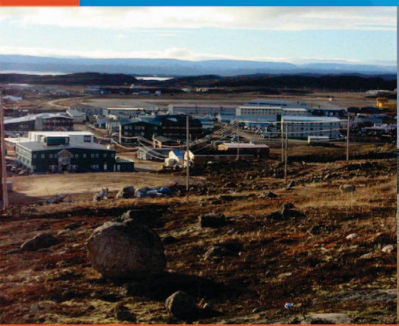
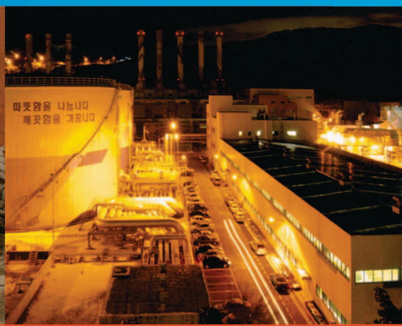
ANNEX IX | 2011 | 8DHC-11-01






IEA DHC|CHP

International Energy Agency
IEA Implementing Agreement on District Heating and Cooling, including the integration of CHP

The Potential for Increased Primary Energy Efficiency and Reduced CO_2 Emissions by DHC

The potential for increased primary energy efficiency and reduced CO_2 emissions by district heating and cooling:

method development and case studies

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Preface (IEA-DHC)

The International Energy Agency (IEA) was established in 1974 in order to strengthen the co-operation between member countries and reduce the dependency on oil and other fossil fuels. Thirty years later, the IEA again drew attention to serious concerns about energy security, investment, the environment and energy poverty. The global situation is resulting in soaring oil and gas prices, the increasing vulnerability of energy supply routes and ever-increasing emissions of climate-destabilising carbon dioxide.

At the 2005 Gleneagles G8 an important role was given to the IEA in advising on alternative energy scenarios and strategies aimed at a clean, clever and competitive energy future. Two years later, at the Heiligendamm G8, it was agreed that “instruments and measures will be adopted to significantly increase the share of combined heat and power (CHP) in the generation of electricity”. District Heating and Cooling is an integral part of the successful growth of CHP: heat networks distribute what would otherwise be waste heat to serve local communities. The IEA is active in promoting and developing knowledge of District Heating and Cooling: while the DHC programme itself is the major global R&D programme, the IEA Secretariat has also initiated the International DHC/CHP Collaborative which assesses global markets and policies for these important technologies.

The IEA’s latest CHP report, "Cogeneration and District Energy: Sustainable energy technologies for today…and tomorrow", released at COGEN Europe meeting in Brussels on 21 April 2009, identifies proven solutions that governments have used to advance CHP and district energy, setting out a practical ‘’how to’’ guide with options to consider for design and implementation. The report concludes that these technologies do not need significant financial incentives; rather they require the creation of a government ‘champion’ to identify and address market barriers. This makes CHP and district energy ideal investments at a time of tight budgets.

The CHP report follows the IEA’s first report from March 2008, "Combined Heat and Power: Evaluating the Benefits of Greater Global Investment". There are also 11 "Country Scorecards" that evaluate different countries’ success in achieving increased use of CHP and DHC. In November 2009, the IEA joined with the Copenhagen District Energy Summit to issue the first Global District Energy Climate Awards in order to recognize communities that have embraced district heating and cooling as a vital sustainable energy solution.

The major international R&D programme for DHC/CHP

DHC is an integrative technology that can make significant contributions to reducing emissions of carbon dioxide and air pollution and to increasing energy security.
The fundamental idea of DHC is simple but powerful: connect multiple thermal energy users through a piping network to environmentally optimum energy sources, such as combined heat and power (CHP), industrial waste heat and renewable energy sources such as biomass, geothermal and natural sources of heating and cooling.
The ability to assemble and connect thermal loads enables these environmentally optimum sources to be used in a cost-effective way, and also offers ongoing fuel flexibility. By integrating district cooling carbon-intensive electrically-based air-conditioning, rapidly growing in many countries, can be displaced.
As one of the IEA’s ’Implementing Agreements’, the District Heating & Cooling programme is the major international research programme for this technology. Active now for more than 25 years, the full name of this Implementing Agreement is ‘District Heating and Cooling including the integration of Combined Heat and Power’. Participant countries undertake co-operative actions in energy research, development and demonstration.

Annex IX

In May 2008 Annex IX started, with the participation from Canada, Denmark, Finland, the Netherlands, Norway, South Korea, Sweden, United Kingdom, United States of America.

Below you will find the Annex IX research projects undertaken by the Implementing Agreement "District Heating & Cooling including the Integration of Combined Heat and Power".

Annex IX (2008 – 2011) research projects Implementing Agreement "District Heating & Cooling including the Integration of Combined Heat and Power".

Project title	Company	Number
The Potential for Increased Primary Energy Efficiency and Reduced CO2 Emissions by DHC	SP Technical Research Institute of Sweden Project Leader: Monica Axell	8DHC-11-01
District Heating for Energy Efficient Building Areas	VTT Technical Research Centre of Finland Project Leader: Kari Sipilä	8DHC-11-02
Interaction between District Energy and Future Buildings that have Storage and Intermittent Surplus Energy	Gagest Inc. Project leader: Tom Onno	8DHC-11-03
Distributed Solar Systems Interfaced to a District Heating System that has Seasonal Storage	Gagest Inc. Project leader: Tom Onno	8DHC-11-04
Policies and Barriers for District Heating and Cooling outside EU countries	Energy-AN Consulting Project leader: Arto Nuorkivi	8DHC-11-05

Benefits of membership

Membership of this implementing agreement fosters sharing of knowledge and current best practice from many countries including those where:

- DHC is already a mature industry
- DHC is well established but refurbishment is a key issue
- DHC is not well established

Membership proves invaluable in enhancing the quality of support given under national programmes. Participant countries benefit through the active participation in the programme of their own consultants and research organisations. Each of the projects is supported by a team of experts, one from each participant country. As well as the final research reports, other benefits include sharing knowledge and ideas and opportunities for further collaboration.
New member countries are very welcome – please simply contact us (see below) to discuss.

Information

General information about the IEA Programme District Heating and Cooling, including the integration of CHP can be obtained from our website www.iea-dhc.org or from:

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Executive summary

- The choice of allocation method has an enormous impact on the final results for emission of greenhouse gases and use of primary energy for district heating systems with combined heat and power (CHP) plants.
- In the marginal scenario, natural gas is the best choice of the analysed fuels, while in the average scenario waste is the best choice.
- The case studies show that an increased power to heat ratio, at constant total efficiency, leads to lower primary energy losses and lower emissions of greenhouse gases per kWh produced district heat.
- There is a trade-off between increasing district heating temperature for higher efficiency of the ABS chiller and lowering the district heating temperature for higher electricity generation efficiency in CHP.

The background to the project is a need to calculate values indicating the “energy performance” for relevant energy chains for district heating and cooling, in accordance with the European Union Energy Performance of Buildings Directive (EPBD). Although the EPBD is an EU directive, the method described is suitable for comparison of different energy supply systems also in countries outside of the EU. Based on the standard EN 15603, the primary energy demand and the greenhouse gas emissions were selected as indicators of energy performance.

In the project, a method for calculation of greenhouse gas emissions and use of primary energy for the total production chain of district heating or cooling has been developed. The model has been used to illustrate the potential of saving primary energy and reducing the impact on global warming by the use of district heating and cooling, focusing on the potential for combined heat and power (CHP) plants. The methodology for system analysis of primary energy demand and greenhouse gas emissions related to heating of buildings is in a stage of development, and this project will provide a contribution to the development of the methodology.

The project has analysed the sub-processes of the production chain of district heating and cooling, in order to evaluate the impact related to each step. By using a Life Cycle Assessment (LCA) approach, a model for calculating the impact on global warming, expressed as CO_2-equivalents (CO_2-eq), and the use of primary energy, expressed with the primary energy factor (PEF), has been developed.

The calculation model for the case studies was developed in Excel. Using Excel has made it possible for all project members to work in the model without the need to install and learn specific programs. The program makes it possible to make a model in which it is easy to vary the parameters.

In the first stage of the calculations all possible steps of relevance are evaluated. For an existing system, some of the energy flows may not exist, or are considered to be negligible compared to other energy flows, and can be excluded if the system fulfils the cut-off rules without them. However, it is difficult to draw any general conclusions valid for all systems regarding the relevance of each step.

In the project, a number of case studies have been made. The case studies have been analysed using two scenarios: a marginal and an average scenario. A marginal perspective is appropriate to use in order to evaluate how a change in the energy system will affect the use of primary energy and emissions of greenhouse gases for the full system. This is of interest, for example, for policy makers or energy companies that are considering building a new plant. For a marginal scenario, the power bonus method is selected for allocation between heat and electricity.

An average perspective is to prefer for bookkeeping purposes, or for a historical reporting of emissions and resources. For the average scenario, the alternative generation method was chosen for allocations.

In order to analyse how the choice of supply and return temperature of the district heating will influence the efficiency of the CHP plant, separate computer simulations of the plant has been made. The simulations show that a decrease of the supply temperature of the district heating increases the electricity efficiency while the heat efficiency will decrease. A decrease of the supply temperature from 120 to 80°C will increase the electricity efficiency with 3 %-points (in the simulation example from 19% to 22%). Lowering the return temperature will have a slight positive impact on the electricity efficiency. The overall efficiency of the plant is almost unchanged by the supply and return temperatures in these simulations.

The case studies show that an increased power to heat ratio, at a constant total efficiency, leads to lower primary energy losses and lower emission of greenhouse gases for the produced district heat. This is the case for both of the analysed allocation methods. The resulting increased electricity efficiency leads to lower emissions allocated to the heat production, even though the heat efficiency will decrease.

Computer simulations have also been made for the absorption (ABS) chiller. The efficiency of the ABS chiller depends on the supply temperature of the district heating water. A higher district heating temperature to the ABS chiller will increase the cooling efficiency. The drawback is that a high district heating temperature decreases the electricity efficiency in the CHP plant. In general, the ABS chillers are mainly operated for production of cooling during the summer, when the district heating temperatures normally are lower than during the winter. Thereby, there is a trade-off between increasing district heating temperature for higher efficiency of the ABS chiller and lowering the district heating temperature for higher electricity efficiency in the CHP plant.

The cases studies of the district cooling show that the results are highly influenced of how the heat is produced. In the marginal scenario, natural gas is the best choice of the analysed fuels, while in the average scenario waste is the best choice. For emissions of greenhouse gases, the direct emissions related to the ABS chiller are more or less negligible, but for the PEF_{DC} value the energy losses in the ABS chiller has a large impact on the final result.

The choice of allocation method has an enormous impact on the final results for emission of greenhouse gases and use of primary energy for district heating systems with CHP plants. The case studies show that for the same system the primary energy factor for the delivered heat will differ from -1 to +1 and the emissions of CO_2-eq allocated to the heat production will differ from -1.7 kg CO_2-eq/kWh to +0.2 kg CO_2-eq/kWh depending on the choice of allocation method.

For the power bonus method used in the marginal scenario, the power to heat ratio has a large impact on the final results, both PEF and CO_2-eq, while for the alternative generation method the inclusion of a renewable fuel in the fuel mix is the most important factor for low emissions of greenhouse gases.

The case studies show that the environmental impact related to the production and use of additives does have an impact on the final results that cannot be neglected. Previous studies often assumed that this component had a more or less negligible influence on the results. Especially for biomass, the effect of the additive will be large. Our study shows that additives represent 35-40% of the total emissions of CO_2-eq in a wood chips CHP plant. However, even for fossil fuels the effect of additives is not negligible. In a CHP plant using natural gas, approximately 5% of the impact on global warming will be due to the use of additives.

The environmental impact for construction and dismantling of plants and district heating grids are in general small, in most cases below 2% of the total. For systems using fossil fuels it will be even smaller. However, the impact from the construction of the plant per kWh produced heat may be larger for plants that produce power or heat only when operated at peak load. In this case, the building and dismantling phase may be a large part of the total. The situation is similar for the district heating grid; in grids with a low energy density the construction and dismantling phase may have a larger influence on the final results.

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Nomenclature and other definitions

α	Power to heat ratio in a combined heat and power plant
ηtot	Total efficiency
2-stage ABS-chiller	Absorption chiller which has an additional 2nd generator and sub-absorber. It is designed to reduce a leaving temperature of DH water and increase COP
ABS-chiller	Absorption chiller
Allocation	Partitioning the input and output flows of a process between the product system under study and one or more other product systems
Allocation $factor_{heat}$	The fraction allocated to the heat production in a combined heat and power plant. Allocation $factor_{heat}$ = 1 – Allocation $factor_{elec}$
Allocation $factor_{elec}$	The fraction allocated to the electricity production in a combined heat and power plant. Allocation $factor_{elec}$ = 1 – Allocation $factor_{heat}$
C&D	Construction and dismantling
CHP	Combined heat and power. Simultaneous generation of usable thermal energy (called heat in this study) and electricity and/or mechanical energy
CO_2-eq	Carbon dioxide equivalents. Unit for the impact on global warming. A greenhouse gases expressed in terms of the amount of carbon dioxide that would have an equivalent impact.
COP	Coefficient of performance. Ratio of the heating capacity to the effective power input to the unit, expressed in Watt/Watt
DC	District cooling
DH	District heating
DHC	District heating and cooling
GHG	Greenhouse gases. Gases with an impact on global warming
GWP	Global Warming Potential. Impact category related to global warming
Heat only plant	A plant producing usable thermal energy only (Compared to a CHP-plant producing both thermal energy and electricity)
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Assessment. Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle.
LCI	Life cycle inventory analysis. Phase of life cycle assessment

	involving the compilation and quantification of inputs and outputs for a product throughout its life cycle
PE	Primary energy. Energy that has not been subjected to any conversion or transformation process
PEF	Primary Energy Factor. Primary energy divided by delivered energy. In this study PEF is equal to the total primary energy factor including primary energy from both renewable and non-renewable sources.
Q_{del}	Energy supplied to a technical building system though the system boarder, to satisfy the users taken into account (e.g. heating or cooling)

1 Introduction

1.1 Goal and scope

The objective with the project is to develop a method for calculations of greenhouse gas emissions and use of primary energy for the total production chain of district heat and cold to buildings. The aim is to illustrate the environmental potential of saving primary energy and reduced the impact on global warming by the use of district heating and cooling, focusing on the potential for combined heat and power (CHP) plants.

The project has analyzed the sub processes related to the production chain of district heating and cooling in order to evaluate the impact related to each step. By using a Life Cycle Assessment (LCA) approach a model for calculating the impact on global warming, expressed as CO_2-equvivalents (CO_2-eq), and the use of primary energy, expressed as PEF, has been developed. The model can be used for calculating the environmental impact for district heating and cooling. Additional the model can be use for calculate the environmental impact of electricity produced in a CHP-plant. For district cooling, only cold produced in an absorption chiller is included, other techniques have been excluded in the study.

To illustrate the environmental potential the calculation model have been used for calculate a number of case studies.

1.2 Project organisation

The project is a joint project between SP Technical Research Institute of Sweden, Korea District Heating Technology Research Institute (KDHC) and SINTEF Energy Research, Norway. SP has been the project leader of the project.

The members of the project group are:

Project member	Organisation	Comment
Mrs. Monica Axell	SP	Project leader
Mr. Markus Alsbjer	SP	
Mr. Markus Lindahl	SP	
Mr. Jacob Stang	SINTEF	
Mrs. Monica Berner	SINTEF	
Mr. Seok Mann Yoon	KDHC	
Mr. Jae-Sik Eom	KDHC	2008- February 2010
Mr. Kye-Ik Eom	KDHC	New project member February 2010

Connected to the project are also an expert group. The members of the expert group are:

Members expert group	Country
Mr. Lars Gullev	Denmark
Mr. Chris Snoek	Canada
Mr. Mark Spurr	USA
Mr. Johan Thelander	Sweden
Ms. Mirja Tiitinen	Finland
Mr. Rolf Ulseth	Norway
Mr. Rune Volla	Norway
Mr. Robin Wiltshire	UK

1.3 System boundaries

The system boundaries of the project are described in Figure 1 below. The project includes all steps from the extraction of the raw material until the heat or cold is delivered to the substation at the end users. This includes all steps from the extraction of the raw material via processing, storage and transports, to combustion and distribution of the heat/cold. The focus was on mapping the steps from the combustion plant until the heat or cold is delivered.

The impact related to each sub process was evaluated in order to see what processes that have an impact on the final result. The relative size between different sub processes was also of interest.

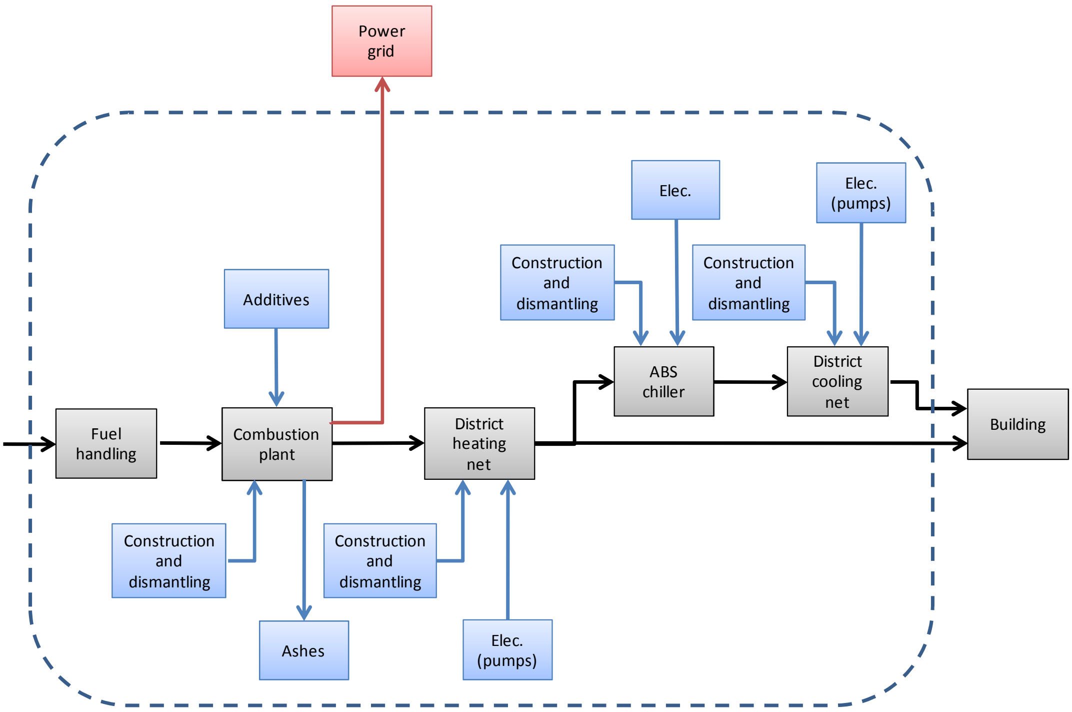

Figure 1 Overview system boundaries

In the project proposal the substation was included in the system to be analysed. In order to be able to calculate the environmental impact in relation to delivered energy it was decided to change the system boundaries and exclude the substation located at the end user. Thereby the project follows the definition of “delivered energy” in EN 15316 [10], where the substation is assumed to be located inside the building and thereby excluded.

1.3.1 *Boundaries towards geography*

The study has an aim to describe the district heating and cooling production chain from a global point of view. In order to achieve this European and Asian members have been included in the project group. The expert group has representatives from Europe and North America.

The methodology used in the project is general and will work globally. Despite the global group of participants in the project there have been difficulties to collect data representing the global situation. The main part of the data and regulations in this study is based on the European situation, using EN standards and EU regulation. Also for data collection related to the sub processes Europe is overrepresented.

1.3.2 *Boundaries towards nature*

All energy resources from nature and all emissions related to climate change is included in the calculations.

1.3.3 *Cut off rules*

A minimum of 99% of the total contribution to global warming potential (GWP) and primary energy respectively is included in the inventory analysis.

1.3.4 *Infrastructure*

The construction and dismantling of facilities for combustion, cold production and nets for district heating and cooling are included in the study, for details see chapter 4 and 5.

1.3.5 *Functional unit*

The functional unit is 1 kWh of delivered heat or cooling to the building.

1.3.6 *Allocation*

Allocation procedures are described in chapter 3.

1.3.7 *Units*

In general SI units are used in the report. Temperatures are expressed in Celsius.

2 Background

The basic idea of this research project is to develop a useful method, which can be used to calculate trustworthy values of the indicators for "energy performance" for relevant energy chains involving DHC according to the EU Directive on the energy performance of buildings (EPBD) [1]. Although, EPBD is an EU directive, this is a suitable method for comparison of different energy supply systems. The directive imposes from now on all EU/EEA countries to implement a system where the buildings shall have an energy certificate which shall express the "energy performance" of the building. To implement this directive in practice several CEN-standards have been developed based on a mandate from the European Commission. One of the most central standards in this context is EN 15603 [2] where the two main indicators of the energy performance are suggested to be use of primary energy and emitted CO_2-eq. The DHC concept has a great competitive potential in this context and it seems important to make the energy sector aware of that in an appropriate way.

The methods for system analysis of primary energy demand and greenhouse gas emissions related to heating of buildings are in a stage of development and this project will hopefully make an impact on the development of the methodology. The EU Directive on energy end-use efficiency and energy services [3] is a supportive directive to the EPBD, and in Sweden, for example, the primary energy indicator is recognized as a suitable measure of the nation's energy saving targets as a result of this directive. Major parts of this chapter are based on Berners report *Primary Energy Efficiency and Life Cycle Assessment* [89].

2.1 Environmental impact of energy carriers in a wider perspective

It seems relevant to mention here that the environmental impact from the energy carriers begins long before the energy is used in the building. It begins already at extraction, production and transportation of the energy to the building. Further environmental impact will arise at transformation (e.g. combustion) of the energy carrier either in the building directly or in a central energy unit that supplies the heating/cooling demand in several buildings. The impact will also arise at construction and dismantling of buildings and infrastructure and at transports related to the energy carrier. To get an overview of the environmental impact, studies have been made on life cycle inventories and life cycle assessments (LCI/LCA) of different energy carriers. Those LCI/LCA studies related to this project were examined. See also chapter 2.2 for a further description on the LCA methodology and different databases.

Energy efficiencies and system boundaries related to the environmental impact of energy usages in buildings have been investigated to some extent. However, further investigations are needed to obtain a better picture of this area. As a good start a Swedish study [4] can be mentioned that have, among other issues, investigated system boundaries regarding the calculation of primary energy usage and how corrections for different efficiencies of different energy carriers are made for heating. Examples for DHC systems are given in the study. Recently Alonso, Ulseth and Stang have carried out a study of the system efficiency within buildings [90].

2.1.1 *Environmental challenges and energy efficiency*

Since around 1970 there has been an increasing attention on energy consumption, air pollution and climate change, formally initiated by the United Nations in 1983 with the Brundtland Commission and the report "Our Common Future"[5]. The Kyoto Protocol [6] from 1998, enforced in 2005, further increased the focus on the relation between greenhouse gasses and climate change.

Reports from IEA [9] shows that the demand for energy services increased by 1.8% per year over the period 1990 /2004 even though energy efficiency measures accounts for annual savings of 16 EJ (i.e. 4440 TWh) which corresponds to 14% of the total energy consumption of 114 EJ in IEA countries.

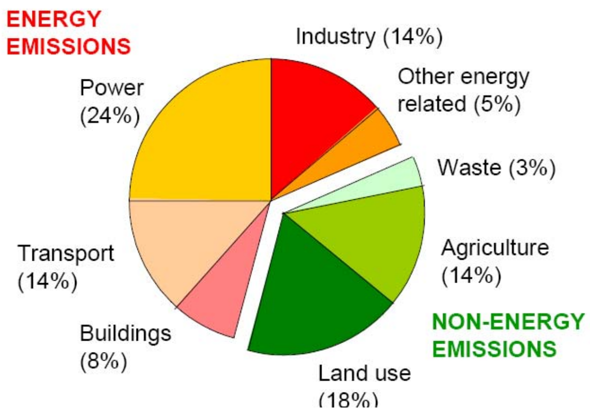

Figure 2 Total emissions in 2002, 42 Gt CO_2-eq from Stern review, based on data from World Resources Institute Climate Analysis Indicator Tools CAIT. (Energy emissions are mostly CO_2, non-energy emissions are CO_2 related to land use and non-CO_2 from agriculture and waste.)

In IEAs Energy Technology Perspective 2010 (ETP 2010) [40] two scenarios are used in order to predict future emissions of greenhouse gases. The Baseline scenario assume a roughly doubling of the energy related CO_2 emissions until 2050, in the same time the primary energy use will rise with 84%. The BLUE Map scenario is more optimistic when it comes to the possibilities to reduce CO_2 emissions and primary energy use. The scenario is based on a reduction of energy related CO_2 emissions by 50% and a reduction of primary energy by 32% until 2050. In Figure 3 emissions of CO_2 for the two scenarios are presented per sector.

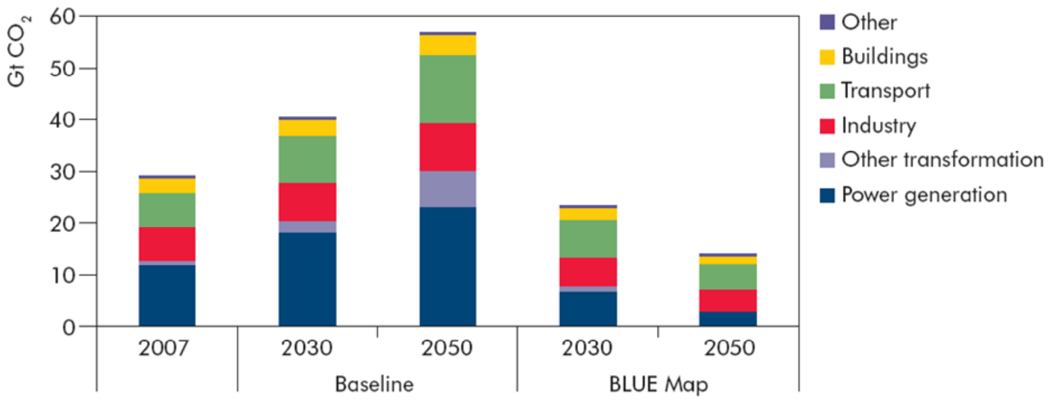

Figure 3. Development of global CO_2 emissions in Baseline and BLUE Map scenarios based on ETP 2010

The European Community (EU) has become aware of the increased energy use in the building sector and especially the use of non-renewable energy sources. 40 % of the energy consumption is related to the building sector. In order to reduce the dependency of non-renewable and also imported energy several new EU directives have been enforced on the subject - among others:

- DIRECTIVE 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings [1]
- Directive 2004/8/EC of the European Parliament and of the Council of 11 February 2004 on the promotion of cogeneration based on useful heat demand in the internal energy marked and amending directive 92/42/EEC [7]
- Commission Decision of 21 December 2006 establishing harmonized efficiency reference values for separate production of electricity and heat in application of Directive 2004/8/EC of the European Parliament and of the Council (notified under document number C(2006) 6817) [8]
- Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/.

- Subsequently new EU mandated standards like the EN 15316-series have been developed and implemented in the whole EU environment, which provides standardized calculation methods for energy efficiency.

The households and service sector in particular have increased the use of electric energy. For some of the countries a majority of the electricity is produced by fossil fuels and the CO_2 emissions have increased. Other countries applying electricity from nuclear or hydro-electric systems seems to have reduced their CO_2 emissions because they are considered to be CO_2-free in the IEA statistics.

On the other hand has the standard EN 15603:2007 *Energy performance of buildings – overall energy use and definition of energy ratings* [2], included CO_2 values for some energy carriers including hydro-electric power. In standards like the EN 15316-series *Heating systems in buildings – Method for calculation of system energy requirements and system efficiencies* [10] the same CO_2 values are used in order to calculate the energy efficiency. The revised EPBD [1] emphasize that the energy efficiency of a building shall be calculated by use of Primary Energy Factors (PEF) and CO_2 emission. Primary energy is energy that has not been subject to any conversion or transformation process. Use of primary energy factors takes into account the energy that are used from the extraction of the energy carrier and all of the losses until energy in desired form like heat, cold or electricity is delivered to the end user. A more detailed definition of PEF and CO_2 emission can be found in chapter 2.3.

This implies that a calculation of PEF and CO_2 emission coefficients also will be needed in the future energy certificates for buildings. Since the standard EN 15603 comprises of only 13 energy carriers it is difficult to calculate the energy efficiency i.e. actual primary energy use and CO_2 emission for a specific energy chain and therefore complicated to make a direct comparison between different energy chains.

An energy chain consists of all of the necessary steps of the chain from where the energy source is extracted until the energy (heat, cold or electricity) is delivered to the end user. Figure 4 shows a principal description of an energy chain. The end user represents the energy that is used in the building for different kind of services like heat, cooling electricity for different appliances. The energy source is the source from extraction like coal, oil, trees, water etc. The terminology energy carrier is not necessarily applied consistent. The energy carriers might change physical properties through the energy chain; wood might be the original energy source and then undergo different treatments like chopping, drying, before it ends up as pellets, where pellets eventually is used in the power plant. The energy carrier oil, on the other hand is usually referred to as oil even though it goes through different refinery processes.

The term energy carrier will subsequently be used to describe energy that is transported in different kind of shapes like oil, bio mass, pellets, water, steam or coal where the transportation of energy is the most relevant issue. The expression energy chain is used to emphasize that the whole chain is included, whereas the energy source is the origin, the “raw material” from where energy is produced.

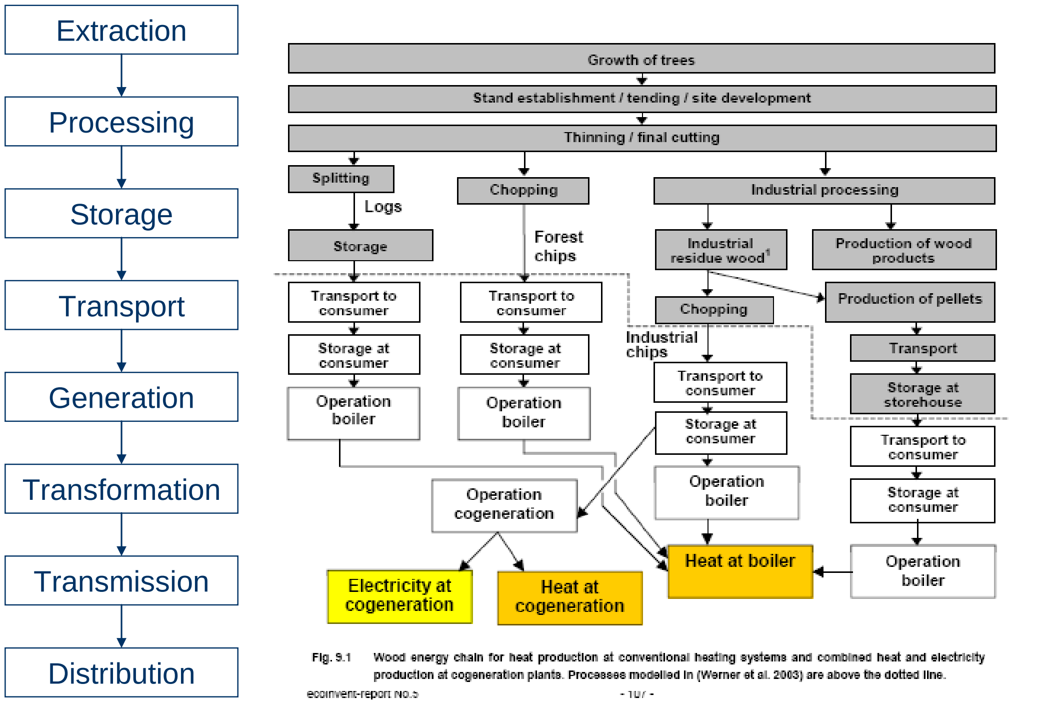

Figure 4 Left figure the principal description of an energy chain. Right figure simplified energy chain with bio mass as energy carrier and heat and electricity as output produced by a combined heat and power plant [11]

In this project a method for analysing the potential for efficiency measures related to production of district heat and cold to buildings was developed. This method is reliable and transparent and it enables the calculation of PEF and CO_2 emissions for different energy chains. This means that the method is based both on existing standards and regulations and future requirements. At the same time the method should enable ranking of different systems. The PEF and CO_2 coefficients from EN 15603 [2] are based on use of life cycle assessment (LCA) methods, hence the need for a new approach. Energy efficiency evaluations are usually based on direct energy and power efficiency, but the new method will have to take the whole energy chain including the infrastructure into account.

Chapter 2.3.1 will further describe the primary energy factor concept whilst chapter 2.2 describes LCA. The description and development of the method itself is described in chapter 8.

2.1.2 *The need for a compilation of research and experience within the area*

As described, above there is a large amount of experience and literature (standards, reports, etc) that have dealt with energy efficiencies and environmental impacts of DHC systems in one way or another. However, there seems to be a lack of compilation of all the results, data and methods that have been produced so far. Today, it is not an easy task to get a complete picture of this area. There seems to be a need for a clear and open description of the processes, efficiencies and methods that could be used to describe the potential of DHC systems in regards of primary energy usages and CO_2 emissions, two measures that become increasingly important, as pointed out in standards related to the Directive on energy performance of buildings [10]

2.2 Life cycle Assessment methodology

2.2.1 *Methods of Life cycle assessment*

Different methods have been and are being developed in order to compare the environmental impact of different products, processes and systems over its entire life cycle. Ecological footprint, embodied carbon footprint, carbon calculation, low carbon, 100% renewable and different phrases with the prefix green, for instance green labelling, are used to describe how environmentally friendly a product or a process is. The variety of methods and parameters causes confusion both among scientists, politicians, decision-makers and the public since they are all used at the same time and no formal link or conversion factor exists between the different methods. The most reliable and well-documented methods are based on Life Cycle Assessments (LCA) with a cradle to grave perspective.

2.2.2 *What is a LCA – The LCA framework*

A life cycle assessment is a systematic method to provide information on the environmental impact of a product from raw material to disposal, also called “an attempted overall evaluation of environmental impacts” [12].

The method was initially developed for products, but has lately gained broadened interest due to a need to describe different systems like energy chains and the comparison between different elements in the systems. During the 1990s a need for a systematic approach was obvious. A number of standards describing the method were developed, especially the EN ISO 14000-series. In 2006 the standards were revised and consist currently of the following standards:

- EN ISO 14040 Environmental management – Life cycle assessment – Principles and framework [13]
- EN ISO 14044, Life cycle assessment – Requirements and guidelines [14]

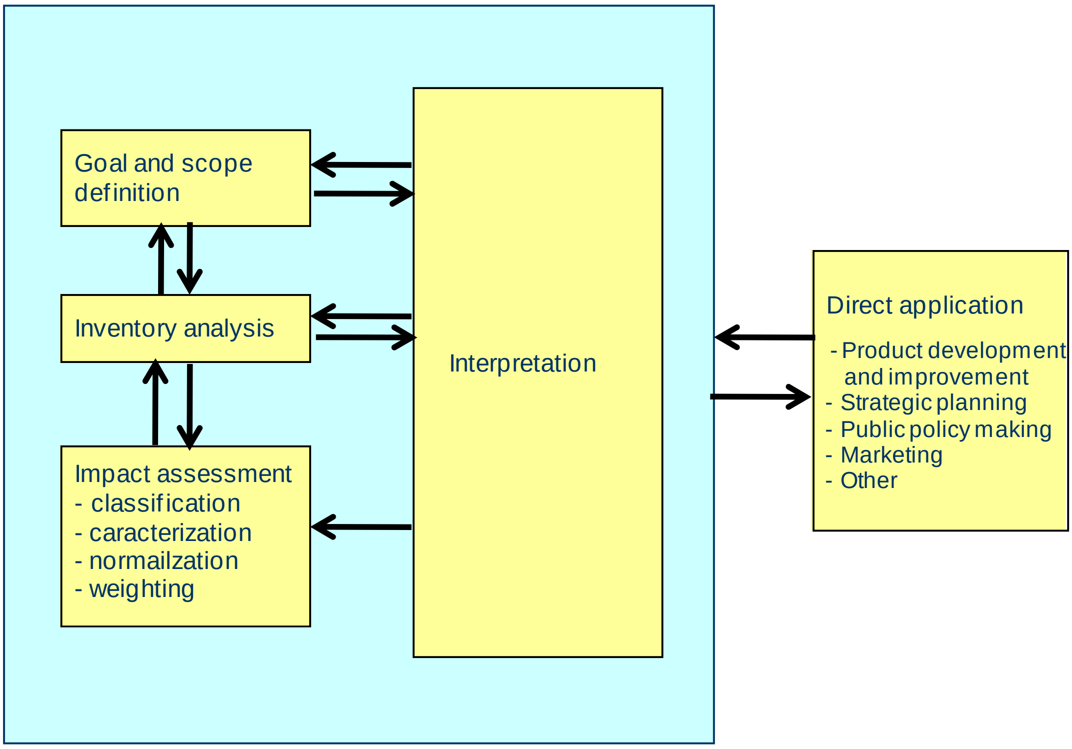

Figure 5 The different phases in a LCA [13]

As illustrated in Figure 5 an LCA consist of four different phases:

- Goal and scope definition
- Inventory analysis
- Impact assessment
- Interpretation

All of the four phases are essential in an LCA, the different phases are described in the following sections. The term assessment is not arbitrary chosen, since the developers of the method wanted to emphasise the difference between a simple calculation and an assessment.

2.2.3 *Goal and scope definition*

The goal and the scope are usually set by an iterative process between the LCA analysts (practitioner) and the commissioner.

According to EN ISO 14040 [13] the goal shall state the intended application, why the study shall be carried out, intended audience and how the results are to be applied. The methodology might differ whether the results are to be used for a stand-alone evaluation, in comparative assertions or if the main intention is to reveal environmental bottlenecks in the chain and/or compare improvements in the chain.

The EN ISO 14040 describes that the scope "... *should be sufficient well defined to ensure that the breadth, depth and detail of the study are compatible and sufficient to address the stated goal."*

During the iterative process of developing goal and scope the system, system boundary, functional unit, impact assessment method, assumptions, limitations, data quality, review and report format should be described.

It is important to show all of the steps that are included in the LCA. The process or system is therefore usually described by a general flowchart showing the whole life cycle of the product, process or system.

Precise definitions of the system boundaries are essential in order to be able to compare different studies. The system boundaries must delimit scope of the LCA. There are at least three different types of boundaries to consider:

- The physical system in relation to the surroundings. This implies a clarification on where the system starts (cradle) and ends (grave) and what is included; the most comprehensive systems considers the whole chain from cradle to grave. Other approaches might be cradle-to-gate where the production is included but not use and disposal.
- A geographical boundary exists for several of the parameters such as the origin of the energy carriers and and the environmental impact from different emissions in different areas.
- The time span is also important, i.e. whether the LCA is supposed to be a retrospective study or if it is to take possible impacts for e.g. 50 or 100 years ahead into account. The most applied Global Warming Index's (GWI) is either based on a 20, 100 or 500 year impact evaluation, and the GWI shows how fast the emissions are removed from the atmosphere.

The results of an LCA are calculated based on the functional unit, a quantitative term describing the performance characteristics of the product/system which the inputs and outputs can be related to. When an LCA for an energy chain providing heat and electricity using different energy carriers are carried out the natural functional units are kWh electricity and kWh heat delivered to the end user. The definition of the functional unit is one of the primary tasks to be performed in the LCA and must be carried out with uttermost care. As an example, the results of an energy chain might differ significantly if the functional unit is a unit energy produced at a power plant instead of a unit energy delivered to the end user.

Systems producing more than one product or services based on the same raw materials have to share the environmental burden between the different products, also called allocation. Some products have a natural division, but others like electricity and heat produced in a CHP have been treated differently in different studies depending on the goal of the LCA. The use of waste (municipal, different kinds of wood residues, industrial) as energy carrier have also been treated in various ways, the environmental burdens must be divided in an appropriate manner. There are no LCA-standards describing a specific allocation method, but in EN 15316-4-5 [10] it is stated that the power bonus method should be used for allocations between electricity and heat produced in a CHP-plant. (See also chapter 3 for more detailed information about allocation methods).

The environmental impact of the system/product can be described by use of different parameters. Emissions to air can be characterized by the specific emission in gram of a substance per functional unit e.g. gram per kWh electricity or heat delivered to the end user. The possible variety of parameters and their direct and indirect environmental effect implies difficulties when a ranking and comparison is needed. Several impact categories are therefore developed in order to restrict the number of parameters to be studied. The most common used are Embodied primary energy use, Acidification Potential, Global Warming Potential, Human Health Respiratory Effects Potential, Ozone Depletion Potential, Smog Potential, Aquatic Eutrophication Potential and

Weighted Resource Use. See also chapter 2.3 for more information.

Most of the impact categories have been developed on a scientific basis, but values might differ from region to region and must be used with caution. The CML approach that originated from Centre of Environmental Science at Leiden University in The Netherlands and their *Guide on Environmental Life Cycle Assessment methodology* have a detailed description of the calculation and what the different impact categories includes [15]. Several LCI (Life Cycle Impact) databases exist, some of them with focus on specific materials other focus on different processes and systems. The largest and mostly well known LCI database is probably Ecoinvent, a Swiss database including information of more than 1200 different energy systems [16].

A major part of the LCA work is the collection of data. A detailed description of the data characteristics/data quality requirements must be decided on during the goal and scope phase since most LCA has to rely on data originated from different sources. In the goal phase the difference between marginal versus average data must be clarified and if the study shall be based on actual and specific data or if average data are satisfying.

The lack of detailed data often introduces a need for average data and cut-offs. Cut-offs means rules describing how parameters that have minor impact can be neglected or how to treat data that are time consuming or impossible to gather. Required specific data sometimes have to be replaced with generic values and subsequently adjusted and corrected in order to reduce the uncertainty and provide consistent data.

When an LCA is carried out several assumptions and limitations affect the final result of the study. It is essential that the assumptions and limitations are thoroughly described since this influence the quality of the study. This includes a description of the data quality, reliability and especially the restrictions on system border and whether the data are generic or specific for the actual product/system.

After an LCA has been performed the study has to be reviewed, either the LCA team or a third party. The report format is usually defined in the first phase because it might affect the choice of inventory groups and detailing level but also adjustments according to the intended users needs.

2.2.4 *Inventory analysis*

The inventory analysis is often the most time-consuming part of an LCA and consists of three phases:

- Data collection
- Data calculation
- Allocation of flows and releases

The inventory analysis is the accounting phase of the inputs (e.g. energy carriers) and outputs (e.g. emissions) of the system based on the flow chart developed in the goal and scope phase. The availability of data varies and for some simple systems and products quantitative data easily can be collected, but for complex systems with multi-input and/or multi-output processes an allocation of environmental impact between different inputs and outputs has to be carried out. (See also chapter 3). The allocation method determines the distribution of used energy resources and environmental impact between the products produced or services provided. An LCA should include a description of the allocation method used.

2.2.5 *Impact assessment*

Impact assessment is an attempt to describe both the immediate, long term and potential environmental consequences related to the inputs and outputs of the described system. A substance (e.g. SO_2) might be emitted to air in gas phase and later as acid rain to the ecosystem locally and to other regions. Since the emissions from a system might consist of numerous substances different methods have been developed in order to aggregate the output i.e. characterize the environmental impact.

The most well-known characterization factor is the Global Warming Potential (GWP) and the appurtenant global warming index (GWI) developed by the Intergovernmental Panel on Climate

Change (IPPC) to provide information on different greenhouse gasses. The global warming potential describes the cumulative effect of a gas over a time horizon, compared to that of CO_2. By this method the global warming effects of different emissions and gases are comparable, which is an important measure when different processes and products are ranked and categorized. Other groups and categories are also developed in order to show other environmental impacts. The most used categories are:

- Embodied primary energy use (Energy Consumption)
- Acidification Potential
- Global Warming Potential
- Human Health Respiratory Effects Potential
- Ozone Depletion Potential
- Smog Potential
- Aquatic Eutrophication Potential
- Weighted Resource Use (land use, water, non renewable materials)

Even though the same categories are used, different compounds might have different impact factor caused by use of different weighting factors and orientation of the study. CML 2002, Ecoindicator'99, Ecological scarcity (1997), EIDP'97, Environmental Design of industrial products, EPS 2000 (environmental priority strategies in product development), Impact 2002+ and IPPC 2001 (Climate change) are commonly used methods. Some of the methods are damage oriented, others are problem or midpoint oriented, since the different methods have different approach to the evaluation and estimation on environmental impact. Usually an LCI consists of the characterization factor like GWP in relation to CO_2, a normalized factor based on the characterization factor divided on the total sum flows, and then a weighting factor that is used to enable summation and aggregation of different impact categories. Each of the above mentioned methods have their own characterization, normalizing, weighting and eventually total impact factors.

In a comparison [36] the environmental impact for NO_X compared with CO_2 varies from 0.524 to 737 depending on chosen method. The difference in impact factor is not constant, but varies depending on substance. This implies that it is not possible to mix gathered data from different LCI or LCA databases without prudence, the correct weighting factors have to be applied.

At present several LCA and LCI databases exist, some of them include information on the environmental impact related to different compounds, materials, transportation, energy chains, energy carriers and can provide a LCA on your own complex systems. Other databases are developed for a specific purpose, e.g. the metallurgical (aluminium) industry, and often have an own data format not compatible with other LCI databases. Several databases also seem to have shut down during the last 5-10 years. The development of a comprehensive LCA database is expensive and time-consuming and needs continuous revision.
Table 1 includes an overview of some of the most relevant databases.

In 2002, SP developed an internet tool, EFFem, which enables a comparison between different heating systems' environmental impact. EFFem is based on life cycle inventories stating the emissions to the air for a number of common heating systems in Swedish houses. The tool is used by energy advisors as well we private house owners. In addition, the Swedish building and energy sectors have shown great interests in the tool. Among others, the Swedish District Heating Association and Elforsk, the Swedish Electrical Utilities R&D Company, have financed the development of EFFem. The tool has also been demonstrated internationally, with great response and interest.

The tool is still in operation on http://www.effektiv.org/ (only in Swedish) and has approximately 100 visitors daily. EFFem was updated with new data in 2008.

