy efficiency per year. District heating implementation (in districts where the heating demand is greater than 60 GWh/km^2) reduces primary energy use and CO_2 emissions by another 15-20%. In the city districts that implement district heating the primary energy use decreases 80% and the carbon dioxide emissions decrease 82%.

The future district heating production, as presented in Figure 13, is assumed to be a waste-to-energy (WTE) plant (11% of peak load, 24% of heating production), natural gas plants that are converted to be able to be used as CHP plants (37% of peak load, 60% of heating production), new natural gas power plants that can be used as CHP plants (25% of peak load, 13% of heating production), and natural gas boilers (27% of peak load, 2% of energy production). The performance of the district heating production is calculated by using the DEPM (Decreased Electricity Production Method) for allocation between the heat and electricity production in the WTE and CHP plants and adding the primary energy use and emissions from the boilers. The DEPM calculate the primary energy use and emissions for heat in CHP plants by examining the decrease in the electricity production when the power plant is used as CHP plant instead of only producing electricity. See Appendix A for more information about DEPM.

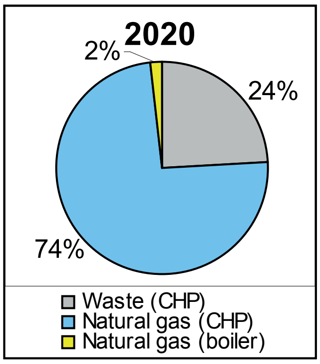


Figure 13. The figure shows the heat production from different kind of fuels and type of production in the scenarios with district heating implementation in 2020.

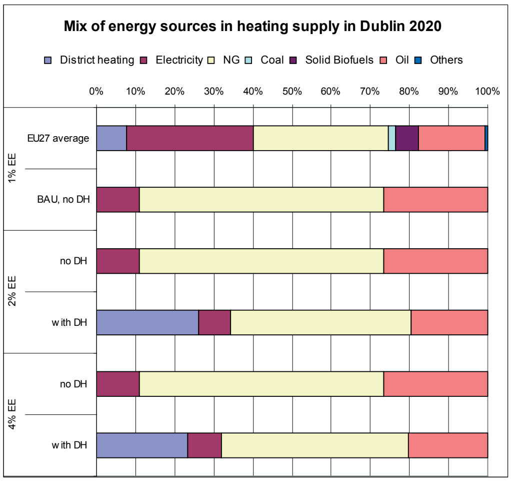


Figure 14. Mix of energy sources in heating supply in Dublin 2020 in the different scenarios

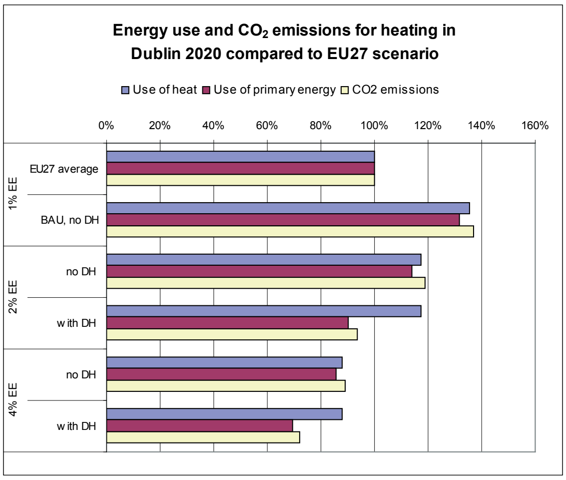
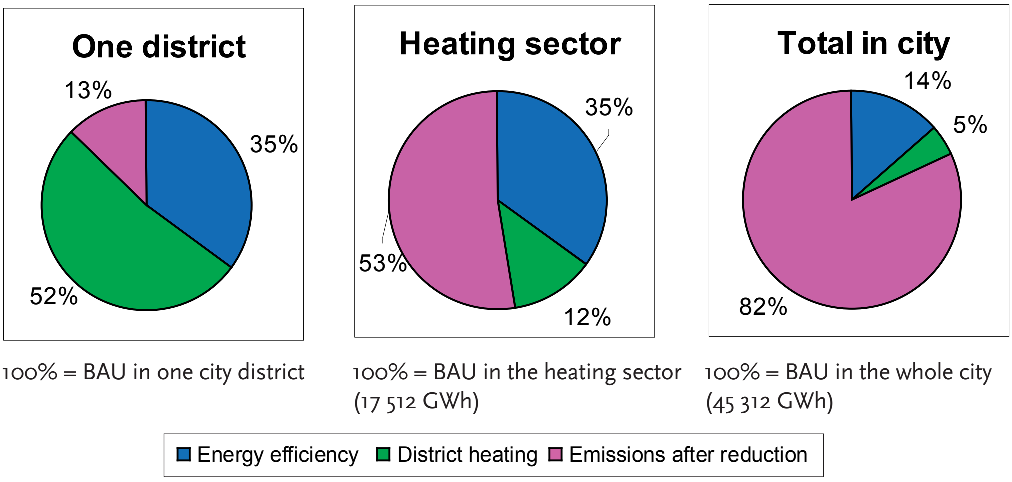


Figure 15. Resulting heating demand, primary energy use and CO2 emissions in Dublin 2020 compared to the EU27 average 2020.

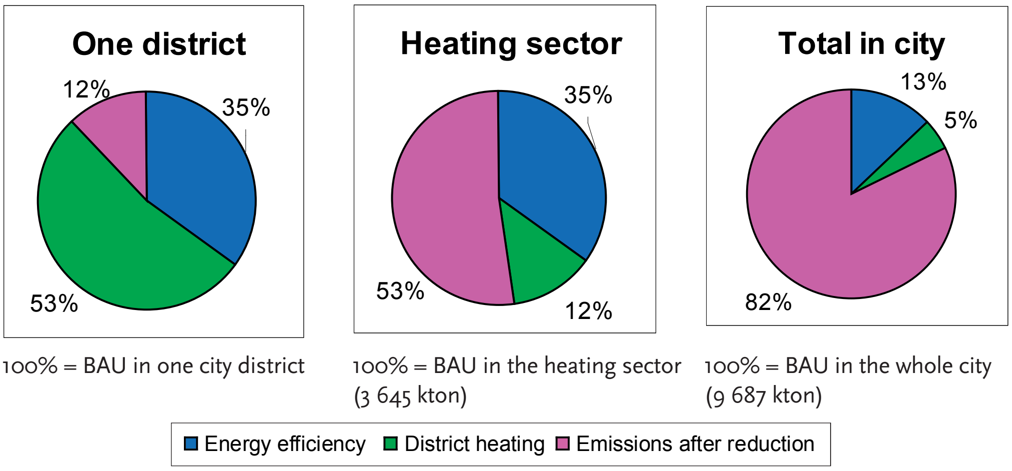


100% = BAU in one city district

100% = BAU in the heating sector (17 512 GWh)

100% = BAU in the whole city (45 312 GWh)

Figure 16. The figures show reduced use of primary energy resources where the energy efficiency measures (4% per year level) is introduced first and then the district heating upgrade is implemented. The impact of the measures is presented for one district that implement district heating, for the heating sector, and as a comparison for the whole city.



100% = BAU in one city district

100% = BAU in the heating sector (3 645 kton)

100% = BAU in the whole city (9 687 kton)

Figure 17. The figures show reduced emissions of carbon dioxide where the energy efficiency measures (4% per year level) is introduced first and then the district heating upgrade is implemented. The impact of the measures is presented for one district that implement district heating, for the heating sector, and as a comparison for the whole city.

8.1.3 Madrid

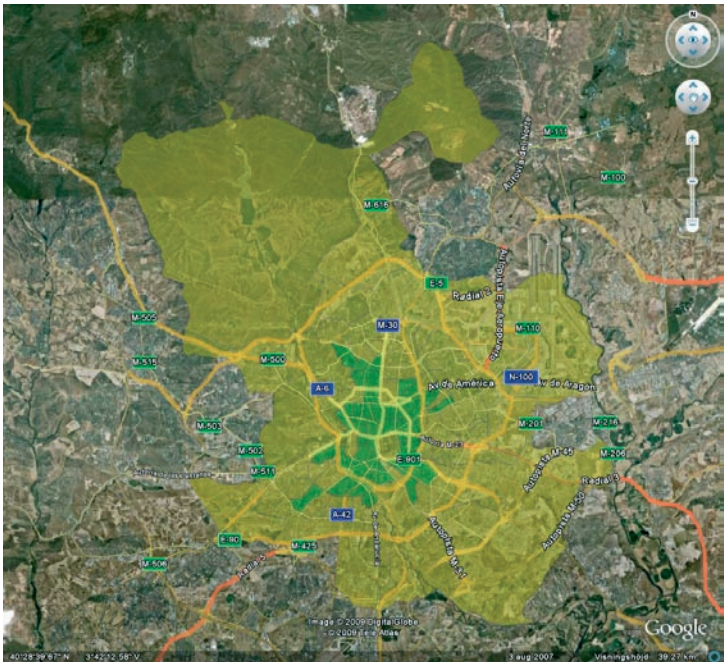


Figure 18. Map of Madrid. The city borders of Madrid are indicated by the yellow areas. The green coloured districts (44 out of 128 districts in the city) show the districts that are covered by district heating 2020 in the scenario with 4% energy efficiency per year. This corresponds to 40% of the total heating demand. District heating is implemented in districts where the heating demand is greater than 60 GWh/km2. Since there is no district heating system in Madrid today, a conservative implementation limit is used.

The resulting mix of energy sources in the heating supply in the scenarios for Madrid 2020 is presented in Figure 20. No district heating exists in Madrid today, which is illustrated in the business-as-usual (BAU) scenario. Compared to the EU27 average mix, the heating supply in Madrid includes more natural gas and coal and less of all the other energy sources.

As shown in Figure 21 the heating demand in Madrid (BAU) is about 28% lower than the climate adjusted EU27 average. Similarly, the primary energy use and CO_2 emissions related to the heat supply is 26-27% lower. Implementation of energy efficiency measures in the building stock reduce heat demand, primary energy use and CO_2 emissions with the same magnitude, since the mix of energy sources for the heating supply is not changed. Full implementation of district heating in district where the heating demand is greater than 60 GWh/km^2 will reduce primary energy use and CO_2 emissions significantly. The impact of district heating implementation is greatest in the scenario with moderate energy efficiency (2% per year), since a larger part of the city has a heating demand that allows for district heating according to the model. With higher energy efficiency the heating demand will decrease and thereby also the emissions, but fewer districts will be covered by district heating. The reduction of primary energy use and CO_2 emissions are therefore almost the same in the scenarios with district heating implementation (more than 50% reduction compared to BAU) regardless of the degree of energy efficiency measures in the building stock.

In the city districts that implement district heating the primary energy use decreases 73% and the carbon dioxide emissions decrease 74%.

The future district heating production, as presented in Figure 19, is assumed to be waste-to-energy (WTE) plants (20% of peak load, 37% of heating production), new natural gas power plants that can be used as CHP plants (40% of peak load, 50% of heating production), and natural gas boilers (40% of peak load, 14% of energy production). The performance of the district heating production is calculated by using the DEPM (Decreased Electricity Production Method) for allocation between the heat and electricity production in the WTE and CHP plants and adding the primary energy use and emissions from the boilers. The DEPM calculate the primary energy use and emissions for heat in CHP plants by examining the decrease in the electricity production when the power plant is used as CHP plant instead of only producing electricity. See Appendix A for more information about this DEPM.

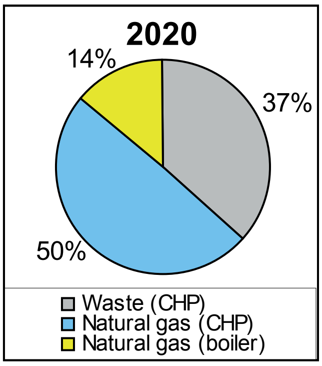


Figure 19. The figure shows the heat production from different kind of fuels and type of production in the scenarios with district heating implementation in 2020.

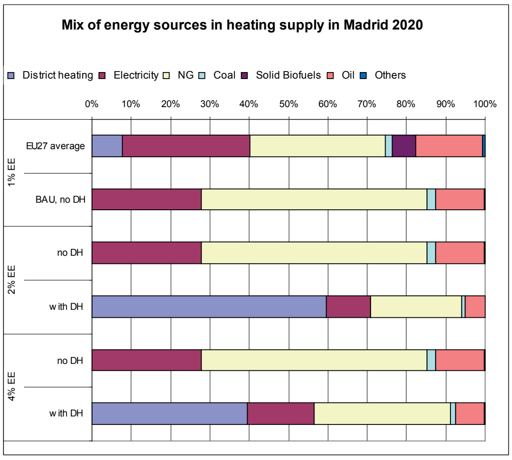


Figure 20. Mix of energy sources in heating supply in Madrid 2020 in the different scenarios

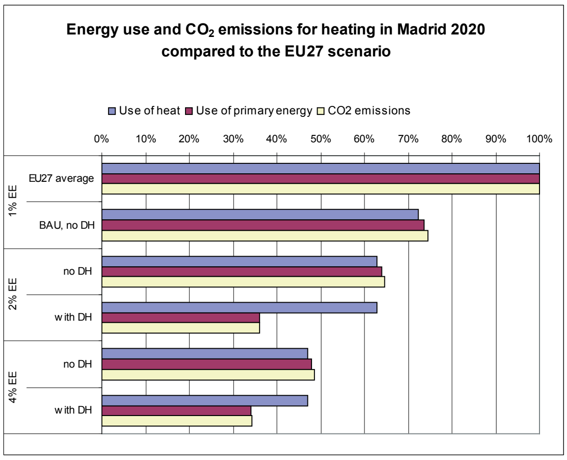
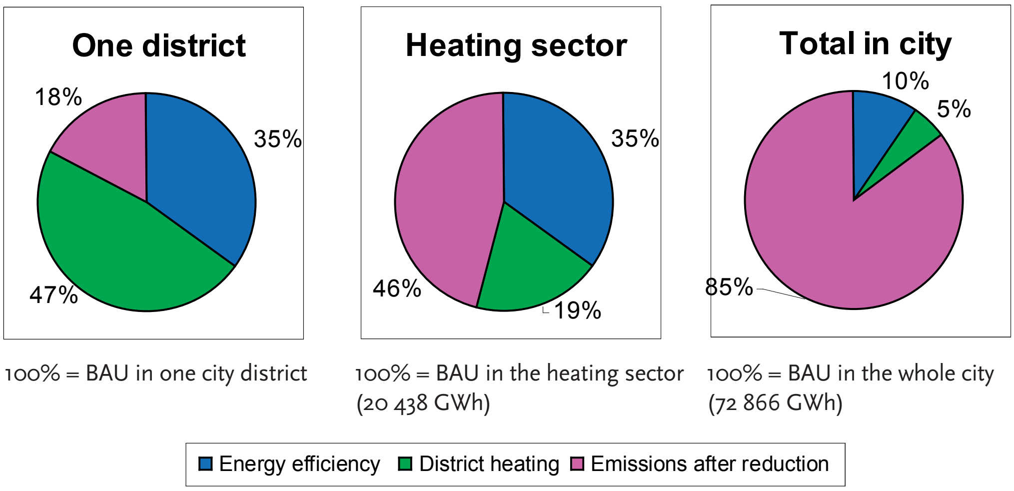


Figure 21. Resulting heating demand, primary energy use and CO$_2$ emissions in Madrid 2020 compared to the EU27 average 2020.

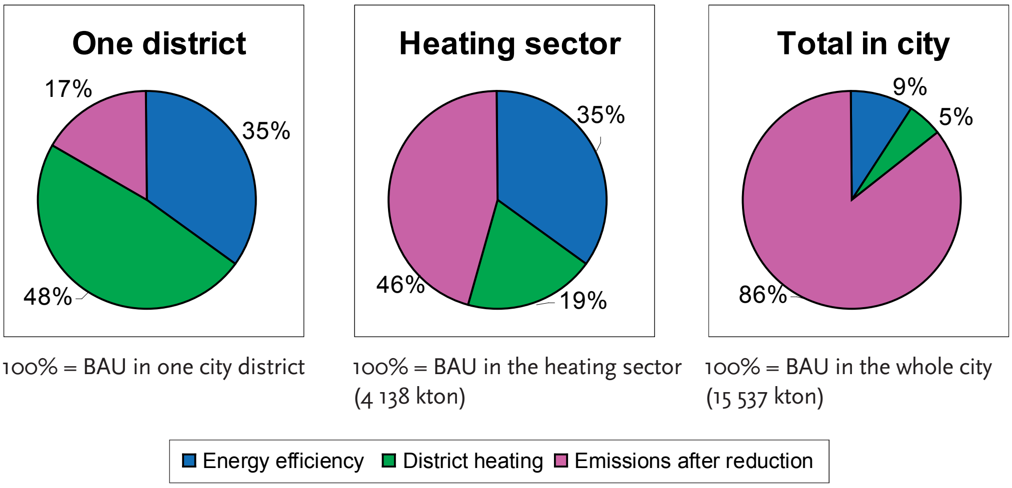


100% = BAU in one city district

100% = BAU in the heating sector (20 438 GWh)

100% = BAU in the whole city (72 866 GWh)

Figure 22. The figures show reduced use of primary energy resources where the energy efficiency measures (4% per year level) is introduced first and then the district heating upgrade is implemented. The impact of the measures is presented for one district that implement district heating, for the heating sector, and as a comparison for the whole city.



