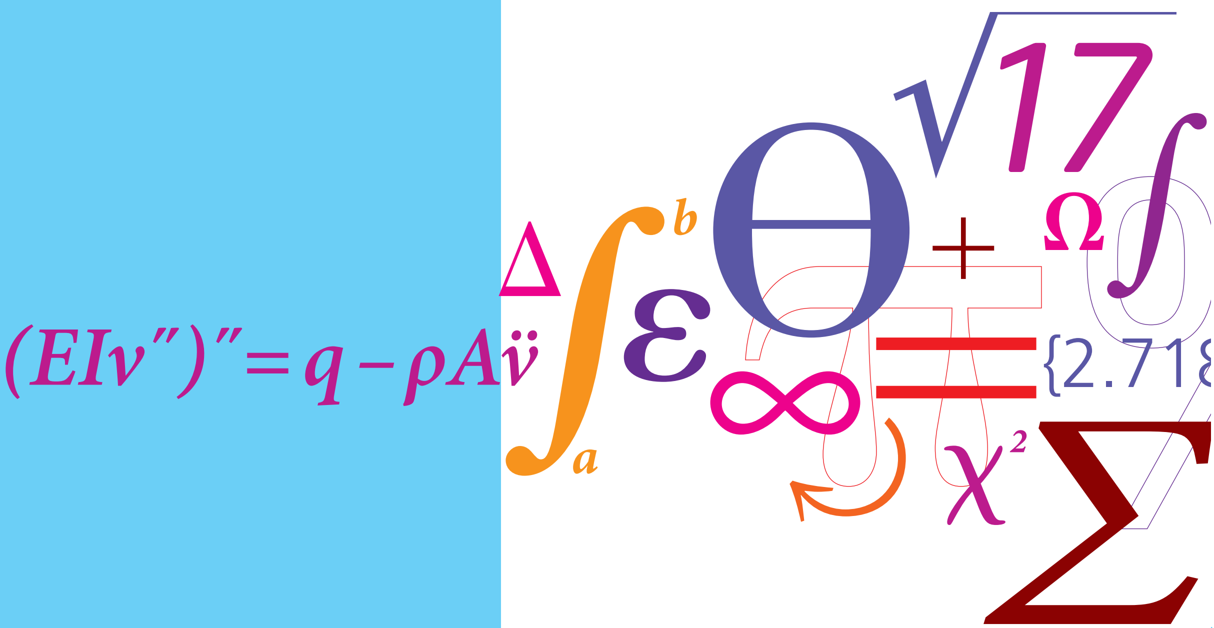
Integration of Heat Pumps in Greater Copenhagen

Master Thesis



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Remarks

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Abstract

The municipality of Copenhagen has the ambitious goal of becoming the first CO_2 neutral capital before 2025. Using large heat pumps for district heat production in Copenhagen can contribute to a more effective way of producing heat in the future, and thereby help to fulfil the goal of CO_2 neutrality. At the same time heat pumps can be an important player in the integration of the fluctuating electricity production from renewable energy sources, and relieve the pressure on the limited biomass resources. This study analyses the technical and economical aspects of integrating heat pumps in the Greater Copenhagen district heating system. Three main aspects of heat pump integration have been investigated: (I) the potential sources, (II) the feasible heat pump technologies, and (III) the economical competitiveness of heat pumps in the district heating system.

The analyses of the heat sources were based upon gathered data on temperatures, flows, hydrography, and locations, as well as considering the technical and economical challenges. The thermodynamic modelling of heat pumps were done in EES. And in this study an auxiliary program, COPcalc, for calculations of seasonal variations in COP and capacities of heat pumps was developed. The output from COPcalc is a COP and capacity profile, which can be implemented in the energy system optimization model Balmorel. The Balmorel model was developed further to make a better representation of heat pumps, for analysing the seasonal variations of COP, and to be enable to represent heat pumps connected on the distribution grid.

The natural heat sources investigated were; sewage water, sea water, drinking water, ground water, air, and ground. The most promising sources for the Copenhagen system were found to be sewage, drinking, and sea water. It is found that total of around 87 MW_{th} could be connected to sewage water facilities, and around 13 MW_{th} could be connected to drinking water facilities. The sea water potential was found to be practically infinite, but there was found to be some challenges with depths, pumping, piping, and freezing of water. From analyses of the demand in the near coast distribution areas it was estimated that a total capacity of 160 MW_{th} of sea water heat pump could be implemented in the system. The potential of sea water as heat source was found to be highly dependent on the hydrography of the system analysed.

The current most suitable heat pump technology for the district heating system, was found to be an ammonia two-stage compression heat pump, heating the district heating water in a tandem system. The operational calculations of such a heat pump connected to the distribution grid yields a COP of around 2.8 to 3.1 in winter time, and a COP of 3.2 to 3.6 in the summer time, depending on the source. Connecting the heat pumps to the transmission grid gives a much lower COP of around 2.5 in winter time and 2.9 in summer time, for all sources.

Using Balmorel to analyse the competitiveness of a total 260 MW_{th} heat pump capacity distributed onto the district heating system, yields around 3500 full load hours for the heat pumps connected to the distribution grids in 2013, and around 4000 full load hours in 2025.

When connected to the transmission grid the number decreases by around 1000 full load hours for both years. The poor competitiveness when connected to the transmission grid was found to be caused by the lower COP. The heat pumps mainly displace production at peak load in winter time, and heat production by combined heat and power plants in summer time. Based on the 3500 full load hours the integration of especially sewage water and drinking water heat pumps was found to be economical feasible already today, if connected to the distribution grid.

The study concludes that implementation of heat pumps directly to the distribution grids in larger cities in Denmark is private economical feasible using the Danish taxation legislation from 2013.

Preface

This master thesis is the final project of Bjarne Bach on the master study program Sustainable Energy at the Technical University of Denmark (DTU). The project is carried out at DTU Mechanical Engineering, in cooperation with DTU Management Engineering and the consultant firm Ea Energy Analyses A/S.

This thesis consist of a significant amount of coloured figures, it is therefore recommended to be read in a coloured version.

Acknowledgements

A number of persons have supervised, helped, and assisted me throughout this project. Persons I would like to acknowledge for their part in this thesis are listed below with an explanation of what they participated with. First are my four supervisors listed, and thereafter people are listed by first name in alphabetic order.

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For supervision with the thermodynamic models and guidance during the project.

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Contents

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Nomenclature

General Notations

In this thesis a number of locations and power plants will be mentioned. The Danish names for all of these are used (e.g. Amagerværket and Sjælland)[1].

The units of heat (thermal) and electricity generation capacity are MW_{th} and MW_{e}, respectively. For total heat production and consumption the energy units MWh_{th} or PJ will be used. For electricity production and consumption the energy unit MWh_{e} will be used.

In some chapters a notation like for example $Q10/C3/T4$ will be used. This may refer to a heat pump with a capacity of $\dot{Q}_{hp} = 10$ MW_{th}, a COP of 3, and an utilization of the source of $\Delta T_{source} = 4$°C.

Explanation of the scenario abbreviations (REF, FCOP, VCOP_DIS, VCOP_TRANS) are given on page 77.

Symbols used in Thermodynamic Modelling

A	Area [m^2]
C_b	C_b coefficient of CHP plant (see Figure 13.3)
C_v	C_v coefficient of CHP plant (see Figure 13.3)
c_p	Heat capacity at constant pressure [kJ/(kg K)]
D	Diameter [m]
E	Electric energy [MJ]
η	Efficiency [-]
f_D	Darcy friction factor [-]
g	Acceleration due to gravity [m/s^2]
H	Head [m]
κ	Specific heat ration [-]
L	Length [m]
$\dot{m}$	Mass flow [kg/s]
μ	Dynamic viscosity [Pa s]
p	Pressure [bar]
π_{bi}	Built in pressure ration
Δp	Pressure difference [bar]
Q	Thermal energy [MJ]

[1]Only exception is the location Copenhagen (København), where the international name is used.

$\dot{Q}$	Thermal capacity [MW_{th}]
ρ	Density [kg/m^3]
T	Temperature [°C]
ΔT	Temperature difference [°C or K]
UA	Value explaining heat transfer coefficient and area [kW/K]
$\dot{V}$	Volume flow [m^3/h]
v	Velocity [m/s]
v_{bi}	Built in volume ratio [-]
x	Vapour quality [-]
$\dot{W}$	Electric power [MW_e]

Notations used in Mathematical Modelling

Sets

a	Areas
c	Countries
e	Emissions (e.g. CO_2, SO_2 and NO_x)
f	Fuel types
g	Generation technologies
r	Regions
t	Time periods (include both year, season and timesteps)
$\mathbb{A}_x$	Subset of areas a containing all exporting areas of a
$\mathbb{A}_c$	Subset of areas a in country c
$\mathbb{A}_r$	Subset of areas a in region r
$\mathbb{G}^{th.}$	Subset of g including all thermal generation technologies
$\mathbb{G}^{e.h.}$	Subset of g including all electric heaters and heat pumps
$\mathbb{R}_x$	Subset of regions including all exporting regions of r

Parameters

$C^{fuel}_{a,f}$	Cost of fuel f in area a [DKK/MWh]
$C^{om,v.}_{a,g}$	Cost of variable O&M for generation technology g in area a [DKK/MWh]
$C^{om,f.}_{a,g}$	Cost of fixed O&M for generation technology g in area a [DKK/MW]
$C^{trans.,el.}_{r_1,r_2}$	Cost of electricity transmission between region r_1 and r_2 [DKK/MWh]
$C^{tax,em.}_{c,e}$	Cost of tax for emission e in the country c [DKK/kg]
$C^{tax,fuel}_{c,f}$	Cost of tax on fuel f in country c [DKK/MWh]
$D^{el.}_{a,t}$	Demand electricity in region r to time period t [MWh]
$D^{heat}_{a,t}$	Demand heat in area a to time period t [MWh]
$E_{g,e}$	Emission factor on emission e for generation technology g [kg/MWh]
$G^{cap.}_{a,g}$	Generation capacity of generation technology g in area a [MW]
$L^{trans.,el.}_{r_1,r_2}$	Limit of transmission capacity between region r_1 and r_2 [MW]
Z_g	$\begin{cases} C_v & \text{for extraction} \\ 1 & \text{other} \end{cases}$
$\eta^{gen.}_g$	Fuel efficiency of generation technology g (see Table 13.1) [-]
$\eta^{trans.,el.}_{r_1,r_2}$	Transmission connection efficiency (derate factor) [-]

Variables

$V^{con.,fuel}_{a,g,t}$	Fuel consumption of generation technology g in area a to time t [MWh]
$D^{dem.,el.}_{a,g,t}$	Demand electricity of technology g in area a to time period t [MWh]

$V^{\text{gen.,el.}}_{a,g,t}$	Electric generation of generation technology g in area a to time t [MWh]
$V^{\text{gen.,heat}}_{a,g,t}$	Heat generation of generation technology g in area a to time t [MWh]
$V^{\text{trans.,el.}}_{r_1,r_2,t}$	Electricity transmission between region r_1 and r_2 to time t [MWh]

Abbreviations

Technical abbreviations

COP	Coefficient of performance [-]
COP^*	Coefficient of performance weighted by demand [-]
COP_t	Coefficient of performance in time period t [-]
FLH	Full load hours
NPSH_A	Available net positive suction head [m]
NPSH_R	Required net positive suction head [m]
SPF	Seasonal performance factor (i.e. COP weighted by production) [-]

Areas

CAML	Amagerland
CHUS	Brønshøj/Husum/Vanløse
COST	Østerbro
CNOR	Gladsaxe/Gentofte
CMID	Frederiksberg/Nørrebro
CTAR	Tårnby
CVAL	Valby
DHCV	Steam Centrum
DSMV	Steam Østerbro
KONN	Converting area North (Østerbro)
KONS	Converting area South (Centrum)
NORDHAVN	Nordhavn
VESTERBRO	Vesterbro
VEKV	Roskilde/Hedehusene/Taastrup
VEKN	Hvidovre/Glostrup/Albertslund
VF	Herlev/Ballerup

Generation units

ARC	Amager Ressource Center (waste-to-energy)
AMV1	Amagerværket CHP plant unit 1
AMV3	Amagerværket CHP plant unit 3
AMV-VAK	Heat accumulator at AMV
AVV1	Avedøreværket CHP plant unit 1
AVV2	Avedøreværket CHP plant unit 2
AVV-VAK	Heat accumulator at AVV
GEO	Geothermal plant
HCV	H.C. Ørsted CHP plant
KARA	KARA/NOVEREN (waste-to-energy)
KKV	Køge CHP plant
PL	Peak load boiler
RLF	Lynetten incineration plant
SMV	Svanemølleværket CHP plant

VF	Vestforbrænding (waste-to-energy)

Subscripts

air	Air
Carnot	Carnot cycle
com	Compressor
con	Condenser
design	Design phase
dh	District heating
drink	Drinking water
eva	Evaporator
FL	Full load
for	Forward water
fric	Friction
high	Hot reservoir
hp	Heat pump
hs	Heat source
hx	Heat exchanger
in	Input or inlet
int	Intermediate
is	Isentropic
low	Cold reservoir
lm	Logarithmic mean
out	Output or outlet
pinch	Pinch point
pump	Pump
ret	Return water
source	Heat source
sea	Sea water
sew	Sewage water
surf	Surface
water	Water

Introduction

1 Background

In the future biomass and wind are expected to play the mayor roles in the Danish energy system. But most experts claim that the biomass resources have to be prioritized to the parts of the transport sector that can not easily be converted to electricity, such as aviation and ships. A consequence of this is that electricity and heat have to be generated from other renewable sources. Wind, photovoltaic, and higher capacities of electricity transmission to Denmark's neighbouring countries could solve the electricity challenge. The heat challenge could to be solved by converting electricity into heat. Here heat pumps are expected to play the most important part.

In this context it seemed very sensible that the Danish parliament's energy agreement of 2012 allocated DKK 35 mill. to support the promotion of new renewable energy technologies, such as large heat pumps[29]. From this money pool have so far been conducted a report on 'Investigation on heat storage technologies and large heat pumps for use in district heating systems' by PlanEnergi, DTI, GEO and Grøn Energi for the Danish Energy Agency[99]. And a new project, concerning a manual for implementing large heat pumps in district heating systems, has been put out to tender this exact month (March 2014)[26].

The City Council of Copenhagen agreed in 2013 on a climate plan making Copenhagen the first CO_2 neutral capital in 2025[18]. Their road map goal is to make the district heating CO_2 neutral in 2025. This is done by using biomass on the CHP plants and by implementing "new heating producing units in Copenhagen"[18, p. 16]. Later they write that; "The municipality of Copenhagen will investigate the basis for using large heat pumps in the district heating network to equalize the total energy balance"[18, p. 37].

Connecting heat pumps to district heating systems has strong political support, but there are, of course, a lot of challenges by implementing a new and rather immature technology to a large and complex district heating system. This thesis will study some of these challenges, by investigating how to implement heat pumps in the district heating system of Greater Copenhagen.

1.1 This Thesis

The aim of this study is to determine how heat pumps can be implemented in the district heating system of the Greater Copenhagen area. The three main key words are; source, technology, and impact. 'Source' refers to the potential heat sources in and near Copenhagen. Where are they and how big is the potential? 'Technology' refers to the actual heat pumps. What kind of heat pumps cycles, refrigerants, and components can be used? How will their performance be? 'Impact' refers to the impact the implementation of heat pumps will have on the district heat system. Compared with the other plants are the heat pumps then competitive?

To study the integration of heat pumps in the district heating system of Copenhagen three main aspects be will investigated;

I. Location and potential of the heat sources
To find technical feasible locations for heat pumps, the potential heat sources in the Greater Copenhagen area will be investigated. These sources will not only determine the locations, but also the feasible sizes of future heat pumps. This study will be based in data analyses and thermodynamic estimations, and will be described in Part I Potential Heat Sources in the Copenhagen Area on page 11.

II. Feasible technologies
After finding the potential heat sources, the applicable heat pump technologies will investigated. There exist a number of different technologies with different cycles, refrigerant, and components. This part of the study will be based on thermodynamic modelling, and will determine operational parameters of the heat pumps, such as the seasonal coefficient of performances (COP) and capacities. This part will be described in Part II Thermodynamic Modelling of Heat Pump Technologies on page 33.

III. Impact on the district heating system
With the heat pump sizes and technical operation parameters (COP and capacity) found from the two previous investigations, the competitiveness of heat pumps in the district heating system will be analysed. It will be determined how competitive the heat pumps are when connected to the distribution grid vs. transmission grid, by measurement of the full load hours of the heat pumps. This part of the study will be done by making a better representation of heat pumps in the mathematical optimisation model Balmorel. This part will be described in Part III Modelling of the District Heating Network of Copenhagen on page 61.

2

The District Heating System of the Greater Copenhagen Area

This chapter will give a brief introduction to the district heating system of the Greater Copenhagen area. The district heating network of Greater Copenhagen is covering a huge area, as shown in Figure 2.1. The network is shared by four suppliers; CTR, VEKS, HOFOR, and Vestforbrænding (VF). In Figure 2.1 the companies' supply areas are shown. In central Copenhagen (HOFOR and CTR) 98% of all consumers use district heating as their heat supply[50].

The network consists of a number of distribution areas supplying the individual households with heat. The transmission grid (shown in Figure 2.1) is supplying heat to heat exchangers in these distribution areas from the producers (e.g. CHP plants). CTR, VEKS and HOFOR cooperate in Varmelast.dk to ensure that the load of the CHP plants in the metropolitan area are distributed by a global economic optimization[117]. The prioritization is:

1. Waste to energy technologies
2. Geothermal
3. CHP
4. Heat storage
5. Peak load stations

The generation plants and storages of Copenhagen in 2013 are shown in Table 2.1. In Figure 2.2 the heat duration curve of Greater Copenhagen in 2012 is shown. The peak load of the system in 2.5 GW_{th}. The total heat demand was in 2012 35 PJ or 9.7 TWh_{th}.

The forward temperature in the distribution grid depends on the demand of heat, and therefore it changes during the year. Figure 2.3 shows the forward temperatures dependency on the ambient temperature. The return water must at least be 55°C to minimize the risk of legionella[66].

HOFOR owns and operate the steam areas in the municipality of Copenhagen. HOFOR is slowly converting the steam based district heating to water based. They expect to be done by 2025. Steam systems were built to supply high temperature district heating to energy intensive industries, which over the years have been moved outside the city area[65].

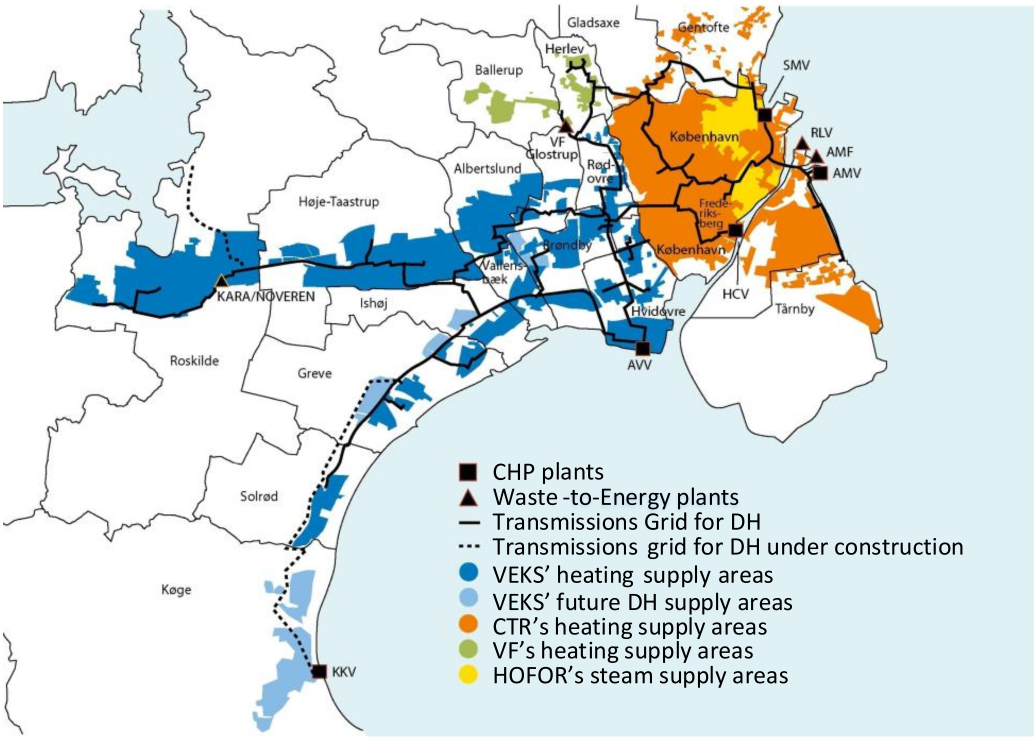

Figure 2.1: Map of the district heating network of the Greater Copenhagen area. (Map is from Sannah Grüner, HOFOR)

Table 2.1: District heating generation technologies in the Greater Copenhagen area.