Table 1. Overview of different LCI and LCA databases and LCA tools

Database	**Short information /area**	**Advantages**	**Disadvantages**
Ecoinvent	Energy systems, materials, transportation, fuel, primary European data, continuation of ETH-ESU 96 database Mainly database, usually used as database together with a calculation tool like SimaPro, Gabi etc.	>1200 energy systems Background for EN 15603 PEF and CO2 values Selectable output category types	Need for other tools to provide LCA (SimaPro, Gabi etc.)
European Reference Life Cycle Database (ELCD)	Mainly database. European scope inventory data sets, key materials, energy carriers, transport, waste management	Free of charge, a possible future	Few datasets, new database, limited possibility to edit LCA datasets, not fully developed
Envest	UK		
US LCI Database project	Public/private research partnership database common materials and processes		Primary developed for US
CML-IA	Impact characterisation factors mentioned in CML, EPS, Eco-indicator 99	Free download version, input to CMCLCS	Only impact assessment
CMCLCA Chain Management by Life Cycle Assessment	Developed in Centre of Environmental Science at Leiden University	Can load numeral processes, allows alteration in allocation, based on matrixes, free of charge for non-commercial use	Difficult user interface, no help desk Last updated in 2004 according their web-site
Franklin US 98	US database, some materials and fuels	Has specific US data set	Old database, limited set of materials and fuels
Idemat	Specific material database	Can be used together with other databases	Lacks detailed upstream calculations
ETH-ESU 96	Developed by ETH and consultant ESU	Detailed information on energy conversion technologies , cheaper than Ecoinvent	From 1996
Gabi	Calculation tool, the tool exchanges data from different databases (materials, Ecoinvent	Good user interface	More expensive than SimaPro, no server versions
SimaPro	Calculation tool, the tool exchanges data from different databases (materials, Ecoinvent)	Applicable user interface	Multi-user and server versions, free student versions
Athena	Building oriented North America		
EFFem	Internet based tool for evaluate environmental impact of different heating alternatives. Developed by SP	Easy to compare different alternatives	Mainly for heating of buildings.

In addition to the inventory databases different LCA tools have been developed, some of them are able to use data directly from several LCI databases other need conversion to be able to utilize data from different sources.
In order to make the calculation model for this study transparent and to make it easy to vary relevant parameters easily it was decided to build the calculation model in Excel. A benefit of using Excel is that it is a well-known program available at most computers. Thereby no special program is needed in order to run the model. A review of the LCA-tools on the market shows that both SimaPro and Gabi would have been appropriate tools. Since they are specially developed LCA-tools they are made to handle and keep track of a lot of data. However the number of flows related to emissions of greenhouse gases and use of primary energy in this project were considered to be possible to manage in Excel.

Ecoinvent [16] is the basis for the PEF and CO2 values in EN 15603 [2] and includes at present the most extensive study of energy systems consisting of more than 1200 analyses. The newly developed European Reference Life Cycle Database (ELCD) [38] includes only a limited number of studies and it is neither compatible with Ecoinvent nor some of the material databases. The other databases might have a better material database, but they lack the extended energy approach. By use of Ecoinvent it is possible to compare results from the model development in this study with other generic studies of the energy systems in Europe. In the further study the major part of the calculations therefore is performed by use of the database Ecoinvent.

2.3 Primary Energy and Global warming

2.3.1 *The primary energy concept*

The Primary Energy Concept is a new method to provide information on primary energy efficiency and the environmental impact of different energy sources, energy conversion processes and energy transport systems [91] [2]. The method uses Primary Energy Factors (PEF) when calculating the amount of actually consumed energy or estimated to be consumed in a building. The method makes it possible to compare different energy chains consisting of several energy carriers by simply using the respective PEF values per delivered unit energy from each energy chain. The CO_2 emissions can also be a part of the calculation of the energy performance of buildings.

Previously net energy savings in the buildings, counted as kWh, and not the environmental impact were the main focus when choosing and ranking different energy solutions.

In the EN standards EN 15603 and EN 15316-series a slightly different approach has been chosen. The primary energy rating of the whole energy chain is calculated where all of the losses are included. At the same time an advanced calculation of the energy needed in a building is performed. The primary energy factors are determined by methods similar to LCA methodology, where the energy needed to extract, process, store, transport, generate, distribute etc. are included in the calculation. New terms and definitions are developed and provided in the different standards, the most important parameters are described in the section below.

2.3.2 *Energy chains*

Figure 4 shows the principal description of an energy chain, where the left figure is a generic figure. Some energy chains include all steps like energy produced by coal fired power plant systems, but other, like heat from municipal waste combustion, usually lack the extraction phase. Other systems might consist of two or more parallel phases due to use of several energy carriers.

During the process from extraction of the energy carrier until energy (heat, cold or electricity) is delivered to the end-user parts of the energy is lost in the process. The energy lost, used or consumed in the different stages varies for the different chains. After extraction some of the energy carriers have to be processed in order to be transported e.g. to the power plant or the heat generation. The transportation phase may vary significantly even with the same energy chain. Wood for example might be produced locally and as a residue from the woodworking industry or transported long distances by boat or truck. Some of the energy carriers like oil might be stored for a period of time, whilst energy from windmills normally is used immediately. The energy losses from generation and transformation processes often depend on both size and load-performance-relations and have thereby a major influence on energy efficiency and emissions of greenhouse gases. The type of energy distribution system and energy intensity is also important with regard to energy loss.

2.3.3 *Principles for calculating primary energy factor*

Definitions

The various terms applied in the Primary Energy Concept are defined in different EN standards. In this document only the most important are described. Further details are available in e.g. EN 15603 Energy Performance of buildings - Overall energy use and definition of energy ratings [2].

<u>Primary energy</u>

According to EN 15603 primary energy is; energy that has not been subject to any conversion or transformation process.

<u>Total Primary energy factor</u>

The total primary energy factor is the sum of non-renewable and renewable primary energy divided by delivered energy for a specific energy carrier. This means energy required to supply one unit of delivered energy included the energy needed for extraction, processing, storage, transport, generation, transformation, transmission, distribution and any other operation necessary for delivery to the building where the energy will be used. Primary energy factor shall therefore include all of the losses.

Non-renewable primary energy factor
Non-renewable primary energy factor is non-renewable primary energy including energy needed for extraction, processing etc. divided by delivered energy.

Exported energy
Exported energy is energy exported through the system boundary and used outside the boundary of the system that is considered. The system boundaries in this project is described in chapter 1.3

Net delivered energy
Net delivered energy is delivered energy from the boundaries of the actual system.

2.3.4 *Primary energy factors for fuels*

The PEF shall include energy used to extract, transport the energy carrier from production site to utilization site and processing, generation, transmission, distribution i.e. energy needed to deliver energy to a building. In addition PEF might include energy used to build transformation units, build the transportation system and removal of wastes and demolition.

Primary energy use for a system is calculated according to *Eq. 1*, it should be noticed that exported energy is subtracted from the delivered primary energy value to the system.

$$E_P = \sum\left(E_{del,i} * f_{P,del,i}\right) - \sum\left(E_{exp,i} * f_{P,exp,i}\right) \quad \textit{Eq. 1}$$

Where

E_P	Primary energy input to the system
$E_{del,\,i}$	Delivered energy, energy carrier i
$f_{P,del,i}$	Primary energy factor, delivered energy carrier i
$E_{exp,\,i}$	Exported energy, energy carrier i
$f_{P,exp,i}$	Primary energy factor, exported energy carrier i

2.3.5 *Principles for calculation of CO_2-equvivalent*

Global warming potential (GWP) is a method developed to provide information on different greenhouse gases. The global warming potential describes the cumulative effect of a gas over a time horizon (usually 20, 50 or 100 years), compared to that of CO_2. By this method the e.g. environmental effects of different pollutants and gases are comparable, which is an important measure when different processes and products are ranked and categorized. GWP are provided from the Intergovernmental Panel on Climate Change (IPCC) for carbon dioxide, methane, nitrous oxide, HFCs, PFCs and SF6 [39]. The GWP is defined as the ratio of the time-integrated radioactive forcing from the instantaneous release of 1 kg of a trace substance relative to that of 1 kg of a reference gas.

$$GWP(x) = \frac{\int_0^{TH} a_x \cdot [x(t)]\, dt}{\int_0^{TH} a_r \cdot [r(t)]\, dt} \quad \textit{Eq. 2}$$

The CO_2 emission coefficient is the amount of CO_2 emitted to the atmosphere per unit of delivered energy. The CO_2 emission coefficient quantifies the mass of CO_2 per kWh that is emitted to the atmosphere by the delivered energy, using the same principles as PEF. According to EN 15603 the coefficient might also include emissions of other greenhouse gases, but this has to be implemented at a national level. In the foundation of the standard the emissions seem to be partly included. This lack of information should be considered when interpreting the results.

CO_2 emissions are defined differently in literature, either as direct CO_2 emission from a combustion process or as CO_2 emitted during a whole lifecycle translated to CO_2 equivalents. Several gases will affect the global warming, and the original comparison of the impact is carried out by use of the GWP of each gas as described in chapter 2.2. Instead of using the GWP the term CO_2 equivalents are introduced, which represents the amount of CO_2 having the same potential as a certain compound. This means that the impact of for example fuels emitting different gasses, the CO_2 equivalent will constitute of the total sum of CO_2 equivalents for all compounds for the so-called greenhouse gases. Other gases might also be described in terms of CO_2 equivalents. In this project the term CO_2 emission, CO_2 emission coefficient and CO_2 values will represent CO_2 equivalents.

$$m_{CO2} = \sum(E_{del,i} * K_{del,i}) - \sum(E_{exp,i} * K_{exp,i}) \qquad \text{Eq. 3}$$

Where

m_{CO2}	emitted mass of CO_2
$K_{del,i}$	CO_2 emission coefficient delivered energy carrier i
$K_{exp,i}$	CO_2 emission coefficient exported energy carrier i

The emitted mass of CO_2 caused by exported energy outside the system border is also subtracted from the total emitted masses cf. Eq. 3.

2.4 Choice of LCA methods

Different LCA tools might not use the same characterization factors and weighting approaches. The midpoint strategy is commonly used in LCA studies and focuses on impacts in the near future like the IPCCs GWP100, which is applied in CML2, CML2001. On the other side is the endpoint method which tries to describe the impact in the distant future like 500 years from now. The ReCiPe method is based on a combination of short term (70%) and long term impact (30%). This implies that LCA studies carried out by different methods usually will differ and the results are not directly comparable.

The term CO_2 equivalent is not consistent. Some studies include only CO_2 that is directly emitted for instance from a combustion process, others use the IPCC method consisting of CO_2 and four gasses and their appurtenant GWP, and other use a broader perspective based on the IPCC values for even more gases like the CML and CML2001 method. In the ReCiPe method even more gases are included.

In this study the GWP100 midpoint strategy is used for calculation of CO_2 equivalents, whilst primary energy factors (PEF) are calculated by use of cumulative energy demand based on use of the database Ecoinvent.

2.5 Reflections about the study in relation to general methodology and standards

In the project proposal use of standardized PEF and CO_2 equivalents for fuel were planned to be the basis for model development and calculation of PEF and CO_2 for different energy chains. A thorough review of the background data related to Annex E in EN 15603 [2] shows that information about the systems boundaries are missing. Additional emissions related to both fuel handling and combustion are included in the data. In order to be able to evaluate the impact from the different phases in the project it is a need to have separate values for fuel handling and combustion. Thereby the project decided to develop PEF and CO_2-eq values for the fuel handling phase based on information from the Ecoinvent database. Combustion data is based on data from actual plants.

We have chosen to consistently use Ecoinvent as the database for PEF and CO_2 equivalents calculations in order to reduce the uncertainty caused by different system boundaries. The use of different terms of CO_2 has been avoided by use of IPCC CO_2 equivalents.

3 Allocation methods

In a combined heat and power plant both district heating and electricity is produced. In order to calculate the energy use and the environmental impact related to the heat and to the electricity production, an allocation of the emissions and use of resources between the heat and electricity is needed. There are a number of different allocation methods today, with varying complexity. The allocation methods might also have been developed for different purposes. This project also follows the stepwise recommendations regarding allocation procedures in ISO 14044 [14]

3.1 Energy method

The energy method is a method rather simple to use. In the method the emissions and recourses are allocated per kWh energy produced, independent of if heat or power is produced. If a CHP process produces 65 units of heat and 35 units of electricity, 65% of the emissions will be allocated to the heat production and 35% to the electricity production. Thereby the emissions allocated to the heat production will be the same as if the heat was produced in a heat plant. The emissions allocated to the power production on the other hand will be a smaller part of the emissions compared to if the power was produced in a power only plant. With this method the power production will have all benefits related to the CHP production [17]. This method does not take any exergy of energy quality aspects into account, allocating lower impact to electricity than the other methods.

$$\text{Allocation factor}_{\text{heat}} = \frac{\text{Heat}_{\text{prod}}}{\text{Heat}_{\text{prod}} + \text{Elec}_{\text{prod}}}$$

Eq.4

3.2 Alternative generation method

In the Alternative generation method both the heat and the power production benefits from the use of a CHP process. The method allocates emissions and resources to the heat and power production in proportion to the fuel needed to produce the same amount of heat or power in separate plants [17]. These alternative plants use the same fuel as the CHP plant. The method was originally developed by the Finnish district heating association and exists in different versions with different complexity [48]. Below one example is presented.

Example Alternative generation method

A CHP plant consumes 100 units of energy while producing 30 units of electricity and 60 units of heat.

Alternative production in two separate plants, heat only plant and condensing plant, has the following efficiency:

Power production: η_{elec}= 0.4

Heat production: η_{heat}=0.9

Thereby the fuel needed for heat and power production in alternative plants would be:

Power production: 30/0.4=75

Heat production: 60/0.9=67

Alternative production has needed a fuel consumption of 75+67= 142 units to produce the same amount of heat and power.

The allocation of heat and power will be based on the amount of fuels needed if separate production plants would have been used:

Allocation electricity 75/142= 53%

Allocation heat 67/142= 47%

Following the example the allocation factor for heat production will be expressed as:

$$\text{Allocation factor}_{\text{heat}} = \frac{\frac{\text{Heat}_{\text{prod\_CHP}}}{\eta_{\text{alt\_heat\_prod}}}}{\frac{\text{Heat}_{\text{prod\_CHP}}}{\eta_{\text{alt\_heat\_prod}}} + \frac{\text{Elec}_{\text{prod\_CHP}}}{\eta_{\text{alt\_elec\_prod}}}}$$ *Eq. 5*

3.3 Power bonus method

With the power bonus method the primary energy allocated to the electricity produced in the CHP-plant will be equal to the primary energy that would have been used to produce the electricity in an alternative production, usually the electricity that will be replaced by the electricity produced in the CHP-plant (the marginal production). The remaining primary energy used by the CHP-plant will be allocated to the heat production. This value can be negative if the electricity efficiency is high enough in the CHP-plant, but due to the standard EN 15613-4-5 [10] negative values should be replaced by zero. The allocation of primary energy expressed with equations will be:

$$\text{PE}_{\text{elec}} = \text{PE}_{\text{alt\_elec\_prod}}$$ *Eq. 6*

$$\text{PE}_{\text{heat}} = \text{PE}_{\text{total\_CHP}} - \text{PE}_{\text{alt\_elec\_prod}}$$ *Eq. 7*

Thereby the allocation factor for heat will be:

$$\text{Allocation factor}_{\text{heat}} = 1 - \frac{\text{PE}_{\text{alt\_elec\_prod}}}{\text{PE}_{\text{total\_CHP}}}$$ *Eq. 8*

The total primary energy used by the CHP-plant includes all energy used in the production of heat and electricity. This includes the primary energy related to fuel handling and combustion as well as primary energy needed for production of additive, handling of ashes, construction and dismantling of the CHP-plant etc.

This is in accordance with EN15316-4-5 [10] which states the PEF for district heating produced in a CHP-plant to be:

$$PEF_{DH} = \frac{\sum_i E_{F,i} * PEF_{CHP} - E_{el,CHP} * PEF_{\text{elec}}}{\sum_j Q_{del,j}}$$ *Eq. 9*

Where

$E_{F,i}$	Fuel input to CHP plant
$E_{el, CHP}$	Electricity production of CHP
PEF_{CHP}	Primary energy factor fuel for CHP
PEF_{elec}	Primary energy factor electricity
$Q_{del, j}$	Heat energy consumption (measured at the primary side of the buildings substation)

Eq. 9 includes the production in the CHP-plant, while the standard, Eq. 10, also includes the distribution of the district heating. The standard also includes a version on how to calculate the primary energy factor based on design parameters:

$$PEF_{DH} = \frac{(1+\sigma)\beta}{\eta_{hn} * \eta_{CHP}} * PEF_{CHP} + \frac{1-\beta}{\eta_{hn} * \eta_{T,gen}} PEF_{T,gen} - \frac{\sigma\beta}{\eta_{hn}} PEF_{elec}$$ *Eq. 10*

This version is not as general as Eq. 9. Eq. 10 above includes use of primary energy related to fuel handling, combustion and distribution. Additional use of primary energy needed for production of additive, construction and dismantling of plant and grid etc. are not included in the definition. This study follows the more general definition and includes all use of primary energy.

Where

PEF_{DH}	Primary energy factor district heating network
PEF_{CHP}	Primary energy factor fuel for CHP
$PEF_{T, gen}$	Primary energy factor fuel for heat only

PEF_{elec}	Primary energy factor electricity
β	Heat from CHP/heat total
σ	prod. power/ prod. heat (also known as α)
η_{hn}	Efficiency distribution network
η_{CHP}	Efficiency co-generation module
$\eta_{T,gen}$	Efficiency heat only production

The power bonus method is developed in order to promote cogeneration of heat and power but also to increase use of renewable fuels in the production of electricity. Its aim is to illustrate the changes from a global perspective. To answer the question: "How is the global energy usage changed if this CHP plant is built?"

According to the standard negative values for the calculated primary energy factors for district heating should be set to zero [10]. Thereby a system expansion is partly avoided for CHP-plants with high power to heat ratio. All emissions and energy use from the CHP-plant will be allocated to the electricity production, but the total effects of how the electricity system is effected will not be included. In this project we have decided to include the system expansion and allow negative values in order to see how the total system is affected. The standard doesn't include how to calculate on greenhouse gases. In this project we have chosen to present negative values for both CO_2-eq and PEF.

3.4 Exergy method

In the exergy method the emissions and recourses are allocated in relation to the exergy content of the produced energy. Exergy can be described as potential work and the exergy content decreases along the energy chain. The exergy content of heat, electricity and fuels are characterised by their Carnot-factors η_c [76]. The amount of emissions and resources allocated to heat can be calculated as below.

$$Exergy_{elec} = Energy_{elec} \quad \text{Eq. 11}$$

$$Exergy_{heat} = \frac{T - T_0}{T} Q \quad \text{Eq. 12}$$

Where

T	Temperature of the medium
T_0	Ambient temperature
Q	Heat energy

$$Allocation\_factor_{heat} = \frac{Exergy_{heat}}{Exergy_{heat} + Exergy_{elec}} \quad \text{Eq. 13}$$

An alternative description of the exergy method is that the fuel is allocated as the amount of fuel used to utilize the heat for the use in district heating compared to total amount of fuel. That means the extra fuel used as a consequence of utilizing the heat. Therefore the heat is only charged the extra fuel needed in order to make the heat production [77].

3.5 200% method

In the allocation method the heat and power production share the benefits from the CHP-production. The method assumes that the heat is produced with the fixed efficiency [77]. This fixed efficiency is chosen as a general average between the energy and the exergy methods. The heat is charged the fuel due to the following equation:

$$allocation\_factor_{heat} = \frac{Heat_{prod}}{2 * Fuel_{in}} \quad \text{Eq. 14}$$

With this allocation method it looks like the heat has been produced with an efficiency of 200%. The method is well accepted in Denmark where there are both minor CHP-plants that primary produce for heat and larger CHP-plant that primary produce for power.

3.6 Economic allocation

In the economic value method the emissions and resources are allocated in relation to the economical value of the products produced. The method makes it possible to allocate emissions for different kind of products with little in common and when it is difficult to find an allocation method based on physical data. The drawback for the method is that prices can differ both over time and from country to country.

$$Allocation\ factor_{heat} = \frac{Economical\ value_{prod\_heat}}{Economical\ value_{prod\_heat} + Economical\ value_{prod\_elec}} \quad \textit{Eq. 15}$$

3.7 Allocation according to PAS 2050

PAS 2050 [78] is a British publically available specification for the assessment of the life cycle greenhouse gas emissions of goods and services. The PAS 2050 specifies how to allocate in a CHP plant. The allocation method is similar to the 200% method but not identical.

$$Allocation\ factor_{heat} = \frac{Heat_{prod}}{n * Elec_{prod} + Heat_{prod}} \quad \textit{Eq. 16}$$

Where n is 2 for gas-turbine-based CHP systems and 2.5 for boiler-based CHP systems.

3.8 Discussion choice of allocation method

The choice of allocation method will have a great impact on the final result. Therefore it is important to carefully analyse the different methods and how they will influence the result. The choice of method in the study has been made using two main criteria:

1. The allocation method should be suitable for its purpose and reflect physically the situation in the plant and the energy system.
2. The allocation method should be well known and accepted both by the energy and LCA society.

Table 2. Evaluation allocation methods

Allocation method	Criteria 1 Suitable, reflects the physical situation	Criteria 2 Well known and accepted
Energy method	(X)	(X)
Alternative generation method	X	X
Power bonus method	X	X
Exergy method	X	
200% method	X	
Economic method		X
PAS 2050 method	X	

In Table 2 the evaluation of the allocation methods are summarised. The evaluation shows that two different allocation methods are mainly used for allocations related to CHP-plants, namely the alternative generation method and the power bonus method. Also the economic method is well known and accepted for LCA, but mainly for allocation of products with little in common which makes it difficult to base the allocation on physical data.

The energy method is easy to use and is therefore used in some studies, but other allocation methods reflect the physical situation better. The Exergy method is based on physical data for heat and power but is not that common, an example where exergy is used for allocations in CHP-plants is the LCA database Ecoinvent [16]. Also the 200% method is rarely used outside Denmark but reflects a realistic physical situation. The PAS 2050 method is similar to the 200% method. The PAS 2050 document is also well known in the LCA society, but there have been few implementations of the allocation method.

Two different perspectives can be identified, the marginal and the average perspective. The evaluation shows that depending on your perspective two different allocation methods will be used.

3.8.1 *Marginal perspective*

The marginal production is the technology/fuel that is the one that will be affected if the consumption of heat or electricity is changed. The marginal perspective is suitable for decision making or to study changes in a system. A typical example is the question: What production will be affected if you turn out the light? Or what will be the environmental effects of heating a new residential area? Normally the marginal technology is the technology with highest production cost. The fuel and technology on the margin can be discussed. In this project coal power plants are considered to be on the margin for electricity production. Data for the electricity will be based on EN 15603 [2] Annex E, "Electricity from coal power plants" with PEF 4.05 and CO_2-eq 1340 g/kWh.

For the marginal perspective the power bonus allocation method (section 3.3) has been chosen. The method is commonly used and recommended for allocations in CHP-plants in the standard EN 15316-4-5:2007 [10]. The method is also recommended in the inquiry SOU 2008:25 [17] ordered by the Swedish government. The method is developed for studies focusing on the effects on the energy system. The method, in the way this study have chosen to use the method, makes a system expansion and reflects how a local change in the energy system will influence the use of energy and emission related to the system as a total. The LCA standard, ISO 14044 [14], is generally recommending system expansions in order to avoid allocations. In the power bonus method you are going half the way, making a systems expansion but it still ends up with an allocation between heat and electricity.

The power bonus method is developed for a marginal perspective. Using the method with an average perspective for an electricity system based on a large part of renewable fuels leads to large changes in the allocation factors compared to the marginal perspective. All other allocation methods are independent of if a marginal or an average perspective is used and can be used for both.

In Figure 6 the effect of the allocation of greenhouse gas emissions using the power bonus method is compared for a natural gas CHP plant located in Sweden. The electricity produced on the margin is based on coal power plants emitting 1340 g CO_2/kWh [2]. The CO_2 emissions for the average production are 34 g CO_2/kWh and are based on the production mixture used for electricity production in Sweden 2006 [19] (The Swedish production mix for electricity is manly based on water and nuclear power). Note that different data sources have been used for the two alternatives, differences in the system borders etc. might occur. Using a marginal perspective gives that -98% of the emissions from the plant should be allocated to the heat production while for an average scenario 95% of the emission should be allocated to heat production.

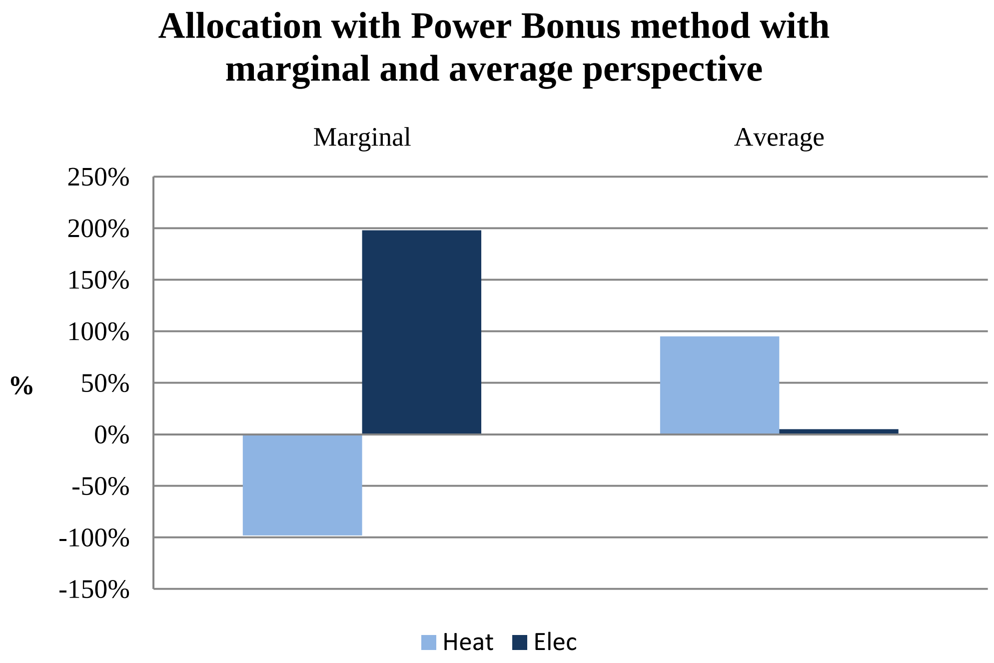

Figure 6. Comparison of allocation with the Power bonus method in a natural gas CHP plant in Sweden based on marginal and average perspective

3.8.2 *Average perspective*

The average perspective is based on average data, normally on a yearly basis, for example showing the average emissions from a plant. This perspective is often used for book keeping purposes, or has an historical view. A typical question where an average perspective often is used is: How much greenhouse gases has my consumption of district heating caused this year? Or how many percent of the greenhouse gases within EU are related to the district heating sector?

For the average perspective the alternative generation method (See chapter 3.2) is chosen for allocations. Using the alternative generation method the emissions from the plant will be divided into two parts for heat and electricity without making any system expansion and thereby the rest of the energy system is not taken into account. The Alternative generation method is used by the international Environmental Product Declaration (EPD) system [48].Another example is the internet based calculation tool EFFem [19], which uses the Alternative generation method.

4 Description of existing process chains and data collection

4.1 Fuels

4.1.1 *Fuel handling*

The fuel handling step is a simplified description of a number of processes that differ from fuel to fuel but also within the same fuel. It summarises emission and energy use from extraction via processing, storage and transports until the fuel is delivered to the plant. Handling processes, transport distances etc. will differ from one source of fuel to another. Data for fuel handling used in the study is taken from Berners study *Primary Energy Efficiency and District heating* [92] based on Ecoinvent [16] (summarised in Table 3). For waste see chapter 4.1.4

Table 3. Data for fuel handling

Fuel	Primary energy (kWh/ kWh fuel)	CO_2-eq (g CO_2-eq/ kWh fuel)
Natural gas	1,05	37
Fuel oil	1,34	45
Antracite	1,06	38
Wood chips	1,19	9
Waste	1.00	0

4.1.2 *Combustion*

During the combustion phase emissions of three greenhouse gases (carbon dioxide (fossil), methane and nitrous oxide), will be taken into account. The amount of each gas emitted during combustion is based on official Swedish national data from the Swedish Environmental Protection Agency [41] and are used for reporting to the UN Climate Convention. The exception is the CO_2-emissions from waste combustion. The data source for these values is the report *CO_2 utsläpp från svensk avfallsförbränning* written by the Swedish company Profu [45]. The figures listed in Table 4 are used in this study.

Table 4. Emission factors for fuels

Fuel	Emission factors (g/kWh)		
	CO_2	CH_4	N_2O
Natural gas	203	0.004	0.007
Fuel oil 2-5	274	0.007	0.018
Anthracite	335	0.007	0.072
Wood chips	0	0.108	0.022
Waste (70% renewable)	90	0.018	0.022

Since only the combustion part of the emissions should be included, neither data from Ecoinvent [16] nor data from EN 15603 [2] is suitable, both sources includes lifecycle values for the fuels.

4.1.3 *Wood chips*

The original data for wood chips in Ecoinvent (Data set: “Wood chips, mixed, u=120%, at forest/RER U”) don’t include any transport of the chips from the forest to the combustion plant. In order to include the impact from the transport in the fuel handling data a separate transport, based on Ecoinvent data, has been added. The transport is set to 0.00105 tkm/kWh wood chips. The figure is based on the transport distance used in the Ecoinvent data set “Wood chips, from forest, mixed, burned in furnace 1000kW/CH U”.

4.1.4 *Waste*

How waste used as a fuel should be evaluated from an environmental point of view is discussed. Different studies have handled the fuel differently. The first question is if the emissions related to the combustion of the waste should be allocated to the production of district heating or if the emissions should be allocated to the original products lifecycle.

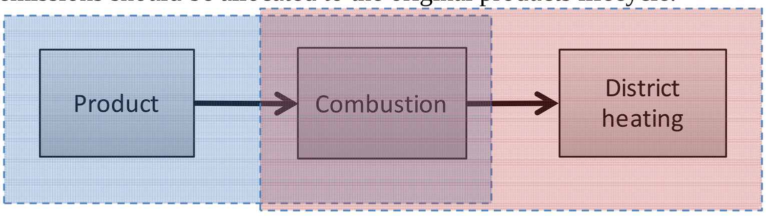

Figure 7. The combustion phase can be allocated either to the original products lifecycle or to the lifecycle of district heating.

In the cases studies made in this project it is chosen to consider waste as a fuel, and allocated emissions and losses of energy to the lifecycle of district heating. It is getting more and more common that the waste is sold and transported to plants far from where the garbage was collected. Today the waste has an economical value indicating that waste is used as a fuel for production of district heat and/or electricity. To allocate the combustion phase of waste to the lifecycle of district heating also makes it possible to compare the emissions and primary energy losses from the combustion of waste with other fuels in the study.

The alternative is to use the polluter pays principle. The principle says that the environmental burden related to the waste handling of a product should be allocated to the original product. Thereby the only impact allocated to the district heating would be related to eventually extra processes needed for producing, transport and deliver the district heating. For instance the Environmental Product Declaration (EPD) system [67] and PAS 2050 [78] is using the polluter-pays approach.

The second issue is to evaluate the amount of renewable material in the waste. The EU directive for renewable energy [64] states that the "biodegradable fraction of industrial and municipal waste" should be defined as biomass and thereby renewable. The question is how many percent of the waste that can be considered to be renewable. Due to the CEWEP report *The renewable energy contribution of "Waste to Energy" across Europe [62]*, approximately 50% of the waste can be considered to be from a renewable origin within EU. Countries that have stated a figure of the share of renewable material in the waste are Denmark (80% renewable), France, Austria (50%) and the Netherlands (48%) A Swedish report made by Profu [45], says that 70% of the CO_2 emissions from waste combustion is considered to come from renewable sources.

Since waste is considered as a fuel with a value in this study, the PEF for waste is set to 1. All additional emissions and energy use related to the fuel handling step (e.g. collection of waste, transports) are allocated to the original products lifecycle. Based on the EU directive for renewable energy [64], the emissions of fossil CO_2 from the combustion of the waste will be in relation to the share of waste with a fossil origin. In this study we have chosen to use emission data for the combustion based on the Profu report [45]. According to the report 30% of the total CO_2 emissions from the combustion will be considered as fossil. The amount of renewable material in the waste differs from location to location. Thereby it is important to use local data when calculating the impact on, in this case, global warming. Table 5 summarises emission data and PEF for waste depending on the assumptions made. In addition to the emissions of fossil CO_2 from the combustion emissions of CH_4 and N_2O will be added, see Table 4.

Table 5. Emission data for waste

Fuel	PEF Fuel handling	Emissions CO_2-eq Fuel handling (g/kWh)	Fossil CO_2 Combustion (g/kWh)
Waste (70% renewable)	1.0	0	90

4.1.5 *Industrial excess heat*

Industrial excess heat or waste heat is not included as a fuel in the case studies of this study. This “fuel” is anyhow an important and interesting heat source for district heating. The district heating system gives the possibility to use industrial waste heat that otherwise should have been emitted to a recipient. The question is if excess heat from the industry would be seen as waste or not. If the excess heat is seen as a resource it would make sense to handle it as a by-product and allocate a part of the emissions from the industrial process to the heat produced. The products produced and the excess heat are in most cases very different products, which makes it difficult to base the allocations on physical quantity, thereby an allocation based on economical values is probably the best alternative.

Today excess heat from the industry is normally treated as waste heat. The *PCR for Electricity, Steam, and Hot and Cold Water Generation and Distribution* [48], connected to the international EPD system says “*Industrial waste steam/hot water that would have been emitted to a recipient (if it were not used in an energy conversion process) is considered to be free of environmental burden i.e. only transportation from the industry shall be allocated to the energy conversion system using the steam/hot water.*”

In Sweden the governmental inquiry *Ett energieffektivare Sverige* [17], states that industrial waste heat should be treated as ”real” waste heat. The waste heat would have been produced in the industrial process anyhow, and thereby been emitted if it was not used for district heating. All emissions and energy use in the industrial process will be allocated to the industrial product.

How to allocate the environmental impact related to industrial excess heat is mainly a political question and not in the scope of this project to decide.

4.2 Additives

For additives used in the combustion processes a standard set of additives are used in the calculations independent of fuel or type of combustion and cleaning technology [92] . The mix and amounts of additives are based on data from nine Swedish [79]-[87] and five South Korean plants [18]. The fuel used and the size of the plants investigated are varying. The number of investigated plants is considered to be too small to be able to draw any conclusions about differences in the use of additives between different technologies and fuels.

The standard mix of additives includes the chemical listed in Table 6. For most of the investigated plants either ammonia or urea are used for flue gas cleaning. In the model both ammonia and urea are included but the amounts of each chemical are reduced with 50% compared to the investigated plants to get a more general mix of chemicals used for flue gas cleaning.

Table 6 Standard mix of additives used in combustion plant

Additive	Amount (g additive/ kWh fuel)	Primary energy (kWh/ kWh fuel)	CO2-eq (g CO2-eq/ kWh fuel)
Sodium hydroxide, NaOH (50%)	0,2	0,0008	0,1
Ammonia, NH3 (liquid 100%)	1,5	0,017	3,1
Urea, CH_4N_2O	2,1	0,039	6,9
Limestone, CaCO3	1,6	0,0002	0,0
Slaked lime, Ca(OH)2	3,0	0,004	2,3
Salt, NaCl	0,4	0,0004	0,1
Total	**8,7**	**0,06**	**12,6**

4.3 Ashes

The combustion process leads to ashes that need to be transported to landfill or other treatments. In the study it is assumed that 80% of the ashes will be sent to a landfill 30 km from the combustion plant. The load of the lorry is assumed to be 100% to the landfill and empty during the return. The total transport to landfill including the return are thereby 60 km. 20% of the ashes are assumed to be hazardous waste which will be transported a longer distance. For treatment of hazardous waste the transport distance is set to 1000 km, without any return transport. The weight percentage of ash will differ depending on the source and treatment of each fuel. The values used in this study are listed in Table 7 [92].

Table 7 Ash amount depending on fuel

Fuel	**Ash amount** (%$_w$)	**Ash amount to landfill** (kg ash/kWh fuel)	**Ash amount hazardous waste** (kg ash/kWh fuel)	**Data source ash amounts**
Natural gas	0%	-	-	Phyllis, (www.ecn.nl/phyllis/)
Fuel oil 2-5	0%	-	-	Phyllis, (www.ecn.nl/phyllis/)
Anthracite	10%	0,010	0,003	Phyllis, (www.ecn.nl/phyllis/)
Wood shavings	1%	0,002	0,001	BIOBIB, (www.vt.tuwien.ac.at/biobib)
Waste	25%	0,071	0,018	BIOBIB, (www.vt.tuwien.ac.at/biobib)

For transports we have assumed that all transports to landfill are made with a lorry size of 16-32 tonnes. For long distance transports of hazardous waste a lorry with a size >32 tones has been assumed.

A combination of the ash amounts for each fuel and the assumptions regarding distances and vehicles for transportation lead to the emissions of greenhouse gases and use of primary energy listed in Table 8.

Table 8 Use of primary energy and emission of greenhouse gases related to transportation of ashes

Fuel	**Primary energy** (kWh/ kWh fuel)	**CO_2-eq** (g CO2-eq/ kWh fuel)
Natural gas	-	-
Fuel oil 2-5	-	-
Anthracite	0,0020	0,0004
Wood shavings	0,0004	0,0001
Waste	0,013	0,0027

4.4 Internal electricity consumption in combustion

The internal energy consumption in the combustion plant is handled in different ways depending on if the plant produces electricity or not. For CHP-plants the internal electricity consumption is assumed to be included in total efficiency of the plant, thereby no additional use of electricity is included. For heat only plants the internal electricity consumption is assumed to be 1.5% of the fuel input to the plant. The assumption is based on estimations from the Swedish trade association Svensk Fjärrvärme that the internal consumption is 1-1.5% of the fuel input [88]. 1.5% is chosen as a worst case.

Emission data and PEF for the production of the electricity is taken from Annex E, EN 15603:2008. For marginal production data for “Electricity from coal power plant” is used. For average production of electricity “Electricity Mix UCPTE[1]” is used.

4.5 Construction and dismantling of combustion plant

Data for the construction and dismantling of the combustion plants are taken from Ecoinvent.

[1] UCPTE: Union for the Co-ordination of Production and Transmission of Electricity.

Ecoinvent includes data for two coal and two gas power plants of different sizes [92]. For oil power plants only data for one size is available.

Table 9 Data source construction and dismantling of power plant

Plant	Size (MW)	Data source Ecoinvent
Coal	500	Hard coal power plant, 500MW/GLO/I S
Coal	100	Hard coal power plant, 100MW/GLO/I S
Gas	300	Gas power plant, 300MWe/GLO/I S
Gas	100	Gas power plant, 100MWe/RER/I S
Oil	500	Oil power plant 500MW/RER/I S
Oil	100	Calculated, based on estimations

Based on the data from Ecoinvent the project had to make a number of assumptions in order to get general figures. First, the project has assumed that the construction and dismantling of a CHP-plant or a heat only plant are equal to a power plant. Second, it has been assumed that the construction and dismantling of a combustion plant for bio mass or waste will be equal to a coal power plant. Third, in order to be able to express the primary energy used and emissions of greenhouse gases as a linear-function of the plant size we have assumed that the slope of the curve for an oil power plant will be the same as the slop for a coal power plant. With these three assumptions it is possible to express the emissions of greenhouse gases and use of primary energy as a function of the plant size for all five fuels included in the case study, see chapter 9.

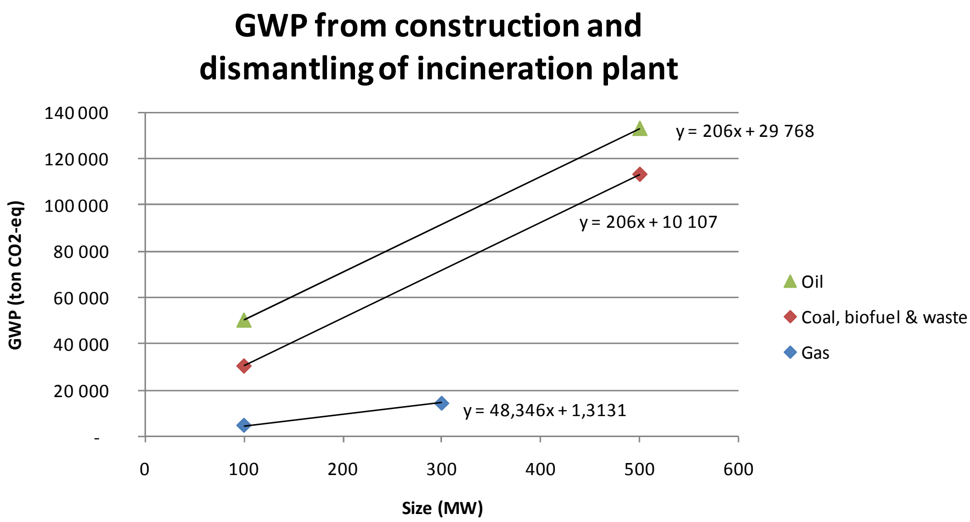

Figure 8 GWP from the constriction and dismantling of a combustion plant as a function of the plant size

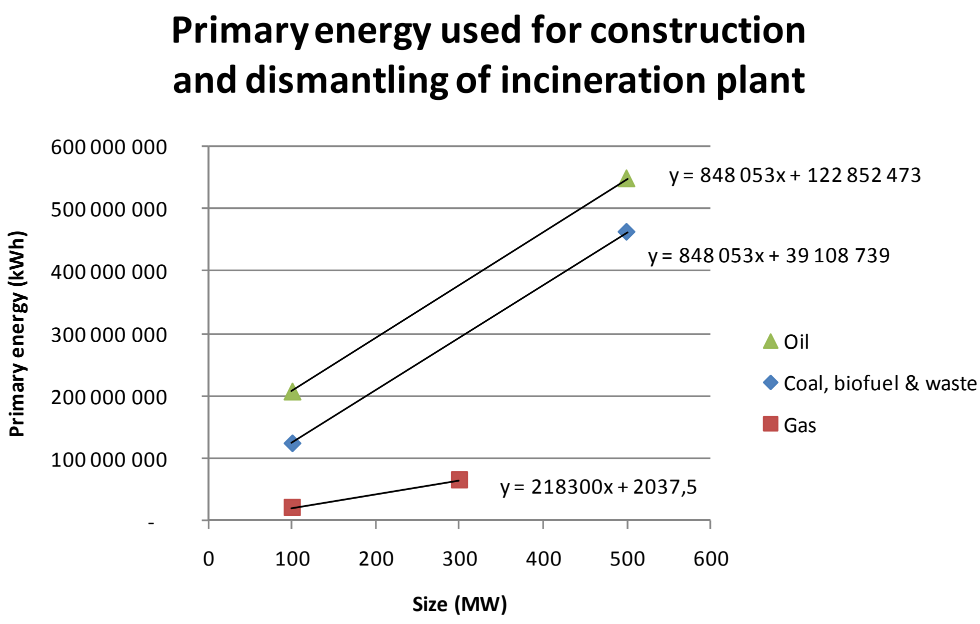

Figure 9 Primary energy from the constriction and dismantling of a combustion plant as a function of the plant size

As standard values the plant size is set to 100 MW, the fuel consumption to 500 GWh/year and the expected lift time of the plant is set to 30 years. Using the values above gives the emissions per kWh fuel.

Table 10 Primary energy and GWP from the construction and dismantling phase of the combustion plant

Fuel	Primary energy (kWh/kWh fuel)	CO2-eq (g CO2-eq/kWh fuel)
Natural gas	0,001	0,3
Fuel oil 2-5	0,014	3,4
Antracite	0,008	2,0
Wood shavings	0,008	2,0
Waste	0,008	2,0

4.6 Construction and dismantling of distribution net

The impact from construction and dismantling of the distribution net for district heating or cooling are calculated for three different grids assuming low, medium and high energy density (MWh/m pipe). The energy use and impact on global warming is based on the estimation of a life length of 30 years for the pipes. For details see chapter 5 and Berners report *Primary Energy Efficiency and District heating* [92]. In the case studies the medium grid density is used if nothing else is specified.

Table 11 PEF and CO_2-eq for construction and dismantling of grid.

Grid	Energy density in grid (MWh/m)	PEF (kWh /kWh delivered heat)	CO2-eq (g/kWh delivered heat)
Low density	3.0	0.0116	2.86
Medium density	8.2	0.0042	1.16
High density	15	0.0008	0.20

4.7 Operation distribution net

The heat losses in the grid and the electricity needed for operation of the pumps used in the system is calculated for three different grids assuming low, medium and high energy density. For details see chapter 5 and [92]. In the case studies the medium energy density grid is used if nothing else is specified.

Table 12 Heat losses and electricity for pumping in the district heating net

Grid	Energy density in grid (MWh/m)	Heat loss (%)	Elec (pumps) (kWh elec/ /kWh delivered heat)
Low density	3.0	13.3%	$3.38*10^{-5}$
Medium density	8.2	4.9%	$1.24*10^{-5}$
High density	15	0.9%	$2.26*10^{-6}$

4.8 District cooling systems

There are two kinds of District Cooling Systems. Either is chilled water (which is produced in the district cooling plant) supplied to the end customer or hot water is supplied to an absorption chiller located at the customers substation. The type of absorption chillers used depends on the district cooling system operational parameters.

The former operation of the district cooling system distributes chilled water to the customer's substation through a DC network after that the cooling machines produced the chilled water using an absorption chiller, turbo chiller, ice storage system etc. (Figure 10)

The latter operation of the DC system supplies hot water to the substation similar to a DH system. But the absorption chiller (which is installed in the customer's side) produced the chilled water and then distributes it to the final customers (Figure 11).

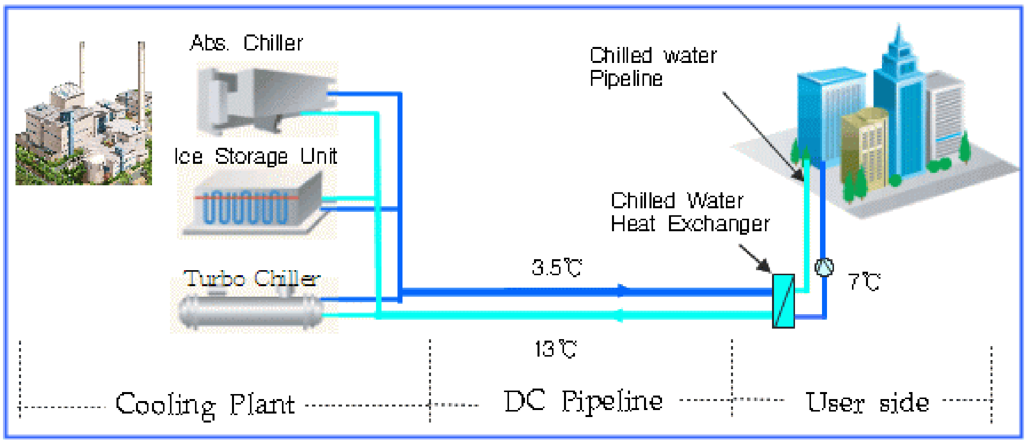

Figure 10 Schematic diagram of chilled water DC system

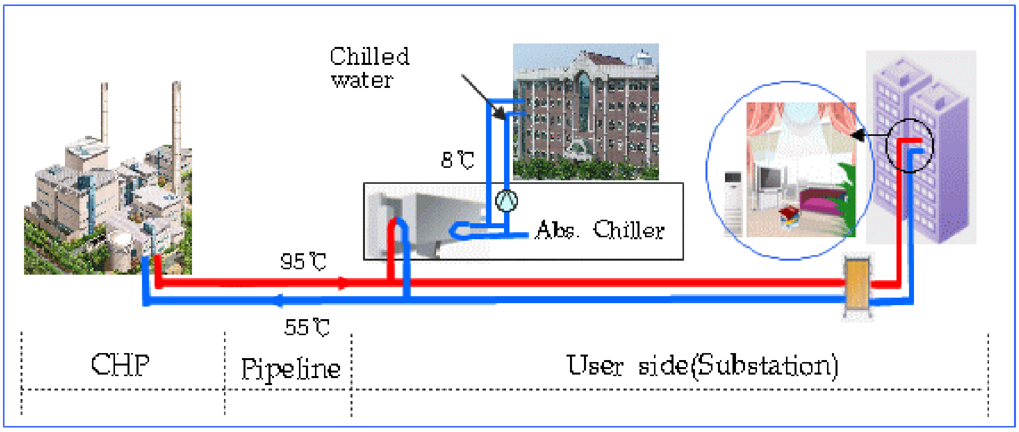

Figure 11 Schematic diagram of hot water DC system

An absorption chiller (ABS) uses water as a refrigerant rather than CFC or HFC gas. Thereby the risk for depletion of the ozone layer in case of leakage is eliminated. Moreover, it helps reduce the electrical peak load during summer. Although it has the disadvantage of lower efficiency compared to a turbo chiller, it is very useful and has relatively higher COP (coefficient of performance) considering heat use instead of electricity. There are two types of absorption chillers. One uses steam for evaporating an absorbent (a solution of lithium bromide, LiBr) and the other type uses hot water.