100% = BAU in one city district

100% = BAU in the heating sector (4 138 kton)

100% = BAU in the whole city (15 537 kton)

Figure 23. The figures show reduced emissions of carbon dioxide where the energy efficiency measures (4% per year level) is introduced first and then the district heating upgrade is implemented. The impact of the measures is presented for one district that implement district heating, for the heating sector, and as a comparison for the whole city.

8.1.4 Tallinn

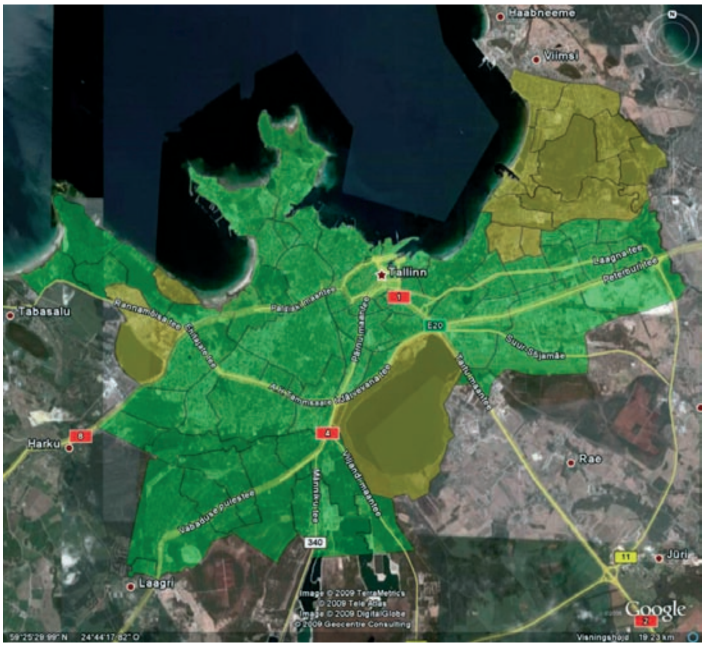


Figure 24. Map of Tallinn. The city borders of Tallinn are indicated by the green and yellow areas. The green coloured districts (7 out of 8 districts in the city) show the districts that are covered by district heating 2020 in the scenario with 4% energy efficiency per year. This corresponds to 98% of the total heating demand. District heating is implemented in districts where the heating demand is greater than 10 GWh/km^2, since Tallinn already has a district heating system today.

The resulting mix of energy sources in the heating supply in the scenarios for Tallinn 2020 is presented in Figure 26. Compared to the diverse mix of energy sources in the EU27 average the heating supply in Tallinn consists of 70% district heating and 30% natural gas.

The heating demand in Tallinn 2020 (BAU) is about 40% lower than the climate adjusted EU27 average, whereas the primary energy use and CO_2 emissions are 68% and 74% lower than EU27 average (Figure 27). This is partly explained by the high share of district heating in Tallinn, which has lower primary energy factor and CO_2 emissions than other heat sources.

Implementation of 2% energy efficiency per year reduces the primary energy use with about 15% and the CO_2 emissions with about 20% compared to BAU. With 4% energy efficiency per year the reductions are twice as high.

Scenarios with district heating upgrading include both an expansion of the district heating system to cover all areas with a heating demand greater than 10 GWh/km^2 and conversion of heat production units, including a new waste incineration plant, a biomass CHP and improvement of the natural gas CHP (Figure 25). The district heating increases from 70% to almost 100% of the total heating demand. As shown in Figure 27, district heating upgrade reduces both the primary energy use and the CO_2 emissions significantly. The upgrade of the production units contribute to a large degree to the improvement (Figure 25). In the city districts that do not have district heating today and that according to the model will have it implemented, the primary energy use decreases 60% and the carbon dioxide emissions decrease 75%.

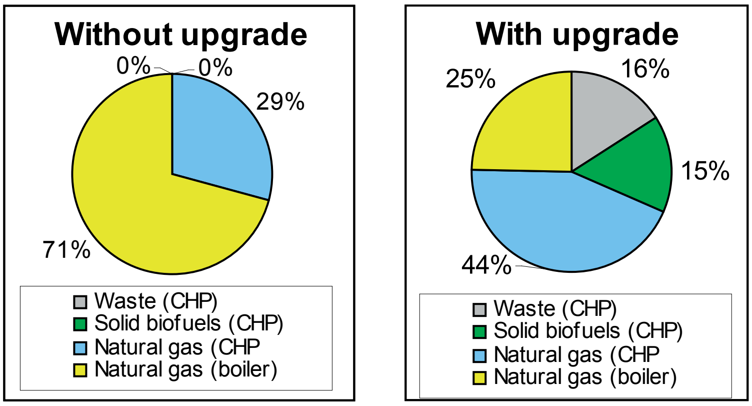


Figure 25. The figure shows the heat production from different kind of fuels and types of production in the scenarios with and without district heating upgrading in 2020.

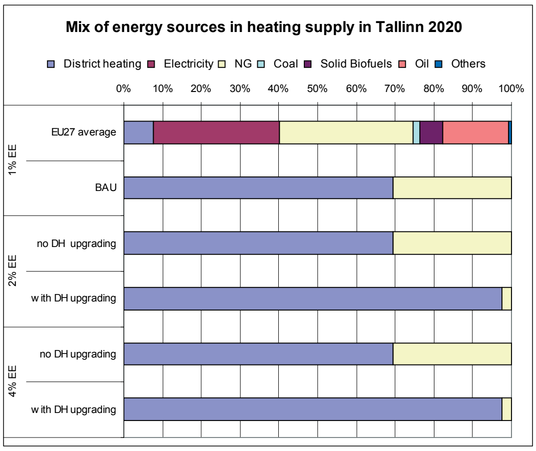


Figure 26. Mix of energy sources in heating supply in Tallinn 2020 in the different scenarios

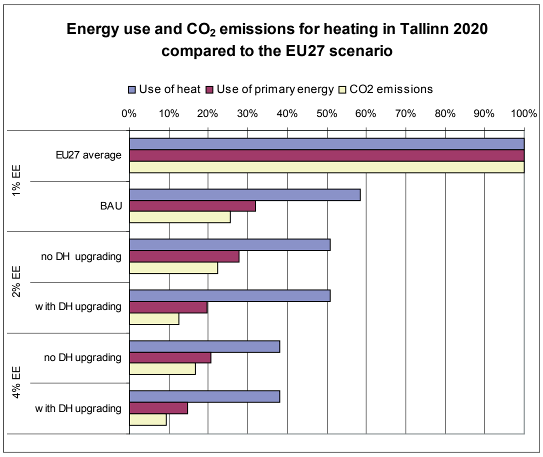
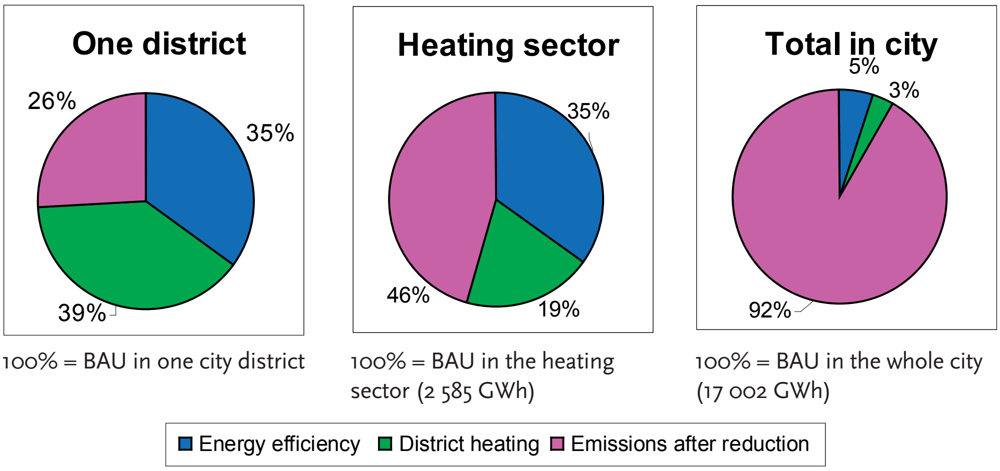


Figure 27. Resulting heating demand, primary energy use and CO_2 emissions in Tallinn 2020 compared to the EU27 average 2020.

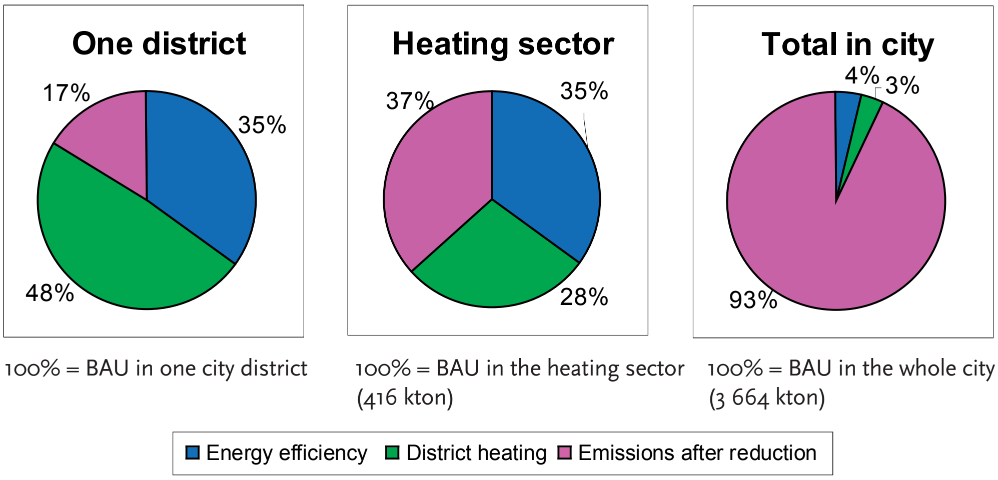


100% = BAU in one city district

100% = BAU in the heating sector (2 585 GWh)

100% = BAU in the whole city (17 002 GWh)

Figure 28. The figures show reduced use of primary energy resources where the energy efficiency measures (4% per year level) is introduced first and then the district heating upgrade is implemented. The impact of the measures is presented for one district that implement district heating, for the heating sector, and as a comparison for the whole city.



100% = BAU in one city district

100% = BAU in the heating sector (416 kton)

100% = BAU in the whole city (3 664 kton)

Figure 29. The figures show reduced emissions of carbon dioxide where the energy efficiency measures (4% per year level) is introduced first and then the district heating upgrade is implemented. The impact of the measures is presented for one district that implement district heating, for the heating sector, and as a comparison for the whole city.

8.1.5 Summarizing results for heating

In Table 13 and Table 14 the savings of primary energy and carbon dioxide in the 4% energy efficiency implementation scenarios compared to the BAU scenario are presented. Even with high implementation of energy efficiency measures the implementation or upgrade of district heating system will give significant reductions of primary energy use and carbon dioxide emissions. The energy efficiency implementation stands for 65% to 74% of the reduction of primary energy use and the district heating implementation/upgrade for 26% to 35%% except for Linköping where the district heating upgrade do not reduce the use of primary energy. The corresponding numbers for carbon dioxide emissions are 40% to 74% for the energy efficiency implementation and 26% to 60% for the district heating systems. With lower energy efficiency implementation the implementation / upgrade of the district heating systems will have larger impact as presented in the figures for each city. The district heating implementation / upgrade is more important for reducing the carbon dioxide emissions than the energy efficiency implementation because district heating provides the possibility to introduce solid biofuels.

To reach the sustainable city as presented in Chapter 12 as fast as possible both the strategies of energy efficiency implementation in the buildings and implementation / upgrade of the district heating system are needed. Individually they will reduce the environmental impact but together the total effect is larger.

The saving potential of primary energy for a city district that implement district heating is between 30% and 87%, and for the heating sector in the cities it is between 30% and 54% in the 4% energy efficiency scenario with implementation /upgrade of district heating compared to the BAU. The savings compared to the total of the whole city is 7% to 18%. The reduction of carbon dioxide is for the heating sector in the cities between 40% and 77% in the 4% energy efficiency scenario with implementation /upgrade of district heating compared to the BAU. The reduction of carbon dioxide compared to the cities total emissions is 7% to 18% for all cities.

Table 12. Performance of the district heating systems for each city in the 2020 scenarios: with and without district heating implementation/upgrading respectively*. Abbreviations in the footnote[16]

	Without DH implementation/upgrading			With DH implementation/upgrading		
	PEF	Kg CO_2/ MWh	Allocation method	PEF	Kg CO_2/ MWh	Allocation method
Linköping	0.71	106	PEM	0.72	35	PEM
Dublin		No district heating system exists		0.33	63	DEPM
Madrid		No district heating system exists		0.46	90	DEPM
Tallinn[17]	1.18	228	PEM	0.63	78	PEM

* The numbers in this table differ from the numbers in Table 6 and Table 7 because the energy losses in the distribution network is included in this table, but not in Table 6 and Table 7.

Table 13. Savings of primary energy 2020 compared to business-as-usual (BAU) in each city.

Heating, Primary Energy (GWh)	Reduction in a city district implementing DH	DH share of reduction	Reduction compared to total for heating in city	Reduction compared to total in city	DH share of reduction
Linköping	30%*	0%*	30%	7%	0%
Dublin	87%	60%	47%	18%	26%
Madrid	82%	58%	40%	15%	35%
Tallinn	74%	53%	54%	8%*	35%

* The reduction in percent in a city district in Linköping is not larger than for the whole heating sector because the district heating already cover 100%.

Table 14. Savings of CO_2 emissions in 2020 compared to business-as-usual (BAU).

Heating, CO_2 emissions (kton)	Reduction in a city district implementing DH	DH share of reduction	Reduction compared to total for heating in city	Reduction compared to total in city	DH share of reduction
Linköping	77%*	60%	77%	14%	60%
Dublin	88%	60%	47%	18%	26%
Madrid	83%	58%	40%	14%	35%
Tallinn	83%	58%	63%	7%**	45%

* The reduction in percent in a city district in Linköping is not larger than for the whole heating sector because the district heating already cover 100%.

** Even though the savings of primary energy and CO_2 are large in the heating sector, they are rather small compa red to the very high total energy use and CO_2 emissions in Tallinn.

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[16] PEF = primary energy factor, PEM = primary energy method, DEPM = decreased electricity production method

[17] A sum of the three main district heating systems and the smaller local district heating systems within Tallinn.

8.2 Cooling

The scenarios for primary energy and carbon dioxide emission reduction for cooling should be seen as examples of how the situation can look like rather than projections over potential future possibilities. The reason is mainly problems to access reliable data. It has in many cases been problematic to access data for heating as well, but the problems have been even larger for cooling. The main reasons are that: i) no detailed data was found of how much of the total electricity consumption in the cities that is used for cooling and ii) for the service sector, where the cooling demand is greatest, only poor data on the specific energy uses is available. There is no easy way to solve these problems. Even if the methodology and quality of the assumptions could be improved, more time will not solve the main problem with lack of statistics.

The calculations for cooling are based on the district cooling demand in Linköping, assumption of the market share for district cooling in Linköping, and the difference in Cooling Degree Days (CDD) between the cities. The differences between the cooling demands in the cities depend on the CDD. The results for implementation of district heating differ because the production of district cooling is adjusted to the situation in each city. Small changes in the uncertain assumptions have large impact on the results.

Table 15. Important characteristics of the main scenarios analysed with the city model for the cooling part. All scenarios are for 2020, based on an annual 1% population growth in the cities and 2% energy use increase per person per year because of behavior changes. Abbreviations in the footnote[18]

Scenario	Cooling demand	Mix of energy sources	DC production
EU27	- 1 060 kWh per inhabitant in average in EU27 calculated based on information from the district cooling system in Linköping and temperature adjusted to the conditions in each city by using the CDD. - 1% energy efficiency implementation in the buildings (about 32% cooling demand increase in the city to 2020).	Electric air-condition machines with assumed average COP of 2.5.	DC not used.
BAU	- Cooling demand today calculated based on information from the district cooling system in Linköping and temperature adjusted to the conditions in each city by using the CDD in the same way as the EU27 average scenario.. - 1% energy efficiency implementation in the buildings (about 32% cooling demand increase in the city to 2020).	City specific statistics in the cases where district cooling is available. In all other cities and city districts the same as for EU27 is assumed.	Only available for Linköping and there it is based on the statistics. 65% absorption cooling machines, 19% "free" cooling, and 15% electric air-condition machines. The absorption cooling machines is assumed to use heat produced by WTE (75%) and biofuel CHP (25%).
2% EE without DC impl/DC upgrade	- Cooling demand today is the same as for BAU - 2% energy efficiency implementation in the buildings (about 14% cooling demand increase in the city to 2020).	The same as for BAU	The same as for BAU
2% EE with DC impl/DC upgrade	- Cooling demand today is the same as for BAU - 2% energy efficiency implementation in the buildings (about 14% cooling demand increase in the city to 2020).	50% district cooling and 50% electric air-condition machines with average COP of 2.5.	- Existing DC production is upgraded according to their own plans => 75% absorption cooling, 22% "free" cooling and 3% electric air-condition machines. - New DC production (Madrid and Dublin) use 90% absorption cooling and 10% electricity air-condition machines. The heat to absorption cooling from WTE (50%) and natural gas CHP (50%). - New DC production (Tallinn) is assumed to be the same as for the upgraded DC production in Linköping except that the heat is produced by WTE (50%) and solid biofuel CHP (50%).
4% EE without DC impl/DC upgrade	- Cooling demand today is the same as for BAU - 4% energy efficiency implementation in the buildings (about 14% cooling demand decrease in the city to 2020).	The same as for BAU	The same as for BAU
4% EE with DC impl/DC upgrade	- Cooling demand today is the same as for BAU - 4% energy efficiency implementation in the buildings (about 14% cooling demand decrease in the city to 2020).	50% district cooling and 50% electric air-condition machines with average COP of 2.5.	The same as for the scenario with 2% EE with DC impl/DC upgrade.

