CHALMERS

District heating in the Nordic countries – modelling development of present systems to 2050

Master's Thesis within the Complex Adaptive Systems programme

JOEL GOOP

Department of Energy and Environment
Division of Energy Technology
CHALMERS UNIVERSITY OF TECHNOLOGY
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Report No. T2012-368

MASTER'S THESIS

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SUPERVISORS:

Mikael Odenberger, Chalmers University of Technology

Erik Axelsson, Profu AB

John Johnsson, Profu AB

EXAMINER

Prof. Filip Johnsson, Chalmers University of Technology

Department of Energy and Environment

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Report No. T2012-368
Department of Energy and Environment
Division of Energy Technology
Chalmers University of Technology
SE-412 96 Göteborg
Sweden
Telephone: + 46 (0)31-772 1000

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ABSTRACT

District heating constitutes a significant part of the total energy use in Sweden, Finland, and Denmark. In a transition to a more sustainable energy system, district heating can play an important role, e.g. through efficiency benefits and possibilities to utilise additional energy sources. In this project a computer-based cost-minimising investment model, describing the development of the production mixes of the national district heating systems in these countries from 2010 to 2050, is constructed using the TIMES model generator. The model is used for a comparative analysis of district heat production in three possible future scenarios, i.e. sets of consistent assumptions about the development in other parts of the energy system, e.g. the electricity supply system.

The national district heating system in each country consists of hundreds of physically separate networks, all operating under different conditions. Modelling all these systems individually is, however, practically difficult, due to the time required for modelling and computation. Therefore a type system approach is used, where an entire class of actual systems, with similar production mixes and annual production volumes, is represented by one type system in the model. Based on a review of all networks described in the national district heating production statistics for each country, six type systems are constructed for Sweden and six for Finland, in total describing 85 % of the national annual district heat production in each country respectively. For Denmark, three type systems are constructed, describing 49 % of the national annual district heat production, and the remainder of the national production mix is described by an aggregation of the remaining actual systems. The constructed type systems are then described in the TIMES model.

Three scenarios are studied. Two scenarios are designed to represent different pathways to reducing carbon dioxide emissions, one market-based approach with high carbon dioxide emission costs and one focusing on energy efficiency and support for renewable energy sources. The third scenario is a reference development, where current policies are extended into the future. Model results show that the cost-minimal development for the district heating systems in Finland and Denmark may include a transition from coal and natural gas to, primarily, biomass fuelled production facilities. If combined with a decreasing demand for district heat, this can lead to a substantial decrease in the electricity production from combined heat and power plants of up to 50 % in Denmark according to the model results. It can also be seen that a decreasing district heat demand in Sweden may, in the cost-minimal development, lead to difficulties in utilising the heat from waste incineration.

Keywords: district heating, energy systems modelling, TIMES

Fjärrvärme i Norden – modellering av utveckling av nuvarande system till 2050

Examensarbete inom masterprogrammet *Complex Adaptive Systems*

JOEL GOOP
Institutionen för Energi och Miljö
Avdelningen för Energiteknik
Chalmers tekniska högskola

SAMMANFATTNING

Fjärrvärme utgör en betydande andel av den totala energianvändningen i Sverige, Finland och Danmark. I en omställning till ett mer hållbart energisystem kan därför fjärrvärme spela en viktig roll, t.ex. genom effektivitetsfördelar och möjligheter att nyttja ytterligare energikällor. I detta projekt konstrueras, i modellgenaratorn TIMES, en datorbaserad kostnadsminimerande investeringsmodell, vilken beskriver utvecklingen av produktionsmixarna i de nationella fjärrvärmesystemen i de aktuella länderna från 2010 till 2050. Modellen används för en jämförande analys av fjärrvärmeproduktionen i tre möjliga framtida scenarier, d.v.s. sinsemellan konsistenta antaganden om utvecklingen i andra delar avenergisystemet, t.ex. elförsörjningssystemet.

Det nationella fjärrvärmesystemet i varje land består av hundratals fysiskt åtskilda nät, som alla drivs under olika förutsättningar. På grund av begränsningar i modellerings- och beräkningstid är det dock inte praktiskt genomförbart att beskriva alla nät individuellt i en modell. Därför tillämpas en typsystemmetod, där en klass av faktiska system, med liknande produktionsmix och årlig produktionsvolym, beskrivs av ett representativt system i modellen. Baserat på en genomgång av alla system beskrivna i varje lands nationella produktionsstatistik konstrueras sex typsystem för Sverige samt sex system för Finland, vilka representerar 85 % av den årliga nationella fjärrvärmeproduktionen i respektive land. I Danmark konstrueras tre typsystem, vilka beskriver 49 % av den årliga nationella fjärrvärmeproduktion, och resterande produktion beskrivs genom aggregering av alla kvarvarande system. De framtagna typsystemen beskrivs i TIMES-modellen.

Tre scenarier studeras. Två scenarier utformas för att beskriva utvecklingar som genom olika tillvägagångssätt leder till minskningar av de totala koldioxidutsläppen i energisystemet. Det ena innebär att marknadsbaserade mekanismer används genom att ett högt pris sätts på koldioxidutsläpp och det andra fokuserar på energieffektivisering och stödsystem för förnybara energikällor. Det tredje scenariot är en referensutveckling, där nuvarande policysystem används under hela modelleringsperioden. Modellresultaten visar att den kostnadsminimala utvecklingen av fjärrvärmen i Finland och Danmark, kan inbegripa en övergång från kol och naturgas till framför allt biomassabaserade produktionsanläggningar. Om detta kombineras med en minskad efterfrågan på fjärrvärme kan det leda till att elproduktionen i kraftvärmeverk minskar kraftigt, upp till 50 % i Danmark enligt modellresultaten. Resultaten visar också att ett minskat fjärrvärmebehov i Sverige kan leda till svårigheter med att få avsättning för värme från avfallsförbränning.

Nyckelord: fjärrvärme, energisystemmodellering, TIMES

Contents

Preface

This thesis work, starting in August 2011, has been performed at Profu (Projektinriktad Forskning och Utveckling i Göteborg AB), with supervision from the division of Energy Technology at the Department of Energy and Environment at Chalmers University of Technology.

I would like to thank my supervisors at Profu, John Johnsson and Erik Axelsson, for guidance and support throughout the project and for answering my many questions. I would also like to thank Thomas Unger at Profu for help with the TIMES model and understanding the Nordic energy system. Thanks also to my supervisor at Chalmers University of Technology, Mikael Odenberger, for helpful advice and many fruitful discussions.

Finally I would like to thank everyone at Profu for providing a friendly atmosphere and a stimulating workplace.

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Joel Goop

1 Introduction

Energy use for heating purposes is an important part of the energy system, especially in countries with a cold climate such as the Nordic countries. For example, in Sweden, 60 % of the total end use of energy in the residential and service sector was used for space heating and hot tap water in 2009 (Energimyndigheten, 2010). More than half of this heating demand, thus constituting a significant share of the total energy use, is supplied by district heating.

For the years to come Swedish authorities are planning measures to promote energy efficiency, while also increasing the share of renewable energy and reducing emissions of greenhouse gases (Energimyndigheten, 2010). For example, one goal is to reduce the energy intensity (energy use per unit of gross domestic product) by 20 % in the period 2008-2020 and another is to reach a share of 50 % renewable energy in the total energy use by 2020. District heating is bound both to influence the development of a changing energy system and to be affected by it.

Previous work

Many aspects of district heating and its role in the energy system have been studied. Some studies specifically examine individual systems. For example the potential for reducing the CO_2 emissions by increasing the share of combined heat and power in Stockholm has been studied (Danestig et al. 2007). Other studies focus on the possibilities of the future development of regional district heat markets (Karlsson et al., 2009). These locally focused studies can contribute with detailed knowledge of how individual district heating networks operate and what potential there is for changes.

On a larger geographical scale and with wider system limits, impacts of different policy measures have been studied. Knutsson et al. (2006) for example, use a static model of all district heating systems in Sweden to study how the green certificate and tradable CO_2 emission permit systems have affected the profitability in investments in combined heat and power technology.

The consequences of a common green certificate and tradable CO_2 permit market for the Nordic countries have also been investigated (Unger & Ahlgren, 2005). Since the electricity market, the market for green certificates, and the district heating sector all interact, these kinds of studies are important to capture for example feedback dynamics in the systems.

1.1 Aim and scope of this thesis

As illustrated above there are many approaches that can be taken to analyse the district heating sector. A difficulty in studying district heating is the variety of different scales involved. Many factors, from the water flow and temperatures in distribution pipes to interactions with global fuel markets and electricity networks spanning several countries, could all affect the overall development of district heating.

The aim of this project is to develop a model capable of describing the national district heating systems in Sweden, Finland, and Denmark and their developments until 2050 under assumptions of future policy scenarios. Norway has a much smaller district heating system, in terms of annual production, and has not been studied in this thesis.

In a model of a national district heating system it is not practically possible to include all details, such as the dynamics of the piping systems in every individual district heating network, because of the time required both for modelling and for computation. However, it is the goal of this project to find a method for modelling entire national district heat production systems, while still capturing some of the effects stemming from the differences between individual district heating networks. The aim is also to use the model for a scenario analysis, comparing the developments of the district heating production systems under different sets of assumptions. Interesting questions to investigate are for example: How can future policy scenarios for district heating be modelled on a national level in a cost-minimising model of the production mix? How can the diversity of individual district heating networks be described in such a model?

This project is limited to analysing the production system of the district heating sector and the model will not include the electricity supply system, except for combined heat and power generation, or fuel supply systems. The analysis is focused on the production mix of district heat and its competitiveness with respect to other heating alternatives will not be studied. Price developments on fuels and electricity, as well as the development of the heat demand will be given to the model as input and will be used to construct different scenarios.

The model-based analysis will compare cost-minimal realisations of the district heating production mix in the constructed scenarios. This means that the results are not to be viewed as forecasts, but that the analysis is intended to compare the responses of the model with different inputs in order to understand the dynamics of the district heating production system.

2 Background and theory

This chapter gives a short introduction to district heating (DH) systems and some of the relevant factors that affect heat production. It also contains a brief description of some of the concepts of energy systems modelling.

2.1 District heating systems

To analyse the development of district heating, a basic understanding of some of the aspects of a district heating system, as well as terminology to describe it, is important. This section briefly describes how a district heating system works and what external factors affect the choices of decision makers in the system.

Simply put a district heating system can be described as a system to produce heat and deliver it to a large number of consumers, covering for example a city district or an entire city. The heat is produced in centralised production facilities and usually distributed using water as an energy carrier. In Sweden it is common to use pressurised water at a temperature of around 120 °C (Werner & Frederiksen, 1993). The heat is normally used for space heating and heating tap water. District heating technology is common for example in the Nordic countries where there is a large heat demand because of the cold climate. It is also possible to use the same type of technology for cooling, but that is a topic outside the scope of this thesis.

The advantages of district heating compared to individual heating of buildings are mainly of two kinds. Firstly, there are the economies of scale that arise when the heat can be produced centrally, e.g. higher efficiencies in conversion processes and lower fuel costs. Secondly, a wide range of additional energy sources, such as excess industrial heat or heat from waste incineration and combined heat and power plants, can be utilised in a district heating system.

Drawbacks to district heating are, for example, the limited range of district heat distribution or the heavy investments that are required, both in production technology and infrastructure.

The discrete nature of district heating systems

The heat that is produced in a district heating plant has to be distributed through a piping system, or grid, to reach the end consumer. Due to high investment costs and grid losses it is not economically viable to transmit heat over long distances (Werner & Frederiksen, 1993, p.133). This implies that it is economically viable to build district heating networks only in areas where the heat demand density is sufficiently high.

A consequence of this, which is important when modelling district heating, is that a national district heating system is in fact composed of a large number of discrete networks where no exchange is possible between networks. Each of these networks functions under very different conditions. The size of the network, for example, will determine the possible sizes when investing in a new production facility. The size of a new production facility, in turn, determines what alternatives are available and what the specific investment cost will be.

The local availability of certain energy sources may also vary between systems. For example, district heating networks situated close to an industrial site where excess heat is produced can use that to supply their demand, and biofuels and waste are cheaper to use close to where they are produced, because of high transport costs.

Energy sources

To generate district heat, many different sources of energy are used. They all have different properties, e.g. availability, suitability for use with different technologies, and environmental properties. They are also associated with different costs. Historically, the most common method for generating district heat has been through combustion of different fuels (Werner & Frederiksen, 1993, p.71). Examples of fuels are biofuels such as forest residues or fossil fuels such as coal. In Sweden and Denmark municipal solid waste, or MSW, is also commonly used as a fuel.

Some of the important aspects to consider for the fuels used are for example the emission coefficients and the heating value of the fuel in question. These parameters, at least partially, determine the efficiency in the production process as well as the transport cost and environmental taxes per unit energy. Traditionally it is common to use the lower heating value when calculating efficiencies in district heating. The lower heating value is defined as the energy that can be extracted from the combustion of a fuel, assuming that none of the resulting water vapour can be condensed (Jernkontorets Energihandbok, 2008). However, it is in fact possible to utilise some of the heat in the vapour in district heat production, using flue gas condensation technology. If the efficiency is calculated as the utilised heat energy divided by the lower heating value, it may therefore be higher than one for fuels with high moisture content, if flue gas condensation is applied.

The possibility to utilise energy sources such as excess industrial heat, for example from cooling at a steel processing plant, is an important benefit of using district heating instead of individual heating. In some locations, it is also possible to produce heat directly from geothermal sources. From low-temperature heat sources such as waste water or, in some areas, lakes, heat can be extracted using electrically driven heat pumps.

Production technologies

A heat-only boiler, or HOB, is as the name indicates a facility where only heat is produced. Most boilers are fuelled by renewable or fossil combustible fuels. However, there are also electric boilers, where electricity is used to directly heat the water. These are most commonly used in smaller systems, where combined heat and power plants are too expensive, but are also necessary to handle peak heat loads in most systems.

Heat can also be cogenerated with electricity in a combined heat and power, or CHP, plant. When electricity is produced through the combustion of fuels only a certain percentage of the supplied energy can be converted to electricity according to the second law of thermodynamics. In a regular power plant, the excess energy is considered a loss and is cooled away. However, if the generated heat is instead used for district heat production, the utilisation of the energy content of the fuel can be significantly increased.

When doing an economic analysis of CHP production, it is necessary to divide costs between electricity and heat production. In order to determine the individual efficiencies and emission coefficients of heat and power production in a CHP plant and to determine the emissions from each part, a method is needed to distribute the consumed fuel between the two. There are a number of such methods and different parts of the production are favoured by different approaches. (Werner & Frederiksen, 1993, pp.377-81)

Large-scale heat pumps can be used for district heat production. This requires access to a low temperature heat source, such as waste water. Heat pumps are generally driven by electricity and their performance is measured by a coefficient of performance, which is the ratio between delivered heat and supplied electricity. A large-scale waste water heat pump can typically have a coefficient of performance of around three (Werner & Frederiksen, 1993, p.120).

Environmental effects from heat production

The production of district heat affects the environment in many ways. One example is the contribution to climate change through emissions of greenhouse gases (GHGs) and primarily carbon dioxide, CO_2 (Werner & Frederiksen, 1993, p.80). CO_2 is formed during combustion of carbonaceous fuels, such as coal, natural gas and wood fuels. However, it is customary to assume that harvested biofuels are replaced with new vegetation, resulting in a zero net emission of CO_2. Sulphur and nitrogen in fuels can also form oxides in the combustion process. These substances can then contribute to acidification (Werner & Frederiksen, 1993, p.78).

All the emissions mentioned above have a relatively direct effect on the environment. Many other environmental effects from district heat production are more complex and must be considered in a life-cycle type of perspective. For example, waste incineration has a direct effect through emissions of CO_2 and other pollutants, but the total effect on the environment also depends on what would otherwise have been done with the waste. Leaving it on a landfill, which is one alternative, will, for example, result in emissions of methane which is also a potent greenhouse gas.

Taxes and environmental costs

The composition of the district heating production mix is heavily affected both by national policies and policies implemented by the EU. For example, the studied countries all have taxes on, mainly fossil, fuels. A common construction is a division of the tax into components for the energy content and the CO_2 emissions from the fuel in question. In all three countries studied in this project there are also taxes on the use of electricity. There are in some cases special rates, for example for manufacturing industry and certain geographic areas, but this will not be considered in this project. In district heat production, the electricity tax mainly affects the production of heat in electric heat-only boilers and in heat pumps.

Since there is a tax on electricity consumption, the fuels used for generation of electricity are generally exempted from taxation, since the transfer of this cost to the electricity consumers would result in double taxation of electricity. For cogeneration plants, tax is then paid only for the part of the fuel used for heat production and the fuel is allocated according to rules specified for each country. These are described in detail in Appendix A.

On top of the taxes, the European Union implemented a trading system (EU ETS) for CO_2 emissions in 2005 (European Commission, 2011). The idea with a system of this kind is to utilise market mechanisms in order to reduce emissions where it is most efficient. The system requires all emitters to have a permit for each unit of CO_2 emitted and the total number of permits is set to match a predetermined limit on emissions. The permits are then traded on a market so that companies that are able to reduce their emissions at a low cost can do so and sell their permits to other companies with higher abatement costs.

Support systems for renewable electricity

In Sweden there is a system of green electricity certificates to support electricity production from renewable sources. Producers of electricity which is classified as “green” receive a certificate for each unit of electricity produced. Examples of green electricity production are wind power, biofuel-based production and small-scale hydropower. Companies supplying electricity to end consumers are then required to hold such certificates corresponding to a given proportion of the sold electricity. This creates a market value for the certificates giving economic support to green electricity producers and transferring the cost for supporting the system to the electricity consumers. The certificate system is planned to remain in place until 2035. (Energimyndigheten, 2009)

Finland uses a different system for supporting electricity production from renewable sources. The Finnish system is based on feed-in tariffs for electricity from wind power or biogas and forest fuels. The feed-in tariff is a fixed price guaranteed by the state for the electricity produced from these sources. There is also an extra premium if the electricity is produced in cogeneration with heat with a total efficiency above a certain value. (Finlex, 2012b)

Denmark also subsidises production of electricity from renewable sources. Producers of electricity from renewable sources can receive either a feed-in tariff or a fixed premium on top of the market price for electricity. The production is supported for a limited period of time after connection to the grid and the length of this time depends on the connection date, but is currently ten years for new plants. (Bubholz & Nowakowski, 2010)

Load variations and the trade-off between fixed and running costs

Mainly due to the change of the seasons, the demand for district heat varies greatly over time. The heat demand variations are often described in a load curve where the heat demand per unit time is plotted in a time series, usually over the period of one year. If the same data points are plotted rearranged in descending order of heat demand per unit time, the resulting graph is called a load-duration curve.

The production of heat is of course, as many other parts of our society, governed by economic incentives. The choices of which production technologies to invest in and which fuels to use, are largely determined by the costs of the available alternatives. The costs of producing heat are often divided into fixed costs, such as capital costs and fixed operating and maintenance costs, and variable costs, such as fuel costs and taxes.

In an investment decision there is usually a trade-off between fixed and running costs. For example a technology with high specific investment cost but low running cost, such as a waste CHP plant, must have a high degree of utilisation in order to be economically viable. The size of the plant should therefore not be too large in order for it to be fully utilised, i.e. the demanded heat output (heat demand per unit time) in a system with such a plant should at most times be higher than the capacity of the plant. This type of technology is often referred to as a base load technology.