A steam absorption chiller is installed in a district cooling plant and uses steam which is produced by an incinerator, boiler or CHP. It has relatively higher efficiency than a hot water absorption chiller. Generally a steam boiler is not installed in a substation. Thus, a customer could not obtain steam from the substation for operating a steam absorption chiller. That is the reason why they use a hot water absorption chiller in the substation.

In the case of using DH water, an absorption chiller can be classified into a 1-stage absorption chiller or a 2-stage absorption chiller in which regenerative heat exchanging is carried out by the high-temperature part and the low-temperature part in order to reduce the return temperature. In this study, we only carried out District Cooling System analysis of a hot water ABS chiller which is installed in the substation. We will calculate the use of primary energy of an ABS chiller in District Cooling and the generation of greenhouse gas. In order to do so, we checked the electricity consumption of equipment such as the refrigerant pump in an ABS chiller and we also investigated energy consumption when each piece of equipment was being manufactured.

4.9 Operation of absorption chiller

The assumed electricity needed for the operation of the absorption chiller is based on data from specification data sheets [20] from World Energy for 1-stage and 2-stage absorption chillers. Based on the data in the sheets for different sizes of absorption chillers the electricity consumption can be described as a function of the cooling capacity, see **Fel! Hittar inte referenskälla.**. Specifying the size of the chiller and if it is a 1-stage or a 2-stage chiller the electricity consumption can be calculated with help of the function for any size of the absorption chiller.

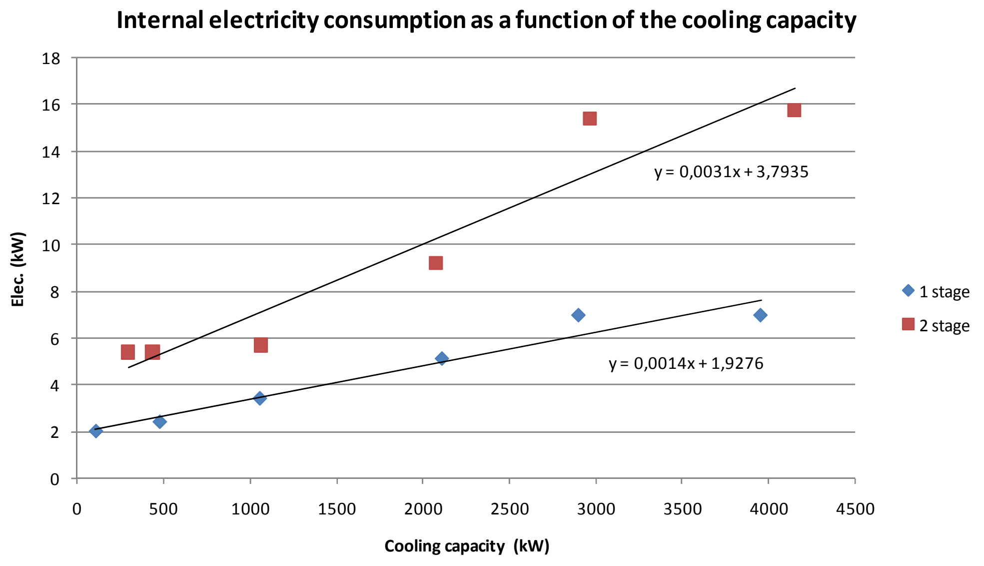

Figure 12. Internal electricity consumption as a function of the cooling capacity for absorption chillers

Equally to the internal electricity consumption for “heat only plants” the emission data and PEF for the production of the electricity is taken from EN 15603:2008 [2]. For marginal production data for “Electricity from coal power plant” is used. For average production of electricity “Electricity Mix UCPTE” is used.

4.10 Construction and dismantling of ABS chiller

The assumed weight of the absorption chiller is based on data from specification data sheets [20] from World Energy for 1-stage and 2-stage absorption chillers. Thereby the data is based on information from one producer only, ABS chillers from other suppliers might have other weights. Based on the data for different sizes of absorption chillers the weight can be described as a function of the cooling capacity, see Figure 13. Specifying the size of the chiller and if it is a 1-stage or a 2-stage chiller the weight can be calculated with help of the function for any size of the absorption chiller.

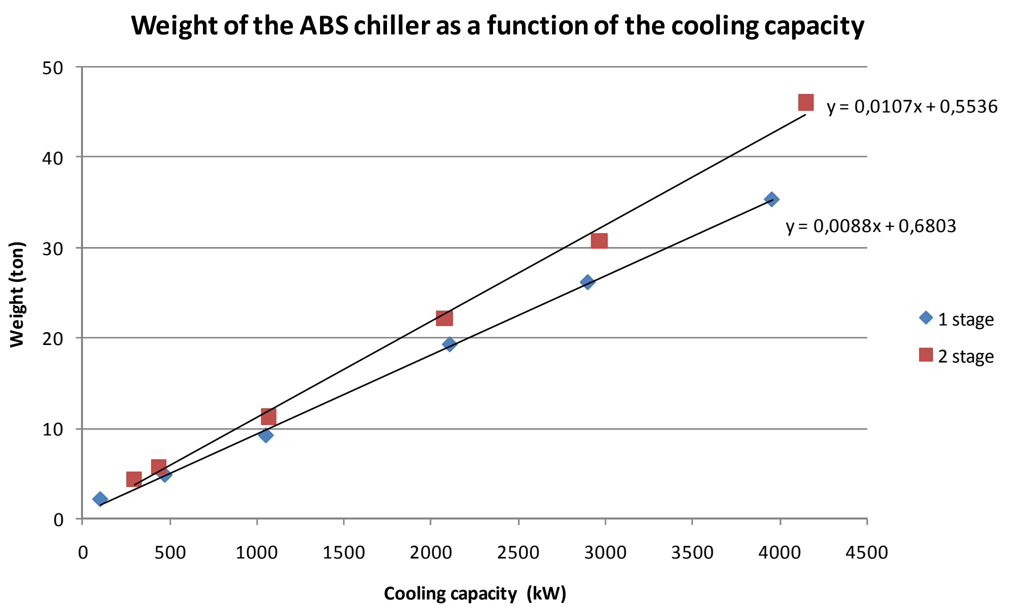

Figure 13 Weight as a function of the cooling capacity for absorption chillers

Based on the total weight of the chiller the amounts of each material used in the construction can be calculated. In the project it is assumed that an absorption chiller is made of 70% rolled steel, 20% cast steel and 10% copper. Only the emissions and the energy needed for the production of the material used in the chiller is included. Energy and emissions related to the production of the ABS chiller is not included, neither is the dismantling phase included in the study. The reason for this is lack of data for these parts of the process. Thereby the impact from the construction and disposal of the ABS chillers will be slightly underestimated. Emission and energy data for the production of the materials used in an ABS chiller is taken from Ecoinvent [92].

Table 13 Material composition of absorption chiller

Material ABS chiller	**Composition**	**Primary energy** (kWh/kg)	**CO2-eq** (kg CO2-eq/ kg)
Rolled steel	70%	10,2	1,8
Cast steel	20%	11,6	2,7
Copper	10%	9,3	1,8

In order to express the emissions from the construction of the ABS chiller per produced kWh of cooling it is assumed that the average cooling production is 325 MWh/year, based on data from 123 ABS chillers installed in 2 heat supply area by KDHC branches. Based on the same data source the average cooling capacity of each unit is 1.3 MW. The average life time is assumed to be 15 years.

4.11 Discussion data quality

The data quality for the processes with the highest impact on the results is in general quite good.

The data used for fuel handling is good but there is likely to be a large range from the best produced fuel to the worst. This has not been investigated in detail. The data for additives is based data from 14 plants located in Sweden and South Korea. Thereby it is probably a good estimation. But the number of plants is too small to be able to draw any conclusions related to differences related to production technology or fuel.

In Table 14 the data quality of the data used for district heating is summarised. Note that even if the impact on the final result is small in this particular study other conditions might change this. One example is the impact related to construction and dismantling, for a plant operating only a shorter period of the year the impact per produced kWh heat might have an impact on the final results.

The data related to production/construction of power plant and absorption chillers are based on a few studies, new improved technologies might deviate from the data presented in figures and equations above.

Table 14. Summary data quality production and distribution of district heating

Process	Impact on result	Data quality	Comment
Fuel handling	Medium/Large	Good/Medium	Data from Ecoinvent is quite good, but the impact differ depending on the process chain for each fuel supplier
Combustion	Large	Good	Data based on official emission data used for reporting to UN
Additives	Medium	Good/Medium	Data based on Ecoinvent is good. The assumed amount of additives used based on data from 14 plants. But the number of plants is too small to have a fuel or technology specific mix of chemicals.
Ashes	Small	Medium	Good quality of transport data from Ecoinvent. The distance is based on estimations.
Internal elec consumption in heat only plant	Small/Medium	Medium	Data for electricity from EN 15603 Annex E. The electricity consumption is a rough estimation.
Construction & dismantling plant	Small	Medium/Poor	Based on similar datasets from Ecoinvent. The impact is based on a number of rough assumptions and estimations. Dismantling is not included in all cases.
Construction & dismantling DH net	Small	Good/Medium	Data based on internal studies
DH net (operation pumps and heat loss)	Small	Good/Medium	Data based on internal studies

Table 15. Summary data quality production and distribution of district cooling

Process	Impact on result	Data quality	Comment
Heat production	Large	-	See Table 14
Operation ABS-chiller	Small	Good	Data based on information from producer
Construction & Dismantling ABS-chiller	Small	Medium	Data based on assumption regarding material use at production. A rough estimation with production steps missing. Dismantling is not included.
DH net (operation pumps and cold loss)	Small	Good/Medium	Data based on internal investigations
Construction and dismantling DC net	Small	Good/Medium	Data based on internal investigations

Most of the parameters will differ depending on the choice of suppliers for the raw material and the local conditions. It is therefore important to use data reflecting the local situation in the calculations of PEF-values and greenhouse gas emissions for real, existing systems.

5 Analyse of distribution and transmission of heat and cool

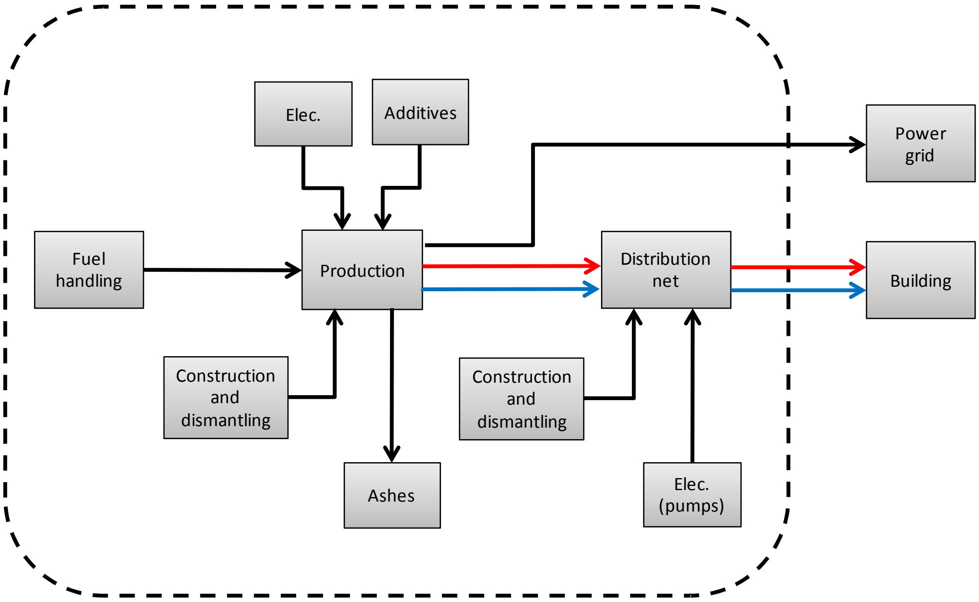

Figure 14. System boundaries

5.1 Introduction

The distribution and transmission system in a district heating grid consist of several parts amongst transmission lines, substations with heat exchangers, distribution lines with heat exchangers and different pumps. This chapter is primarily based on [92].

The developed method is based on both energy calculations to decide the energy loss in the operation phase and LCA methods to allocate the PEF and CO_2 emission related to the building of infrastructure like pipelines, heat exchangers, pumps, valves, excavation of ditches and production of different material applied in the process.

In accordance with the method developed in previous chapters like 2.3.3 the distribution and transmission is divided in four parts or subsystems; the production of the pipes, the excavation of trenches, the operation phase which is divided in two, energy for operation of the pumps, and heat loss from the pipelines.

Those systems also consist of other subsystems, but the primary focus has been the parameters that have the most influence on the PEF and emissions of CO_2-eq and a simplified approach have been chosen, according to the cut-off rule of 1%.

Some tables and figures are shown in order to illustrate different parameters impact, for a more detailed description see [92]. The four different parts are described in the following chapters 5.4 to 5.7.

5.2 Limitations and specifications

Previously, a functional unit of 1 kWh heat/cold is chosen and this is related to delivered energy at the end user. Since the unit is delivered energy, the calculations are made for pipelines of different diameters and velocities according data from pipeline producers. Standard steel pipelines with average insulation level and roughness are chosen. Delivered heat is calculated by use of artificial years consisting of three seasons with three different temperature levels, see Figure 15Temperature levels for heating vary depending on the season, and thus the velocity. Cooling is only calculated for the temperature levels 6/16 and 8/31. The need for cooling might vary and a more detailed calculation of the actual number of hours will influence on the corresponding PEF and CO_2 values per delivered kWh. Construction and dismantling of substations and pumps are not included in the CO_2 emissions and PEF, since none of the producers were able to provide information useable for calculations.

5.3 Model development district heating/cooling grid

In our case studies an artificial heating year have been chosen consisting of winter, spring/fall and summer season as described in Figure 15 and Table 16. The load levels are aggregated from hourly measurements from two different district heating producers in the Nordic countries.

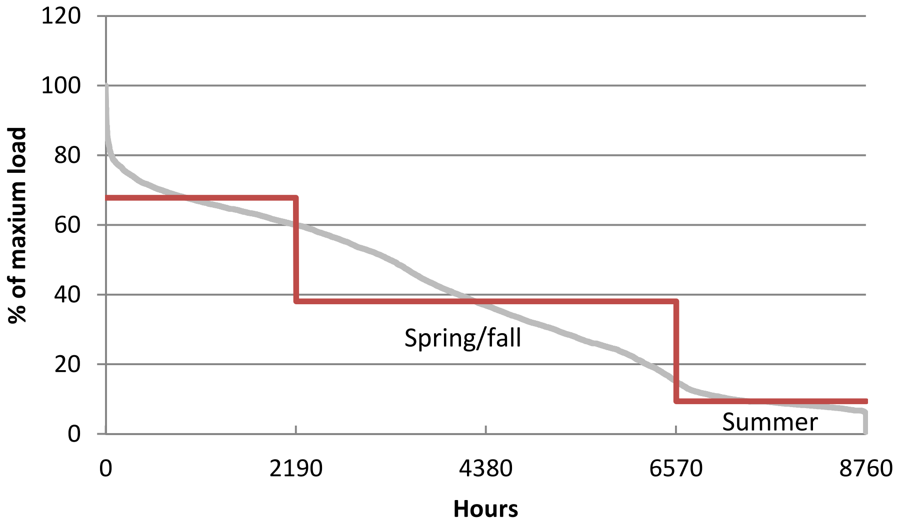

Figure 15 Yearly heat load from a district heat producer

Table 16 District heating division in different seasons

Season	% of the year	Temperature supply/return [C]
Winter	25	105/50
Spring/autumn	50	80/40
Summer	25	70/35

The chosen temperature levels have been selected based on discussions in the project group and the Expert Group, in addition to suggestions in literature e.g. [22].

5.3.1 *Cooling*

The PEF and emissions of greenhouse gases per delivered kWh depend on the cooling load. The cooling load depends among others on the kind of customers in the grid location and no standard cooling load pattern exists to, thus three separate methods have been applied [23][24]:

Case I Constant cooling load 8760 hours/year

Case II Base load 8 months (5840 hours), intermediate period 2 months and maximum load 2 months (1460 hours) [25]

Case III Base load 8 months (5840 hours), intermediate period 2 months and maximum load 2 months (1460 hours) [26].

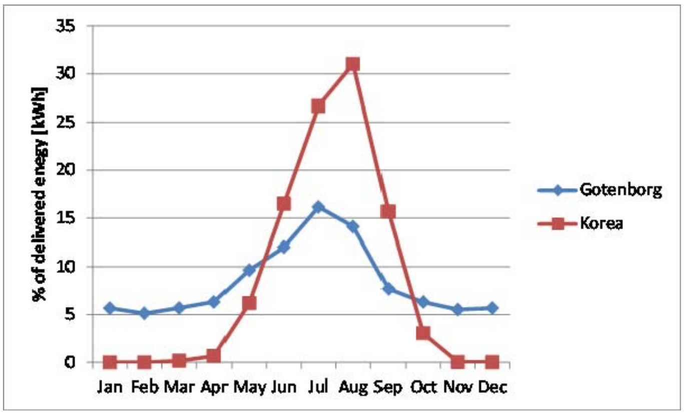

Figure 16. Yearly cold load distribution in Gothenburg and South Korea

Figure 16 shows a significant difference in the percentage-distribution need between Sweden and South Korea. The base load is lower in Korea than Sweden, whilst the maximum energy need is probably higher in Korea. This will affect the PEF and greenhouse gas emissions. According to Gullev [96], the figures from Korea are not representative, so only the Swedish distribution is used in the case studies.

In the case study the PEF and CO_2 equivalent values are related to the delivery of 1 kWh heat or cold to the end user. This implies that the PEF and CO_2 equivalent have to be distributed on the total energy delivered to the end user during the assumed lifetime of the transmission and distribution net.

5.3.2 *Adjustment of energy consumption*

In this study five yearly distribution models have been applied, since the energy demand during a year is not constant. The different distribution models have been designed based on information in literature and from two DH distributors [93] in the Nordic countries see Table 17.

Table 17 Overview of different load levels used in the development of a calculation method for PEF and CO_2 equivalents for the distribution and transmission of heat and cool

Case	Winter		Spring/autumn/intermediate		Summer	
	% load	hours	% load	hours	% load	hours
Heating season						
Case A	80	4380	35	2190	18	2190
Case B	67	4380	38	2190	18	2190
Case C	67	4380	38	2190	9	2190
Cooling season						
Case I					80	8760
Case II	30	5110	51.5	2190	78	1460

The flow is assumed to be constant during a whole season, and the calculations are based on the possible flow for each pipeline dimension. Maximum flows/velocities for the different dimensions are based on product information and recommendation from the producers. The average flows for the other seasons are calculated by means of the percentages of maximum heat/cold load in addition to use of seasonal supply and return temperatures.

Both temperatures and velocities for the heating net are altered during the year, applying supply and return temperatures from
Table 16. The cooling calculations are carried out with constant temperatures and only the mass flow is altered. Furthermore, several other parameters will depend on the flow and temperature in the pipelines; the details are described in the following chapters.

The load variation will influence the PEF and CO_2 emissions. If the estimated heat demand in the winter season is high (80%) the yearly delivered energy will be higher per year than for a more typical average load at 67% in the winter season. Thereby the PEF and CO_2 values will be lower, in addition to increased heat loss per delivered kWh.

Peak load boilers/heaters are excluded. This will probably have an influence on the PEF value and CO_2 emissions, because the peak load might be supplied by another technology and/or by with different fuel, which should be accounted for. The effects of different peak load supplies should be further examined in a later study.

5.4 Production of pipelines

5.4.1 *Background*

Today is two kinds of piping systems are primary used, pre insulated steel pipelines either single or twin pipes, or flexible plastics pipelines [27]. The most commonly used plastics pipelines are; PEX – Cross linked polyethylene, HDPE – High density polyethylene and LDPE – Low density polyethylene. In this study only steel pipelines have been considered, LCA studies on plastics are ongoing by some of the main producers, but they have not been able to provide data yet. During the project period several attempts have been made to gather data from different producers of transmission and distribution pipelines without succeeding. Instead a standardized steel pipeline has been chosen with an inner pipe made of steel, an insulation layer made of PUR foam and an external pipe or coating of made of polyethylene HDPE. This excludes PEF and CO_2 related to possible use of glue and leak detection wires. In a study [30] that were carried out in cooperation with a private Swedish company the impact of those parameters is negligible according a cut-off rule of 1%, and therefore consequently excluded.

An LCA calculation has been carried out for different dimensions of pipelines based on available information on www.powerpipe.se, which is in accordance with information from www.logstor.com. The production of the pipes is based on available information on dimensions and materials from producers and EN 253. No producers were willing or able to provide information on actual energy consumption in their own factories. The database Ecoinvent has been the basis for the inventory. The amount of the different materials are based on inner and outer diameter, thickness of the coating and given weight per meter and the volume of foam. In the inventory European values are applied, steel pipelines produced by average European steel and waste from foam production is neglected. PEF and CO_2 related to construction and demolition of the factory/ production units including machinery are excluded since no data were available.

As a result of new and improved pipelines major DH companies in Norway now uses an economical lifetime of 50 years [28]. The lifetime of the pipelines are set to 30 years, even though studies from Denmark show a substantially longer lifetime [94].

Table 18. PEF and CO_2 equivalents related to production of a meter pipeline

	DN 25 Pipeline single	DN 25 Pipeline Twin	DN 80 Pipeline single	DN 80 Pipeline Twin	DN 100 Pipeline single	DN 200 Pipeline single	DN 200 Pipeline Twin	DN 600 Pipeline single
PEF Non-renewable, fossil [kWh/m]	72,5	69,1	233,3	194,8	279,0	615,4	724,5	2452,7
PEF Non-renewable, nuclear [kWh/m]	12,2	13,7	45,5	40,9	52,2	110,6	171,9	387,2
PEF total Non-renewable [kWh/m]	84,7	82,8	278,9	235,7	331,2	726,0	896,4	2839,8
kg CO_2 eq/m	20,0	21,9	73,2	48,1	84,6	180,5	270,2	322,8

5.4.2 *District heat transfer studios, distributor stations, substations, heat exchangers and pumps*

Transmission and distribution nets are usually separated by substations and/or central heat exchangers. Manufacturing of the substations (transmission substations) should be included in the inventory, but none of the producers were able to provide data. The lifetime of a substation is usually set to 20 years, and since they are produced and delivered in units the whole unit will be replaced every 20 year.

Substations at the end users (house stations) are considered to be a part of the internal distribution system and shall not be included in order to prevent double counting. The total weight of a substation and a heat exchanger are relative small compared to the total size of a district heating/cooling grid. In an article by Perzon [29] this steel amounts to/constitutes to 0.15 kg steel/meter pipe, but this has not been possible to verify since the article lacks information on the appurtenant flow.

The pumps are usually made of cast iron, where the weight depends on size from 7 to around 900 kg (http://www.grundfos.no/). The lifetime of the pumps are also estimated to 20 years. In a district heating/cooling grid the number and sizes of pumps depends on the layout. A more detailed model should preferably include pumps, transfer stations and heat exchangers in addition to the leak detection wires.

In this study the same outer dimensions is chosen for heating and cooling, as shown in Table 1. A reduction of insulation thickness will lower the PEF and CO2 emission both for production and excavation per meter of pipeline. This implies an overestimation of the PEF and CO2 emission due to production and excavation of pipelines, but increased heat loss.

5.5 Excavation of trenches

The excavation of trenches consists of several steps from digging of ditches, lying of pipes, welding, mounting, back filling of trench etc. A total overview of all of the necessary operations lies outside of the scope of this study, but on the other hand detailed information is essential when the environmental impact of the whole process shall be calculated.

A method describing the LCA of a district heating system in urban areas is presented in [30]. Due to lack of time and resources a thorough LCA of all possible elements in an excavation process, like shown in Figure 17 is not possible.

Several attempts to gather information from construction enterprises were carried out, without success. One anonymous firm was finally willing to provide some data related to machine hours for excavation works for different dimensions and locations. Together with information about the necessary cross-sectional area for a trench [31] and the results of [46] it was possible to reduce the number of parameters. An LCA were carried out by SimaPro and the Ecoinvent database, which form the foundation of a simplified method.

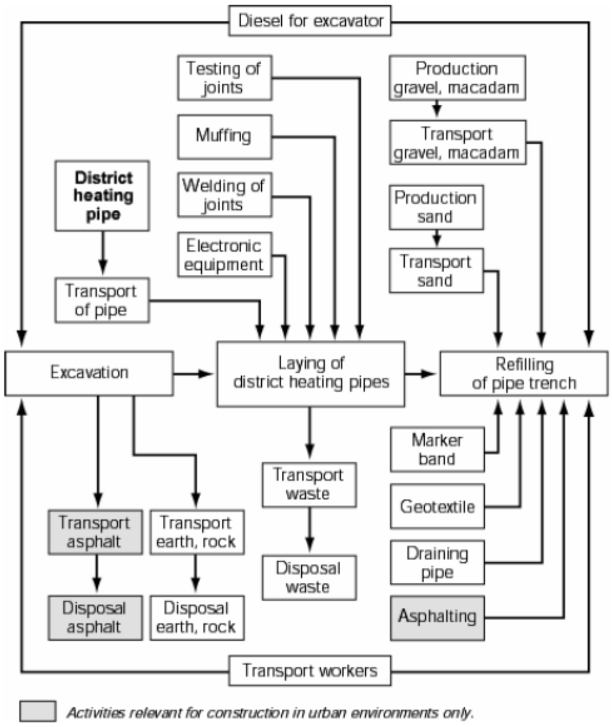

Figure 17 The most important elements of the excavation works for a district heating network in urban environment. Illustration from Life Cycle Assessment of the District Heating System, Part 2 Network Construction, M. Fröling, M. Svanstrom, Chalmers, Int J LCA, 10 (6) p 425-435

A new data program is currently under development by Asplan Viak [33][32] [32] and it might be possible to do a thorough calculation of the CO_2 emissions related to excavation also for no-dig methods, but the PEF values are not included in this tool.

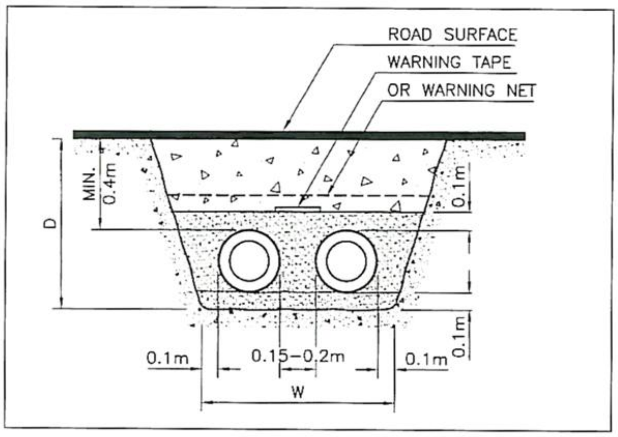

Figure 18 Cross-sectional area district heating/cooling trench [31]

The cross sectional area of a trench is descried by width W and depth D, and varies depending on the dimension of the pipeline [31] By use of the similar geometry a LCA for urban and rural areas are carried out. It is assumed a rise of the walls of 1/3, a transport distance of 30 km. For rural areas no asphalt is replaced and removed and it is assumed that 20% of the original mass can be reused. In urban areas the asphalt is removed and transported 30 km and replaced with new asphalt. Diesel consumption varies from 1.5 to 12.5 kg per meter produced trench, depending on the volume of mass removed. The bottom layer is filled with sand and the top layer consists of gravel, in urban areas additional 5 cm asphalt. Sand and gravel is based on European average values. PEF values and CO_2 equivalent per meter pipeline related to excavation of trenches in urban and rural areas.

Table 19 PEF and CO_2 equivalents per meter related to excavation of trenches in urban and rural areas, only selected dimensions

Urban area		DN 25	DN80	DN100	DN200	DN600
Total PEF	kWh-eq/m	383,0	617,2	707,4	1339,5	3960,7
PEF -renewable	kWh-eq/m	4,4	5,0	5,6	9,1	14,3
CO_2 eq	kg CO_2-eq/m	59,2	118,7	136,3	267,9	488,5
Rural area						
Total PEF	kWh-eq/m	170,6	375,6	337,1	906,6	3726,4
PEF -renewable	kWh-eq/m	0,5	0,5	0,6	1,0	12,7
CO_2 eq	kg CO_2-eq/m	35,8	91,5	106,0	216,8	452,2

Table 19 shows that the renewable part of PEF for larger dimensions are less than 1% of the total PEF. There is a significant difference between urban and rural excavation cased both by use of asphalt in urban areas and reuse of material in rural areas.

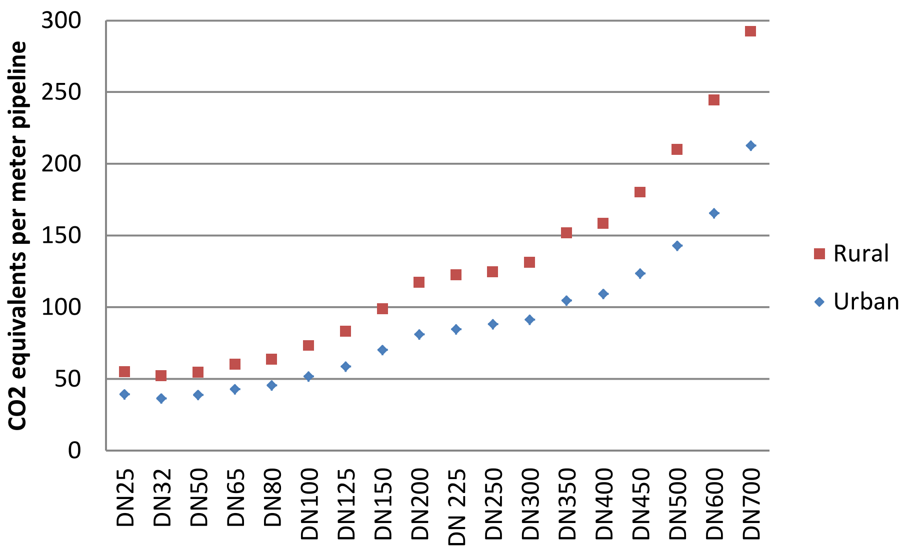

Figure 19 CO_2 equivalents per meter fore excavation of pipeline of different dimensions

A calculation for suburban areas was also carried out, but the difference between urban and suburban areas was negligible for both the PEF and CO_2 equivalents. In this project there exists no information about the ratio between urban and rural area, so the further calculation is performed on district heating/cooling grids in urban area. This implies an overestimation of the PEF and CO_2 equivalents for rural areas.

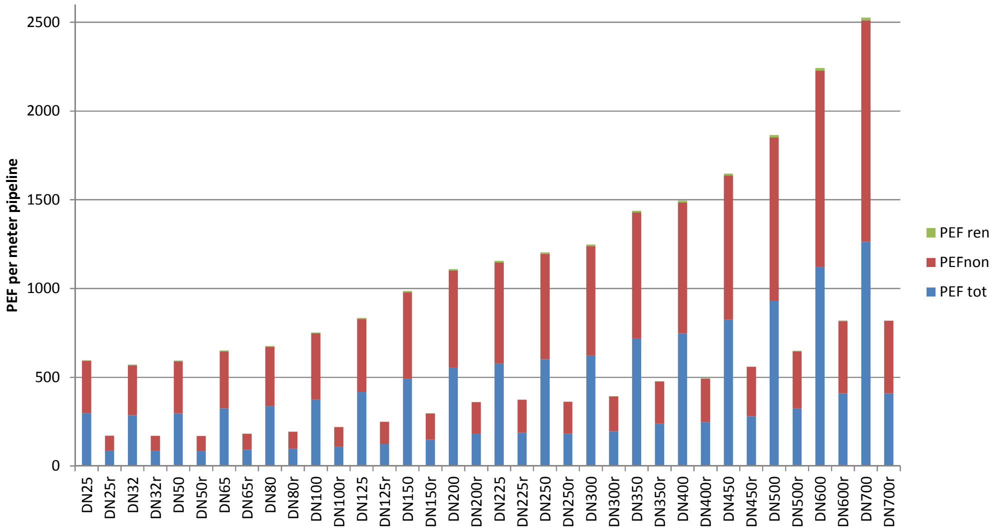

Figure 20 PEF excavation of trenches per meter of pipeline for urban area and rural area (notation r)

5.5.1 *Energy needed for pumps*

District heating/cooling grid might have different layout, in this study a rather simple design is assumed; one heat source without any loops. The head loss is calculated for 1 meter of pipeline of the actual dimensions. The energy needed for the pumping/transport of the fluid in the district heating grid can be calculated according;

$$P = V\frac{\Delta P_p}{\eta_p} \qquad \textit{Eq. 17}$$

Where

V	Flow	[m3/s]
ΔP	Necessary pressure needed to circulate the fluid in the supply and return pipes	[Pa]
η_p	Pump efficiency	[-]

In this case constant pump efficiency is assumed and the possible heat recovery from the pumps is neglected.

The necessary pressure can be calculated by:

$$\Delta P_p = (\Delta P_s + \Delta P_r + \Delta P_{per}) \cdot 1.15 \qquad \textit{Eq. 18}$$

Where

ΔP_s	head loss/ pressure drop in the supply pipes
ΔP_r	head loss/ pressure drop in the return pipes
ΔP_{per}	difference between supply and return, design pressure differential

5.5.2 *Head loss/pressure drop in the pipes*

For Reynolds number Re>3500, and turbulent flow the pressure drop can be described by [33]

$$\Delta p = 62544 \cdot \frac{q^2}{d_i^5}\left[\frac{0.25}{log\frac{d_i}{\varepsilon}+0.57} + \left[\frac{0.938}{log\frac{354\,q}{\nu\,d_i}}\right]^{2.393} \cdot e^{-3.05\left[\frac{\varepsilon\,q}{\nu\,d_i^2}\right]^{0.33}}\right] \qquad \textit{Eq. 19}$$

Where

q	Flow	[l/h]
di	Inside diameter	[mm]
ε	Roughness	-
ν	Kinematic viscosity	[cst]
γ	Relative density	

The head loss /pressure drop is calculated by use of Eq. 19 above. There exist several other empirical methods that enable a calculation of the head loss, like Coolebrook's formula and Swamee and Jains formula, based on the Reynolds number, [34] [35] Eq. 19 is chosen in order to enable an evaluation of the effect of variation of roughness for instance by use of different material or to examine the effect of corrosion.

The flow is calculated based on the actual velocity in pipelines of different dimensions at average winter, spring/autumn and summer load. The kinematic velocity and relative density is calculated for each temperature level, whilst a roughness of 0.05 is applied for steel pipes.
According to [33] the roughness for rusty steel varies from 0.15 to 2. For older pipelines the chosen values will underestimate the pressure loss and thereby increase the PEF and CO_2 values.
ΔP_{per} is often 1-2 bar in an ordinary district heating systems, this implies that ΔP_{per} and therefore ΔP_{per} can be neglected. In addition is the calculation of the head loss related to the delivered kWh, which is based on a meter of pipe. A complete district heating network will consist of a various number of pipelines of different dimensions. Since the head loss is calculated by meter pipeline, ΔP_{per} should be divided on the actual/ total length of the district heating pipes and in order to prevent overestimation of the head loss ΔP_{per} is excluded.

The effect of roughness is most important at low temperatures and should be taken into account for older pipelines designed for cooling.

5.5.3 *Total head loss*

The pressure loss is calculated separately for the supply and return flow, since both γ and ν varies with temperature. The head loss cannot be calculated without knowledge of the heat load, since the average temperature and velocity depends on the load. Changes in direction and dimension and necessary branching will contribute to an additional 10-20%, in this case a conservative approach of 15% has been chosen.

Table 20 Head loss per meter of pipeline for selected cases Case A (38% winter, 38 % spring, 18% autumn) and Case C (winter 67%, 38% spring, 9% summer)

		DeltaP 6/16	DeltaP 8/31	DeltaP 70/35	DeltaP 80/40	DeltaP 105/50
Case A - heating	DN25	-	-	57	151	383
	DN80	-	-	28	74	188
	DN100	-	-	24	65	167
	DN200	-	-	23	61	158
	DN600	-	-	10	28	72
Case C – heating	DN25	-	-	16	176	273
	DN80	-	-	8	86	134
	DN100	-	-	7	76	119
	DN200	-	-	6	72	112
	DN600	-	-	3	32	51
Case I cooling	DN25	188	182	-	-	-
	DN80	91	88	-	-	-
	DN100	80	77	-	-	-
	DN200	74	72	-	-	-
	DN600	33	32	-	-	-

As Table 20 shows depends the head loss on the choice of load pattern, since the velocity will be influenced by the average load for each season, and thereby will the PEF and CO_2 emission values be affected.

The energy needed for pumps is calculated for different energy intensities assuming no heat recovery and an efficiency of 85%. Finally a calculation of electrical energy needed for pumps per delivered kWh is calculated, see Table 21.

Table 21 Power needed for pumps per delivered kWh to the end user (MWh_{el}/MWh_{heat})

MW	Low intensity (3 MWh/m)	Medium intensity (8,2 MWh/m)	High intensity (15 MWh/m)
Heating	2,23E-05	8,13E-06	1,48E-06
Cooling	3,38E-05	1,24E-05	2,26E-06

5.6 Heat loss from the pipelines

Most of the heat loss from the pipelines is not recoverable and will thereby increase the PEF values and the emissions of greenhouse gases.

In this text the term energy loss is used, this does not imply that energy actually is lost, but transferred to another form and usually in a form that is not recoverable or only partly recoverable. Energy that is used in a pump will be calculated as loss, even though a part of the energy is recoverable as transferred heat.

5.6.1 *Heat loss from the district heating/cooling network*

A detailed calculation of the heat loss from the pipelines, consist of amongst others of heat loss from the fluid to the pipeline, from the pipeline to the insulation, from the insulation to the casing, from the casing to the ground, from the ground to the air, but also between supply and return pipelines.

At present there exist several methods for simplified calculation of heat loss from the pipelines [22]. Different producers provide calculation programs like Isoplus and Logstor. The Danish District Heating association is currently starting a study providing simplified tables for calculation of heat loss. The heat loss trough the piping depends on, the u-value of the pipe, insulation and soil, based on coefficients of thermal conductivity, but also on the temperature difference between the fluid and the environment, e.g. the temperature in the ground, dimensions of the pipes, distance between pipelines, the piping layout (single, twin, triple, burial depth), filling material, temperature in supply, return and in the soil. In addition to the method described in equations Eq. 19 and Eq. 20 below, the following standards EN 253 and EN 15632 might be applied.

The heat loss per pipe pair can be calculated by

$$\phi_f = U_1\left(t_f - t_s\right) - U_2\left(t_r - t\ \right) \qquad \textit{Eq. 20}$$

$$\phi_r = U_1\left(t_r - t_s\right) - U_2\left(t_f - t_s\right) \qquad \textit{Eq. 21}$$

Where

U_1, U_2	Heat loss coefficients	[W/m ºC]
t_f	Supply temperature	[ºC]
t_r	Return temperature	[ºC]
t_s	Soil temperature	[ºC]

The overall heat loss can then be calculated by

$$\phi_f + \phi_r = 2((U_1 - U_2)\left(\frac{t_f + t_r}{2} - t_s\right) \qquad \textit{Eq. 22}$$

In this project only heat loss from single pipe pair have been calculated, but the heat loss from twin pipes can be calculated by methods described in EN 253.

The heat loss for symmetric pipes can be calculated by

$$U_1 = \frac{R_s + R_i}{(R_s + R_i)^2 - R_h^2} \qquad \textit{Eq. 23}$$

$$U_2 = \frac{R_h}{(R_s + R_i)^2 - R_h^2} \qquad \textit{Eq. 24}$$

Where

R_s	Specific insulation resistance of the soil	[m ºC/W]
R_i	Specific insulation resistance of the insulating material	[m ºC/W]
R_h	Specific insulation resistance of the heat exchange between flow and return pipe	[m ºC/W]

By neglecting the heat loss from the soil to the surroundings the overall heat loss can be described by:

$$U_1 - U_2 = \frac{1}{R_s + R_i + R_h} \qquad \textit{Eq. 25}$$

The following assumptions have been made;

- No temperature drops in the pipelines (According to [22] the temperature drop will vary from 1 K during the wintertime to 4 K in the summertime due to reduced flow).
- Steady state conditions, assumes constant temperature in the pipelines and the surroundings
- Neglect thermal resistance between soil and air, assumes constant soil temperature, isotherm conditions.

According to the District Heating Handbook [31] the specific insulation resistance of the soil can be calculated by:

$$R_s = \frac{1}{2\pi\lambda_s} ln \frac{4Z_c}{D_c} \qquad \textit{Eq. 26}$$

Z_c	A corrected value of the depth of the pipelines, that includes the surface transition resistance R_o, $Z_c = Z + R_o \cdot \lambda_s$
Z	Depth of burial from the surface to the center of the pipe Specific insulation resistance of the insulating material [m]
R_o	Surface transition resistance [m ºC/W] [m ºC/W]
λ_s	Coefficient of thermal conductivity of the soil. Typical values wet soil 1.5-2 [W/m ºC], dry sand 1[W/m ºC]
D_c	The diameter of the insulation material [mm](inside diameter casing)

In [31] is the specific resistance of the insulation material

$$R_{i=\frac{1}{2\pi\lambda_i} ln \frac{D_{PU}}{d_o}} \qquad \textit{Eq.27}$$

Where

D_{PU}	The diameter of the insulation material (inside diameter casing)	[mm]
do	Outer diameter of the service pipe (inside diameter insulation)	[mm]
R_o	Surface transition resistance	[m ºC/W]
λ_i	Coefficient of thermal conductivity of insulation. Maximum limit in EN 253 is 0,033 W/m ºC. Typical values for new steel pipelines with PU insulation is between 0.020 - 0.030 depending on temperature level. Due to the risk for degradation over time a conservative value 0.030 is chosen	[W/m ºC]

The specific insulation resistance of the heat exchange between flow and return pipe can be estimated by:

$$R_h = \frac{1}{4\pi\lambda_s} ln \ \frac{D_{PU}}{d_o} \qquad \textit{Eq. 28}$$

For our calculations the following input values have been chosen, λs thermal conductivity soil 1,5 (wet soil) (dry sand 1.0 W/m°C), λ insulation 0.033 W/m°C, Ro surface transition = 0.0685 m2 °C/W, with a minimum depth of burial of 610 mm according to minimum depth (District heating Handbook)

Table 22 Heat and cold loss per meter of pipeline for a selection of diameter

Dimension	tf- flow temp	tr -return temp	ts-soil temp	Heat loss [W/m]	Cold loss [W/m]
DN25	105	50	8	27,4	
	80	40	8	20,5	
	70	30	8	16,6	
	6	16	8		-0,5
	6	16	6		-0,1
	8	31	8		-0,2
	8	31	6		0,2
DN80	105	50	8	44,1	
	80	40	8	33,3	
	70	30	8	26,9	
	6	16	8		-0,9
	6	16	6		-0,2
	8	31	8		-0,5
	8	31	6		0,1
DN100	105	50	8	46,2	
	80	40	8	34,6	
	70	30	8	27,9	
	6	16	8		-0,9
	6	16	6		-0,2
	8	31	8		-0,5
	8	31	6		0,2
DN200	105	50	8	68,0	
	80	40	8	50,9	
	70	30	8	41,1	
	6	16	8		-1,4
	6	16	6		-0,5
	8	31	8		-1,0
	8	31	6		-0,1
DN600	105	50	8	140,8	
	80	40	8	105,4	
	70	30	8	85,1	
	6	16	8		-3,9
	6	16	6		-1,8
	8	31	8		-4,2
	8	31	6		-2,2

Both a change in u-value will influence on the heat loss, and the surrounding materials as well as the temperature of the soil. The cold loss increases with increasing diameter, but the effect of diameter is significantly lower than for heating pipelines due to the low temperature differences between soil and pipelines. In this study the same types of pipelines are applied for heating and cooling. Since the cold loss is lower per meter than heat loss is it common to use pipelines with reduced insulation levels and thereby increase the cold loss.

5.7 Development of case grid

The energy intensity in an area will influence on both PEF and CO_2 equivalents. At the same power/output will a low intensity area; transport the fluid for a longer distance, and thereby increase the heat loss and the energy for pumps compared with a high intensity area. This again will increase the PEF and CO_2 equivalent for per delivered kWh heat/cool.

We have chosen to develop some artificial DH grids based on input from the expert group, the grids have the same proportion of the different dimensions. The grid is aggregated, consisting of 14.5% DN 25-60, 7.7% DN80, 23.9% DN100-150, 51.8% DN 200-500 and 2% DN>500.

Table 23 Example Composition of grid, lengths of different dimensions for low intensity area 3 kWh/m

Maximum Power [MW]	DN 25 [m]	DN 80 [m]	DN 100 [m]	DN 200 [m]	DN 600 [m]
5	802	427	1329	2877	113
10	1604	854	2657	5754	227
20	3208	1709	5315	11509	453
25	4010	2136	6643	14386	566
100	16042	8543	26573	57543	2266
200	32083	17086	53147	115087	4531
400	64166	34171	106294	230174	9062
1000	160415	85428	265734	575434	22655

Table 24 Example composition of grid, lengths of different dimensions for low density areas cooling

Maximum Power [MW]	DN 25 [m]	DN 80 [m]	DN 100 [m]	DN 200 [m]	DN 600 [m]
5	916	488	1517	3284	129
10	1831	975	3033	6568	259
20	3662	1950	6066	13137	517
25	4578	2438	7583	16421	646
100	18311	9751	30332	65683	2586
200	36621	19502	60664	131366	5172
400	73242	39004	121329	262731	10344
1000	183105	97511	303321	656828	25860

5.7.1 *Infrastructure*

Infrastructure is based on calculation of production of pipeline and excavation per meter of pipeline. The infrastructure must be divided on the delivered kWh over the expected lifetime. It is therefore possible to combine pipeline production and excavation of trenches in one parameter assuming the same lifetime of 30 years. This is a worst case scenario since most pipelines today are expected to last for more than 50-60 years.