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[18] Business As Usual (BAU), District Cooling (DC), Cooling Degree Days (CDD), Waste-to-Energy Plant (WTE), Combined Heat and Power (CHP).

8.2.1 Linköping

District cooling covers already 30%[19] of the cooling demand in Linköping today and this is also assumed for 2020 in the business-as-usual scenario as shown in Figure 30. In the EU27 average all cooling is produced in electric air-condition machines. In scenarios with upgrading of the district cooling system, it is assumed that the district cooling network is expanded to cover 50% of the total projected cooling demand. The upgraded district cooling is produced by 75% absorption cooling from district heating (increase from 65%), 22% ”free” cooling (increase from 19%), and 3% electric air-condition machines (decrease from 15%). The heat to the absorption cooling machines is produced with 75% WTE and 25% solid biofuel CHP.

The primary energy use for cooling is 10% lower in Linköping 2020 (BAU) compared to EU27 average and the CO_2 emissions 17% lower, due to the existing district cooling system (Figure 31).

Implementation of energy efficiency measures and expansion and upgrading of district cooling system both have significant impacts under prevailing assumptions. However, the achieved reductions of CO_2 emissions are larger with upgrading of the district cooling system. With 4% energy efficiency per year and upgrading of the district cooling system the primary energy use would be about 40% lower than EU27 average and the CO_2 emissions about 50% lower according to the calculations.

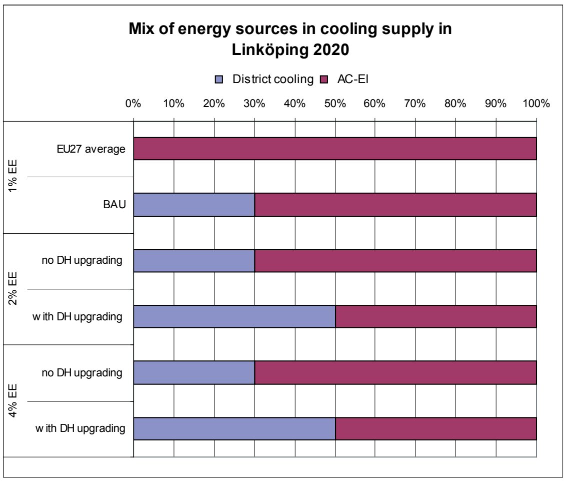

Figure 30. Mix of energy sources for the cooling supply in Linköping 2020.

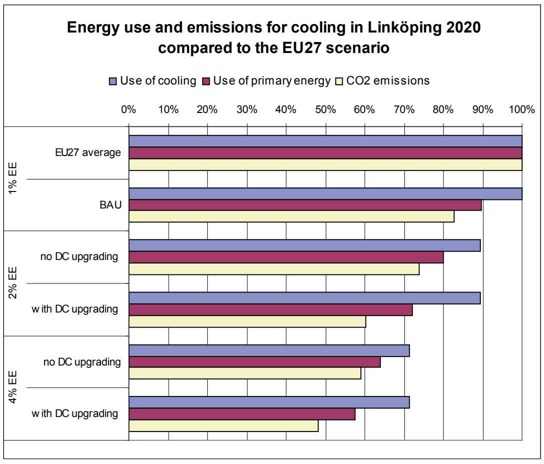

Figure 31. Resulting cooling demand, primary energy use and CO_2 emissions in Linköping 2020 compared to the EU27 average 2020.

The saving potentials of primary energy resources for a building without district cooling that implement both the energy efficiency measures (4% per year) and district cooling are 57%. The potential in percent is lower for the whole cooling sector because the market share of district cooling only raises from 30% to 50%. The potential savings in the cooling sector is small compare to the use of primary energy resources in the whole Linköping. (Figure 32)

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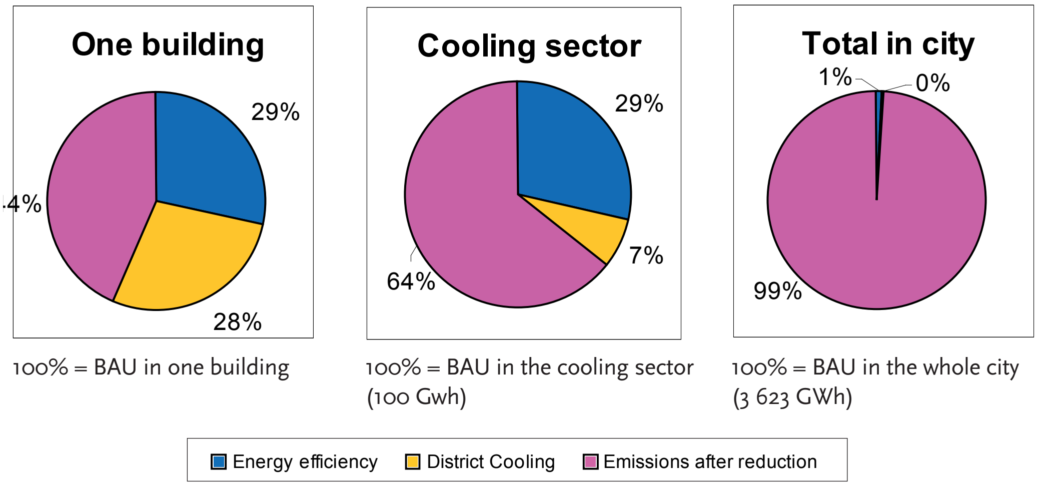
[19] Uncertain assumption based on pers comm with Jimmy Fornander at the energy company in Linköping (2009).

The saving potentials of carbon dioxide emissions from district cooling implementation is in percent larger than the primary energy resources savings as can be seen in Figure 33.

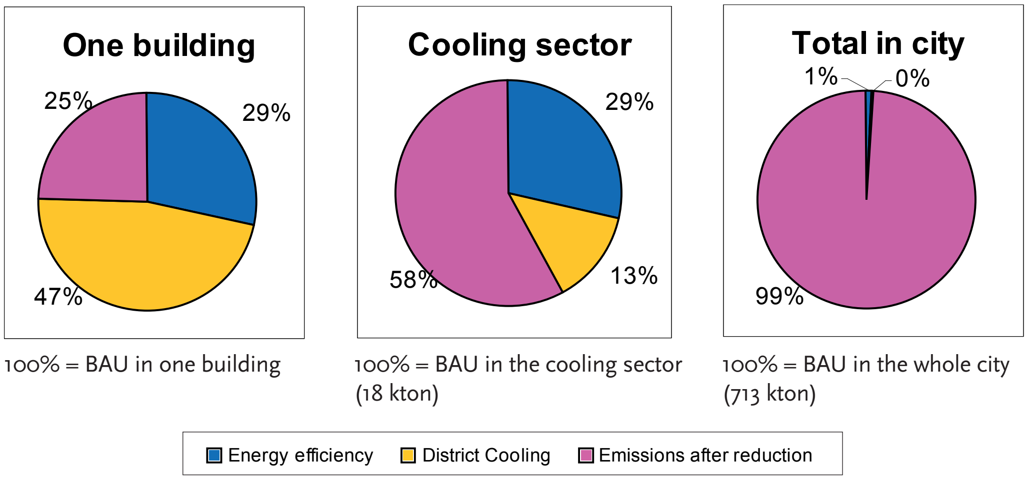


100% = BAU in one building

100% = BAU in the cooling sector (100 Gwh)

100% = BAU in the whole city (3 623 GWh)

Figure 32. The figures show reduced use of primary energy resources where the energy efficiency measures (4% per year level) is introduced first and then the district cooling upgrade is implemented. The impact of the measures is presented for one building implementing district cooling, for the cooling sector, and as a comparison for the whole city.



100% = BAU in one building

100% = BAU in the cooling sector (18 kton)

100% = BAU in the whole city (713 kton)

Figure 33. The figures show reduced emissions of carbon dioxide where the energy efficiency measures (4% per year level) is introduced first and then the district cooling upgrade is implemented. The impact of the measures is presented for one building implementing district cooling, for the cooling sector, and as a comparison for the whole city.

8.2.2 Dublin and Madrid

No district cooling system exists in Dublin or Madrid today and it is for both cities assumed that the cooling demand 2020 is covered by electric air-condition machines in scenarios without district cooling just like the EU27 average (Figure 34). In Madrid, a few commercial or administrative centres have local heat pumps or co-generation plants coupled with absorption cooling, but since the magnitude is not known this were not included in the calculations. In scenarios with district cooling implementation 50% of the total projected cooling demand is covered by district cooling. The district cooling is produced by absorption cooling from district heating (90%) and large scale air-condition machines (10%). The heating to the absorption cooling machines is produced by 50% WTE and 50% natural gas CHP plants.

Since the same assumptions about the cooling system are used, the relative results compared to the EU27 average scenario are the same for Dublin and Madrid (Figure 35). However, the estimated cooling demand is 1.2 MWh/person and year in Dublin and 1.8 MWh/person and year in Madrid in the BAU scenarios in 2020. The effect of the scenarios in total numbers will thus be higher for Madrid (due to a larger cooling demand per person and a larger population), but the relative effect compared to the EU27 average scenario will be the same.

The cooling demand, energy use and CO_2 emissions in the BAU scenarios for Dublin and Madrid are the same as the climate-adjusted EU27 average, as shown in Figure 35[20]. District cooling decreases the primary energy use and the CO_2 emissions by about 10% compared to the scenarios without district cooling. Implementation of energy efficiency measures within the buildings has a larger effect. With 4% energy efficiency per year and implementation of 50% district cooling, the primary energy use and the CO_2 emissions would be almost 40% lower than EU27 average according to the calculations.

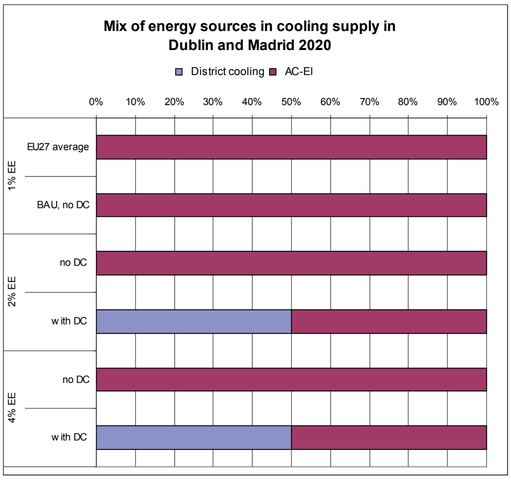


Figure 34. Mix of energy sources for the cooling supply in Dublin and Madrid 2020.

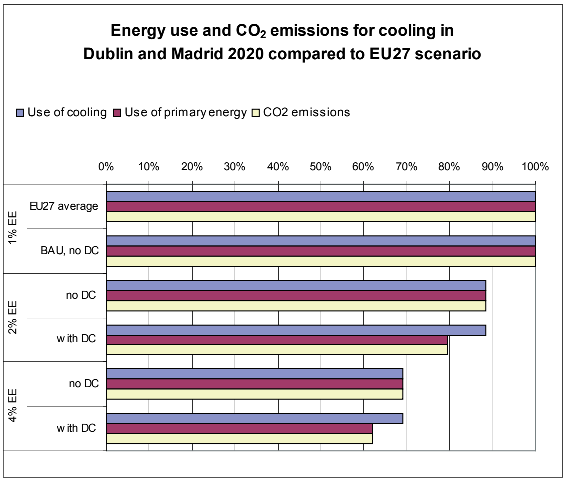


Figure 35. Resulting cooling demand, primary energy use and CO_2 emissions in Dublin and Madrid 2020 compared to the EU27 average 2020.

The saving potentials of primary energy resources for a building without district cooling that implement both the energy efficiency measures (4% per year) and district cooling is

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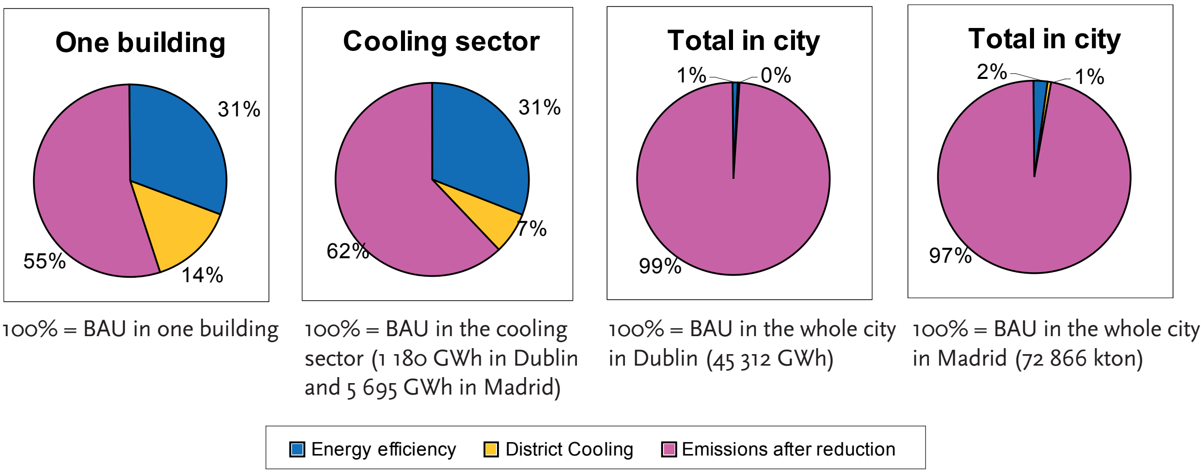
[20] The reason is that the EU27 average and the BAU scenarios are calculated with the same assumptions.

45%. The potential in percent is lower for the whole cooling sector because the market share of district cooling "only" raises from 0% to 50%. The potential savings in the cooling sector is small compare to the use of primary energy resources in the whole Dublin and Madrid. However, the potential is larger in Madrid than in Dublin because of warmer climate. (Figure 36)

The saving potentials of carbon dioxide emissions are in percent equal to the saving potentials for primary energy resources as can be seen in Figure 37.



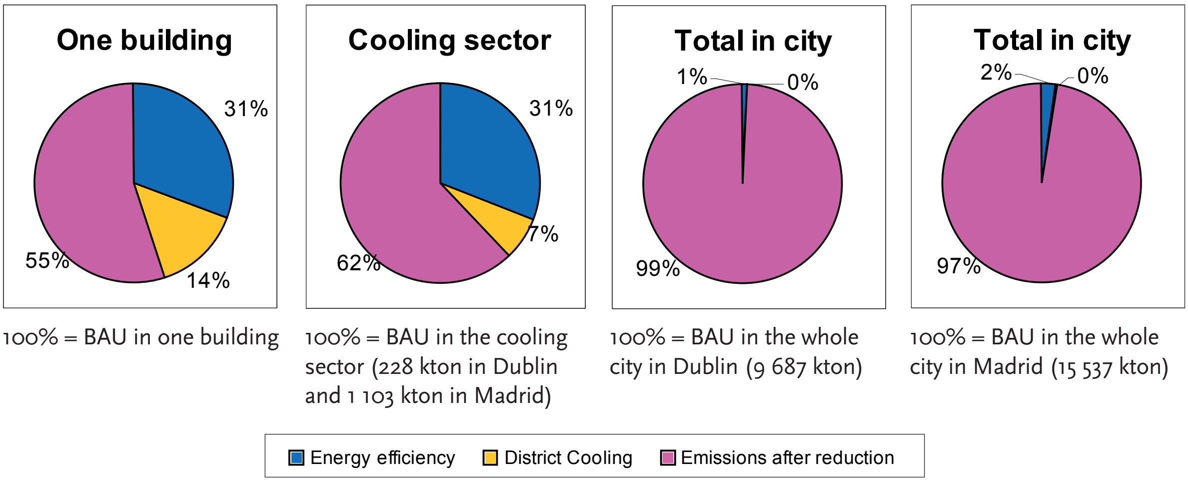
100% = BAU in one building

100% = BAU in the cooling sector (1 180 GWh in Dublin and 5 695 GWh in Madrid)

100% = BAU in the whole city in Dublin (45 312 GWh)

100% = BAU in the whole city in Madrid (72 866 kton)

Figure 36. The figures show reduced use of primary energy resources where the energy efficiency measures (4% per year level) is introduced first and then the district cooling upgrade is implemented. The impact of the measures is presented for one building implementing district cooling, for the cooling sector, and as a comparison for the whole city.