On the other hand, a technology with a lower investment cost, such as an oil HOB, has high running costs due to high fuel prices and taxes. It is therefore suited to use as a peak load technology, i.e. only at the highest points on the load curve, since the low investment cost makes it cheap to keep as reserve capacity.

2.2 Computer-based modelling of energy systems

The term energy system can include anything from the dynamics of combustion processes to global fuel markets. All these processes can be connected and they can all affect the dynamics of the entire system. When constructing a computer model of an energy system, all its parts cannot be described in detail. Therefore, the choice of modelling technique depends on what aspect of the system that is studied, e.g. economic interactions and market dynamics or more technical aspects of for example electricity or heat production.

It is common to loosely classify energy system models as either top-down or bottom-up, depending on the basis on which the model is built. Top-down models include the energy system as a part of a description of the entire macro economy. Entire sectors of the energy system are then often described by highly aggregated production functions, where for example a certain quantity of electricity can be produced at a certain level of input of labour and capital. These descriptions are then linked to macroeconomic factors such as unemployment and overall price levels. In bottom-up models the focus is shifted towards technological aspects of the energy system. Different technological options are modelled more explicitly and with a higher level of detail, e.g. through providing performance data and costs specifically for each technology. (see Odenberger, 2009, and references therein)

Modelling the future development

There are several alternative approaches to modelling the future development of an energy system, and which one is most suitable depends, as always, on what questions are being asked. Often, these models can be said to be either descriptive or prescriptive, where a descriptive model is designed to answer questions of the kind: If this is what we know, what will happen? For the purpose of creating a long-term description of a large part of the energy system, a descriptive or simulating model is often difficult to apply, because it is hard to accurately capture the required level of detail.

However, a different type of question can be: If this is what we want, how should we get there? When the purpose of the model is answering questions of this kind, i.e. telling us what to do under a given set of constraints, it is called prescriptive. Models of this kind are often formulated as an optimisation problem. A target function to be minimised (or maximised) is constructed, e.g. the total system cost. The modeller then determines constraints such as a maximum level of emissions to be reached by a certain year and provides a description of the system. The model then finds the optimal solution, with respect to the target function.

An optimising model is usually constructed with perfect foresight, which means that the target function contains the information of all future costs without uncertainties. Since this is not a realistic, the results from the model should not be viewed as forecasts, but as a description of possible future scenarios.

3 Methods

All individual district heating systems operate under very different conditions. For the purpose of capturing some of this diversity in a model several type systems are constructed for each country. The type systems are designed to be typical representations, in terms of production mix and annual production volume, of as many actual systems as possible and are based on statistical data on the production of individual networks in each country.

All the actual systems in the data are then, if similar enough to one of the type systems, classified as being described by that type system. The sum of the annual district heat production of the systems in each category is then assumed to be the total annual production that can be described by this particular type system in the model.

The type system representation is then used as a basis for building a cost-minimising investment model of the future development of district heating in Sweden, Finland, and Denmark. Each type system is represented with different initial production mixes and different technology options for future investments.

3.1 Cost-minimisation investment modelling in TIMES

The TIMES model generator is chosen as a tool for building an optimising linear investment model of the district heating systems in Sweden, Finland, and Denmark. The TIMES model operates by minimising an objective function, basically representing the discounted costs of all investments and activities during the model horizon. While doing this, the model must also, for each time period, meet a specified energy demand and comply with a number of constraints. The demand is met by investing in and using production technologies to generate the demanded energy commodity.

The time horizon of the model consists of a number of years over which decisions are made in the model. Each year can then be divided further into "time slices" of variable length, intended to allow for sub-annual variations in for example the energy demand.

Objective function

The objective function VAR_OBJ to be minimised is written (Loulou et al., 2005b, p.145)

$$VAR\_OBJ(z) = \sum_{r \in \{\text{Regions}\}} REG\_OBJ(z,r) \ ,$$

where z denotes years within the modelling horizon. The regions are defined by the user and can represent, for example, different countries. A simplified version of the regional objective functions $REG\_OBJ(r)$ can, if the parts that are not important in this project are left out, be formulated as

$$REG\_OBJ(z,r) =$$

$$\sum_{y \in (-\infty,+\infty)} DISC(y,z) \times \{INVCOST(y,r) + FIXCOST(y,r) + VARCOST(y,r)\} \ .$$

This equation states that the regional objective function, for each year z within the modelling horizon, is the sum of the discounted annual costs from all years y where costs arise from the decisions made within the modelling horizon. $DISC$ is the discount factor and all costs are discounted to a year specified by the user. The components of the costs are:

- $INVCOST$: costs stemming from investments in production technology
- $FIXCOST$: fixed annual costs from the installed capacity of production technology
- $VARCOST$: running costs associated with the activity of the production technology

In the complete objective function (Loulou et al., 2005b, p.145) a number of additional cost terms are included, but they are not relevant in the model built in this project. They represent, for example, taxes and subsidies on investments and technology decommissioning costs, which are not described in this model.

Input and output of the model

When constructing the model, all available technological options for each type system are specified through a number of parameters, e.g. conversion efficiencies and costs (for more details see Section 4.1). The currently installed capacity of each technology is also specified according to the production mixes of the type systems. All prices developments for the entire modelled period, for example for fuels and electricity, but also for EU ETS emission permits and green certificates, are also supplied as input to the model. The district heat demand, i.e. the minimal amount of district heat that must be produced annually in the model, is also specified for the entire period. As output the model determines the cost-minimal investments and flows of fuels and electricity into the production processes, as well as flows of district heat, electricity, and CO_2 emissions (that are covered by EU ETS) out of the production processes. The output values of interest in this project are primarily the fuels and production technologies used for district heat production, and the produced electricity in CHP generation.

Scenario analysis using the TIMES model

The results from the model with a few chosen sets of input assumptions, or scenarios, are studied and compared. Differences in the results between different scenarios and countries are identified and analysed. In order for the assumptions in each scenario to be internally consistent, the scenarios are constructed using results from other models including the electricity markets and competition with other heating alternatives, thereby providing plausible developments of the district heat demand and the electricity prices.

4 Assumptions, scenarios, and input data

In order to construct a model describing the district heating sectors in the selected countries, much input data and many assumptions are needed, regarding for example the current district heating systems and future developments of costs and policies. This chapter contains three sections, where the first explains the general input and assumptions used for all scenarios, the second describes scenario specific assumptions, and the third covers the type system representations of the district heating systems used to construct the model. All prices are given as real values with base year 2010.

4.1 Model input and assumptions

This section describes the assumptions in the model that are common to all scenarios, for example regarding economic parameters, heat load distribution, and fuel prices.

Economic assumptions

To assess the current value of future costs and revenues, it is necessary to assume a discount rate. In this project a rate of 7 % is assumed.

Where currency conversions are necessary, the rates have been assumed to be constant at:

- 1 EUR = 9 SEK
- 1 DKK = 1.2 SEK

Time slices and load curve

Each year is divided into twelve time slices, three slices for each of the four seasons. The three slices of a season are designed to represent the average day, average night and the peak load of a typical day during that season. The structure of the time slice division is schematically illustrated in Figure 1.

A load curve is constructed by specifying duration and heat demand for each time slice. The load curve used in the model is based on an analysis done by Profu of the hourly district heat consumption in a typical Swedish DH system during one year (Axelsson, 2012a). The shape of the curve is assumed to be the same for all countries and type systems in the model. Figure 2 shows the load-duration curve assumed in the model, i.e. demanded heat output, which is the heat demand during a time slice divided by the duration of the time slice, plotted against the cumulative durations of the time slices. The figure also shows an actual load-duration curve of a typical Swedish DH system.

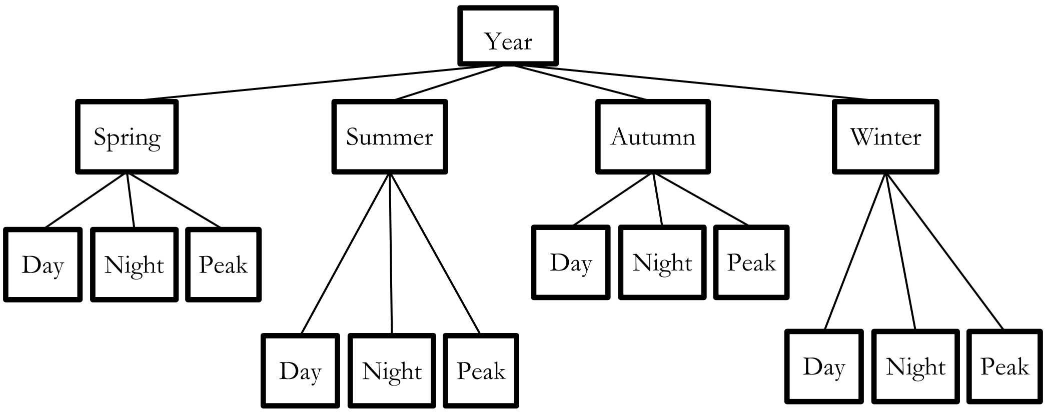

Figure 1: Schematic illustration of the time slice division used in the constructed TIMES model. The twelve slices at the bottom level of the tree are the slices used for calculations in the model.

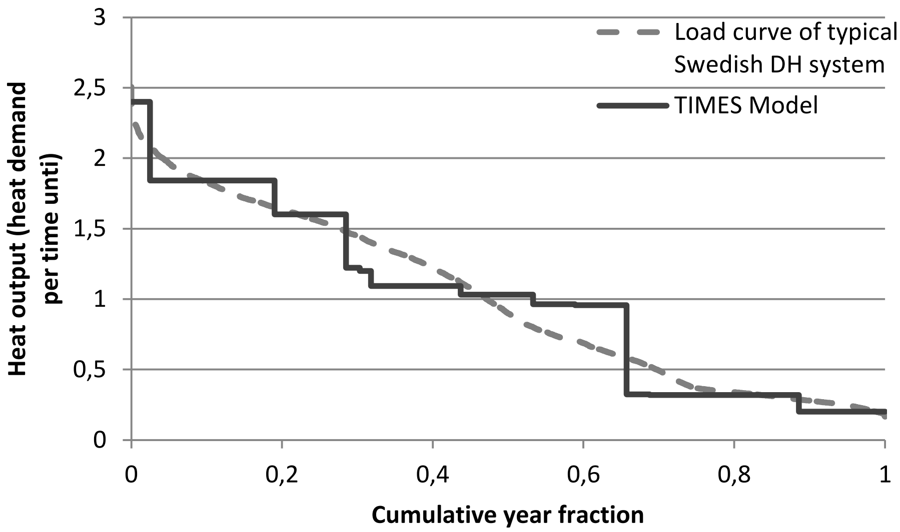

Figure 2: The load-duration curve of a typical Swedish DH system and the load-duration curve assumed in the TIMES model. The y-axis represents the demanded heat output (heat demand per unit time) and the x-axis shows the cumulative time, measured as a fraction of one year. The time slices are shown in descending order of heat output.

Available energy sources and prices common to all scenarios

The assessments of the available supply and the prices of domestically produced fuels, such as biofuels and peat, are based on predictions of the production capacity and cost for different sources of each fuel in each of the countries. The fuels biooil and biogas are only included for Sweden, where information is easily accessible. These fuels constitute a very small fraction of the total fuel consumption for district heat production in Finland and Denmark. In Denmark, production from biooil represented about 1 % and biogas less than 1 % of the national district heat production in 2010 (Danish Energy Agency, 2010). In Finland all biofuels other than “Forest wood” and “Industrial wood residues” represented 1.1 % of the total national district heat production in 2010 (Finsk Energiindustri, 2011).

In the case of biooil in Sweden, the price has been set to follow the price of heavy fuel oil (including taxes), since applications of these fuels are similar. The fraction of the heavy fuel oil price used for biooil is set to 75 % based on today's price levels, based on calculations made by (Axelsson, 2012b).

Natural gas is assumed to be fully available in Denmark and Finland. In Sweden, the infrastructure is not as well developed, and natural gas is therefore assumed only to be available in Gothenburg and Malmö (type system D, see Section 4.3), where it is currently used in district heat production.

In Finland, using waste as a fuel in district heat production is very uncommon and constitutes around 2 % of district heat production 2009 (Finsk Energiindustri, 2010b). Therefore waste is assumed not to be available as a fuel in the systems included in the model. Excess heat is, in all countries, assumed only to be available in the systems where it is already used for district heat production.

The heat that can be supplied by heat pumps is limited for example due to the availability of low temperature heat sources. Based on simulations of a typical individual DH system made by Profu, the total share of the annual heat production produced by heat pumps is assumed to be limited to 15 % (Axelsson, 2012c).

Taxes and subsidies

Support systems for renewable electricity have been included in the model for all countries. The support scheme that has been assumed in Denmark is a fixed premium of 150 DKK/MWh of electricity from biomass-fuelled CHP plants. In Finland, a feed-in tariff of 83.5 EUR/MWh and an additional fixed premium of 20 EUR/MWh have been assumed to be paid for electricity production from biomass. In Sweden, renewable electricity production is supported by the green certificate system, with market prices assumed for each scenario (for details, see Section 4.2). Tax levels are assumed to be the same in all scenarios and the values used in the model are shown in Table 1.

Data on production technologies

To describe each heat production technology in the TIMES model the following technology specific parameters need to be estimated:

- Specific investment cost (SEK/kW)
- Fixed operating and maintenance cost (SEK/kW annually)
- Variable operating and maintenance cost (SEK/MWh output)
- Fuel efficiencies
- Heat to power ratio (for CHP technologies)
- Availability
- Economic and technical life time

In order for the type system description to be useful, these parameters also need to be adapted to the specific conditions that apply for that type system. Assumed data for heat-only production technologies can be found in Table 2. Data for combined heat and power technologies are given in Table 3.

Table 1: Tax levels for Sweden, Finland, and Denmark used in the constructed TIMES model.

			Sweden	Finland	Denmark
Electricity tax [SEK/MWh,el]			282	152	870-950[a]
CO_2 tax [SEK/tonne CO_2]		CHP	70	135	180
		HOB	990	270	180
Energy tax [SEK/MWh,fuel]	Coal	CHP	25	63	19.1-19.5[a]
		HOB	80	63	19.1-19.5[a]
	HFO	CHP	25	69	19.1-19.5[a]
		HOB	80	69	19.1-19.5[a]
	Peat	CHP	-	17-35[a]	-
		HOB	-	17-35[a]	-
	Natural gas	CHP	25	27-69[a]	19.1-19.5[a]
		HOB	80	27-69[a]	19.1-19.5[a]

[a] The higher rate is applied from 2015

Table 2: Assumed technical and economic data for heat-only production technologies. Based on data from models developed at Profu (Axelsson, 2012d) in turn based on the MARKAL-NORDIC model (Unger, 2003). Costs are adjusted to represent different output capacities of production units.

	Fuels/ input	Typical heat capacity [MW]	Investment cost [SEK/kW]	Fix O&M cost [SEK/kW, year]	Var O&M cost [SEK/MWh]	Efficiency [%]
Solid HOB (small)	Biomass, peat, coal	7	8,600	107	20	90-95[c]
Solid HOB (medium)	Biomass, peat, coal	17	8,000	100	20	90-95[c]
Solid HOB (large)	Biomass, peat, coal	30	7,300	91	20	90-95[c]
Waste HOB (medium)	MSW[a]	17	13,200	400	40	90
Waste HOB (large)	MSW[a]	30	12,000	360	40	90
Natural gas HOB	Natural gas	-[b]	4,000	25	15	92
Oil HOB	Oil	-[b]	4,000	25	15	90
Electric HOB	Electricity	-[b]	1,000	15	10	95
Heat pump (small)	Electricity	1	8,000	80	10	300
Heat pump (medium)	Electricity	5	7,000	70	10	300
Heat pump (large)	Electricity	20	6,000	60	10	300
Excess industrial heat	-	-	5,000	-	10[d]	-

[a] Municipal solid waste

[b] All sizes represented with the same data.

[c] Lower value for peat and coal and higher for biomass.

[d] Includes price paid to the producer for delivered heat.

Table 3: Assumed technical and economic data for combined heat and power production technologies. Based on "El från nya och framtida anläggningar" (Nyström et al., 2011). Size distribution from biomass technologies is used for all technologies.

	Fuels/ input	Typical size [MW,e]	Investment cost [SEK/kW,e]	Fix O&M cost [SEK/kW,e, year]	Var O&M cost [SEK/MWh,e]	Net electric efficiency [%]	Power-to-heat ratio
Solid CHP (small)	Biomass, peat	5	56,500	1250	92	24-25[c]	0.29-0.32[c]
Solid CHP (medium-small)	Biomass, peat	10	45,000	920	94	26.5-28[c]	0.33-0.36[c]
Solid CHP (medium-large)	Biomass, peat	30	34,500	580	90	29-31[c]	0.38-0.42[c]
Solid CHP (large)	Biomass, peat	80	25,500	380	87	31-33[c]	0.40-0.43[c]
Coal/peat CHP (small)	Coal, peat[a]	5	42,700	950	88	25	0.38
Coal/peat CHP (medium-small)	Coal, peat[a]	10	33,600	690	91	28	0.40
Coal/peat CHP (medium-large)	Coal, peat[a]	30	26,000	440	86	30	0.50
Coal/peat CHP (large)	Coal, peat[a]	80	18,300	270	84	32	0.56
Waste CHP (small)	MSW[b]	7	87,200	3,000	280	19-20[c]	0.24-0.26[c]
Waste CHP (medium)	MSW[b]	20	77,000	2,200	280	19-20[c]	0.24-0.26[c]
Waste CHP (large)	MSW[b]	50	60,000	1,500	280	19-20[c]	0.24-0.26[c]
NGCC[d] (medium)	Natural gas	40	12,500	300	22	46-48.5[c]	1.05-1.14[c]
NGCC[d] (large)	Natural gas	150	9,500	200	16	50.5-52.5[c]	1.22-1.30[c]
Oil CHP	Oil	-	11,000	165	40	30	0.5
Gas motor CHP	Biogas, landfill gas, natural gas	1	9,000	135	100	40	0.83

[a] Available fuels vary between countries and type systems.
[b] Municipal solid waste
[c] Lower values are used for the period 2005-2020 and higher values for the period 2020-2050.
[d] Natural gas combined cycle.

4.2 Scenarios

The scenarios constructed for the analysis are based on assumptions of fuel and policy developments as well as of the district heat demand. This section describes the three constructed scenarios and the basis on which they are built.

Required input data

The scenarios that are analysed and compared in this project are composed of time series data on prices of certain commodities and the district heat demand in each of the countries studied. All the conditions that vary between scenarios are:

- Prices
    - Fossil fuels: coal, oil and natural gas

    - Electricity
    - Green electricity certificates in Sweden
    - CO_2 emission permits within EU-ETS
- District heat demand

The fossil fuels are assumed to be traded on a world market and are therefore priced the same in all countries. For electricity prices and demand for district heat, different developments are used for Sweden, Finland and Denmark respectively. The share of the national heat demand covered by each type system is assumed not to change during the modelled time period.

Basis for scenarios

The three constructed scenarios are inspired by two of the scenarios of the World Energy Outlook 2011. The scenario chosen as a basis for the Reference scenario is the Current Policies scenario (International Energy Agency, 2011), which describes a future where no additional policies are implemented other than the ones currently in place (as of 2011).

The other two scenarios in this project, called Regional Policy and Climate Market, are both based on the New Policies scenario in the World Energy Outlook (International Energy Agency, 2011), where policies are assumed to be implemented in accordance with current governmental commitments and goals, even where specifics of the implementation are yet to be decided upon. The Regional Policy and the Climate Market scenario analysed in this project, are designed to represent two different approaches, explained more thoroughly below, to reducing CO_2 emissions from the energy system. They are based on the Policy and the Market scenario from European Energy Pathways (Johnsson, 2011).