Demolitions of the pipes are not included in the LCA, since major parts of the pipes are recyclable. Replacing of old pipelines will be carried out by the same method as excavation, where is possible to reuse even more of the sand and gravel, still the asphalt must be removed and replaced. To prevent double counting only the initial excavation is included.

Table 25 PEF and CO_2 equivalents per yearly delivered kWh heat to the end user for Case A,

	Low intensity 3 MWh/m		Medium intensity 8.2 MWh/m		High intensity 15 MWh/m	
	30 years	60 years	30 years	60 years	30 years	60 years
PEF non-renewable per kWh	0,01164	0,00582	0,00420	0,00235	0,00078	0,00039
CO_2 equivalents per kWh	2,86	1,43	1,16	0,58	0,19	0,10

Since the designed layout of the grid has the same proportions for all sizes of the power plant, the PEF and CO_2 equivalents will be the same for all examined geometries. Both the PEF and CO_2 equivalent will vary with energy intensity, because the production is proportional with the length of the net.

5.7.2 *Heat and Cold loss*

The heat loss (cooling) and head loss is dependent on the operation of the pipes. The most important factors are the flow, supply, return and soil temperature, insulation and dimensions of the pipes. In this study a few sizes have been chosen DN25, DN25 twin, DN80, DN80 twin, DN100, DN200, DN200 twin and DN600. An actual piping network will consist of different sizes of pipes and the results cannot be directly applied to calculate existing networks. The intention with this study was to provide information on the parameters with most impact on CO_2 emissions and PEF. Average pipelines have previously been used in Danish studies in order to simplify the calculation of head loss, but the result from this study cannot be directly applied without further studies.

Table 26 Case A and Case I Percentage heat/cold loss for different energy intensities

	Low intensity 3 MWh/m	Medium intensity 8.2 MWh/m	High intensity 15 MWh/m
Case A	13,29	5,36	0,89
Case II 6/16	11.4	4.1	2.8

5.7.3 *Determination of pump energy*

The energy for operation of pumps depends on the length of the pipelines and the flow as described in chapter 5.5.3.

Table 27 Example calculation of energy for operation of pumps for different power plant sizes

Power Plant [MW]	Low intensity 3 MWh/m	Medium intensity 8,2 MWh/m	High intensity 15 MWh/m
5	370	135	25
10	741	271	49
20	1482	541	99
25	1852	676	123
100	7410	2706	494
200	14819	5411	988
400	29639	10823	1976
1000	74097	27057	4940

Since the layout of the DH grid of different sizes is similar, the size will not influence on the PEF and CO_2 values. The actual layout of a small and a large DH will usually not be similar; a large grid will often have a different composition, with more transmission lines.

5.8 Conclusion district heating and cooling grid

The same calculation methods are applied for calculation for heating and cooling. The district heating grid will influence both the PEF and CO_2 emissions; the main impact parameter is related to the energy density. In a low density area, the impact from infrastructure will increase the PEF and CO_2 emissions per delivered kWh to the end user, due to the increased length of the grid. Both the head loss and the heat loss increases with length.

The temperature difference between supply and return is substantially lower for cooling than heating. The PEF and CO_2 equivalents per meter of pipeline and excavation will be higher, in addition to higher head loss due to alterations in kinematic viscosity at lower temperatures. The heat loss will be reduced by reduced temperature difference between supply and return temperature and the soil temperature.

Increasing lifetime expectancies will significantly reduce the impact of the pipelines and excavation of pipes, newer pipelines will probably last for more than the assumed lifetime of 30 years. For practical purposes can the PEF values for excavation of trenches be neglected, but the CO_2 emissions will have an impact in low intensity areas. Some studies [32] and show reduced CO_2 emission when no-dig methods are applied. In urban areas no-dig methods should be integrated in methods for calculation of PEF and CO_2 equivalents.

Only pre-insulated single steel pipelines have been examined. Twin, triple and quadruple pipelines should also be surveyed, since this might affect both PEF and CO_2 both in the building phase and the operational phase caused by reduced heat/cold loss. We have used a conservative u-value of 0,033 [W/m°C] slightly below requirements in EN 253, even though new pipelines might have significantly lower u-values which will reduce the heat loss. New materials like flexible PEX-pipelines, specially designed for low intensity areas should be examined. According the producers are both the u-value and the excavation cost lower, some of the producers also claim that LCA inventories will be carried out.

The head loss depends amongst others on the flow and the roughness; reduced flow will reduce the head loss whilst the delivered energy will be reduced. Corrosion will increase the roughness and thereby increase the energy needed for pumps. Different materials in the service pipe might have different roughness, and the head loss must be recalculated. The effect of possible additives has not been examined due to lack of consistent data. Some studies shows a reduction in friction, but the possible impact on heat exchangers efficiency is not documented.

In this study, the efficiency of the pump is assumed constant (85%), newer pumps with improved automatically variable speed will improve the efficiency and reduce need for power. Due to the Power bonus method and the weighting of power/electricity, the minor changes in the efficiency of pumps will affect the PEF and CO_2 emissions.

6 Analysis of CHP plant simulations

6.1 Simulation conditions

The purpose of CHP simulation is to evaluate the potential for efficiency improvements by choice in the DH water return and supply temperature. We chose three kinds of fuel for CHP - woodchip, oil and natural gas (NG). We selected a general size CHP according to each fuel. Chapter 6.2**Fel! Hittar inte referenskälla.** contains the analysis of the relation between efficiency (heat, electricity, total) and the return temperature of the district heat. Chapter 6.3 describes the analysis of the relation between efficiency and DH water supply temperature. Chapter 6.4 shows the analysis of the relation between efficiency and power to heat ratio.

Modelling standards

1. Base Condition
   Atmosphere temperature: -5°C
   Return temperature of DH water: 50 °C
   Supply temperature of DH water: 105°C
2. Gas turbine model in the case of NG CHP: MHI501F installed in Hwa-Sung branch of KDHC
3. Modelling program : Thermoflex [37]
4. The figures below shows schematic diagram of the analysed systems, for details see the heat balance diagram in Appendix A.

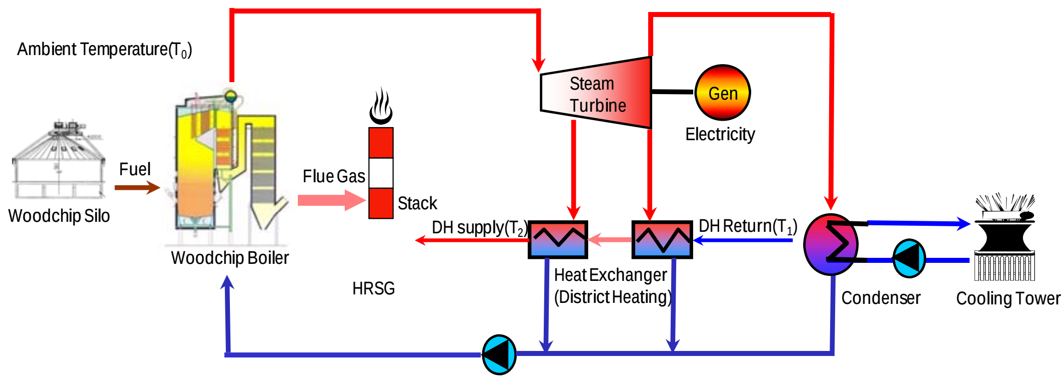

Figure 21 Woodchip CHP Schematic Diagram

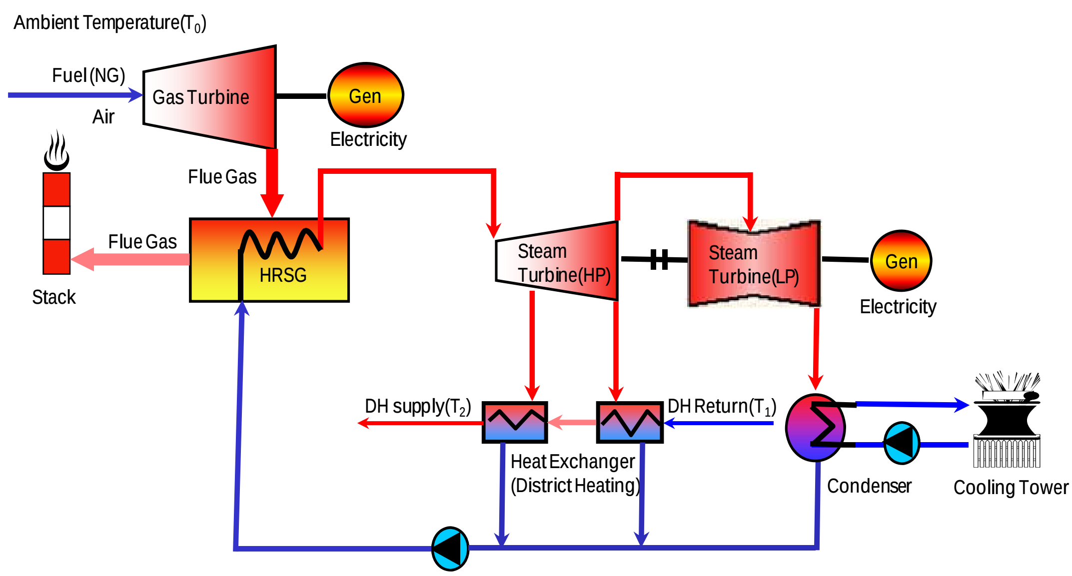

Figure 22. NG CHP Schematic Diagram

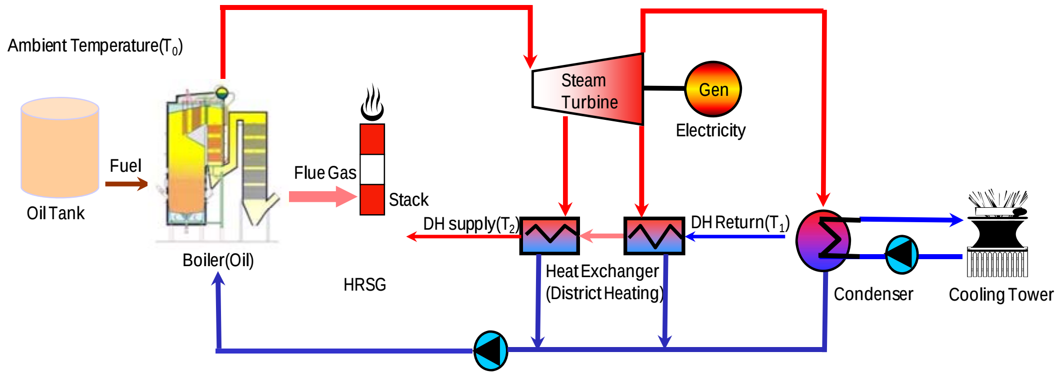

Figure 23. Heavy Oil CHP Schematic Diagram

<u>Capacity of CHP (electricity + heat output) and main equipment</u>

1. Woodchip CHP modelling capacity: 75MW grade
   Main equipment: Boiler, Steam turbine, DH heat exchanger
2. NG CHP modelling capacity: 1,000MW grade
   Main equipment: Gas turbine (MHI 501F), Heat Recovery Steam Generator (HRSG), Steam turbine, DH heat exchanger
3. Heavy Oil CHP Modelling size: 100MW grade
   Main equipment: Boiler, Steam turbine, DH heat exchanger

<u>Simulation execute condition using modelled CHP</u>

1. Atmosphere temperature (-5°C, 10°C, 20°C)
2. DH supply temperature variation 120°C, 105°C, 90°C, 70°C at DH return temperature 50°C
3. DH return temperature variation 60°C, 55°C, 50°C, 45°C, 40°C at DH supply temperature 105°C

Appendix B includes the result data of this simulation using each type of CHP model.

6.2 CHP efficiency variation with return temperature of DH water

This simulation was carried out in order to assess the improvement of total energy efficiency, by examine the variation of CHP efficiency caused by variations in DH return temperature. The figures below show the variation of CHP efficiency by change of DH return temperature (inlet temperature of heat exchanger) for each type of CHP when the DH supply temperature (outlet temperature of heat exchanger) was fixed at 105°C.

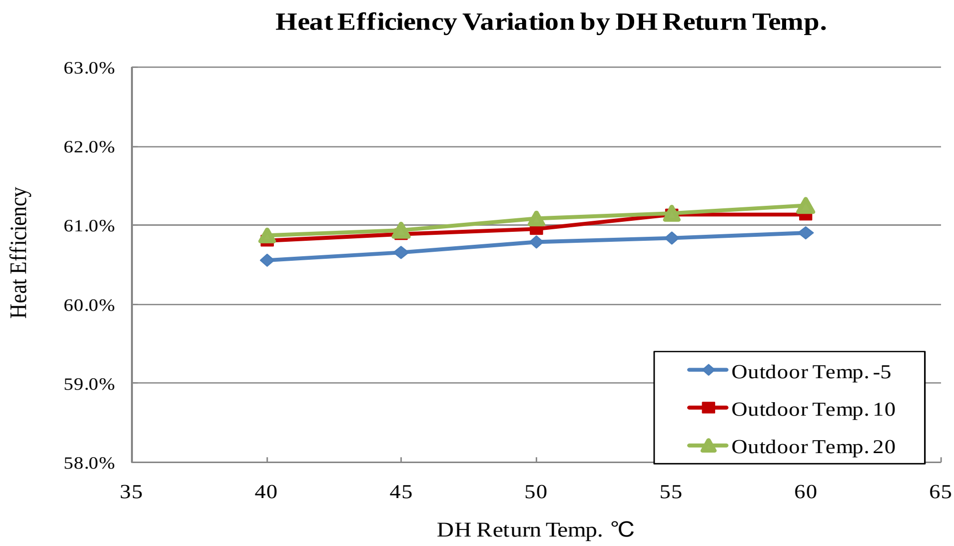

Figure 24 Woodchip CHP (75MW Grade) – Heat Efficiency Variation by DH Return Temp

Figure 24 shows the relation between woodchip CHP heat efficiency variation and DH water return temperature. In this figure we can find that higher DH return temperature can increase heat efficiency. In the case of DH return temperature increase, internal vapour pressure of the heat exchanger also increases. This phenomenon can cause exhaust steam pressure ascension and high steam energy used for more heat output. We can also find that ambient temperature drop can decrease heat efficiency. Because combustion heat is added to compensate lower total output due to lower ambient temperature. It is the reason why heat efficiency and output decreases by lower ambient temperature.

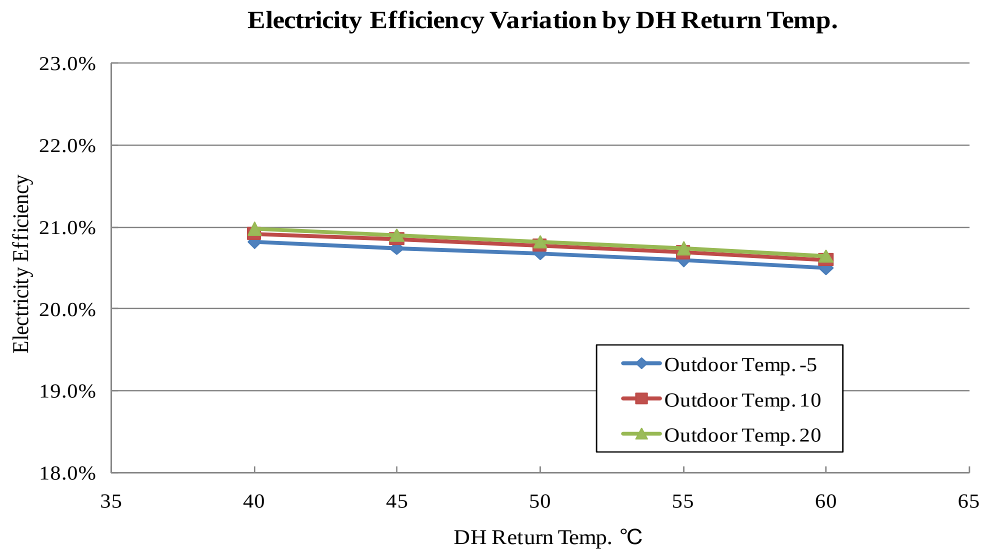

Figure 25 Woodchip CHP(75MW Grade) – Electricity Efficiency Variation by DH Return Temp

Figure 25 shows the relation between electricity efficiency variation and DH water return temperature. In this figure we can find that higher DH return temperature can decrease electricity efficiency. This is caused by increased heat output and efficiency.

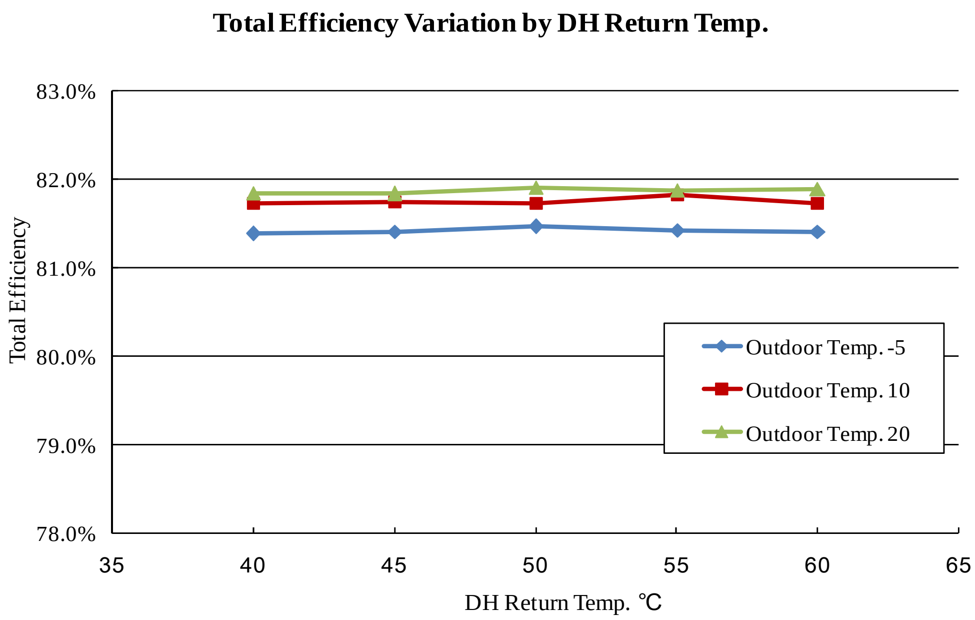

Figure 26 Woodchip CHP (75MW Grade) – Total Efficiency Variation by DH Return Temp

Figure 26 shows the relation between total efficiency variation and DH water return temperature. In this figure we can find that total efficiency is almost constant. There is no relationship between total efficiency of CHP and DH water return temperature. Because decreased electricity efficiency is balanced by increased heat efficiency.

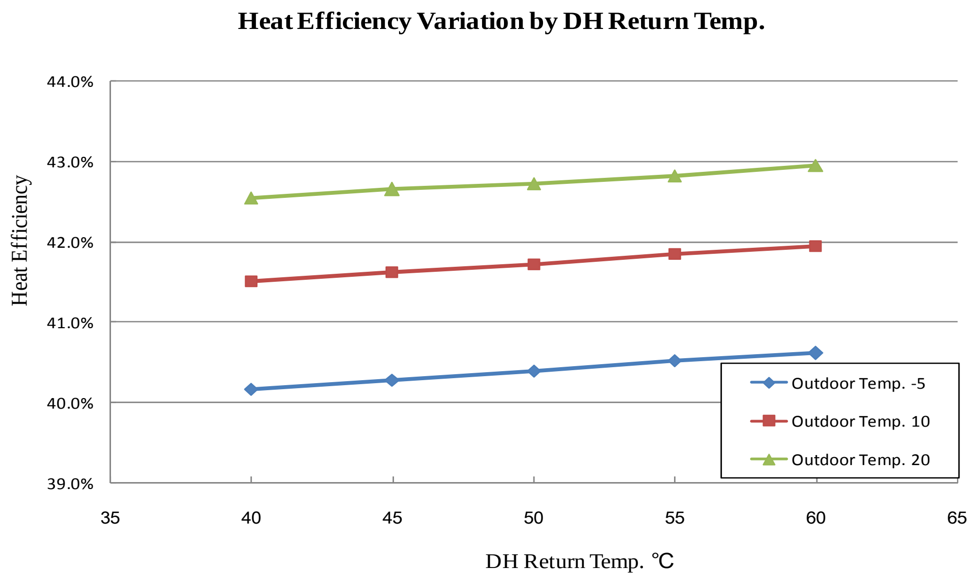

Figure 27 NG CHP (1000MW Grade) –Heat Efficiency Variation by DH Return Temp

Figure 27 shows the relation between NG CHP heat efficiency variation and DH water return temperature. In this figure we can find that higher DH return temperature can increase Heat efficiency. This result is same to woodchip CHP and the reason is also same. When the ambient temperature decreases, air density increases. For same combustion temperature as in a gas turbine, more fuel will be needed and output will increase. So ambient temperature drop can increase heat output in NG CHP. But the efficiency will decrease by the increasing heat rate (fuel injection rate as the same output). Finally, the efficiency is increased by the decreasing heat rate as ambient temperature increases.

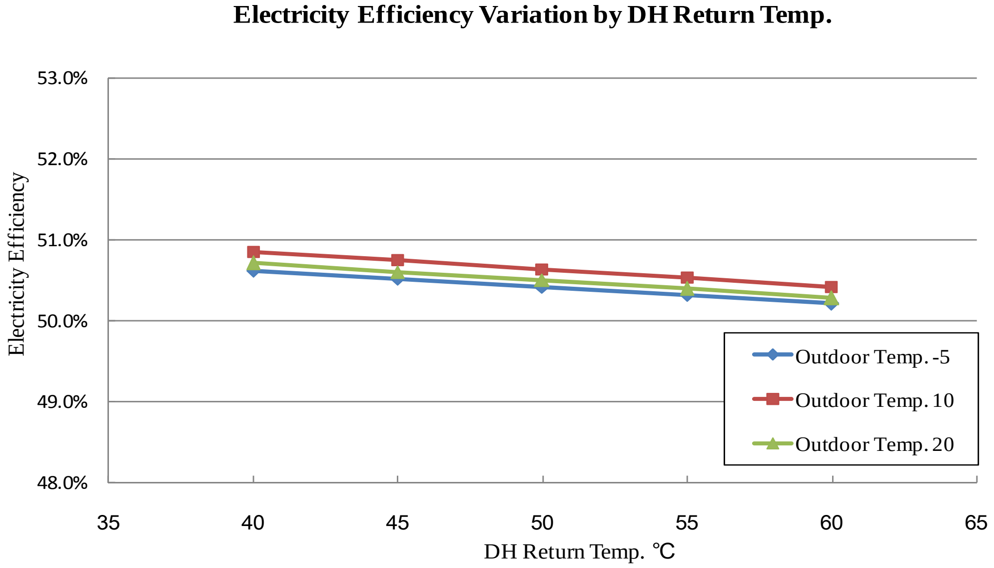

Figure 28 NG CHP (1000MW Grade) – Electricity Efficiency Variation by DH Return Temp

Figure 28 shows the relation between electricity efficiency variation and DH water return temperature. In this figure we can find that higher DH return temperature can decrease electricity efficiency. This result is same to woodchip CHP and the reason is also same.

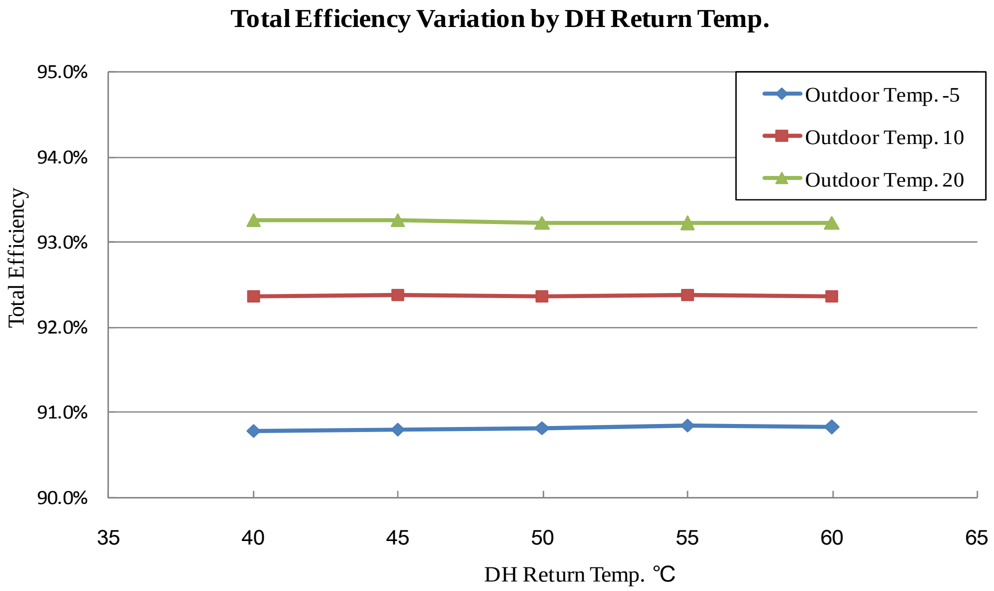

Figure 29 NG CHP (1000MW Grade) – Total Efficiency Variation by DH Return Temp

Figure 29 shows the relation between total efficiency variation and DH water return temperature. total efficiency is almost constant. It is same to woodchip CHP and reason is also same.

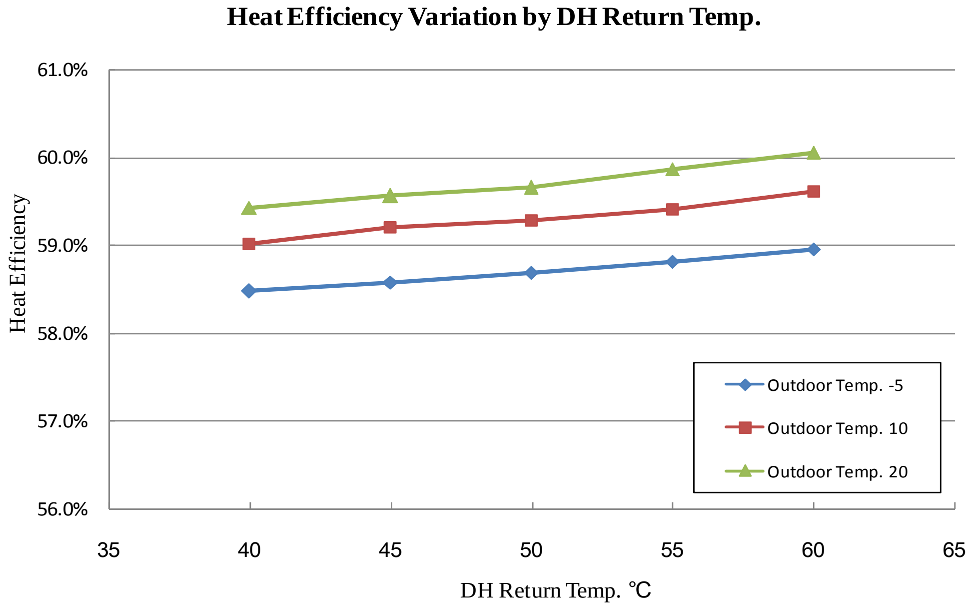

Figure 30 Oil CHP (100MWGrade) – Heat Efficiency Variation by DH Return Temp

Figure 30 shows the relation between oil CHP heat efficiency variation and DH water return temperature. In this figure we can find that higher DH return temperature can increase heat efficiency. Influence of ambient temperature is same to woodchip CHP.

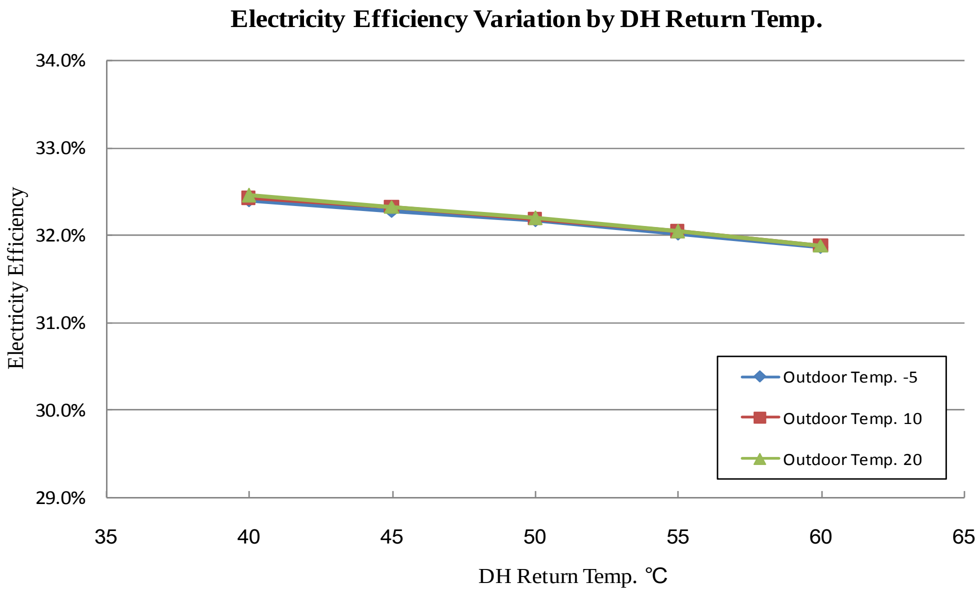

Figure 31 Oil CHP (100MWGrade) – Electricity Efficiency Variation by DH Return Temp

Figure 31 shows the relation between electricity efficiency variation and DH water return temperature. In this figure we can find that higher DH return temperature can decrease electricity efficiency.

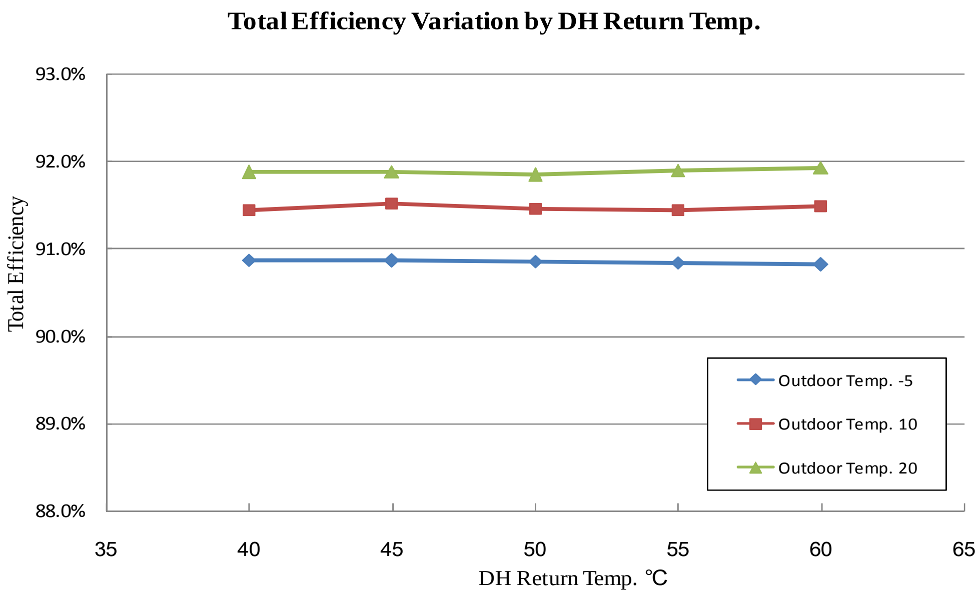

Figure 32 Oil CHP (100MWGrade) – Total Efficiency Variation by DH Return Temp

Figure 32 shows the relation between total efficiency variation and DH water return temperature. Total efficiency is almost constant.

As the above figures indicate, the more the return temperature is increased (ΔT is decreased, because of the fixed DH supply temperature), the more the heat efficiency is increased and electricity efficiency is decreased. But whole efficiency is almost constant because the decreased electricity efficiency is balanced by the increased heat efficiency. In the case of increasing DH return temperature, internal vapour pressure of the heat exchanger also increases. This phenomenon can cause exhaust steam pressure to increase and high steam energy are used for not more electricity but more heat output. Eventually heat output will increase and electricity output will decrease by an increase of DH return temperature. Heat and electricity efficiency also followed similar results as in the above figures.

We can find that total output of CHP is not affected by DH return temperature variation. But if we choose alternative generation method or power bonus method as an allocation method, then decrease of DH return temperature - can reduce PEF_{dh} & GWP_{dh} . That's why low DH return temperature can increase electricity efficiency and it will lead to reduce an allocation $factor_{heat}$ due to an increase of electricity efficiency. This can demonstrate that to reduce return temperature is more valuable to us in view of reducing GWP & the use of PE.

In addition, at lower return temperature, transfer power is decreased because of the decrease in forward flow caused by an increase of temperature deference. The reduction of feed flow rate decreases the size of the network pipeline that will be needed. By reducing installation cost and weight loss of piping, a good plan can be put into effect to reduce primary energy and CO2 emissions.

In the case of NG used as fuel for the CHP, when the ambient temperature decreases, air density increases. For same combustion temperature as in a gas turbine, more fuel will be needed and output will increase, but the efficiency will decrease by the increasing heat rate (fuel injection rate as the same output).

On the other hand, in the case of using wood chips or heavy oil, when ambient temperature decreases, combustion heat is added which leads to a lower total output and efficiency. This phenomenon is shown as the opposite side of NG CHP. However, any action of improving efficiency and output is not considered because there is no operation to control ambient temperature.

6.3 CHP efficiency variation with supply temperature of DH water

This simulation was performed to investigate the total energy efficiency increase by changing the efficiency of the CHP at different DH supply temperatures. In the next charts below, it is shown that efficiency changes as the DH supply temperature (return temperature set to 50°C) changes for different fuels used during the simulation.

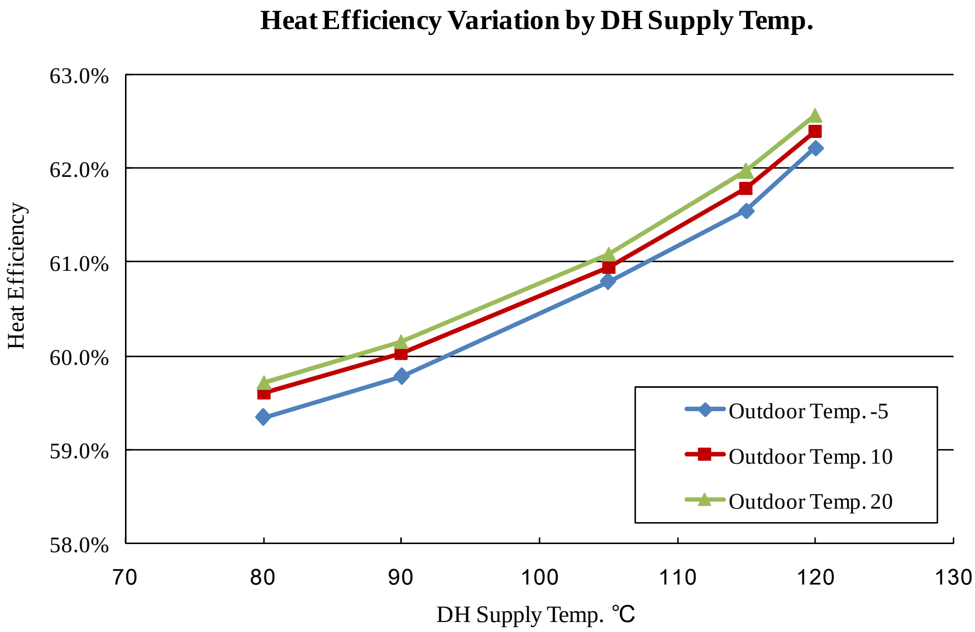

Figure 33 Woodchip CHP(75MW Grade) – Heat Efficiency Variation by DH Supply Temp

Figure 33 shows the relation between woodchip CHP Heat efficiency variation and DH water supply temperature. In this figure we can find that higher DH supply temperature can increase Heat efficiency. If the flow rate of the exhaust or extract steam at the steam turbine is raised for increasing DH heater supply temperature at the constant condition of DH return temperature, it will decrease electricity output but increase heat output. Efficiency also remains the same regarding output variation. Influence of outdoor temperature is also same to DH return temperature cases.

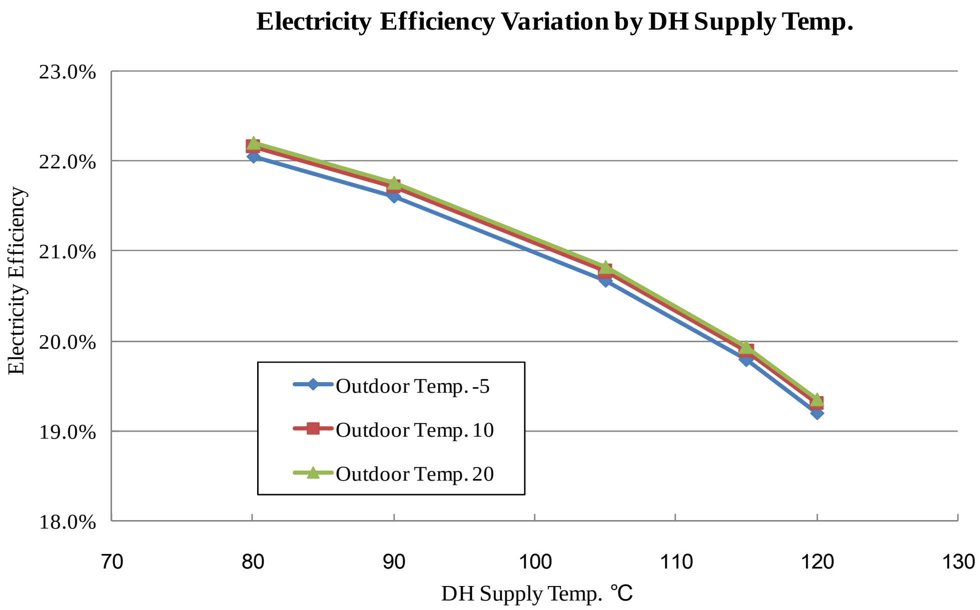

Figure 34 Woodchip CHP(75MW Grade) – Electricity Efficiency Variation by DH Supply Temp

Figure 34 shows the relation between electricity efficiency variation and DH water supply temperature. In this figure we can find that higher DH supply temperature can decrease electricity efficiency. This is caused by increased heat output and efficiency.

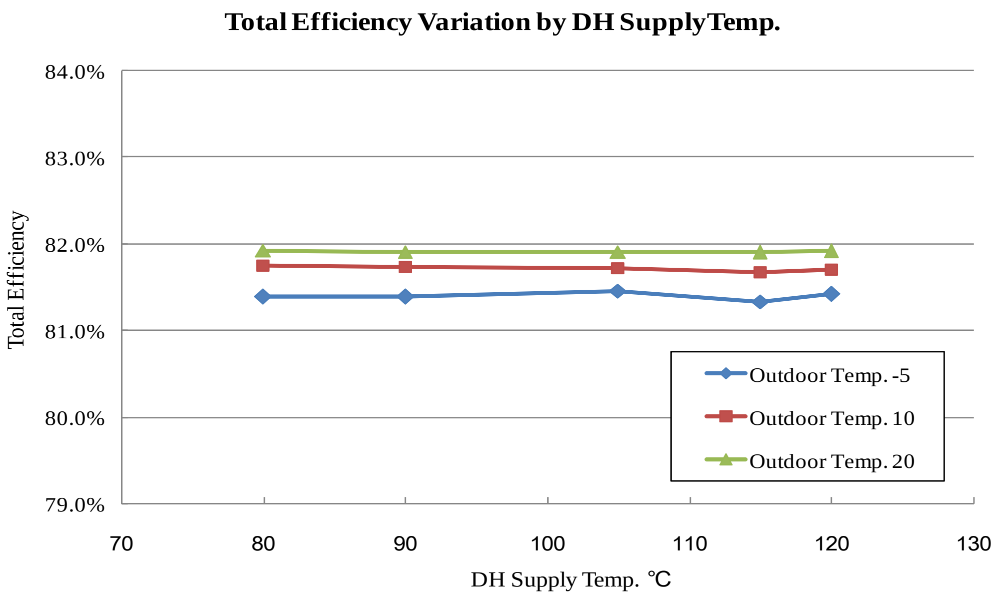

Figure 35 Woodchip CHP (75MW Grade) – Total Efficiency Variation by DH Supply Temp

Figure 35 shows the relation between total efficiency variation and DH water supply temperature. In this figure we can find that Total efficiency is almost constant. There is no relationship between total efficiency of CHP and DH supply temperature. Because decreased electricity efficiency is balanced by increased heat efficiency.

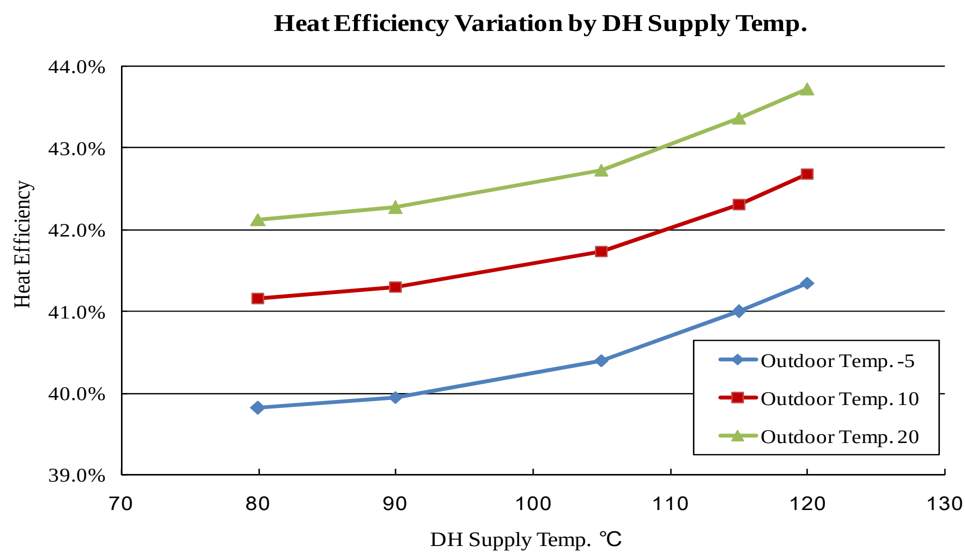

Figure 36 NG CHP (1000MW Grade) – Heat Efficiency Variation by DH Supply Temp

Figure 36 shows the relation between NG CHP heat efficiency variation and DH water supply temperature. In this figure we can find that higher DH supply temperature can increase heat efficiency. This result is same to woodchip CHP and the reason is also same.

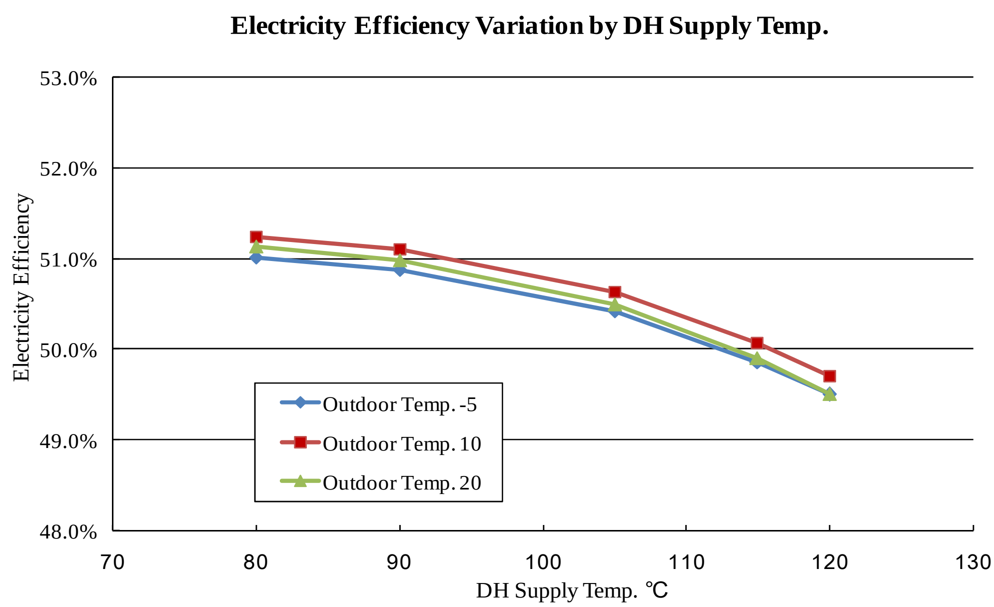

Figure 37 NG CHP (1000MW Grade) – Electricity Efficiency Variation by DH Supply Temp

Figure 37 shows the relation between electricity efficiency variation and DH water supply temperature. In this figure we can find that higher DH supply temperature can decrease electricity efficiency. This result is same to woodchip CHP and the reason is also same.

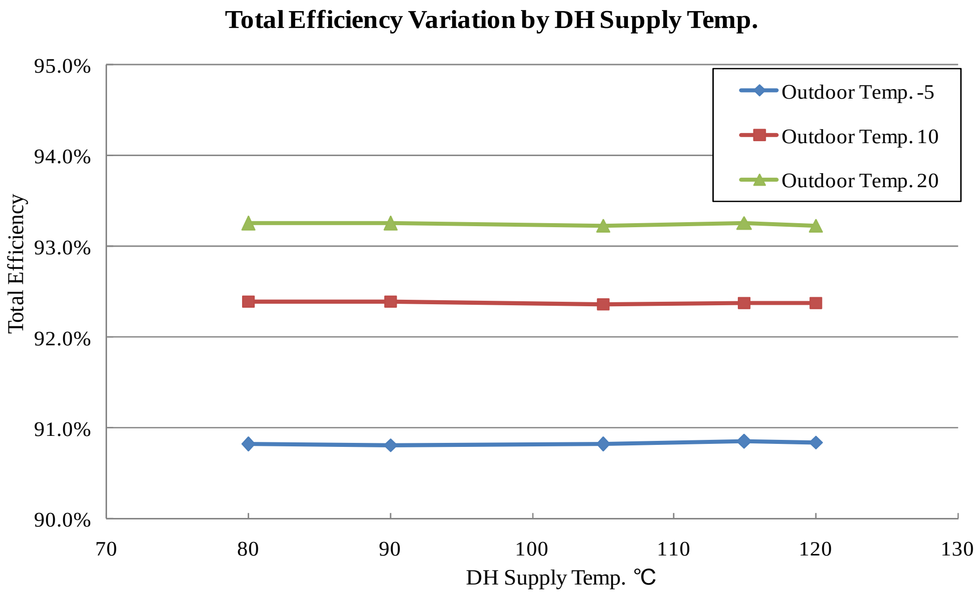

Figure 38 NG CHP (1000MW Grade) – Total Efficiency Variation by DH Supply Temp

Figure 38 shows the relation between total efficiency variation and DH water supply temperature. In this figure we can find that total efficiency is almost constant. It is same to woodchip CHP and reason is also same.