100% = BAU in one building

100% = BAU in the cooling sector (228 kton in Dublin and 1 103 kton in Madrid)

100% = BAU in the whole city in Dublin (9 687 kton)

100% = BAU in the whole city in Madrid (15 537 kton)

Figure 37. The figures show reduced emissions of carbon dioxide where the energy efficiency measures (4% per year level) is introduced first and then the district cooling upgrade is implemented. The impact of the measures is presented for one building implementing district cooling, for the cooling sector, and as a comparison for the whole city.

8.2.3 Tallinn

Like Dublin and Madrid there is no district cooling system in Tallinn today and it is assumed that the cooling demand 2020 is covered by electric air-condition machines (Figure 34) in the BAU scenario. In conformity with the other cities, in scenarios with district cooling implementation, it is assumed that 50% of the total projected cooling demand is covered, and the district cooling is produced in the same way as for Linköping by absorption cooling from district heating (75%), by "free" cooling (22%), and large scale air-condition machines (3%). The heating to the absorption cooling machines is produced by 50% WTE and 50% natural gas CHPs.

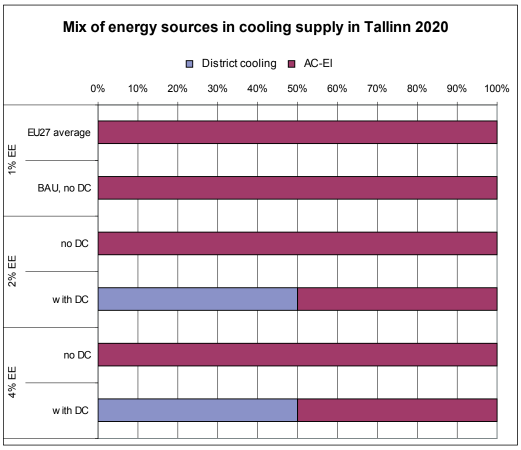


Figure 38. Mix of energy sources for the cooling supply in Tallinn 2020.

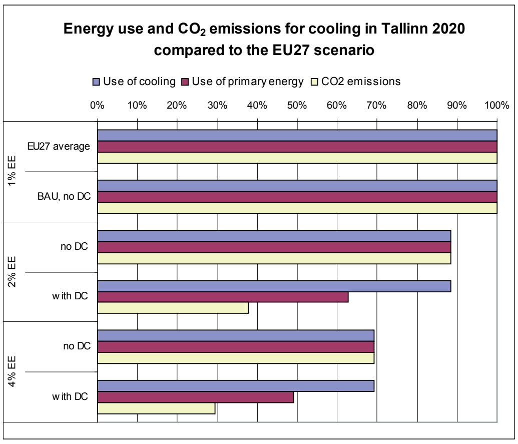


Figure 39. Resulting cooling demand, primary energy use and CO_2 emissions in Tallinn 2020 compared to the EU27 average 2020.

Opposed to Dublin and Madrid, district cooling implementation in Tallinn decreases the primary energy use and especially the CO_2 emissions significantly compared to the scenarios without district cooling. Implementation of energy efficiency measures within the buildings has smaller effect on primary energy use and CO_2 emissions than implementation of a district cooling system. The reason is the low primary energy factor assumed for the heat used in the absorption machines[21] and the possibility to use "free" cooling during winter[22] in Tallinn. About half of the heat needed in the absorption machines is produced in a biomass CHP, which explains why CO_2 emissions are reduced more than primary energy use. With 4% energy efficiency per year and implementation of 50% district cooling, the primary energy use would be 50% lower and the CO_2 emissions 70% lower than EU27 average and business-as-usual (BAU).

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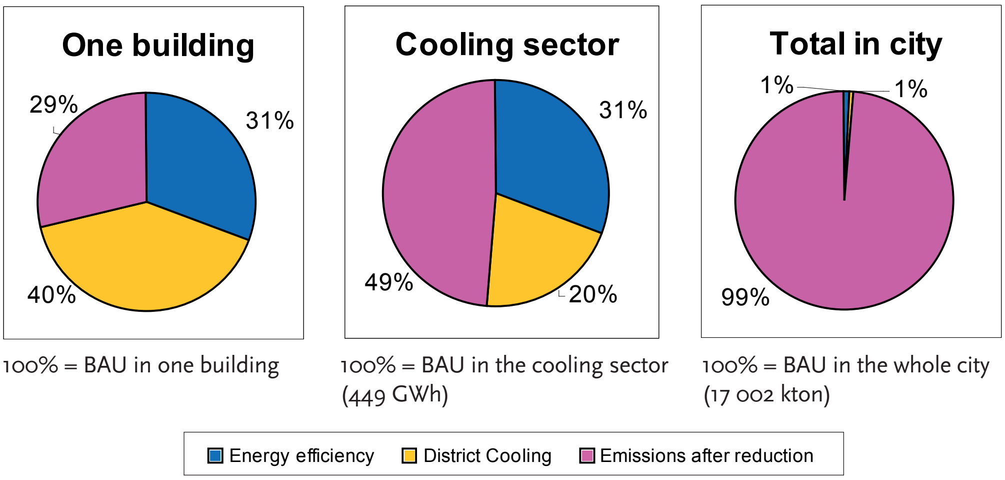
[21] The heat produced for the absorption machines is assumed to be produced to 50% by WTE and to 50% by solid biomass CHP in Tallinn. The primary energy factor for the heat to the absorption machines in the Tallinn is lower than in Dublin and Madrid, since natural gas used in Dublin and Madrid is replaced by solid biomass in Tallinn and since different allocation methods are used (DEPM in Dublin and Madrid, PEM in Linköping and Tallinn).

[22] It is assumed that "free" cooling is only possible in Linköping and Tallinn (of the cities included in this study) because it is not cold enough in Dublin and Madrid during winter.

The saving potentials of primary energy resources for a building without district cooling that implement both the energy efficiency measures (4% per year) and district cooling is 71%. The potential in percent is lower for the whole cooling sector because the market share of district cooling "only" raises from 0% to 50%. The potential savings in the cooling sector is small compare to the use of primary energy resources in the whole Tallinn. (Figure 40)

The saving potentials of carbon dioxide emissions are in percent are larger for the implementation of district cooling than the saving potentials for primary energy resources as can be seen in Figure 41.


One building

100% = BAU in one building

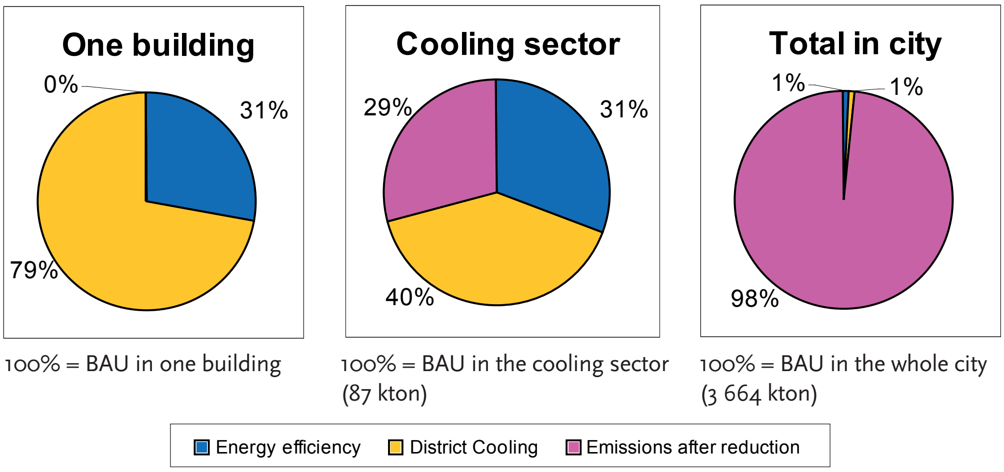
Cooling sector

100% = BAU in the cooling sector (449 GWh)

Total in city

100% = BAU in the whole city (17 002 kton)

Figure 40. The figures show reduced use of primary energy resources where the energy efficiency measures (4% per year level) is introduced first and then the district cooling upgrade is implemented. The impact of the measures is presented for one building implementing district cooling, for the cooling sector, and as a comparison for the whole city.


One building

100% = BAU in one building

Cooling sector

100% = BAU in the cooling sector (87 kton)

Total in city

100% = BAU in the whole city (3 664 kton)

Figure 41. The figures show reduced emissions of carbon dioxide where the energy efficiency measures (4% per year level) is introduced first and then the district cooling upgrade is implemented. The impact of the measures is presented for one building implementing district cooling, for the cooling sector, and as a comparison for the whole city.

9. DISCUSSION / SENSITIVITY ANALYSIS

9.1 The most important input parameters and assumptions

Heating demand

The methods used to estimate the heating demand in the cities have been designed to get as reliable results as possible. However, the uncertainties can still be significant. The city-specific energy statistics that is used in the project are based on different assumptions. Additional assumptions have been used to calculate the heating demand from the energy statistics. However, a comparison between the city-specific data with the calculated heating demand based on the data from Ecoheatcool WP1 (Werner, 2006) and Odyssee (2009) for the specific nation show large similarities (Table 16). The differences between the temperature-adjusted EU27 averages and the city-specific data are, for example, much larger. This supports the quality of the method used in the project

The city-specific data are in most cases slightly lower than the average of the nations. This could partly be explained by the fact that the city-specific data collected represent the bought heating demand and the other numbers are bought energy for heating including, for example, transformation losses in boilers.

Table 16. Comparison between heating demand calculations from different sources of information.

kWh / inhabitant	Temp correlated EU average statistics[23]	Calculated based on Ecoheatcool and Odyssee statistics	Calculated based on city specific statstics	City specific statistics divided by Ecoheatcool and Odyssee statistics	City specific statistics divided by EU average
EU27 average	6 671	6 671	n.a.	n.a.	n.a.
Spain / Madrid	4 430	3 359	3 220	96%	73%
Ireland / Dublin	6 671	8 749	9 041	103%	136%
Estonia / Tallinn	10 410	7 350	6 099	83%	59%
Sweden / Linköping	9 357	12 444	11 265	91%	120%

n.a.: not applicable

The heating demand is in this study distributed on the city districts in proportion to the sum of inhabitants and employees in each city district. This method was considered most suitable, since no statistics of heating demand for each city district was available. However, there are some drawbacks with this simplification. For instance, the heating demand per employee is very different depending on what she/he is working with, and people could have different heating demand depending on different size of dwellings and energy efficiency levels. In average this does not affect the result. However, some areas will get too high heating demand densities and some too low. The model might then introduce district heating in areas that do not fulfil the heating demand density

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[23] The EU27 average is calculated based on the Ecoheatcool WP1 (Werner, 2006) and Odyssee (2009-02-14) statistics. In this column this EU27 average is adjusted to the temperatures in each city respectively.

requirements. Or the opposite. This could lead to both over- and underestimations of the potential of district heating.

In the case where it has not been possible to obtain data on the number of employees on district level (for example in Tallinn) only the number of inhabitants in each city district have been used as distribution tool. The problem with this is that service sector dense districts, such as central parts of town with typically many employees, but rather few inhabitants, get less heating demand in the model and with typically few employees, but large amounts of inhabitants, get higher heating demand than there is in reality. The city centres will probably be covered by district heating in the model anyway. However, the higher heating demand in the suburbs than in reality may overestimate the potential for district heating there and the reduction potential for district heating implementation might be overestimated.

Calculation of exploited area

The calculations of heating demand density have been done per km^2 exploited area where green areas as larger areas of parks, lakes, forests, or other types of areas without heating demand has been excluded. There are risks of both underestimations and overestimations of the green area which lead to overestimations and underestimations of the heating demand density. There are, for example, indications that not all areas that should be excluded according to the purpose in this project are included in the green area statistics. For example lakes close to Tallinn where not included in the green area[24]. In the cases this is true it results in underestimation of the heating demand density. The consequences could be that the model implements too little district heating. The reduction by district heating implementation as presented in the result chapter may therefore be underestimated.

Construction of district heating production

We have tried to use the most realistic district-heating sources for each city. This means that there are possibilities to improve the performance even further. For instance, it could be possible to build solid biofuel CHP or solar heating that eventually could be integrated into the district heating network. We have searched for industries with waste heat that could be used in a district heating system, but it was very difficult to find reliable statistics of that. Probably there is waste heat in different parts of the towns or industries that would benefit from cooperation with a district heating system. This would increase the performance of the district heating system and result in even better results than presented in the result chapter.

Cooling demand

There are large uncertainties with the cooling demand estimations. Small adjustments in the assumptions that are described in the methodology chapter could give large changes

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[24] The green areas for each city districts has been corrected for Tallinn in the model calculations done. However, it has not possible within the time frame of the study to know if this problem exista for some of the other cities as well.

in the results. Table 17 shows that there are both similarities and differences to the Ecoheatcool WP2 (Dalin et al, 2006) cooling demand estimations. Our results correspond relatively well to Ecoheatcool for the cooling demand of Linköping/Sweden and Madrid/Spain (Table 17) However, the difference is significant for Dublin and Tallinn. The explanations are mainly found in the different breaking temperatures[25] used in the calculation of Cooling Degree Days (CDD) which gives different impact for Dublin compared to the other cities, and in the assumptions regarding the part of the cooling demand that is more or less independent from the outdoor temperature[26], which gives a minimum demand of about 500 kWh cooling demand per inhabitant in all cities. Dalin et al (2006) also uses the amount of residential and service space area in each country to estimate the cooling demand. This affects the results because the residential and service sector area per inhabitant differs between the countries. This is one reason why the cooling demand in Madrid and Tallinn in this project exceeds the estimates for Spain and Estonia done by Dalin et al (2006). Using the residential and service sector areas is a good method. However, this information was not available at city level. Considering the cooling demand that do not change with outdoor temperature is judged to be an improvement of the Ecoheatcool project (Dalin et al, 2006) weather the benefit of selecting a breaking temperature of 10 degrees[27] instead of 18 degrees could be questioned. A higher breaking temperature will probably decrease the cooling demand in Dublin, but also disqualify the methodology used because the monthly mean temperature in Linköping never exceeds 16.4 degrees C.

Table 17. Comparison between the cooling demand calculated in this project for 2020 in the BAU scenario and the cooling demand calculated in the Ecoheatcool project WP2 (Dalin et al, 2006).

kWh cooling / inhabitant	Based on district cooling demand in Linköping (BAU scenario 2020)	Calculated based on Ecoheatcool estimations for 2020
EU27 average	n.a.	1 022
Madrid / Spain	1 834	1 551
Dublin / Ireland	1 191	425
Tallinn / Estonia	1 161	1 111
Linköping / Sweden	1 188	571

District cooling production

In the project it is assumed that absorption cooling will be the main supplier in a district cooling system. However, large scale electric cooling production that uses sea water

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[25] The breaking temperature is the temperature above which it is assumed that cooling is needed. CDD is in this project only used to scale the cooling demand between the different climate in different cities.

[26] This includes for example, cooling of computer rooms

[27] 10 degrees is selected because many buildings need comfort cooling already from this temperature.

with a Seasonal System Energy Efficiency Ratio (EER)[28] of 25 may have a better performance. If this technology is better depend on how the heat to the absorption cooling machines is produced and the assumed external production of electricity. In our base case selection of allocation method and alternative production of electricity large scale production that uses sea water for cooling would have a better performance than the absorption cooling in Madrid and Dublin, but equal performance as the absorption cooling in Tallinn. The reason is mainly that in Tallinn increased use of heat for cooling will increase the operational hours for the CHP:s. In Madrid and Dublin, as a contrast, the increased use of heat reduces the electricity production in the power plants/CHP:s in our model.

Electric cooling and absorption cooling will have essentially equal performance also in Madrid and Dublin, if increased heat demand during summer results in increased investments in CHPs. If the external electricity production is coal power, absorption cooling would be better than the high-performance large-scale cooling machines that use sea water for cooling.

Which production option that is best apparently depends on the systems consequences of the implemented technology. These consequences are difficult to identify with certainty, and they may change over time.

However, district cooling is beneficial in both of these options; it is "only" the way of production that differs. In the cases of Madrid and Dublin large scale cooling machines using sea water may increase the performance of the district cooling system and may increase the benefits to introduce district cooling compared to the results presented in the result chapter.

District cooling implementation levels

It is assumed that the district cooling could supply 50% of the cooling demand in 2020. This is optimistic. However, the cooling demand is more concentrated to large users in the service sector than the heating demand and a large coverage may be reached relatively quickly with ambitious implementation.

Energy efficiency implementation levels in buildings

Energy efficiency measures can be defined in different ways. In this project the focus is on energy efficiency from a systems perspective. The energy efficiency is divided into two different parts: i) energy efficiency in the buildings that reduce the demand for heating and cooling, ii) and more efficient energy supply that is achieved through implementation/upgrade of district heating.

The specific energy efficient measures in buildings have not been determined separately, only an overall estimation on the energy efficiency ratio has been assumed. The efficiency measures for buildings could for example consist of better building envelopes, more efficient installations, improved heating and cooling at the individual buildings or behaviour change through individual metering and charge.

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[28] This states the output of yearly useful cooling energy per unit of yearly electrical energy input in the system. It is used, for example, as base for financial calculations. In industrial chillers the EER can be up to 25 (Dalin et al, 2006).