Name	**Explanation**
ARC	Amager Ressource Center (waste-to-energy)
AMV1	Amagerværket CHP plant unit 1
AMV3	Amagerværket CHP plant unit 3
AMV-VAK	Heat accumulator at AMV
AVV1	Avedøreværket CHP plant unit 1
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VF	Vestforbrænding (waste-to-energy)

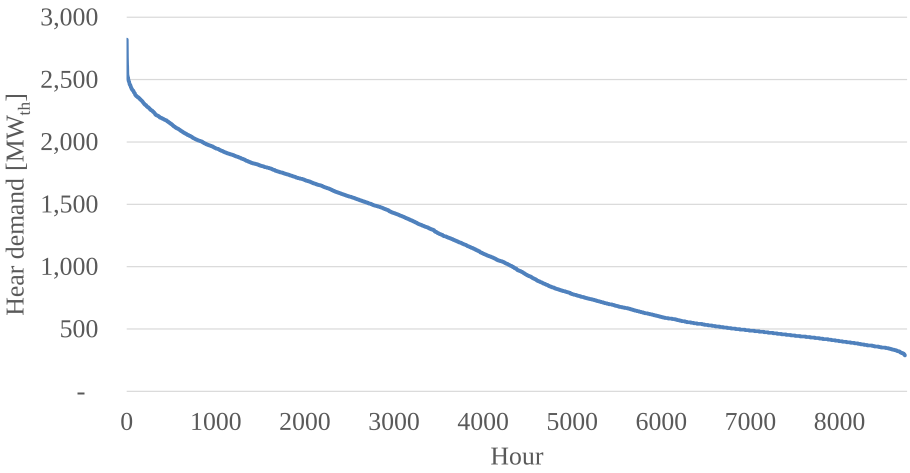


Figure 2.2: District heating duration curve of Greater Copenhagen.

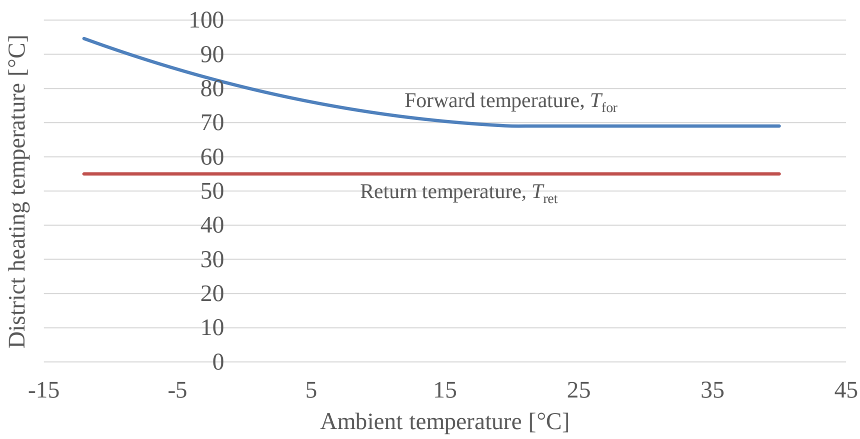


Figure 2.3: Requested temperature of the district heating forward and return water depending on the ambient (outdoor) temperature. (Data from Sannah Grüner, HOFOR[61])

3

Heat Pumps

A heat pump is a device that moves heat from a cold reservoir (source) to a hotter reservoir (sink) (see Figure 3.1). Basically it is the same as a refrigerator, with the only difference that the utilized product is the heat added to the hot reservoir instead of the heat removed from the cold reservoir. The *coefficient of performance* (COP) is defined as the ratio between the heat produced by the heat pump, $\dot{Q}_{\text{high}}$, and the compressor power, $\dot{W}_{\text{com}}$.

$$\text{COP} = \frac{\dot{Q}_{\text{high}}}{\dot{W}_{\text{com}}} \tag{3.1}$$

This coefficient is usually around 3[56], meaning that in a heat pump around 2/3 of the energy comes from the cold reservoir (source), and 1/3 is supplied by the compressor. According to the first law of thermodynamic the maximum COP possible (Carnot efficiency) is

$$\text{COP}_{\text{Carnot}} = \frac{T_{\text{high}}}{T_{\text{high}} - T_{\text{low}}}, \tag{3.2}$$

where T_{high} and T_{low} is the temperature (in Kelvin) of the hot and cold reservoir, respectively (see Figure 3.1). In practise a heat pump's COP is around 60% to 70% of the Carnot COP. The energy from the heat source can in most cases be considered as free, i.e. it is heat that is not used for anything else.

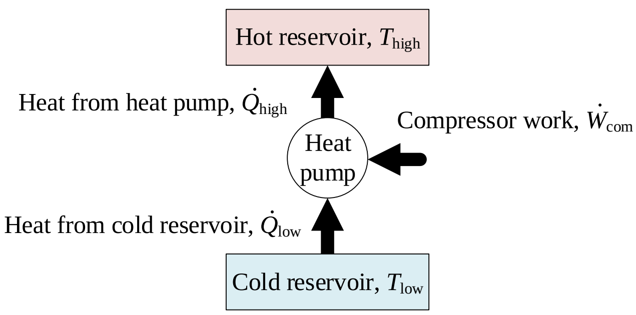


Figure 3.1: Principle sketch of a heat pump.

Because the heat pump uses electricity for heat production the price of a unit heat produced by a heat pump depends on the electricity price. A higher electricity price, yields a higher heat price. This is relevant when studying the district heating market and investigating what other units a heat pump have to compete with. The heat price of a heat-only boiler has no connection with the electricity prices, whereas the heat price of a CHP unit will be lower when the electricity price is high. This correlation between CHP units heat and electricity prices is governed by the specific contract between the CHP plants and the heat costumers, thus it is not a physical correlation governed by the thermodynamics of the plant. A principle sketch is shown in Figure 3.2.

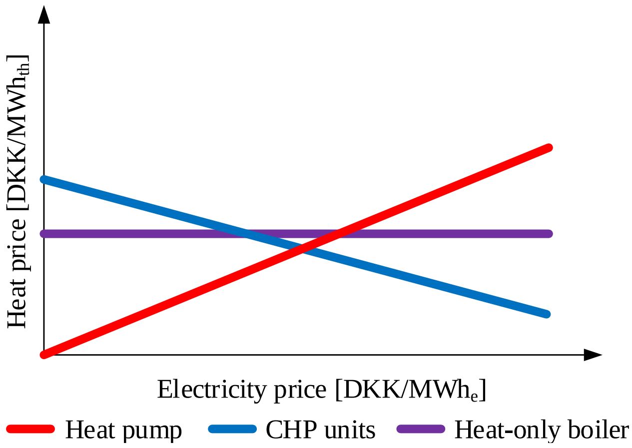


Figure 3.2: Sketch of the relation between electricity and heat prices for heat pumps, heat only boilers, and CHP plants.

3.1 Existing Heat Pumps Connected to District Heating Systems

Heat pumps are already used in a number of district heating systems. For decades Sweden has used heat pumps as part of the base load in its heating systems. Stockholm has a total of 420 MW_{th} heat pump capacity, utilizing heat from sea water, connected[52]. Since 1981 the Swedish town Sala has had a 3.3 MW_{th} heat pump, utilizing heat from sewage water, connected to their district heating network[81]. Some newer systems is the 14 MW_{th} ammonia heat pump in Drammen, Norway, using sea water as heat source. And the 1 MW_{th} CO_2 heat pump in Frederikshavn, Denmark, using sewage water[5, 109]. A brand new system has been built in Bjerringbro where waste heat from the pump company Grundfos is storage in a ground water reservoir in the summer time, and utilized in in three 1 MW_{th} ammonia heat pumps in the winter time[68].

Part I

Potential Heat Sources in the Copenhagen Area

4

Introduction to Heat Sources

Investigations of potential heat sources have been done on a general level in different studies. MacAller (2013)[85] made a study of the potential of heat recovery from drinking water. He showed that the amount of heat available in one of the large transport pipes of the Copenhagen network can heat around 10,000 homes. Frijns et al. (2013)[51] investigated the potentials of the domestic water as energy carrier. They estimate the potentials of the water in the states from ground water and surface water, to its final state as waste water (see Figure 4.1). An overall potential estimation for the whole of Denmark has been done by PlanEnergi in cooperation with Danish Technological Institute, GEO, and Grøn Energi[99].

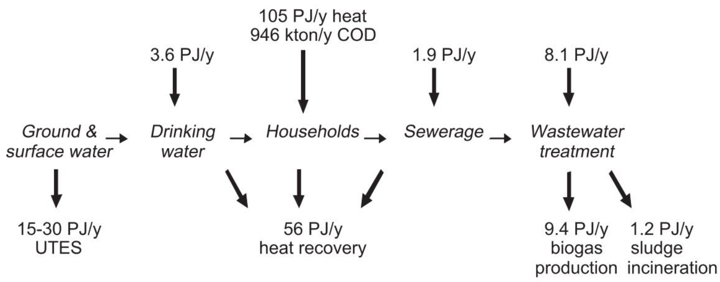


Figure 4.1: Schematic overview of the energy potentials of the Dutch municipal water sector from the paper by Frijns et al.[51]

In this part I will investigate the potentials of natural heat source that can be utilized in Copenhagen. By a natural heat source, is meant a sustainable source that is expected to be unchanged the next many decades. The investigation and evaluation will be built upon data, calculations, and estimation. In the last discussion chapter I will make recommendations and a prioritization list of heat sources.

5

Evaluation of Potential in Heat Sources

The following chapter concerns the potential heat sources in the Copenhagen area. The sources investigated are natural sources, i.e. not dependent on industries, other power plants or other human activities. This to ensure that they represent future sustainable heat sources, that do not depend on whether or not e.g. industrial production increases or decreases in Copenhagen. Overall the sources investigated are: air, ground and water, where the water sources investigated are sewage water, sea water, ground water and drinking water.

The calculations will be based upon winter operation, because a heat pump often will be constructed with the winter operation as its full load capacity[1]. Meaning, that the result on the specific investigation will be an estimation of the minimum heat pump capacity that it would be possible to apply to the specific heat source.

To estimate the heat (thermal) potentials in the source, $\dot{Q}_{\mathrm{source}}$, the equation

$$\dot{Q}_{\mathrm{source}} = \dot{m}_{\mathrm{source}} c_{\mathrm{p,source}} \Delta T_{\mathrm{source}} \tag{5.1}$$

is often used. Here $\dot{m}_{\mathrm{source}}$ is the mass flow of the source, $c_{\mathrm{p,source}}$ is the specific heat capacity of the source (e.g. air or water), and $\Delta T_{\mathrm{source}}$ is the temperature decrease of the source.

For some cases a heat pump are used for estimation of the feasibility of utilization. This heat pump has a certain capacity ($\dot{Q}_{\mathrm{hp}}$), COP, and temperature decrease of source ($\Delta T_{\mathrm{source}}$). For simplification the notation $Q\#/C\#/T\#$ is used, where # are the values of the capacity ($\mathrm{MW_{th}}$), COP, and temperature decrease (°C), respectively. For example does $Q10/C3/T4$, refer to a heat pump with a capacity of 10 $\mathrm{MW_{th}}$, a COP of 3, and the source is decreased by 4°C.

5.1 Sewage Water

Sewage water (or waste water) is actually not a natural source, but in reality it can be assumed as such. It will be save to assume that there still will be sewage water for the next many decades, if not centuries. Sewage water has been used as a heat source for larger heat pumps for decades, among others in Sweden, but has first resonantly been used as source in

[1]This will be more thoroughly explained in Part II about heat pump technologies.

a Danish system (the Frederikshavn project[5]).

The sewage water in Copenhagen is cleaned at two facilities, Lynetten and Damhusåen. As seen in Figure 5.1(a) the amount of sewage water does not change much over time. People use the same amount of water each year and the amount of rain is the same each year. The peaks in Figure 5.1(a) is caused by large rainstorms. The average daily flow on a monthly basis is shown in Figure 5.1(b). The daily flow fluctuate a bit over the year, which is mainly due to variation in the amount of rain fall. Looking at the daily flow over the week in Figure 5.1(c) it is seen, as expected, that peoples' consumption of water is equally distributed over the week and in a longer time frame (years) it rains equally throughout the week.

The temperature of the sewage water varies over the year. From around 11°C in the winter time to 20°C in summer time (see Figure 5.2). The cleaning process consists among other steps of a biological treatment[84]. This process needs a temperature above 10°C to run properly[72]. Due to the fact that the winter temperature of the water is around 11°C it is necessary to extract the heat after the biological tank; otherwise the biological process will stop.

According to operational manager of the heat pump at Frederikshavn Forsyning, Kim Arp[4], the best place for utilisation of the water is just after the clearing tank, which is just before letting the water out to the sea. The sewage water heat pump configuration in Sala, Sweden, is similar as it utilizes the heat just before outlet to the river[81]. The flow of water in and out of Damhusåen is shown in Figure 5.3. It shows that there is no storage of water in the tanks to regulate the outflow. Applying the same profile to Lynetten gives a minimum water flow for Lynetten of around 4500 m^2/h and for Damhusåen around 2000 m^2/h.

According to the executive order BEK 1433 on *environmental targets on streams, lakes, coastal waters, and ground water*, the change, caused by human interaction, in sea water near the coast have three acceptable ecological levels; high, good, and moderate[30]. The physical and chemical points of quality for these state depend on the temperature, oxygen balance and visibility depth (clarity). The limits are, according to a private conversation with Anne-Christine Duer[39] from the Ministry of Environment, defined and approved for each individual case by the Technical and Environmental Committee in the given municipality. How much it will be possible to decrease the water temperature will depend on this approval.

Cleaning facilities already discharge the clean water at the temperatures shown in Figure 5.2. In the winter periods this is much higher than the sea temperature. During winter the sea temperature near Copenhagen is around 0°C to 4°C, so a decrease of the sewage water to 2°C seems reasonable to get an approval of (i.e. $\Delta T_{\text{source}} \simeq 8$°C). This yields a $Q27/C3/T8$ heat pump at Damhusåen, and a $Q60/C3/T8$ heat pump as Lynetten.

5.2 Sea Water

Øresund is a very interesting seaway, both geographically, biologically and thermodynamically. The Baltic Sea is connected to Kattegat through Øresund, as well as the Great Belt and Little Belt. The Baltic Sea is fed with about 470 km^3 water from rivers in the east European countries. About 100 km^3 of these will leave through Øresund in a north going flow[95]. This flow spans from the surface to a depth of 10 m to 15 m. At the same time heavier salt water from Kattegat flows in to the Baltic Sea beneath this top layer. Therefore Øresund has a top layer of 10 m to 15 m depth of brackish water (salt level of 10‰ to 15‰) moving North and a bottom layer of salt water (salt level of 30‰ to 35‰) moving South[95]. Above and below this thermocline the salt level and temperature are very different from each other. The top layer has a temperature of 17°C to 20°C in the summer and 0°C to 4°C in

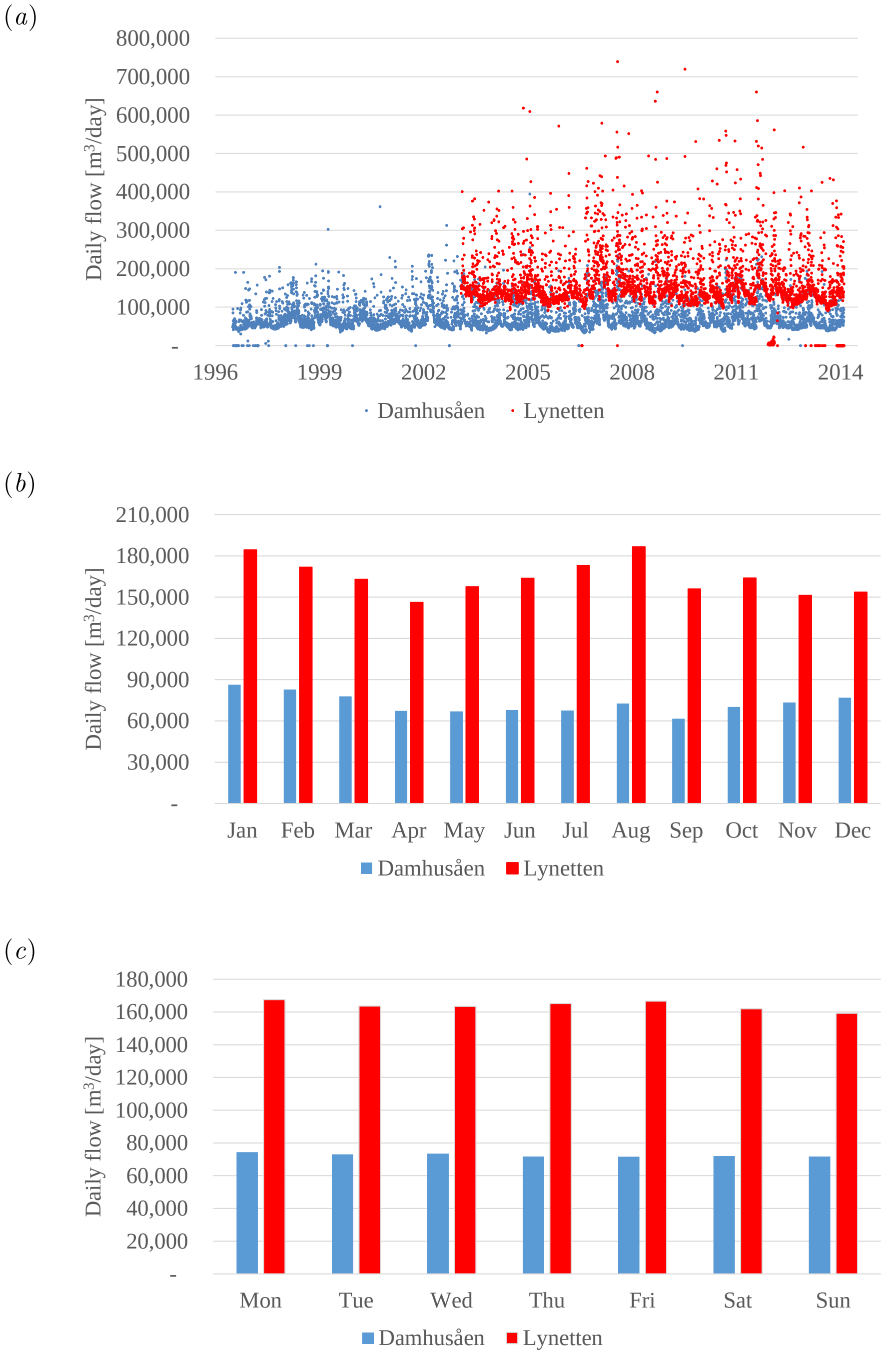


Figure 5.1: (*a*) The flow of sewage water into the cleaning facilities Lynetten and Damhusåen. (*b*) The monthly flow found from data from 1996 to 2013 for Damhusåen and from 2003 to 2013 for Lynetten[114]. The flow varies during the year, which is mainly do to rain (DMI rain statistics 2001-2010[28]). (*c*) The average daily flow taken over a period from 1996-2013. (Data from Dines Thornberg, Lynettefællesskabet[114])

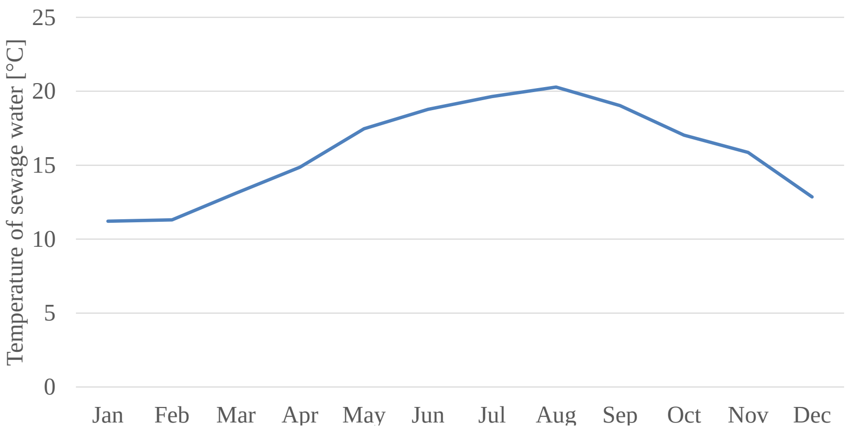


Figure 5.2: Average sewage water temperature at different months. The temperature is more or less constant during a week. (Data from Sannah Grüner[60])

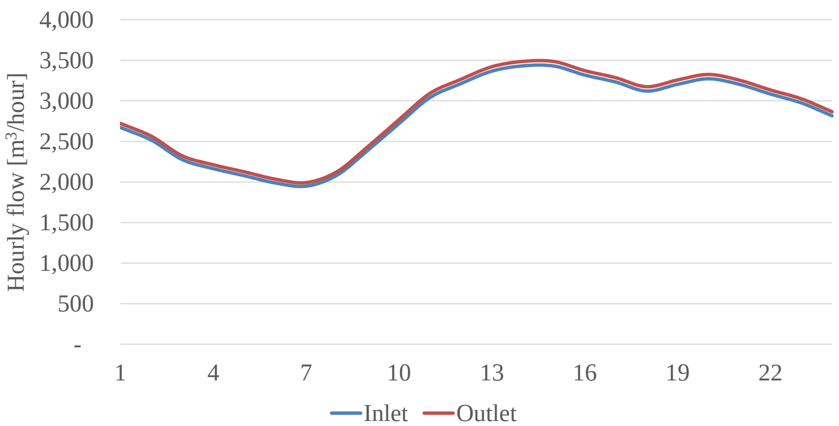


Figure 5.3: The average daily sewage water profile from inlet and outlet of water at Damhusåen. We see that there is no storage of water in the tanks to regulate the outflow. (Data from Dines Thornberg[114])

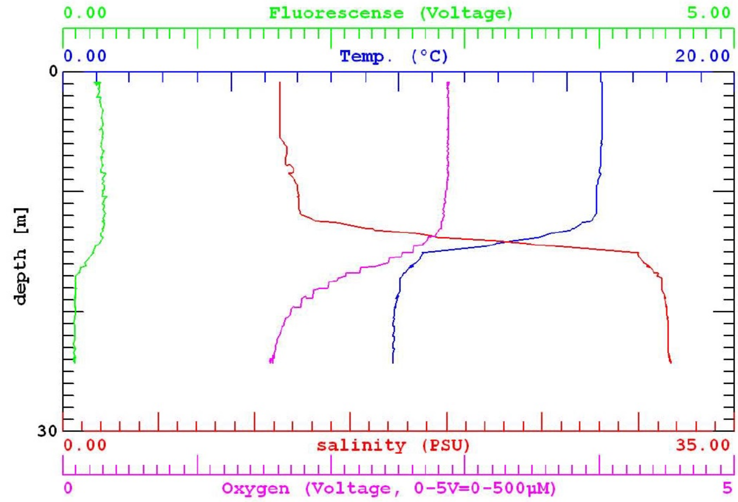


Figure 5.4: Temperatures in different water depths just North of island Ven in the summer time. The temperature is close to constant above and below the thermocline. (Screen shot from Jens Peder Jeppesen[74], The Øresund Aquarium)

the winter (see Figure 5.4). The bottom layer reaches a temperature of 11°C in summer, and decreases until spring where it reaches a minimum of approximately 5°C. Even at very cold winters the temperature in the bottom layer rarely goes bellow 3°C[95, 116].