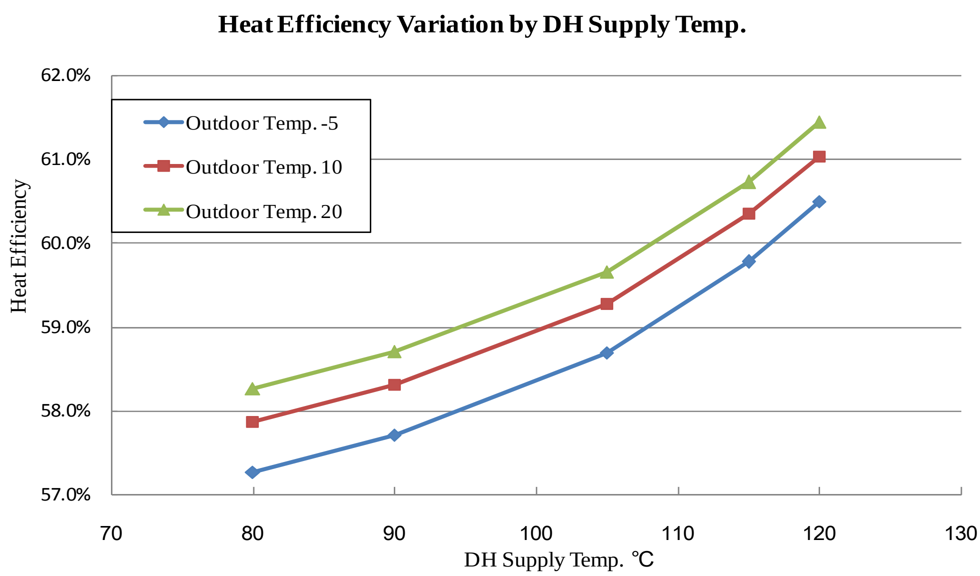

Figure 39 Oil CHP (100MWGrade) – Heat Efficiency Variation by DH Supply Temp

Figure 39 shows the relation between oil CHP heat efficiency variation and DH water supply temperature. In this figure we can find that higher DH supply temperature can increase heat efficiency.

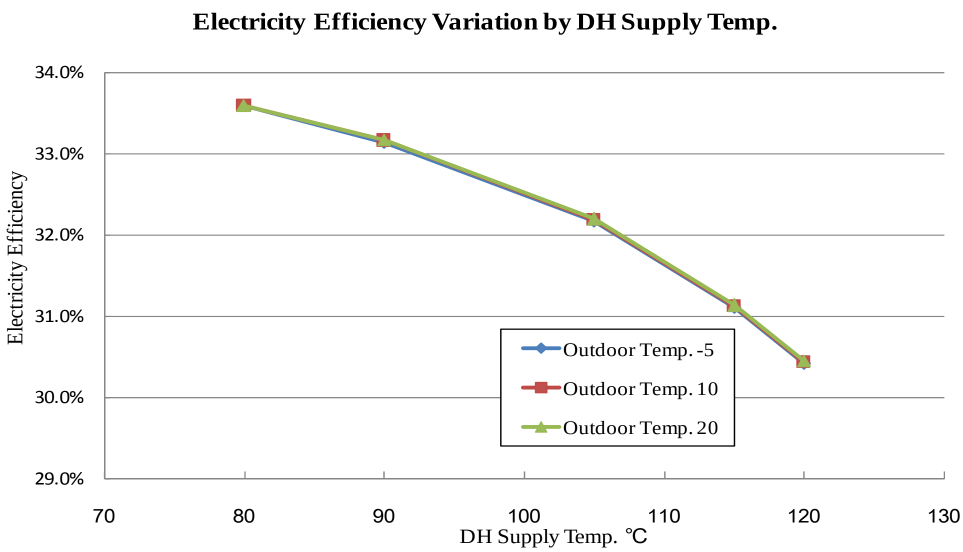

Figure 40 Oil CHP (100MWGrade) – Electricity Efficiency Variation by DH Supply Temp

Figure 40 shows the relation between electricity efficiency variation and DH water supply temperature. In this figure we can find that higher DH supply temperature can decrease electricity efficiency.

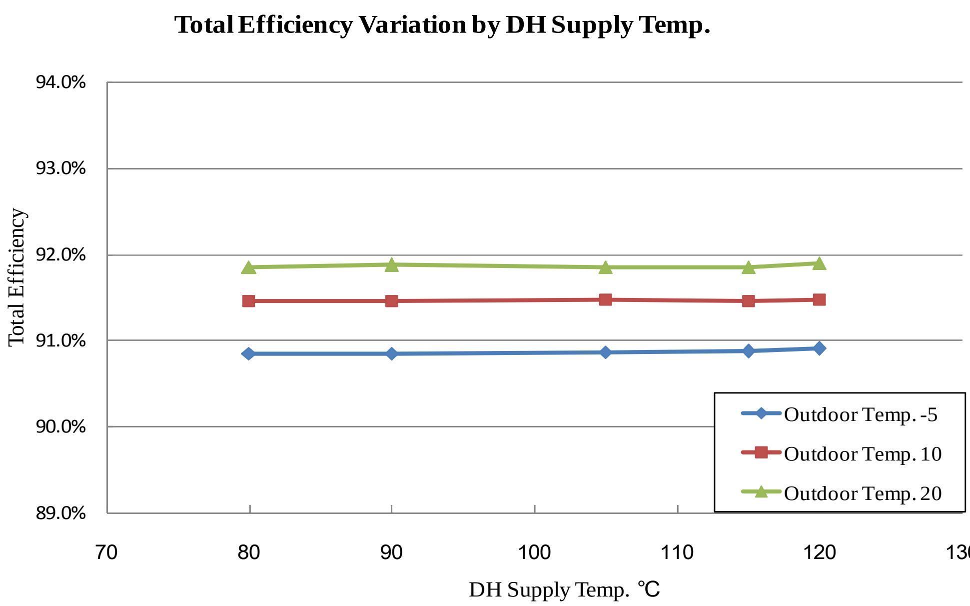

Figure 41 Oil CHP(100MWGrade) – Total Efficiency Variation by DH Supply Temp

Figure 41 shows the relation between total efficiency variation and DH water supply temperature. In this figure we can find that total efficiency is almost constant.

From the graph, higher temperature leads to more thermal efficiency and less electrical efficiency. Total efficiency is insignificant because of the counterbalance of more thermal efficiency and less electrical efficiency.

If the flow rate of the exhaust or extract steam at the steam turbine is raised for increasing DH heater supply temperature at the constant condition of DH return temperature, it will decrease electricity output but increase heat output. Efficiency also remains the same regarding output variation.

It can be supposed that DH supply temperature also has little impact on total output. As DH return temperature, it makes sure that energy consumption of the DH area is decreased if a power bonus or alternative production method is used to find out primary energy consumption, but not in an energy method. Given these facts, turning down the DH supply temperature can be a sort of solution to produce useful energy and to reduce the use of primary energy and CO_2 emissions related to the DH system.

A decrease of the DH supply temperature appears to have another benefit in that will lengthen the DH pipeline's lifetime because carbonization of polyurethane insulator of DH pipeline is postponed. But if return temperature is fixed and supply temperature is turned down, transfer power increases according to an increase of transfer flow followed by a decreased temperature difference. In this case, the increase of transfer flow can cause the increase of the diameter of the DH pipeline. Hence in the case of a decrease of DH supply temperature, it has to equally decrease the DH return temperature for using same size of DH pipeline.

The graph below displays the efficiency change by a DH supply temperature and return increase of 1℃ in each of the fuels.

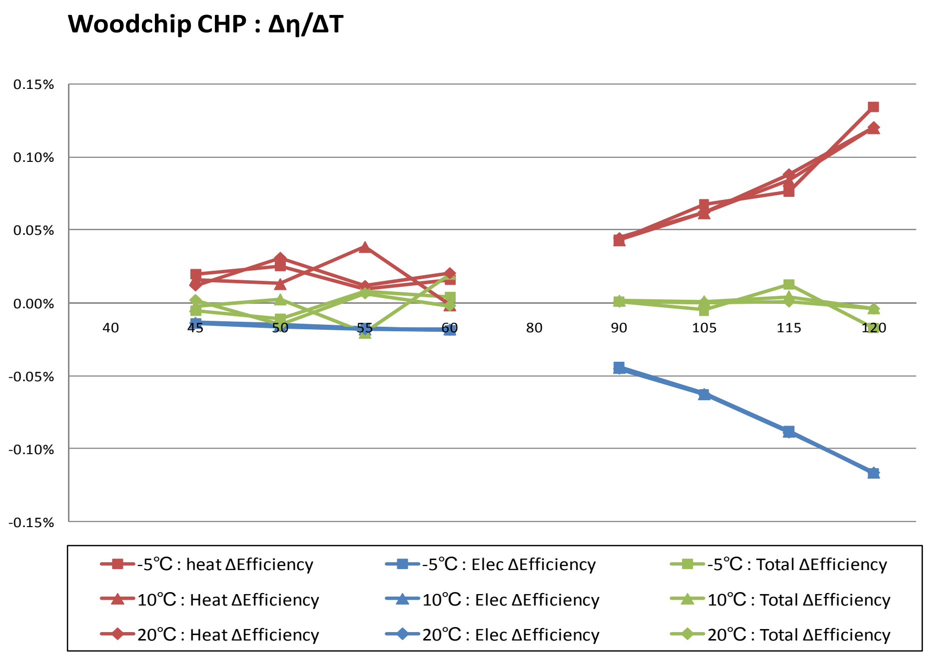

Figure 42 Woodchip CHP(75MW Grade) – Efficiency Variation rate by unit DH Temp. increase

Figure 42 shows the efficiency change by a DH supply temperature and return increase of 1℃ in woodchip CHP.

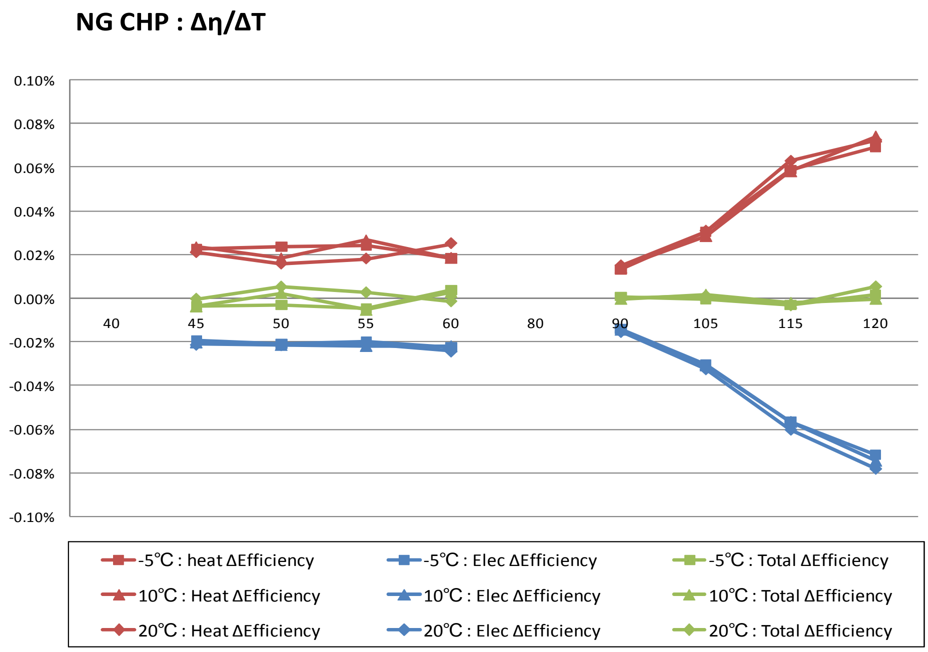

Figure 43 NG CHP (1000MW Grade) – Efficiency Variation rate by unit DH Temp increase

Figure 43 shows the efficiency change by a DH supply temperature and return increase of 1℃ in NG CHP.

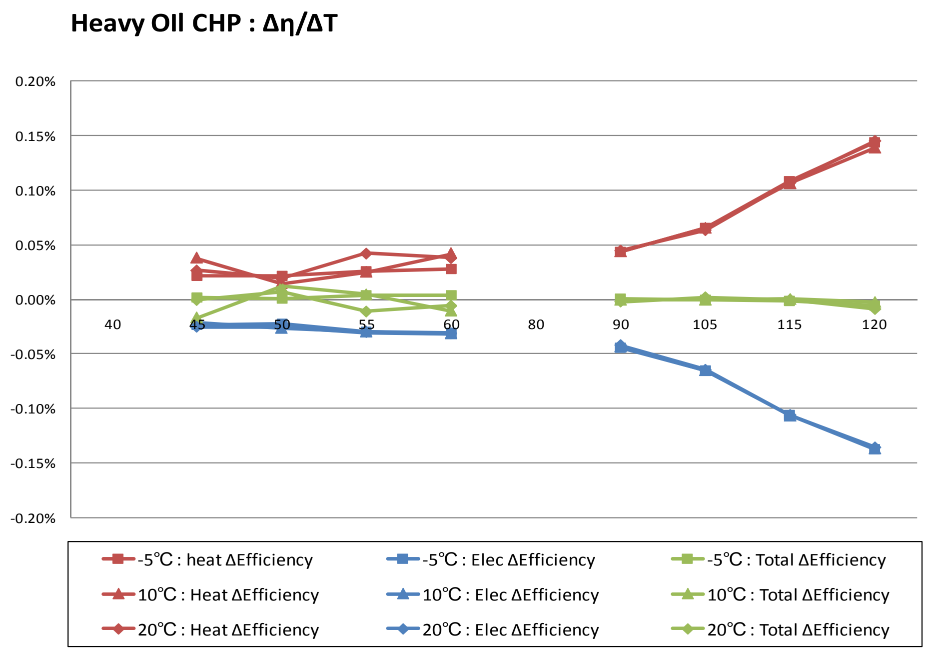

Figure 44 Oil CHP (100MW Grade) – Efficiency Variation rate by unit DH Temp increase

Figure 44 shows the efficiency change by a DH supply temperature and return increase of 1℃ in oil CHP.

In the figures we can find the fact that thermal output and an increased efficiency rate ascends where the temperature zone will increase, but the relative electricity output and efficiency increasing rate descends.

We can know there is no big change of whole output and efficiency where the temperature zone changes. This is because whole output and efficiency is not effected by DH supply and return temperature.

We also attempted to compare the increasing rate of electric efficiency in regards to changes of the DH supply and DH return temperature. The method of lowering DH supply temperature can achieve a more effective result compared to lowering DH return temperature in order to affect an electricity efficiency increase. Thus the most effective way to reduce GWP and the use of PE in DH system is to drop DH supply temperature.

When we need to select the DH supply and return temperature for high electricity efficiency, the most effective method is to choose a lower DH supply and return temperature. But if we can not change both of them, lowering supply temperature is much better.

6.4 The relation between CHP efficiency and power to heat ratio

The figure below shows the variation of CHP Total efficiency by power to heat ratio change in each type of fuel.

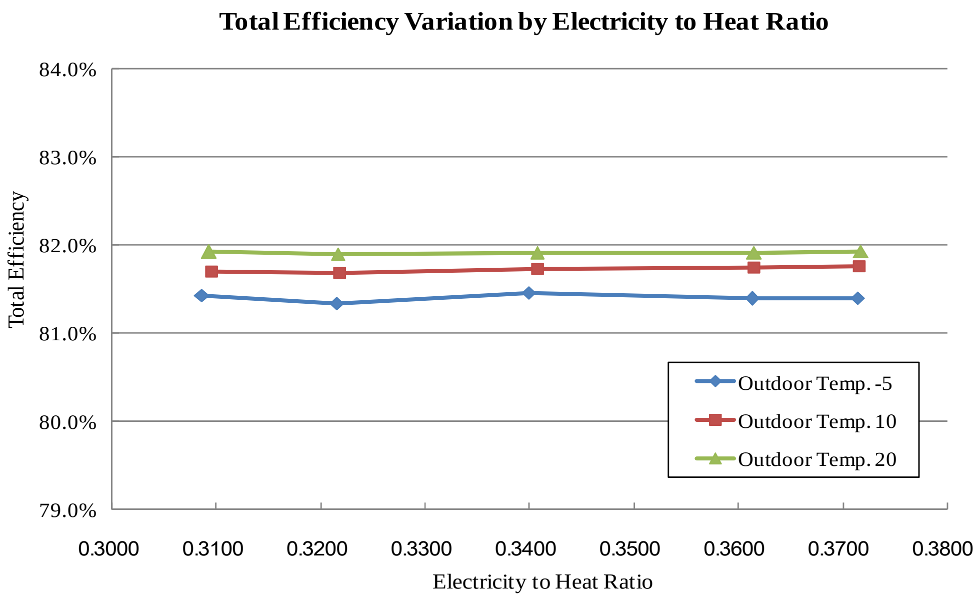

Figure 45 Woodchip CHP (75MW Grade) – Efficiency Variation by Electricity to Heat Ratio

Figure 45 shows the Total efficiency variation by a power to heat ratio change in Woodchip CHP.

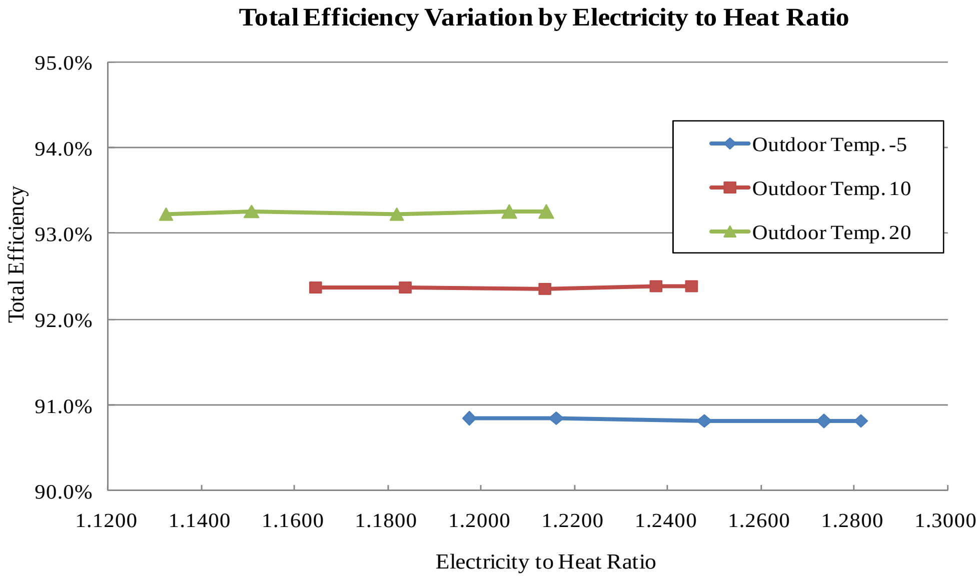

Figure 46 NG CHP (1000MWgrade) – Efficiency Variation by Power to Heat Ratio

Figure 46 shows the Total efficiency variation by a power to heat ratio change in NG CHP.

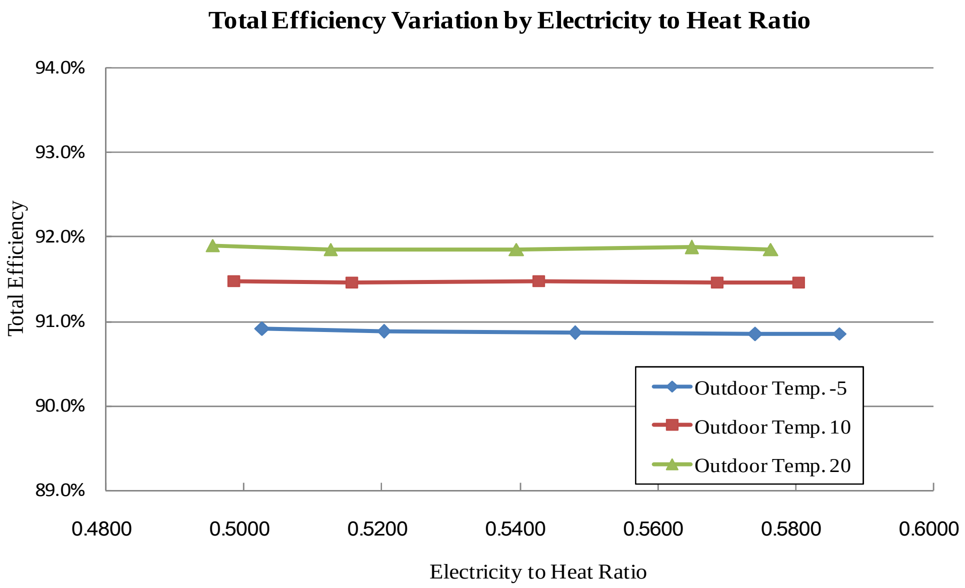

Figure 47 Heavy Oil CHP (100MWgrade) – Efficiency Variation by Power to Heat Ratio

Figure 47 shows the total efficiency variation by a power to heat ratio change in NG CHP. Power to heat ratio is usually set at the design point and can be regarded as a characteristic value. Its range of variation is very narrow, however operation conditions can change. As the above figure indicates, we can see that power to heat ratio can not impact the CHP efficiency variation. It is because power to heat ratio is directly related to DH water temperature and it shows a similar trend to the DH supply temperature versus CHP total efficiency.

7 Analysis of Absorption chiller simulations

7.1 Simulation conditions

We used a 1, 2 stage hot water ABS chiller located in a substation for the simulation. The product model data for this simulation was contributed by World Energy Company. So result of this simulation can be different depending on specific the chiller manufacturers, but its range will be very narrow.

In chapter 9.2, it contains the analysis of the relation between cooling capacity of ABS chiller and entering DH water temperature. In chapter 9.3, it contains the analysis of the relation between COP of ABS chiller and entering DH water temperature. In chapter 9.4, it contains the analysis of the relation leaving DH water temperature and types of ABS chiller.

Equipment design standards

1. DH water entering temperature 95°C and leaving temperature 80°C at the generator(in the case of 2 stage 55°C)
2. Chilled water return temperature 13°C, supply temperature 8°C at the evaporator.
3. Cooling water return temperature 31°C at the absorber, supply temperature 36°C at the condenser.

Simulation conditions

1 Entering DH water temperature was varied from 70℃ to 120℃ at 5℃ intervals

2 Chiller efficiency, DH water leaving temperature, Cooling capacity variation by entering DH temperature change based on 1, 2 stage hot water ABS chiller (2stage chiller auxiliary cycle on/off).

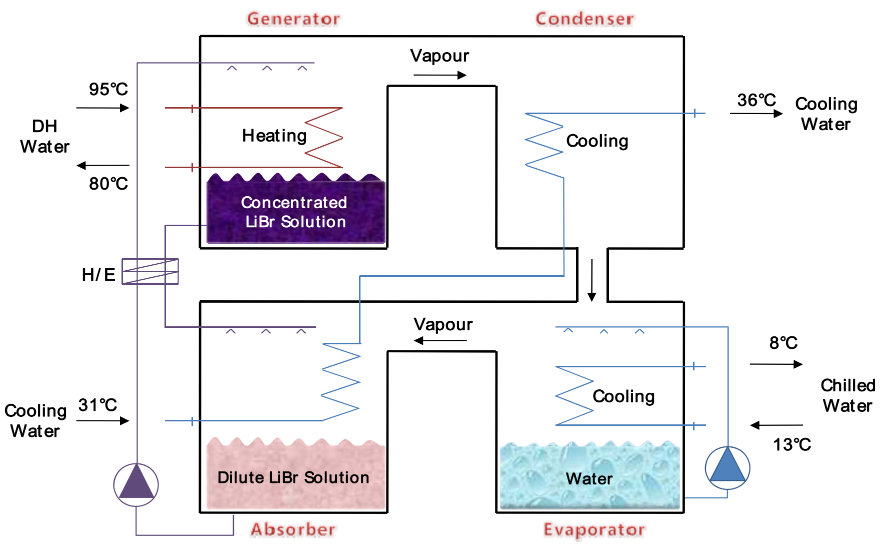

Figure 48. 1-stage ABS chiller schematic diagram

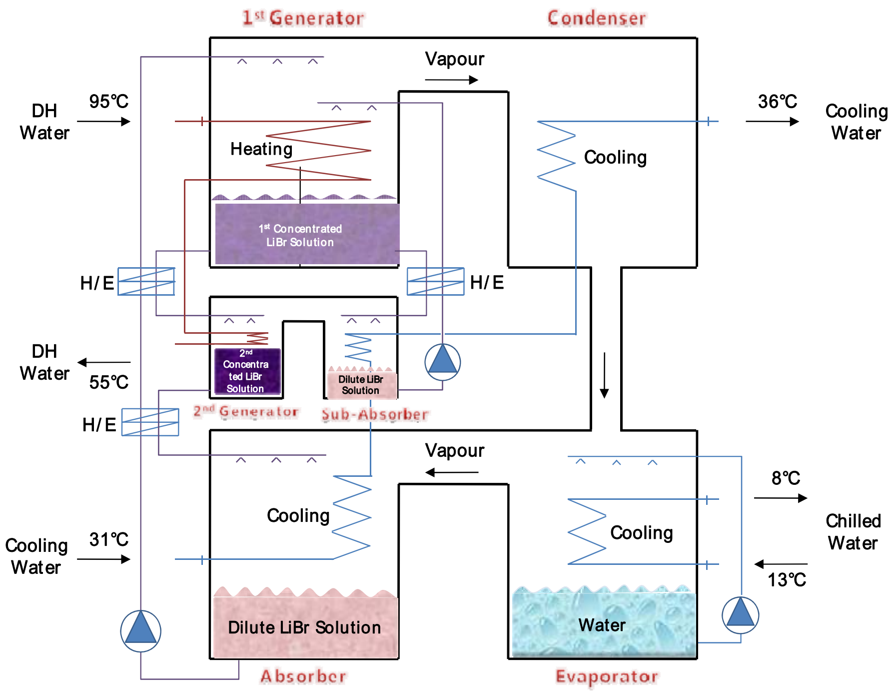

Figure 49. 2-stage ABS chiller schematic diagram

7.2 Cooling capacity variation with entering DH water temperature

The figure following shows the variation of ABS chiller capacity by entering DH water temperature variation. Capacity of the ABS chiller increased in the case of a DH water entering temperature increase. When the DH water entering temperature is over 110℃, capacity of the ABS chiller (1 stage and 2 stage ABS chiller – auxiliary cycle on) does not increase. But if the auxiliary cycle is "off" in a 2stage ABS chiller, then capacity will increase. We can know that the capacity change rate of a 1 stage ABS chiller is larger than that of a 2 stage. It means a 1 stage ABS chiller is more sensitive to DH entering temperature.

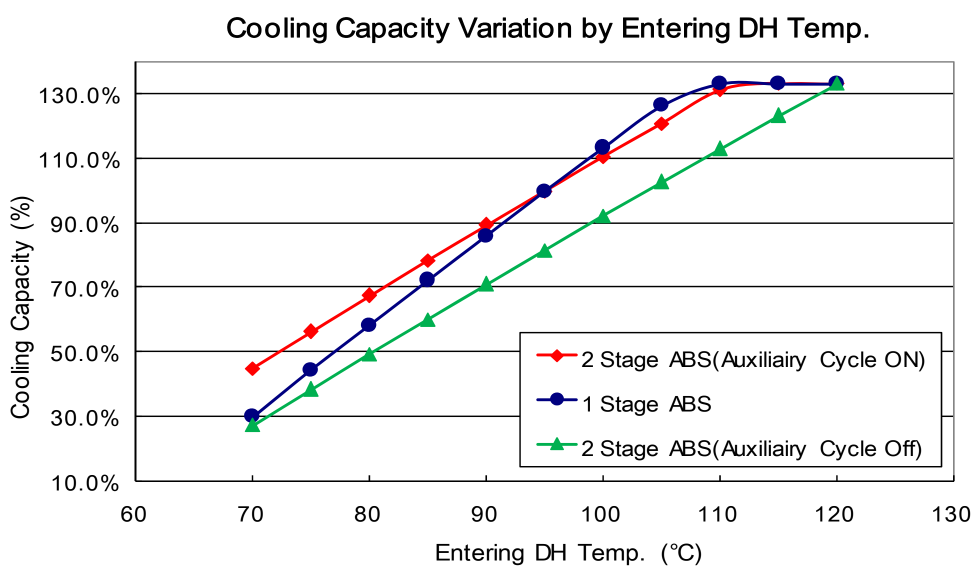

Figure 50 Cooling capacity variation by entering DH Temp, for absorption chiller

7.3 COP variation with entering DH water temperature

Figure 52 shows the valuation of COP by the entering DH water temperature change. In a one-stage ABS, COP is concerned if the entering DH water temperature is over 100 degrees. But in the same condition in a two-stage absorption chiller, COP is continuously increased. In the case of a two-stage ABS without an auxiliary cycle, it is almost steady regardless of the entering DH water temperature. The figure also shows that COP is relatively higher than ABS with an auxiliary cycle.

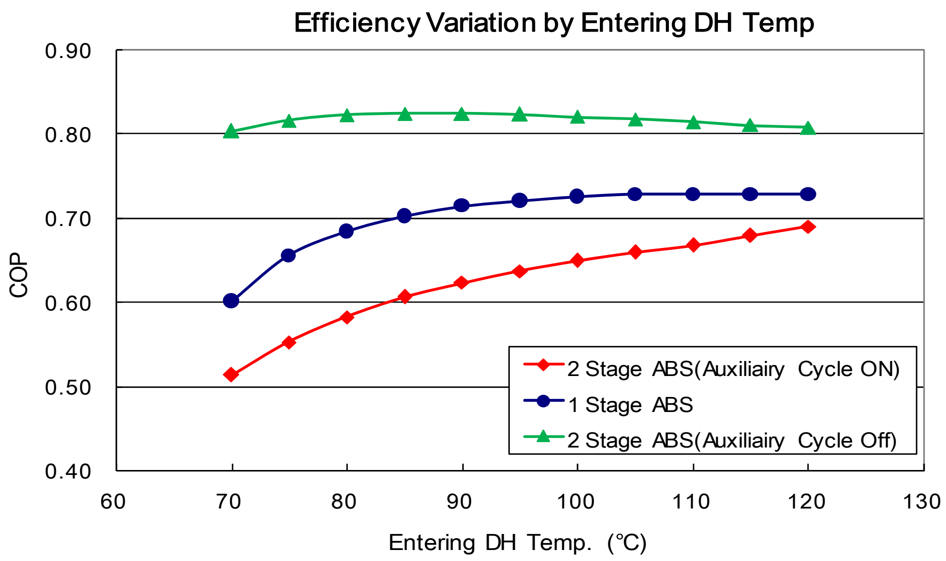

Figure 51 Efficiency variation by entering DH Temp, for absorption chillers

7.4 Leaving DH water temperature variation with types of ABS chillers

We can check the variation of DH water leaving temperature by DH water entering temperature like the below figure shows as follows. So as to improve the efficiency of the CHP, it is a solution that DH water return temperature is decreased. Hence a two-stage ABS was designed to turn down the DH water leaving temperature of the chiller. As a result of the simulation, DH water leaving temperature of the two-stage absorption chiller was 25 °C lower than in the one-stage ABS in the design condition and if entering temperature of the DH water is 105°, it can be turned down by 28 degrees. Even though it shut down the auxiliary cycle of the two-stage absorption chiller, it can be turned down about 10 degrees (maximum 13 degrees) in the design condition. Thus in summer, it is possible to turn down the total DH water return temperature.

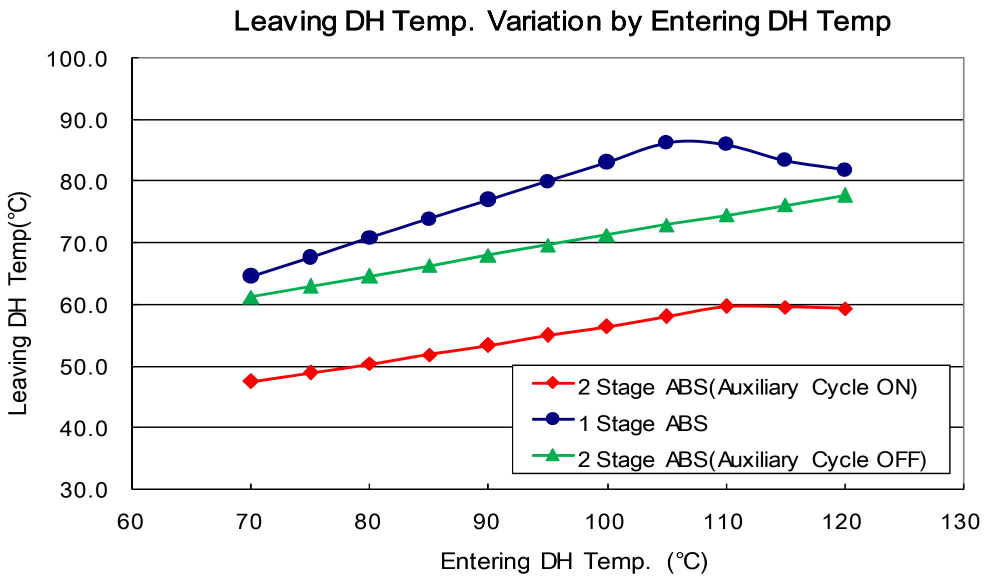

Figure 52 Leaving DH Temp, variation by entering DH Temp, for absorption chillers

8 Description of model for calculation of PEF and GWP

8.1 Calculation model

A general method for calculating the primary energy factor and emissions of greenhouse gases related to district heating and district cooling are described below. At a first stage all possible steps of relevance should be evaluated. For an existing system some of the flows might not exist or are considered to be negligible compared to other flows and might be excluded if the system fulfils the cut off rules without them.

The model is focusing on two impact categories, global warming potential (GWP) and use of primary energy (PE). GWP includes emissions of greenhouse gases such as carbon dioxide, methane and nitrous oxide and is expressed in g CO_2-equivalents. The primary energy use is in the model expressed as primary energy factor (PEF) defined as primary energy use divided by the delivered energy. The calculations of GWP and primary energy use have been described in chapter 1 and in [95].

An overview of the system for district heating and cooling is shown in Figure 53.

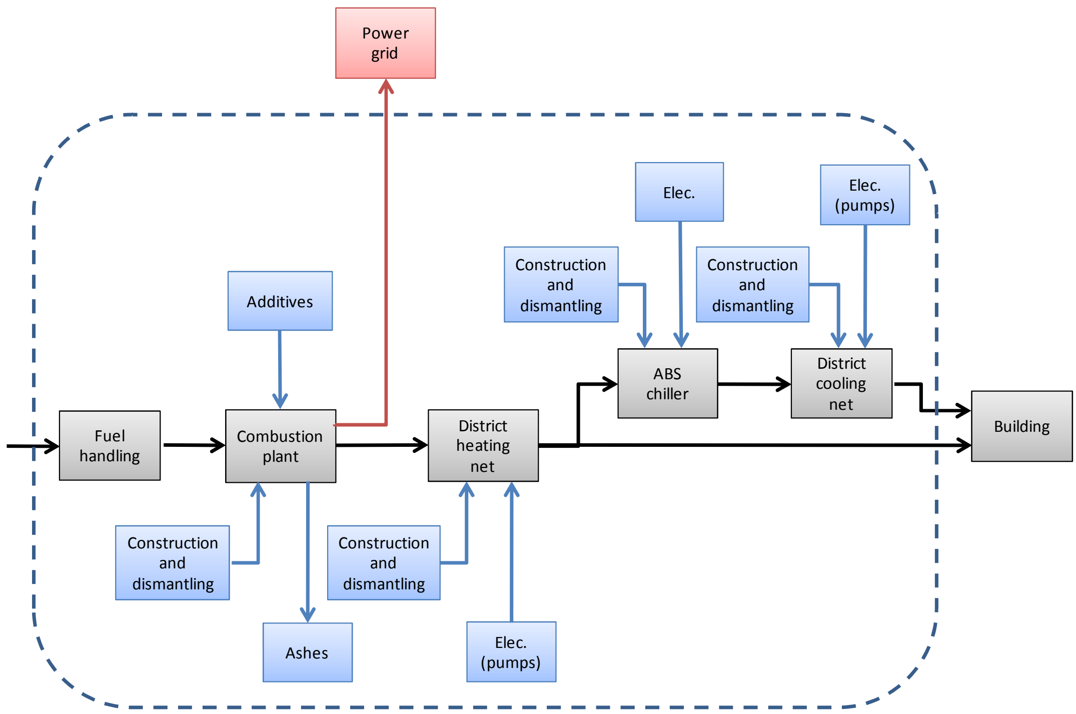

Figure 53 Production and distribution of district heating and cooling

8.2 District heating

The production chain for district heating includes three main steps. Each step includes supporting processes related to the system.

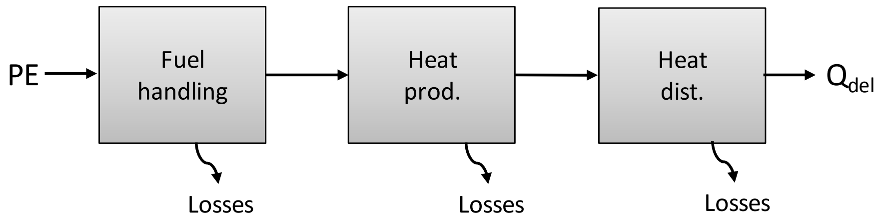

Figure 54 Production and distribution of district heating

For each of these boxes a more detailed flowchart can be made including sub processes

8.2.1 *Fuel handling*

The fuel handling step is a simplified description of a number of processes that differ from fuel to fuel. The fact that the handling processes differs makes it impossible to make one general flowchart for all fuels.

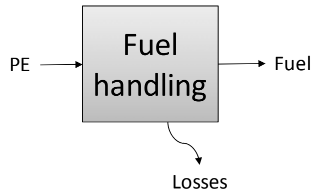

Figure 55 Overview of fuel handling

In an analysis of a specific case it is relevant to evaluate the emissions and the energy used in the extraction, processing and transportation of the fuel. This study does not focus on the differences in fuel handling. Therefore general emission data and primary energy factors from the fuel handling step were used. However, they are specific to fuel groups such as oil, natural gas, wood pellets and waste

8.2.2 *Combustion*

The heat production can either take place in a combined heat and power plant or produced in a heat only plant. Related to the combustion process a number of sub processes are identified. This project has included the environmental impact related to additives, construction and dismantling of the plant and transportation of ashes to waste handling. For heat only plants the electricity consumption in the plant is also included. For CHP-plants the electricity is assumed to be produced internally, and thereby no input of external electricity is needed. Instead the internal electricity consumption will influence the efficiency figures of the plant.

For CHP-plants the emissions of greenhouse gases and primary energy use will be allocated between heat and electricity. There is a number of existing allocation methods. In this study two allocation methods have been used; the power bonus method and the alternative generation method. The choice of allocation method is further discussed in chapter 3.

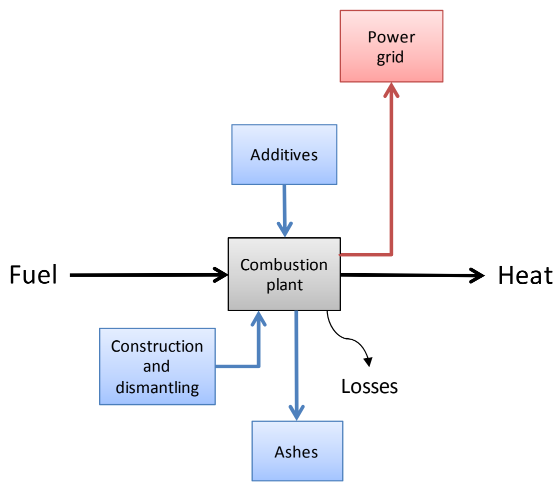

Figure 56 Overview heat production in combustion plant

8.2.3 *Distribution of district heat*

An important factor for the heat distribution net is the heat losses in the system. Impact from the construction and dismantling of the net and from electricity to operate the pumps in the system is also included.

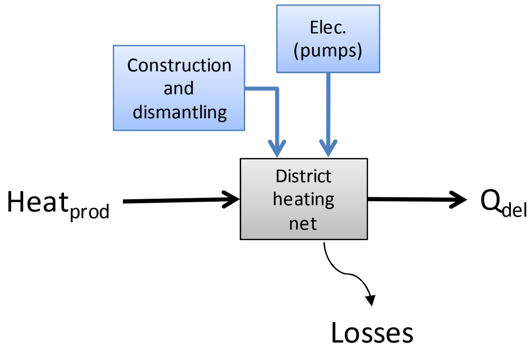

Figure 57 Overview distribution of district heat

8.2.4 *Calculation of greenhouse gas emissions*

The emissions of greenhouse gases emitted during the production and distribution of the district heat can be divided into two main steps:

$$GWP_{dh} = GWP_{heat\_prod} + GWP_{heat\_dist} \qquad \text{Eq. 29}$$

The impact on global warming from the heat production can be expressed as:

$$GWP_{heat\_prod} = Allocation\_factor_{heat} * Q_{fuel} * \sum GWP_i \qquad \text{Eq. 30}$$

Where i includes the combustion and all sub processes related the combustion plant. According to Eq. 30 GWP_i should be expressed as a function of the fuel input to the combustion.

The impact on global warming related to the district heating net can be described as:

$$GWP_{heat\_dist} = \sum GWP_j \qquad \text{Eq. 31}$$

Where j includes all sub processes related to the heat distribution.

The amount of fuel needed for the production of a specific amount of delivered heat can be expressed as:

$$Q_{fuel} = \frac{Q_{del} * (1 + \alpha)}{\eta_{net} * \eta_{tot\_CHP}} \qquad \text{Eq. 32}$$

Where α (power to heat ratio) will be zero for a heat only plant. Combining the equations above gives:

$$GWP_{dh} = Allocation\_factor_{heat} * \frac{Q_{del} * (1 + \alpha)}{\eta_{net} * \eta_{tot\_CHP}} * \sum GWP_i + \sum GWP_j \qquad \text{Eq. 33}$$

For the system in the study the following sub processes with an impact on global warming have been identified related to combustion:

GWP_{fuel_hand}	Emissions of greenhouse gases related to fuel handling (extraction, processing, storage, transports etc.) until the fuel is delivered to the plant
GWP_{incin}	Emissions of greenhouse gases related to the combustion of the fuel

GWP_{add}	Emissions of greenhouse gases related to the use and production of other substances needed in the process (e.g. chemicals or sand for a fluid bed)
GWP_{ash}	Emissions of greenhouse gases related to waste handling of ashes (e.g. transports)
$GWP_{C\&D\_plant}$	Emissions of greenhouse gases related to the construction, maintenance and dismantling of the plant
GWP_{elec_plant}	Emissions of greenhouse gases related to the production of electricity consumed in the plant.

Related to the district heating net the following sub processes have been identified:

$GWP_{C\&D\_net}$	Emissions of greenhouse gases related to the construction, laying and dismantling of the district heating net
GWP_{elec_pump}	Emissions of greenhouse gases related to the production of electricity consumed by the pumps for distribution of the district heat.

Including the sub processes listed above into Eq. 33 the impact on global warming for a district heating system will be:

$$GWP_{dh} = Allocation_{factor_{heat}} * \frac{Q_{del} * (1+\alpha)}{\eta_{net} * \eta_{tot_{CHP}}} * \left(GWP_{fuel\_hand} + GWP_{incin} + GWP_{add} + GWP_{ash} + GWP_{C\&D\_plant} + GWP_{elec\_plant}\right) + GWP_{C\&D\_net} + GWP_{elec\_pump} \quad \textit{Eq. 34}$$

8.2.5 *Calculation of the primary energy factor*

The primary energy factor for the district heating system can be expressed as:

$$PEF_{dh} = \frac{PE_{fuel} + PE_{sub\_processes}}{Q_{del}} \quad \textit{Eq. 35}$$

The used primary energy can be divided into two parts. One related to the production chain where the raw material for fuels is converted into heat for deliver. This part includes the losses in the production chain from fuel extraction to delivered heat described in Figure 54. Additional use of primary energy is related to the sub processes needed for the production and distribution of district heat.

The energy needed for the conversion of the fuel raw material into district heating can be expressed as:

$$PE_{fuel} = Allocation\_factor_{heat} * PEF_{fuel\_hand} * Q_{fuel} \quad \textit{Eq. 36}$$

Combination *Eq. 32* and *Eq. 36* gives:

$$PE_{fuel} = Allocation\_factor_{heat} * PEF_{fuel\_hand} * \frac{Q_{del} * (1+\alpha)}{\eta_{net} * \eta_{tot\_CHP}} \quad \textit{Eq. 37}$$

Similar to the calculations of greenhouse gases the primary energy consumption related to the sub processes can be expressed as:

$$PE_{sub\_processes} = Allocation\_factor_{heat} * \frac{Q_{del} * (1+\alpha)}{\eta_{net} * \eta_{tot\_CHP}} * \sum PE_i + Q_{del} * \sum PE_j \qquad \text{Eq. 38}$$

Where PE_i includes the sub processes related to the combustion and PE_j includes sub processes related to the distribution net.

For the system in this study the following energy consuming sub processes have been identified related to the combustion:

PE_{add}	Primary energy consumption related to the use and production of other substances needed in the process (e.g. chemicals or sand for a fluid bed).
PE_{ash}	Primary energy consumption related to transports of ashes to waste handling.
$PE_{C\&D\_plant}$	Primary energy consumption related to the construction, maintenance and dismantling of the plant.
PE_{elec_plant}	Primary energy consumption related to the production of electricity consumed in the plant.

Related to the district heating net the following sub processes have been identified:

$PE_{C\&D\_net}$	Primary energy consumption related to the construction, maintenance and dismantling of the plant
PE_{elec_pump}	Primary energy consumption related to the production of electricity consumed by the pumps for distribution of the district heat.

Including the sub processes listed above into *Eq. 38* in combination with *Eq. 37*, the consumption of primary energy related to the sub processes will be:

$$PE_{dh} = Q_{del} * (Allocation_{factor_{heat}} * \frac{1+\alpha}{\eta_{net} * \eta_{tot_{CHP}}} * \left(PEF_{fuel_{hand}} + PE_{add} + PE_{ash} + PE_{C\&D_{plant}} + PE_{elec_{plant}}\right) + PE_{C\&D_{net}} + PE_{elec_{pump}}) \qquad \text{Eq. 39}$$

The primary energy factor for the district heating system will be:

$$PEF_{dh} = (Allocation\_factor_{heat} * \frac{1+\alpha}{\eta_{net} * \eta_{tot\_CHP}} * \left(PEF_{fuel\_hand} + PE_{add} + PE_{ash} + PE_{C\&D\_plant} + PE_{elec\_plant}\right) + PE_{C\&D\_net} + PE_{elec\_pump}) \qquad \text{Eq. 40}$$

8.3 District cooling

Production of district cooling in an absorption chiller will add two extra steps in the production chain compared to district heating. The district heat will be used to produce cooling in an absorption chiller and thereafter the cooling will be distributed to the end user. If the ABS-chiller is located at the combustion plant the impacts related to the heat distribution net will be negligible. Production of district cooling using other techniques than absorption chillers will not be included in the study.