The ratio 2 and 4% energy efficiency per year for the buildings are assumed values. The 2% assumption gives an energy saving of 25% year 2020 (2006 is the base year). That is higher than the scenario developed for example in Dublin for 2020, 18% energy saving potential (Wardell et al, 2008), when more moderate energy saving measures are applied. But it still represents well the "Market & Policy" path described in the conceptual model in chapter 4. The 4% energy saving ratio per year gives 45% energy savings until the year 2020 which can be compared to the scenario developed by Codema in Dublin (Wardell et al, 2008), which gives 44% savings until 2020, when more costly savings are introduced. In Codemas scenario energy efficient measures in the energy system[29] are also included which means that the 4 % energy saving scenario in this study is a tough target to reach. To obtain this reduction as an average for the whole city large efforts are therefore needed. Hence the 4% energy saving scenario represents well the path way "Plan & Control" (se also Chapter 4 conceptual model).

As shown in the result, even with large energy efficiency improvements in the buildings, district heating could further reduce the primary energy use and carbon dioxide emissions for the heating of a city. If high rates of energy efficiency improvements are difficult and expensive to achieve in the buildings, in many cases the same targets of reduced primary energy use can be reached by introducing district heating in a higher degree than calculated in this study. It has not been a part of this study to estimate the cost for energy efficiency measures in the buildings and therefore the costs for introducing district heating compared to energy efficient measures in buildings have not been valuated. If a city should enforce energy efficiency measures in buildings or introducing district heating (or cooling) or a combination of both, the cost effectiveness needs to be calculated based on the characteristics of the building stock and the local conditions both for energy efficiency implementation in buildings and introduction of district heating.

It is important to try to minimise the primary energy use in a systems perspective where the buildings and the energy supply is included as one system. As the case in Linköping shows, when the energy system is already improved, energy efficient measures in the building stock give the largest improvement potential and for Dublin and Tallinn where the introduction of district heating is important likewise as energy efficient measures in buildings. Both types of energy efficiency improvements may have large impacts on reducing primary energy use and carbon dioxide emissions. In combination they can speed up the process in the cities on their way to become more sustainable as well as being backup plans for each other if one of them fails.

9.2 Sensitivity analysis for selected parameters

Effects of allocation method

There are different ways to allocate energy use and emissions between heat and electricity when they are produced simultaneously in CHP plants. The choice of approaches is guided by the decision to model expected consequences if district heating is implemented / upgraded. In Madrid and Dublin natural power plants and waste-to-energy

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[29] That in this study is included in the implementation / upgrade of district heating and not included in the energy efficiency implementation in the buildings.

(WTE) plants converted to CHP plants is assumed to be used to produce heat when/if district heating is implemented. The consequence of introducing district heating and using the heat from the natural gas or WTE power plants is that the electricity production in these plants will decrease. The energy use and environmental impact associated with compensating for this loss in electricity production are allocated to the district heating. We call this allocation method "decreased electricity production method" (DEPM).

In Linköping and Tallinn, where district heating already exist and where the CHP plants only is used when there is a heating demand[30], the so called primary energy method (PEM) is used for allocation. The reason is that increased use of district heating will result in increased use of the CHP plant, and hence in increased electricity production in the CHP plant. This electricity will reduce the need for alternative electricity production (see below for more information about alternative production of electricity). The full energy use and environmental impacts of the CHP plant are allocated to the district heat, but also the benefits of reducing the alternative electricity production.

If new CHP production capacity is built because of the introduction of district heating in Madrid or Dublin it could be more reasonable to use PEM for allocation in these cities as well. However, as presented in Figure 42 the difference between the results from the two allocation methods are quite small. The differences are larger if the alternative production of electricity is coal power instead of natural gas power (Figure 44). Then the primary energy method give results with much higher reduction potential, especially for the district heating introduction, but also for the energy efficiency measures. This illustrates the fact that when marginal electricity production has poor performance, the performances of district heating systems depend on whether they add to or reduce electricity production in the local CHP and power plants.

If a power plant is built close to Linköping or Tallinn for producing electricity the whole year around and also can be used as a CHP plant it could be reasonable to use the DEPM as allocation method for that production unit instead of PEM[31]. However, the production units used today and the planned ones to be taken into operation to 2020 in Linköping and Tallinn are not optimised for electricity production and performs poorly if only electricity is produced without using the heat during large parts of the year. Therefore it is not realistic to use the DEPM for allocation in these cases.

Both the approaches of allocation are relatively beneficial for the heat. The choice of methods is explained by the purpose to model expected consequences of implementation / upgrade of district heating. It could also be defended by considering the difference between how difficult it is to produce electricity and heat respectively. However, other methods exist. The most conservative approach would be the energy method (EM), which does not consider the difference between heat and electricity. Figure 42 shows that the reduction potentials are smaller in the case of Madrid with

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[30] During short times of the year the CHP may produce some electricity without heating demand. However, this is small volumes. It is not economical to use these CHP plants as power plants during longer times.

[31] In Malmö in Sweden a new natural gas power plant that can be used as a CHP during the winter season has been built.

EM as allocation method instead of DEPM. The same result is valid if EM is used instead of PEM in the cases of Linköping and Tallinn.

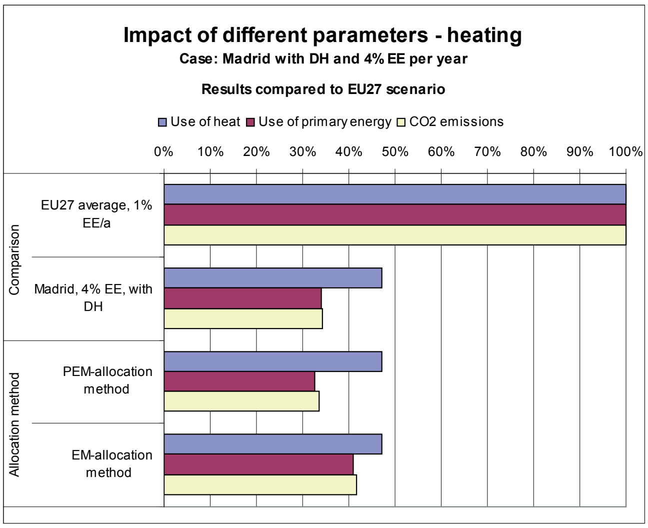

Figure 42. The sensitivity analysis for different allocation methods in the case of Madrid. The scenarios compared are the Madrid scenario with 4% energy efficiency implementation per year with district heating implementation with natural gas power as the alternative production of electricity. In the first Madrid scenario DEPM is used as allocation method and in the other two PEM and EM respectively.

Primary energy factors (PEFs)

The selection of PEFs (the number of MWh primary energy used to produce one MWh fuel, heat or electricity) for different energy carriers also affects the results. The PEF includes the primary energy in the fuel itself, the conversion losses, and the help energy needed. Different opinions exist about which fuels and heat sources that should be counted as use of primary energy. In this project the choice of PEFs is guided by the decision to model expected consequences of the implementation / upgrade of district heating. This means that we focus on the alternative use or the alternative production of the energy carriers, depending on which is the most likely to be affected.

The only fuels or heat sources that are not estimated to significantly affect the use of primary energy in this project are waste and waste heat from industries, even if some energy losses and energy recovery at city dumps for waste are taken into account. In the future, if many WTE plants are built, there could be a competition over waste as fuel. Then use of waste in the investigated district-heating system would affect the use of primary energy. The sensitivity analysis shows (at least for Madrid) that the PEF for waste has minor effect. For cities that have implemented a lot of WTE plants as Linköping, or where the primary energy method (PEM) for allocation is used instead of the "decreased electricity production method" (DEPM), the impact is larger.

The waste heat is not considered use of primary energy because it does not have any other use according to the definition.

The PEF for electricity differs depending on the assumed alternative or external production of electricity. If the alternative production for electricity would have been assumed to be coal power or wind and hydro power instead of natural gas power, the PEF for electricity would be different. Natural gas power has been selected as the alternative production for electricity because natural gas power plants is the power plants that will be considered to be built in 2020 if there is a need for new power production.

In the case the short term effects are interesting to examine it is probably more correct to use coal power production as the alternative production of electricity. Figure 43 shows that the reduction potential does not change with coal power as the alternative production for electricity for Madrid. If the results are examined more closely it shows that the reduction potentials decrease for district heating implementation, but increase for energy efficiency implementation measures. In Linköping and Tallinn where the PEM is used for allocation (see above) coal power as the alternative production for electricity would increase the potential for the use of district heating. The same would be valid for Madrid in the case PEM would be a more appropriate allocation method (see above) as presented in Figure 44.

In the case of examining the effects in a long-term sustainable future it might be more appropriate to use hydro power or wind power as the alternative production of electricity. Then the opposite results as for using coal power as alternative production will be obtained.

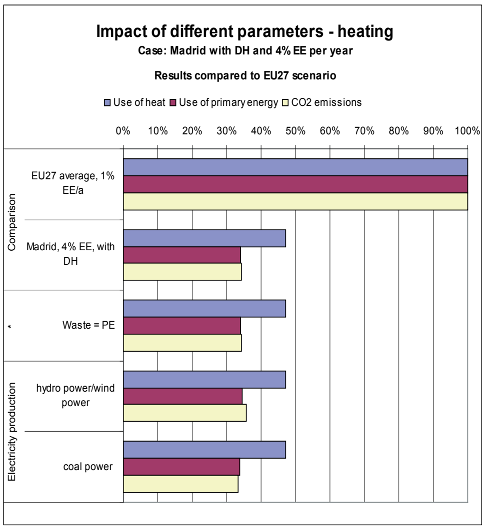

Figure 43. The sensitivity analysis for using other primary energy factor for waste and different alternative productions of electricity. When the comparisons have been done with the EU27 average the primary energy factor for waste and for the alternative productions for electricity have been changed as well.

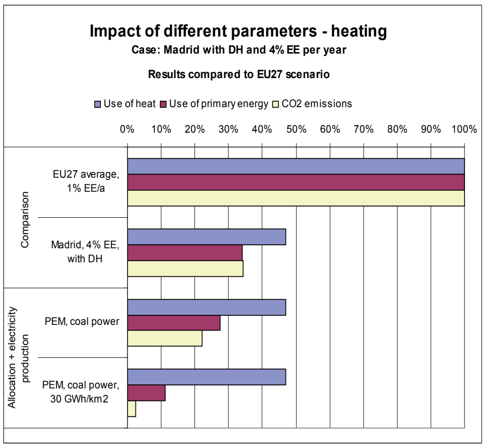

Figure 44. The sensitivity analysis with the combined effect of changed allocation method and changed alternative production of electricity. The last scenario also combines the effect with lower heating demand limit for introduction of district heating (see below for further discussion). When the comparisons have been done with the EU27 average the alternative productions for electricity have been changed as well.

Emission factors

The emission factors from Uppenberg et al. (2001) are used in our model. These are valid for Swedish conditions. However, for carbon dioxide the difference between countries is rather small. The emission factors include emissions from production, transport and use of the fuel in the same way as for the primary energy factors. Emission factors for NO_X, SO_X and other emissions are more difficult than for CO_2. These emissions depend on the technologies for combustion and exhaust-gas cleaning in each production unit. The emission factors can differ a hundred times between different production units with the same fuel because of different regulations. The results are therefore so unreliable that we have decided to exclude them from this report.

The emissions are allocated in the same way as the primary energy above. The emissions also change with changed alternative electricity production.

There are differences between large scale and small scale energy production. The differences in conversion efficiency are considered in the project. However, the differences between large scale and small scale heating production units for NO_X, SO_X and other emissions than CO_2 has not been fully accounted for in this project. It is even more problematic to know the emissions in small scale units than in the larger ones. However, it is reasonable to assume that a few large scale units usually have better emission performance than many small scale units.

The level of heat demand density

In Linköping and Tallinn that started to implemented district heating a long time ago, the district heating system is implemented in areas with heating demand density down to 10 GWh / km^2 exploited area.

In cities without district heating today, such as Madrid and Dublin, a much higher heating demand density level is assumed to be required for investments in district heat: 60 GWh / km^2 exploited area. This high level is selected because it is more interesting to introduce district heating in the areas with the highest heating demand density. It is not probable that there will be enough time and resources to implement district heating in city districts with lower heating demand before the year 2020 (except in new developments where it is cheaper to introduce district heating). The cost calculation also shows that 60 GWh / km^2 is a reasonable level (see the result chapter for more information).

When the district heating is already established, it is possible that it can expand into districts with lower heating demand, especially if the cost calculations have a longer time perspective than year 2020. The consequences of this is presented in Figure 46 and Figure 47where a heating demand density level of 30 GWh / km2 exploited area is used for Madrid. Then the district heating share increase from 40 % to 73% of heating demand and the number of covered city districts increase from 44 to 88 out of 128. In there is lack of money or other reasons of delay it may be realistic to implement district heating only in the areas with heating demand density above 90 GWh / km^2 exploited area. Then still 23% of the heating demand will be covered by district heating as presented in Figure 47.

It is much cheaper and easier to introduce district heating in new developments. It is common to start to build the district heating in new developments even if the heating demand density is lower than indicated above with higher degree of energy efficiency measures in new buildings. This project has focused on existing building stock even if new developments might be important when introducing district heating.

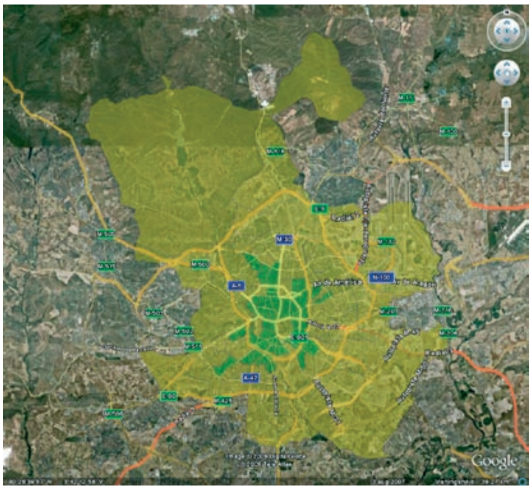

Figure 45. Madrid with the district heating implementation limit of 60 GWh / km2 for the city districts in the 4% Energy efficiency implementation per year with district heating implementation scenario.

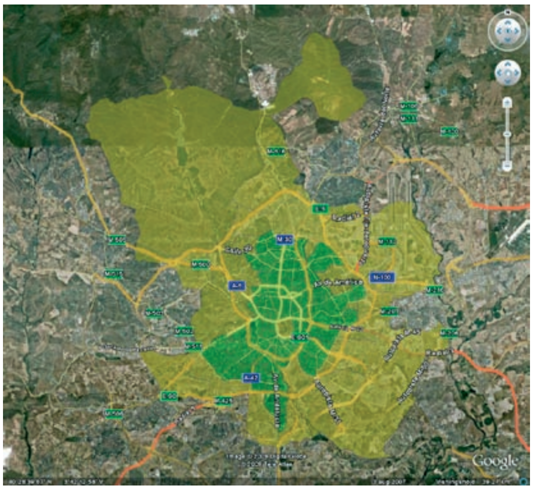

Figure 46. Madrid with the district heating implementation limit of 30 GWh / km2 for the city districts in the 4% Energy efficiency implementation per year with district heating implementation scenario.

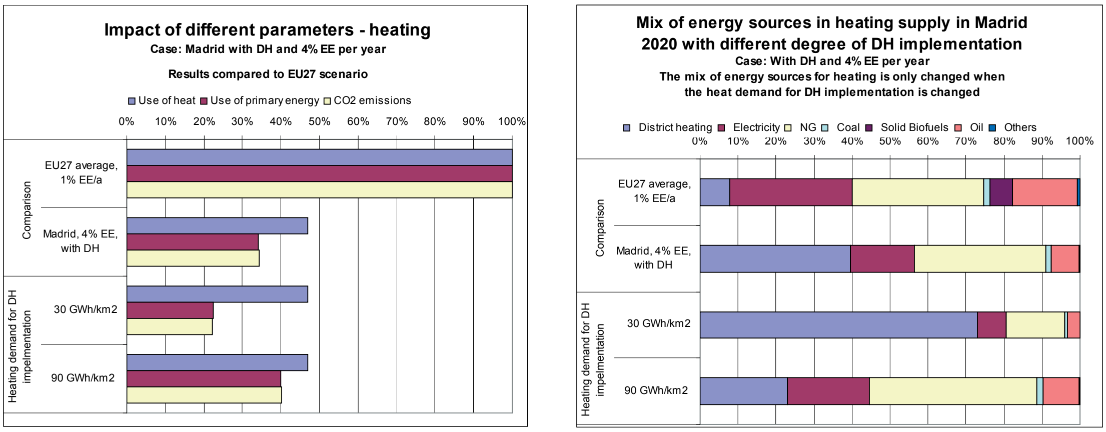

Figure 47. Comparison between scenarios with different heating demand density levels. The levels of 30 and 90 GWh / km² exploited area is compared with the level of 60 GWh / km².
Calculation of the cost to implement district heating

If district heating is assumed to be introduced in all residential buildings and premises 2020 in city districts with a heating demand greater than 60 GWh/km^2, the total investment cost is estimated to 1.8 billion Euro (Table 18). The annual cost savings due to reduced primary energy consumption is estimated to approximately 138 million Euro. In total, it is estimated that introduction of a district heating network in large parts of Madrid would cost 37 million Euro per year. This corresponds to a cost of 17 Euro per saved ton CO_2. A large share of the cost is associated with conversion of apartments that lack water based heating systems (ca 17% of the apartments). If these apartments are excluded from the district heating network, which might be more realistic, this will get the annual costs and savings in balance (= 0) according to the calculations.