This leaves two possible options for utilization of sea water. A ‘near’ option, where water is utilized near coast. Due to the low depth near the coast it is not possible to get below the thermocline.

The other one is the ‘far’ option. Here the water is pumped far from the coast, where the sea is so deep that the water below the thermocline can be utilized.

Potential of Øresund’s Bottom Layer (‘far’ option)

The bottom layer of Øresund seems to have a great heat source potential all year around. The bottom layer is below the thermocline at approximately 15 m. Depth profiles of Øresund are shown in Figure 5.5. At Helsingør (’III’) the depth is 40 m less than hundreds meter from the coast. Thus, in Helsingør it would be easy to utilize the heat of the bottom layer in a heat pump. Profile ’VIII B’ shows that the depth outside Copenhagen is only 12 m. The Taarbæk profile (’VII’) shows a depth of more than 15 m around 8 km from the coast. Gentofte is the area within Copenhagen closest to the deep area in the Taarbæk profile (∼12 km).

Implementing a 12 km pipe into Øresund is, of course, possible. The question is whether a pump, that can provide the necessary work, exist, and whether this work exceeds the energy utilized from the sea water. If the pump is placed on the coast, then it has to make a suction that will overcome the 12 km pipe friction. If this suction is too big, then the pump has to create a vacuum so large, that the water will instantly go into cavitation[59]. This threshold is called the *available net positive suction head* ($NPSH_A$), and is measured in meter[2]. The chosen pump needs a *required net positive suction head* ($NPSH_R$) that is lower than the $NPSH_A$ minus some security margin (usually 0.5 m[59]).

[2]So it can easily be compared with the total pump head, which also is measured in meter.

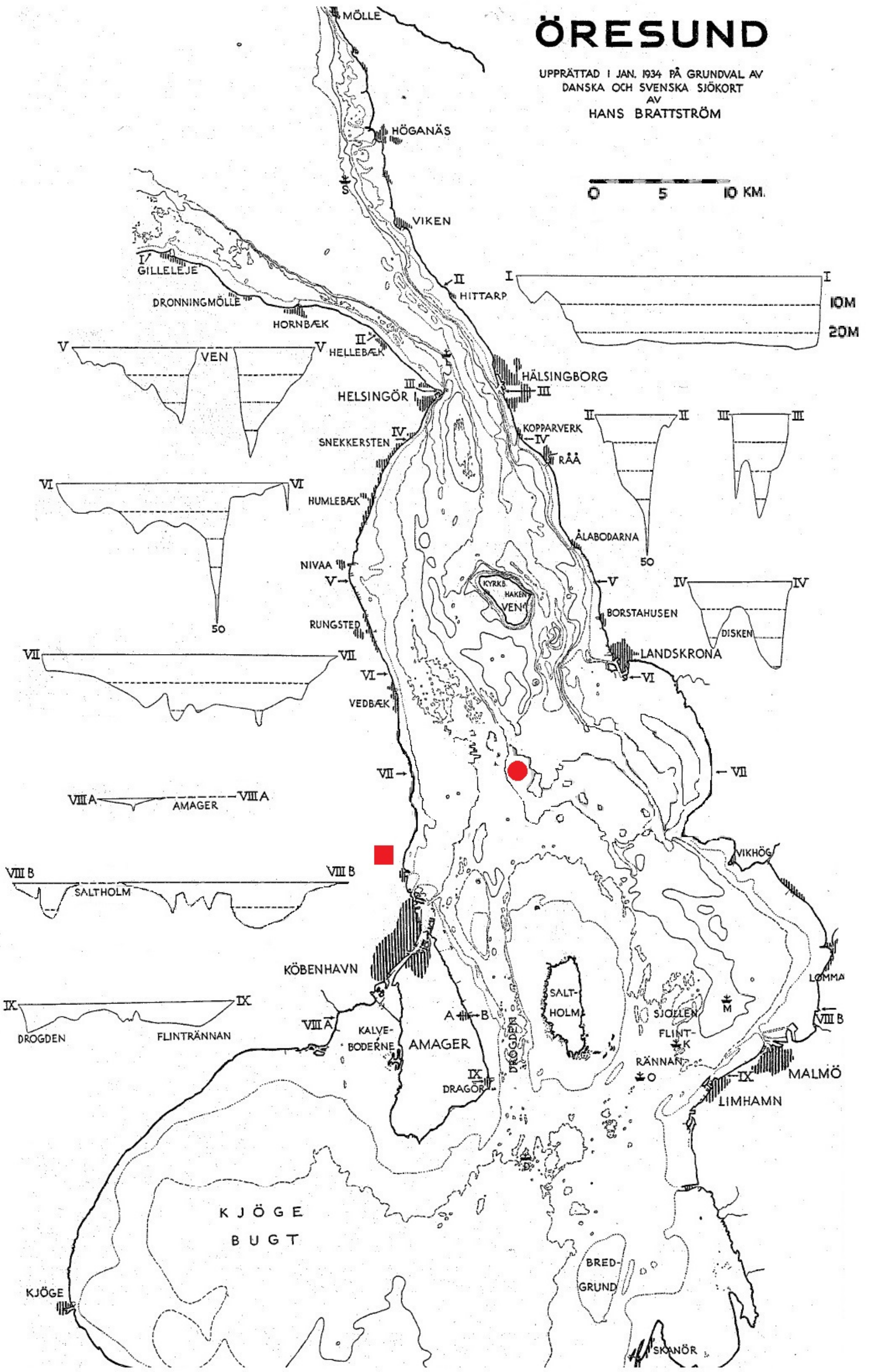


Figure 5.5: Øresund depth profiles. The red square (■) indicate the Northern area of the district heating system (Gentofte). The red circle (•) indicate where it is possible to get below the thermocline. (Drawing by Hans Brattström (1934). Source: [73].)

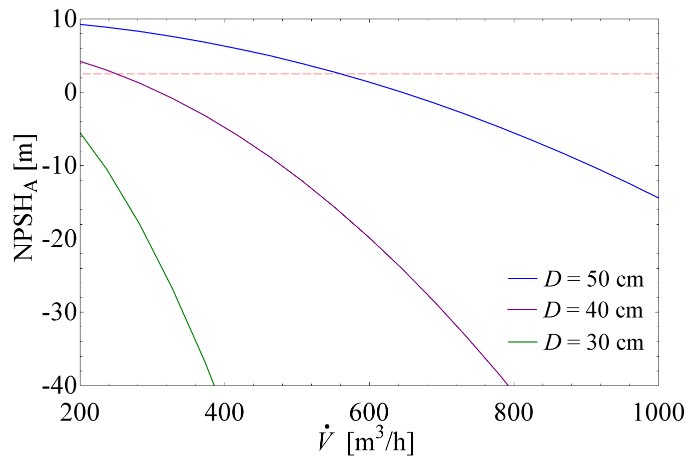


Figure 5.6: The $\mathrm{NPSH_A}$ plotted as a function of the volume flow of water for different diameters of the pipe.

In Figure 5.6 the $\mathrm{NPSH_A}$ as a function of the volume flow for different diameters of the pipe is shown. The dashed red line indicate the $\mathrm{NPSH_R} = 2$ m plus a security margin of 0.5 m (total of 2.5 m) [3]. The pressure drop due to friction depends highly on the diameter of the pipe ($\Delta p \propto L\dot{m}^2/D^5$). The maximum flow possible is around 600 $\mathrm{m^3/h}$ with a pipe diameter of 50 cm. This can give a $Q2/C3/T3$ heat pump. If heat pump with larger capacity than 2 $\mathrm{MW_{th}}$ is needed, then a parallel coupling has to be made.

According to private conversation with Jens Erik Tredal[115], Engineer at Grundfos, another possible solution will be to add some booster modules/pumps to the inlet of the pipes, i.e. at the bottom of the sea. These booster modules will supplying some extra pressure, and make it possible to have a higher water flow or a smaller diameter of the pipe.

The pump work is around 20 kW for the previous mentioned pump. The overall COP of the system can be calculated from the COP of the heat pump alone ($\mathrm{COP_1}$), the pump work, $\dot{W}_{\mathrm{pump}}$, and the heat pump capacity, $\dot{Q}_{\mathrm{hp}}$.

$$\mathrm{COP} = \frac{\dot{Q}_{\mathrm{hp}}}{\dot{W}_{\mathrm{com}} + \dot{W}_{\mathrm{pump}}} = \frac{1}{\mathrm{COP}_1^{-1} + \dot{W}_{\mathrm{pump}}/\dot{Q}_{\mathrm{hp}}}, \tag{5.2}$$

Which for the previous mentioned $Q2/C3/T3$ heat pump with a pump work of 20 kW give a COP of 2.9. It is possible to extract from the below the thermocline in Øresund, but attention have to be made when constructing the pipe and pumping system.

Potential of the Sea Water near the Coast ('near' option)

The near coast water at Copenhagen is shallow. The highest depth is around 10 m and is located in a 700 m belt just East of Northern Amager and Nordhavn (see Figure 5.7). A total replacement of the water in Øresund takes place every 6 day in average. Here the top 5 m is exchanged faster (2.5 days) and the bottom slower (20 days). At 10 m depth the water is in average exchanged every 6 day. Øresund's surface covers an area of 900 $\mathrm{km^2}$. The area shown in Figure 5.7 covers 2 $\mathrm{km^2}$. Assuming that the flow is steady throughout Øresund, the time for exchanging water at 10 m depth in the 2 $\mathrm{km^2}$ is between 10 min to 15 min (rough calculation). With a utilization of just $\Delta T = 1$°C at the bottom 1 m layer,

[3] The $\mathrm{NPSH_R} = 2$ m is from a data catalogues of suction-pumps from Grundfos[57].

Figure 5.7: Sea area east of Amager and Nordhavn that could be used as heat source. Total area is around 2 km^2 and depth is around 12 m. (Map and depths from Krak[79].)

this gives a potential of around ~10,000 MW_{th}. The potential is in practise infinite.

The energy can be utilized in open or closed systems. Open systems pumps the water from the sea through the evaporator and back. Closed systems consists of a network of pipes placed at the bottom of the sea, through which a brine is circulated to extract heat from the sea water[99]. Normally the heat transfer per pipe length is around 20 W/m pipe[99]. This means that for a 10 MW_{th}heat pump more than 300 km of pipe is needed. Closed systems is often used in smaller residential systems. Existing larger systems using sea water, such as the heat pump in Drammen, uses an open system.

The temperatures of the water near Copenhagen in the period 2000 to 2014 are shown in Figure 5.8. The freezing point of the sea water in Øresund is −2°C to −1°C, depending on the salt level[6]. As mentioned in section 5.1 the temperature of water discharged to the sea has to be approved by the municipality for each individual case[39]. The utilization will depend on this approval. This approval will also determine if there are some periods during the year where it is not possible to use the heat pump, because the outlet water will be to cold. Assuming no restrictions from the municipality, it might be cooled as low as 0°C (in theory lower). The number of days in a year that the water is below 1°C, 2°C, and 3°Cis shown in Figure 5.9. This gives an indication of how much heat can be utilized versus how many days the heat pump will be out of operation because of a too cold heat source. If it is chosen to extract heat corresponding to $\Delta T = 3$°C from the sea, then in some years the heat pump would be out of operation for more than two months. The two months where the heat demand is highest. Even for $\Delta T = 1$°C then more than half the years it is out of operation more than two weeks. Only three years have no outage at all due to cold water temperatures.

Taking the heat pump out of operation for more than a few weeks is assumed undesirable, so a $\Delta T = 1$°C will possibly be the only feasible solution. Conclusion; there is a large potential in near coast sea water, but there will possibly be a few weeks (sometimes more) each year where the heat pump will be out of operation.

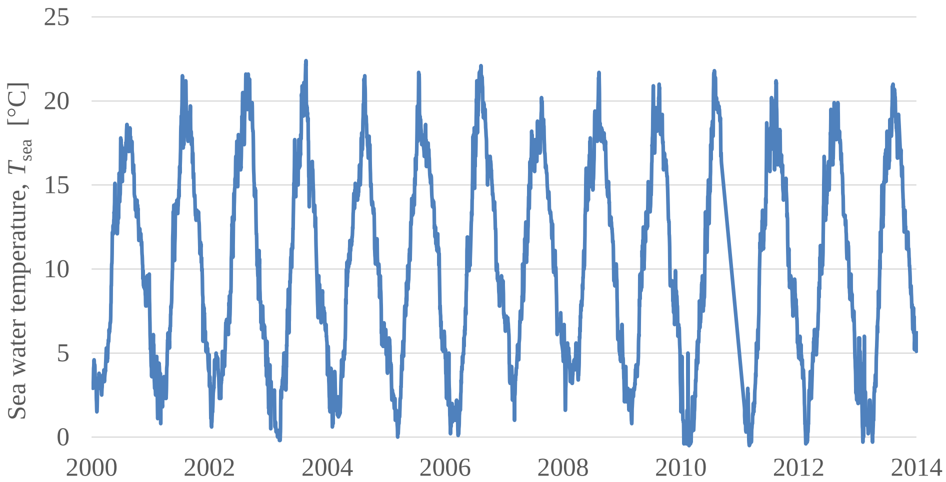


Figure 5.8: Temperature of the sea near Copenhagen measured at Nordhavn. (Data provided by DMI[27])

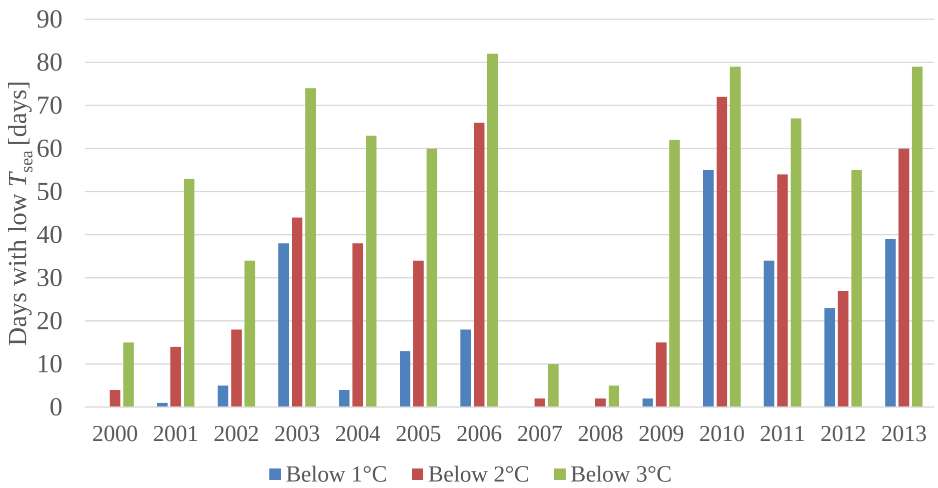


Figure 5.9: Temperature of sea near Copenhagen in 2013. (Data provided by DMI[27])

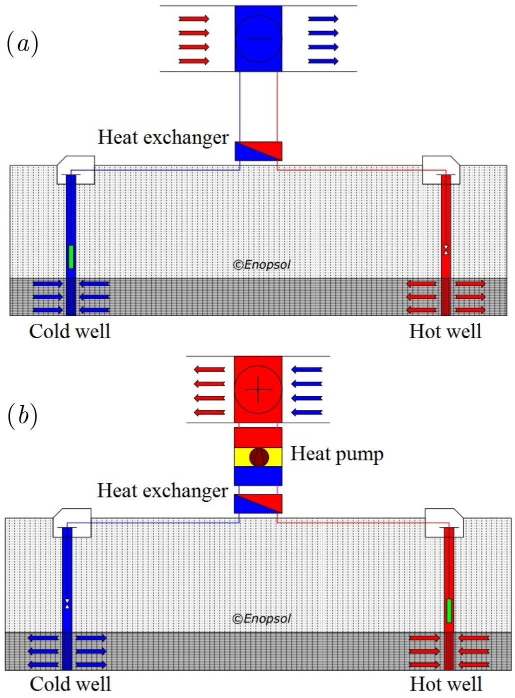


Figure 5.10: Sketch of the ATES system. (a) shows the cooling of ventilation air, and (b) shows the utilization of the ground water heat using a heat pump. (Source: [110, fig. 1 and 2])

5.3 Ground Water

Aquifer Thermal Energy Storage (ATES) is the use of ground water wells as heat storage. In the summer time where the demand is low, heat from CHP plants, solar heating systems or cooling systems can be stored in the water 50 m to 100 m under ground. The water is pumped from the extraction well up over ground and through one or more heat exchangers, utilizing the cool water for cooling in condensers to power plants or air-conditioning (see Figure 5.10(a)). Then it is pumped back in to the well through another boring to minimize the mixing of cold and heated water. Thus, there is no consumption of water, but only heating of it. In the winter time the cycle is reversed, as the heated water is pumped up to the surface and utilized in a heat pump for local or district heating[110] (see Figure 5.10(b)).

ETP in cooperation with GEO have analysed the feasibility of constructing ATES systems in Denmark, using data from GAUS' database of the Danish geology[76]. As seen in Figure 5.11 they found that the Greater Copenhagen areas ground is very suitable for ATES systems.

The district heating supplier Bjerringbro Fjernvarme constructed a low temperature ATES system in cooperation with the pump manufacturing company Grundfos in 2013. Grundfos' waste heat is stored in a ground water reservoir, and utilized by heat pumps to the district heating network in winter operation. The system has three heat pumps connected, each with 1 MW_{th} capacity. This system supplies the city of Bjerringbro with 15% of it's district heating demand[58]. The project was planed by Enopsol and COWI, while Rambøll was consultants on the piping. The cost of the entire system was DKK 27.7 mill.