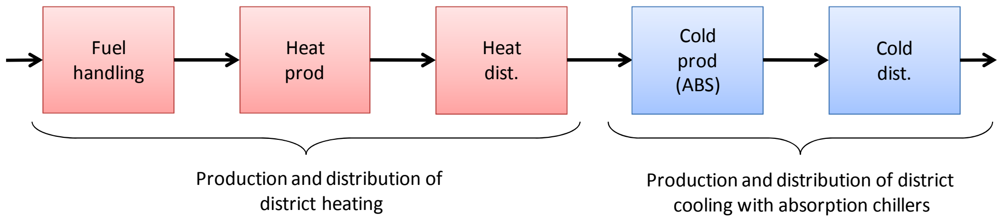

Figure 58 Production chain for district cooling

8.3.1 *Absorption chiller*

The district cooling produced in an absorption chiller needs an input of heat. In the model impact from the heat production is calculated in the district heating part. For operation the absorption chiller also consumes electricity. Additional sub processes identified in relation to the absorption are the construction and dismantling of the chiller.

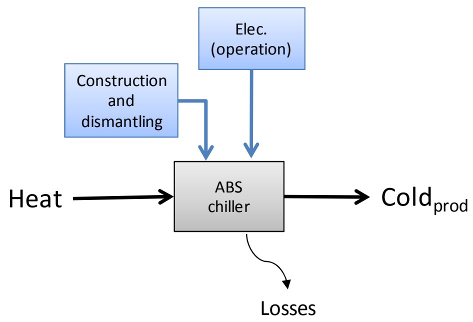

Figure 59 Overview cold production in absorption chiller

8.3.2 *District cooling net*

For the cold distribution net the cold losses in the system is included. Impact from the construction and dismantling of the net and from electricity to operate the pumps in the system are also included.

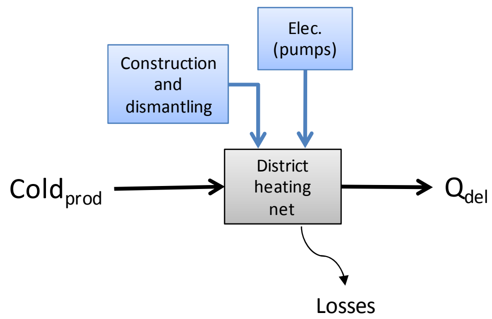

Figure 60 Overview distribution of cold

8.3.3 *Calculation of greenhouse gas emissions*

The emissions of greenhouse gases related to the production and distribution of district cooling can be divided into three parts:

$$GWP_{dc} = Q_{del} * \left[GWP_{dh} + GWP_{cold\_prod} + GWP_{cold\_dist}\right] \qquad \textit{Eq. 41}$$

For details about the calculation of GWP_{dh} see chapter 8.2.4.
The impact on the global warming related to the cold production can be expressed as:

$$GWP_{cold\_prod} = Q_{prod\_cold} * \sum GWP_i$$ *Eq. 42*

Where i include the operation of the ABS-chiller as well as all sub processes related to the cold production. GWP_i should be expressed as a function of the produced cold and Q_{prod_cold} depends on the efficiency of the district cooling net:

$$Q_{prod\_cold} = \frac{Q_{del}}{\eta_{net}}$$ *Eq. 43*

The impact on the global warming related to the cold distribution can be expressed as:

$$GWP_{cold\_dist} = \sum GWP_j$$ *Eq. 44*

Where j include all sub processes related to the cold distribution. GWP_j should be expressed as a function of the delivered cold.

Combining the equations above gives:

$$GWP_{dc} = Q_{del} * \left[\frac{GWP_{dh}}{\eta_{abs} * \eta_{net}} + \frac{\sum GWP_i}{\eta_{net}} + \sum GWP_j\right]$$ *Eq. 45*

For the system in this study the following sub processes with an impact on the global warming have been identified related to the absorption chiller:

GWP_{elec_abs}	Emissions of greenhouse gases related to the production of electricity consumed by the absorption chiller
$GWP_{C\&D\_abs}$	Emissions of greenhouse gases related to the construction and dismantling of the absorption chiller

Related to the district cooling net the following sub processes have been identified:

GWP_{elec_pump}	Emissions of greenhouse gases related to the production of electricity consumed by the pumps for distribution of the district cold
$GWP_{C\&D\_net}$	Emissions of greenhouse gases related to the construction, laying and dismantling of the district cooling net

Including the sub processes listed above into Eq. 45 the impact on global warming for a district cooling system will be:

$$GWP_{dc} = Q_{del} * \left[\frac{GWP_{dh}}{\eta_{abs} * \eta_{net}} + \frac{GWP_{elec\_abs} + GWP_{C\&D\_abs}}{\eta_{net}} + GWP_{elec\_pump} + GWP_{C\&D\_net}\right]$$ *Eq. 46*

8.3.4 *Calculation of the primary energy factor*

The use of primary energy to the production and distribution of district cooling can be divided into three parts:

$$PE_{dc} = Q_{del} * \left[PEF_{dh} + PE_{cold\_prod} + PE_{cold\_dist}\right]$$ or expressed as the PEF *Eq. 47*

$$PEF_{dc} = PEF_{dh} + PE_{cold\_prod} + PE_{cold\_dist}$$ *Eq. 48*

For details about the calculation of PEF_{dh} see chapter 0.

Following the argumentation related to calculation of impact on global warming in chapter 8.3.3 the use of primary energy can be expressed as:

$$PE_{dc} = Q_{del} * \left[\frac{PEF_{dh}}{\eta_{abs} * \eta_{net}} + \frac{\sum PE_i}{\eta_{net}} + \sum PE_j\right] \qquad \textit{Eq. 49}$$

Where i include the operation of the Abs-chiller as well as all sub processes related to the cold production and j include all sub processes related to the cold distribution. GWP_i should be expressed as a function of the produced cold and GWP_j should be expressed as a function of the delivered cold.

For the system in the study the following sub processes with an impact on the global warming have been identified related to the absorption chiller:

PE_{elec_abs}	Primary energy consumption related to the production of electricity consumed by the absorption chiller
$PE_{C\&D\_abs}$	Primary energy consumption related to the construction and dismantling of the absorption chiller

Related to the district cooling net the following sub processes have been identified:

PE_{elec_pump}	Primary energy consumption related to the production of electricity consumed by the pumps for distribution of the district cold
$PE_{C\&D\_net}$	Primary energy consumption related to the construction, laying and dismantling of the district cooling net

Including the sub processes listed above into Eq. 49 the impact on global warming for a district cooling system will be:

$$PE_{dc} = Q_{del} * \left[\frac{PEF_{dh}}{\eta_{abs}*\eta_{net}} + \frac{PE_{elec\_abs}+PE_{C\&D\_abs}}{\eta_{net}} + PE_{elec\_pump} + PE_{C\&D\_net}\right] \qquad \textit{Eq. 50}$$

Or expressed as the primary energy factor:

$$PEF_{dc} = \frac{PEF_{dh}}{\eta_{abs}*\eta_{net}} + \frac{PE_{elec\_abs}+PE_{C\&D\_abs}}{\eta_{net}} + PE_{elec\_pump} + PE_{C\&D\_net} \qquad \textit{Eq. 51}$$

8.4 Calculation model in Excel

The calculation model based on the equations described in chapter 8 is made in Excel. Data for the different sub processes are described in detail in chapter 4.

The benefit of using Excel instead of a specific LCA calculation tool is that the calculation procedure in Excel is more transparent. Using Excel has also made it possible for all project members to work in the model without the need to install and learn specific programs. The program makes it possible to make a model where it is easy to vary the parameters. In the developed calculation model dropdown menus have been used in order to make it easy to change the most commonly used parameters.

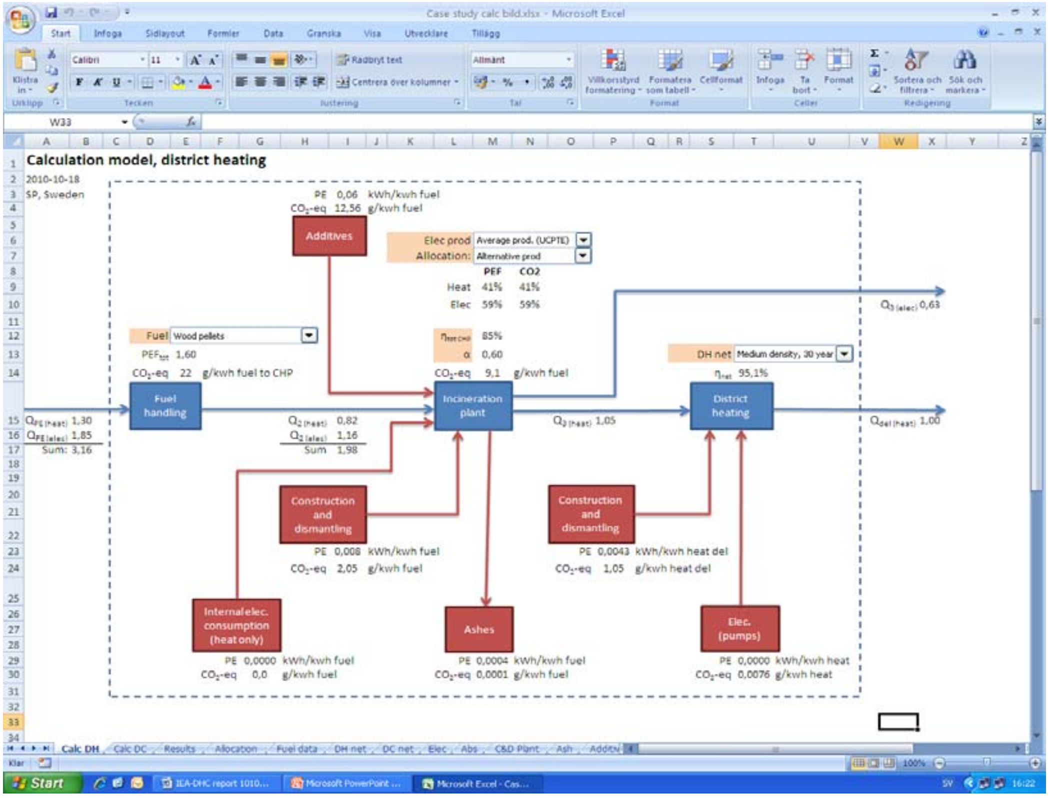

Figure 61 Overview calculation model in Excel

9 Case studies

9.1 Description case studies

In the project proposal it was stated that a number of case studies will be made in order to demonstrate the developed calculation method and the potential of CHP-plants in comparison to heat only plants. The project group together with the expert group decided to divide the cases studies into six areas. These do not correspond directly with the suggestions in the project proposal, but were considered to reflect reality better and demonstrate the most important aspects/differences in the process chains:

- Study the choice of fuel for CHP-plants
- Study the choice of fuel for heat only plants, to be compared with a CHP alternative
- Study the dominance analyse of the production chain
- Study the choice of size of the plant
- Study district cooling with absorption chiller
- Study the choice of allocation method

The case studies have been analysed using two scenarios, a marginal and an average scenario.

9.1.1 *Marginal scenario, power bonus method*

A marginal perspective is appropriate to use in order to evaluate how a change in the energy system will affect the use of primary energy and emissions of green house gases for the whole system. This is of interest for example for policy makers or energy companies about to build a new plant.

For a marginal scenario Power bonus is chosen for allocation between heat and electricity, as explained in chapter 3.8.1. Electricity is the only parameter where different data have been used for the marginal and the average scenario. In this study all other recourses is assumed to be independent of if a marginal or a average scenario is used.

9.1.2 *Average scenario, alternative generation method*

An average perspective is to prefer for bookkeeping purposes, or has a historical reporting of emissions and resources.

For the average scenario the alternative generation method was chosen for allocations, as explained in chapter 3.8.2. The alternative generation method allocates the emissions and resources from the plant without taking the energy system outside the plant into account.

9.1.3 *Data for fuel handling and combustion of fuels*

The case studies for fuels have been analysed. In Table 28 below the data used for fuel handling and combustion is summarised. Primary energy losses in the combustion phase depend on the efficiency of the plant. For details see chapter 4.1.

Table 28. Data used in case studies for fuel handling and combustion of fuel

Fuel	PEF fuel handling (kWh/ kWh fuel)	CO_2-eq fuel handling (g CO_2-eq/ kWh fuel)	CO_2-eq combustion (g CO_2-eq/ kWh fuel)
Natural gas	1,05	37	206
Fuel oil	1,34	45	280
Wood chips	1,19	9	9
Waste	1.00	0	97

9.1.4 *System expansion and negative values for PEF and CO_2-eq*

In the marginal perspective a system expansion has been made. Thereby also the effects of the system outside the production chain of the district heating are included in the result. If a change in a system leads to savings of primary energy and greenhouse gases the values will be negative.

When the power bonus method is used for allocations negative values for the primary energy factor from the allocations should, according to the standard EN 15316-4-5 [10], be set equal to zero. In the case studies of this project it is chosen to include the system expansion for all plants and show negative values in the result. This makes it possible to evaluate how different alternatives affect the system as a total.

In general the total primary energy factor for any fuel or energy carrier cannot be below one. In some cases the PEF-value, due to definitions and allocations, can be given values down to zero. A PEF value of zero means two things. First one uses energy from a resource without consuming any primary energy. Industrial excess heat or solar heat might be examples where PEF_{fuel} is set to zero (depends on definitions and allocations). Second no additional primary energy is used in the process to make the energy accessible.

9.1.5 *Study the choice of fuel*

Four cases with the same conditions except fuel for the CHP plant are compared to show how much the choice of fuel affect the total system in terms of PEF and CO_2-eq emissions. Size was chosen to 100 MW as far as the data set available in the project allowed. For natural gas there was no data for a 100 MW plant, therefore a 1000 MW plant was chosen. This could be argued to be of more interest, since in order to make a natural gas CHP plant interesting a combined cycle is required, which in turn demand a big plant size.

Table 29 Size, efficiency and power to heat ratio for choice of fuel cases

Fuel	Size (MW)	η (%)	α
Bio mass CHP	100	101.3	0.36
Waste CHP	100	108.0	0.31
Natural gas CHP	1000	88.4	1.81
Oil CHP	100	90.4	0.46

9.1.6 *Study the choice of size*

Six cases with two different fuels with three different sizes are compared. These cases show how much the plant size affect PEF and CO_2-eq emissions for a district heating system.

Most of these values are from collected data from actual plants. For some plants, where no data from actual plants could be found, data were taken from “*El från nya anläggningar – 2007”* [65].

Table 30 Size, efficiency and power to heat ratio for choice of size cases

Fuel	5 MW		10 MW		25 MW		100 MW		1000 MW	
	η (%)	α	η (%)	α	η (%)	α	η (%)	α	η (%)	α
Biomass CHP			110	0.32	110	0.37	101.3	0.36		
Natural gas CHP	81	0.87	81	0.87					88.4	1.81

9.1.7 *Heat only, to be compared with CHP*

To show the benefits of CHP, four simulations with heat only plants with different fuel are presented.

Table 31 Size and efficiency for heat only plants

Fuel	Size (MW)	η (%)
Bio mass (heat only)	25	90
Waste (heat only)	25	105
Natural gas (heat only)	100	94.5
Fuel oil (heat only)	200	92.7

9.1.8 *District cooling with absorption chiller*

The analyse of the production of district cooling produced in an ABS chiller is based on the production of district heat used as a heat input to the ABS chiller. In the cases studies it is assumed that the ABS chiller is located close to the end user. The heat is produced in a CHP-plant or in a heat only plant and then distributed to the ABS chiller via the district heating net. Since the chiller is located close to the cold sink no district cooling net is included.

In the cases studies the heat is produced using either waste or natural gas as a fuel, either in a CHP-plant or in a heat only plant. Data for the plants is summarised in Table 32 and Table 33.

Table 32. Data for CHP-plants used in the cases studies for district cooling

Fuel	Size (MW)	η (%)	α
Waste	100	108	0.31
Natural gas	1000	88.4	1.81

Table 33. Data for heat only plants used in the cases studies for district cooling

Fuel	Size (MW)	η (%)
Waste	25	105
Natural gas	100	84.5

The ABS chiller is assumed to have a size of 1300 kW and the technology chosen is 1-stage. The chosen performance of the chiller is based on data from installed chillers in Korea [26].

9.1.9 *Study the choice of allocation method*

Due to big differences in results depending on allocation method an extra comparison between these cases are shown. In the same charts a heat only case is also presented to give a reference to the other results. The cases are taken from chapter 9.2 and 9.3.

9.2 Analyse choice of fuel in CHP-plants

9.2.1 *Marginal scenario (Power bonus method)*

In the marginal scenario the power bonus method is used for allocations, see chapter 3.3 for details. The power bonus method gives credit for the electricity produced in the CHP-plant. The electricity produced in the CHP-plant is evaluated with the same impact as the marginal production of electricity as the electricity from the CHP-plant is assumed to replace. The emissions allocated to the heat production will be the total emissions from the plant subtracted with the marginal emissions from the electricity. This means that the allocation to heat can become negative if the total emissions from the CHP plant are lower than the emissions from the replaced power plant (granted they produce as much electricity). The standard EN15316-4-5 [10] stipulates that negative values should be set to zero, but in this project we have chosen to show the total effects on the system and present the negative numbers to be able to show differences between cases. It also shows how the total impact from the energy system will be effected, not only the plant.

In Figure 62 the emissions of greenhouse gases from the production and distribution of district heating for different fuels are shown. All emissions are negative which means all plants have better efficiency on the power part alone, than the coal power plants on the margin, which is replaced by the CHP plant. A negative result means that the global emissions for the energy system in total are reduced when the plant is used.

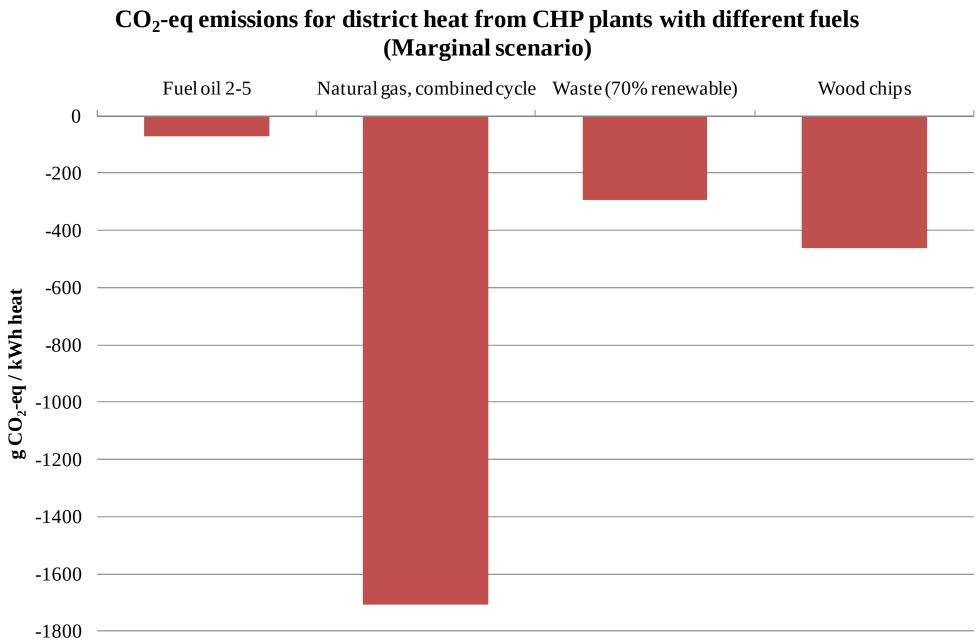

Figure 62 CO_2-eq emissions for district heating produced in CHP-plants with different fuels calculated with the power bonus method

Natural gas stands out due to the big power to heat ratio and has the largest reduction of greenhouse gases. The case study shows that a plant using fossil fuel can save more greenhouse gases globally than a plant using bio mass if the power to heat ratio is high.

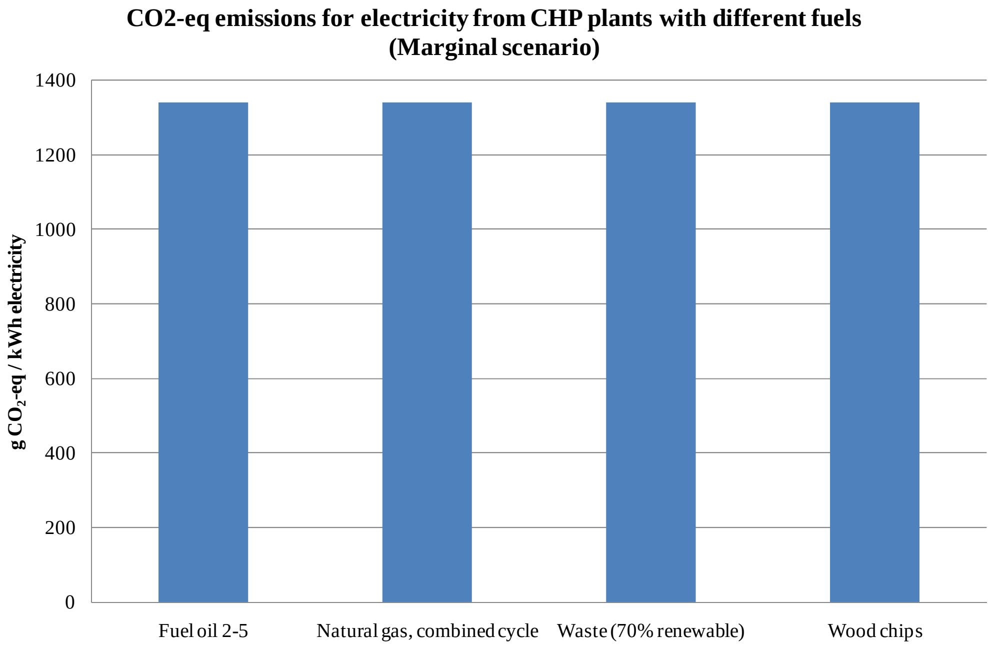

Figure 63 CO_2-eq emissions for electricity produced in CHP-plants with different fuels calculated with the power bonus method

All CO_2-eq emissions related to the electricity production is the same due to the allocation method, see Figure 63. For all scenarios shown in Figure 63, the electricity from the CHP-plant is considered to replace a coal power plant on the margin which emit 1340 g CO_2-eq/kWh electricity. Therefore the emissions of CO_2-eq allocated to the electricity production in these CHP plants is 1340 g CO_2-eq/kWh by default, independent of the fuel chosen.

In Figure 64 and Figure 65, the results on primary energy factor for heat and electricity using the power bonus method can be found.

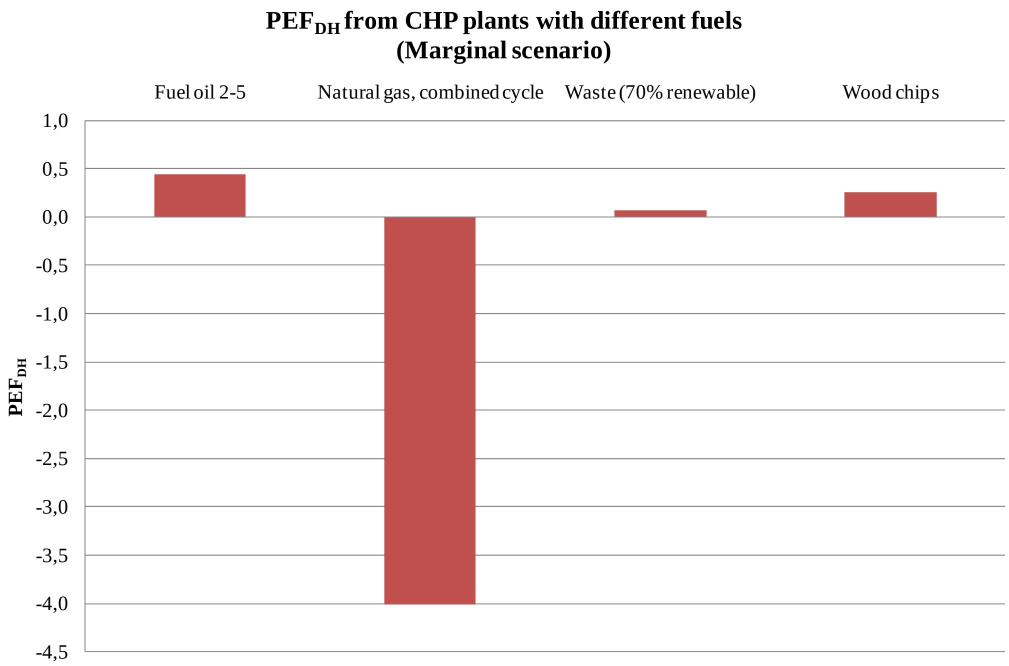

Figure 64. PEF_{DH} for district heating produced in CHP-plants with different fuels calculated with the power bonus method. Negative values for PEF_{DH} is shown in order to see differences between alternatives and impact on the energy system in total.

The primary energy factor (PEF) for district heating produced in a CHP-plant calculated with the power bonus method is below 1 in all four cases, which means that you need less than 1 kWh primary energy to produce and distribute 1 kWh district heating. For natural gas the PEF becomes negative, again due to high power to heat ratio and that the study has included total effects of the system expansion.

The relative order between the different fuels is not the same for primary energy use as for CO_2-eq emissions. Wood chips goes from second best if you look at the CO_2-eq emissions to third place for PEF, and switch places with waste. This is due to the fact that use of renewable energy from bio mass is included in the use of primary energy but not give any emissions of greenhouse gases.

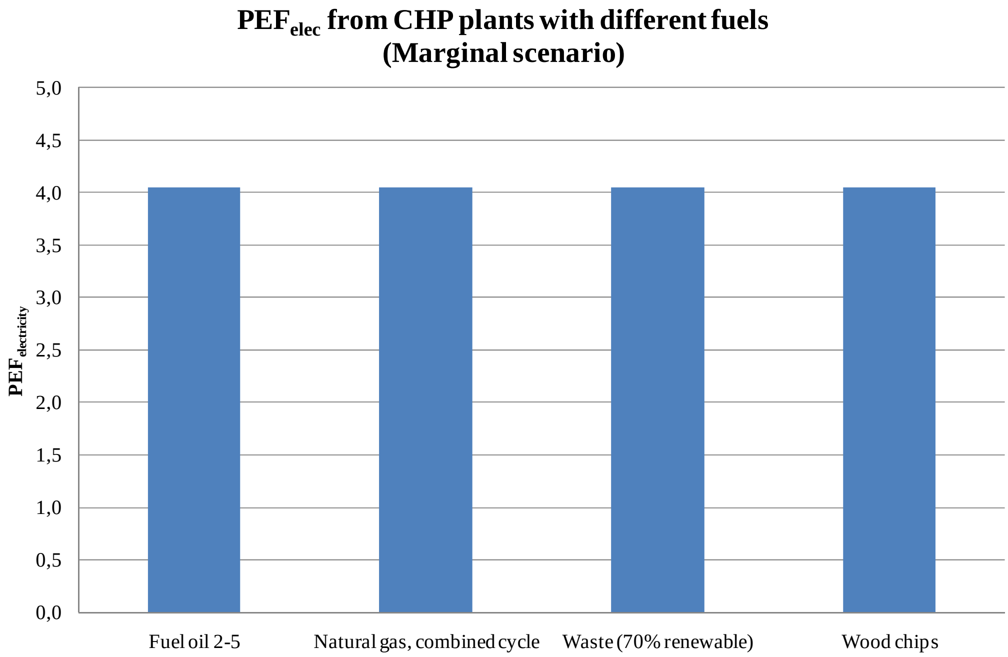

Figure 65 PEF$_{elec}$ for electricity produced in CHP-plants with different fuels calculated with the Power bonus method

As in the global warming case the PEF for all fuels are the same for the electricity produced. This is always the case using the power bonus method since the allocation method is defined that way. PEF for a coal power plant on the margin is 4.05, therefore the PEF for electricity produced in any CHP plant is also 4.05.

9.2.2 *Average scenario (Alternative generation method)*

For the average scenario allocations between electricity and heat are calculated using the alternative generation method, see chapter 3.2 for details.

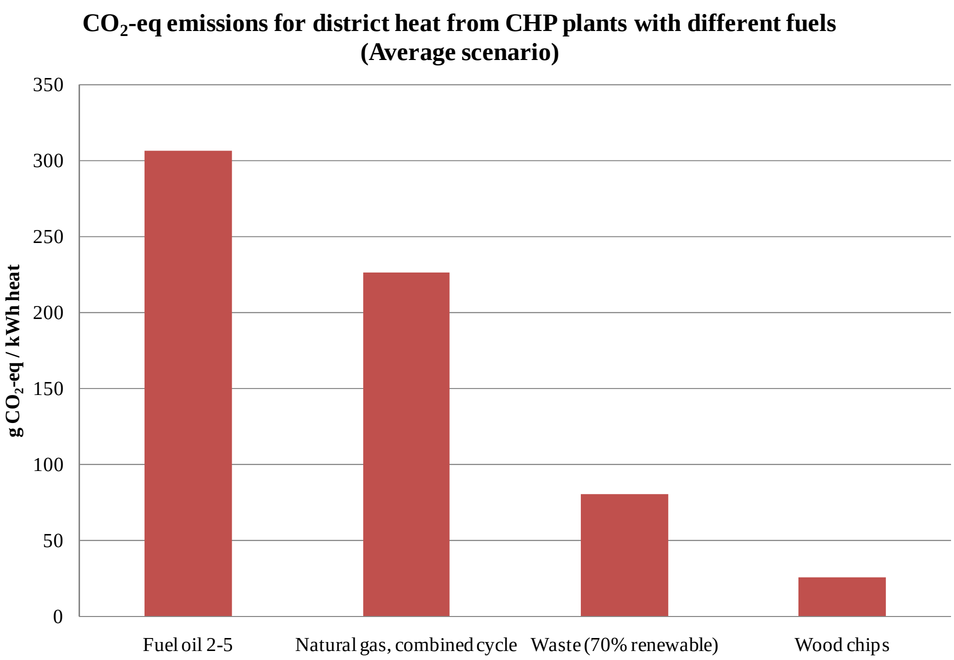

Figure 66 CO_2-eq emissions for district heating produced in CHP-plants with different fuels calculated with the alternative generation method

With the alternative generation method it becomes much more important that the fuel is renewable in order to get low emissions of greenhouse gases, the plants power to heat ratio does not have the same effect on the results. This result in much higher CO_2-eq emissions for natural gas compared to the power bonus method. Wood chips have the lowest emissions with 30 g CO_2/kWh, waste have 80 g, natural gas 230 g and fuel oil 310 g. Independent of the fuel used in average scenario the emissions related the district heat is higher compared to the marginal scenario.

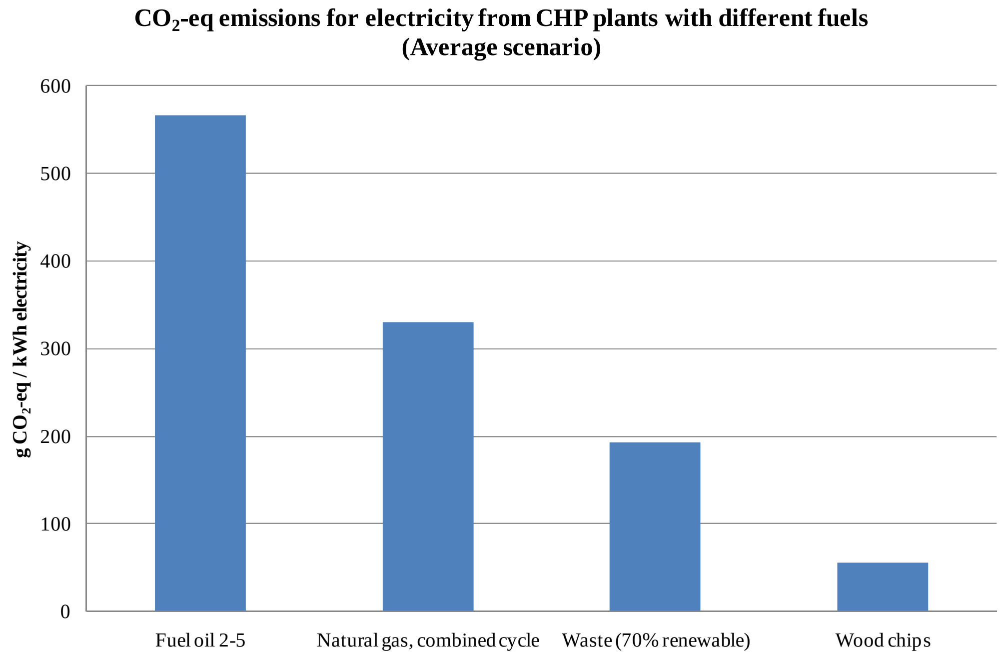

Figure 67 CO_2-eq emissions for electricity from CHP plants with different fuels calculated with the alternative generation method

In this cases study the electricity produced in the CHP plant using wood chips emits 60 g CO_2/kWh, the waste plant 190 g, the natural gas plant 330 g and the fuel oil plant 570 g CO_2/kWh electricity. A comparison to Figure 63 shows that for all fuels the emissions related to the electricity production will be lower in the average scenario compared to the marginal scenario.

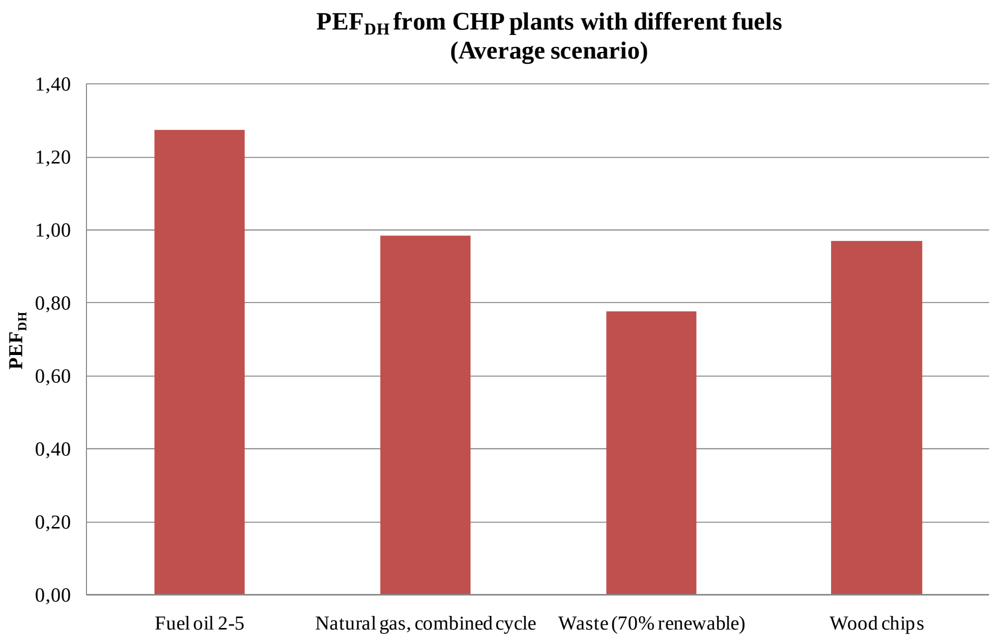

Figure 68 PEF_{DH} for district heating produced in CHP-plants with different fuels calculated with the alternative generation method

When the PEFs is calculated there is no difference made between renewable and fossil fuels. In this comparison fuel oil has the highest PEF_{heat} followed by natural gas and wood chips with more or les the same value. Lowest PEF_{DH} will waste have. For natural gas, waste and wood chips the PEF_{DH} is below 1.0. Thereby for all of these three fuels you will need less than 1 kWh primary energy to produce and deliver 1 kWh district heating.

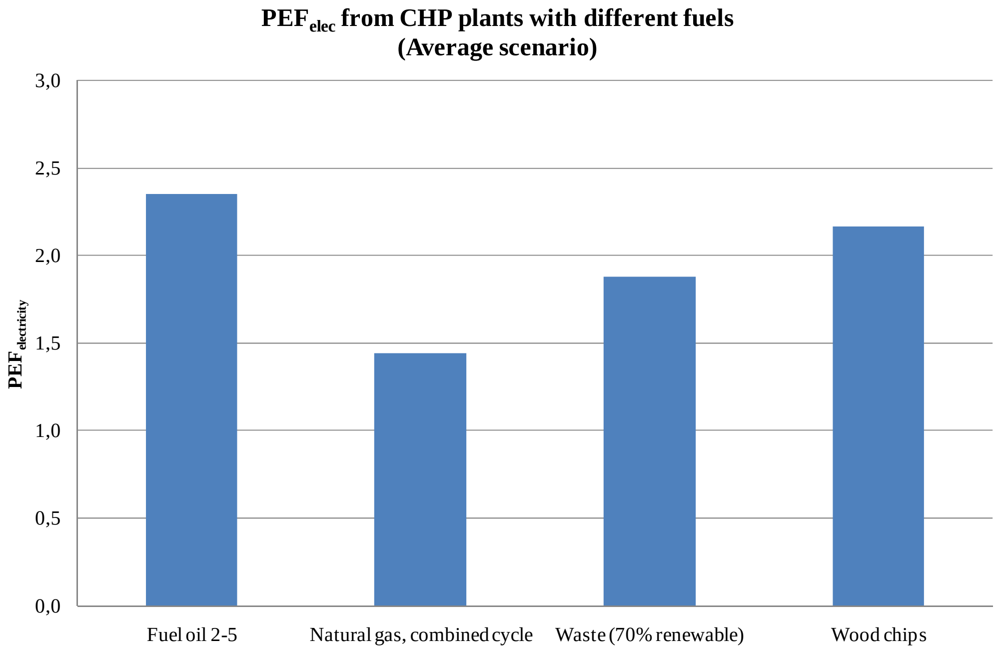

Figure 69 PEF_{elec} from CHP plants with different fuels calculated with the alternative generation method

For electricity production in this scenario fuel oil end up with the highest PEF, 2.3. Wood chips will have a PEF_{elec} of 2.2, waste have 1.9 and natural gas 1.4.

9.3 Analyse the choice of fuels for heat only plants

The heat only plants are much more independent of if a marginal or average scenario is used. This is due to the fact that no electricity is produced in the plant and thereby there is no need to allocate the emissions and resources between the district heating and the electricity production. For internal electricity consumption in the plant, pumps in the district heating net etc. average data have been used.

A comparison between different fuels for heat only plants shows that that the emissions of CO_2-eq for the production and distribution of the district heating produced by fuel oil is approximately four times the emissions for district heat from waste combust, and eight times the emissions from wood chips. Producing 1 kWh heat with fuel oil 2-5 emits 400 g CO_2-eq/kWh, natural gas emits 300 g, waste emits 120 g and wood chips 50 g CO_2-eq.

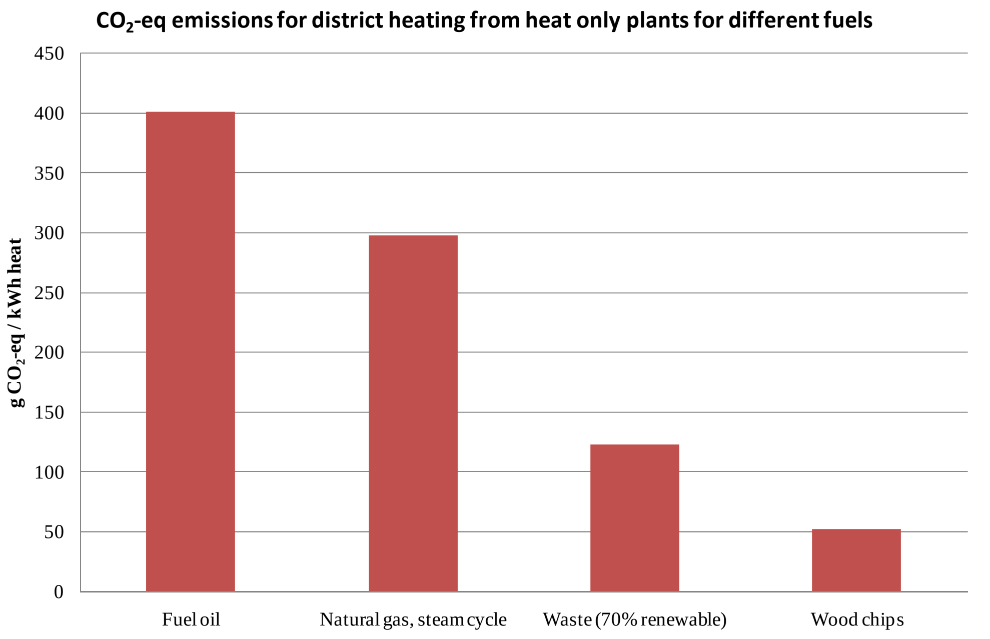

Figure 70 CO_2-eq emissions for heat only plants

PEF for producing district heat in a heat only plant is 1.7 for fuel oil, 1.6 for wood chips, 1.3 for natural gas and 1.1 for waste. Noticed that wood chips is the fuel with the lowest emissions of greenhouse gases, but second form the bottom when it come to use of primary energy. You can also note that the effects related to the benefits from the combined production of heat and electricity that gave PEF values for district heat below 1 for heat produced in a CHP-plant is above 1 for all heat only plants.

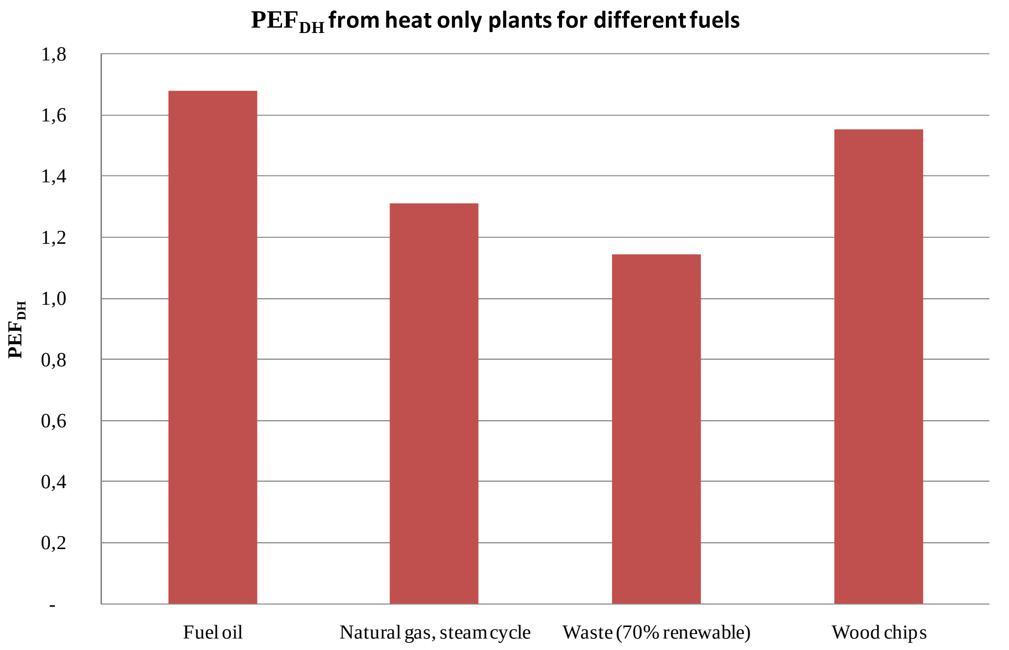

Figure 71 PEF_{DH} for heat only plants

9.4 Dominance analyse production of district heating

9.4.1 *CHP-plant marginal scenario*

In the marginal scenario the power bonus method has been used for allocations in the CHP-plant. The method shows how the energy system in total will be affected when district heating is produced. To show how the allocation method will affect each sub-process can be done theoretically but the result is difficult to analyse. Therefore the impact form each sub process related to the CHP-plant will be show as a total, including the emissions and use of resources allocated to both heat and electricity production. Thereafter the emissions and resources allocated to the electricity production are subtracted from the total (shown as a separate sub process in the figures below). The "total-bar" shows the sum of the emissions allocated to the district heating production and distribution. Sub-processes regarding the distribution net are related to the district heating only and are thereby not influence by the allocations.

Figure 72 is based on the same data as Figure 62, but with a breakdown by origin. The main sub-processes regarding emissions of CO_2-eq for oil, natural gas and waste is the combustion process. For district heating made from wood chips, the impact from the production of the additives is the main contributor to the final result. There are three sub processes that mainly contribute to the final result when it comes to green house gas emissions, the fuel handling, the combustion and the production of the additives.

As seen in Figure 72 the emissions allocated to the electricity production is larger than the actually total emissions in the CHP-plant. Thereby will the summarized emissions related to the production and distribution of district heating be negative.

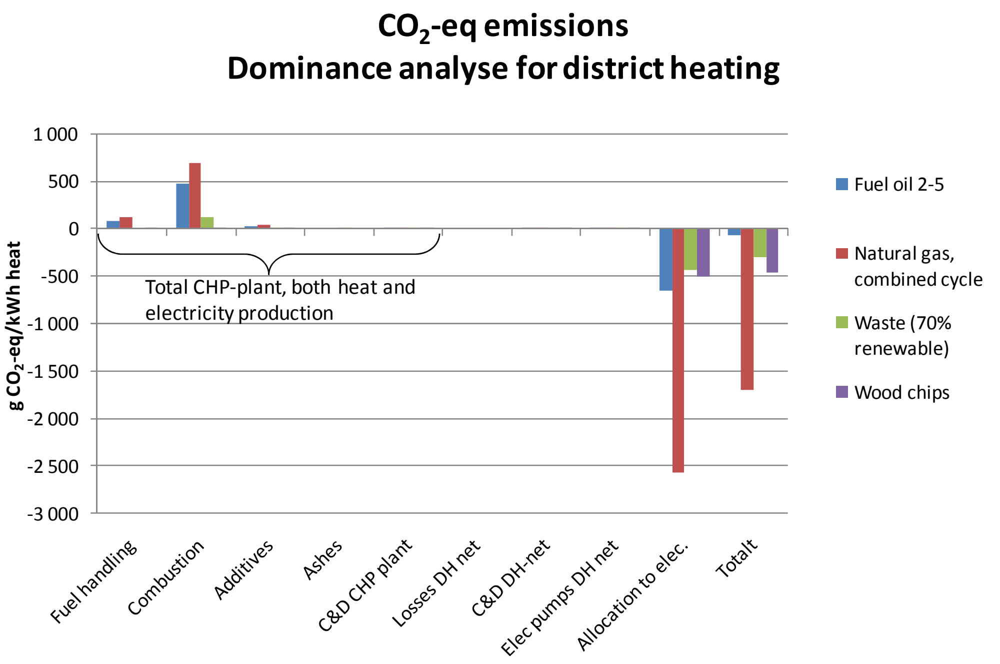

Figure 72 Impact on global warming divided into sub processes. The allocation method used in the CHP-plant is the power bonus method.(C&D= Construction and dismantling)

The tendencies for primary energy losses are similar to the tendencies for greenhouse gases. The losses related to the combustion phase looks higher in the diagram than it actually is. The reason is that all energy not ending up as district heat is shown as losses in the diagram. Thereby the produced electricity in the combustion phase is shown as a loss. This is corrected in the allocation phase and the total shows the primary energy losses allocated to the district heat production.