Developments on prices of the fossil fuels coal, oil and natural gas are based directly on information from the World Energy Outlook. The assumed fossil fuel prices are shown in Figure 3. In order to construct consistent developments of other input data such as heat demand and electricity prices these data are obtained from scenario analyses made by Profu (Unger, 2012) using the MARKAL-NORDIC model developed by Unger (2003).

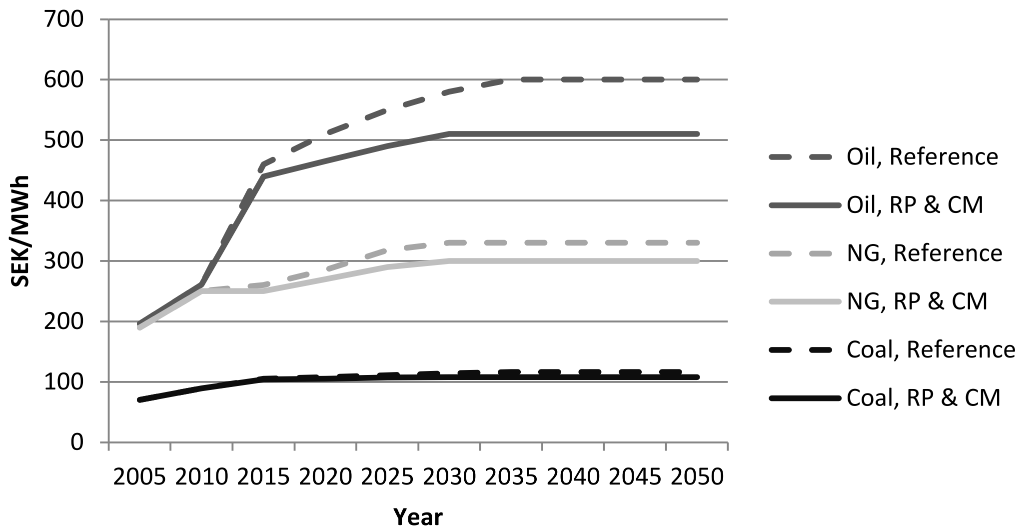

Figure 3: Prices for the fossil fuels oil, coal, and natural gas (NG) assumed for the Reference scenario and for the Regional Policy (RP) and Climate Market (CM) scenarios. Source: World Energy Outlook (International Energy Agency, 2011).

The Reference scenario

The first constructed scenario is basically a "business as usual" scenario, where no further action is taken to reduce emissions of greenhouse gases and other pollutants, but currently implemented policies are left in place. The role of this scenario is to serve as a point of comparison to study the differences between continuing the current course of action and introducing stronger policy initiatives to reduce emissions.

The price of CO_2 emission permits and green electricity certificates in this scenario are based on today's prices, whereas the electricity prices will be affected by, for example, the developments on the fossil fuel markets. The assumptions made for prices and district heat demands in the three countries are given in Table 4.

Table 4: Assumed prices and district heat demands for Sweden, Finland, and Denmark in the Reference scenario. Fossil fuel prices are assumed to be the same for all countries.

	Electricity price [SEK/MWh]								
	2010	2015	2020	2025	2030	2035	2040	2045	2050
Sweden	410	430	450	450	450	475	500	500	500
Finland	430	450	470	460	450	475	500	500	500
Denmark	410	430	450	466	483	500	516	533	550

	Annual district heat demand [TWh]								
	2010	2015	2020	2025	2030	2035	2040	2045	2050
Sweden	51.3	51.7	52.3	52.7	53.1	53.5	53.8	54.1	54.4
Finland	32.1	32.8	34.0	35.1	36.0	35.9	35.8	35.6	35.5
Denmark	32.4	35.2	36.6	38.1	40.5	42.9	43.8	43.8	43.8

	Fossil fuel prices [SEK/MWh]								
	2010	2015	2020	2025	2030	2035	2040	2045	2050
Coal	89	105	108	111	114	116	116	116	116
Oil	261	460	510	550	580	600	600	600	600
Natural gas	250	260	285	318	330	330	330	330	330

	Other prices [SEK]								
	2010	2015	2020	2025	2030	2035	2040	2045	2050
1 green certificate[a], Sweden	200	200	200	200	200	200	0	0	0
1 EUA[b]	200	200	200	200	200	200	200	200	200

[a] Corresponds to 1 MWh of electricity produced from a renewable source.
[b] EU allowance unit within EU ETS corresponding to one tonne of CO_2.

The Regional Policies scenario

This scenario focuses on policy measures designed to reduce end-use of energy and to increase the share of renewable sources. It therefore depicts a future where not only economic policy measures are implemented but where for example technology regulation and behavioural changes leads to a reduction of the energy use. (Johnsson, 2011)

The prices of both ETS emission permits and electricity will reach higher levels in this scenario than in the Reference scenario. In order to maintain and increase the use of renewable energy sources, the prices of electricity certificates in Sweden will also increase and the certificate system or a corresponding support system will be prolonged throughout the entire period. Motivated by the efforts towards energy efficiency, the district heat demand is assumed to decrease to 2030 in all three countries. Table 5 shows the assumptions made for prices and district heat demands in the three countries in the Regional Policy scenario.

Table 5: Assumed prices and district heat demands for Sweden, Finland, and Denmark in the Regional Policy scenario. Fossil fuel prices are assumed to be the same for all countries.

	Electricity price [SEK/MWh]								
	2010	2015	2020	2025	2030	2035	2040	2045	2050
Sweden	410	450	485	520	510	580	600	620	620
Finland	430	460	465	470	460	500	560	620	620
Denmark	410	450	485	520	540	580	600	620	620
	Annual district heat demand [TWh]								
	2010	2015	2020	2025	2030	2035	2040	2045	2050
Sweden	50.9	49.3	45.9	42.8	41.0	41.0	41.0	41.0	41.0
Finland	31.7	30.3	28.3	26.6	25.5	25.5	25.5	25.5	25.5
Denmark	31.6	30.3	28.3	26.6	25.5	25.5	25.5	25.5	25.5
	Fossil fuel prices [SEK/MWh]								
	2010	2015	2020	2025	2030	2035	2040	2045	2050
Coal	89	104	105	107	108	108	108	108	108
Oil	261	440	465	490	510	510	510	510	510
Natural gas	250	250	270	290	300	300	300	300	300
	Other prices [SEK]								
	2010	2015	2020	2025	2030	2035	2040	2045	2050
1 green certificate[a], Sweden	200	200	200	225	250	250	250[c]	250[c]	250[c]
1 EUA[b]	200	250	300	350	500	550	550	550	550

[a] Corresponds to 1 MWh of electricity produced from a renewable source.
[b] EU allowance unit within EU ETS corresponding to one tonne of CO_2.
[c] The certificate system is assumed to be prolonged or replaced with a corresponding support system beyond 2035.

The Climate Market scenario

This scenario represents a future development where the emission reduction measures are more dependent on market mechanisms. The dominating effect is therefore a high cost associated with greenhouse gas emissions. The specific measures taken to reduce emissions are not controlled in detail and the implementation is left to the market actors. (Johnsson, 2011)

In terms of the input data used in this project, the main effect is high prices on EU-ETS emission permits. The price on permits also drives up the electricity price which will therefore be higher than in the Regional Policy scenario. However, since the high emission costs are already driving a shift towards renewable energy sources, the price of electricity certificates is assumed be lower than in both the Regional Policy and the Reference scenario. The assumptions made for prices and district heat demands in the three countries in the Climate Market scenario are shown in Table 6.

Table 6: Assumed prices and district heat demands for Sweden, Finland, and Denmark in the Climate Market scenario. Fossil fuel prices are assumed to be the same for all countries.

	Electricity price [SEK/MWh]								
	2010	2015	2020	2025	2030	2035	2040	2045	2050
Sweden	410	480	515	550	620	640	645	650	650
Finland	430	490	530	570	600	620	630	640	640
Denmark	410	480	525	570	630	660	665	670	670
	Annual district heat demand [TWh]								
	2010	2015	2020	2025	2030	2035	2040	2045	2050
Sweden	51.3	51.7	52.3	52.7	53.1	53.5	53.8	54.1	54.4
Finland	32.1	32.8	34.0	35.1	36.0	35.9	35.8	35.6	35.5
Denmark	32.4	35.2	36.6	38.1	40.5	42.9	43.8	43.8	43.8
	Fossil fuel prices [SEK/MWh]								
	2010	2015	2020	2025	2030	2035	2040	2045	2050
Coal	89	104	105	107	108	108	108	108	108
Oil	261	440	465	490	510	510	510	510	510
Natural gas	250	250	270	290	300	300	300	300	300
	Other prices [SEK]								
	2010	2015	2020	2025	2030	2035	2040	2045	2050
1 green certificate[a], Sweden	200	116	116	116	53	0	0	0	0
1 EUA[b]	200	250	300	350	500	650	775	900	900

[a] Corresponds to 1 MWh of electricity produced from a renewable source.
[b] EU allowance unit within EU ETS corresponding to one tonne of CO_2.

4.3 Type systems

National district heating statistics for each country have been analysed in order to design type systems representing as much as possible of the total national district heating sectors in the three countries studied.

Descriptions of the constructed type systems in Sweden

From the information in the Swedish district heating statistics, four type systems have been constructed. The production mixes of these four systems are shown in Figure 4. Stockholm, which is the largest system in Sweden, with respect to annual heat production, has been modelled separately and the second and third largest systems Gothenburg and Malmö have been aggregated into one system. The systems D and E representing these three systems are not shown in the figure but can be seen in Figure 5, showing the total annual DH production represented by each type system. The type systems are briefly described in Table 7. The production technologies assumed to be available in each type system are listed in Table 8 (for specific data on the technologies, see Table 2 and Table 3).

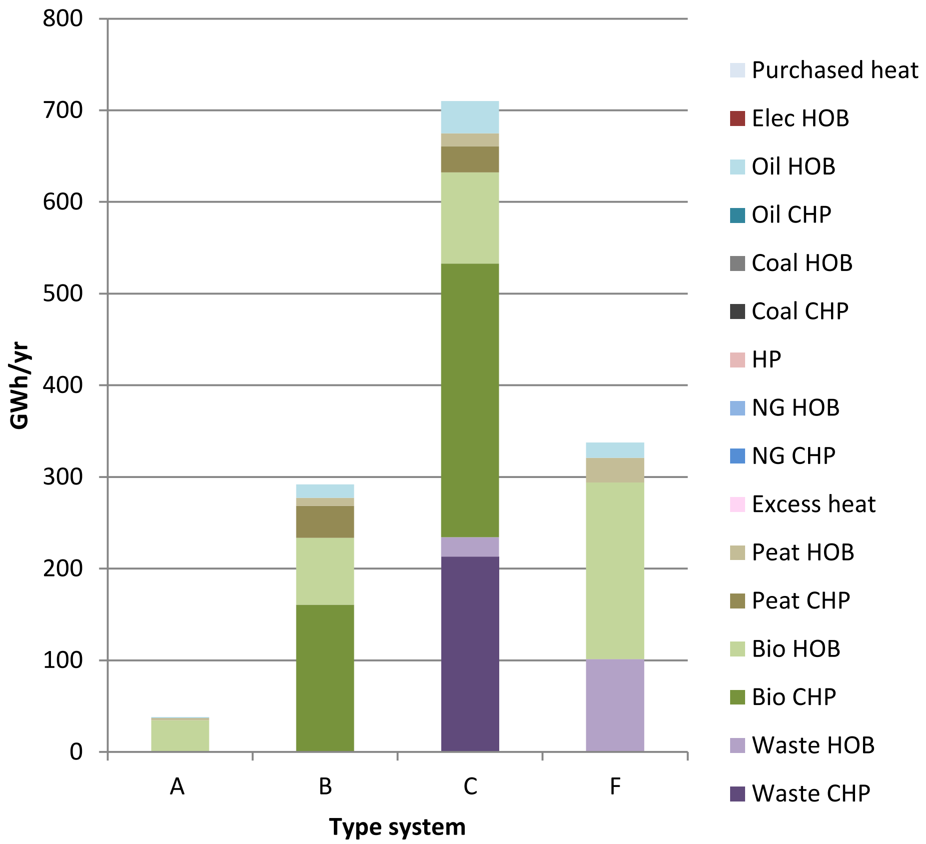

Figure 4: Current production mixes of the type systems A, B, C, and F for the Swedish district heating system. The annual production of each system is set to the average of the real systems of that type. Each colour represents an energy source and the lighter and darker shades represent heat produced in HOB and CHP plants respectively. Gothenburg/Malmö (system D) and Stockholm (system E) are not shown in the figure, but can be found in Figure 5 showing the total annual DH production represented by each type system.

Table 7: Descriptions of the constructed type systems for Sweden. Production mixes of the systems A, B, C, and F are shown in Figure 3. Based on fuel statistics from the Swedish District Heating Association (Svensk Fjärrvärme 2011a).

System	Description
A	Small systems, typically with yearly heat deliveries of up to 100 GWh, that use bio-fuelled heat-only boilers for almost all heat production.
B	Medium-sized systems, most with annual productions between 200 GWh and 1,000 GWh. Mainly use biomass CHP production.
C	Medium- to large-sized systems with mainly biomass- and waste-based CHP production.
D	Aggregation of Gothenburg and Malmö. Main production from waste- and natural gas-fuelled CHP plants, and excess industrial heat.
E	Describes the Stockholm system, which represents about 15 % of total annual Swedish district heat production. Production based mainly on biomass CHP and heat pumps. Smaller contributions from coal and waste.
F	Medium-sized systems with biomass- and waste-based heat-only production.

Table 8: Availability of production technologies and fuels in the different type systems in Sweden. Data on technologies can be found in Table 2 and Table 3.

Type system	Technology	Fuels/input
A	Solid HOB (small)	Biomass, peat, coal
	Solid CHP (small)	Biomass, peat
	Coal CHP (small)	Coal
	Heat pump (small)	Electricity
	Gas motor CHP	Biogas, landfill gas
	Oil HOB	Oil
	Electricity HOB	Electricity
B	Solid HOB (medium)	Biomass, peat, coal
	Solid CHP (medium-small)	Biomass, peat
	Solid CHP (medium-large)	Biomass, peat
	Coal CHP (medium-small)	Coal
	Coal CHP (medium-large)	Coal
	Waste HOB (medium)	Municipal solid waste
	Waste CHP (small)	Municipal solid waste
	Waste CHP (medium)	Municipal solid waste
	Gas motor CHP	Biogas, landfill gas
	Heat pump (medium)	Electricity
	Oil HOB	Oil
	Electricity HOB	Electricity
C	Solid HOB (medium)	Biomass, peat, coal
	Solid CHP (medium-large)	Biomass, peat
	Coal CHP (medium-large)	Coal
	Waste HOB (medium)	Municipal solid waste
	Waste CHP (medium)	Municipal solid waste
	Gas motor CHP	Biogas, landfill gas
	Heat pump (medium)	Electricity
	Oil HOB	Oil
	Electricity HOB	Electricity

Type system	Technology	Fuels/input
D	Solid HOB (large)	Biomass, peat, coal
	Solid CHP (large)	Biomass, peat
	Coal CHP (large)	Coal
	Waste HOB (large)	Municipal solid waste
	Waste CHP (large)	Municipal solid waste
	Excess industrial heat	-
	NGCC CHP (large)	Natural gas
	Gas motor CHP	Biogas, landfill gas
	Heat pump (large)	Electricity
	Oil/gas HOB	Oil, natural gas
	Electricity HOB	Electricity
E	Solid HOB (large)	Biomass, peat, coal
	Solid CHP (large)	Biomass, peat
	Coal CHP (large)	Coal
	Waste HOB (large)	Municipal solid waste
	Waste CHP (large)	Municipal solid waste
	Oil CHP	Oil
	Gas motor CHP	Biogas, landfill gas
	Heat pump (large)	Electricity
	Oil HOB	Oil
	Electricity HOB	Electricity
F	Solid HOB (medium)	Biomass, peat, coal
	Solid CHP (medium-small)	Biomass, peat
	Solid CHP (medium-large)	Biomass, peat
	Coal CHP (medium-small)	Coal
	Coal CHP (medium-large)	Coal
	Waste HOB (medium)	Municipal solid waste
	Waste CHP (small)	Municipal solid waste
	Waste CHP (medium)	Municipal solid waste
	Gas motor CHP	Biogas, landfill gas
	Heat pump (medium)	Electricity
	Oil HOB	Oil
	Electricity HOB	Electricity

Table 9: Number of systems and total annual DH production represented by each type system in Sweden.

	Type system					
	A	B	C	D	E	F
Number of systems	252	30	16	2	1	10
Total annual DH production [TWh/yr]	9.6	8.8	11	6.5	8.4	3.4

Categorisation of existing Swedish systems

When the existing district heating systems are classified into the designed type systems, the sums of their annual production volumes show the heat production that can be represented by each type system. The number of systems and the total annual DH production represented by each type system in Sweden are stated in Table 9, and the annual DH production is shown in Figure 5.

Adding up all the heat production represented by the type systems, results in a national production mix for Sweden. In Figure 6, this mix is compared to the national production mix as approximated from the fuel consumption statistics (Svensk Fjärrvärme, 2011a). This applied type system description covers about 85 % of the total national annual DH production. The parts that are not covered include large shares of excess heat and production from heat pumps.

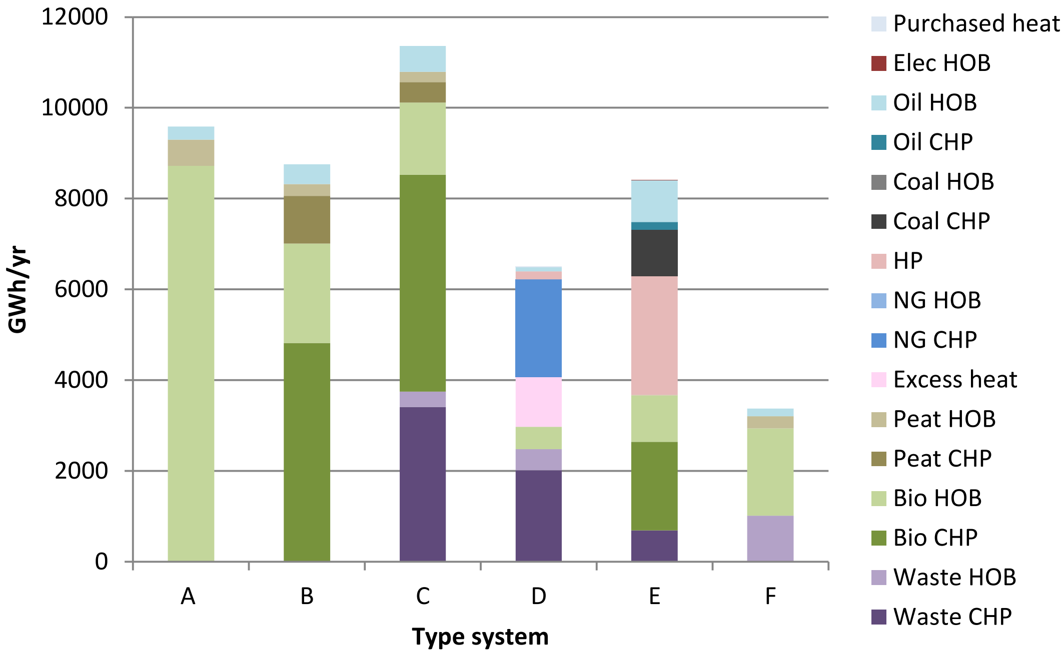

Figure 5: The annual production represented by each type system in Sweden calculated as the sum of the annual production volumes of all existing DH systems classified into each type category.