Copenhagen Airport put a similar system in operation in 2013 to DKK 55 mill. The cooling

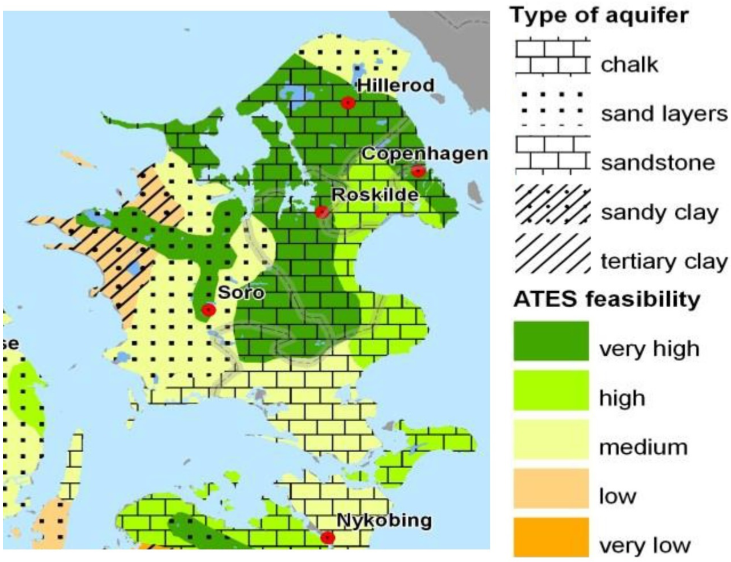


Figure 5.11: Map of the feasibility for using ATES on Sjælland. The area around Copenhagen has a very high rank. (Map is from Klootwijk (2013)[76])

system extracts 5 MW_{th} heat, for the air-conditioning, from the 9°C ground water, and pumps 18°C water back in the well. In winter operation the 18°C water is pumped back up and utilized by a heat pump for comfort heating[3]. The system is expected to have an annual electricity saving of 4.3 GWh_e and generate a surplus of DKK 50 mill. by 2020[3, 87].

ATES is a seasonal heat storage and not a heat source, which means that heating of the water in the well is required during summer time. In Bjerringbro Grundfos needed cooling of the process all year around, and in the airport the air-conditioning needed cooling in the summer time. Copenhagen does not have any big industries producing waste heat. An if it had; will it still be there the next 20 years?

5.4 Drinking Water

The municipality of Copenhagen consumes around 50 mill. m^3 drinking water each year. The water is distributed by HOFOR and comes from 700 drillings located in municipalities around Greater Copehagen. The network consists of 7 water facilities that aerates and cleans the drinking water (see locations in Figure 5.12).

A simple flow calculation yields a flow around 800 m^2/h for each facility, assuming that the water is equally distributed over the year and between all 7 facilities. The temperature of the water is 7°C in the winter months rising to 15°C in July (see Figure 5.13). According to the executive order BEK 1024 about water quality, the supplier should pursue to deliver drinking water under 12°C[31]. There is no minimum temperature limit in the order, so the minimum must come from a subjective evaluation of at what temperature the consumers wants their drinking water[4]. Let's assume that it can be cooled to 4°C, which is the normal temperature of a fridge. In the winter months a temperature difference of $\Delta T = 3$°C can be utilized, which gives a potential of around 3 MW_{th} from the source. Which yields a

[4]The drinking water temperature in Copenhagen have actually increased from 8°C to 13°C the last 40 years[34], so cooling the water with a heat pump could be a solution to keep under the 12°C limit.

Figure 5.12: Map of the location of the water facilities in the Copenhagen area. (Map is from Google Maps and locations are from HOFOR[77])

$Q4.5/C3/T3$ heat pump on each facility.

Comparing Figure 5.12 with the map of the district heating of Greater Copenhagen (Figure 2.1), it is seen that only three of the seven water facilities is located within the district heating network. The total heat pump capacity from drinking water is therefore between 10 $\mathrm{MW_{th}}$ and 15 $\mathrm{MW_{th}}$.

5.5 Air

Potentially air is an inexhaustible source, but in reality it is not an optimal source for larger heat pumps. The heat capacity of air, $c_{\mathrm{p,air}}$, is only one fourth of what it is for water. In order to produce the same amount of energy a four times higher mass flow, $\dot{m}$, or a four times larger decrease in air temperature, ΔT, is required. Air does not freeze like water, so a higher ΔT is not a direct problem. But air contains water, which means that frost is formed at the cooling side of the evaporator surface[10]. This can already happen with outdoor temperatures under 7°C[5] and will lower the COP with 10% to 20%[99, p. 53]. In 2012 the average day temperature were below 7°C in 154 days; all in the heating season (November to March). At the same time the Carnot COP is around 3.6, which means that the actual COP of the heat pump is around 2.3.

For a $Q10/C3/T6$ heat pump, the air flow through the evaporator needs to be around 1100 $\mathrm{m^3/s}$ or 400,000 $\mathrm{m^3/h}$. For comparison the new wind tunnel planed to be build at DTU Risø has a maximum flow of only 760 $\mathrm{m^3/s}$[71].

From Granryd et al. (2011)[56] table 8.23a the thermal transmittance, U, of a forced convection air evaporator with fined coils is in the range 12 $\mathrm{W_{th}/(m^2\,K)}$ to 25 $\mathrm{W_{th}/(m^2\,K)}$. Based on this a rough estimate of the heat transfer area can be calculated from the relation $A = \dot{Q}/(U\Delta T)$. Using a $Q10/C3/T6$ heat pump as before, the calculation yields a heat transfer area of 40,000 $\mathrm{m^2}$ to 90,000 $\mathrm{m^2}$. According to Rule of thumbs in Coker (2007)[20] a plate and fin heat exchanger has an effective heat transfer area of 1150 $\mathrm{m^2}$ per $\mathrm{m^3}$. This

[5]Calculated from optimum mean log temperature and air temperature decrease mentioned in Granryd et al. (2011)[56]. Calculations are shown in Appendix A.2.

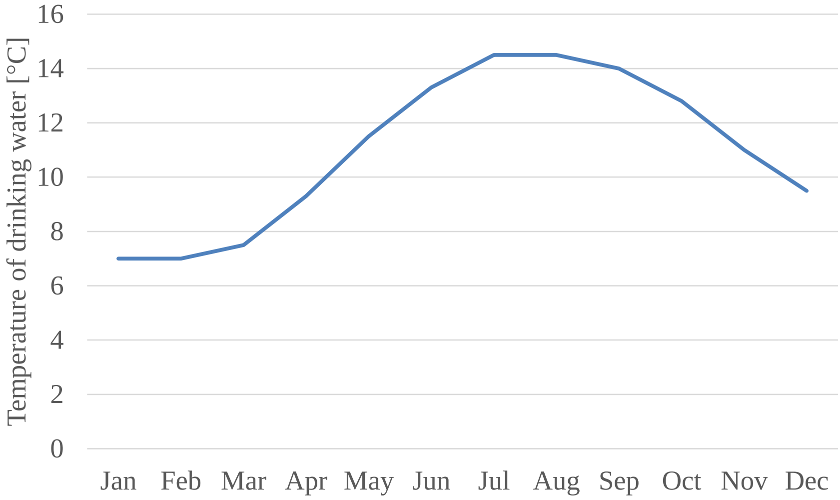


Figure 5.13: Temperature of the drinking water in the water facilities. (Data from MacAller (2013)[85])

gives a volume of the evaporator of 35 m^3 to 80 m^3, or roughly the same size as four vans. Assuming that the hight of the evaporator is 1 m, the fan area is around 80 m^2, which requires a fan capacity of around 0.1 MW_e (around 1% of the heat pump capacity[6]). The energy consumption of the fan is of little importance.

On the other hand the fan noise can be a problem. Broyce (1984)[13] mentions that even small residential heat pumps can give noise disturbances to the closets neighbours.

Air as a source for heat pumps does not have the same potential as water sources, and should only be used where no other option is available. Air is only relevant if the water heat pumps near coast can not supply inland areas of Copenhagen. In that case large and noisy heat pumps must be built in Frederiksberg and Valby. Air is a possible but not optimal heat source.

5.6 Ground

Ground as heat source is often used for smaller heat pumps for local residential heating. At 1 m the ground is around 8°C all year around. With horizontal piping you can typically utilize 40 kWh_{th}/m^2 yearly from the ground[99]. For a household with a 3 kW_{th} heat pump this gives an area of 300 m^2. For a 10 MW_{th} heat pump the same area is 100 ha or roughly the same size as 140 soccer fields, which could be a problem to find the space for.

Investigations in the Elforsk project j.nr. 342-066 with the English title 'Heat pumps with vertical ground collector'[100], shows that vertical collectors could be interesting for households in the future, but that it at the present is too expensive. According to their calculations one could get around 1 kW_{th} for each hole (70 m to 85 m). This means that we will need around 6,600 holes to get heat enough for a 10 MW_{th} heat pump. According to the Danish executive order BEK 1312 considering geothermal heating systems §10 part 8 the distance between each hole have to be above 20 m[32]. Calculating the area using close-packing of equal sphere gives a minimum of 114 ha – so roughly the same size as for horizontal piping.

[6]which is en good consistency with other rule of thumbs

Using ground as heat source is evaluated to use to much space and have to little potential compared to other water based sources.

6

Discussion and Recommendation of Heat Sources

6.1 Overall Discussion and Recommendation

Overall six different sources are analysed: sewage water, sea water, ground water, drinking water, air and ground. Some of the estimated potentials and source temperatures are shown in Table 6.1 and a plot of the temperatures for some of the sources is shown in Figure 6.1. The following priority of the sources is suggested;

1. Sewage water
2. Drinking water
3. Sea water
4. Air
5. Ground
6. Ground water (as seasonal heat storage)

The potential of sewage water is around 87 $\mathrm{MW_{th}}$ in total, where drinking water is only around 13 $\mathrm{MW_{th}}$ in total. These two sources are the easiest to utilize directly. The reason is that both sources already have a flow, so a pump is not necessary, and both sources have a high temperature even in the winter time ($T_{\mathrm{sew}} \sim 10°\mathrm{C}$ and $T_{\mathrm{drink}} \sim 7°\mathrm{C}$).

For the sea water the ‘far’ option is chosen for further studies. The discussion of sea water as heat source is done in the next section.

Air is a possible but not very attractive solution. The Carnot COP is only around 3.6 in the winter time, which in practise gives a COP of around 2.3. For the water based sources this number is 2.8 to 2.9. At the same time noise pollution could be a problem in high populated areas. Ground is a well known heat source for residential purposes, but for larger heat pumps the covered area is simply to big.

Table 6.1: Overview of the natural heat sources near Copenhagen. The Carnot COP is calculated from the winter and summer forward temperatures in the district heating distribution grid (70°C and 90°C).

	Temperature Min./Max. [°C]	**Potential [MW]**	**Carnot COP Winter/Summer**
Sewage water	10 / 20	87	4.5 / 6.9
Sea water (near)	0 / 20	∞	4.0 / 6.9
Sea water (far)	5 / 10	∞	4.3 / 5.7
Ground water	8 / 18	-	4.4 / 6.6
Drinking water	7 / 15	15	4.4 / 6.2
Air	-10 / 25	∞	3.6 / 7.6
Ground	7 / 9	∞	4.4 / 5.6

Ground water is only an option if waste heat is present in the summer time. Ground water can be used as seasonal heat storage, but is not a heat source in itself.

Due to the fact that sea water in practise has infinite potential, I will recommend that future heat pumps utilize either sewage, drinking, and/or sea water. The other sources should only be considered if these sources is not available for some reason, e.g. if it is not possible to connect the heat pumps to the transmission grid.

6.2 Discussion of Sea Water as Source

There are two options of utilizing sea water. The easy way is to take it 'near' coast, i.e. taking it just a few hundred meter from the coast. The temperatures varies from 0°C in winter time to about 20°C in summer time. The downside is that when the temperature is below 1°C it will be very hard to utilize any heat. In practice this means that the heat pump will be out of operation 2 to 3 weeks a year in average. Unfortunately this is the time where the heat demand is highest. Another way is the 'far' option, where water is pumped from 12 km offshore. Here the water temperature is almost constant all year around, and especially in the winter time the "hot" 4°C water would be excellent to utilize in a heat pump. In the summer time water near coast can be used, similar to the 'near' solution. Both sources have a very large (almost infinite) potential.

The pump work for getting the sea water for both situations is not negligible, but depends on the mass flow and pipe diameter (and less on the actual length of the pipe). The important question is; what is the investment cost of employing 12 km of pipe into the sea? The investment cost of oil pipelines at sea is around DKK 10 mill. per km pipe[108]. These pipes are, of course, made of metal, and a lot of time and money are spent on making sure they do not leak and are fasten securely. The sea water pipeline into Øresund can be made of plastic and it does not matter if it leaks a bit. In Figure 6.2 the yearly costs[1] are plotted for a 20 MW_{th} heat pump for the 'far' and 'near' options. A technical lifetime of 20 years is assumed[47].

The 'far' option is assumed to have 4000 full load hours (FLH)[103], whereas the 'near' option has a forced outage of one month each year giving it 3380 FLH. In the 'Worst case' the pipelines are assumed to cost the same as oil pipes (DKK 10 mill. per km pipe), and in the 'Best case' it costs a tenth of that (DKK 1 mill. per km pipe). The investment of the actual heat pump is DKK 44 mill.[2], and the heat pump is assumed to represent 50% of the

[1] This is a simple economical calculations not taking discount rate and inflation into consideration.

[2] The price is calculated from information from Torben Henriksen[63] at ICS Energy who sells larger heat pumps for industrial and district heating purposes. The received offer was on a 5 MW_{th} heat pump to

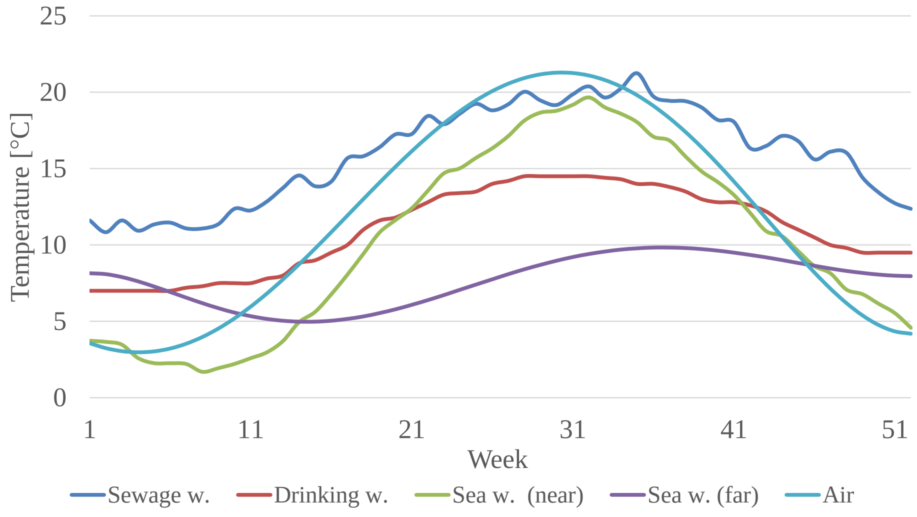


Figure 6.1: Average temperatures of the heat sources during the year. Air temperature is from DMI[28]. Sea water (near) is also from DMI and represents the average over the years 2000–2014[27]. Sea water (far) is an estimation of the temperature of the bottom layer, made from information and plots in Nørrevang et al. (1968)[95]. The drinking water is a weekly version of Figure 5.13.

investment[47]. The remaining 50% includes auxiliary equipment, connection to the district heating grid, consultant work, etc. (exclusive the pipes in the sea).

The yearly operation and maintenance (O&M) costs is DKK 0.5 mill. for the 'Best case' and DKK 1.0 mill. for the 'Worst case' (lower and higher bound in the Danish Energy Catalogue 2012[47]). The electricity costs is calculated from the average 2012 electricity price of DKK 270 per MWh_e. The taxes is from the 2013 legislation (DKK 406 per MWh_e).

The revenue is calculated from the average heating price in the Copenhagen center (DKK 380 per MWh_{th}, i.e. 'Worst case') and Amager (DKK 514 per MWh_{th}, i.e. 'Best case') in 2012[48]. As seen both the 'Best case' scenarios have a fine profit of around DKK 15 mill., whereas the 'Worst case' scenarios both break even. The highest profit is for the 'Best case (far)' scenario, and the second highest is the 'Best case (near)'. The 'Worst case (far)' has the lowest profit, which suggest that there is an investment cost of the pipes where the 'far' and 'near' options have the same profit. This cost is around DKK 6 mill. per km pipe (i.e. around half of what oil pipes costs) in the 'Best case' scenario and around DKK 3 mill. per km pipe for the 'Worst case' scenario. So whether the 'near' or the 'far' solution is the best depends on the investment costs of the pipes.

I will recommend the 'far' option for two reasons. Firstly I will weight the security of supply higher than the extra investment cost. Secondly I assume that the pipe investment cost is less than half of what oil pipes costs, which means that the profit for this option should be larger.

On thing that could change this choice, is the stratification of water in winter time. Water has its highest density at 4°C, which means that below this temperature the cold water (< 4°C) will raise to top, while the hotter water (~ 4°C) will drop to the bottom. This could mean that in winter time the bottom (~ 10 m) would still be a couple of degrees

DKK 11 mill.

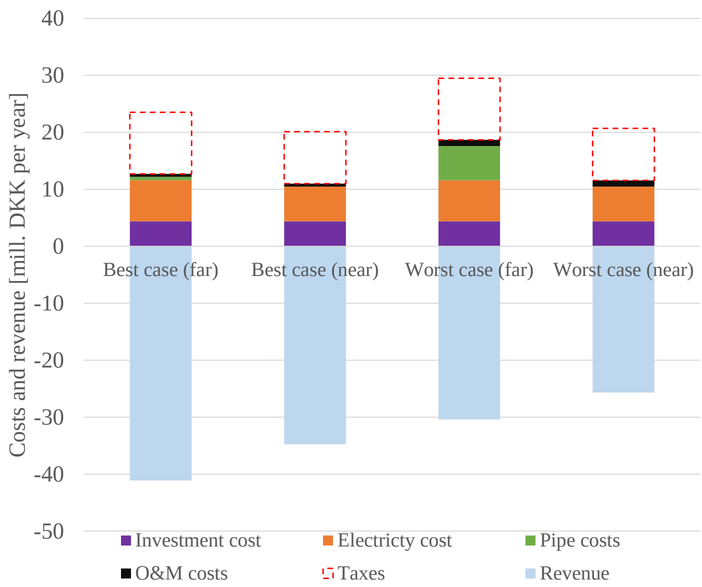


Figure 6.2: The yearly cost of a 20 MW_{th} heat pump. The taxes is dashed to indicate the difference between the private and socio-economic results.

Celsius, and therefore be able for utilization. This stratification depends highly on the natural flow in the sea water, which makes it very hard to estimate. To determine whether the temperature at 10 m depth is high enough all year around (and in all years), actual temperature measurements at the bottom has to made over a significant number of years.

Another thing to consider is that even with a water pump located at, the set-up still need some booster pumps in the other end of the pipes (i.e., far from land under the sea). The investment cost of this set-up is uncertain, as well is the variable costs of inspecting a number of booster pumps 12 km at sea and 15 m below surface. This could very well tip the scale on whether to choose the the near coast or the far coast (deep sea) option. Future case studies for the two options have to determine this.

Part II

Thermodynamic Modelling of Heat Pump Technologies

7

Introduction to Heat Pump Technologies

A heat pump is as described in chapter 3 a device that moves heat from a source to a sink. The principle of the technology dates back to the mid 18^{th} century. The technology have in over a century been used in small scale in fridges and freezers, but have the the last couple of decades grown to MW_{th} size heat pump used in industries and district heating systems.

Some of the large heat pumps are Star Refrigeration's 'Neatpump' using ammonia, and Avansor's 'compHEAT' using CO_2 (see Figure 7.1). The heat pump in Drammen and in Bjerringbro is both of the model 'Neatpump'. The heat pump in Frederikshavn is of the model 'compHEAT'.

The goal for this part is to find a suitable heat pump technology, and determine its seasonal COP and capacity. This is done by first describing different refrigerants, components and cycles of heat pumps, and thereafter choosing a suitable heat pump technology. Secondly, set-up a thermodynamic model of the heat pumps, and calculating the operational values.

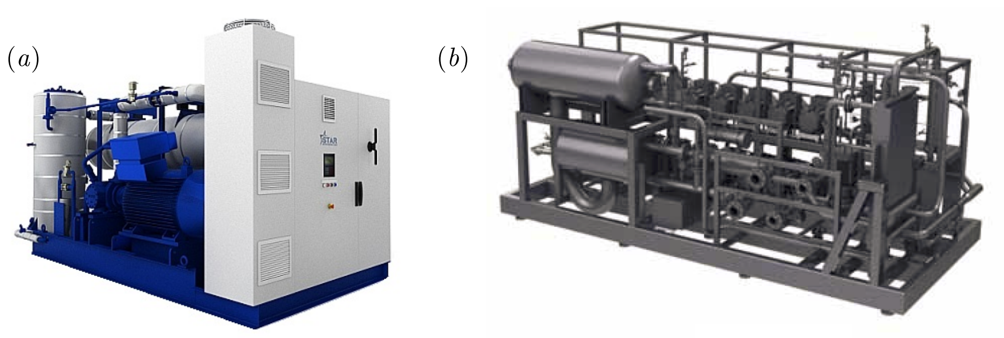


Figure 7.1: Pictures of two MW_{th} size heat pumps (a) the 'Neatpump' from Star Refrigeration[111], and (b) the 'compHEAT' from Advansor[1].

8

Choosing the Heat Pump Technology

In this chapter the possible choices of refrigerants, components and cycles are discussed. The heat pump technology chosen for the further study is summarized at the end of the chapter.