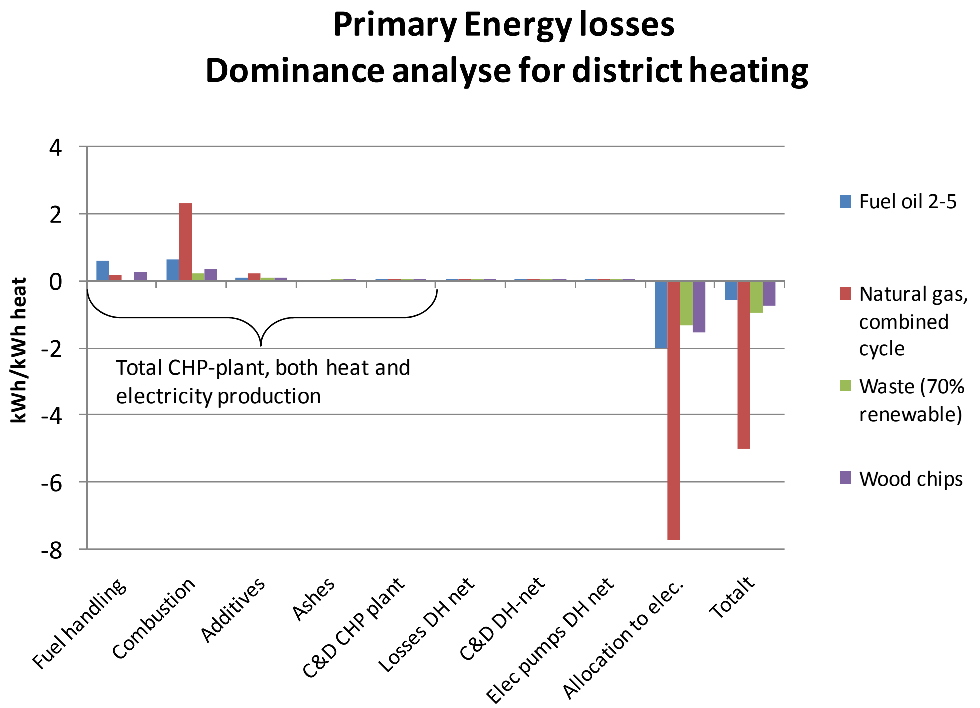

Figure 73. Primary energy losses divided into sub processes. The allocation method used in the CHP-plant is the power bonus method.(C&D= Construction and dismantling)

9.4.2 *CHP-plant average scenario*

Figure 74 shows the emission of greenhouse gases divided by origin. The allocation method used in the average scenario is the alternative generation method. One can see that the combustion phase is the dominating phase for oil, natural gas and waste, where it stands for approximately 80% of the total emissions of greenhouse gases. For district heating made from wood chips, the impact from the production of the additives is the main contributor to the final result. There are three sub processes that mainly contribute to the final result when it comes to green house gas emissions, the fuel handling, the combustion and the production of the additives. The transportation of ashes and the electricity related to pumps in the district heating net is less than 1 per mille in all investigated cases.

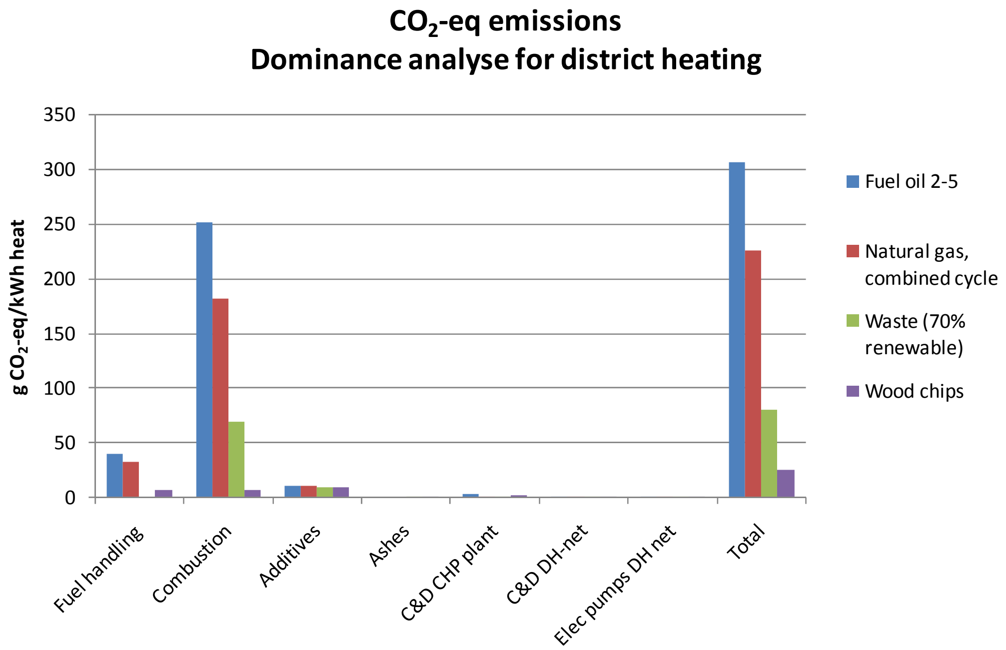

Figure 74. Impact on global warming divided into sub processes. The allocation method used in the CHP-plant is the alternative generation method.(C&D= Construction and dismantling)

For fossil fuels the combustion phase is the main contributor of the total emissions. For bio mass on the other hand the impact from the fuel handling and production of additives are approximately on the same size as the combustion. Greenhouse gases from the combustion of bio mass are related to emissions of methane and N_2O, CO_2 from renewable resources are not included.

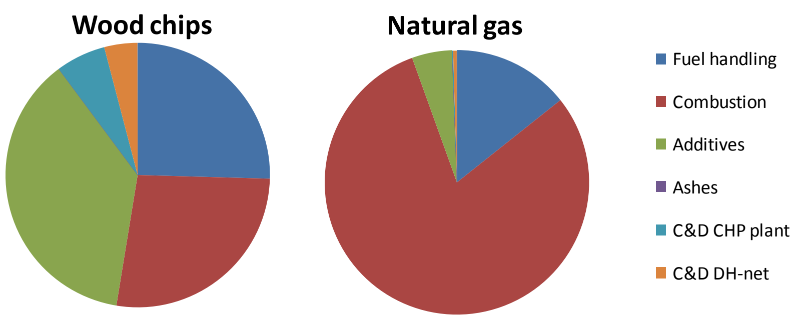

Figure 75. Emissions of greenhouse gases. Percental division by origin for district heating produced by bio mass (wood chips) and a fossil fuel (Natural gas) in a CHP-plant.(C&D= Construction and dismantling)

For primary energy losses the benefits from producing both heat and electricity in the CHP-plant is shown very clear in the sub-process "combustion". In the alternative generation method used for allocations, the main parts of the emissions and resources are allocated to the electricity. The result is that you will save primary energy by doing the combined production, which results in negative energy losses.

The losses of primary energy in the fuel handling step vary from fuel to fuel. For waste no energy or emissions is allocated to the fuel handling, instead it is allocated to the former product from which the waste origins from. Other main contributor to the losses of primary energy is energy losses in the district heating net and the production of additives. Note that it is losses of primary energy that is shown in Figure 76, not the PEF values. Extracted primary energy actually delivered as district heat is not included in the figure.

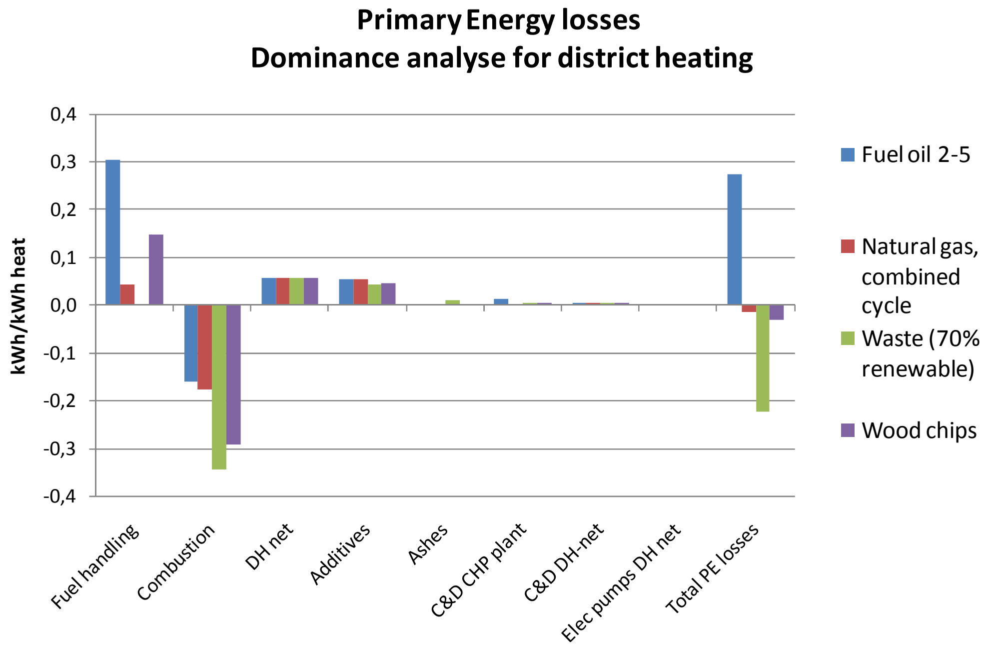

Figure 76. Primary energy losses divided into sub processes. The allocation method used in the CHP-plant is the alternative generation method.(C&D= Construction and dismantling)

9.4.3 *Heat only plant*

The trends in the dominance analyse for heat only plants shown in Figure 77 is similar to the trends for a CHP-plant, see Figure 74. For heat only plants the impact related to the internal electricity consumption in the plant is separated as an own sub process, for CHP-plants the electricity consumption is included in the figures for the combustion. A comparison also shows how the benefits from co-production of heat and electricity leads to lower emissions of greenhouse gases for the district heat produced.

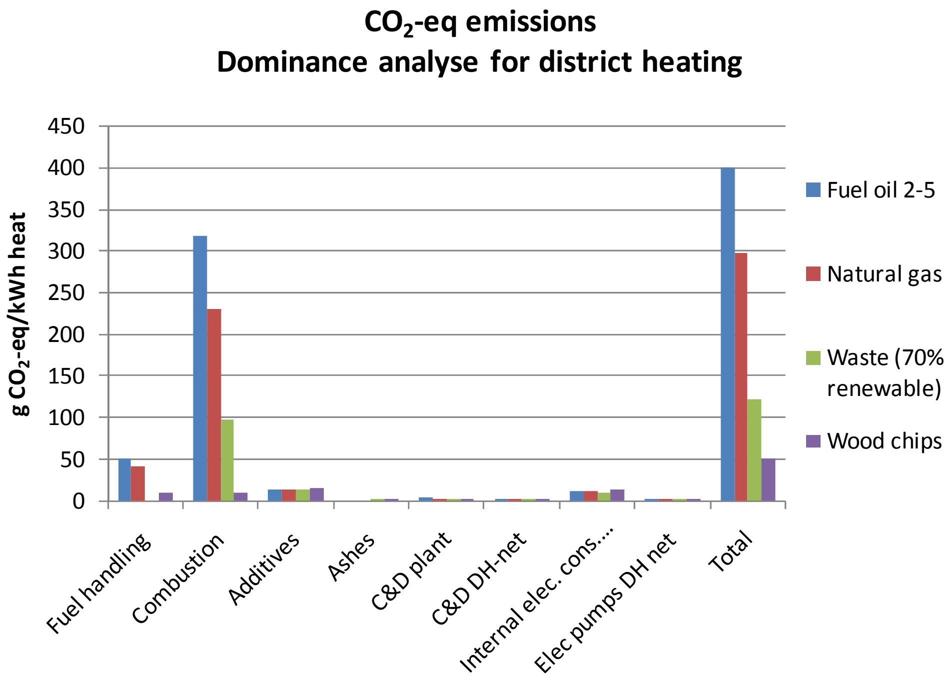

Figure 77. Impact on global warming divided into sub processes (C&D= Construction and dismantling)

There is a large difference of origin of CO_2-eq emission if you compare different fuels for heat only plants. For the fossil fuel natural gas the combustion is very dominant with 77% of the emissions. Fuel handling emits 14%, additives 5% and internal electricity within the plant emit 4%.

For waste, combustion stands for 80%, additives for 10% and internal electricity within the plant for 8%. Construction and dismantling of the plant emits 2% and construction and dismantling of the net emits 1%. Fuel handling gets no emissions because these are allocated to the product the waste originated from.

For wood chips fuel handling stands for 19%, additives for 28%, internal electricity consumption for 25% and combustion for 21%. Construction and dismantling of the plant emits 5% and construction and dismantling of the net 2%.

Most interesting is the impact related to the additives, this is a sub process excluded in many studies. But the results indicate that the impact is not negligible.

In Figure 78 the losses of primary energy is shown for the heat only cases. The combustion phase for heat only plants result in energy losses, compared to CHP-plants where primary energy was saved due to the co-production. The negative losses for the waste case are due to the efficiency above 100%.

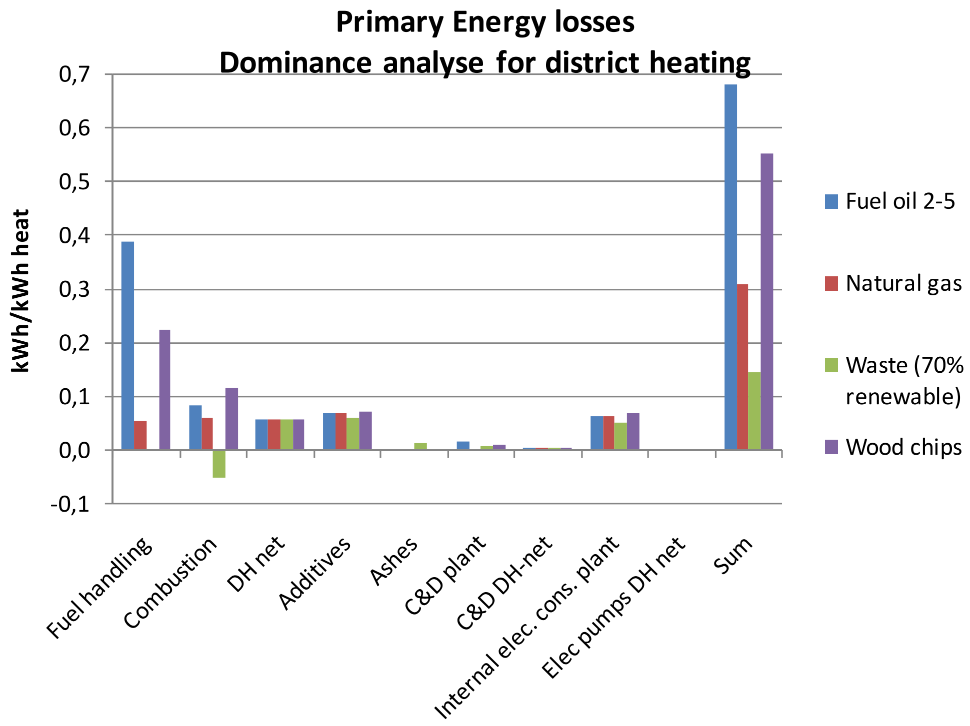

Figure 78. Primary energy losses divided into sub processes (C&D= Construction and dismantling)

9.5 Analyze choice of plant size

To analyze the relation between environmental impact and the plant size it was chosen to analyze one renewable alternative (wood chips) and one fossil (natural gas). Unfortunately the data set gathered is not complete which led to a big leap in size in the case of natural gas (5, 10 and 1000 MW). There is also a change in the technology used for the small natural gas plants using a steam cycle and the large plant based on a combined cycle. The 1000 MW gas plant also have a very high power to heat ratio with 1.81.

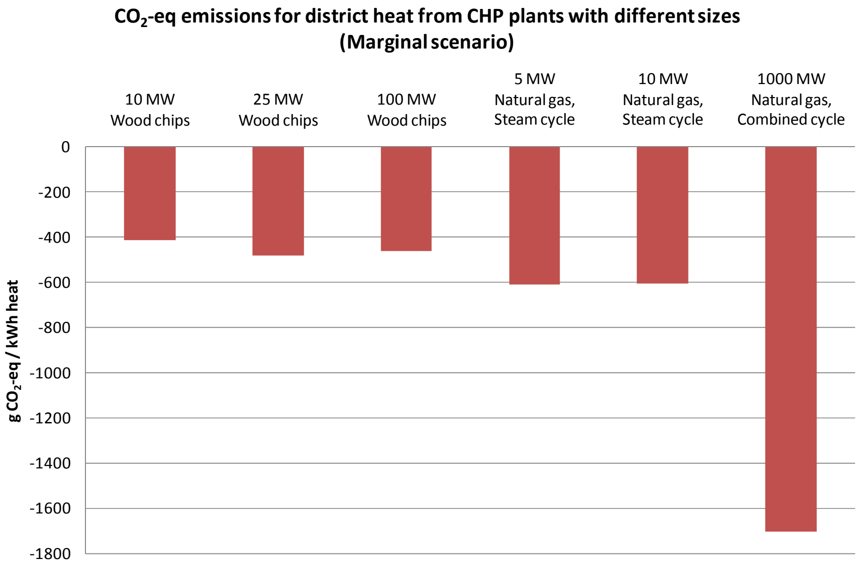

Figure 79 CO_2-eq emissions for heat from CHP plants with different sizes calculated with the Power bonus method

This diagram shows there is little to no difference between different sizes as long as the same technique is used. The leap for natural gas is mostly due to change in technique, from steam cycle to combined cycle which leads to a higher power to heat ratio and better total efficiency. The power bonus method favour CHP-plants with a high power to heat ratio.

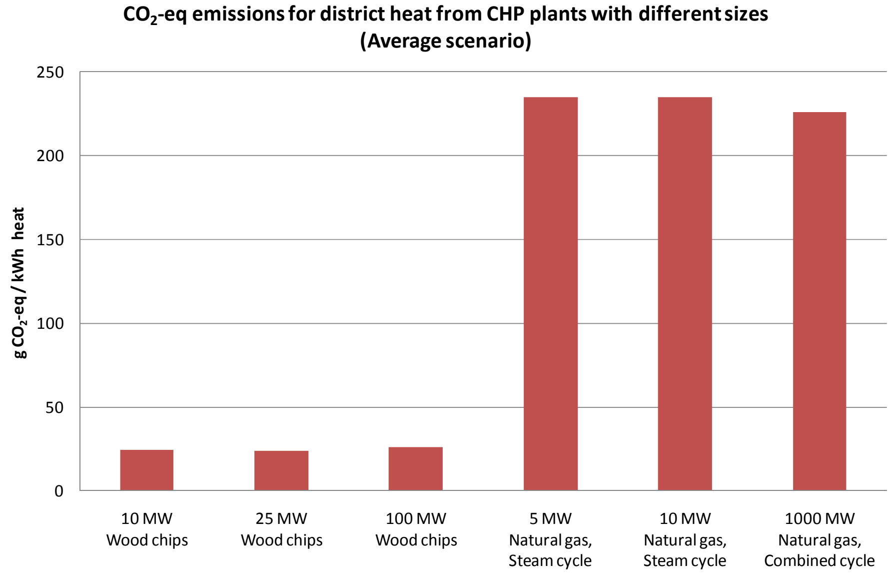

Figure 80. CO_2-eq emissions for heat from CHP plants with different sizes calculated with the alternative generation method

Using an marginal scenario and allocate with the alternative generation method there is almost no difference related to the size of the plant. Even with a change in technology from steam cycle to combined cycle for natural gas the effect on the emissions will be small. Here the impact on global warming is manly based on the properties of the fuel chosen.

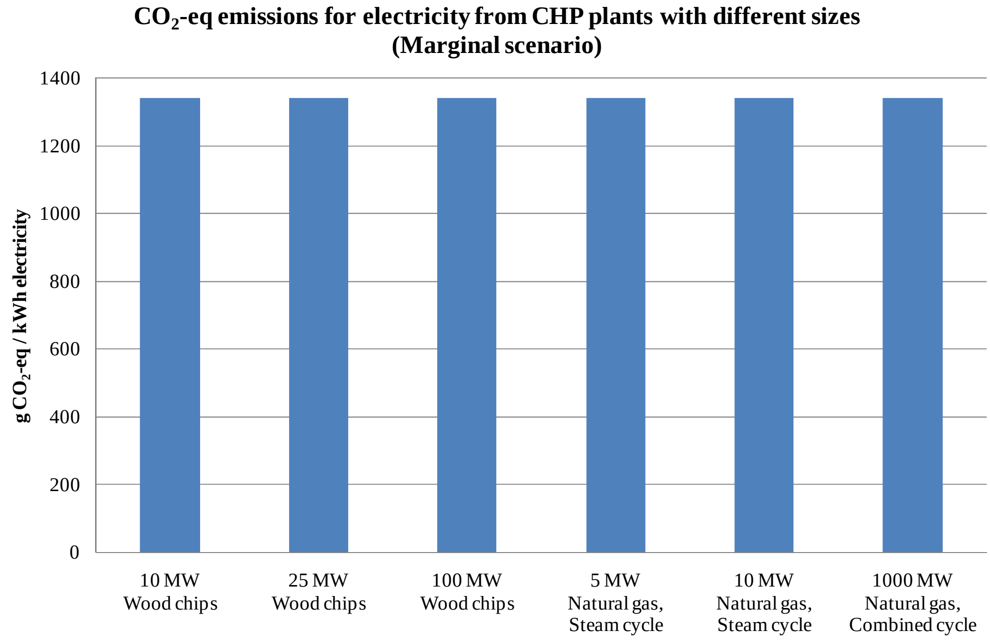

Figure 81. CO_2-eq emissions for electricity from CHP plants with different sizes calculated with the Power bonus method

Figure 81 shows the emissions for producing 1 kWh of electricity allocated with the power bonus method. Because of the allocation method there is no difference between the different cases; all end up at 1340 g CO_2-eq/kWh which is the emissions related to the marginal production of electricity.

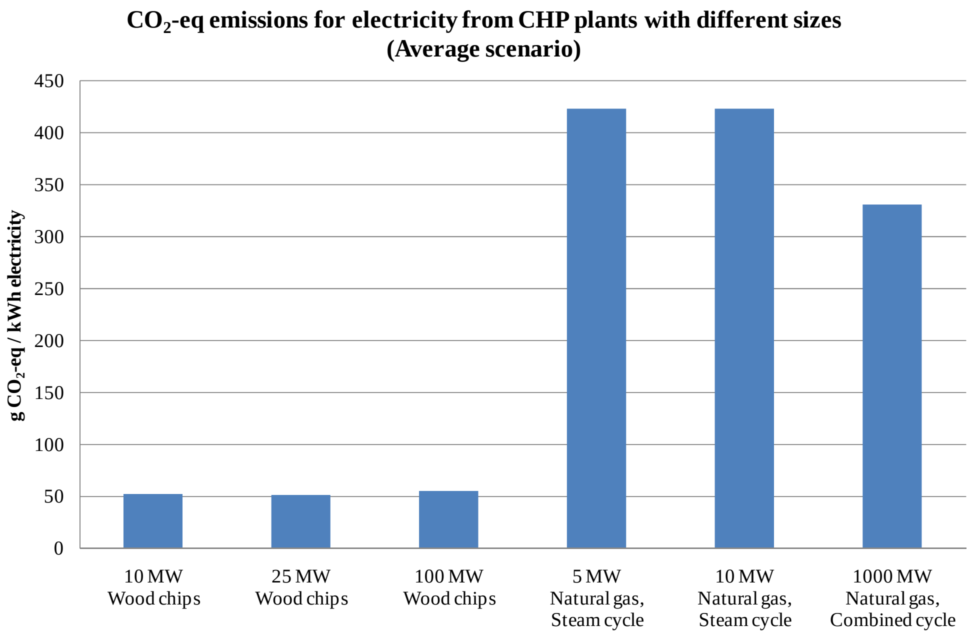

Figure 82. CO_2-eq emissions for electricity from CHP plants with different sizes calculated with the alternative generation method

With an average scenario the comparison between different sizes for two fuels show that size have little influence. The technique change from a steam cycle to a combined cycle for natural gas CHP plants leads to a reduction of greenhouse gases with 22%, from 420 g/kWh to 330 g/kWh.

9.6 Analyse production of district cooling

9.6.1 *Cold production, average scenario*

Figure 83 shows the calculated emission of green house gases and Figure 84 the primary energy factor for the delivered cold in this case study. The ABS chiller is assumed to be located at the substation and is supported with heat from the district heating net. The calculations are based on average data and the allocation method used is the alternative generation method. The data for heat only plants are more or less independent of if an average or a marginal perspective is used. Only emissions related to consume electricity will differ between the two scenarios. In the case studies it is chosen to show the data for the heat only plants in combination with average scenario.

The result is highly influenced of how the heat is produced. Waste as a fuel is a better choice compared to natural gas for both emissions of CO_2-eq and the PEF_{DC}. One can also see that heat produced in a CHP-plant will have lower emissions and lower primary energy factor compared to a heat only plant.

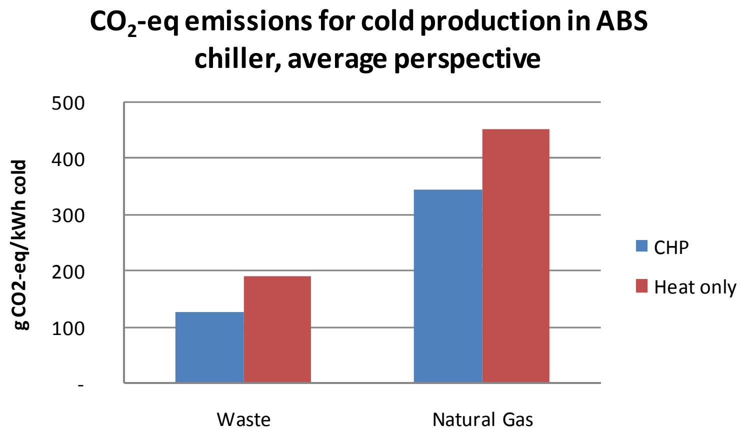

Figure 83.Emissions of CO_2-eq per kWh cold delivered to the customer based on fuel used and production technology. ABS chiller installed at sub-station. Allocation method used for CHP-plant is alternative generation method.

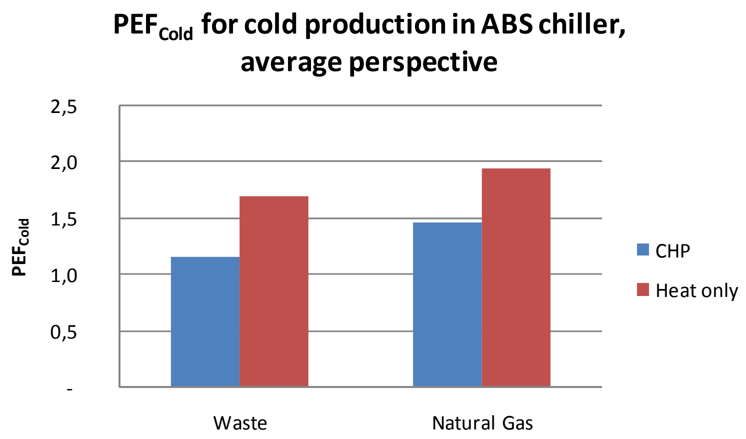

Figure 84. PEF for cold delivered to the customer based on fuel used and production technology. ABS chiller installed at sub-station. Allocation method used for CHP-plant is alternative generation method.

A dominance analyze of the result was made in order to see what parts of the lifecycle that are mainly contributing to the results. For emissions of greenhouse gases it is clear that the impact related to the cold production in the ABS chiller is small compared to the heat production, see Figure 85. The impact from the sub processes in the heat production is analyzed in chapter 9.4.

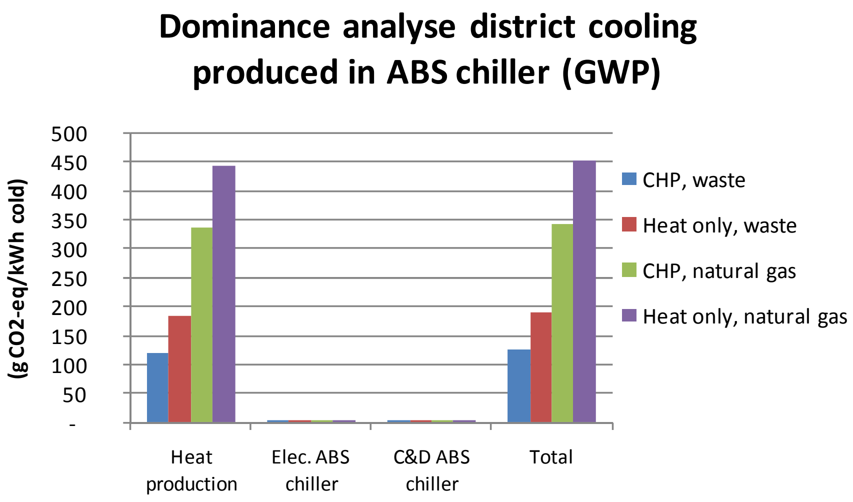

Figure 85. Impact on global warming divided into sub processes. The allocation method used in the CHP-plant is the alternative generation method.(C&D= Construction and dismantling)

Figure 86 show that the energy losses in the ABS chiller are a main contributor to the result in combination with the heat production. Since there is no difference in the input data for the cold production the use of primary energy related to this part will be the same for all analyzed scenarios. Note that the total primary energy losses in the diagram are not equal to the primary energy factor. Only the losses are shown in the diagram, the energy actually used for cooling in the building is not included.

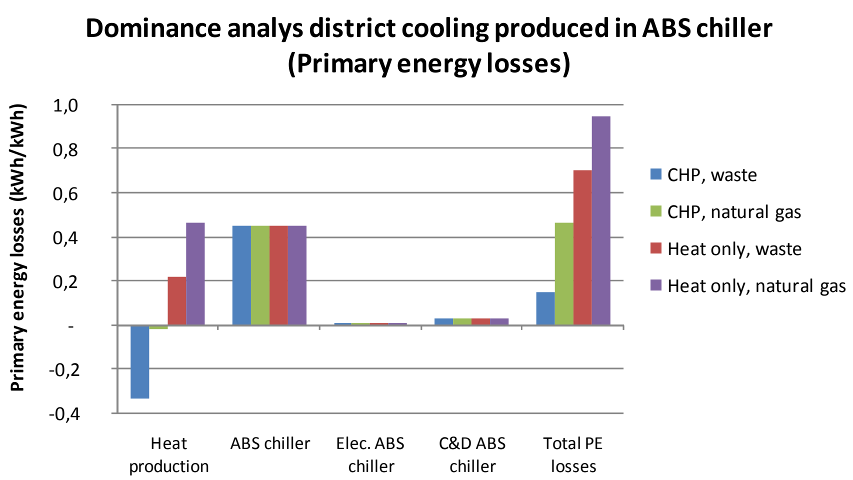

Figure 86. Primary energy losses divided into sub processes. The allocation method used in the CHP-plant is the alternative generation method.

9.6.2 *Cold production, marginal scenario*

In the marginal scenario only the cold produced in an ABS chiller based on district heating from a CHP-plant has been analyzed. The ABS chiller is assumed to be located at the substation and is supported with heat from the district heating net. Marginal data have been used for the electricity used. For the allocation between heat and electricity in the plant the power bonus method has been used.

Due to the large amount of avoided emissions of greenhouse gases when the electricity produced in the CHP-plant replaces the electricity on the margin also the result for the produced cold will be negative. As described in chapter 9.1.4 negative values is shown in the marginal perspective in order to see the total effects to the system. The savings of CO_2-eq and primary energy are larger in the natural gas case due to the high power to heat ratio used in the case study for natural gas. Thereby in the marginal scenario natural gas is the best choice of fuel, while in the average scenario waste is the best choice related to the analysed parameters.

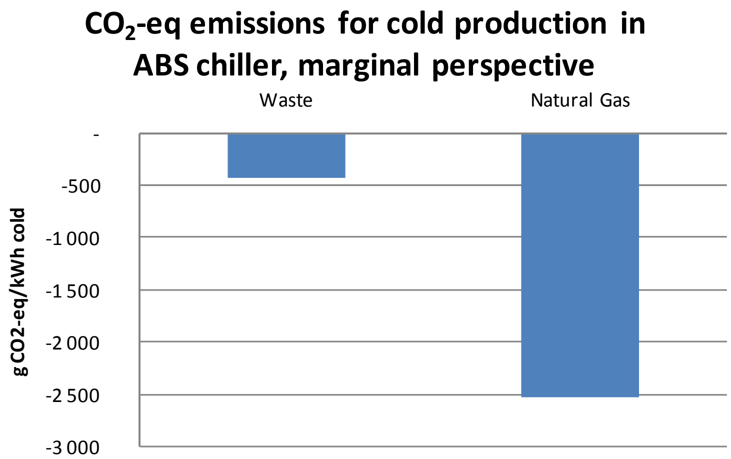

Figure 87. Emissions of CO_2-eq per kWh cooling delivered to the customer based on fuel used. ABS chiller installed at sub-station. Allocation method used for CHP plant is power bonus method.

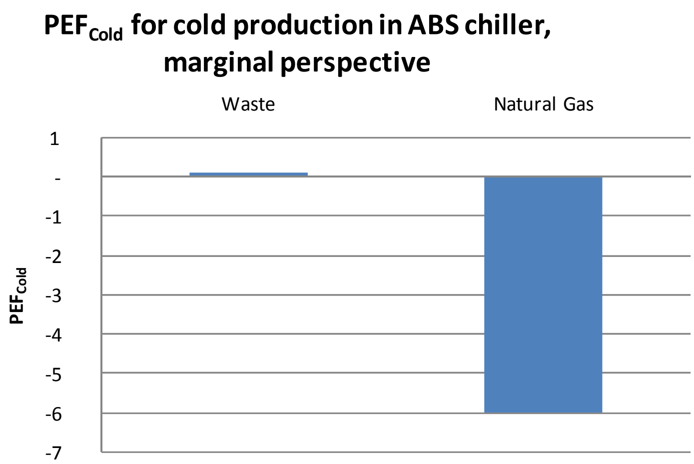

Figure 88. PEF for cold delivered to the customer based on fuel used and production technology. ABS chiller installed at sub-station. Allocation method used for CHP-plant is power bonus method. Negative values for PEF_{DC} is shown in order to see differences between alternatives and impact on the energy system in total.

The dominance analyse in Figure 89 shows that the impact related the cold production steps are small compared to the heat production.

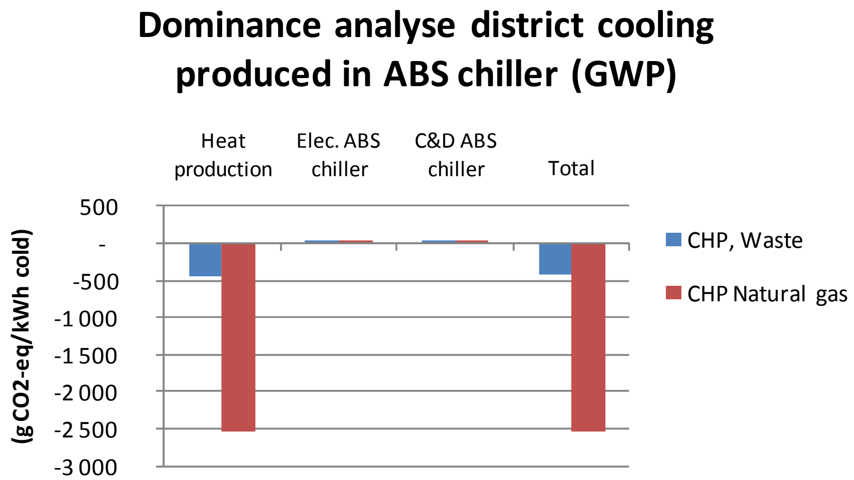

Figure 89. Impact on global warming divided into sub processes. The allocation method used in the CHP-plant is the power bonus method.

The trend for consumption of primary energy is similar to the emissions of greenhouse gases. For natural gas the heat production part is totally dominating the result. For waste as a fuel the losses when the heat is "transformed" to cooling in the ABS chiller is not negligible. As for the average scenario the total primary energy losses in the diagram are not equal to the primary energy factor. Only the losses are shown in the diagram, the energy actually used for cooling in the building is not included.

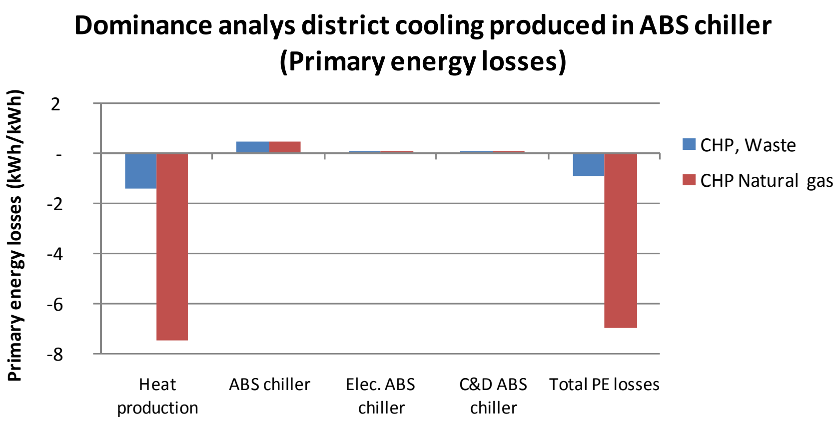

Figure 90 Losses of primary energy divided into sub processes. The process "delivered cold" includes the energy delivered and is no loss. "Total" gives the Primary Energy Factor. The allocation method used in the CHP is the power bonus method.(C&D=Construction and dismantling)

9.7 Analyse choice of allocation method

In the cases studies above two scenarios (marginal and average) with two different allocation methods are shown. It is obvious that the choice of allocation method has a great impact on the final result. To illustrate the differences between allocation methods more clearly this chapter will compare the allocation methods by presenting them in the same chart. Note that efficiency and size for the heat only plant might differ from the CHP-plant.

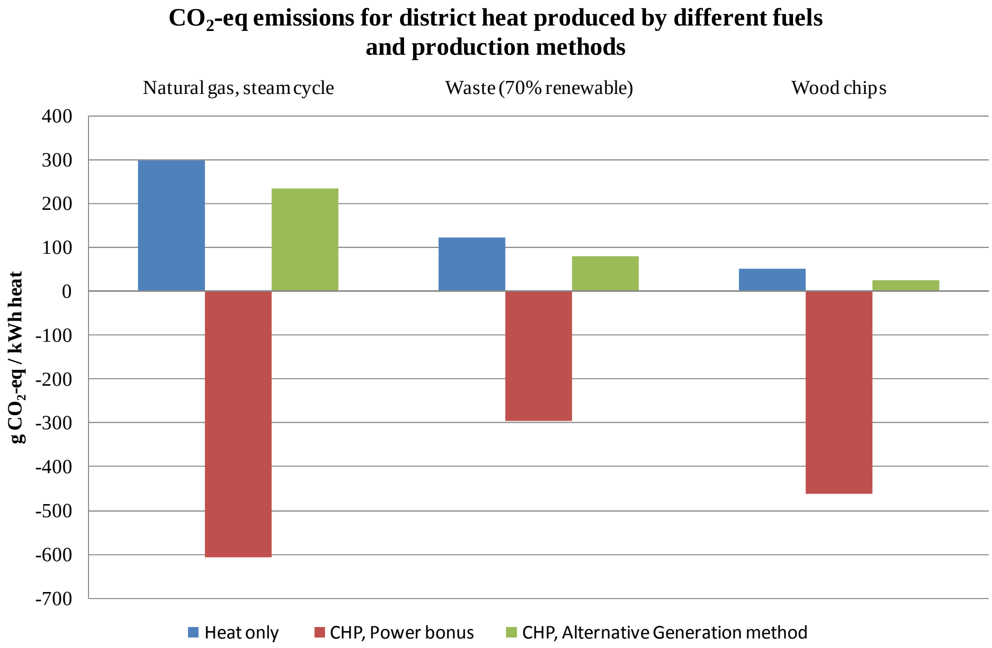

Figure 91 CO_2-eq emissions for heat production with different fuels and production methods

In this chart three smaller CHP plants are compared; Natural gas 10 MW, Waste 25 MW and Biomass 25 MW. In the heat only case the following sizes are simulated; Natural gas 100 MW, Waste 20 MW and Biomass 25 MW. Due to gaps in the collected data it was not possible to analyse heat only plants with the same size as the CHP-plant.

Figure 91 clearly shows the enormous difference in result between allocation methods. For the alternative generation method the impact on global warming allocated to heat is positive for all three fuels. For the power bonus method all three fuels give negative impact allocated to heat. For natural gas the difference is biggest. The allocation goes from 230 g CO_2-eq/kWh heat to -600 g. If the alternative generation method is used natural gas is the worst fuel to chose from a CO_2-eq emission perspective, but if the power bonus method is used it is the best fuel.

The importance of this difference cannot be stressed enough. The choice of allocation method is more important than the size of the plant, properties of the distribution net, plant technology and even more important than which fuel that is used. When analyzing the environmental performance of different CHP-plant it is important that the same allocation method is used for all plants and that the reader is aware of the effects related to the allocation method used.

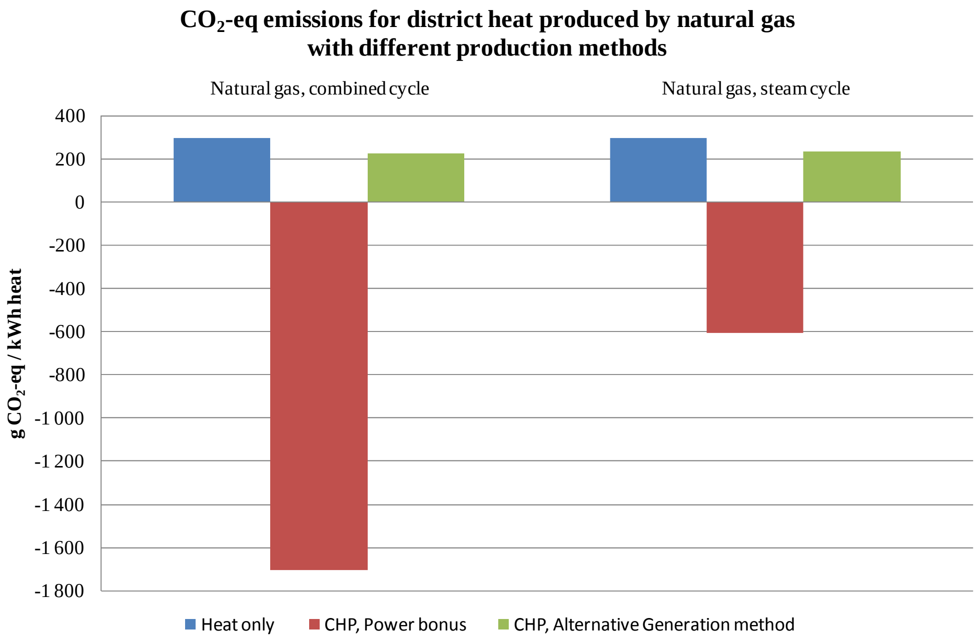

Figure 92 CO_2-eq emissions for district heating produced with natural gas with different production methods

Throughout the case studies different technologies for natural gas plants are presented. To visualize the difference a chart is presented with a combined cycle plant at 1000 MW and a steam cycle plant at 10 MW.

The difference for the power bonus method is huge. This is mainly due to the difference in power to heat ratio. The steam cycle plant has a power to heat ratio of 0.87 while the combined cycle has 1.81. The “bonus” that comes from replacing coal power plants with a big combined cycle natural gas plant is 2430 g CO_2-eq/kWh heat. For a steam cycle plant the “bonus” is 1170 g CO_2-eq/kWh heat (values taken from the calculation model made in the project). The difference if you use the alternative generation method is marginal.

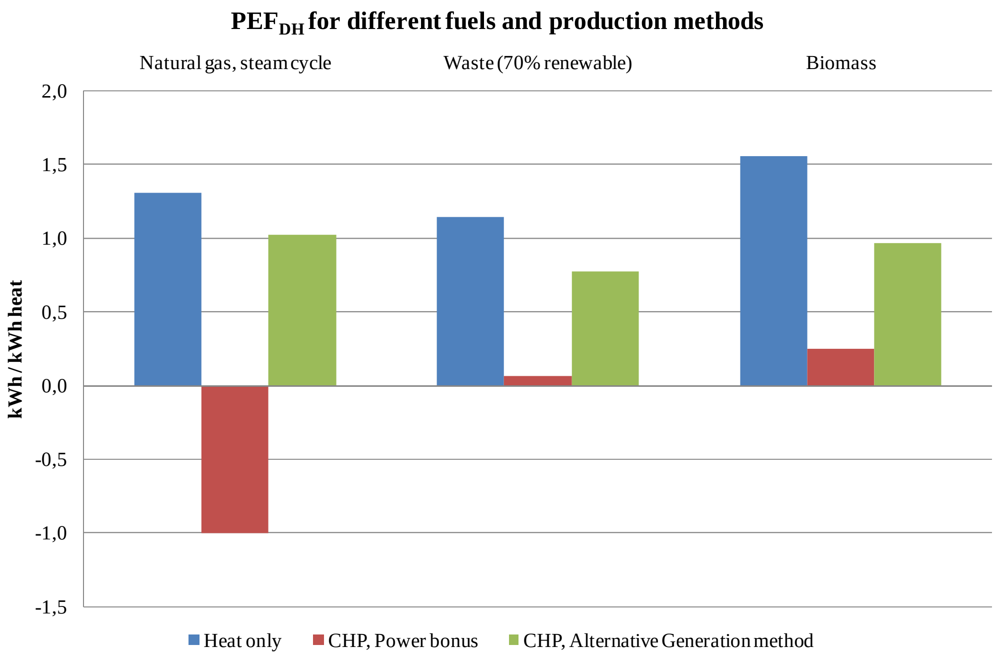

Figure 93. PEF_{DH} for district heat production with different fuels and production methods. Negative values for PEF_{DH} is shown in order to see differences between alternatives and impact on the energy system in total.

The impact the choice of allocation method has on the primary energy factor for district heating is compared in the same way as for greenhouse gases. Differences between the two allocation methods are once again very big. As for CO_2-eq emissions the difference is biggest for natural gas plants, where the PEF_{DH} goes from -1 for the power bonus method to 1 for the alternative generation method. For waste and wood chips the difference in PEF_{DH} depending on the choice of allocation method is approximately 0.7.