As a comparison, if the limit for district heating implementation in a city district is reduced to a heating demand greater than 30 GWh/km^2, the annual cost would be 50 million Euro or 18 Euro/ton CO_2. Excluding installation of water based radiator systems in non-equipped apartments, there will be an annual total saving of 19 million Euro. Very large simplifications have been used in the cost and saving calculations and the result is associated with large uncertainties.

Table 18. Summary of cost estimates for the introduction of a district heating system in Madrid 2020 based on the scenario with 4% energy efficiency per year (all existing heating is converted to district heating in areas where the heating demand is greater than 60 GWh/km^2).

Type of cost	**Total investment cost (MEuro)**
Conversion of existing power plants to CHP	14
Construction of new peak load heating plants	68
Construction of a city wide underground distribution network	332
Installation of heat exchangers in each building (apartment houses and premises)	406
Installation of pipe systems within buildings for connection of apartments (apartment houses)	377
Installation of water based radiator systems in non-equiped apartments	428
Total investment cost	1 823
Annual cost/saving	**(MEuro/year)**
Operation&Maintanance cost for distribution network (0.5% of investment cost per year)	9
Annual cost for investments *	166
Total annual savings (reduced primary energy consumption)	138
Total balance (savings minus costs)	-37
Cost per saved ton CO2 (Euro/ton CO_2)	17

* Based on an interest rate of 6% and 20 years depreciation time.

10. CONCLUSIONS

The primary energy use and the carbon dioxide emissions from heating are 17% to 39% of the examined cities total primary energy use and carbon dioxide emissions. There is a large potential to reduce these in the heating sector by introducing district heating and energy efficient measures in buildings and thus moving in the direction towards a sustainable city. The corresponding numbers are much lower and more uncertain for cooling. However, for cities in the south of Europe they can be relatively close to the heating numbers. Cooling demand is also projected to grow fast in the future because of a predicted climate change.

The primary energy savings in a city district that implement district heating are between 30% and 87%, and in the heating sector these are between 30% and 54% in the scenario with 4% energy efficiency implementation per year together with the introduction /upgrade of district heating compared to a business as usual (BAU) scenario. The savings compared to the total primary energy demand for the whole city is 7% to 18%. The reduction in carbon dioxide emissions from a district that implement district heating are between 77% and 88%, and from the heating sector in the cities it is between 40% and 77%. The reductions are, compared to the total carbon dioxide emissions for the whole city, 7% to 18%.

The primary energy savings in a building that implement district cooling are between 45% and 71%, and in the cooling sector these are between 36% and 51% in the scenario with 4% energy efficiency implementation per year together with the introduction /upgrade of district heating compared to a business as usual (BAU) scenario. The savings compared to the total primary energy demand for the whole city is 1% to 3%. The reduction in carbon dioxide emissions from a district that implement district heating are between 75% and 100%, and from the heating sector in the cities it is between 38% and 71%. The reductions are, compared to the total carbon dioxide emissions for the whole city, 1% to 3%. However, it should be noted that the calculations the results for cooling rely on is of less good quality then the ones for heating. The data accessibility is lower for cooling demand and that affect the quality of the results.

An annual 4% increase in energy efficiency in the buildings has a larger effect on the reduction of primary energy use compared to the BAU scenario (two thirds) than the implementation / upgrade of district heating (one third). However, district heating has a larger effect on the reduction of carbon dioxide emissions than on the primary energy use, because district heating open up the possibility to introduce solid biofuel combined heating and power (CHP) and Waste-to-Energy (WTE) plants.

The heating situations in the studied cities differ. In Madrid and Dublin no district heating exists today, in Linköping the district heating cover almost 100% of the heating demand, and in Tallinn the district heating covers about two thirds. Madrid has the warmest climate and the lowest heating demand per inhabitant. The population density in the cities differs also and affects the density of heating demand per square kilometres. The city districts in Madrid with the highest population density have a higher heating demand density than the most populated city districts in Dublin even tough the heating demand per person is almost three times higher in Dublin. The specific background and circumstances in each city affect the primary energy and carbon dioxide reduction potential.

In city districts that implement district heating, the use of primary energy and carbon dioxide emissions for heating decrease by 30% to 88%. The impact on the cities as a whole is much less (see above), since the increase of district heating is less than half the cities' heating demand in our scenarios with high energy efficiency. In Linköping the district heating cannot increase more, in Tallinn the district heating is assumed to increase from 68% to 98% of the heating demand, in Madrid district heating is assumed to cover almost 40% and in Dublin 23% in the 4% per year energy efficiency scenarios with district heating implementation / upgrade. The reason why the district heating does not expand more in Madrid and Dublin is that the limit for introducing district heating in an area is set to a heating demand density greater than 60 GWh / km^2 exploited area. If district heating is introduced, that limit will probably decrease by time. In Tallinn and Linköping district heating cover city districts with heating demand density down to 10 GWh / km^2. The total impact of district heating implementation will then improve.

A combination of energy efficiency implementation in buildings and implementation / upgrade of the district heating system typically give the largest effect. However, in the case of Madrid the increased energy efficiency implementation from 2% to 4% per year does not reduce the use of primary energy and the carbon dioxide emissions. The reason is that the heating demand density decreases and the heating demand density in many city districts drop below the limit of 60 GWh / km^2 exploited area. The district heating system in that case decreases its share of the total heating demand from 60% to 40%. On the other hand, the upgrade of the district heating system in Linköping does not reduce the use of primary energy at all; only the carbon dioxide emissions are reduced. For Linköping the energy efficiency implementation saves more primary energy.

The combination of energy efficient measures in buildings and district heating implementation / upgrade depend on each other on the path towards a sustainable city with low primary energy use: a delay for either one of the two leads to a lower overall decrease of the primary energy.

The potential for the 4% energy efficiency per year scenario is not very realistic since it represents the path way "Plan & Control" where very extensive action is taken for energy efficiency. Nevertheless it shows that the introduction of district heating has a great potential even if the energy efficient ratio is high. There is also a potential to even further reduce the use of primary energy and carbon dioxide emissions through the district heating system by introducing alternative energy resources. Introduction of waste heat from industries, solar heat or further implementation of solid biofuel CHPs may reduce environmental impact even further. The same effect would the introduction of district heating at lower heating demand density levels give.

The selection of allocation method between heat and electricity in CHPs can significantly affect the results of studies such as ours. However, the sensitivity analysis shows that the effect is relatively low in our case. The allocation method has larger impact if the alternative production of electricity is assumed to be coal power than natural gas power. If the alternative production of electricity is coal power, a change in allocation method will in the case of Madrid increase the environmental benefits of district heating.

The selection of primary energy factors (the number of MWh primary energy used to produce one MWh fuel, heat or electricity) for different fuels also affects the results. Even if there are different assumptions of primary energy factors, the study concludes that it is only for electricity and waste where large uncertainties exist on how these should be valued. The sensitivity analysis shows (at least for Madrid) that the primary energy factor for waste has minor effect. For cities that have implemented a lot of waste-to-energy (WTE) plants as Linköping, or where the primary energy method (PEM) for allocation would have been used instead of the "decreased electricity production method" (DEPM), the effect would have been larger. The primary energy factor for electricity would be different if the alternative production for electricity would have been assumed to be coal power or wind and hydro power instead of natural gas power. Another primary energy factor for electricity would significantly affect the results. In the case of Madrid electricity produced by coal power would decrease the reduction potentials for district heating, but increase them for energy efficiency measures. The opposite would happen with electricity produced by hydro power and wind power.

It is difficult to compare the costs for energy efficiency implementation measures compared to the implementation / upgrade of the district heating system. The cost calculation of introducing district heating in Madrid in the 4% energy efficiency scenario shows that the costs is 17 Euro per ton CO_2 that is saved, with an interest rate of 6% and a depreciation time of 20 years. However, investments in district heating systems in, for example, Linköping and Tallinn have been done with a much longer time perspective. The costs of the energy efficiency implementations have not been estimated in the project.

Both implementation of energy efficiency and district heating is much cheaper in new developments than in existing building stock.

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APPENDIX A

– DETAILS FOR THE CITY MODEL

1.1 Rational for the choice of system boundaries

The "Allt-eller-inget"-study (Persson et al., 2005) discusses which energy losses that should be included when comparing different buildings and different heating systems. Their conclusion is that either losses after the point marked as number 1 or 5 in Figure 1 below should be used. Point 1 should be used if the performance of the building itself is the main objective of the comparison. If the objective is to compare the heating systems of different buildings, point 5 should be used. In our study where the heating systems for sustainable cities are compared to each other it is natural to select point 5.

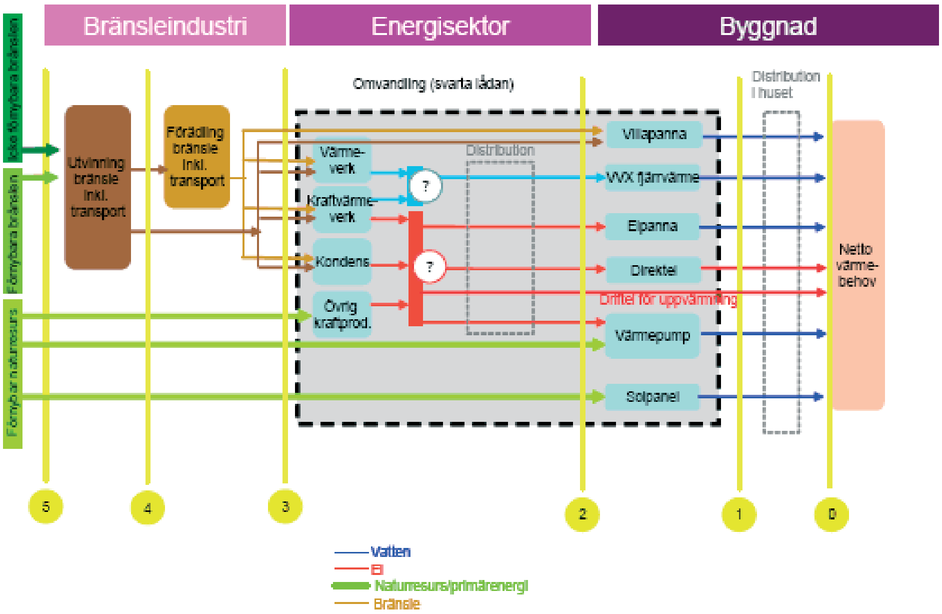

Figure 1. The top figure shows an overview of different points for measuring the energy use that can be considered when analysing the energy use of buildings. The figure is collected from Persson (Person et al. 2005)

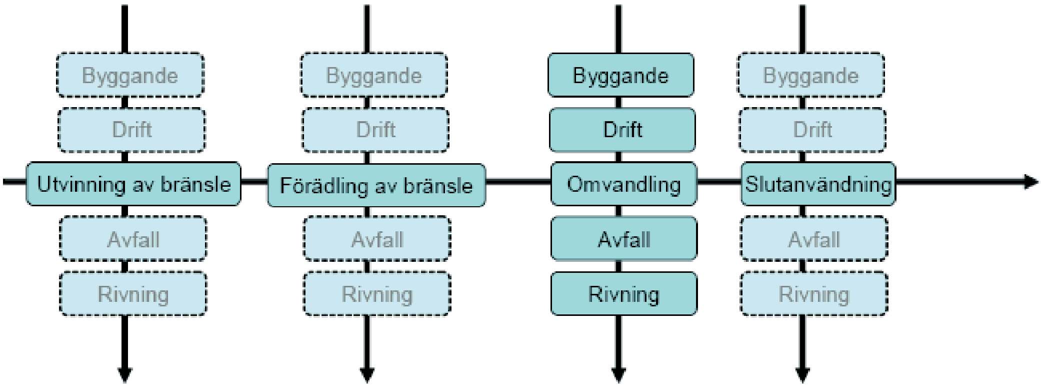

Figure 2. The bottom figure not only include the efficiency losses in the different steps (horizontal line), but also include the vertical lines for the different parts of the life cycle of a fuel that is used for example for heating purposes. The figure is collected from Persson (Person et al. 2005)

Figure 2 also includes the vertical processes represented along the horizontal line. The vertical processes includes for example construction, operation, waste and demolition of power plants, buildings, machines, transportation system, etc., that is needed for the different processes along the horizontal line. Persson (Person et al. 2005) conclude that the energy used for constructing the energy facilities that transform the fuel in to for example electricity and heat, the vertical processes in Figure 2, should not be included since they represent a very small part of the primary energy.

The primary energy use for the construction, waste and demolition of a building can represent quiet a large part of the total energy use during the buildings life cycle. The construction phase represent up to 15% (Adalbert, 2000; Erlandsson, 2001) of the total for a normal energy efficient building. For even more energy efficient buildings the construction phase can represent up to 50% of the total. However, this does not mean that the energy used for the construction phase increase in absolute terms. The evaluation of the introduction of more energy efficient standards for buildings in some projects show that the total energy use only increases a few percent for the construction phase (Älvstranden, 2009). Of course can the manufacturing of energy efficient devices contribute greater or lesser to the primary energy use and also if the energy efficient solution means a shift of energy carrier, for example from district heating to electricity, the primary energy use can change. In this study the aim is to analyse the consequence of introducing a larger share of district heating and cooling not to study the consequences of different energy efficient solutions for buildings, therefore has not the energy use for manufacturing and installation of insulation material, heat recovery systems etc. been included. Energy efficient solutions for the built environment are also assumed to be implemented anyway since EU has set up an overall goal for energy efficiency on 20% to the year 2020.

The primary energy perspective, as defined above, has been chosen when comparing different systems for heating and cooling of buildings in this project. Figure 3 presents a picture of the system investigated. In the figure some of the energy flows cross the system boundary. These energy flows have been defined through literature references and will be discussed further on in the text below.

APPENDIX A

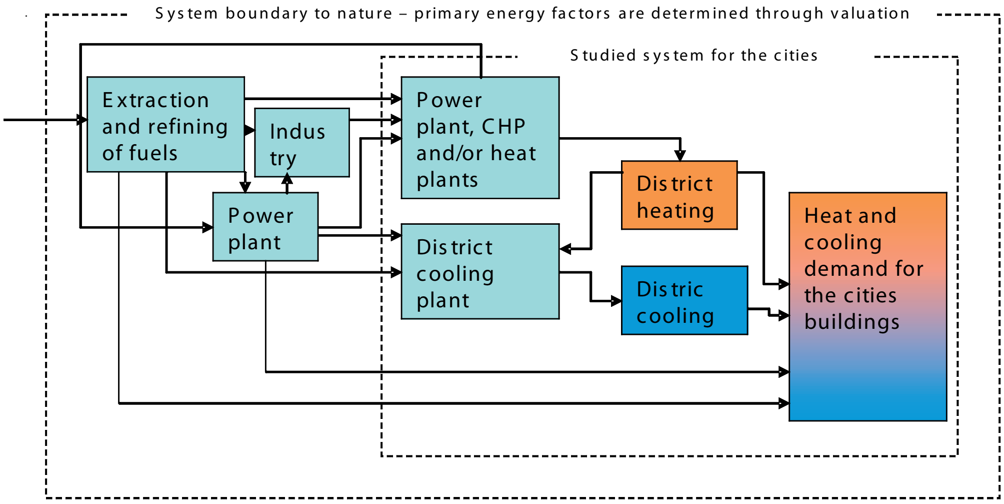

Figure 3. Overview of the investigated system. The system within the city is inventoried for each city. The fuels and energy carriers supplied to the cities the primray energy factors are determined though valuation.

1.2 Rational for the definition of Primary Energy factors for fuels and energy carriers

According to the CEN-standard 15603:2008 (CEN, 2008) there are two conventions for defining primary energy factors:

a) Total primary energy factor: the conversion factors represent all the energy overheads of delivery to the point of use (production outside the building system boundary, transport, extraction). In this case the primary energy conversion factor always exceeds unity.

b) Non-renewable primary energy factor: the conversion factors represent the energy overheads of delivery to the point of use but exclude the renewable energy component of primary energy, which may lead to a primary energy conversion factor less than unity for renewable energy sources.

While the CEN (2008) only distinguishes between renewable and non-renewable energy resources, Persson et al. (2005) divides them into three categories:

- **Non-renewable:** Oil, Natural Gas, Coal, and Uranium
- **Renewable, not freely flowing:** Solid biofuels, Hydro power, Landfill Gas/Bio-gas, Waste, and surplus heat
- **Renewable, freely flowing:** Wind energy, solar energy, streaming water, and waves

The two different ways of defining primary energy in the CEN (2008) are the clearest ways of defining primary energy. However, as indicated in Persson et al. (2005) there are different kinds of renewables. How to divide the renewables and to say which ones that should be considered to have a primary energy factor above unity and which ones that have not is problematic and will always to some degree be a valuation. As illustrated in Table 1 below different standards and reports arrive at different primary energy factors. The pure fossil fuels are in all of these cases considered to have a primary energy factor above unity. However, for the other fuels and energy carriers the definition differs.

Table 1. A collection of Primary Energy Factors (PEF) from different sources of information.