8.1 Absorption and Compression Heat Pumps

There exist two kind of heat pumps, absorption and compression. Absorption heat pumps use high temperature heat from flue gas or steam to extract heat from a lower temperature heat source. An absorption heat pump therefore depends on a heat input that often originates from burning of some kind of fuel[99]. In the Copenhagen area there is already connected a geothermal plant that uses the steam from Amagerværket (or the steam grid) to extract more heat from a geothermal well 2.6 km below ground level. This plant has a capacity of 27 MW_{th} where 13 MW_{th} originates from the steam and 14 MW_{th} originates from the ground[33].

The compression heat pumps operate on electric energy. If the heat source is a natural source, such as air, sea water or ground (i.e. not waste heat from industry or similar), the heat pump is independent of fuels[99]. The compression heat pump could therefore, along with heat accumulation in the district heating network, be an important player in the utilization of the fluctuating electricity production from renewable energy sources. For this reason this study will focus on compression heat pumps.

8.2 Refrigerant

Danish legislation dictates that all heat pumps and refrigeration systems have to use natural refrigerants if the system exceeds 10 kg of refrigerant. Smaller heat pumps in the kW_{th} size consist of 2 kg to 5 kg refrigerant, and can therefore use HFC refrigerants such as R134a and R404A. Larger heat pumps in the MW_{th} size consist of 500 kg R134a per MW_{th}, and 190 kg ammonia per MW_{th}. Even with very secure and tight systems, loses of refrigerant during service and maintenance is unavoidable. A loss of 1% per year is not unusual[64]. The global warming potential (GWP) of HFCs is more than a thousand times bigger than what it is for natural refrigerants as seen in Table 8.1. For a 10 MW_{th} heat pump using ammonia (NH_3) instead of R134a saves the emission of 65 tons of CO_2 equivalents per year.

Table 8.1: Global warming potential for different refrigerants. (Source: [113])

Refrigerant	**GWP [kg CO_2eq/kg]**
R134a	1300
R404A	3300
R717 (NH_3)	0
R744 (CO_2)	1

Overall this leaves two refrigerants; carbon dioxide and ammonia.

Carbon dioxide, CO_2 (R744)
A natural non toxic refrigerant with very little GWP. It operates in the supercritical area and needs very high pressures (∼100 bar). Works best with low inlet temperatures at sink side.

Ammonia, NH_3 (R717)
A natural refrigerant with no GWP. It is toxic, but easy to detect due to its characteristic smell even at low concentrations. Ammonia has a relatively high temperature out of the compressor, and is therefore often applied in a two-stage system[56].

A study made by Christensen & Markussen (2010)[17] shows that a heat pump using CO_2 as refrigerant is better than one using NH_3 only if the inlet temperature of the sink (district heating return temperature) is below 28°C. The district heat return temperature in Copenhagen is 55°C in the distribution network and higher in the transmission. So ammonia would be the better chose.

The heat pump connected to the district heating network in Frederikshavn is CO_2 based. According to engineer Kim Arp from Forsyningen Frederikshavn they would probably choose ammonia if they had to choose again. This is mainly because of the higher operation and maintenance cost due to the high pressure. For these reasons the ammonia based heat pumps seems like the best fit.

8.3 Compressors

There exist five types of compressors:

- reciprocating/piston compressors
- rotary compressors
- scroll compressors
- screw compressors
- turbo compressors

The first four are displacement type compressors. The last is defined as a dynamic compressor. There are advantages and disadvantages with all. The biggest difference is the capacity of the volume flow as shown in Table 8.2. To get heat pumps in MW_{th} size a flow of around 1200 m^3/h is needed (see calculations in Appendix A.3). So for larger heat pumps screw or turbo compressors are used. Turbo compressors can only handle a limited pressure ratio, which can be a problem for larger heat pumps[56]. The screw compressor is therefore often the best fit.

A compressor's isentropic efficiency is highly dependent on the pressure ratio. Due to its design a screw compressor has a 'built in volume ratio', v_{bi}, which as a consequence gives a

Table 8.2: Approximate inlet gas flow volumes for different compressor types. (Data from Granryd et al. (2011)[56, p. 7:4]).

Type of compressor	Min. m^3/h	Max. m^3/h
Reciprocating	<1	500
Rotary	<1	20
Scroll	5	100
Screw	180	6000
Turbo	1000	-

'built in pressure ratio', π_{bi}. To express the influence of the pressure ratio on the isentropic efficiency, the following relation from Granryd et al. (2011)[56] is used:

$$\eta_{is} = \eta_{opt} \frac{(p_{out}/p_{in})^{(\kappa-1)/\kappa} - 1}{\pi_{bi}^{(\kappa-1)/\kappa} - \frac{\kappa - 1}{\kappa} \pi_{bi}^{-1/\kappa} (\pi_{bi} - p_{out}/p_{in}) - 1}. \tag{8.1}$$

where $\kappa = 1.3$ is the specific heat ratio for ammonia[56, p. 7:19], and p_{out}/p_{in} is the ratio between the pressure in and out of the compressor. The relation is plotted in Figure 8.1 for different 'built in pressure ratios'.

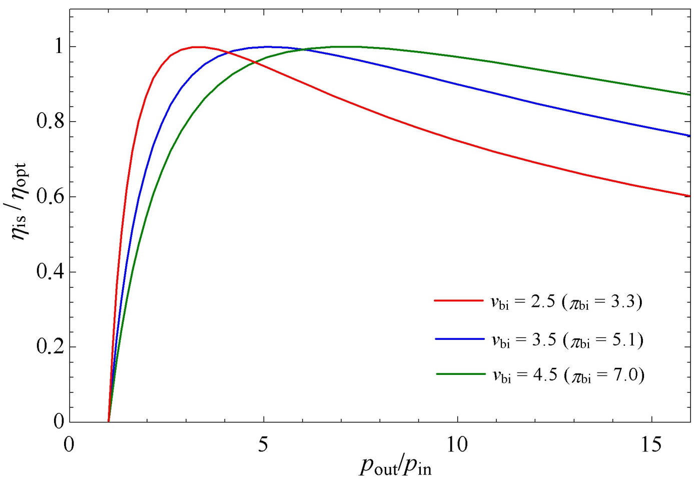


Figure 8.1: Isentropic efficiency of a screw compressor, (8.1), for different built in pressure ratio, π_{bi}.

In a screw compressor oil is used as a sealing agent. For larger compressors (>1000 m^3/h) the amount of oil is in hundreds of litres per minute. By cooling the oil before entering the compressor the oil can have a cooling effect preventing excessively high gas temperatures during compression[56].

One of the best ammonia compressors on the marked is the Vilter VSM and VSS single screw compressors[43]. This exact model is used in in the heat pump, Neatpump, by Star Refrigeration, which is the model used in the Drammen project[44]. The Vilter compressor is also used in the 3.5 MW_{th} heat pump connected to Bjerringbro's district heating system[68]. The compressor has a volume slide making it possible to control the volume ratio. This has a damping effect on the influence of the pressure ratios on the isentropic efficiency. The

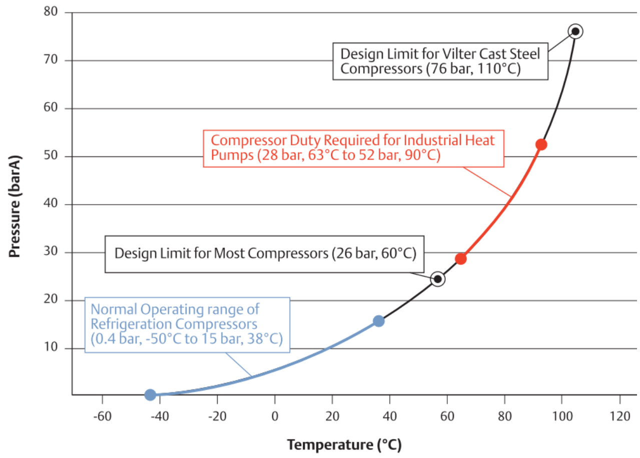


Figure 8.2: Ammonia pressure-temperature relationship, with the Vilter compressors operation area. (Figure from Vilter catalogue[42])

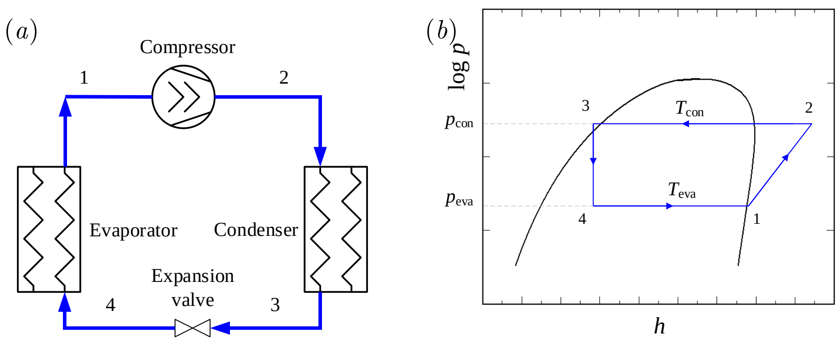


Figure 8.3: Sketch of a simple heat pump cycle.

Vilter compressor can go up to 76 bar (see Figure 8.2), which will be necessary if the heat pump shall be connected to the transmission grid.

8.4 Heat Pump Cycle

The simplest possible heat pump cycle consist of an evaporator, a compressor, an expansion valve, and a condenser. The corresponding process and instrumentation diagram, and the p, h-diagram are shown in Figure 8.3.

However for high temperature lift, i.e. large difference between condensing and evaporator temperatures, it is better to have two compressor stages, a so called 2-stage cycle. The reason is the mentioned relation between pressure ratio and isentropic efficiency (Figure 8.1). For a lift from 10°C (sewage water) to 90°C (forward temperature) the pressure ratio is $p_{\text{out}}/p_{\text{in}} = 8$. This gives a decrease in the isentropic efficiency of around 20% ($\pi_{\text{bi}} = 3.3$). Using a two-stage compression system as shown in Figure 8.4 and the intermediate pressure $p_{\text{int}} = \sqrt{p_{\text{in}} p_{\text{out}}}$ the pressure ratio for each stage is $p_{\text{out}}/p_{\text{in}} = 2.9$ and the isentropic efficiency is almost optimal. This gives an increase in COP of more than 10%, as showed in Figure 8.5. Each compressor is approximately half the size of the compressor in the one-stage cycle, thus

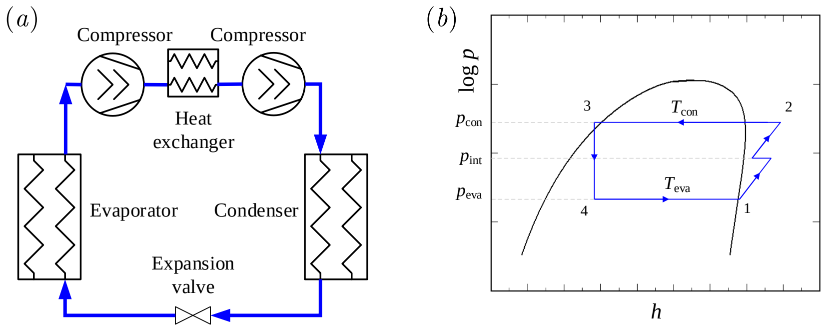


Figure 8.4: Sketch of heat pump cycle with 2-stage compression.

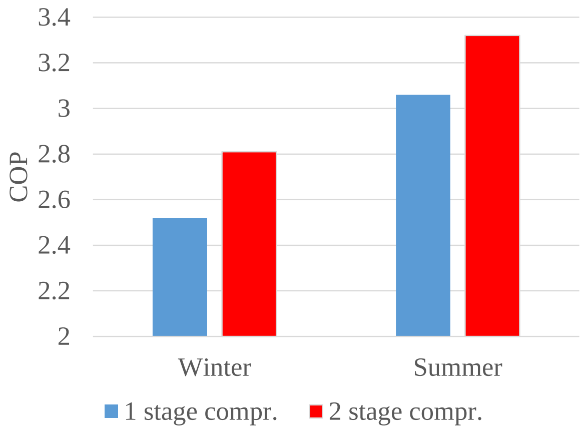


Figure 8.5: COP for one and two stage cycle in winter and summer operation.

the overall investment cost does not increase drastically.

8.5 Evaporator

For larger systems using colder sources a special kind of parallel-flow plate evaporator is often used. This design makes it easy to clean (needed for sewage and sea water), and there is no risk of damage due to freezing (possible in sea and lake)[56, p. 8:8]. This makes it possible to use low temperature heat sources such as sea water, because the water can be cooled close to 0°C.

In ammonia heat pumps a flooded evaporator is often used because this is much more efficient than dry expansion evaporators[98]. The reason is that the whole refrigerant side is wet, which gives a higher heat transfer coefficient. A sketch of a system with a flooded evaporator is shown in Figure 8.6. In state 1, at the outlet of the evaporator, the refrigerant is in a two-phase state. In the receiver the refrigerant is collected and split in pure liquid ($x = 0$) and pure gas ($x = 1$). The liquefied refrigerant is circulated in a heat exchanger, which heats the refrigerant in the receiver. The heat utilized in the heat exchanger is from the outlet of the condenser. The heat exchanger supplies the system with an extra sub-cooling (3 to 3'). Overall the difference is a higher sub-cooling and a pure gas inlet to the

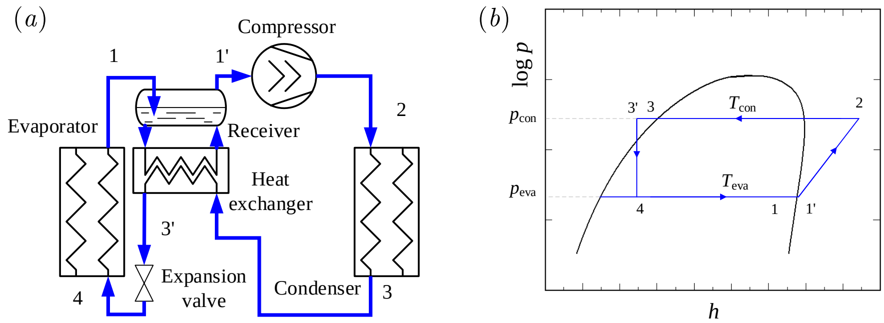


Figure 8.6: Sketch of heat pump cycle with a flooded evaporator.

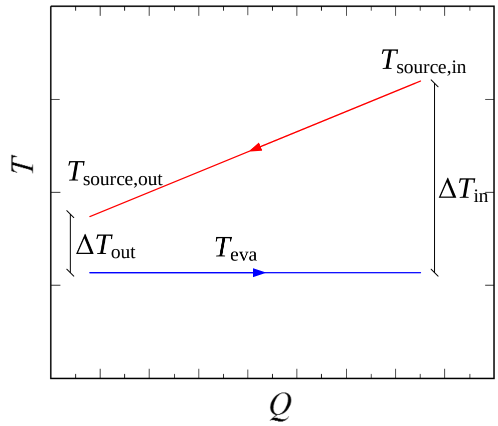


Figure 8.7: Sketch of the Q, T-diagram of an evaporator.

compressor (i.e. no super-heating).

In Figure 8.7 the Q, T-diagram of an evaporator is sketched. $T_{\text{source,in}}$ refer to the temperature of the source, (e.g. sewage or sea water). Because it is a flooded evaporator the temperature of the refrigerant is constant (T_{eva}). The pinch temperature (i.e. the lowest temperature difference) is $\Delta T_{\text{pinch}} = \Delta T_{\text{out}} = T_{\text{source,out}} - T_{\text{eva}}$.

The optimum temperature differences have been analysed by Bäckström (1940)[8]. Even though the analysis is old it has been shown that the conclusion still holds[56]. Bäckström found that the optimal decrease of source temperature in a liquid cooler is 3°C, and that the logarithmic mean temperature difference, ΔT_{lm}, depends on the operating hours per year. The logarithmic mean temperature difference, $\Delta T_{\text{lm,eva}}$, is defined as;

$$\Delta T_{\text{lm,eva}} = \frac{\Delta T_{\text{in}} - \Delta T_{\text{out}}}{\ln\left(\dfrac{\Delta T_{\text{in}}}{\Delta T_{\text{out}}}\right)}, \tag{8.2}$$

where the parameters are visually explained in Figure 8.7. In Table 8.3 the optimal logarithmic mean temperature differences for a plate evaporator are listed from Bäckström (1940)[8].

Table 8.3: Optimum temperature differences for evaporator and condenser. (Source: [8, 9, 56]).

Yearly operation hours		**1000**	**2000**	**5000**	**8000**
Evaporator					
Logarithmic mean temperature difference [°C]	$\Delta T_{\text{lm,eva}}$	7.2	6.0	4.0	3.5
Temperature decrease of source water [°C]	ΔT_{source}	3.0	3.0	3.0	3.0
Condenser					
Logarithmic mean temperature difference [°C]	$\Delta T_{\text{lm,con}}$	10.0	8.5	6.0	5.5

8.6 Condenser

The standard condenser for larger heat pumps is either the tube-in-shell or the gasketed plate-type heat exchangers. Most often it is the tube-in-shell that is used. The principle of a tube-in-shell heat exchanger is shown in Figure 8.8. The condensing medium (i.e. the refrigerant) condenses on the outside of the tubes (shell side), and the cooling medium (i.e. district heating) is running through the tubes. In Figure 8.9 the Q, T-diagram of the condenser is sketched. The logarithmic mean temperature difference method assumes that the heat transfer coefficient is constant throughout the heat exchanger. This is not the case in an condenser, where there is a big difference between the heat transfer in the de-superheating phase (right of the pinch point in Figure 8.9) and in the condensing phase (left of the pinch point)[12, p. 486]. This therefore a ΔT_{lm} has to be calculated from each of the two phases

$$\Delta T_{\text{lm,ds}} = \frac{\Delta T_{\text{pinch}} - \Delta T_{\text{out}}}{\ln\left(\dfrac{\Delta T_{\text{pinch}}}{\Delta T_{\text{out}}}\right)}, \tag{8.3}$$

and

$$\Delta T_{\text{lm,con}} = \frac{\Delta T_{\text{in}} - \Delta T_{\text{pinch}}}{\ln\left(\dfrac{\Delta T_{\text{in}}}{\Delta T_{\text{pinch}}}\right)}. \tag{8.4}$$

In reality the ΔT_{lm} should also be calculated for the sub-cooling area, but this is often assumed as a part of the condensing area, because the heat transfer is negligible compared to the condensing area. The optimal logarithmic mean temperatures for a tube-in-shell condensing phase are found by Bäckström (1970)[9] and shown in Table 8.3.

8.7 Tandem System

According to ICS Energy consultant Torben Henriksen[63] it is not unusual to use a tandem system when constructing larger heat pumps in the MW size. ICS Energy has bid on a project concerning a 27.3 MW_{th} sea water heat pump, where they use exactly such a system[67]. A principle sketch of a tandem system is shown in Figure 8.10. A tandem system is just two or more heat pumps connected in series. The district heating water is heated in steps, first to a intermediate temperature, T_{int}, and then up to the desired temperature. Chang et al. (2011)[15] showed by simulation and experiments that a sea water tandem system consisting of 2 heat pumps increased the COP by 15%. The mass flow of the sources can be either split (parallel flow) so the inlet temperature of the source is the same in each heat pump (as shown in Figure 8.10) or connected in series, so it is the same flow through both evaporators. With a tandem system consisting of two heat pumps, each heat pump will apply approximately half of the capacity. Assuming that investment costs of larger heat pumps have a constant price per MW_{th}[47], then the overall investment

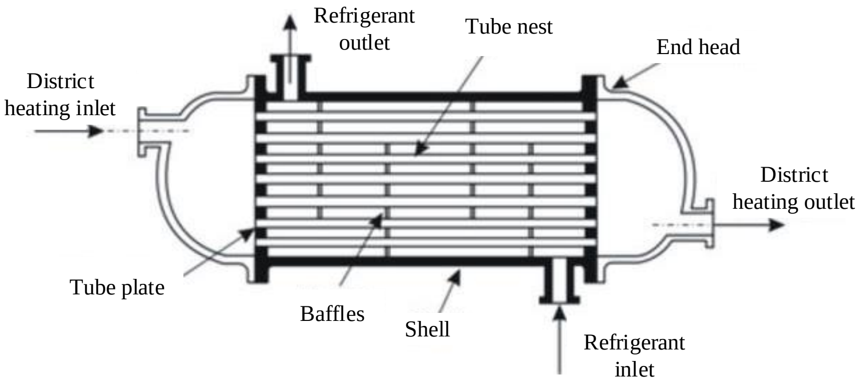


Figure 8.8: Sketch of a tube-in-shell heat exchanger condenser. (Original figure from GNS Science[55])

of the system do not increase significantly. The sea water heat pump in Drammen uses a three-steps tandem system with parallel source flow[97].