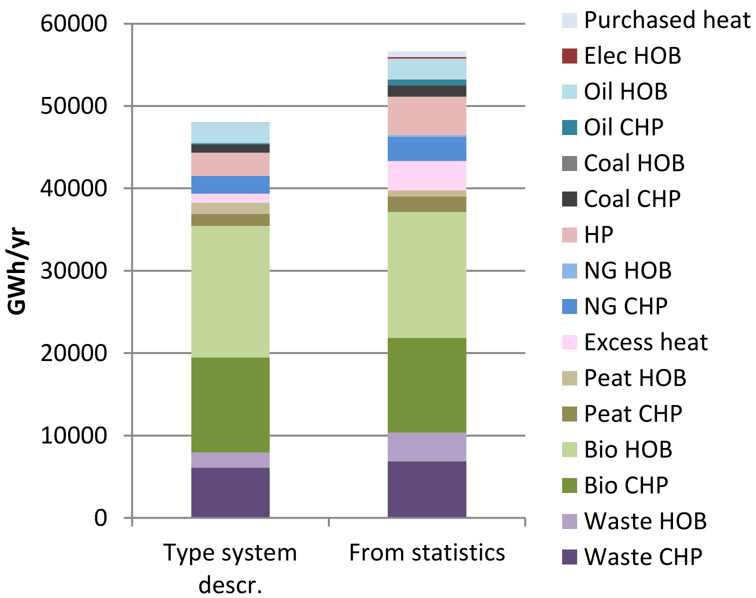

Figure 6: The national DH production mix for Sweden obtained from the type system description applied in this project, compared to the total estimated DH production mix from the fuel consumption statistics (Svensk Fjärrvärme, 2011a).

Descriptions of the constructed type systems in Finland

To represent the Finnish district heating systems five type systems have been designed in addition to the Helsinki system. Their production mixes are shown in Figure 7. Helsinki, the largest system, in terms of annual production, is separately described in the type system E and is not shown in the figure, but can be seen in Figure 8 showing the total annual DH production represented by each type system. A description of each type system is given in Table 10. The production technologies assumed to be available in each type system are listed in Table 11 (for specific data on the technologies, see Table 2 and Table 3).

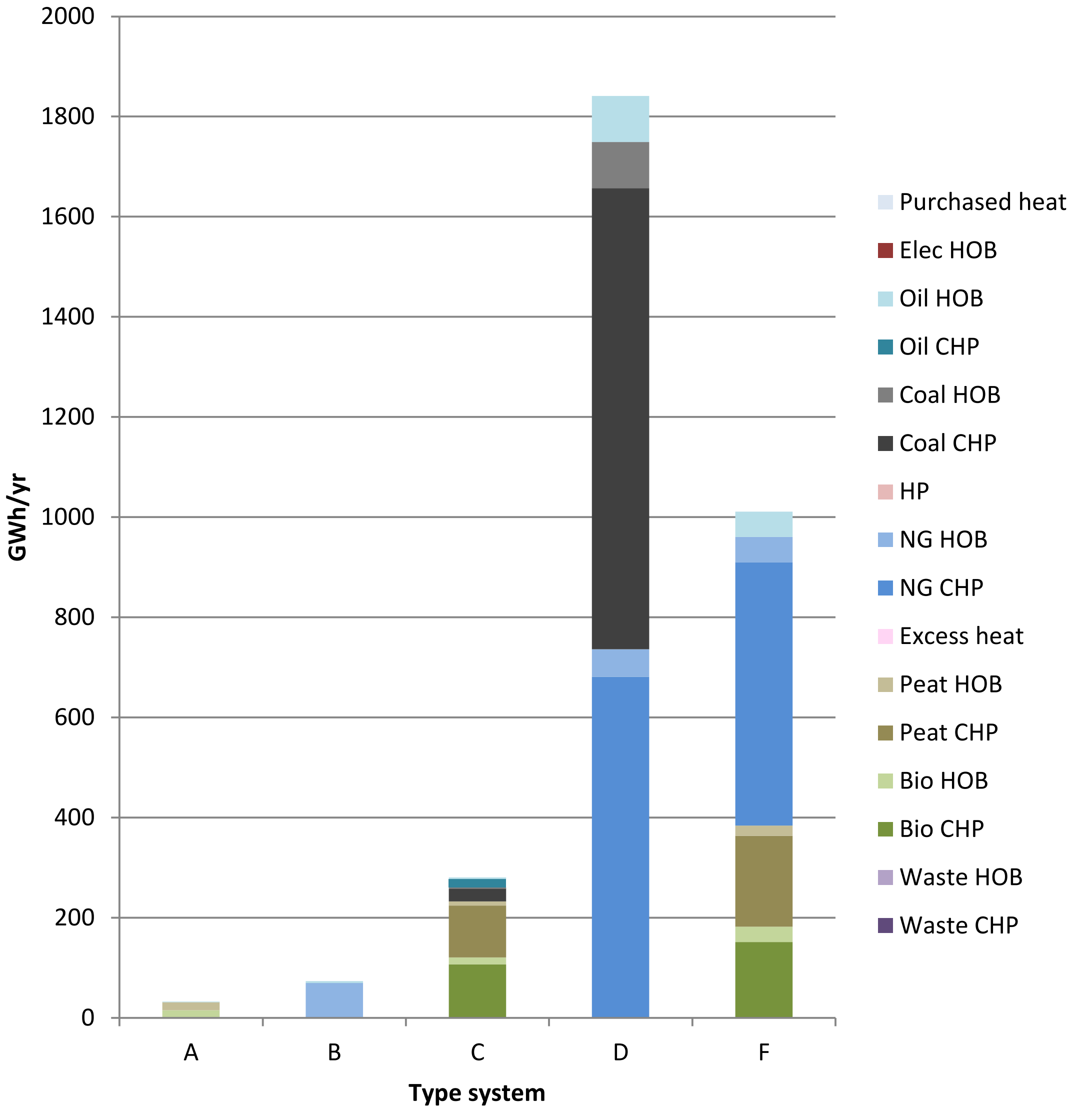

Figure 7: Production mixes of the type systems A, B, C, D, and F in the Finnish district heating system. The annual production of each system is set to the average of the actual systems of that type. Each colour represents an energy source and the lighter and darker shades represent heat produced in HOB and CHP plants respectively. The Helsinki system (system E) is not included in the figure, but can be found in Figure 8, showing the total annual DH production represented by each type system.

Table 10: Descriptions of the constructed type systems for Finland. Production mixes for the systems A, B, C, D, and F are shown in Figure 7. Based on fuel statistics from the Finnish Energy Industry (Finsk Energiindustri, 2010b).

System	Description
A	Small bio- and peat-based systems with heat-only production. Typically with annual heat deliveries of less than 100 GWh.
B	Small systems in the same size category as A systems, but with natural gas-based heat-only production.
C	Medium-sized systems, usually delivering 100 GWh and 1,000 GWh of heat annually. Production is based on biomass and peat CHP.
D	Large systems, typically with annual heat deliveries between 1,000 GWh to 2,000 GWh, with coal- and natural gas-fuelled CHP.
E	Describes Helsinki. Mainly production from coal and natural gas in CHP production.
F	Medium- to large-sized systems mainly using natural gas CHP together with bio- and peat-fuelled CHP.

Table 11: Availability of production technologies and fuels in the different type systems in Finland. Data on technologies can be found in Table 2 and Table 3.

Type system	Technology	Fuels/input
A	Solid HOB (small)	Biomass, peat, coal
	Solid CHP (small)	Biomass, peat
	Coal CHP (small)	Coal
	Gas motor CHP	Natural gas
	Heat pump (small)	Electricity
	Oil HOB	Oil
	Natural gas HOB	Natural gas
	Electricity HOB	Electricity
B	Solid HOB (small)	Biomass, peat, coal
	Solid CHP (small)	Biomass, peat
	Coal CHP (small)	Coal
	Gas motor CHP	Natural gas
	Heat pump (small)	Electricity
	Oil HOB	Oil
	Natural gas HOB	Natural gas
	Electricity HOB	Electricity
C	Solid HOB (medium)	Biomass, peat, coal
	Solid CHP (medium-small)	Biomass, peat
	Solid CHP (medium-large)	Biomass, peat
	Coal/peat CHP (medium-small)	Coal, peat
	Coal/peat CHP (medium-large)	Coal, peat
	NGCC CHP (medium)	Natural gas
	Heat pump (medium)	Electricity
	Oil/gas HOB	Oil, natural gas
	Electricity HOB	Electricity
D	Solid HOB (large)	Biomass, peat, coal

Type system	Technology	Fuels/input
	Solid CHP (large)	Biomass, peat
	Coal/peat CHP (large)	Coal, peat
	Coal CHP (large)	Coal
	NGCC CHP (large)	Natural gas
	Heat pump (large)	Electricity
	Oil/gas HOB	Oil, natural gas
	Electricity HOB	Electricity
E	Solid HOB (large)	Biomass, peat, coal
	Solid CHP (large)	Biomass, peat
	Coal/peat CHP (large)	Coal, peat
	Coal CHP (large)	Coal
	NGCC CHP (large)	Natural gas
	Heat pump (large)	Electricity
	Oil/gas HOB	Oil, natural gas
	Electricity HOB	Electricity
F	Solid HOB (large)	Biomass, peat, coal
	Solid CHP (medium-large)	Biomass, peat
	Coal/peat CHP (medium-large)	Coal, peat
	NGCC CHP (large)	Natural gas
	Heat pump (large)	Electricity
	Oil HOB	Oil
	Electricity HOB	Electricity

Table 12: Number of systems and total annual DH production represented by each type system in Finland.

	Type system					
	A	B	C	D	E	F
Number of systems	73	20	26	3	1	3
Total annual DH production [TWh/yr]	2.4	1.5	7.3	5.5	7.2	3.0

Categorisation of existing Finnish systems

As for Sweden, the annual production volumes of the systems represented by each type system in Finland are summed up. Table 12 summarises the number of systems and the annual DH production represented by each type system. The total annual production mixes of the type systems are shown in Figure 8. The national production mix from the type system description is shown in Figure 9 compared to the national production mix as approximated from the fuel consumption statistics (Finsk Energiindustri, 2010b). The type system covers about 85 % of national annual production, missing some of the more uncommon (in Finland) energy sources such as biogas, excess heat, and waste.

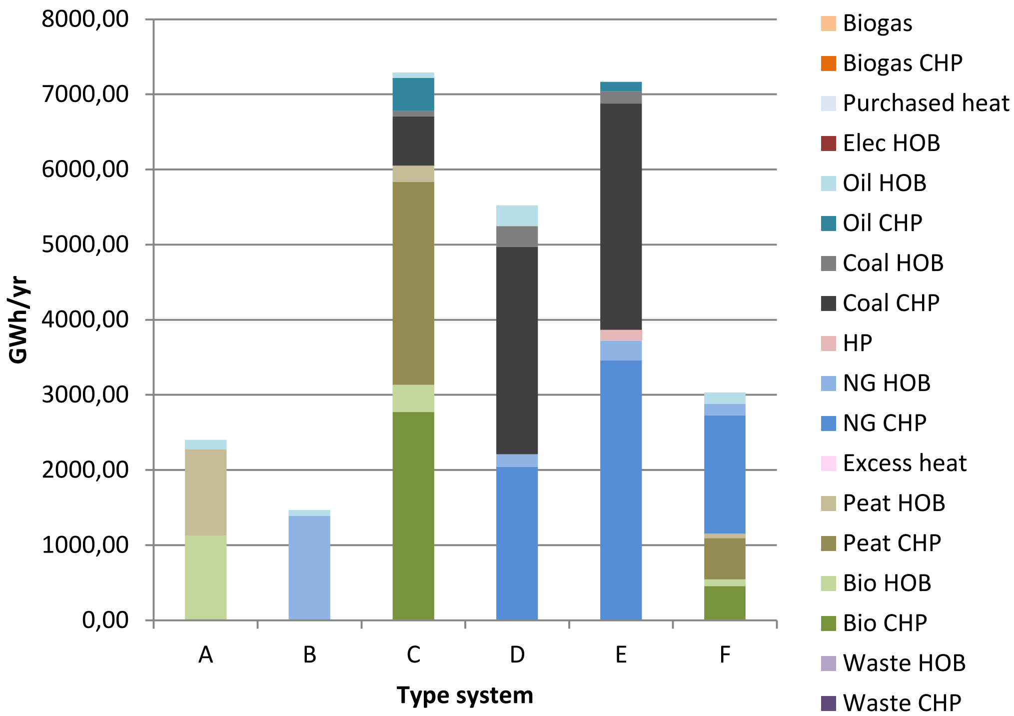

Figure 8: The annual production represented by each type system in Finland calculated as the sum of the annual production volumes of all real systems classified into each type category.

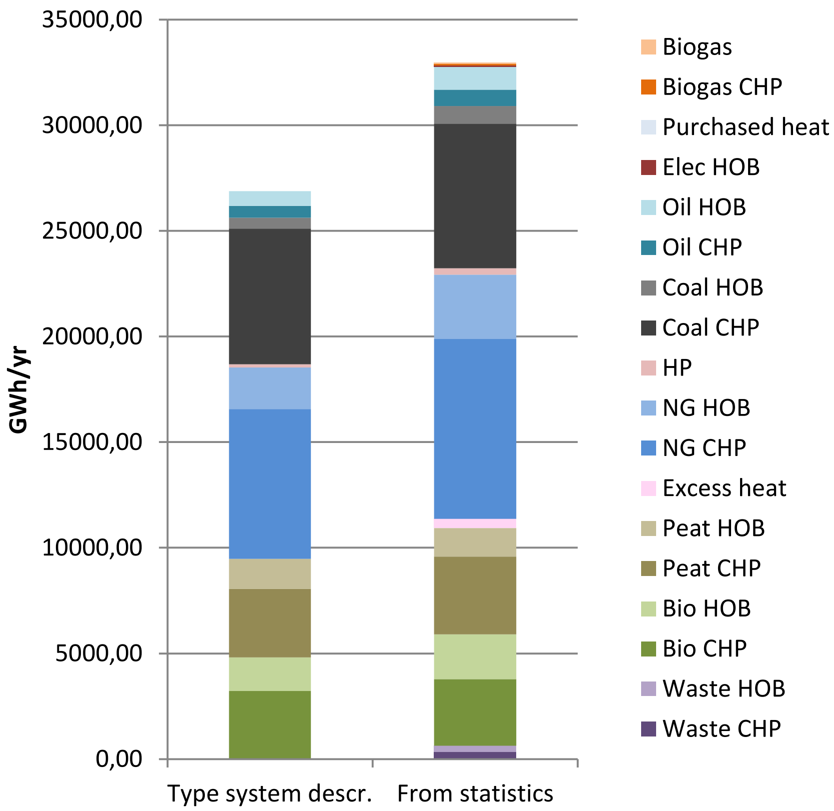

Figure 9: The national production mix for Finland obtained from the type system description, compared to the total estimated DH production mix from the fuel consumption statistics (Finsk Energiindustri, 2010b).

Descriptions of the constructed type systems in Denmark

The available statistical data for Denmark is not as complete and transparent as for Sweden and Finland. However, three type systems and a fourth aggregated system (for convenience designated type system D) have been designed. The first one is based on a report on the future of district heating in the Copenhagen area (Varmeplan Hovedstaden, 2011), the second and third are based on statistics on fuel consumption from the Danish District Heating Association (Dansk Fjernvarme, 2010a), and the fourth is an estimation of the remainder of the national production mix based on the report "Heat plan Denmark" (Rambøll Danmark, Aalborg Universitet, 2010).

Table 13: Description of type systems constructed for Denmark. The A system is based on the report "Varmeplan Hovedstaden" (Varmeplan Hovedstaden, 2011) and the B and C systems are designed based on the annual fuel statistics from the Danish District Heating Association (Dansk Fjernvarme, 2010a). National production data is taken from the report "Heat plan Denmark" (Rambøll Danmark, Aalborg Universitet, 2010).

System	Description
A	Designed to describe the Copenhagen system. A production mix based on biomass, waste, coal, and natural gas, where almost all heat is produced in CHP plants. Represents about 9.5 TWh of annual district heat production, which is almost 30 % of the total national production.
B	Represents three large systems, producing a vast majority of their district heat in coal-fired CHP plants. The combined annual production of these systems corresponds to about 20 % of the total national production.
C	Small systems with natural gas-based production from CHP as well as HOB plants.
D	Aggregated system describing the remainder of the national annual production not covered by the systems A, B, and C. The D system represents more than 100 systems responsible for about half of the national annual district heat production in Denmark.

Table 14: Availability of production technologies and fuels in the different type systems in Denmark. Data on technologies can be found in Table 2 and Table 3.

Type system	Technology	Fuels/input
A	Solid HOB (large)	Biomass, coal
	Solid CHP (large)	Biomass
	Coal CHP (large)	Coal
	Heat pump (large)	Electricity
	NGCC CHP (large)	Natural gas
	Waste CHP (large)	MSW
	Waste HOB (large)	MSW
	Oil HOB	Oil
	Natural gas HOB	Natural gas
	Electricity HOB	Electricity
B	Solid HOB (large)	Biomass, coal
	Solid CHP (large)	Biomass
	Coal CHP (large)	Coal
	Heat pump (large)	Electricity
	NGCC CHP (large)	Natural gas
	Waste CHP (large)	MSW

Type system	Technology	Fuels/input
	Waste HOB (large)	MSW
	Excess industrial heat	-
	Oil HOB	Oil
	Natural gas HOB	Natural gas
	Electricity HOB	Electricity
C	Solid HOB (small)	Biomass, coal
	Solid CHP (small)	Biomass
	Coal CHP (small)	Coal
	Gas motor CHP	Natural gas
	Heat pump (small)	Electricity
	Oil HOB	Oil
	Electricity HOB	Electricity
D	Solid HOB (small)	Biomass, coal
	Solid CHP (medium-large)	Biomass
	Coal CHP (medium-large)	Coal
	Waste HOB (medium)	Municipal solid waste
	Waste CHP (medium)	Municipal solid waste
	NGCC CHP (medium)	Natural gas
	Heat pump (medium)	Electricity
	Natural gas HOB	Natural gas
	Oil HOB	Oil
	Electricity HOB	Electricity

Table 15: Number of systems and total annual DH production represented by each type system in Denmark.

	Type system			
	A	B	C	D
Number of systems	1	3	74	Appr. 327[a]
Total annual DH production [TWh/yr]	9.6	6.5	2.1	16[b]

[a] The number represents the members of the Danish District Heating Association not represented by the other type systems. All members in total represent 98 % of the annual DH production in Denmark. (Dansk Fjernvarme, 2010b)

[b] Remaining annual production according to the "Heat plan Denmark" report (Rambøll Danmark, Aalborg Universitet, 2010) not represented by the type systems.

Classification of existing Danish systems

The first two type systems are designed to describe the systems in the four largest cities in Denmark. The third type system represents a much larger number of small systems, with a total annual production of about 2 TWh. The number of systems and total annual DH production represented by each type system are stated in Table 15. Figure 10 shows the total annual DH production mix represented by each type system. The national production mix described by the type system representation is shown with the total national production mix as described in the "Heat plan Denmark" report (Rambøll Danmark, Aalborg Universitet, 2010).