	European						
	Eco-heat-cool	EN 15603:2008 (informative)			SOU 2008:25	ER 2006:32	Person et al (2005)
Reference	Eco-heat-cool (2006)	CEN (2008)			SOU (2008)	Swedish Energy Agency (2006)	Person et al (2005)
Fuels	PRF	Non-renewable PEF	Total PEF		PEF?	PEF?	PRF/PEF?
Solid biofuels (e.g. wood)	0.1	0.06-0.10	1.06-1.10		1.08	1.08	0.1 / 1.04
Processed biomass					1.2	1.15	1.11-1.18
Sorted biomass waste					0.66	1.04	
Waste	0				0.66	1.16	0
Surplus heat	0.05				0 / 0.05	0.05	0.05
Solar heat					0 / 0.05		
Landfill Gas	0				0 / 0.05	1.16	
Natural Gas	1.1	1.36	1.36			1.16	1.1 / 1.16
Oil	1.1	1.35	1.35		1.2	1.18	1.1 / 1.16
Coal	1.2-1.3	1.19-1.40	1.19-1.40			1.04	1.2-1.3
Peat						1.04	
Electricity	2.5				1.5 / 2.5	2.74	
Electricity from hydraulic power plant		0.5	1.5				
Electricity from nuclear power plant		2.8	2.8				
Electricity from coal power plant		4.05	4.05				
Electricity Mix UCPTE		3.14	3.14				

Comments to Table 1:

- The table presents primary energy factors for fuels used in larger energy facilities.
- The Ecoheatcool-report refers to the proposed CEN-standard (CEN Draft Standard TC 228 WI 00228 027), which probably is the preliminary work that later became the EN 15603:2008 (CEN, 2008). However, the informative values given have obviously changed from the preliminary work to the final version.
- The values given for ER2006:32 (Swedish Energy Agency, 2006) are calculated from efficiency values given in Appendix 2 in that report.
- Usually only conversion efficiencies and help-energy are included in calculation of the PEF. However, the CEN (2008) includes construction of the energy and transportation system in the PEF they present in their informative appendix. That is at least one reason why the PEF in the CEN-standard is higher than in the other sources of information.
- PRF stands for Primary Resource Factor and only includes non-renewable energy resources. PEF stands for Primary Energy Factor and includes non-renewable resources and in many cases also renewables. What is included in PEF has to be stated clearly.

In this study we examine the consequences of introducing a change of the energy system. Therefore we use an approach that examines the consequences of using different fuels and energy carriers. Our definition of primary energy should therefore be based on the likely alternative use of each fuel. Below, each fuel and energy carrier, that could be used for heating or cooling, directly or indirectly through district heating and cooling, is discussed.

1.2.1 Solid biofuels

The alternative use for solid biofuels is in this study considered to be use in another energy facility and should therefore have a primary energy factor above unity. Solid biofuels could be considered to be a by-product from the forest industry with no other use. However, the development of solid biofuel markets and increased prices is clear signs of a competition of solid biofuels. This competition is the main argument to give solid biofuels a primary energy factor above unity. Including conversion losses in the production the PEF is 1.08 for solid fuels (Swedish Energy Agency, 2006)

1.2.2 Waste

The alternative use of waste is considered in SOU (2008). They conclude that 50% of the waste could be separated and used as biomass and, hence, assign the primary energy of solid biofuels to 50% of the waste. However, we investigate the expected consequences of changes in the energy system. Our focus is not on how the waste *could* be used but on how it *is likely* to be used, if it is not incinerated in the city we investigate.

Most European countries send a significant share of the municipal solid waste to landfill (SWM 2008a). The reason is that the quantity of combustible waste is much greater than the capacity for waste incineration, biological treatment etc. If waste incineration is reduced in a city in one of these countries, more waste is likely to be deposited at landfill. If landfill gas is extracted at these landfills, approximately 15% of the energy will be utilised. Since landfill gas extraction is common and increasing in

Europe, we assume that15% of the energy in the waste at European landfills is utilised. Applying the approach of alternative use, we assign a primary energy factor of 0.15 to waste that is incinerated or digested in these countries. This estimate might be too high, if not all European landfills have landfill gas extraction in the year 2020, or if the use of food waste disposers continues to increase in European households. It might be too low if landfill gas extraction becomes more efficient.

In a few countries, for example Sweden, Denmark and the Netherlands, direct landfill of municipal solid waste is more or less eliminated (SWM 2008a). Different types of landfill bans are implemented in these countries and, recently, also in Norway (SWM 2008b). As a result of these bans, the Swedish capacity for waste incineration has more than doubled during the past ten years (SWM 2009). If waste incineration is reduced in a city in Sweden, the capacity for waste incineration has to increase elsewhere to meet the landfill bans. The full energy in the waste is then likely to be recovered in a district heating system elsewhere in the region, replacing mainly biofuel but also other energy sources (Sahlin et al. 2004). Applying the approach of alternative use, we could assign a primary energy factor above unity to waste that is incinerated or digested in Sweden.

However, assigning different primary energy factors to waste in different countries is a bit problematic, since combustible waste is transported between countries. Sweden imports waste for energy recovery, and did so even when the national capacity of waste incineration was too small to meet the national landfill bans. It is possible, at least as a short-term effect, that reduced waste incineration in a Swedish city means that less waste will be imported, and more waste ends up at landfills in other countries.

An argument for distinguishing between waste in different countries rests on the observation that the expansion in waste incineration seems to be driven by the continuous increase in domestic waste quantities, and not by the availability of combustible waste at an international level. At least, the recent strong expansion in waste incineration coincided with the discussion and implementation of the national landfill bans. The long-term effects, which seem more relevant when discussing sustainability, are then the ones identified above.

The PEF for waste is 0.31 including energy and conversion losses in the production in this study (0.15 from alternative use and 0.16 from energy and conversion losses). In the sensitivity analysis the PEF for waste is 1.16.

1.2.3 Sorted biomass waste

This category is considered to be waste. However, for this category of waste there is competition because the similarity with solid biofuels. Therefore "Sorted biomass waste is considered to have a primary energy factor above unity. The same PEF as for solid biofuel is selected.

1.2.4 Surplus heat / industrial waste heat

In the sense of valuing surplus heat from the alternative use there is no other use of surplus heat outside the system boundaries. There is, in some cases, possibilities to build transmission lines to other district heating systems or to store the energy in salt and transport it by train. However, these alternatives are considered to be minor and are neglected in this study.

An alternative use for surplus heat could in some perspective be that the surplus heat is not produced at all. Even if the process (that deliver surplus heat) is optimised at the time of the decision, the income from delivered surplus heat may lead to reduced incentives to make energy efficiency measures in the long run. If the surplus heat generates money it is less interesting to decrease the production of surplus heat than it would have been otherwise. The result is that without possibility to sell surplus heat the production of surplus heat will probably be smaller. This could be used as an argument to assign surplus heat some use of primary energy. However, this is assumed to be a minor problem and is neglected in this study.

The conclusion is that surplus heat can be considered to have no or limited alternative use beyond heating apartments etc. in the city investigated. Hence, primary energy calculated based on alternative use is nearly zero for surplus heat. The PEF is 0.05 in this study (Swedish Energy Agency, 2006).

1.2.5 Electricity

Many previous studies use a primary energy factor of 2.5 for electricity. The reason is that 2.5 is proposed in Appendix 2 of the EU directive 2006/32/EG (EU, 2006). A selection of 2.5 as PEF for electricity is also consistent with a coal power plant with 40% efficiency, if the energy demand for coal extraction and transport is not accounted for.

Referring to Table 1, SOU (2008) uses 1.5 as Nordic average and 2.5 for marginal electricity. Swedish Energy Agency (2006) calculates the primary energy factor to 2.74 for marginal production. In the informative appendix in CEN (2008), most electricity PEFs are higher than 2.5 (Hydro power 0.5/1.5[1], Nuclear 2.8, Coal power plants 4.05, Electricity mix UCPTE 3.14/3.31)[2]. In the examples in the CEN-standard EN 15316-4-5:2007 (CEN, 2007) the PEF 2.8 is used for electricity.

A change in electricity demand or in local electricity production does not equally affect all technologies for electricity production. Instead, most of the effect occurs in the technology or technologies providing the marginal production of electricity (see for example, Ekvall & Weidema (2004)). Hence, the marginal electricity should be used to determine the primary energy factor for electricity in our study.

Economists distinguish between short-term and long-term effects of a change. Short-term effects only include those caused by a change in the utilization of existing production capacity. The capacity itself is assumed to be constant in the short-term perspective. When long-term effects are investigated, the production capacity is assumed to adapt to the change, and the utilization of this capacity is assumed to be constant. This distinction is valuable when calculating the environmental impacts in a life cycle assessment (Ekvall & Weidema, 2004). It is also useful for examining effects on the primary energy demand.

The short-term marginal electricity is fairly easy to identify: it is coal power in, for example, the Scandinavian countries. However, in the context of sustainability, it seems

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[1] Depend on which definition that is used: Total primary energy factor or primary resource factor

[2] All of these values are based on informative Annex E to the CEN (2008).

much more relevant to use the long-term marginal electricity to determine the primary energy factor.

The long-term marginal technologies in the year 2020 are the technologies where production capacity is affected by the electricity use in 2020. They might include technologies in power plants constructed in approximately the years 2025-30. They might also include technologies in power plants that are shut down in approximately the years 2020-2025.

The long-term marginal power technology is uncertain and may differ between different parts of Europe. It is likely to be complex and depends heavily on assumptions and boundary conditions (Mattsson et al, 2003). We use a sensitivity analysis to deal with this uncertainty.

In the base case, we assume that the marginal technology is combined cycle designed for natural gas 20 years from now. The efficiency of this technology is assumed to be 60%, and the energy demand for the production and transport of the gas is assumed to be 16%. The primary energy factor is 1.16/0.6=1.93.

In the low case, we assume that the marginal technology is windpower or hydropower with a primary energy factor close to 1.

In the high case, we assume that the marginal technology is old coal-power plants that are shut down 15 years from now. The efficiency of this technology is assumed to be 35%, and the energy demand for the production and transport of the coal is assumed to be 4%. The primary energy factor is 1.04/0.35=2.97.

1.2.6 Fossil fuels

The primary factors calculated based on information in the Swedish Energy Agency (2006) is used for the fossil fuels.

1.3 Rational for allocation within the system boundary

In the cases when more than one product is produced in the same process the environmental impact and energy use have to be allocated between these products. The allocation can be done in a number of different ways. For each allocation method for electricity and heat below a case will also be described for how the allocation could be done between products and by-products:

Energy method

The primary energy used is divided according to the proportions of electricity respectively heat that is produced. With this method the electricity get all the benefits from the cogeneration, when it is compared to separate production of electricity and heat.

Exergy method

This is a modification of the energy method, where the primary energy used is allocated according to the exergy of the electricity and heat that is produced. In this method, more primary energy is allocated to the electricity, since it has a higher exergy value. This typically means that both the electricity and the heat gain from the cogeneration.

Economic allocation method

This is a modification of the energy method, where the primary energy used is allocated according to the price or economic value of the electricity and heat that is produced. The allocation will vary with the prices over time and between places. Both the electricity and the heat will often gain from the cogeneration.

Alternative production method

A method that takes into account the efficiencies for only producing electricity respectively heat (the alternative way of producing electricity and heat with the same fuel). In this method both the electricity and the heat gain from the cogeneration.

In the case of a refinery that produce a main product and surplus heat as a by-product the primary energy consumption should be divided according to the alternative ways of producing only the product and only the surplus heat. For this allocation method the surplus heat get slightly less primary energy allocated than for the Energy method above.

Primary Energy Method (PEM)

According to the primary energy allocation method the electricity produced in the CHP plant is valued according to the PEF for electricity. When calculating the primary energy consumption for the heat produced the electricity produced is multiplied with the PEF for electricity and removed from the primary energy consumption for the CHP. The rest of the primary energy is considered to be the primary energy consumption for heat. In some cases the calculated result for heat will then be below 0. However, the PEF can never be below zero in a whole system because of the definition of PEF. If the calculation result is 0 or less, the PEF is set to 0. With this method the heat get all the benefit from the cogeneration.

Decreased Electricity Production Method (DEPM)

The allocation methods are developed to describe the reality as good as possible. The reality differs as well as the purposes for calculations and therefore different allocation methods are developed. None of the above described methods explains the consequences of using heat from a fuel based power plant. Using heat from a power plant will increase the total efficiency, but decrease the electricity efficiency. The "decreased electricity production method" calculates the environmental impact from the heat used by multiplying primary energy factors and emission factors for the alternative production of electricity with the decreased amount of electricity and divides it with the amount of heat used.

An increase in outlet temperature from 40 C to 120 C which is necicary to use the heat for district heating result in a decrease in electricity efficiency from 38% to 30% for a coal power plant and from 55% to 49% for a natural gas power plant (Rydstrand et al, 2004). A reduction of 6 percentage points have been used for natural gas power plants and a reduction of 8 percentage points for coal, waste, and solid biofuels in the cases plants specific data was not obtained.

The DEPM usually results in low primary energy factors and emission factors for the heat used. However, the impact will never be zero as could happen with the PEM.

Discussion

It is not possible to answer which allocation method that is best without considering the special circumstances and purposes in each case. In this study the aim is to describe the consequences of introducing / upgrade district heating and cooling. This impact the selection of allocation method. In cities where increased use of district heating will increase the use of CHP plants and therefore increases the electricity production within the studied system the PEM will be used for allocation because that method best describe the consequences. In cities where increased use of district heating will decrease the electricity production in the power plants within the studied system the DEPM better describe the consequences.

1.4 Rational for conversion efficiencies within the system boundary

To be able to compare different heating systems the conversion efficiencies for large scale and small scale heat production units are needed, see Table 2 and Table 3. These are used if no city case-specified numbers are found. Conversion efficiencies for cooling are presented in Table 4.

The energy losses in the distribution for both district cooling and district heating is assumed to be the same as for district heating (Swedish Energy Agency, 2006). The electricity for pumps in the district cooling network is assumed to be 10% of the cooling production (Fornander, 2009), but is assumed to include electricity for "free cooling" and absorption cooling as well.

Table 2. Conversion efficiencies for new heat and power production facilities and future production facilities for different fuels. The calculations are based on the low heating value (LHV). These data are used in the case city specific data has not been found.

Fuel	Process	Size ($MW_{electricity}$)	Electricity efficiency	Total efficiency (both electricity and heat)
Solid biofuels	Steam cycle, CHP	80	34%	110%
Waste	Steam cycle, CHP	30	22%	91%
Natural gas	Combined cycle, power plant	400	58% / 60%*	90%**
Natural gas	Combined cycle, CHP	150	49%	90%

* 58% has been used for power plants built in the years from now to 2020 that may be used as CHP plants when there is district heating heat demand. When the heat from the power plants is used the electricity efficiency decreases as described above. 60% is used for power plants that potentially are built in the year 2020 (used for the alternative production for electricity).

** Assumed total efficiency if used as CHP plant.

Source: Hansson et al. (2007)

APPENDIX A

Table 3. Conversion efficiencies in small scale heat producing units (Swedish Energy Agency, 2006).

Conversion efficiencies in the building representing the situation in 2004 in Sweden	Dwellings	... Apartment buildings	Offices
Oil	0.74	0.80	0.74
Electricity	0.99	0.99	0.99
Solid biofuels	0.70	0.68	0.68
Natural gas	0.73	0.77	0.77

Table 4. Conversion efficiencies for cooling machines.

	EER*$_{heat}$	EER$_{electricity}$	Source
Absorption cooling	0.7	-**	Rydstrand et al, 2004
Large scale cooling modern electric driven machines in district cooling networks		6	Fornander, 2009
Small scale cooling electric driven machines at consumers (an average of private and business consumers)		Average of 2.5 in the range of 1.5 to 3.5	Dalin et al, 2006

* EER = (Seasonal System) Energy Efficiency Ratio

** Assumed to be included in the electricity for pumps in the district cooling network.

APPENDIX B

– METHOD FOR CALCULATING HEATING DEMAND

In the Ecoheatcool WP1 (Werner, 2008) information about energy used for heating in all European countries are presented. The statistics is divided into different fuels and according to the three sectors; residential, service and industry. The two main problems of using these numbers directly: i) is that these represent an average for each country which not necessary is representative for the cities of investigation, ii) and that the statistics include all electricity used in these sectors and not only the electricity for heating. The reason is that it is difficult to divide the electricity statistics into different use. It could also be argued that all electricity, even if it used for other things, result in heating as a by-product, for example lamps that produce light, but also heat. However, a large part of this electricity is used when there is no heating demand, especially in the service sector that has a large electricity demand. In the service sector some of the electricity is even used for cooling the heat produced by electricity appliances.

In this project we exclude the electricity for electric appliances by using the share of electric appliances in the dwellings in each country respectively presented in the Odyssee (2009). For the residential sector this information is enough to calculate the share of electricity used for heating purposes from the Ecoheatcool statistics (Werner, 2008). The total amount of energy used for heating and the mix of fuels (except the share produced by electricity) is calculated from city specific statistics.

For the service sector statistics about the share of electricity to electric appliances do not exist. Instead in the project it has been assumed that in the mix of energy carriers for heating the share from electricity in the service sector is the same as in the residential sector. It is difficult to estimate how correct this estimate is. However, to assume the same share of electricity for heating in the service and residential sectors respectively is not totally unrealistic. A large part of the energy use for heating in Werner (2006) in the service sector is electricity that will be excluded from energy for heating with this methodology.