8.8 Alternative Heat Pumps

Other technologies could be of interest especially in the future. One of these is the hybrid heat pump using a mixture of water and ammonia as refrigerant. Minea & Chiriac (2006)[90] made field studies on a 4.5 MW_{th} hybrid heat pump, and found that hybrid heat pumps can achieve better performance than the simple fluid cycle for high output temperatures (100°C to 120°C).

Another future technology is the vapour compression heat pump, which uses water as refrigerant. This technology can utilize the latent heat of the phase transition from water to ice. For many years Danish Technological Institute (DTI) has researched and made demonstration plants using water as refrigerant. The compressors used for this system is massive compared to normal systems, and the future commercial breakthrough of these heat pumps will depend on the price level of these compressors[86]. According to head of cooling and heat pumps at DTI Claus S. Poulsen, and senior consultant at HOFOR Magnus Foged, they are in cooperation building a vapour compression heat pump planned to be connected to the Copenhagen district heating system in 2015.

8.9 Summary of Choosing Heat Pumps

For further study it has been decided to use a heat pump with the characteristics summarized in Table 8.4.

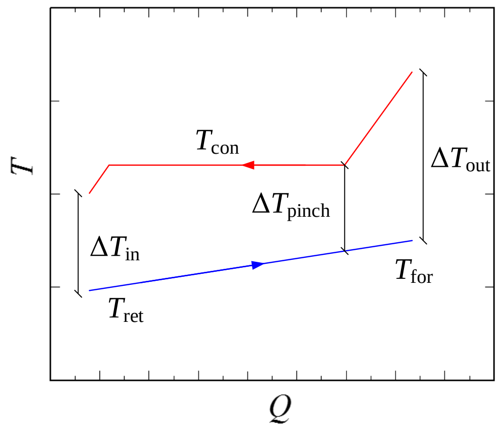


Figure 8.9: Sketch of the Q, T-diagram of a condenser. To the right of the pinch point the refrigerant is in the de-super-heating phase. Left of the pinch point it is in the condensing phase.

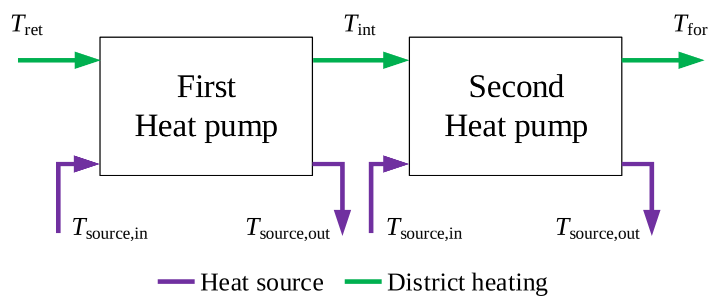


Figure 8.10: Principle of a tandem system, consisting of 2 heat pumps.

Table 8.4: Chosen heat pump technology to be used for further studies.

Type	Compression heat pump
System	Tandem with 2 heat pumps
Refrigerant	Ammonia (R717)
Cycle	Two stage compression
Compressor	Single screw (Vilter)
Evaporator	Flooded parallel plate evaporator
Condenser	Tube-in-shell condenser

9

Method for Modelling of Heat Pumps

The COP and capacity of a heat pump will always depend on its operation parameters. When the demand is high in the winter the temperature of the district heating forward water is around 20°C higher than in the summer time. For all of the studied heat sources the temperature follows the opposite trend. The temperature of sewage water drops from 20°C to 10°C from summer to winter, and sea water 'near' drops from 20°C to 0°C. The temperature has a huge impact on especially the COP, but also the full load capacity depends on how the heat pump is operated.

In this chapter I will go through the thermodynamic methods I will use to calculate the seasonal COPs and full load capacities for a heat pump using sewage water, sea water and drinking water as heat source.

9.1 Principle of Modelling Heat Pumps

Modelling a heat pump cycle consist of two phases;

1. The design phase (full load)
2. The off-design phase (part load)

The design phase is used to find the size of the evaporator and condenser. The size is quantified by the *UA*-value. The *UA*-value is a physical value describing the size of heat transfer coefficient and area of the heat exchanger (evaporator and condenser). In the design phase assumptions have to be made of some parameters such as evaporating and condensing temperatures, and pinch temperatures. These assumptions should be for full load operation (usually winter operation for a heat pump). From these calculations the *UA*-values of the evaporator and condenser are found.

When the size of the evaporator and condenser (quantified by the *UA*-values) are determined and a suitable compressor is found, the heat pump design is completed. Due to the fact that the *UA*-value represent the properties of a physical component, it can not change during the year. So in the off-design phase the *UA*-value is fixed, and instead two other variables (usually the pinch temperatures or evaporating/condensing temperatures) are released. Now it is possible to operate in part load mode and find the capacities and COP during the yearly phases.

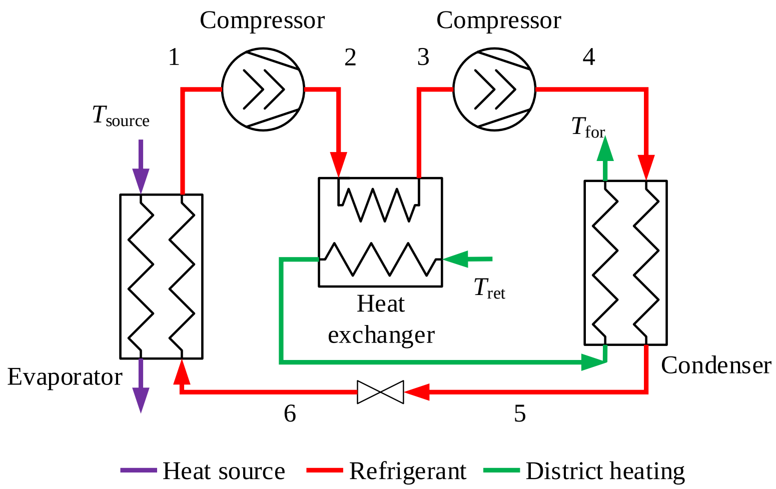


Figure 9.1: Sketch with components of the heat pump cycle.

9.2 Assumptions for Cycle Calculations

The assumptions for the cycle calculations are briefly described in this section. The equations for the design and off-design calculations can be seen in Appendix D in EES format. The cycle calculations are made following procedures of thermodynamic state calculation as described in refrigeration notes by Skovrup & Jakobsen (2003)[107], and Cloutier (2001)[19]. The design phase is based on the winter operation.

The system analysed is a tandem system consisting of 2 two-stage compression heat pumps. The cycle for each heat pump is shown in Figure 9.1. The compressors chosen are two single screw compressor having a isentropic efficiency of, $\eta_{is} = 0.7$, and following the relation (8.1) (with a built in volume ratio of $v_{bi} = 2.5$). The intermediate temperature in the tandem system is chosen to be $T_{int} = T_{ret} + 0.6\,(T_{for} - T_{ret})$, and is shown in Figure 9.2 for the distribution grid. The forward temperature for the transmission grid is between 98°C and 110°C, and is assumed to have the same profile as in the distribution grid. The return temperature is assumed to be 65°C. The refrigerant is ammonia (R717). In the design phase the pinch temperatures are defined and the *UA*-values are found for the evaporator and condenser, and in the off-design phase the *UA*-values are fixed as the design values and the pinch temperature are variable. The *UA*-value of the condenser consist of two values: the value for the de-super-heating phase and for the condensing phase (see Figure 8.9). The condensing phase is the most important one, where most heat is transferred. The fixed *UA*-value is therefore chosen to be the *UA*-value for the condensing phase, whereas the *UA*-value for tha de-super-heating phase is kept variable.

No super-heating in the flooded evaporator, and a sub-cooling of 5°C in the condenser are assumed. The intermediate pressure is $p_2 = \sqrt{p_1 p_4}$. The temperature decrease of the source water is assumed to be the optimum of 3°C (if possible), found from investigations by Bäckström (1940)[8] (see Table 8.3). The distribution grid forward, intermediate, and return temperatures in the design phase are $T_{for} = 90$°C, $T_{int} = 75$°C, and $T_{ret} = 55$°C respectively. In the transmission grid $T_{for} = 110$°C, $T_{int} = 90$°C, and $T_{ret} = 65$°C are assumed. The pinch temperatures in the design phase are $\Delta T_{pinch,eva} = 3$ (gives $\Delta T_{lm,eva} \sim 4$°C) and $\Delta T_{pinch,con} = 3$°C (gives $\Delta T_{lm,eva} \sim 6$°C). The rest of the design parameters is listed in

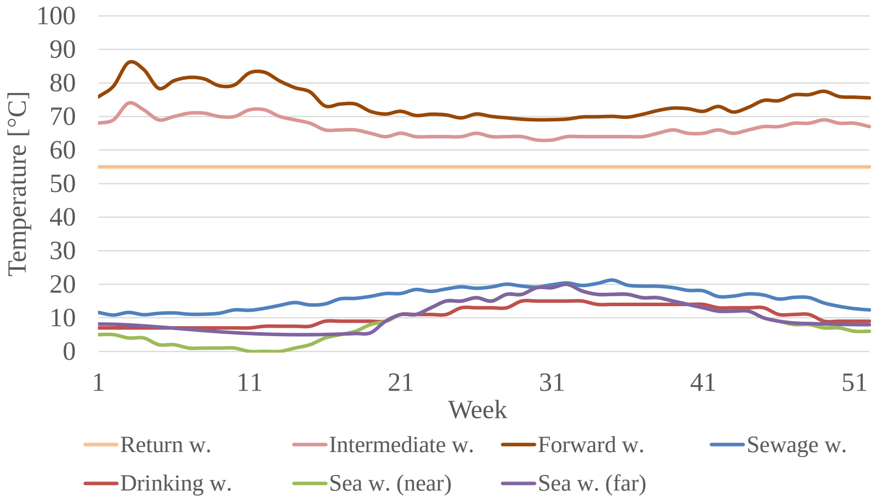


Figure 9.2: The seasonal return and forward temperatures, and the intermediate temperature used for tandem operational heat pumps. In the bottom of the plot the seasonal source temperatures for sea, sewage and drinking water are shown.

Table 9.1: Design parameters for the individual heat pumps in the tandem system (winter operation).

	Sewage w.	**Drinking w.**	**Sea w.(near)**	**Sea w. (far)**
Total mass flow [kg/s]	900	200	1000	700
Temperature source [°C]	10	7	1	5
Source decrease [°C]	3	3	1	3
Salt concentration [‰]	0	0	15	30

Table 9.1.

9.3 Key Results

One key result is the average COP_t of tandem heat pump system for a given time period/season (the source and system temperatures depends season in the year). The concept of time periods is described more thoroughly in Part III Modelling of the District Heating Network of Copenhagen. For both heat pumps in the tandem system is calculated a COP_t and full load capacity, $\dot{Q}_{t,\text{FL}}$. The total COP of the system is then calculated from,

$$\text{COP}_t = \frac{\text{COP}_{t,1}\dot{Q}_{t,\text{FL},1} + \text{COP}_{t,2}\dot{Q}_{t,\text{FL},2}}{\dot{Q}_{t,\text{FL},1} + \dot{Q}_{t,\text{FL},2}} \tag{9.1}$$

Another parameter that will be used later on in the system modelling (Part III), is the seasonal performance factor (SPF), defined as,

$$\text{SPF} = \frac{\sum_t Q}{\sum_t E} \tag{9.2}$$

where $\Sigma_t Q$ is the total useful energy delivered from the heat pump during the year, and $\Sigma_t E$ is the total operating energy consumed by the heat pump during the year (compressor, pump, fans, etc.). The water pump is taken into account in the sea water heat pumps, but not for the drinking and sewage water, because these have a natural flow of water.

9.4 Auxiliary Program for COP and Capacity Calculation (COPcalc)

Designing heat pumps, as described in the previous sections, is rather complex for users not familiar with refrigeration engineering. The idea is that the operation parameters such as COP and capacities shall be used in Balmorel by scientists, engineers and consultants for analysing purposes. Users that not necessarily have the thermodynamic competences for calculating these parameters. For helping the users I developed an auxiliary program for designing heat pumps, using the thermodynamic model explained in the previous sections.

The 'Diagram Window' tool in EES is used to make a user-friendly interface. In Figure 9.3 a screen shot of the interface is shown. The screen is split into three parts; *Fixed parameters*, *Design parameters*, and *For seasonal run*.

Fixed parameters

The fixed parameters is the parameters that will change from each design, but does not change when you have designed the heat pump. Some of these are natural constant, such as the salt concentration of the source water, whereas others are a chosen constant, such as the mass flow of the source water, which is controlled by a pump. The subcooling and decrease of temperature of the source water are in this model assumed as design constants as well, because these are often determined by the heat exchangers.

Design parameters

The design parameters include the source temperature and the district heating forward temperature (i.e. indirect the evaporator and condenser temperatures), as well as the return temperature of the district heating water. When choosing 'Design' the pinch temperatures are fixed, and the calculated *UA*-values are shown above the Q, T-diagrams of the evaporator, heat exchanger, and condenser. When choosing 'Off-design' the *UA*-values are fixed, and the pinch temperatures become free variables. The EES equations for the design and off-design can be seen in Appendix D. The calculated COP and capacity are shown in bold.

Seasonal run

When the heat pump design is found, and the extreme situations (e.g. summer operation) are controlled in the off-design phase (single calculation), the program can be set to calculate a series of runs (in off-design). A macro is set to open an excel document with source temperatures, as well as return and forward temperatures listed. The program will run the defined number of timesteps (data sets in the excel sheet), e.g. 52 (weeks) or 8760 (hours in a year). After calculation the program copy the calculated COPs and capacities into the same excel sheet.

In EES I use the 'Make Distributable Program' tool, to make an executable program that can be used on any PC, no matter if EES is installed or not. The program, named COPcalc, can be downloaded from the website listed in reference: [7].

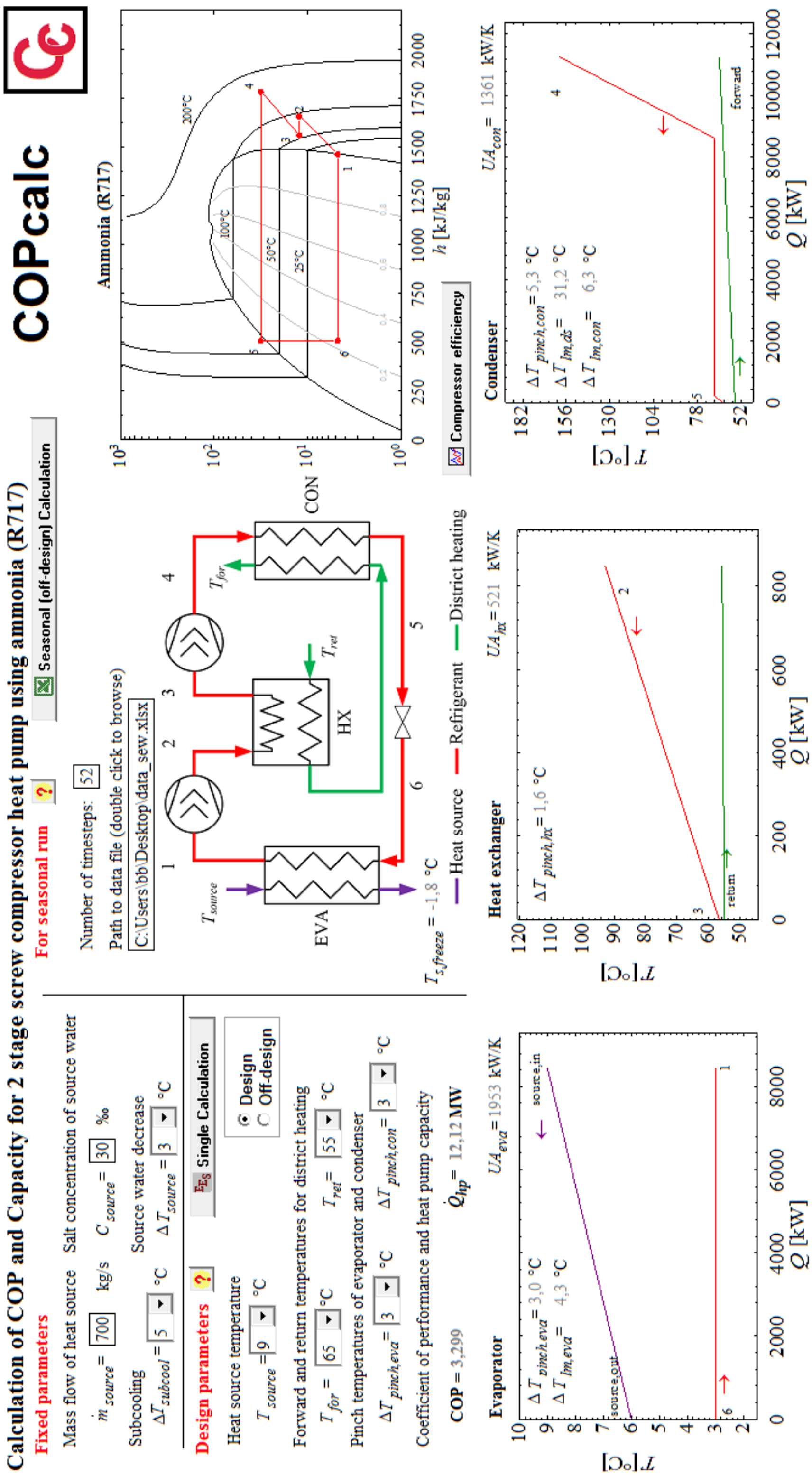


Figure 9.3: Interface of the auxiliary program for calculating seasonal COP.

10

Results on Heat Pump Calculations

In this chapter the results of the thermodynamic modelling are shown and described. They will be commented on and discussed in the next chapter.

By use of the COPcalc program found the COPs and capacities are found for the heat pumps using: sewage water, drinking water, and sea water (near) and (far). The program can only calculate for one heat pump at the time. Calculating the tandem situation, is therefore done in two steps.

Based on the values of COP_t and the corresponding values of the Copenhagen heat demand, D_t, a weighted COP^* for the entire year is calculated in the following way:

$$\text{COP}^* = \frac{\sum_t \text{COP}_t D_t}{\sum_t D_t} \tag{10.1}$$

These are shown in Table 10.1 for the heat pumps connected to the distribution and transmission grid. The COPs of the heat pumps connected to the transmission grid are 15% to 20% lower than the heat pumps connected to the distribution grid.

The seasonal COP_t for the different heat pump systems is plotted in Figure 10.1(a) and Figure 10.2(a) for the distribution and transmission grid respectively. The seasonal calculated part load capacity (i.e. the part load that depends on seasonal temperature differences) will be defined as the seasonal max capacity, $\dot{Q}_{t,\text{max}}$. The reason is that it will be used as a max capacity in the system modelling in Part II.

The variations of the seasonal max capacities are shown Figure 10.1(b) and Figure 10.2(b). In Figure 10.1(c) and Figure 10.2(c) the COP_ts of the heat pumps compared to the ideal COP (Carnot) are shown.

In Figure 10.3 examples of the Q, T-diagrams for the evaporator and condenser of the sea water (far) heat pump in winter and summer operation are shown. The diagrams are of the first heat pump in the tandem[1].

[1]Winter operation: $T_{\text{ret}} = 55°\text{C}$ to $T_{\text{int}} = 75°\text{C}$, and $T_{\text{source}} = 5°\text{C}$. Summer opereation: $T_{\text{ret}} = 55°\text{C}$ to $T_{\text{int}} = 65°\text{C}$, and $T_{\text{source}} = 18°\text{C}$.