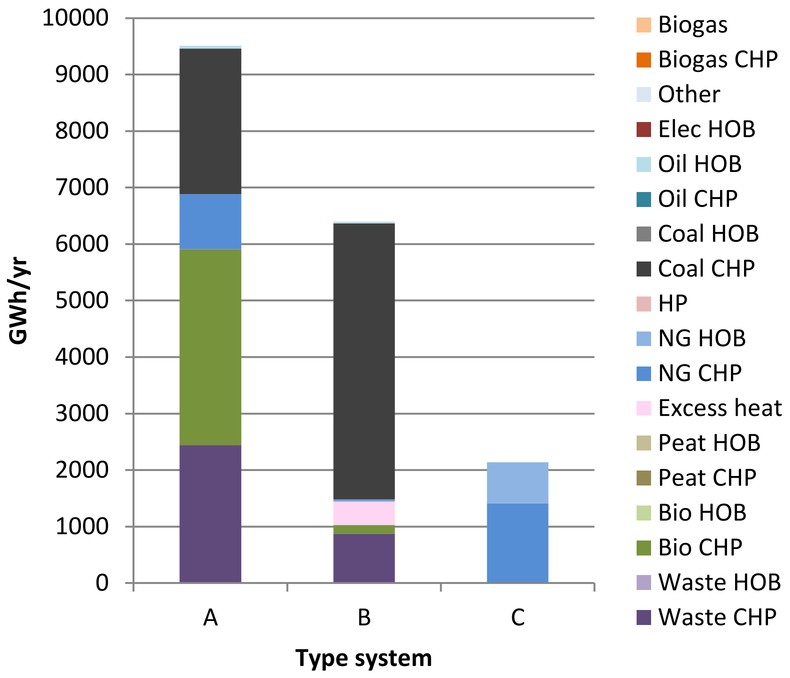

Figure 10: The annual production represented by each type system in Denmark calculated as the sum of the annual production volumes of all real systems classified into each type category.

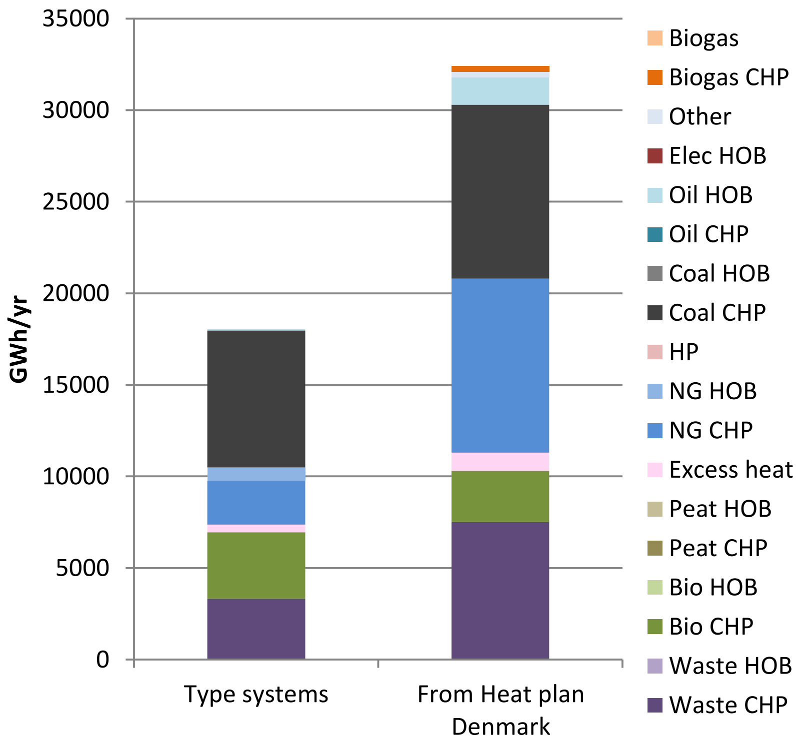

Figure 11: The national production mix for Denmark obtained from the type system description (excluding the D system, since that contains the remainder of the national annual heat production), compared to the one estimated from “Heat plan Denmark” (Rambøll Danmark, Aalborg Universitet, 2010).

5 Results

The results from the model analysis of the cost-minimising developments of the district heating production mixes in Sweden, Finland, and Denmark in the three scenarios are presented in this chapter.

5.1 Scenario analysis results

For each scenario, the results for each of the three countries are shown and described separately. Figures showing the results for individual type systems described in this section can be found in Appendix B.

The Reference scenario

The development of the national Swedish production mix is shown in Figure 12. The energy sources are the same as currently used in district heat production, but the heat pumps significantly increase their share. The district heat production from waste increases in order to dispose of the increasing amounts of generated waste (all available waste fuel is used). For top load production, biooil and electric HOBs are most commonly used.

It can be noted that the share of heat from CHP production, and thereby also the produced electricity, decreases compared to the current situation. An analysis of the individual type system results shows that some of the biomass CHP production in medium-sized systems of type B is replaced by heat only production from waste incineration. It also shows that the somewhat larger type C systems have waste-based CHP production today (corresponding to about 30 % of the total annual DH production), phase out that technology and replace it with heat only production.

The small type A systems in Sweden continue to produce the largest share of their heat in bio-fuelled HOBs, while the larger systems B, C, and D mainly use biofuels in CHP plants, when it is used at all. Heat pumps contribute in almost all systems.

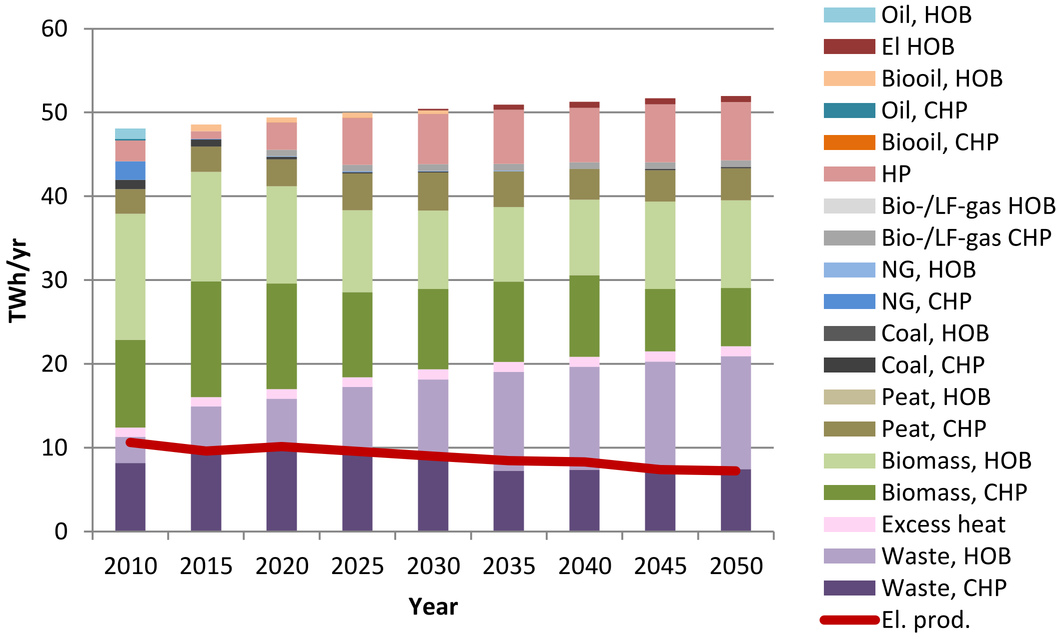

Figure 12: Development of the national annual district heat production in Sweden in the Reference scenario. The results are shown for the modelled period 2010-2050.

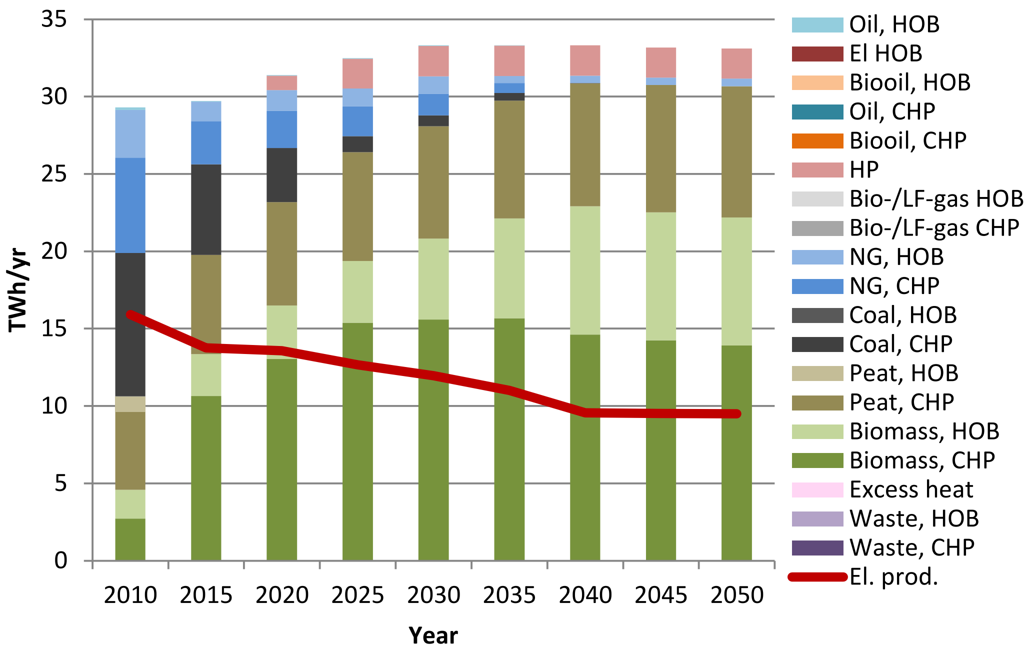

Figure 13: The national annual district heat production in Finland in the Reference scenario. The results are shown for the modelled period 2010-2050.

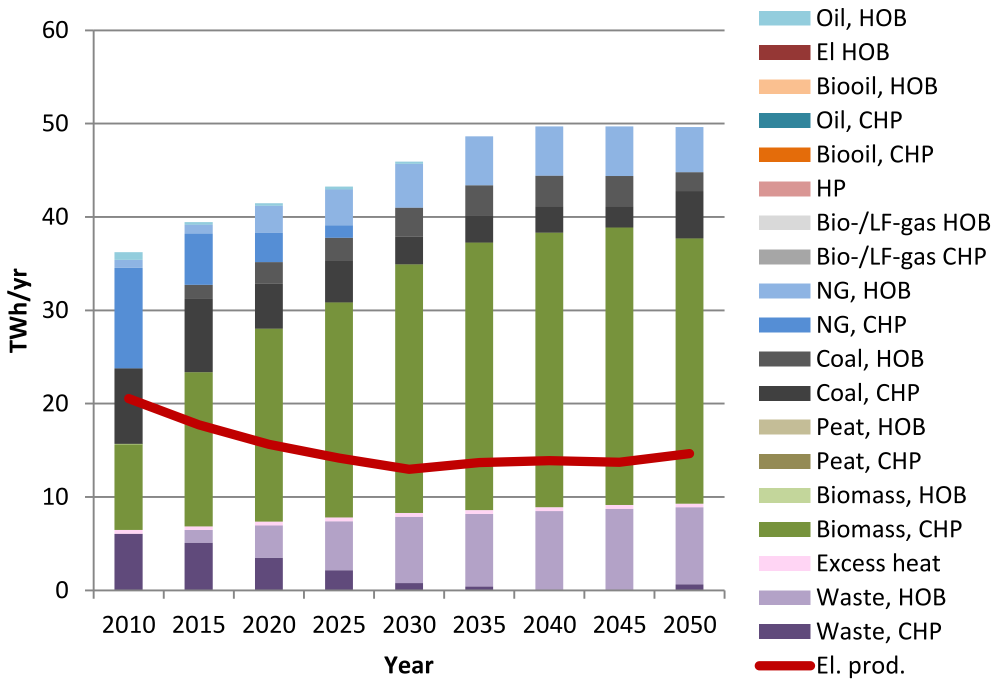

Figure 14: National annual production of district heat in Denmark in the Reference scenario. The results are shown for the modelled period 2010-2050.

Figure 13 shows the national annual district heat production in Finland. There is a decrease in the electricity production in district heating systems, which is also seen in Sweden. This is caused both by a decrease in the share of heat produced in CHP facilities and by a shift from technologies with high power-to-heat ratios, such as natural gas CHP plants, towards bio- and peat-fuelled plants with a much lower electricity production per unit of heat.

The decrease in the overall CHP share, when studied on the type system level, is mainly a decrease in CHP production in the type systems C, D, E, and F, that currently utilise CHP technology. The D and E systems are very large, corresponding to systems with annual DH production larger than 1,000 GWh. The C and F systems are generally somewhat smaller. The smallest systems of type A and B, that do not currently have any CHP production, actually start to invest in bio-fuelled CHP production technologies as soon as it is possible in the model. However, this effect cannot counter the decrease of CHP in the C, D, E, and F systems, since the A, and B categories represent a much smaller share of the total national DH production.

In Finland, natural gas is the most common top load fuel and the heat pumps, in contrast to Sweden, appear only in a few systems, which explains the smaller national share of DH production in heat pumps. Most of the fossil fuels natural gas and coal, currently used in the Finnish district heat production, is phased out rather rapidly in the model results.

The development of the Danish district heat production mix over the modelled period is shown in Figure 14. Biomass-fuelled CHP production increases to meet the rising demand, but some coal-based production remains in the mix. As in Sweden, the increase in waste-based heat production is due to the increased amounts of combustible waste available to the DH producers.

The natural gas-based heat production, currently common in Denmark, is replaced by biomass CHP production in the larger systems and by coal heat-only production in the smaller systems. This transition from small-scale natural gas CHP production to coal HOBs in the small C systems and the introduction of waste HOBs in the aggregated D implies a shift away from CHP technologies lowering the share of heat cogenerated with electricity. The decrease in the share of CHP production and the phase-out of natural gas leads to a significantly lower electricity production at the end of the period. The remaining natural gas in the production mix is only used for peak load heat production.

The Regional Policy scenario

The development of the production mix in the Regional Policy scenario, with a significantly lower demand for district heat than the Reference scenario, is shown in Figure 15. It can be seen that the share of both biofuel CHP and waste CHP increases. The electricity production increases to a level higher than in the Reference scenario towards the end of the modelled period. The share of heat produced by heat pumps is somewhat smaller than in the Reference scenario.

The strong support for renewable electricity production in this scenario makes the biomass CHP production an attractive alternative. On the type system level, the analysis shows that small type A systems invest in CHP technologies in contrast to in the Reference scenario. There is also a slight over-production of heat from waste CHP plants in system E, meaning that it is economically justifiable to produce more heat than demanded, due to the revenues from electricity sales and the gate fees for waste.

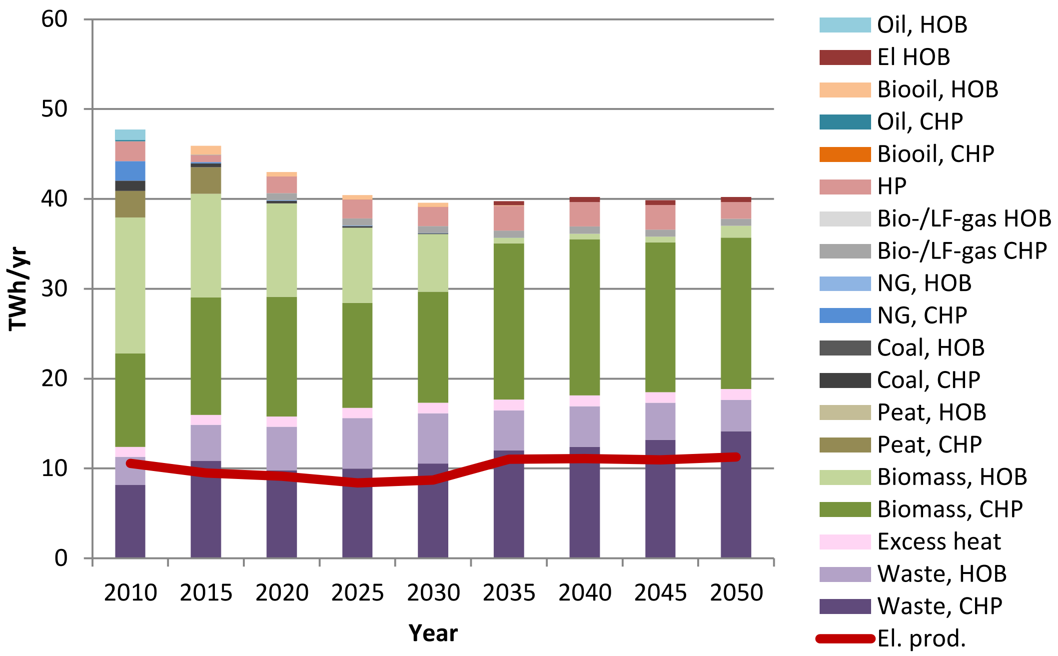

Figure 15: The national annual production of district heat in Sweden in the Regional Policy scenario, shown for the modelled period 2010-2050.

In Finland, the development is similar to that in the Reference scenario, except for the lower demand, which makes it possible to supply almost all heat from bio-fuelled plants. The share of heat produced in CHP is also slightly higher than in the Reference scenario. The development of the production mix in the Regional Policy scenario is shown in Figure 16.

In the small systems A and B, the resulting production mixes have a composition almost identical to that in the Reference scenario, with an increasing share of bio-based CHP production. However, in the larger systems C and F, biomass CHP forces out the peat CHP that dominates the reference production mix. In these systems there is also a contribution from heat pumps. In the largest D and E systems, almost all heat is produced in bio-based CHP plants towards the end of the modelled period.

The transition from coal- and natural gas-based CHP production towards a mix dominated by biofuel also leads to a significant decrease in the electricity production from district heating facilities, which, as mentioned earlier, is caused by the lower electricity-to-heat ratios of these technologies.

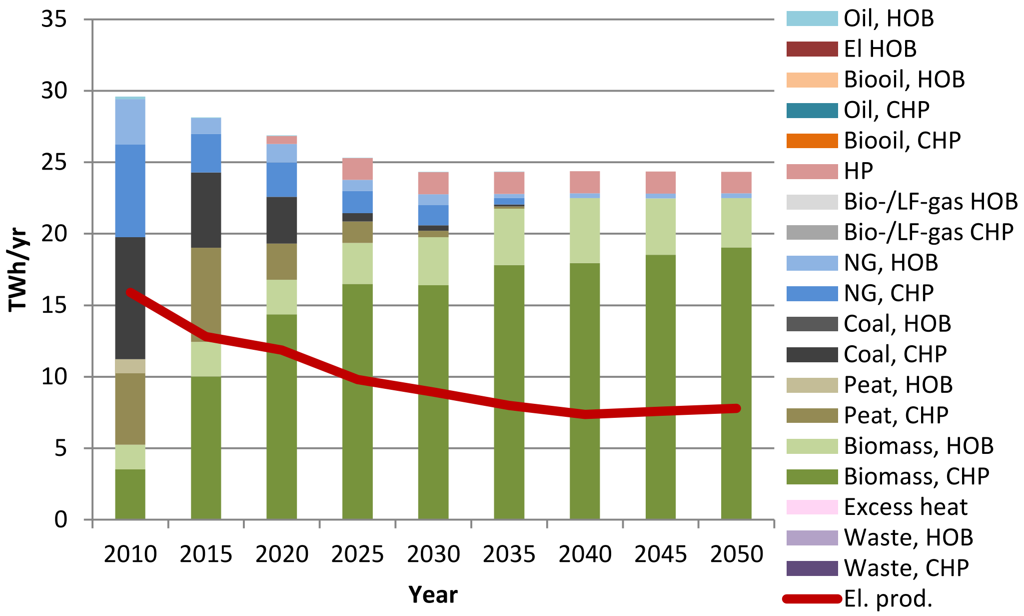

Figure 16: The national annual production of district heat in Finland in the Regional Policy scenario, shown for the modelled period 2010-2050.