The method is exemplified for EU27 average in Table 1. The columns marked ”old” is data for EU27 from The Ecoheatcool project (Werner, 2006). These data has been recalculated by using the share of energy used for electric appliances that is 14.25% in dwellings in EU27 (Odyssee, 2009). The electricity consumption is decreased with 14.25% of total energy use in Residential sector which decrease the electricity for heating to 13%. The electricity use for heating in the service sector has been decrease so the share will be 13% in the service sector as well.

The method has mainly been used to determine the size of the heating demand for the service sector in the cities. In EU27 the heating demand in the service sector is 31% of the heating demand in the residential sector. The share of electricity for heating is also used. However, the mix of fuels (except electricity) is taken from city specific statistics as well as the total energy use. For EU27 the mix of fuels and total energy use for heating is taken from the Table 1.

APPENDIX B

Table 1: Example of how the methodology for calculating heating demand has been used.

	Residential + Service		Residential		Service	
	Old	Recal-culated	Old	Recal-culated	Old	Recal culated
Natural gas	35%	45%	38%	44%	27%	47%
Electricity	32%	13%	25%	13%	49%	13%
Fuel oil	17%	22%	18%	21%	16%	27%
Heat	8%	10%	8%	10%	6%	11%
Combustible renewables	6%	8%	8%	9%	1%	2%
Coal and coal products	2%	2%	2%	3%	1%	1%
Geothermal heat	0%	1%	1%	1%	0%	1%
Solar heat	0%	0%	0%	0%	0%	0%
Energy for heating in EU27 (TWh)	4 940	3 819	3 408	2 923	1 531	896

APPENDIX C

– DIMENSION OF DISTRICT HEATING PRODUCTION

When constructing the future district heating system our approach has been to use the identified heat suppliers and then add new WTE CHP and/or natural gas CHP plants as base load units until these represent at least 60% of the maximum peak load heating demand. This base load production corresponds to about 90% of the total heat demand. The less than 40% of the peak load to reach 100% is assumed to be produced by natural gas boilers.

To calculate the relationship between maximum peak load needed and the heating demand, temperature series of daily average temperatures within different months for the different cities have been used (Worldclimate, 2009). The monthly data is derived from statistics over the years 1961-90. Variances within each month have been calculated from a temperature series over 2 years for Uppsala with 1h-resolution. With the total heat demand, the temperature series for each city with average monthly temperatures, and the variance of the temperature within a month (based on the Uppsala temperatures for 2004 and 2005) the maximum heating peak load needed could be approximated. In this calculation the demand of hot water that is independent of heat demand during the year has been considered.

APPENDIX D

– CALCULATION OF COSTS AND SAVINGS OF INTRODUCING DISTRICT HEATING, CASE STUDY OF MADRID

A very rough cost estimation is done for implementation of a district heating system in Madrid. The total investment costs needed are estimated and are compared to the potential cost savings achieved by the conversion of the existing heating system to district heating. The cost estimation for Madrid is valid for a district heating system introduced in already exploited areas where the heating demand is larger than 60 GWh/km^2. As a comparison, calculations are also made for a lower implementation level of 30 GWh/km^2.

It should be noted that the actual cost is very dependent on local conditions and restrains, how the district heating system is designed and detailed knowledge about the building stock characteristics. It should also be noted that the most common way is to design the buildings and the area for district heating during construction. Post-construction of a district heating network in a city and conversion of heating systems in existing buildings is much more complicated and expensive than for new buildings.

1.1 The model

The model for estimating total cost for the establishment of a district heating system is made up of the following parts:

1. additional costs associated with the central heat producing units for providing heat for district heating
2. costs for constructing the main pipeline system for distributing hot water from the various heat sources to all buildings in the urban areas of interest
3. costs for installation of a central heat exchanger in the buildings
4. costs for installation of a district heating system within the building
    a. Heating pipelines to each apartment
    b. Installation of a hot water radiator system in apartments that lack a water based heating system today
5. operation and maintenance cost for the distribution network

The investment costs are translated to annual costs by using the "annuity method" and the total annual system cost is then calculated by the equation below:

$$\text{Total annual system cost} = \frac{I * r}{1 + (1 + r)^{-T}} - \text{S}$$

I = investment cost
r = rate of interest = 6%
T = depreciation time = 20 years
S = cost savings per year

The cost savings are made up of decreased primary energy consumption (mainly natural gas) in the system when district heating is introduced.

1.2 Data collection and assumptions

Practically no district heating exists today in Madrid and all apartments are assumed to have their own heating systems. At least 17% of the apartments lack a water based radiator system today (INE, 2009). In this study only very rough cost calculation have been done, based on assumptions of typical "average" investment costs applied on existing information about number of buildings, estimated heating demand etc. However, the cost estimation may give an indication of the size of investments that are necessary.

1.2.1 Costs associated with heat producing units

The following costs are of importance:

- Costs for adjustment of power plants to be able to be run at CHP mode, so that produced heat can be used to deliver hot water at 120°C into the district heating network
- Investments of new peak load heating plants
- Costs for heat exchangers and other investments associated with utilising other sources of waste heat, mainly from large thermal processes in the industry. For Madrid no such sources was included.

A typical Swedish district heating system is designed to have large scale heat production units with low running cost for about 60% of the peak load. These base load units will usually cover as much as about 90% of the total annual heat demand. These base load units usually consist of waste heat from industries, WTEs, or CHPs with various kind of fuels. Heat boilers are built to cover the heat production when the load exceeds the maximum capacity of the base load units.

Heat boilers are cheaper per installed MW than building new CHP. However, to convert a power plant to a CHP (if the power plant is designed for that from the beginning) is cheaper per MW than building new heat boilers.

In this study it is assumed that 20% of the peak load is covered by conversion of WEP into CHP-mode, 40% is covered by converted natural gas CHPs, which are the base load units. The rest, 40% of the peak load, is covered by new natural gas heat boilers. See the main report and Appendix C for further description about the district heating production. The typical investment cost at the heat producing units used in the calculations are shown in Table 2.

Table 1 Typical investment cost at heat producing units in the district heating system (Gaillot et al, 2008)

Cost	Euro/MW
Conversion of existing power plants to CHP	22 300
New peak load heating plants	153 900

1.2.2 Construction of underground district heating distribution system

The cost for constructing an underground pipe network from heat producing plants to all buildings in an exploited city area depend on many factors, such as pipe length and pipe dimensions, constraints to the construction work such as regulations, traffic and underground space deficits in city centres with many underground constructions as well as the local labour cost. The total needed pipeline length depend on design and planning of the network, number of buildings to be connected and how densely distributed the buildings are within the area. What pipe dimensions that are needed depend on the maximum heating demand (effect) and how the network is designed in relation to the location of the heat production plants. (SDHA, 2007; Öberg, 2009; Andersson, 2009; Eriksson, 2009).

The total network length can be roughly calculated from an estimated line density, which is the unit delivered heat per culvert meter. The line density of district heating network in Sweden is 1-10 MWh per culvert meter, where the highest value is valid for district heating networks in the most densely populated cities (SDHA, 2007). The areas in Madrid subject to district heating (heat demand > 60 GWh/km^2) are densely populated parts of the city and are therefore assumed to have a line density of 10 MWh per culvert meter in the calculations. Applied on the annual heating demand of each city district the needed total culvert length is estimated.

Typical culvert construction cost in Swedish inner city areas are given for different culvert dimensions in Table 2 (SDHA, 2007). As shown in the table the cost per meter increases with the dimension of the culvert. From a feasibility study for construction of a smaller district network in Dublin with a peak heat effect of 300 MW (Gaillot et al, 2008) it can be calculated that the average cost per culvert meter corresponds to a culvert dimension of DN250-300 mm for that network. The modelled maximum heat capacity needed for the subdistricts in Madrid (where heat demand > 60 GWh/km^2) varies between 20-70 MW per district, with a total effect of 1 820 MW. An average culvert dimension of DN400 mm is assumed for the Madrid district heating network, which corresponds to an average heat capacity of 75 MW (with ΔT=55°C). This large average dimension may be an over estimation, but since the cost for the very large culverts that will be needed at some distances are much higher than for the smaller pipes that connect to the buildings, DN400 is considered as a high but reasonable average dimension for the cost estimation (Andersson, 2009).

Table 2 Typical construction cost for district heating culverts in inner city areas (SDHA, 2007)

Category A, inner city		
Nominal Dimension DN (mm)	**SEK/m**	**Euro/m***
25	2 800	255
32	3 200	291
40	3 700	336
50	4 100	373
65	4 600	418
80	5 000	455
100	5 600	509
125	6 150	559
150	6 800	618
200	7 800	709
250	8 700	791
300	9 900	900
400	**12 000**	**1 086**
500	13 800	1 255
600	15 800	1 436

* Assuming 1 Euro=11 SEK

1.2.3 Installation of district heating systems within the buildings and apartments/premises

The costs for installation of a common central heating system for a building and for all apartments (and premises) in the building depends on what type of heating system that is already installed. There are three main categories considered in the cost estimations:

1. Building that has block heating: a common central water based heating system is already installed for the whole building (or a group of buildings), including all apartments. No (or very small) adjustments are needed in the buildings.
2. Building where the apartments (or premises) have there own separate heating system with hot water radiators, with a boiler or heating unit in each apartment. A central heat exchanger and connecting pipes from the heat exchanger to each apartment in the building must be installed, but no adjustments are needed within the apartments.
3. Buildings where no water based heating system is installed in the apartments (electric radiators or mobile stoves are used for instance). A water based heating system must be installed in all apartments in the whole building.

APPENDIX D

It is very uncommon with central heating systems for whole buildings in Madrid (Fernando del Valle, 2009). It is assumed that all apartments and premises in Madrid have their own heating system. A central heat exchanger and connection pipes to the apartments must therefore be installed in each building.

The cost for a heat exchanger depends on the heating demand of the building, but no such information is availible for Madrid. Based on the available information about number of buildings of different types in Madrid and typical installation cost for different building categories, a rough estimation of the total cost for installation of heat exchangers was done. The assumed heat exchanger installation cost used in the calculations vary between 25 000 SEK (ca 2300 Euro) for buildings with 1-4 apartments to up to 200 000 SEK (ca 18200 Euro) for hospitals, hotels etc. as shown in Table 3. The typical costs are mainly estimated based on information provided by Eriksson (2009). It should be noted that these figures are very rough estimates, especially the cost for premises and others (hotels, hospitals etc.) are associated with large uncertainties since the size distribution of these buildings are not specified in the available information for Madrid.

The cost for installation of connecting pipes from the heat exchanger to all apartments in the building is also very difficult to estimate on a large scale. The cost depends on the number of floors in the building and how many apartments on each floor. In the calculations a typical value of 8000 SEK (ca 730 Euro) per apartment for installation of connecting pipes to the heat exchanger is assumed, which is associated with large uncertainties when applied on the whole building stock (Eriksson, 2009). This cost is only estimated for residential buildings (premises are not included).

83% of the apartments in Madrid Community are equiped with a central heating system according to Census 2001 (INE, 2009). For the rest of the apartments, a water based radiator system must be installed. The cost for installation of a full radiator system is approximately 50 000 SEK (ca 4550 Euro) per apartment as an indicative value (Eriksson, 2009).

Table 3 Estimated typical cost used in the calculations for installation of heat exchanger, pipe system for connection to all apartments and water based radiator system in apartments.

Type of cost	**Cost**
Estimated typical cost for heat exchanger installation of different building types	[SEK/building]
Residential, 1-4 apartments	25 000
Residential, 5-9 apartments	50 000
Residential, 10-19 apartments	70 000
Residential, 20-39 apartments	100 000
Residential, > 40 apartments	140 000
Premises	50 000
Other (hospitals.hotels etc.)	200 000
	[SEK/apartment]
Estimated typical cost for intallation of a pipe system within buildings	8 000
Estimated typical cost for installation of a water based radiator system in apartments	50 000

The total cost for installation of a heat exchanger and pipe systems within each building and a water based radiator system in the apartments that lack such equipment, is calculated by multiplying the typical installation costs given in Table 3 with the number of buildings or apartments in the subdistricts where district heating are to be introduced. Estimations of number of buildings and apartments year 2020 are calculated from available statistics from Census 2001 (INE, 2009), proportional to the assumed population increase.

1.2.4 Cost savings

Table 4. Primary energy factors (PEF) in Madrid 2020 with and without district heating implementation and assumed price for primary energy (in terms of natural gas) used in the calculations

PEF for the heating system in Madrid 2020 without district heating (business as usual)	1.71
PEF for the district heating system in Madrid 2020	0.46
Assumed price for natural gas 2020 (Euro/MWh)	36.4
Assumed price for primary energy in the calculations (Euro/MWh)	31.4

The primary energy factor (PEF) for the mix of heat sources that is used in Madrid today is calculated to 1.71 MWh primary energy per MWh heating demand. The same calculation has been performed for the potential district heating system. The PEF for the district heating system is calculated to 0.46 MWh primary energy per MWh heating demand.

In the calculation of the cost savings it is assumed that all primary energy is natural gas. The reason is that a large part of the fuel bought for heating today is natural gas and that the electricity, that is used to calculate the PEF for the district heating in Madrid, is assumed to be produced by natural gas.

In the feasibility study for district heating in Dublin (Gaillot et al, 2008) a price of 36.4 Euro/MWh is assumed for natural gas. Compared to the natural gas price in Elforsk (2007) of 14.5 Euro/MWh[1] the price in the feasibility study is very high. However, the price in Elforsk (2007) is for large scale production units and the price in the feasability study is the price paid by the individual dwellings. In this project it is more reasonable to use the feasability study price.

Natural gas has a PEF of 1.16 (see main report and Appendix A for more information). The price for primary energy used in the calculations are therefore the natural gas price of 36.4 Euro/MWh divided by 1.16.

The assumptions indirectly result in a price of electricity of around 63 Euro/MWh.

The cost savings of introducing district heating are calculated by multiplying the primary energy saved by introducing district heating with the assumed price for primary energy.

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[1] Using an exchange rate of 11 SEK/Euro.

1.3 Result of cost calculations for district heating implementation

The calculations are based on the Madrid scenario where an energy efficiency of 4% per year is assumed. Introducing district heating in all residential buildings and premises 2020 in city districts with a heating demand greater than 60 GWh/km^2, would lead to a total investment cost of approximately 1.8 billion Euro (Table 5). The annual cost savings due to reduced primary energy consumption is estimated to approximately 138 million Euro. In total, it is estimated that introduction of a district heating network in large parts of Madrid would cost 37 million Euro per year (assuming an interest rate of 6% and 20 years depreciation time). This corresponds to a cost of 17 Euro per saved ton CO_2. A large share of the cost is associated with conversion of apartments that lack water based heating systems (ca 17% of the apartments). If these apartments are excluded from the district heating network, which might be more realistic, the annual costs and savings would be equal (0 Euro per saved ton CO_2).

As a comparison, if the limit for district heating implementation in a sub-district is reduced to a heating demand greater than 30 GWh/km^2, the annual cost would be 50 million Euro or 18 Euro/ton CO_2. Excluding installation of water based radiator systems in non-equipped apartments, there will be an annual total saving of about 19 million Euro. Very large simplifications have been used in the cost and saving calculations and the result is associated with large uncertainties.

Table 5 Summary of cost estimates for the introduction of a district heating system in Madrid 2020 based on the scenario with 4% energy efficiency per year (all existing heating is converted to district heating in areas where the heating demand is greater than 60 GWh/km^2).

Type of cost	**Total investment cost (MEuro)**
Conversion of existing power plants to CHP	14
Construction of new peak load heating plants	68
Construction of a city wide underground distribution network	332
Installation of heat exchangers in each building (apartment houses and premises)	406
Installation of pipe systems within buildings for connection of apartments (apartment houses)	377
Installation of water based radiator systems in non-equiped apartments	428
Total investment cost	1 823
Annual cost/saving	**(MEuro/year)**
Operation&Maintanance cost for distribution network (0.5% of investment cost per year)	9
Annual cost for investments *	166
Total annual savings (reduced primary energy consumption)	138
Total balance (savings minus costs)	-37
Cost per saved ton CO2 (Euro/ton CO_2)	17

* Based on an interest rate of 6% and 20 years depreciation time.

FJÄRRSYN Fjärrsyn – research and development to increase the knowledge about district heating, district cooling and combined heat and power a growing part of an energy future that is ecologically sound and financially and socially sustainable. Fjärrsyn is managed by the Swedish District Heating Association and financed in collaboration with the Swedish Energy Agency.

SUSTAINABLE CITIES' ENERGY DEMAND AND SUPPLY FOR HEATING AND COOLING

District heating and cooling in combination with energy efficiency measures in buildings can reduce the carbon dioxide emissions by up to 77 per cent by 2020 for the heating and cooling market in several European cities.

The Swedish model for heating the cities leads to roughly 60 per cent lower use of energy resources and carbon dioxide emissions in the heating sector compared to an average city in the European Union.

District heating in combination with energy efficiency means a large reduction of carbon dioxide emissions. For the entire heating sector, the reductions can make a total of between 40 and 77 per cent. For district cooling in combination with energy efficiency, the reductions for the entire cooling sector are between 38 and 71 per cent. District heating accounts for approximately one third of the reduction of emissions.

The results also show that both the energy supply systems as well as the buildings need to be more efficient in order to achieve a more sustainable city in the future. It is not enough with just energy efficient buildings or just an efficient supply system.

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