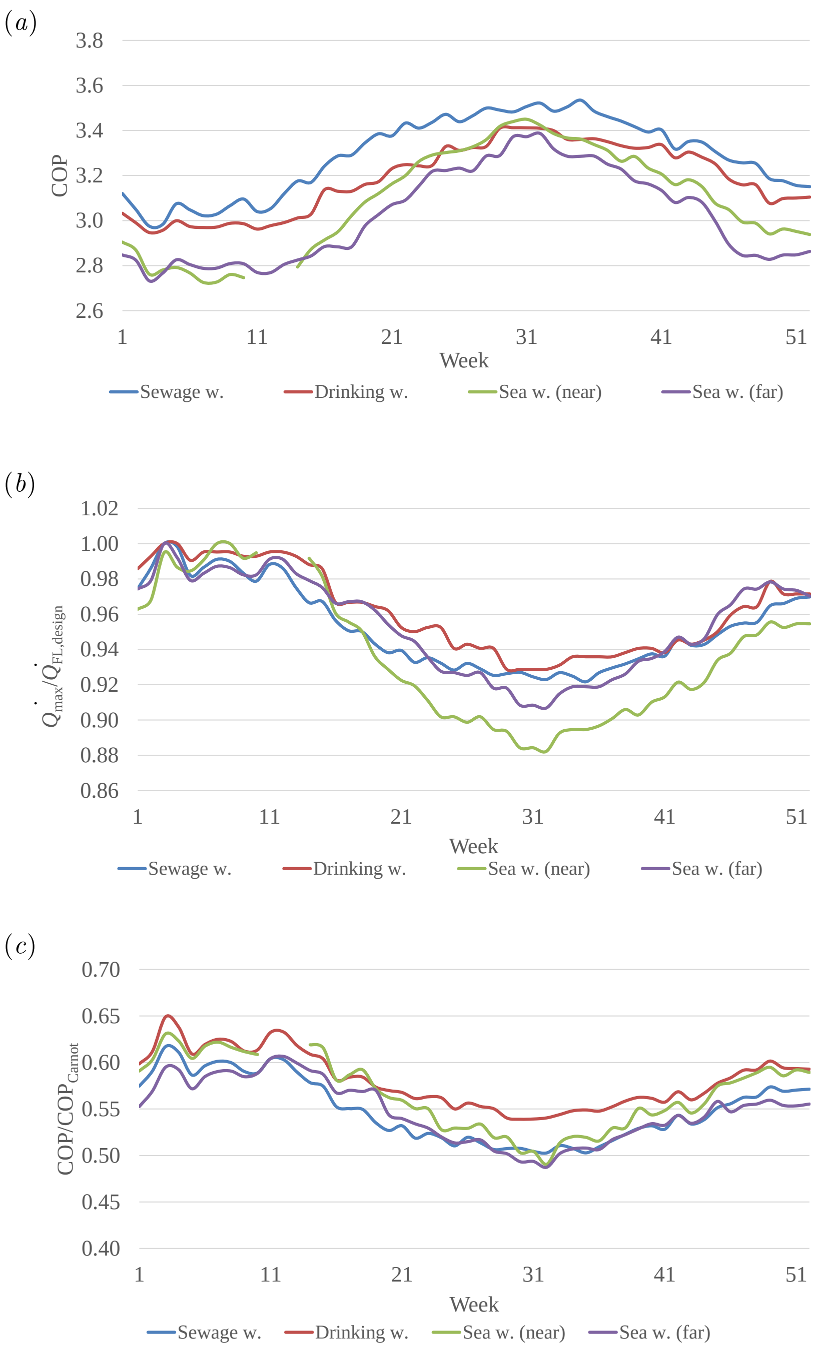


Figure 10.1: (*a*) Seasonal COP and (*b*) seasonal max capacity (part load) compared to full load capacity at design phase for sea, sewage and drinking water heat pumps connected to the **distribution grid**. (*c*) COP compared to ideal COP (Carnot). The sea water in weeks 11 to 13 were to cold in 2013 for a heat pump to utilize it. The temperature was below 1°C.

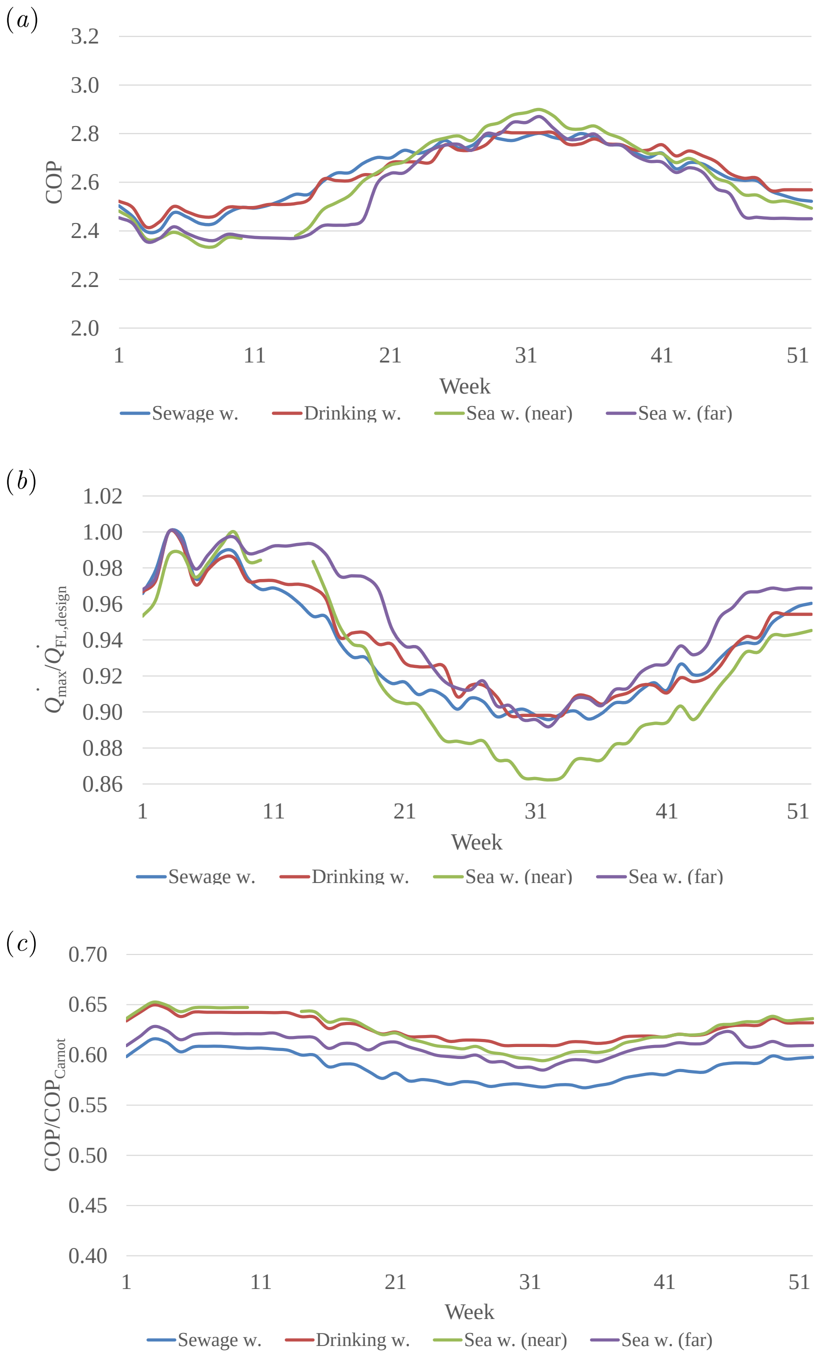


Figure 10.2: (*a*) Seasonal COP and (*b*) seasonal max capacity compared to full load capacity at design phase for sea, sewage and drinking water heat pumps connected to the **transmission grid**. (*c*) COP compared to ideal COP (Carnot). The sea water in weeks 11 to 13 were to cold in 2013 for a heat pump to utilize it. The temperature was below 1°C.

Table 10.1: Average COP* weighted by heat demand.

	Distribution grid	Transmission grid	Difference
Sewage w.	3.2	2.6	19%
Drinking w.	3.1	2.6	16%
Sea w. (near)	3.0	2.5	17%
Sea w. (far)	2.9	2.5	14%

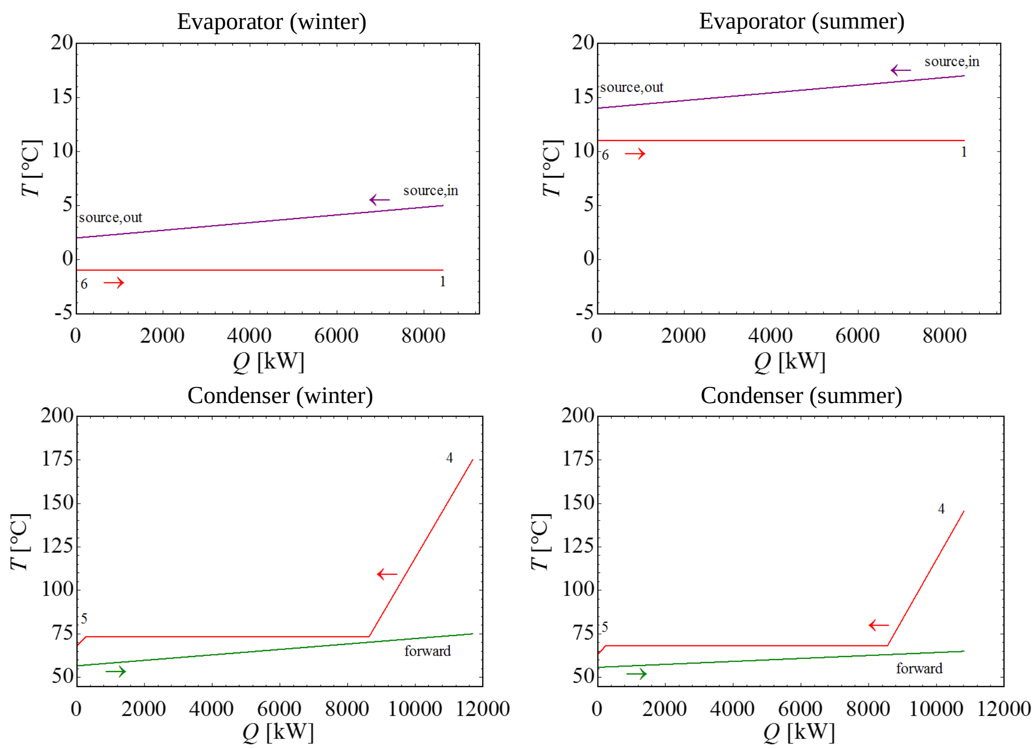


Figure 10.3: Q, T-diagrams for winter and summer operation of the first tandem heat pump utilizing sea water (far) and connected to the distribution grid. The UA-values in the given system are; $UA_{\text{eva}} = 1953$ kW/K, and $UA_{\text{con}} = 1361$ kW/K.

11

Discussion of Heat Pumps

11.1 Method Discussion

The the heat pump technology chosen is one of many possible technologies. I have assumed that a compressor exist that can make a pressure of 75 bar, which is necessary for the condensing temperature to be 110°C. At the present moment only the Vilter compressor claim to be able to do that. There has not, to my knowledge, ever been built a heat pump that can go to this temperature using purely ammonia as refrigerant. I have still assumed that this will come in a near future. The question is whether the developments of hybrid heat pumps and vapour compression heat pumps growth faster.

The design *UA*-value for the condenser is found from the logarithmic mean temperature difference in the condensing phase. The *UA*-value for the de-super-heating phase is assumed as an variable in the off-design calculations. In reality both *UA*-values should be fixed after design. The reason for only choosing the the condensing phase is for simplification of the model. It is a reasonable assumption due to the fact that the majority (around 3/4) of the heat transfer takes place in the condensing phase.

It is important to notice that the seasonal part load capacities and COPs only represent the seasonal temperature differences in the system. A heat pump can, of course, also run on demand depending part load, which also will have an influence on the COP. This part load is not represented by these calculations, and will not be calculated. For the rest of the study the part load capacities will be defined as the seasonal max capacity, $\dot{Q}_{t,\max}$.

The COPcalc program sometimes have some problems making some off-design calculations. EES performs iterative solving, meaning it generates a sequence of improving (convergent) approximations. This means that it depends on the quality of the guess (initial) values. The design mode problem in COPcalc are significantly simpler to solve for EES, than the off-design problem. A macro is developed for making sure that the guesses for each off-design calculation is updated, but if an off-design calculation is significantly more different than previous off-design calculation, the guess values will be to far from the solution and the iterations is not converging. A lot of time an effort has been used on trying to improve this, but only to some extent.

11.2 Results Discussion

The demand weighted COPs are between 2.5 and 3.2, which is in the same range as other large heat pump technologies such as the one in Drammen[88] (design COP of 3.3) using sea water as source and ammonia as refrigerant, and the sewage and sea water heat pump in Helsinki[53] with a COP of 3.5 (design) and 3 (off-design) using halocarbon as refrigerant. The CO_2 based in Frederikshavn have a COP of 2.6 to 3.2 from winter to summer[5]. Granryd et al. (2011) also list that heat pumps using lakes, seas or rivers have a production weighted COP of 2.4 to 3.3[56].

The heat pumps COP is 15% to 23% better in the summer time than in design load. The max capacities on the other hand decreases by around 8%. The reason is that the evaporator is design with a fixed ΔT_{source}. Therefore will the heat given in the evaporator be constant. The definition of COP is

$$\text{COP} = \frac{Q_{\text{hp}}}{W_{\text{com}}} = \frac{Q_{\text{source}} + W_{\text{com}}}{W_{\text{com}}} = \frac{Q_{\text{source}}}{W_{\text{com}}} + 1, \tag{11.1}$$

found by using the first law of thermodynamics,

$$Q_{\text{hp}} = Q_{\text{source}} + W_{\text{com}}. \tag{11.2}$$

From (11.1) is seen that if Q_{source} is constant and COP increases, then W_{com} decreases. And thereby decreases Q_{hp} according to (11.2).

How well the COPs are compared with the Carnot COP depends very much on the source and season. The heat pump is designed for winter operation, which also gives the highest utilization of the ideal process. In the design phase the COP is between 60% and 65% of the Carnot COP. In summer time they all drop to around 50% of the Carnot COP. This emphasise that it is important to calculate the real cycle to find the COP. It is not enough to use for instance 65% of the Carnot COP, which would be a lot easier.

The COPs of the sea water (near) and sea water (far) heat pumps are almost the same. The sea water (near) has an average COP weighted by demand of 3.0, against the 'far' options of 2.9. The difference is so small that I will still recommend the 'far' option, due to the fact that the previous study showed that there could be weeks and even months during a year that the 'near' option would be out of operation.

Connecting the heat pump to the transmission grid decreases the COP by 14% to 19%. The reason is the higher forward temperature, and thereby the higher condensing temperature (i.e. higher pressure). When connected to the distribution grid, the compressor has to create a pressure of 33 bar in the summer time ($T_{\text{for}} = 70°\text{C}$). Connecting the heat pump to the transmission grid, yields a pressure of 63 bar ($T_{\text{for}} = 100°\text{C}$), i.e. almost twice as high.

The transmission grid connected heat pump has a more stable COP when compared to the Carnot COP. The individual heat pumps COP only vary around 5% from the mean utilization of the Carnot COP. For the sewage water heat pump an average of 59% of the Carnot COP could be used for further calculations.

11.3 Investment Costs of Heat Pumps

Estimates from Granryd et al. (2011)[56] gives investment costs of a sea water heat pump between DKK 1.9 mill. per MW_{th} and DKK 6.0 mill. per MW_{th}. The costs of a 5 MW_{th} sewage water heat pump from ICS Energy is around DKK 11 mill. (DKK 2.2 mill. per MW_{th})[1]. The

[1] Private conversation with Torben Henriksen[63] from ICS Energy.

1 MW_{th} CO_2 heat pump in Frederikshavn had a total investment cost of DKK 5 mill.[80] (auxiliary equipment and implementation costs included). The total investment of a heat pump alone using a natural source seems to be between DKK 2 mill. per MW_{th} to DKK 4 mill. per MW_{th}. This is exactly the same range (€ 0.3 mill. to € 0.5 mill.) as the Danish Energy Agency list in their technology catalogue of larger generation technologies[47].

Part III

Modelling of the District Heating Network of Copenhagen

12

Introduction to Modelling and Scenarios

As mentioned before a lot of politicians, organisations, and energy experts talk about heat pumps as an integrated part of the future district heating systems. The question is; is the implementation realistic? Ommen et al. (2013)[96] showed that by implementing the correct capacity of heat pumps, would give a 1.6% reduction in fuel consumption. Münster et al. (2012)[92] found in all their scenarios (reference, saving and regulation) that individual heating will be based on heat pumps in 2025, where as the heat pump integration in the district heating system will be negligible. Both of these studies have analysed the heat pumps as a homogeneous mass, and the integration does not take into consideration if there is a heat source of an appropriate size in the area where it is invested. Instead of getting a model yo optimise the location and capacity of heat pumps, how competitive would they be if placed in areas and with the capacities obtained in the previous part about potential of heat sources?

Most studies of heat pump integration in Copenhagen have assumed a constant COP in their simulations[21, 61, 62, 92, 96]. Whether or not this is a good assumption have not been investigated, which makes it rather interesting to study if this has a significant impact on the results.

Another thing is whether to connect the heat pumps to the distribution grid or the transmission grid. Connecting them to the distribution grid has the advantage that the temperature lift is smaller, i.e. the COP is better. Connecting them to the transmission grid gives an smaller COP, but the production is not limited to the distribution area demand, i.e. it can compete with neighbouring generation technologies.

All these discussions suggest three main questions to answer;

1. Is integration of heat pumps competitive in the district heating system?
2. What is the impact of seasonal dependent COP versus constant COP on the results?
3. Is it best to connect heat pumps to the distribution or the transmission grid?

These questions will be answered in this part of the report. The next section will give an introduction to mathematical modelling, and the next chapter will give an introduction to the model used for this study, Balmorel. In Chapter 14 the scenarios is described, and hereafter is described the actual modelling of Balmorel so it can be applied to model the scenarios.

12.1 Introduction to Mathematical Modelling

Mathematical modelling is trying to describe a system with mathematical concepts and language. It is used for solving problems, in a huge amount of areas such as logistic, physics, programming, economic, social science, statistics, etc. For this study it is used for system analyses, and especially analyses of energy systems with optimization of the economy (i.e. minimizing the total costs).

An example of a very simple system, is a heat pump supplying heat to an area with a given demand. The heat pump (hp) has a certain capacity and can supply to the demand area or to a heat storage (hs). The storage has a certain energy volume and can also supply to the area with the same capacity as the heat pump. A sketch of the system is shown in Figure 12.1. The system can be described by the mathematical model in (12.1). The first equation (12.1a) is called the *objective function*, which is *subject to* (s.t.) to the equations below (constrains). In an optimization it is the objective function that is minimized (e.g. cost or CO_2 emission) or maximized (e.g. profit) to find the optimal solution.

$$\min \quad \sum_t V_t^{\text{hp}} C_t (\eta_t^{\text{hp}})^{-1} \tag{12.1a}$$

$$\text{s.t.} \quad V_t^{\text{hp}} + V_t^{\text{hs,dch}} - V_t^{\text{hs,ch}} = D_t^{\text{dh}}, \quad \forall\ t \tag{12.1b}$$

$$V_t^{\text{hs}} = V_{t-1}^{\text{hs}} + V_{t-1}^{\text{hs,ch}} \eta^{\text{hs}} - V_{t-1}^{\text{hs,dch}} (\eta^{\text{hs}})^{-1}, \quad \forall\ (t > 1) \tag{12.1c}$$

$$u_t\, L^{\text{hp,min}} \leq V_t^{\text{hp}} \leq u_t\, L^{\text{hp,max}}, \quad \forall\ t \tag{12.1d}$$

$$L^{\text{hs,min}} \leq V_t^{\text{hs}} \leq L^{\text{hs,max}}, \quad \forall\ t \tag{12.1e}$$

$$\alpha_t\, L^{\text{hs,min}} \leq V_t^{\text{hs,dch}} \leq \alpha_t\, L^{\text{hs,max}}, \quad \forall\ t \tag{12.1f}$$

$$\beta_t\, L^{\text{hs,min}} \leq V_t^{\text{hs,dch}} \leq \beta_t\, L^{\text{hs,max}}, \quad \forall\ t \tag{12.1g}$$

$$\alpha_t + \beta_t \leq 1, \quad \forall\ t \tag{12.1h}$$

$$V_t^{\text{hp}}, V_t^{\text{hs,dch}}, V_t^{\text{hs,ch}}, V_t^{\text{hs}} \geq 0, \quad u_t, \alpha_t, \beta_t \in \{0, 1\}, \quad \forall\ t \tag{12.1i}$$

The set t indicate the time period. The notation V indicate a positive variable, and the η, D, L and C indicate a efficiency (or COP), demand, limit and cost parameter respectively. α, β and u are binary variables. The notation $\forall\ t$ means *for all t*. The objective function (12.1a) defines the total cost of producing heat with a heat pump. Equation (12.1b) is the demand balancing equation, defining the supply and demand. Equation (12.1c) explains the heat storage level. The equations (12.1d) to (12.1g) are limiting restrictions, making sure that the heat pump capacity, charge and discharge from the heat storage, and storage volume are within the limits given. Equation (12.1h) makes sure that the storage can not charge and discharge at the same time.

If the problem do not have binary variables and non of the variables are in a order different than 1, then it is called a linear programming problem. If a problem like that only has one or two variables it can easily be solved by hand, but with a problem like the above with four positive variables and three binary variables, then a computer has to be used (or a damn lot of time and luck). In Appendix E is shown the model (12.1) written in the mathematical optimization language GAMS[54].

By running the model (12.1) for a household with a total yearly heat demand of 8700 kWh_{th} using an air source 3 kW_{th} heat pump and a 3 kWh_{th} heat storage gives the operation shown in Figure 12.2.

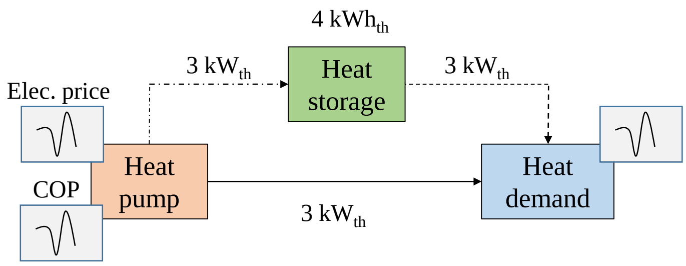


Figure 12.1: Sketch of a simple heat pump operation model.