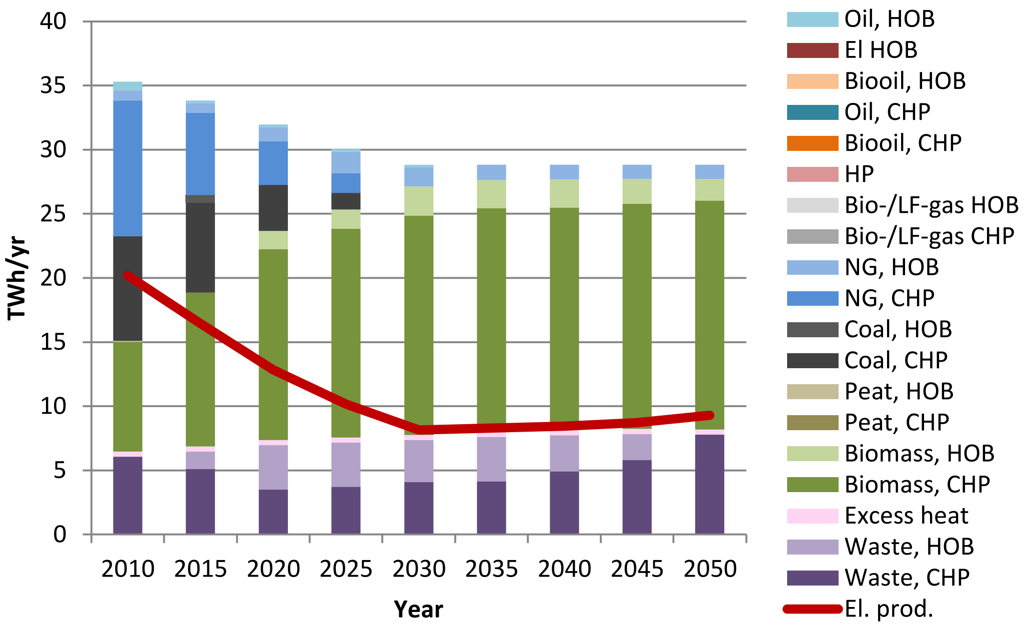

Figure 17: The national annual production of district heat in Denmark in the Regional Policy scenario, shown for the modelled period 2010-2050.

In the Regional Policy scenario, Danish district heating develops in much the same way as the Swedish and Finnish systems. The production from biomass CHP plants increases rapidly and fossil fuels are phased out. Figure 17 shows the production mix in Denmark from 2010 to 2050.

An analysis on the type system level shows that the larger systems A and B both converge towards biomass and waste CHP production, whereas the smaller type system C switches from natural gas to biomass, but mainly uses heat-only technologies.

As is also seen in Finland, the electricity production in CHP plants decreases substantially in this scenario. However, the effect is even more noticeable in Denmark where electricity production from CHP is less than half 2050 than it is today. The reason is the transition from natural gas and coal technologies with high power-to-heat ratios, towards the bio-based production.

The Climate Market scenario

Figure 18 shows the development of the national district heat production mix in Sweden. Compared to the results in the Reference scenario (see Figure 12), the higher electricity price leads to a higher share of CHP production and a somewhat lower utilisation of heat pumps for district heat production.

Almost all the type systems converge to a production mix based on biomass and waste, with relatively large, but slightly varying, proportions of CHP production. Only the small A systems have a production mix based almost entirely on heat-only production and they also constitute a significant part of the total national production from biomass HOBs.

Figure 19 shows the production mix for Finland in the Climate Market scenario. The main difference compared to the Reference scenario (see Figure 13) is that the peat is replaced by biomass due to the high emission permit prices. The share of heat from CHP production and the electricity generation are approximately the same in the two scenarios and non-CHP production mainly comes from biomass HOBs and heat pumps. The contribution from heat pumps is somewhat larger than in the Reference scenario.

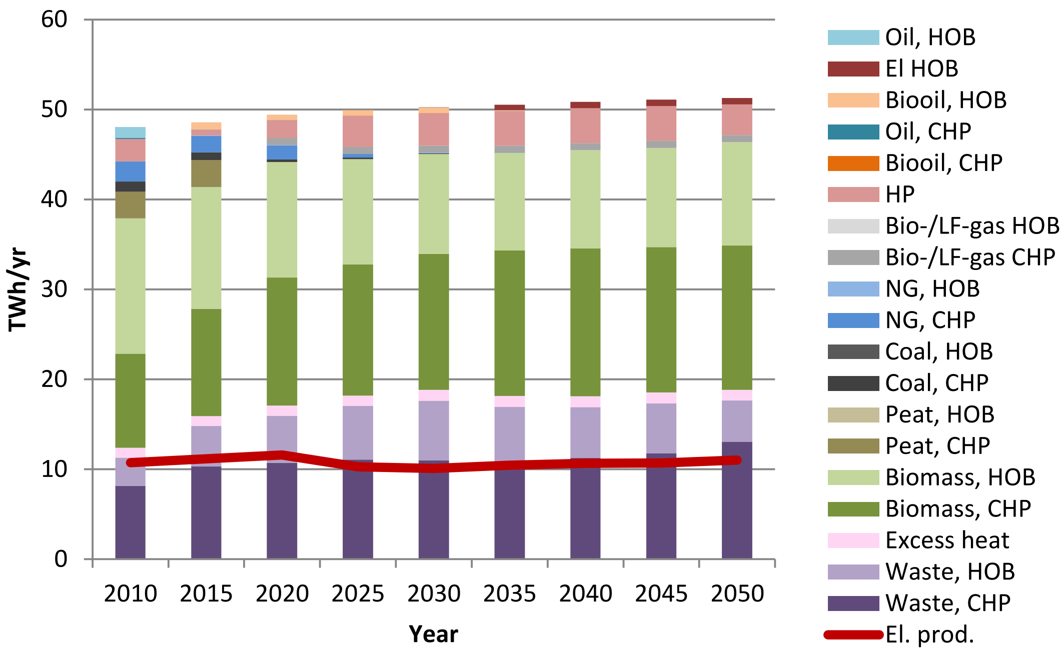

Figure 18: The national annual production of district heat in Sweden in the Climate Market scenario, shown for the modelled period 2010-2050.

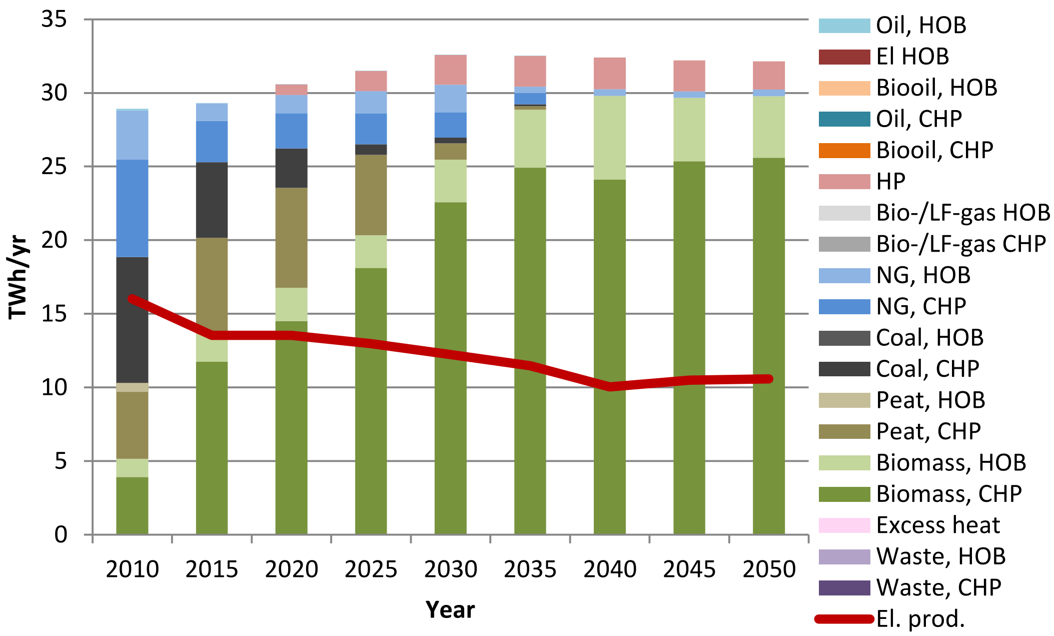

Figure 19: The national annual production of district heat in Finland in the Climate Market scenario, shown for the modelled period 2010-2050.

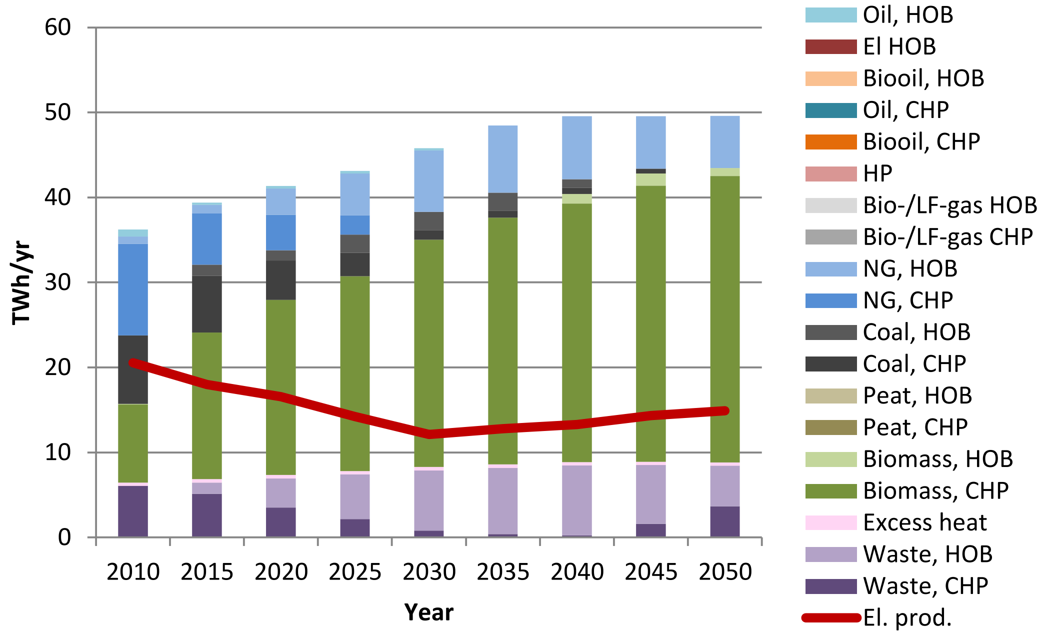

Figure 20: The national annual production of district heat in Denmark in the Climate Market scenario, shown for the modelled period 2010-2050.

The development of the Danish district heating mix in the Climate Market scenario can be seen in Figure 20. The results are quite similar to the Reference scenario (see Figure 14), except that the coal production is phased out. However, the composition of the production mix differs slightly from the Regional Policy scenario (shown in Figure 17) through more production from natural gas and significantly higher electricity production.

The smallest of the Danish type systems, system C, keeps part of the natural gas currently present in the production mix. However, most of it is replaced by heat-only production from biomass and coal. In the other type systems the coal and natural gas are slowly phased out to give room for biomass CHP production.

6 Discussion

In this chapter, the relevance and implications of results and applied methods are analysed. In order to understand the meaning of results some of the differences between the current district heating systems in the studied countries are also discussed.

6.1 Differences between countries in current district heating systems

The mapping of the current district heating systems in Sweden, Finland, and Denmark, shows that there are significant differences in the fuels and technologies currently used for district heat production. Some of the differences could be caused by the differences in the electricity supply systems in these countries, although historical policy choices have probably also been important.

In Denmark, and to some extent in Finland, it has traditionally been common to use plants fired by coal and natural gas for electricity production (Danish Energy Agency, 2010) and cogeneration plants have been built in order to utilise the heat as well. The historical electricity production may also be partly explained by availability of natural resources, such as natural gas in Denmark.

In Sweden, on the other hand, the electricity supply is mainly based on nuclear and hydro-power. Hydro-power does not generate any significant thermal losses, which can be utilised as heat, and the excess heat from nuclear power plants is usually not utilised for other reasons, e.g. that the plants are usually built on a distance from the more densely populated areas.

This would be consistent both with the larger, compared to Sweden, shares of district heat production from coal and gas and the higher CHP shares in Denmark and Finland. This means that the electricity generation in CHP plants is much more important in Denmark and in Finland, than it is in Sweden. This also reflects in the fact that Denmark and Finland allocates smaller fractions of the fuel used in CHP to the taxed heat side (see Appendix A for more details on fuel allocation in CHP).

6.2 Validity and usefulness of the type system descriptions

The type systems are very useful when trying to capture some of the special characteristics of district heating. For Sweden and Finland the type system description can be seen as representing the entire national system fairly well, since only a small part of the total national production is not covered. In Denmark, however, the type systems only represent about half of the national production, and the remainder is described in an aggregated system. This cannot, of course, provide as detailed a picture as for Sweden and Finland, but the differences in the developments between the type systems can still be interesting, since it can, for example, show the difference in the developments between small and large systems.

Modelling the type systems separately enables more detailed analyses of the results. For example, the distribution of some fuels, such as biofuels and waste (in Sweden and Denmark), between systems can be studied. Both of these fuels are limited resources and it is interesting to study the optimal, in the sense of this model, way of distributing them. However, it should be considered when interpreting the results, that the geographical aspects, i.e. the local availability and the transport costs, are not considered in the model. The same applies to the load curve used in the model. In reality, the load curve varies geographically. The further up north the systems are located, the higher the demand for space heating during the cold parts of the year.

It is important, in fact, to remember that what differs between the type systems as described in this model, are only their sizes, determining the costs of new technology, and their starting points, in terms of the current composition of the production mix. Since the technological options and costs for these are the same for all type systems in the same size category, the result in the long run will generally be the same since the starting point loses its importance as the old technology is retired.

6.3 Strengths and weaknesses of the modelling approach

Representing the type systems separately in the model has clearly given an advantage compared to the aggregated approach. In the Reference scenario in Sweden, for example, the small A system, keeps its biomass heat-only production throughout the period. Even though all other type systems converge to high CHP shares, there is a significant contribution to the total national production that comes from these small systems. This is an effect of the diversity of district heating systems and it is captured, at least to some extent, by the model developed in this thesis. The model can, compared to for example the MARKAL-NORDIC model (used in Unger & Ahlgren, 2005), incorporate more of the specific characteristics of DH. The trade-off is of course that the system limits are much narrower and all dynamics arising from market interactions, such as electricity trade, are sacrificed.

The optimising property of the TIMES model is in many ways suitable for modelling district heating systems. The choices of what technologies to use for heat production in a real district heating system at any given time are usually made so that the capacities are dispatched in order of running cost. The technology with the lowest running cost is first used to the maximum capacity and then the technology with second lowest running cost and so on. This is also exactly how technology will be dispatched in the model.

The general idea of cost minimisation is at least one of the most important factors of decision making in real systems. However, an important difference between real world decision making and the model is that while the model optimises on a system-wide level, real decisions are made to minimise the costs, or even maximise the profit, of an individual system or company. The model results are therefore, as mentioned earlier, not to be seen as forecasts or simulations of behaviour in the real district heating systems.

As discussed in section 2.2, the choice of modelling approach depends on what questions are being asked. The optimising property of the model, in connection with the type system description, enables, for example, the possibility to study the optimal allocation of some limited fuels between type systems. This is a form of prescriptive modelling where the best solution on a national level, and not the cost-minimising course of action for each DH company, is sought for.

Since the model is only based on cost minimisation, there are some factors that are not considered. For example, the only policy instruments included in the model are the economic measures, such as taxes and subsidies. This means that the possible effects of, for example, local energy planning are not taken into account. Other factors, such as the public opinion and goodwill effects, are not described in the model either.

The model is also constructed with perfect foresight. This means that all the future costs arising from a certain decision are fully known when the decision is made. For a prescriptive model telling us what is a possible, minimal-cost outcome, this is a reasonable modelling technique. However, it should be considered, that in a real decision, this is not true. There are always uncertainties. In, for example, an investment in a CHP plant, fuel prices, policies, and other factors would have to be known 30 years into the future in order to be able to make a fully informed decision. In the model, since everything is perfectly known, sensitivities to changes in, for example, prices are not taken into consideration. In reality, it would be important to make a decision that is robust with respect to different possible future developments. Also, uncertainties and risks are judged differently by different actors, which would lead to more spread between different alternatives. The optimising model will always choose the cheapest option only.

When considering all properties of the model discussed above it should be emphasised that the results from a model of this kind are not meant to be interpreted as forecasts. They are instead approximate descriptions of cost-minimal realisations of possible futures.

The method of dividing the year into time slices, which is used in the model, helps to describe the effect of the load curve in district heating systems. However, since the lengths are free for the user to choose, it is possible that there are choices more suitable to represent the load in a district heating system. The time slices used are designed to represent the seasons separately, which is not necessarily optimal. Spring and autumn, for example, are relatively similar, with respect to heat demand. It is possible that a more efficient time division could be found. Dividing the slices by season, on the other hand, can also have some advantages, since it can be useful for interpretation of results and some inputs may be differentiated by season.

6.4 Scenario results

The developments of the production mixes are, as could be expected, slightly more dominated by renewable sources in the Climate Market and Regional Policy scenario compared to the Reference scenario. Policy aims in both cases (though implemented differently in the two scenarios) at decreasing greenhouse gas emissions. The main difference is that the lower demand in the Regional Policy scenario, leads to a faster transition. A low DH demand and a large share of renewable energy sources would indicate a smaller environmental impact, e.g. through decreased greenhouse gas emissions. However, the decreasing demand also has the effect of decreasing the electricity production from CHP in Finland and Denmark. As discussed above the electricity from CHP is of great importance in both these countries, and if the reduction in electricity generation capacity has to be replaced by other technologies the environmental effects are unclear.

In Sweden, interestingly, the generated electricity is actually higher in the Regional Policy scenario, than in the other two. This is because there are strong policy measures to promote renewable electricity generation in Sweden in this scenario. Since the share of CHP in district heat production is currently rather low in Sweden it is possible to increase the CHP production while fully utilising the generated heat. This CHP expansion is not possible in Denmark and Finland, where the share of district heat produced in CHP generation is already high.

The Regional Policy scenario also depicts a future where the amounts of combustible waste is much higher than today, while the demand for district heat is significantly lower. In the results for Sweden in this scenario, a tendency towards an overproduction of heat can be seen. This indicates that if incineration is used for disposing of waste, it may be a problem to utilise all the generated heat. However, it should be noted that the forecast of available combustible waste is the same in all scenarios, while in reality it may differ for example through energy efficiency measures leading to a decrease in waste generation.

In the Climate Market scenario it can be seen that, larger shares of fossil fuels, compared to the Regional Policy scenario, remain in the production mixes of, primarily, Finland and Denmark for a longer period of time. Even though high shares of renewable energy sources are reached towards the end of the modelled period, some contributions from fossil fuels are necessary to meet the higher demand. This does, however, also contribute to making the decrease in electricity production somewhat less dramatic.