10 Conclusions

The choice of allocation method has an enormous impact on the final results for emissions of greenhouse gases and the use of primary energy for district heating systems with CHP plants. The case studies show that for the same system the primary energy factor for the delivered heat will differ from -1 to +1 depending on the choice of allocation method. A PEF below 1 means that less primary energy is used in the production and distribution than what is actually delivered as district heat to the end customer. A negative value of PEF_{DH} or PEF_{DC} is the result of using the power bonus method for allocations in CHP plants with a high power to heat ratio. According to the standard EN 15316-4-5 [10],[10] negative values for PEF should be set equal to zero; however, in this study we have allowed negative values in order to emphasize the total effects on the system. More primary energy is saved in the system when the produced electricity from the CHP plant replaces the electricity on the marginal than what is consumed during the production of the district heat or cold. Thereby the PEF values become negative.

For emissions of greenhouse gases, the differences due to the choice of allocation method will be even larger, as the power bonus method gives -1.7 kg CO_2-eq/kWh heat and the alternative generation method gives +0.2 kg CO_2-eq/kWh heat.

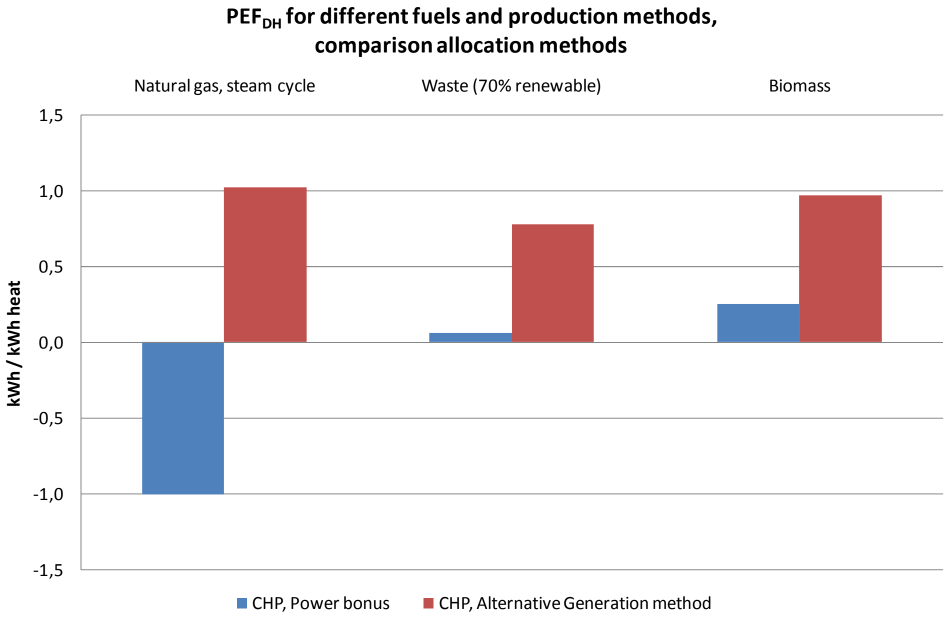

Figure 94. Comparison allocation methods, PEF. Negative values for PEF_{DH} are shown in order to see differences between alternatives and the impact on the energy system in total.

For the power bonus method, the power to heat ratio has the largest impact on the final results, see Figure 95 below, where it should be noted that the main difference between the combined cycle and the steam cycle for combustion of natural gas is the power to heat ratio. Using the power bonus method for a system with a combined cycle with a higher power to heat ratio, the CO_2-eq savings are almost three times larger than for a system with a steam cycle. In contrast, for the alternative generation method there is almost no difference between the two alternatives. For the alternative generation allocation method, a renewable fuel is the most important single factor for low emissions of greenhouse gases.

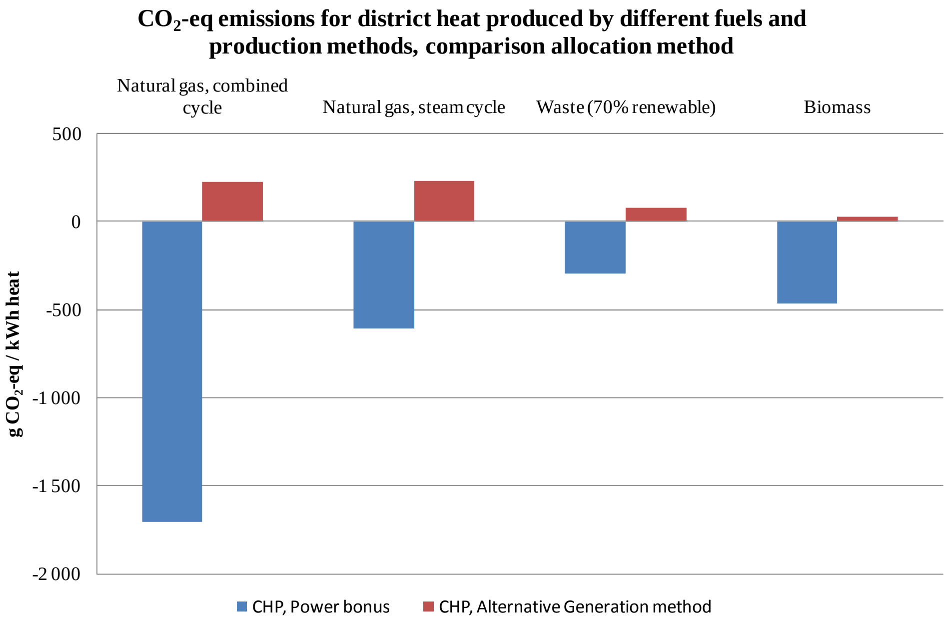

Figure 95. Comparison allocation methods, CO_2-eq

The case studies show that the environmental impact related to production and use of additives has an impact on the final results that cannot be neglected. Previous studies often assumed that this component had a more or less negligible influence on the results. Especially for biomass the effect of the additive will be large. Our study shows that additives represent 35-40% of the total CO_2 emissions in a wood chips CHP plant. However, even for fossil fuels the effect of additives is not negligible. In a CHP plant using natural gas, approximately 5% of the impact on global warming will be due to the use of additives.

The environmental impact for construction and dismantling of plants and district heating grids are in general small, in most cases below 2% of the total. For systems using fossil fuel it will be even smaller. However, the impact per kWh produced heat may be larger for plants that only produce power or heat when operated at peak load. In this case the building and dismantling phase may be a large part of the total. The situation is similar for the district heating grid, in grids with a low energy density the construction and dismantling phase may have a larger influence on the final results. Thus, for a specific system one has to evaluate all sub-processes related to the production and distribution of district heat or cold in order to see what part has an impact on the total. At present it is not possible to draw any general conclusions about sub-processes that will always be excluded due to the cut off rules.

In order to analyse how the choice of supply and return temperature of the district heating water affects the efficiency of the CHP plant, separate computer simulations of the plant have been performed. The main purpose with the simulations was to evaluate the possibilities for efficiency improvements by optimizing the return and supply temperature.

The simulations show that a decrease of the supply temperature of the district heating increases the electricity efficiency, while the heat efficiency decreases. A decrease of the supply temperature from 120 to 80°C will increase the electricity efficiency with 3 %-points (in the simulation from 19% to 22 %). The total efficiency of the plant is more or less independent of the supply temperature. Thus, the heat efficiency will decrease when the electricity efficiency increases, and the power to heat ratio will increase. Another advantage with a low supply temperature is that a low temperature will extend the lifetime of the DH pipelines. A change of the return temperature will only have a minor effect on the efficiency.

The case studies show that an increased power to heat ratio (at a constant total efficiency) leads to lower primary energy losses and lower emission of greenhouse gases for the produced district heat. This is the case for both of the analysed allocation method. The resulting increased electricity efficiency leads to lower emissions allocated to the heat production, even though the heat efficiency will decrease.

The efficiency of the ABS chiller depends on the supply temperature of the district heating water. A higher district heating temperature to the ABS chiller will increase the cooling efficiency. The drawback is that a high district heating temperature decreases the electricity efficiency in CHP plants.

In general the ABS chillers are mainly operated for production of cooling during the summer, when the district heating temperatures normally are lower than during the winter. Thereby, there is a trade-off between increasing district heating temperature for higher efficiency of the ABS chiller and lowering the district heating temperature for higher electricity efficiency in the CHP plant.

11 Future work

A calculation of the total environmental impact of a district heating/cooling system requires knowledge of the whole energy chains life cycle. The PEF and CO_2-eq values also include energy to extraction, production, transformation and transportation before the energy is delivered to the end user. This includes for example energy to build, operate, maintain and demolish the energy plant and the distribution system.

A detailed calculation of PEF and CO_2 equivalents imply use of both Life Cycle Assessment (LCA) methods and energy calculations. A complete LCA includes collection of a large amount of data, often more than 6000 parameters. Likewise, a detailed energy calculation of DH/DC networks to provide PEF and CO_2 equivalents presuppose i.e. calculation of heat/cold load, heat losses, head loss and information on layout.

This project has revealed that there still are some shortcomings in the developed method. As lack of consistency in the data and a need for documented and transparent data before the method could be implemented and applied by DHC companies, energy planners and regulators.

The method described in EN 15603[2] is rather general and provides PEF and CO_2 values for only 13 energy carriers and chains, based on average European values and cannot be utilized for DHC. However, calculation of all the parameters affecting the PEF values is time-consuming. A simplified method that enables comparison of the PEF and CO_2 equivalents from different energy chains is required.

The new series of CEN-standards like the EN 15316-series [10] developed in connection with the EPBD [1] needs PEF and data about emissions of greenhouse gases as input values. Direct use of the existing European PEF and CO_2 equivalents in EN 15603 might give misleading values for DHC.

One of the major drawbacks of the current available material in the area is the lack of transparency and traceability of the presented data. There is a need for a further development both in the general methodology and in the allocation methods. PEF and CO_2 equivalents for different fuels delivered at different locations are required.

There is also a need for a general method for calculation of fuels based on residuals from other processes and waste heat.

In order enable a comparison of different energy chains and technology is it essential to develop a computer based calculation tool, since each system has to be evaluated and calculated separately. The calculation model developed in this project for the case studies is a good start but is not developed for external use. One has to know how the model is working in order to be able to vary the different parameters. There is also of interest to add data for additional fuels, allocation methods etc.

The results from the cases studies have shown that the choice of allocation method has a great impact on the final result. There are a number of additional allocation methods briefly described in this project and not analysed in detail. Each allocation method will influence the result in different ways. It is of interest to deeper analysing how the choice of allocation methods will influence the result.

A second outcome of the case studies is the impact of the final result related to the production and use of additives. The impact related to the chemical use is excluded in many studies but the results from this study show that it is not negligible. The amounts of additives included in this study is independent the choice of fuel and technology. It would be of interest to deeper analyse how the chemical use and thereby related emissions of greenhouse gases and losses of primary energy differs between different plants with different use of additives.

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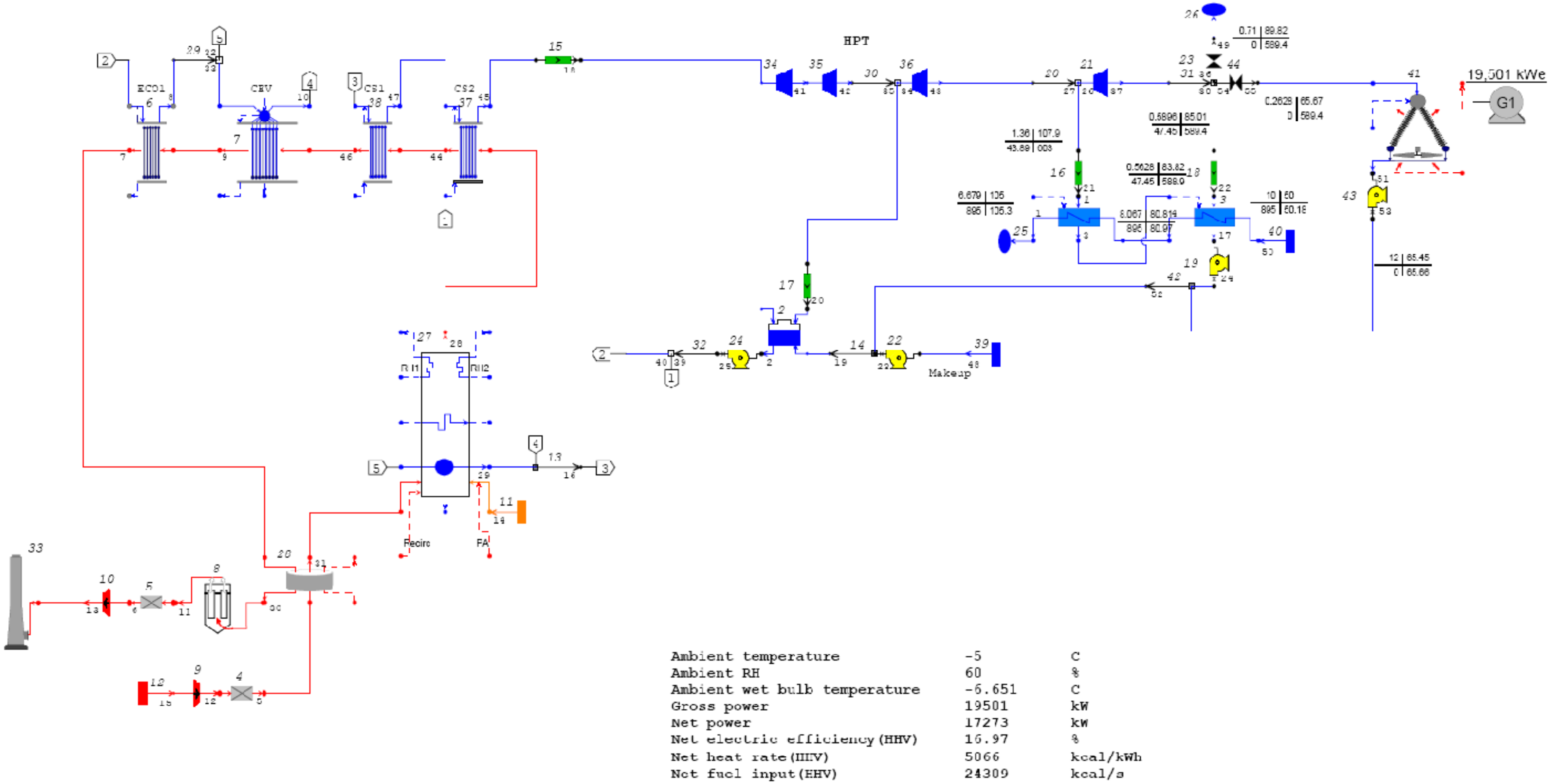
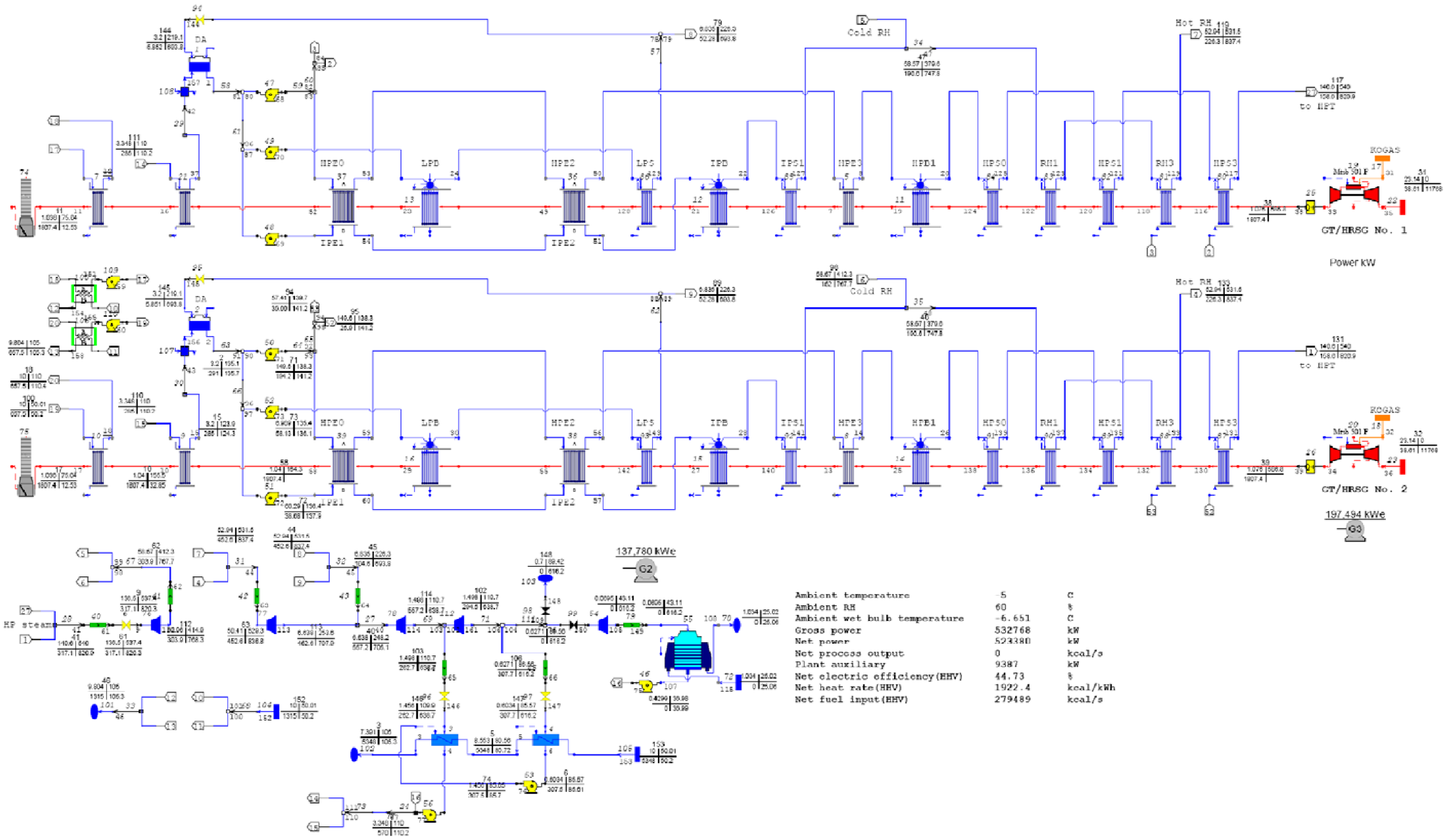
13 Appendix

Appendix A

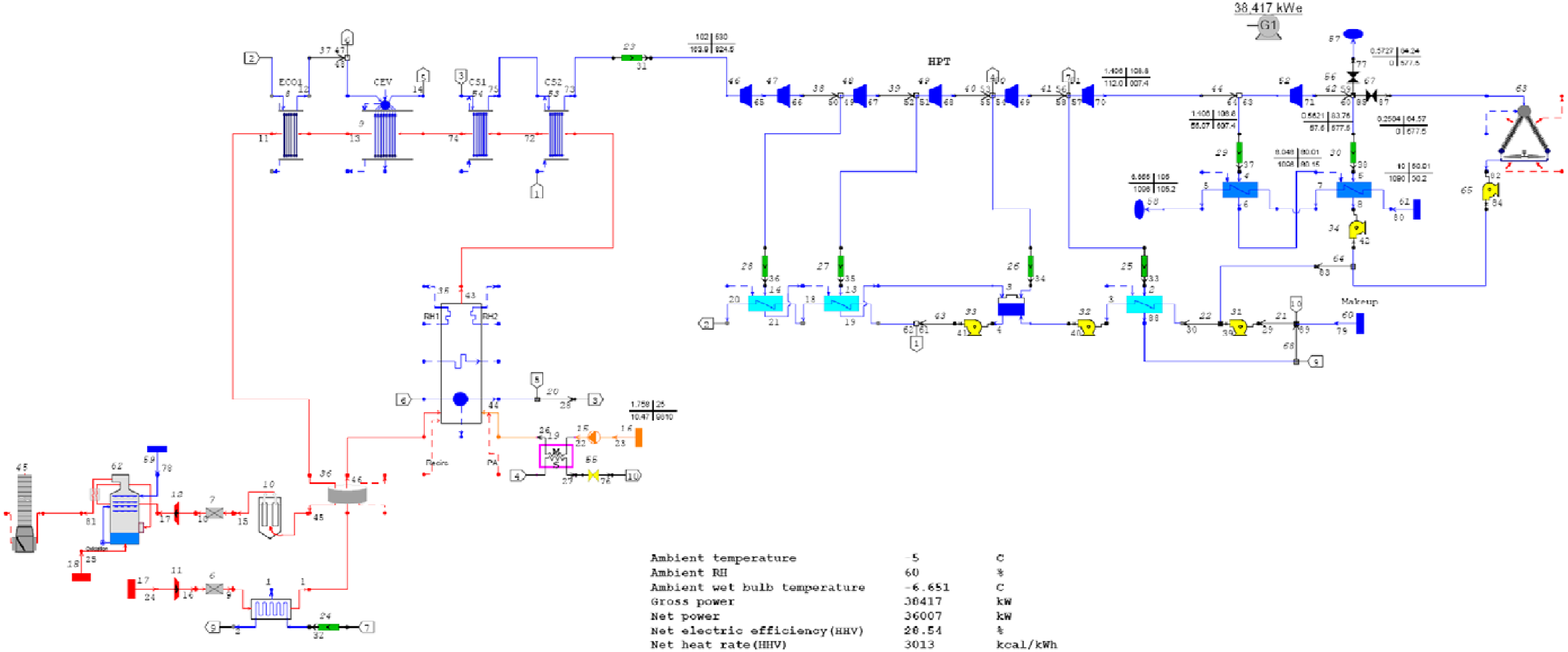
Heat Balance diagram (Woodchip CHP, Base Condition, -5 , DH return 50 , supply 105)



Heat Balance diagram (LNG CHP, Base Condition, -5 , DH inlet 50 , supply 105)



Heat Balance diagram (Oil CHP, Base Condition, -5 , DH return 50 , supply 105)



Ambient temperature	-5	C
Ambient RH	60	%
Ambient wet bulb temperature	-6.651	C
Gross power	38417	kW
Net power	36007	kW
Net electric efficiency(HHV)	28.54	%
Net heat rate(HHV)	3013	kcal/kWh
Net fuel input(HHV)	30132	kcal/s

Appendix B

CHP Simulation Data

Case 1 - Woodchip

◻ Return Temp. 50℃

Outdoor Temp. - 5℃

Efficiency versus Output Temp.

Supply	Efficiency(%)					
Temp.(℃)	Heat	Δη/ΔT	Power	Δη/ΔT	Total	Δη/ΔT
80	59.35%		22.04%		81.39%	
90	59.78%	0.043%	21.60%	-0.044%	81.39%	0.001%
105	60.79%	0.067%	20.67%	-0.062%	81.46%	-0.005%
115	61.55%	0.076%	19.79%	-0.088%	81.34%	0.012%
120	62.22%	0.134%	19.20%	-0.117%	81.42%	-0.017%

Ratio [Power / Heat]

Supply	Output (Gcal)						Ratio	Total
Temp.(℃)	Heat	ΔE/ΔT	Power	ΔE/ΔT	Total	ΔE/ΔT		Efficiency
80	48.16		17.89		66.05		**0.3714**	81.39%
90	48.51	0.035	17.53	-0.036	66.04	-0.001	**0.3614**	81.39%
105	49.33	0.055	16.77	-0.051	66.10	0.004	**0.3399**	81.46%
115	49.95	0.061	16.06	-0.071	66.00	-0.010	**0.3215**	81.34%
120	50.49	0.109	15.58	-0.095	66.07	0.014	**0.3086**	81.42%

Outdoor Temp. 10℃

Efficiency versus Output Temp.

Supply	Efficiency(%)					
Temp.(℃)	Heat	Δη/ΔT	Power	Δη/ΔT	Total	Δη/ΔT
80	59.60%		22.15%		81.75%	
90	60.03%	0.043%	21.71%	-0.044%	81.74%	0.001%
105	60.95%	0.061%	20.77%	-0.062%	81.72%	0.001%
115	61.79%	0.084%	19.89%	-0.088%	81.68%	0.004%
120	62.39%	0.120%	19.31%	-0.116%	81.70%	-0.004%

Ratio [Power / Heat]

Supply	Output (Gcal/h)						Ratio	Total
Temp.(℃)	Heat	ΔE/ΔT	Power	ΔE/ΔT	Total	ΔE/ΔT		Efficiency
80	48.37		17.97		66.34		**0.3716**	81.75%
90	48.71	0.035	17.61	-0.036	66.33	-0.001	**0.3616**	81.74%
105	49.46	0.050	16.85	-0.051	66.32	-0.001	**0.3407**	81.72%
115	50.14	0.068	16.14	-0.071	66.28	-0.004	**0.3219**	81.68%
120	50.63	0.097	15.67	-0.094	66.30	0.003	**0.3095**	81.70%

Outdoor Temp. 20℃

Efficiency versus Output Temp.

Supply	Efficiency(%)					
Temp.(℃)	Heat	Δη/ΔT	Power	Δη/ΔT	Total	Δη/ΔT
80	59.72%		22.20%		81.92%	
90	60.16%	0.044%	21.75%	-0.045%	81.91%	0.001%
105	61.09%	0.062%	20.82%	-0.062%	81.91%	0.000%
115	61.97%	0.088%	19.93%	-0.089%	81.90%	0.001%
120	62.57%	0.120%	19.35%	-0.116%	81.92%	-0.004%

Ratio [Power / Heat]

Supply	Output (Gcal/h)						Ratio	Total
Temp.(℃)	Heat	ΔE/ΔT	Power	ΔE/ΔT	Total	ΔE/ΔT		Efficiency
80	48.46		18.02		66.48		**0.3718**	81.92%
90	48.82	0.036	17.65	-0.036	66.47	-0.001	**0.3616**	81.91%
105	49.57	0.050	16.89	-0.051	66.47	0.000	**0.3408**	81.91%
115	50.28	0.071	16.17	-0.072	66.46	-0.001	**0.3216**	81.90%
120	50.77	0.097	15.70	-0.094	66.47	0.003	**0.3093**	81.92%

◻ Supply Temp. 105℃

Outdoor Temp. - 5℃

Efficiency versus Input Temp.

Return	Efficiency(%)					
Temp.(℃)	Heat	Δη/ΔT	Power	Δη/ΔT	Total	Δη/ΔT
40	60.57%		20.81%		81.38%	
45	60.67%	0.020%	20.74%	-0.014%	81.41%	-0.006%
50	60.79%	0.025%	20.67%	-0.014%	81.46%	-0.011%
55	60.84%	0.009%	20.58%	-0.017%	81.42%	0.008%
60	60.92%	0.015%	20.49%	-0.019%	81.41%	0.004%

Ratio [Power / Heat]

Return	Output (Gcal/h)						Ratio	Total
Temp.(℃)	Heat	ΔE/ΔT	Power	ΔE/ΔT	Total	ΔE/ΔT		Efficiency
40	49.15		16.89		66.04		**0.3436**	81.38%
45	49.23	0.016	16.83	-0.011	66.06	0.005	**0.3418**	81.41%
50	49.33	0.020	16.77	-0.012	66.10	0.009	**0.3399**	81.46%
55	49.37	0.007	16.70	-0.014	66.07	-0.006	**0.3383**	81.42%
60	49.43	0.012	16.63	-0.015	66.06	-0.003	**0.3363**	81.41%

Outdoor Temp. 10℃

Efficiency versus Input Temp.

Return	Efficiency(%)					
Temp.(℃)	Heat	Δη/ΔT	Power	Δη/ΔT	Total	Δη/ΔT
40	60.81%		20.91%		81.72%	
45	60.89%	0.016%	20.84%	-0.014%	81.74%	-0.002%
50	60.95%	0.013%	20.77%	-0.015%	81.72%	0.002%
55	61.15%	0.038%	20.68%	-0.018%	81.83%	-0.020%
60	61.14%	-0.002%	20.59%	-0.018%	81.73%	0.020%

Ratio [Power / Heat]

Return	Output (Gcal/h)						Ratio	Total
Temp.(℃)	Heat	ΔE/ΔT	Power	ΔE/ΔT	Total	ΔE/ΔT		Efficiency
40	49.35		16.97		66.32		**0.3439**	81.72%
45	49.41	0.013	16.91	-0.011	66.33	0.002	**0.3423**	81.74%
50	49.46	0.011	16.85	-0.012	66.32	-0.002	**0.3407**	81.72%
55	49.62	0.031	16.78	-0.015	66.40	0.017	**0.3382**	81.83%
60	49.61	-0.001	16.71	-0.015	66.32	-0.016	**0.3367**	81.73%

Outdoor Temp. 20℃

Efficiency versus Input Temp.

Return	Efficiency(%)					
Temp.(℃)	Heat	Δη/ΔT	Power	Δη/ΔT	Total	Δη/ΔT
40	60.88%		20.97%		81.84%	
45	60.94%	0.012%	20.90%	-0.014%	81.83%	0.002%
50	61.09%	0.031%	20.82%	-0.016%	81.91%	-0.015%
55	61.15%	0.012%	20.73%	-0.018%	81.88%	0.006%
60	61.25%	0.020%	20.64%	-0.018%	81.88%	-0.002%

Ratio [Power / Heat]

Return	Output (Gcal/h)						Ratio	Total
Temp.(℃)	Heat	ΔE/ΔT	Power	ΔE/ΔT	Total	ΔE/ΔT		Efficiency
40	49.40		17.01		66.41		**0.3444**	81.84%
45	49.45	0.010	16.96	-0.011	66.41	-0.002	**0.3429**	81.83%
50	49.57	0.025	16.89	-0.013	66.47	0.012	**0.3408**	81.91%
55	49.62	0.009	16.82	-0.015	66.44	-0.005	**0.3390**	81.88%
60	49.70	0.016	16.74	-0.015	66.45	0.001	**0.3369**	81.88%

Case 2 - NG(Natural Gas)

□ Return Temp. 50℃

Outdoor Temp. -5℃

Efficiency versus Output Temp

Supply Temp.(℃)	Efficiency(%) Heat	Δη/ΔT	Power	Δη/ΔT	Total	Δη/ΔT
80	39.81%		51.01%		90.82%	
90	39.94%	0.013%	50.87%	-0.014%	90.81%	0.001%
105	40.40%	0.031%	50.42%	-0.030%	90.82%	0.000%
115	40.99%	0.059%	49.86%	-0.056%	90.85%	-0.003%
120	41.34%	0.069%	49.50%	-0.071%	90.84%	0.002%

Ratio [Power / Heat]

Supply Temp.(℃)	Output (Gcal/h) Heat	ΔE/ΔT	Power	ΔE/ΔT	Total	ΔE/ΔT	Ratio	Total Efficiency
80	361.77		463.56		825.33		**1.2814**	90.82%
90	362.95	0.118	462.28	-0.128	825.24	-0.009	**1.2737**	90.81%
105	367.13	0.278	458.17	-0.274	825.30	0.004	**1.2480**	90.82%
115	372.51	0.538	453.07	-0.510	825.58	0.028	**1.2163**	90.85%
120	375.67	0.632	449.83	-0.648	825.50	-0.017	**1.1974**	90.84%

Outdoor Temp. 10℃

Efficiency versus Output Temp

Supply Temp.(℃)	Efficiency(%) Heat	Δη/ΔT	Power	Δη/ΔT	Total	Δη/ΔT
80	41.15%		51.24%		92.39%	
90	41.29%	0.014%	51.10%	-0.014%	92.39%	0.000%
105	41.72%	0.029%	50.64%	-0.031%	92.36%	0.002%
115	42.31%	0.058%	50.07%	-0.056%	92.38%	-0.002%
120	42.68%	0.074%	49.70%	-0.074%	92.38%	0.000%

Ratio [Power / Heat]

Supply Temp.(℃)	Output (Gcal/h) Heat	ΔE/ΔT	Power	ΔE/ΔT	Total	ΔE/ΔT	Ratio	Total Efficiency
80	366.28		456.09		822.37		**1.2452**	92.39%
90	367.55	0.128	454.82	-0.127	822.37	0.000	**1.2374**	92.39%
105	371.39	0.256	450.73	-0.272	822.12	-0.016	**1.2136**	92.36%
115	376.57	0.518	445.72	-0.502	822.29	0.016	**1.1836**	92.38%
120	379.87	0.660	442.42	-0.660	822.29	0.000	**1.1647**	92.38%

Outdoor Temp. 20℃

Efficiency versus Output Temp

Supply Temp.(℃)	Efficiency(%) Heat	Δη/ΔT	Power	Δη/ΔT	Total	Δη/ΔT
80	42.12%		51.14%		93.25%	
90	42.27%	0.015%	50.98%	-0.015%	93.25%	0.000%
105	42.73%	0.031%	50.50%	-0.032%	93.23%	0.001%
115	43.36%	0.063%	49.90%	-0.060%	93.26%	-0.003%
120	43.72%	0.072%	49.51%	-0.078%	93.23%	0.005%

Ratio [Power / Heat]

Supply Temp.(℃)	Output (Gcal/h) Heat	ΔE/ΔT	Power	ΔE/ΔT	Total	ΔE/ΔT	Ratio	Total Efficiency
80	357.16		433.63		790.78		**1.2141**	93.25%
90	358.43	0.128	432.34	-0.129	790.77	-0.001	**1.2062**	93.25%
105	362.37	0.262	428.24	-0.273	790.61	-0.011	**1.1818**	93.23%
115	367.70	0.533	423.16	-0.508	790.85	0.025	**1.1508**	93.26%
120	370.76	0.614	419.86	-0.660	790.62	-0.047	**1.1324**	93.23%

□ Supply Temp. 105℃

Outdoor Temp. -5℃

Efficiency versus Input Temp

Return Temp.(℃)	Efficiency(%) Heat	Δη/ΔT	Power	Δη/ΔT	Total	Δη/ΔT
40	40.17%		50.62%		90.79%	
45	40.28%	0.023%	50.52%	-0.019%	90.80%	-0.003%
50	40.40%	0.024%	50.42%	-0.021%	90.82%	-0.003%
55	40.52%	0.024%	50.32%	-0.020%	90.84%	-0.005%
60	40.61%	0.018%	50.21%	-0.022%	90.82%	0.004%

Ratio [Power / Heat]

Return Temp.(℃)	Output (Gcal/h) Heat	ΔE/ΔT	Power	ΔE/ΔT	Total	ΔE/ΔT	Ratio	Total Efficiency
40	365.03		459.98		825.01		**1.2601**	90.79%
45	366.06	0.206	459.11	-0.175	825.16	0.032	**1.2542**	90.80%
50	367.13	0.215	458.17	-0.187	825.30	0.027	**1.2480**	90.82%
55	368.24	0.221	457.28	-0.178	825.52	0.043	**1.2418**	90.84%
60	369.06	0.165	456.27	-0.202	825.33	-0.037	**1.2363**	90.82%

Outdoor Temp. 10℃

Efficiency versus Input Temp

Return Temp.(℃)	Efficiency(%) Heat	Δη/ΔT	Power	Δη/ΔT	Total	Δη/ΔT
40	41.51%		50.84%		92.36%	
45	41.63%	0.024%	50.74%	-0.020%	92.37%	-0.003%
50	41.72%	0.019%	50.64%	-0.021%	92.36%	0.003%
55	41.86%	0.027%	50.53%	-0.022%	92.38%	-0.005%
60	41.95%	0.019%	50.42%	-0.022%	92.37%	0.003%

Ratio [Power / Heat]

Return Temp.(℃)	Output (Gcal/h) Heat	ΔE/ΔT	Power	ΔE/ΔT	Total	ΔE/ΔT	Ratio	Total Efficiency
40	369.51		452.58		822.09		**1.2248**	92.36%
45	370.56	0.210	451.68	-0.179	822.24	0.031	**1.2189**	92.37%
50	371.39	0.165	450.73	-0.189	822.12	-0.024	**1.2136**	92.36%
55	372.58	0.238	449.77	-0.193	822.35	0.045	**1.2072**	92.38%
60	373.41	0.167	448.80	-0.194	822.21	-0.027	**1.2019**	92.37%

Outdoor Temp. 20℃

Efficiency versus Input Temp

Return Temp.(℃)	Efficiency(%) Heat	Δη/ΔT	Power	Δη/ΔT	Total	Δη/ΔT
40	42.55%		50.71%		93.26%	
45	42.65%	0.021%	50.61%	-0.021%	93.26%	0.000%
50	42.73%	0.016%	50.50%	-0.021%	93.23%	0.005%
55	42.82%	0.018%	50.39%	-0.021%	93.22%	0.003%
60	42.95%	0.025%	50.27%	-0.024%	93.22%	-0.001%

Ratio [Power / Heat]

Return Temp.(℃)	Output (Gcal/h) Heat	ΔE/ΔT	Power	ΔE/ΔT	Total	ΔE/ΔT	Ratio	Total Efficiency
40	360.80		430.03		790.83		**1.1919**	93.26%
45	361.69	0.179	429.14	-0.178	790.83	0.000	**1.1865**	93.26%
50	362.37	0.135	428.24	-0.180	790.61	-0.046	**1.1818**	93.23%
55	363.14	0.154	427.35	-0.178	790.48	-0.024	**1.1768**	93.22%
60	364.20	0.214	426.33	-0.205	790.53	0.009	**1.1706**	93.22%

Case 3 - Heavy Oil

□ Return Temp. 50℃

Outdoor Temp. -5℃

Efficiency versus Output Temp.

Supply Temp.(℃)	Efficiency(%)					
	Heat	Δη/ΔT	Power	Δη/ΔT	Total	Δη/ΔT
80	57.26%		33.58%		90.85%	
90	57.70%	0.044%	33.14%	-0.044%	90.84%	0.001%
105	58.69%	0.066%	32.17%	-0.065%	90.86%	-0.001%
115	59.77%	0.108%	31.10%	-0.107%	90.87%	-0.001%
120	60.49%	0.144%	30.41%	-0.137%	90.90%	-0.006%

Ratio [Power / Heat]

Supply Temp.(℃)	Output (Gcal/h)						Ratio	Total Efficiency
	Heat	ΔE/ΔT	Power	ΔE/ΔT	Total	ΔE/ΔT		
80	58.82		34.49		93.31		**0.5865**	90.85%
90	59.27	0.045	34.04	-0.046	93.30	-0.001	**0.5743**	90.84%
105	60.28	0.068	33.04	-0.067	93.32	0.001	**0.5481**	90.86%
115	61.39	0.111	31.94	-0.109	93.33	0.002	**0.5204**	90.87%
120	62.13	0.148	31.24	-0.141	93.36	0.006	**0.5028**	90.90%

Outdoor Temp. 10℃

Efficiency versus Output Temp.

Supply Temp.(℃)	Efficiency(%)					
	Heat	Δη/ΔT	Power	Δη/ΔT	Total	Δη/ΔT
80	57.86%		33.59%		91.46%	
90	58.30%	0.044%	33.16%	-0.043%	91.46%	0.000%
105	59.28%	0.065%	32.19%	-0.065%	91.46%	0.000%
115	60.34%	0.106%	31.12%	-0.107%	91.46%	0.000%
120	61.03%	0.139%	30.44%	-0.137%	91.47%	-0.002%

Ratio [Power / Heat]

Supply Temp.(℃)	Output (Gcal/h)						Ratio	Total Efficiency
	Heat	ΔE/ΔT	Power	ΔE/ΔT	Total	ΔE/ΔT		
80	59.43		34.50		93.94		**0.5805**	91.46%
90	59.88	0.045	34.06	-0.044	93.94	0.000	**0.5688**	91.46%
105	60.89	0.067	33.06	-0.067	93.94	0.000	**0.5430**	91.46%
115	61.98	0.109	31.96	-0.109	93.94	0.000	**0.5157**	91.46%
120	62.69	0.143	31.26	-0.140	93.95	0.002	**0.4987**	91.47%

Outdoor Temp. 20℃

Efficiency versus Output Temp.

Supply Temp.(℃)	Efficiency(%)					
	Heat	Δη/ΔT	Power	Δη/ΔT	Total	Δη/ΔT
80	58.26%		33.59%		91.85%	
90	58.70%	0.045%	33.17%	-0.042%	91.87%	-0.002%
105	59.65%	0.063%	32.19%	-0.065%	91.84%	0.002%
115	60.72%	0.107%	31.13%	-0.106%	91.85%	0.000%
120	61.44%	0.145%	30.45%	-0.136%	91.89%	-0.009%

Ratio [Power / Heat]

Supply Temp.(℃)	Output (Gcal/h)						Ratio	Total Efficiency
	Heat	ΔE/ΔT	Power	ΔE/ΔT	Total	ΔE/ΔT		
80	59.84		34.50		94.34		**0.5766**	91.85%
90	60.29	0.046	34.06	-0.044	94.36	0.002	**0.5650**	91.87%
105	61.27	0.065	33.06	-0.067	94.33	-0.002	**0.5396**	91.84%
115	62.37	0.110	31.97	-0.109	94.34	0.000	**0.5127**	91.85%
120	63.11	0.149	31.27	-0.139	94.38	0.009	**0.4956**	91.89%

□ Supply Temp. 105℃

Outdoor Temp. -5℃

Efficiency versus Input Temp.

Return Temp.(℃)	Efficiency(%)					
	Heat	Δη/ΔT	Power	Δη/ΔT	Total	Δη/ΔT
40	58.47%		32.39%		90.87%	
45	58.58%	0.021%	32.28%	-0.023%	90.86%	0.002%
50	58.69%	0.021%	32.17%	-0.022%	90.86%	0.001%
55	58.82%	0.026%	32.02%	-0.030%	90.84%	0.004%
60	58.95%	0.027%	31.86%	-0.031%	90.82%	0.004%

Ratio [Power / Heat]

Return Temp.(℃)	Output (Gcal/h)						Ratio	Total Efficiency
	Heat	ΔE/ΔT	Power	ΔE/ΔT	Total	ΔE/ΔT		
40	60.06		33.27		93.33		**0.5540**	90.87%
45	60.17	0.022	33.15	-0.024	93.32	-0.002	**0.5510**	90.86%
50	60.28	0.022	33.04	-0.023	93.32	-0.001	**0.5481**	90.86%
55	60.41	0.026	32.89	-0.030	93.30	-0.004	**0.5444**	90.84%
60	60.55	0.028	32.73	-0.032	93.28	-0.004	**0.5405**	90.82%

Outdoor Temp. 10℃

Efficiency versus Input Temp.

Return Temp.(℃)	Efficiency(%)					
	Heat	Δη/ΔT	Power	Δη/ΔT	Total	Δη/ΔT
40	59.02%		32.42%		91.44%	
45	59.21%	0.038%	32.32%	-0.021%	91.52%	-0.017%
50	59.28%	0.014%	32.19%	-0.026%	91.46%	0.012%
55	59.40%	0.025%	32.04%	-0.030%	91.44%	0.005%
60	59.61%	0.042%	31.88%	-0.031%	91.49%	-0.011%

Ratio [Power / Heat]

Return Temp.(℃)	Output (Gcal/h)						Ratio	Total Efficiency
	Heat	ΔE/ΔT	Power	ΔE/ΔT	Total	ΔE/ΔT		
40	60.62		33.30		93.92		**0.5494**	91.44%
45	60.81	0.039	33.19	-0.022	94.00	0.017	**0.5458**	91.52%
50	60.89	0.015	33.06	-0.027	93.94	-0.012	**0.5430**	91.46%
55	61.01	0.025	32.91	-0.030	93.92	-0.005	**0.5393**	91.44%
60	61.23	0.043	32.74	-0.032	93.97	0.011	**0.5348**	91.49%

Outdoor Temp. 20℃

Efficiency versus Input Temp.

Return Temp.(℃)	Efficiency(%)					
	Heat	Δη/ΔT	Power	Δη/ΔT	Total	Δη/ΔT
40	59.42%		32.45%		91.87%	
45	59.56%	0.026%	32.32%	-0.026%	91.88%	-0.001%
50	59.65%	0.019%	32.19%	-0.026%	91.84%	0.007%
55	59.86%	0.042%	32.04%	-0.030%	91.90%	-0.011%
60	60.05%	0.038%	31.88%	-0.032%	91.93%	-0.006%

Ratio [Power / Heat]

Return Temp.(℃)	Output (Gcal/h)						Ratio	Total Efficiency
	Heat	ΔE/ΔT	Power	ΔE/ΔT	Total	ΔE/ΔT		
40	61.04		33.33		94.37		**0.5461**	91.87%
45	61.17	0.027	33.20	-0.026	94.37	0.001	**0.5427**	91.88%
50	61.27	0.020	33.06	-0.027	94.33	-0.007	**0.5396**	91.84%
55	61.48	0.043	32.91	-0.031	94.39	0.012	**0.5352**	91.90%
60	61.68	0.039	32.74	-0.033	94.42	0.006	**0.5309**	91.93%

Appendix C

Absorption chiller simulation data.

Efficiency variation by DH Temp.

Entering DH Temp to ABS(℃)	2 Stage ABS(Auxiliary Cycle ON)				1 Stage ABS				2 Stage ABS(Auxiliary Cycle OFF)			
	Leaving DH Temp(℃)	Chilling Capacity(%)	DH Flow rate(%)	COP	Leaving DH Temp(℃	Chilling Capacity(%)	DH Flow rate(%)	COP	Leaving DH Temp(℃)	Chilling Capacity(%)	DH Flow rate(%)	COP
120.0	59.3	133.3%	81.3%	0.69	81.8	133.3%	51.8%	0.73	77.7	133.3%	100.0%	0.81
115.0	59.6	133.3%	90.6%	0.68	83.4	133.3%	62.5%	0.73	76.1	123.3%	100.0%	0.81
110.0	59.7	131.3%	100.0%	0.67	86.0	133.3%	82.1%	0.73	74.5	113.1%	100.0%	0.81
105.0	58.0	121.0%	100.0%	0.66	86.2	126.6%	100.0%	0.73	72.9	102.8%	100.0%	0.82
100.0	56.4	110.7%	100.0%	0.65	83.1	113.6%	100.0%	0.73	71.2	92.3%	100.0%	0.82
95.0	55.0	100.0%	100.0%	0.64	80.0	100.0%	100.0%	0.72	69.6	81.7%	100.0%	0.82
90.0	53.3	89.4%	100.0%	0.62	77.0	86.2%	100.0%	0.71	67.9	71.1%	100.0%	0.82
85.0	51.9	78.5%	100.0%	0.61	73.9	72.5%	100.0%	0.70	66.3	60.3%	100.0%	0.82
80.0	50.4	67.5%	100.0%	0.58	70.8	58.5%	100.0%	0.68	64.6	49.5%	100.0%	0.82
75.0	48.9	56.4%	100.0%	0.55	67.6	44.7%	100.0%	0.66	62.9	38.6%	100.0%	0.82
70.0	47.5	45.2%	100.0%	0.51	64.6	30.2%	100.0%	0.60	61.2	27.5%	100.0%	0.80

1. Base of DH Entering Temp. is 95℃(100%)
2. Produced Chilling Water Temp. 8℃, Entering Cooling Water Temp. 31℃

IEA DHC|CHP

International Energy Agency
IEA Implementing Agreement on District Heating and Cooling, including the integration of CHP

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Photographs: Iqaluit, Nunavut: installing piping for the new northern system that feeds the hospital, Canada - Hamilton Community Energy plant under construction, Canada - Bundang Plant, South Korea - Avedøre CHP plant, Denmark, photo: DONG Energy