It should be mentioned that some of the developments seen in the scenario analyses are not quite realistic due to known limitations in the model. For example the use of electric HOBs in Sweden towards the end of the modelling periods in all scenarios, is likely to be overestimated. In the model this is used for peak load production, and while the electricity price in the model is constant over the entire year, in reality it is not. Instead, since both the electricity demand and the heat demand are affected by factors such as outside temperature, the electricity price is generally higher during the winter, when peaks in the heat demand occur. This effect could be captured in the model by specifying different electricity prices in different time slices, but that has not been attempted in this project.

It has also been assumed that there is no significant development of DH production technologies during the modelled period, apart from small improvements in the efficiency and heat-to-power ratio. However, in terms of technological change in DH production the years remaining until 2050 is not such a long time and most investment decisions in the model are taken much earlier in the period.

Finally it can be seen that although the results clearly differs between the scenarios, the results for the reference scenario indicate that the policies currently in place could also lead to more renewable district heat production than today. The coal and natural gas used in Finland and Denmark is largely phased out without new policies being implemented. This also means that the drop in electricity production may become a challenge even if current policies are not strengthened in the future.

7 Conclusions

In this thesis, the district heating systems in Sweden, Finland, and Denmark have been mapped. For each country a number of type systems, representing classes of existing systems, have been designed. The type systems together describe, to a large extent, the current district heating production systems in the three countries. The constructed type system representations have then been used to build a computer-based cost-minimising model of the future developments of the national production mixes, using the TIMES model generator. Using the model, three future scenarios have been analysed.

The current production mixes in the three countries differ substantially. Sweden has a district heating system that is dominated by biofuels and waste incineration, but with a relatively low share of combined heat and power generation. Both Finland and Denmark currently generates more than half of their district heat from the fossil fuels natural gas and coal, with a much larger percentage being cogenerated with electricity. It can be concluded that the type system descriptions of the current district heating systems provide a diversified picture of the composition of the national district heat production mix. Small systems can represent significant shares of the total national production mix in a country.

The future developments of these smaller systems can also differ considerably from that of a larger system, as is demonstrated by the model results. This can be difficult to capture in an aggregated model and shows the usefulness of the modelling approach taken in this project.

Both the scenarios, which are designed to represent future developments with strong incentives for reduction in emissions of greenhouse gases, show that the share of renewable fuels in DH production does increase. However, the decreased demand demonstrated in the Regional Policy scenario, may lead to complications. In Sweden there may be problems in utilising the generated heat from disposing of waste through incineration. In Denmark and Finland the decreased demand for district heat, in combination with a shift in the energy sources used for heat production, can lead to a significantly decreased electricity production from cogeneration with heat. This may have very noticeable effects on the electricity supply systems in these countries.

The Climate Market scenario leads to higher shares of fossil fuels remaining longer in the production mixes of Finland and Denmark, but reduces the drop in electricity production over the modelled period.

Interesting aspects to study further would for example be to investigate what would be the locally cost-minimising solution, for the futures described in the three scenarios, for actual systems corresponding to the modelled type systems. A comparison with the model results in this project could certainly deepen the understanding of how to interpret them. It would also be interesting to couple the model used in this project, with its fairly detailed description of the national district heating systems, to a model including the electricity supply systems in, primarily, Denmark and Finland. How the cost-minimising solution for district heating would have to change when an electricity demand also has to be met, would be of great interest to better understand the results in this thesis.

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Appendix A Calculation of taxed fuels in CHP

In all three countries, fuels for electricity production are exempted from taxes. However, the methods to allocate fuels to heat (taxed fuels) differ between countries. This section describes the methods used in Sweden, Finland, and Denmark respectively. Fuel amounts are measured in terms of their energy content.

A.1 Sweden

In Sweden the fuels are allocated according to the ratio of produced heat and electric energy. This means that the amount of fuels taxed as heat fuel will be the total amount multiplied by the factor E_h/E_{tot}, where E_h is the net produced heat energy and E_{tot}, is the net total produced energy, both heat and electricity. The factor can also be written $1/(1+\alpha)$, where $\alpha = E_{elec}/E_h$. E_{elec}, is the net produced electric energy. (Notisums Lagbok, 2011)

A.2 Finland

In Finland the amount of heat fuel is simply determined by assuming an efficiency of $1/0.9 \approx 1.11$ for heat production, which means that with the same notation as above the fuel for heat production is $E_h \cdot 0.9$. (Finlex, 2012a)

A.3 Denmark

In Denmark the fuel allocated to heat production is chosen as the minimum of two alternatives referred to as the E and V formulas. With the fuel for heat production denoted x_h and the total amount of fuel denoted x_{tot}, the E formula is defined as

$$x_h = x_{tot} - \frac{E_{elec}}{0.67} ,$$

which is the same as assuming an electricity efficiency of 0.67, and allocating the remainder of the fuel to heat production. The alternative, or the V formula, instead assumes an efficiency of the heat production of 1.2, and is defined as

$$x_h = \frac{E_h}{1.2} .$$

For plants with low electric efficiency and a low α, such as biomass CHP plants, the second alternative is usually beneficial. The first alternative is common for plants with high electric efficiency and a high α, such as natural gas CHP plants. (Tang, 2010)

Appendix B Type system results

B.1 Reference scenario

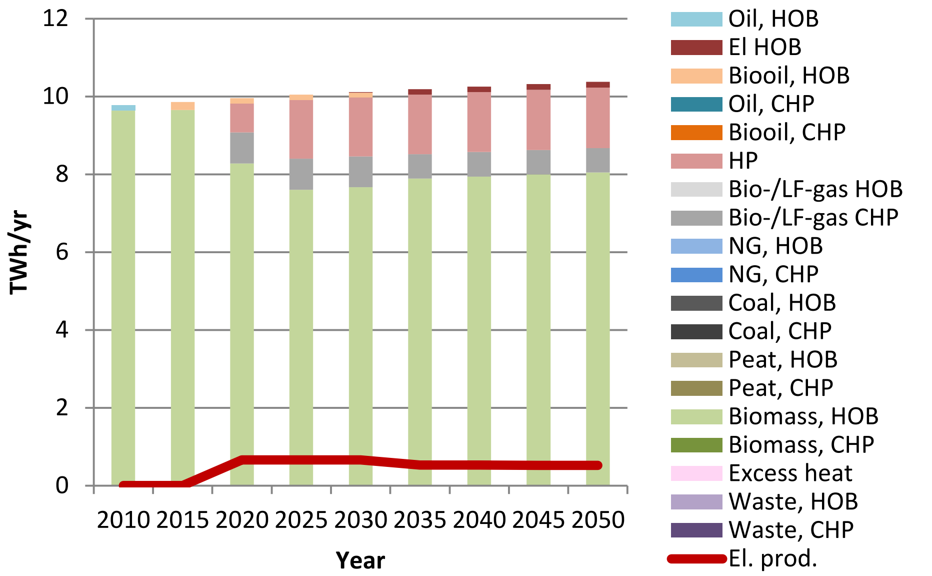

Figure 21: Production mix development for type system A in Sweden in the Reference scenario.

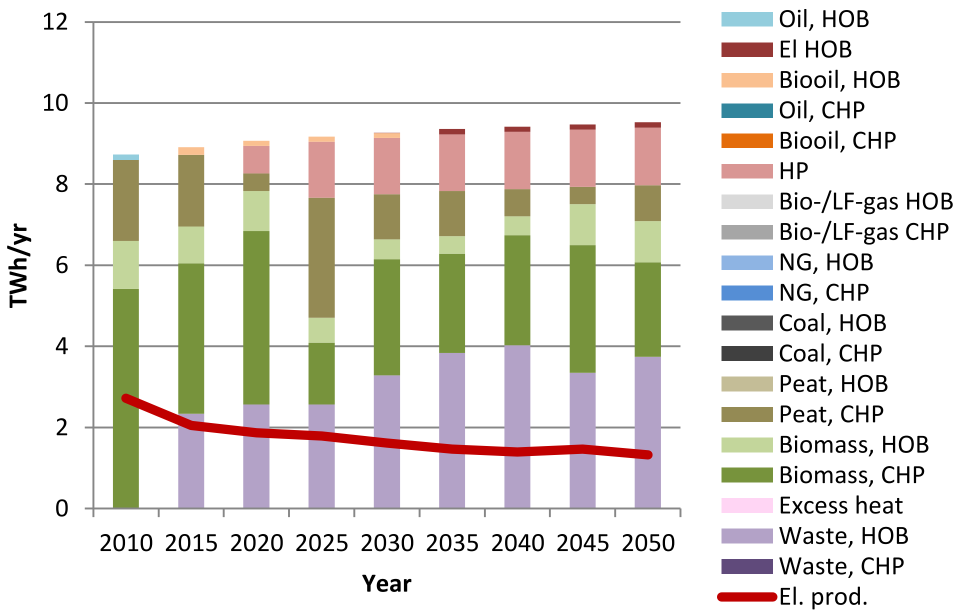

Figure 22: Production mix development for type system B in Sweden in the Reference scenario.

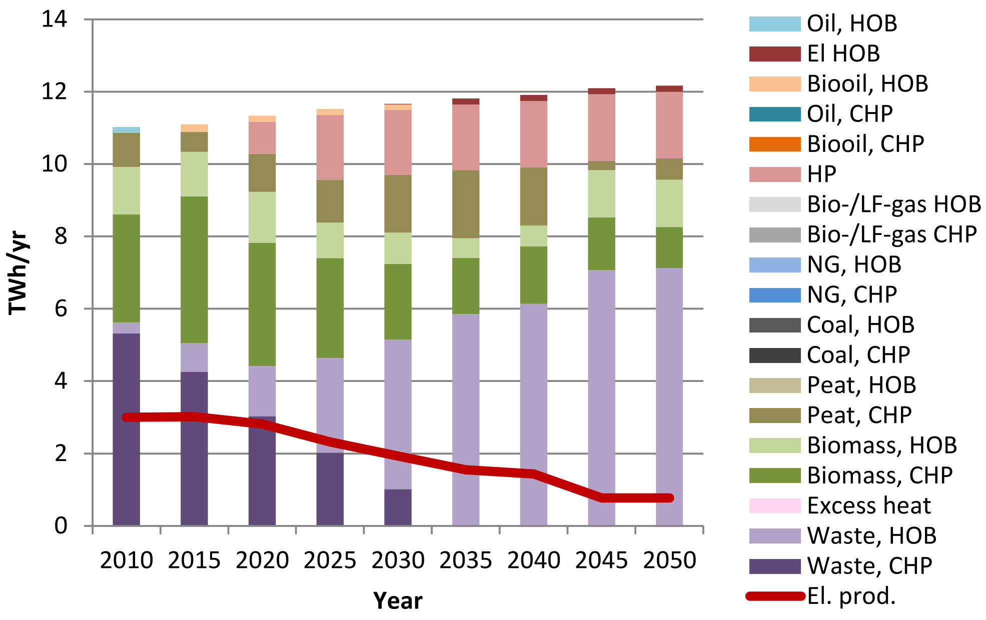

Figure 23: Production mix development for type system C in Sweden in the Reference scenario.

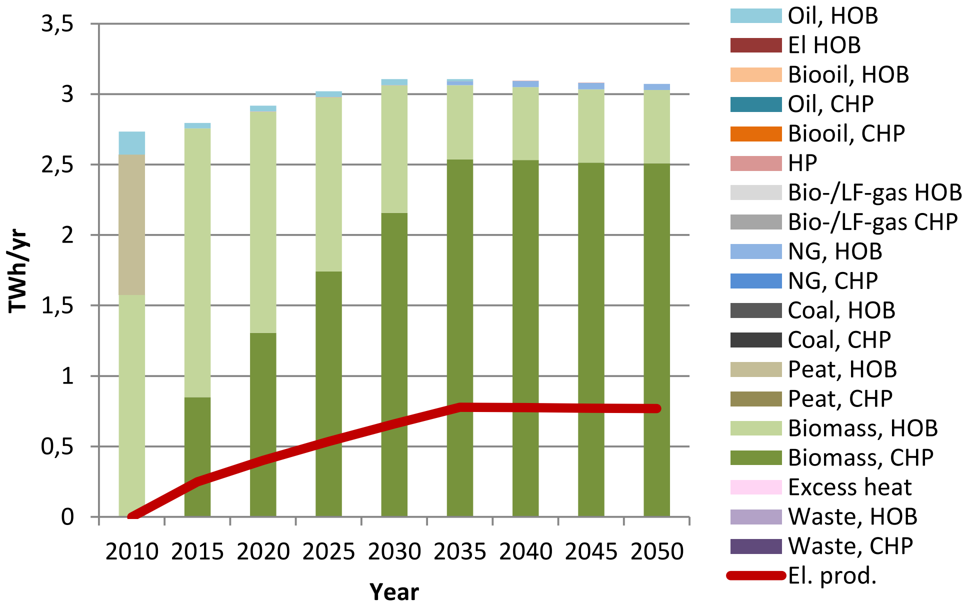

Figure 24: Production mix development for type system A in Finland in the Reference scenario.

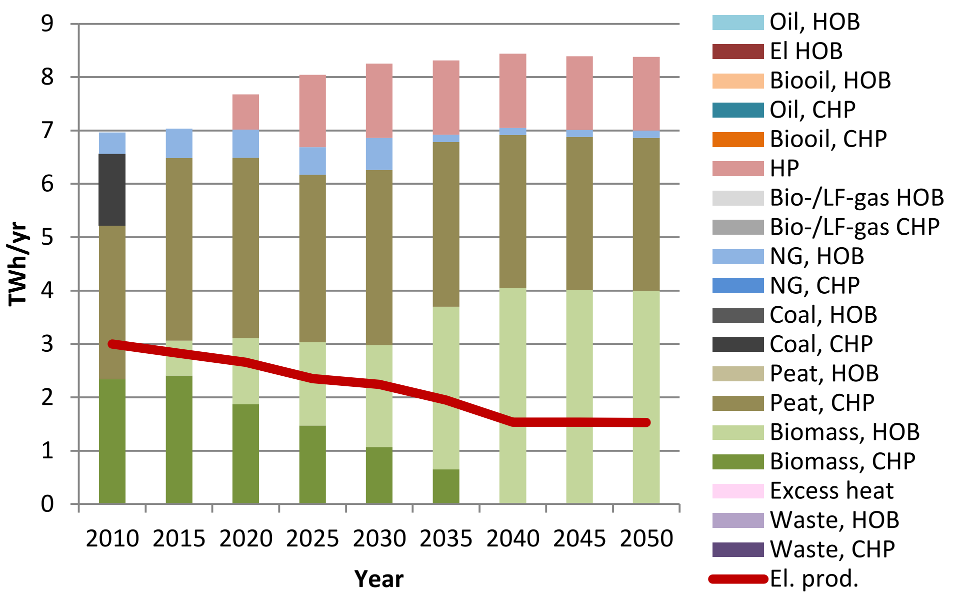

Figure 25: Production mix development for type system C in Finland in the Reference scenario.

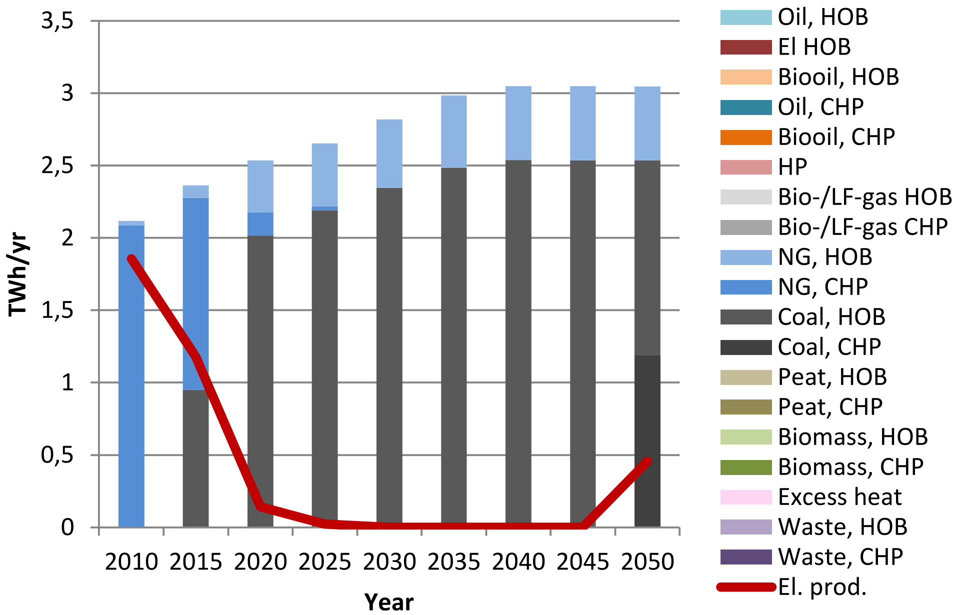

Figure 26: Production mix development for type system C in Denmark in the Reference scenario.

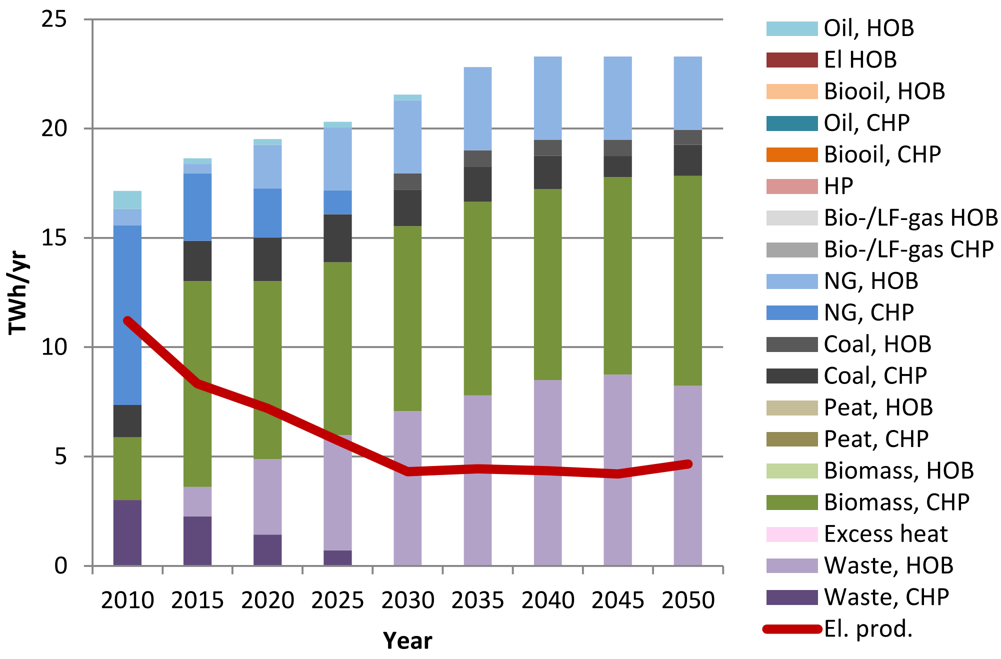

Figure 27: Production mix development for type system D in Denmark in the Reference scenario.

B.2 Regional Policy scenario

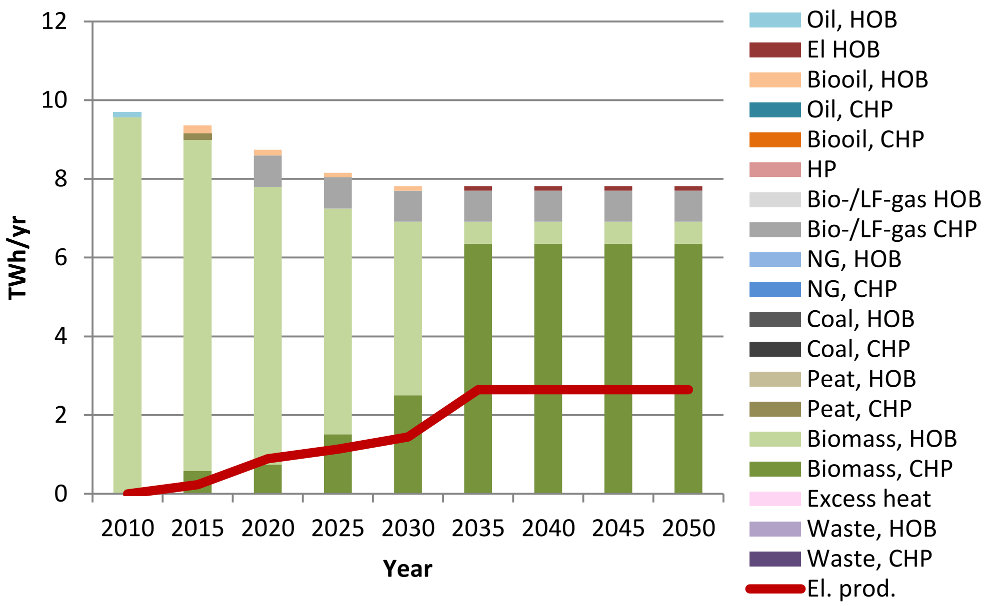

Figure 28: Production mix development for type system A in Sweden in the Regional Policy scenario.

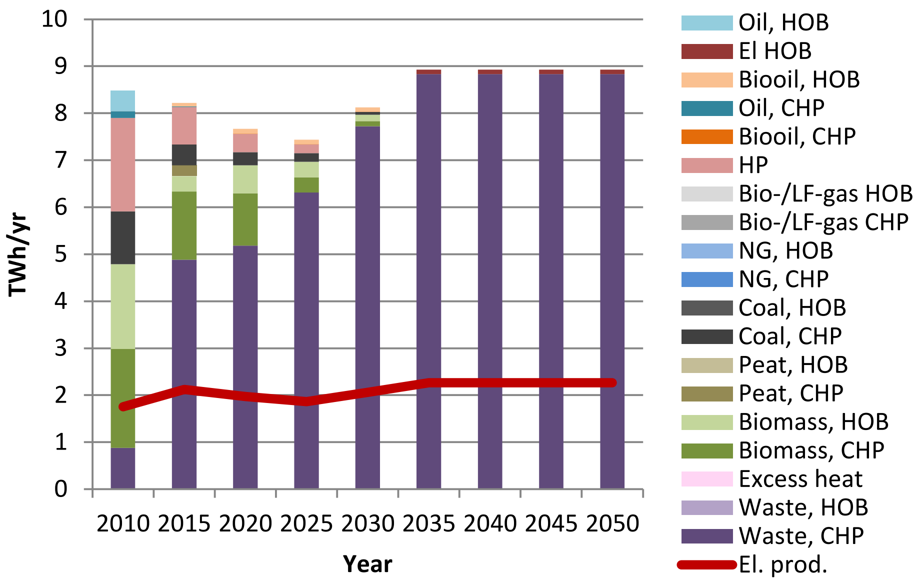

Figure 29: Production mix development for type system E in Sweden in the Regional Policy scenario.

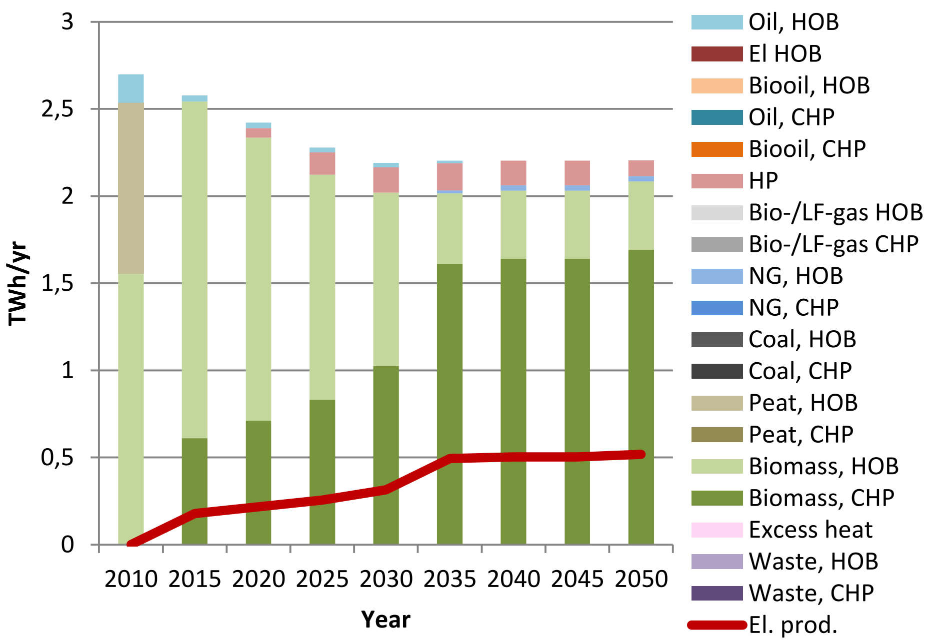

Figure 30: Production mix development for type system A in Finland in the Regional Policy scenario.

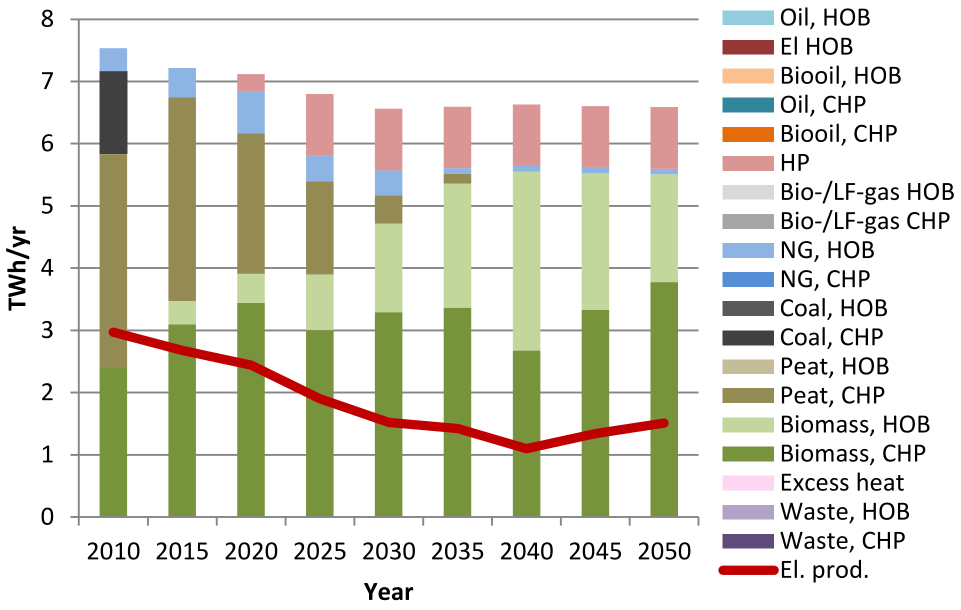

Figure 31: Production mix development for type system C in Finland in the Regional Policy scenario.

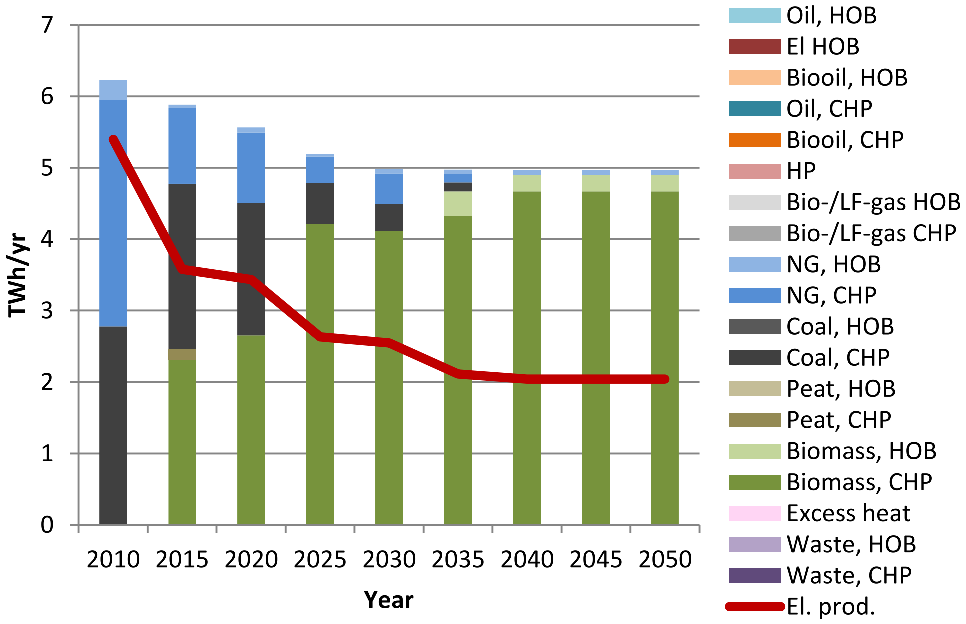

Figure 32: Production mix development for type system D in Finland in the Regional Policy scenario.

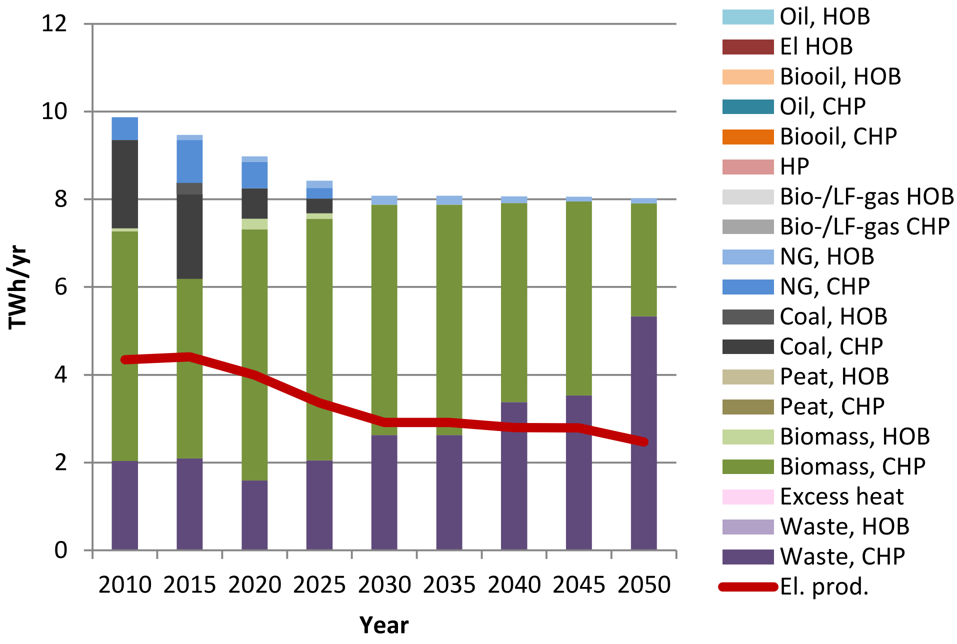

Figure 33: Production mix development for type system A in Finland in the Regional Policy scenario.

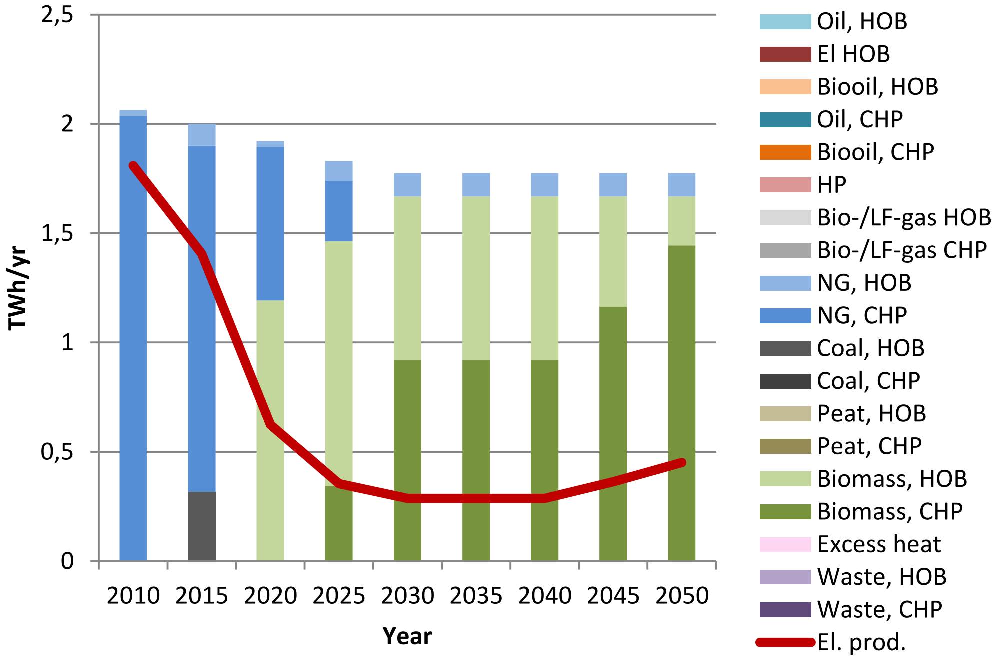

Figure 34: Production mix development for type system C in Denmark in the Regional Policy scenario.

B.3 Climate Market scenario

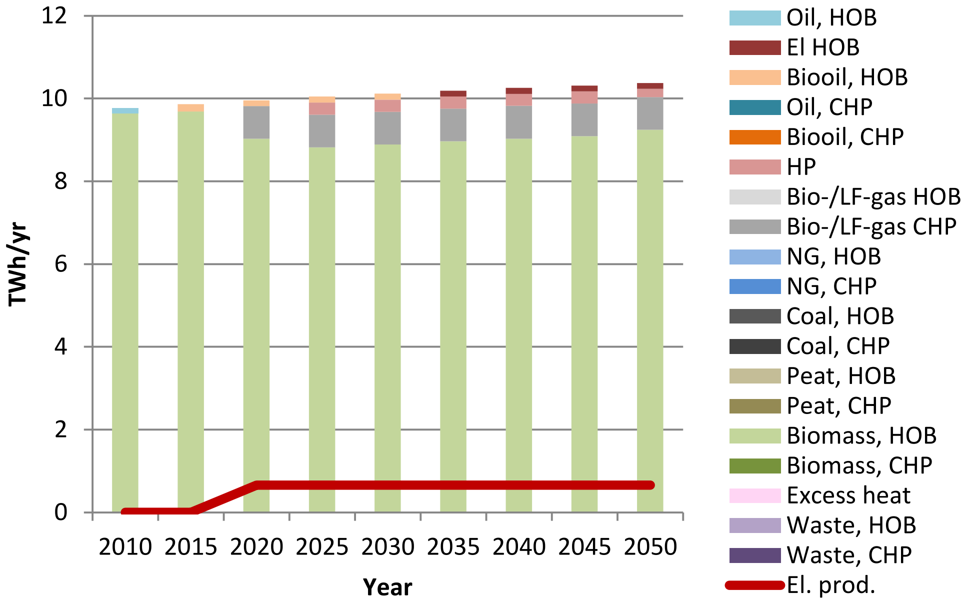

Figure 35: Production mix development for type system A in Sweden in the Climate Market scenario.

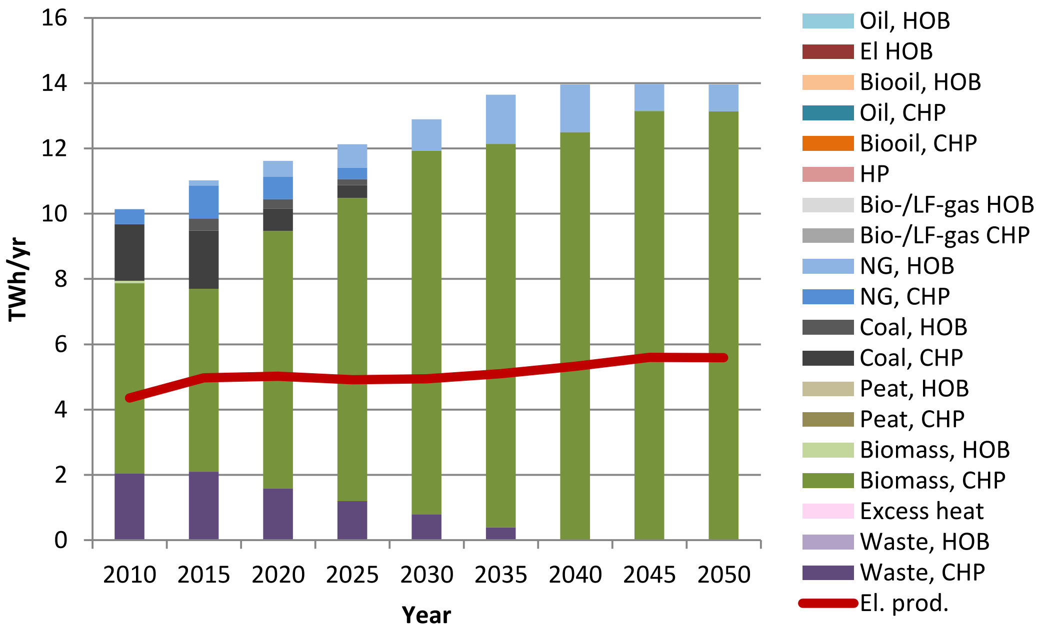

Figure 36: Production mix development for type system A in Denmark in the Climate Market scenario.

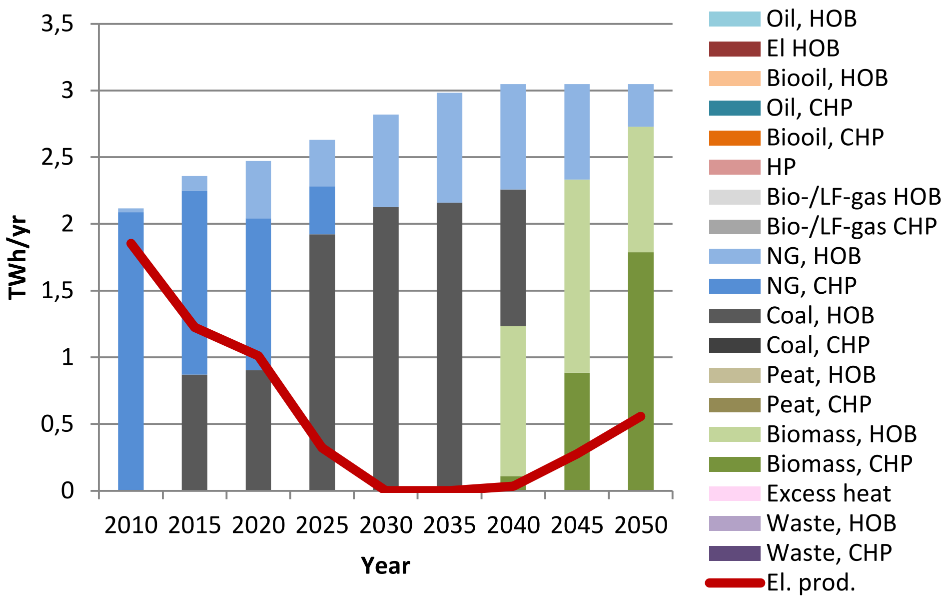

Figure 37: Production mix development for type system C in Denmark in the Climate Market scenario.