The principles of this simple model have to be integrated in the Balmorel model, which will be explained in the following chapters.

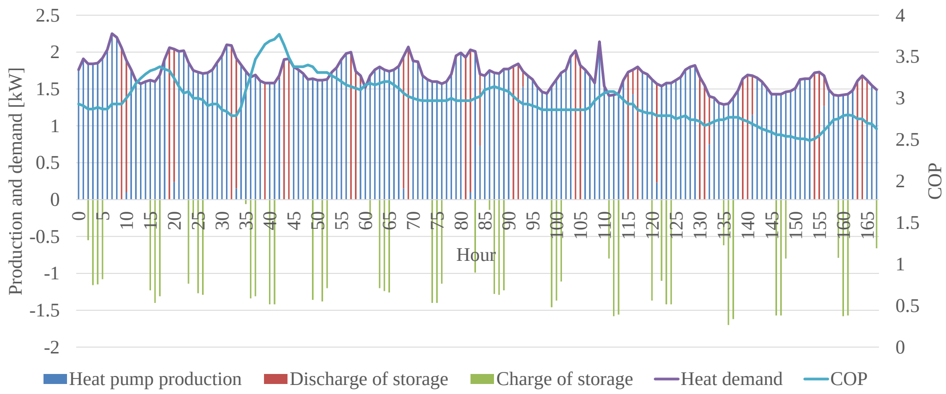


Figure 12.2: Results of a household use of an air source 3 kW$_{th}$ heat pump with a 3 kWh$_{th}$ heat storage in week 10 in 2012.

13

Introduction to Balmorel

Balmorel is energy systems analysing model, with focus on electricity and heat, developed by Ravn et al. in 2001[101]. Balmorel is a bottom-up economical dispatch model, that minimizes cost of the system, covering operational and maintenance, emission, and fuel costs. Balmorel assumes perfect competition in the system, and is deterministic assuming perfect foresight. The model was developed for analysing the Baltic Sea regions, but has over time been expanded and has also been used in projects in Austria, Ghana, Mauritius, Canada, China, Ireland and Great Britain.

Balmorel has different versions used for different studies. Add-ons can be applied for time aggregation, unit commitment, investments, policy requirements, etc. The version applied for this study uses unit commitment, which includes start-up costs, minimum loads required, and part load efficiencies. The version used does not include renewable energy requirements or automatic investments in new technologies[1].

The following sections explain the model's structure concerning geographic and time structures, generation technologies, fuels, demands, transmissions, and taxes.

13.1 Geographic Structure

The model has three main types of geographical units; countries, regions and areas. Each country contains a number of regions, and each region a number of areas.

Countries describe the overall regulatory framework and economical data of a set of regions (see Figure 13.1). The country *Denmark* has two regions, *Western Denmark* and *Eastern Denmark*, both with the same taxes (e.g. CO_2 tax) and political restrictions (e.g. maximum emission level).

Regions represent the transmission aspects and thereby the different electricity prices. Data included on a regional level is total electricity demand and demand profiles, plus elasticity, and the electric transmission capacity between the regions[101].

On an area level heat demands and consumption profiles are given. Technologies are placed in an area, which determined what region it belongs to (for electricity generation), as well as to where the technology can supply heat[101]. A technology can only supply heat to the

[1] Investment runs are however used to find price profiles for 2025 as explained in section 14.2 Assumptions and Data

area where it is located, unless the area is connected with a heat transmission line to another area (as is the case in this Greater Copenhagen study). Capacity profiles and full load hours for solar, run-of-river hydro plants and wind farms are also given on an area level.

13.2 Time Structure

Balmorel's time structure is split into three units; years, seasons and timesteps. Here is distinguished between *input-time* and *simulated-time*. Input-time units are the time structure used for input of data. As input-time a year consists of 52 seasons (weeks), and each season consists of 168 timesteps (hours in a week). The simulated-time can be time aggregated for improvement of the run time of the simulation. So fewer time units represent for instance work hours, peak, base and weekend hours. Depending on the Balmorel options chosen the simulation can be individual weeks or year split into seasons (e.g. summer/winter, months, etc.). The best resolution is, of course, the same as the input-time structure.

Choosing what simulated time structure to use depends on the study. If the study concerns the average electricity prices or total costs of a whole system, then an aggregated time structure could work fine. But if the study investigate how technologies interact between each other or how a curtain technology is used then a higher time resolution is needed. This is illustrated in the plot from Ravn et al.[101] shown in Figure 13.2, where the total cost of a system does not change much for the time structure cases, but the use of a hydro storage is highly depended on the selection of time structure.

13.3 Generation Technologies

Generation of electricity and heat can overall be classified into five types; back-pressure power plants, extraction plants, electricity only generation (e.g. condensing plants and wind turbines), heat only boilers, and electric heaters/heat pumps. In Figure 13.3(a) and (e) the types' feasible operation area is shown. Besides the generation types there are two kinds of storage; electricity storage (e.g. pumped hydro) and heat storage (e.g. accumulation tanks). The electricity only generation is of course split into a lot of very different technologies, such as condensing power plants, wind turbines, photovoltaics, and hydro run-of-river. The only thing they have in common is that they do not produce any heat.

Each technology is further characterized by a number of constant physical and economical values, such as fuel type, efficiency (COP), C_b and C_v values (see Figure 13.3(a) and (b)), variable and fixed costs, etc.

The generation technologies of Greater Copenhagen consist of 760 MW_e back-pressure units, and 500 MW_e extraction units. Besides that there is 175 MW_th base load heat-only units, in the order of 2 GW_th peak load units[2] for heat distributed all around the distribution areas, and 2730 MW_th heat accumulators. The units are listed in Appendix F. The physical and economical parameters for the specific plants are classified. Table 13.1 shows a range of approximate values.

13.4 Fuels

The fuels have some physical characteristics such as CO_2 and SO_2 emissions, as well as economical parameters such as fuel prices and taxes. The economical parameters are geographical restricted, i.e. given on a country or area basis.

[2]In the model is used 17 GW_th, to be sure that there are sufficient capacity to supply demand.

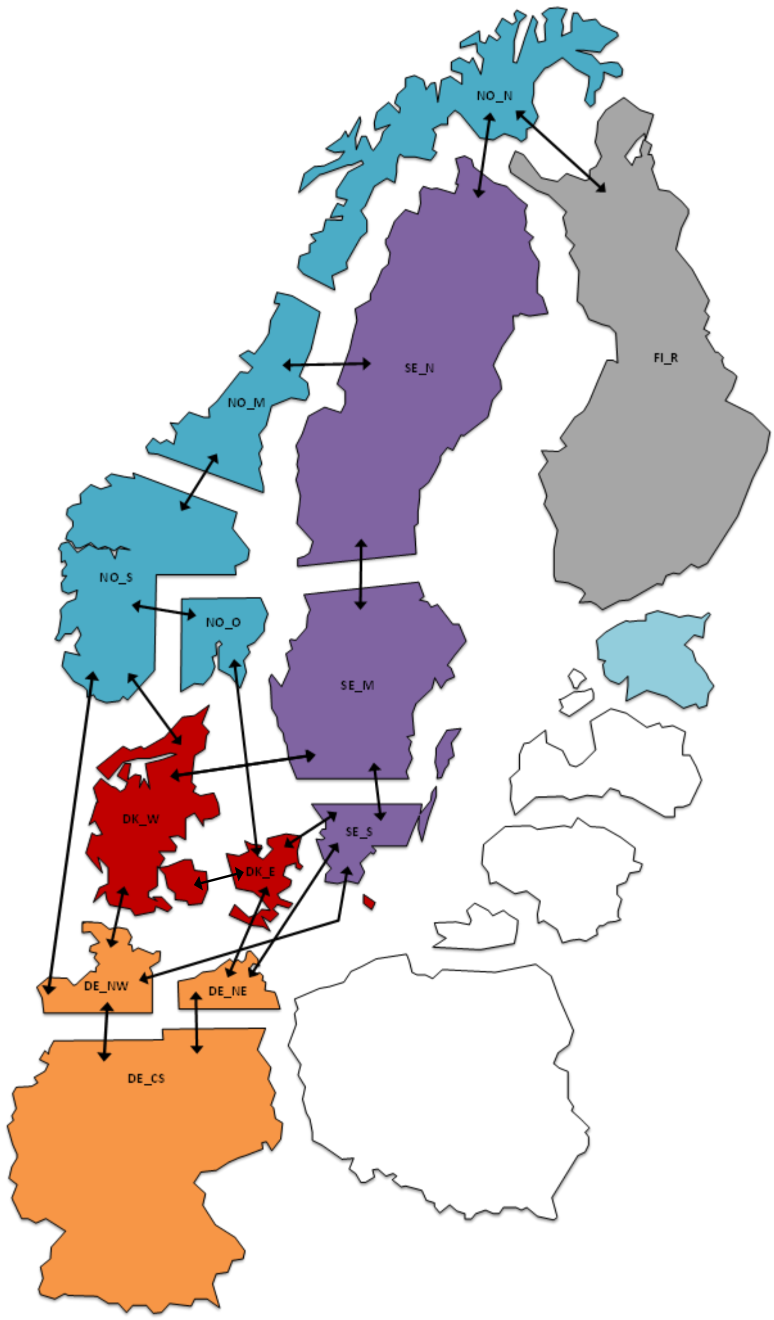


Figure 13.1: Schematic sketch of the regions and connections in Balmorel. The colors indicate countries, whereas the fractions connected with arrows indicate regions. (Sketch made by Niels-Peder Nimb and Rune Brus, Ea Energy Analyses)

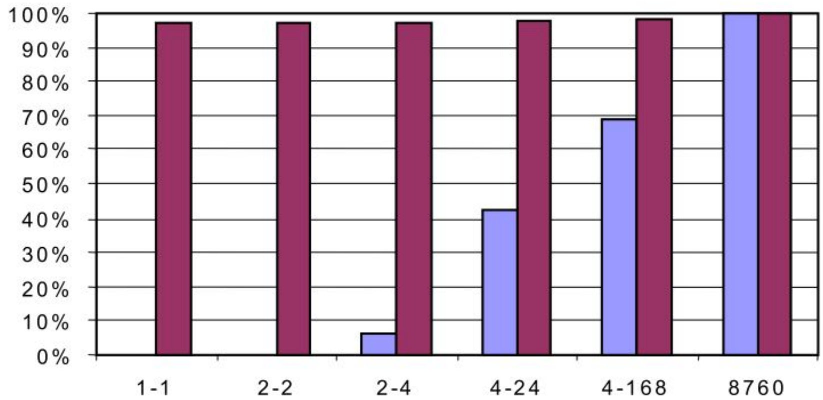


Figure 13.2: Plot from Ravn et al.[101, fig. 6.11] illustrating the importance of using the right simulation time structure. Purple bars are the total cost and blue bars are a hydro-storage use on the market (both normalized). 1-1 means that the year is split into 1 season with 1 time period (i.e. no subdivision of the year), 2-2 means 2 seasons with 2 time periods, and so on. 8760 is all hours in a year[101, p. 62].

Table 13.1: Parameters of the generation technologies. Fixed costs in mill. DKK/MW$_e$ for back-pressure and extraction and in mill. DKK/MW$_{th}$ for heat-only boilers. Variable costs are in DKK/MWh$_e$ for back-pressure and in DKK/MWh$_{th}$ for heat-only boilers. For back-pressure and heat-only the efficiency is the thermal fuel efficiency, and for extraction it is the electrical fuel efficiency.

	Back-pressure	**Extraction**	**Heat-only boilers**
Fuel efficiency	0.8-1.0	0.3-0.5	0.7-1.0
C_b-value	0.2-0.8	0.6-0.7	0
C_v-value	0	0.1-0.3	0
Fixed cost	0.2-6.0	0.1-1.0	0.02-0.6
Variable cost	5.0-95.0	5.0-95.0	5.0-95.0

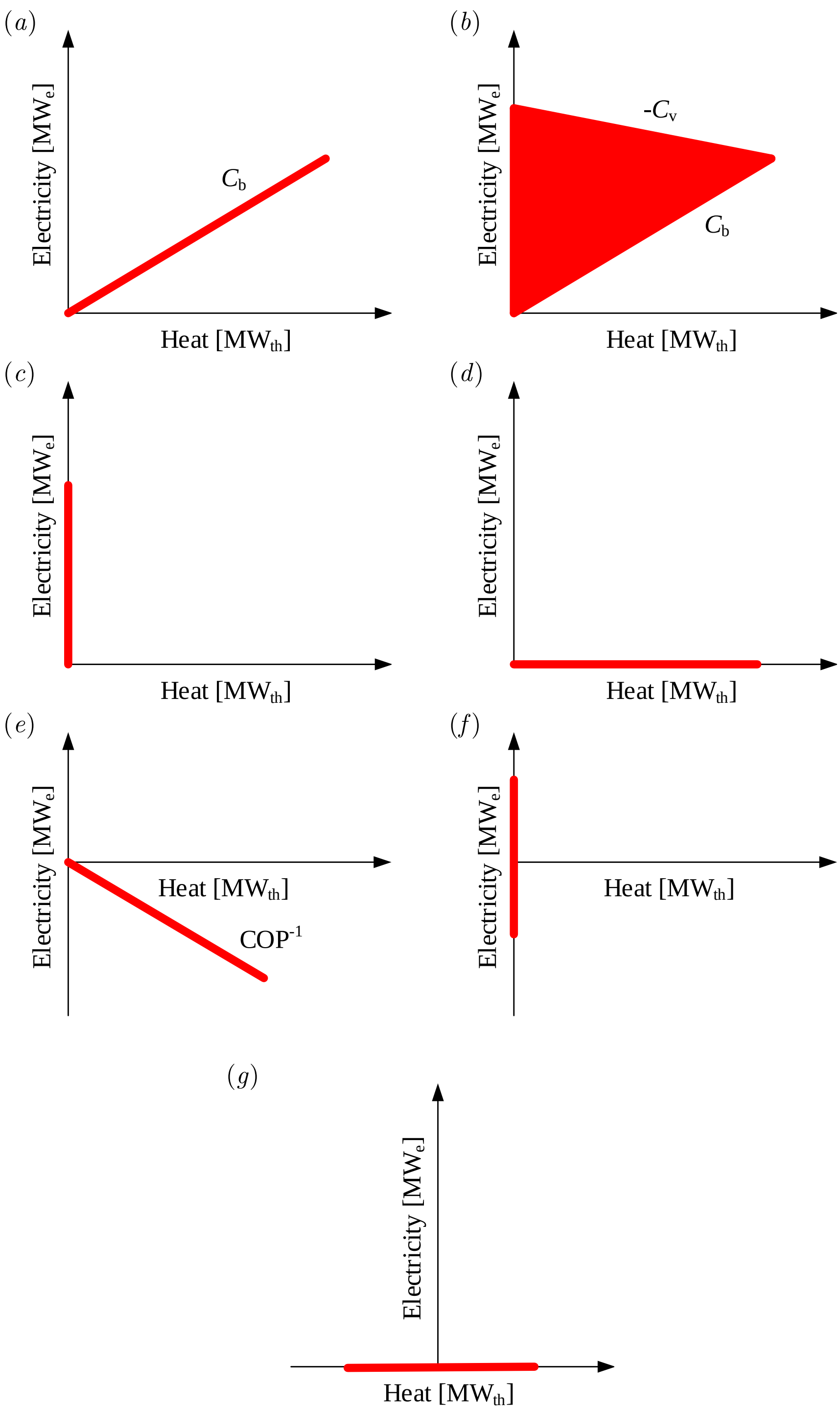


Figure 13.3: Feasible operation areas for different generation types; (*a*) back-pressure power plant, (*b*) Extraction power plant, (*c*) condensing power plant, wind turbines, photovoltaic, and hydro plant, (*d*) heat only boiler, (*e*) electric heater/heat pump, (*f*) electricity storage, and (*g*) heat storage.

The limitations of fuels are set as a geographical parameter. Waste could for instance be restricted on an area level, whereas oil shale could be on country level.

13.5 Demand

Demand of electricity and heat is specified as the total annual nominal demand on an area and a region respectively. The nominal demand is then distributed onto a nominal demand profile specified for each area or region. An elasticity function then provides the relation between quantity and prices for deviation from the nominal demand profiles[101].

13.6 Transmission

Transmission of electricity is possible between regions, whereas the heat is as standard restricted to be consumed in the same area that it is produced.

An exception is the model of the district heating system of Copenhagen. The district heating network of the Greater Copenhagen area in Balmorel is shown in Figure 13.4, and an explanation of the areas is listed in Table 13.2. The structure was made by Ea Energy Analyses in dialogue with the distribution companies.

Table 13.2: Greater Copenhagen district heating areas in Balmorel[22].

Name	**Areas (Cities)**	**Distribution company**
VEKV	Roskilde/Hedehusene/Taastrup	VEKS
VEKN	Hvidovre/Glostrup/Albertslund	VEKS
CAML	Amagerland	CTR
CHUS	Brønshøj/Husum/Vanløse	CTR
CMID	Frederiksberg/Nørrebro	CTR
CNOR	Gladsaxe/Gentofte	CTR
COST	Østerbro	CTR
CVAL	Valby	CTR
NORDHAVN	Nordhavn	CTR
VESTERBRO	Vesterbro	CTR
CTAR	Tårnby	CTR
VF	Herlev/Ballerup	Vestforbrænding
DHCV	Steam Centrum	HOFOR
DSMV	Steam Østerbro	HOFOR
KONN	Converting area North (Østerbro)	HOFOR
KONS	Converting area South (Centrum)	HOFOR

13.7 Objective Function and Constrains

This section gives an overview of the most important parts of the Balmorel model. Some of the equations are simplified to save space and to help clarify the most important terms and constrains. The sets, parameters and variables are listed below.

Sets

a	Areas
c	Countries
e	Emissions (e.g. CO_2, SO_2 and NO_x)
f	Fuel types

g	Generation technologies
r	Regions
t	Time periods (include both year, season and timesteps)
$\mathbb{A}_x$	Subset of areas a containing all exporting areas of a
$\mathbb{A}_c$	Subset of areas a in country c
$\mathbb{A}_r$	Subset of areas a in region r
$\mathbb{G}^{\text{th.}}$	Subset of g including all thermal generation technologies
$\mathbb{G}^{\text{e.h.}}$	Subset of g including all electric heaters and heat pumps
$\mathbb{R}_x$	Subset of regions including all exporting regions of r

Parameters

$C^{\text{fuel}}_{a,f}$	Cost of fuel f in area a [DKK/MWh]
$C^{\text{om,v.}}_{a,g}$	Cost of variable O&M for generation technology g in area a [DKK/MWh]
$C^{\text{om,f.}}_{a,g}$	Cost of fixed O&M for generation technology g in area a [DKK/MW]
$C^{\text{trans.,el.}}_{r_1,r_2}$	Cost of electricity transmission between region r_1 and r_2 [DKK/MWh]
$C^{\text{tax,em.}}_{c,e}$	Cost of tax for emission e in the country c [DKK/kg]
$C^{\text{tax,fuel}}_{c,f}$	Cost of tax on fuel f in country c [DKK/MWh]
$D^{\text{el.}}_{a,t}$	Demand electricity in region r to time period t [MWh]
$D^{\text{heat}}_{a,t}$	Demand heat in area a to time period t [MWh]
$E_{g,e}$	Emission factor on emission e for generation technology g [kg/MWh]
$G^{\text{cap.}}_{a,g}$	Generation capacity of generation technology g in area a [MW]
$L^{\text{trans.,el.}}_{r_1,r_2}$	Limit of transmission capacity between region r_1 and r_2 [MW]
Z_g	$\begin{cases} C_{\text{v}} & \text{for extraction} \\ 1 & \text{other} \end{cases}$
$\eta^{\text{gen.}}_g$	Fuel efficiency of generation technology g (see Table 13.1) [-]
$\eta^{\text{trans.,el.}}_{r_1,r_2}$	Transmission connection efficiency (derate factor) [-]

Variables

$V^{\text{con.,fuel}}_{a,g,t}$	Fuel consumption of generation technology g in area a to time t [MWh]
$D^{\text{dem.,el.}}_{a,g,t}$	Demand electricity of technology g in area a to time period t [MWh]
$V^{\text{gen.,el.}}_{a,g,t}$	Electric generation of generation technology g in area a to time t [MWh]
$V^{\text{gen.,heat}}_{a,g,t}$	Heat generation of generation technology g in area a to time t [MWh]
$V^{\text{trans.,el.}}_{r_1,r_2,t}$	Electricity transmission between region r_1 and r_2 to time t [MWh]

In (13.1), significant parts of the objective function are shown. Balmorel seeks to minimize the costs of the whole system, such that the entire system performs as cost efficient as possible.

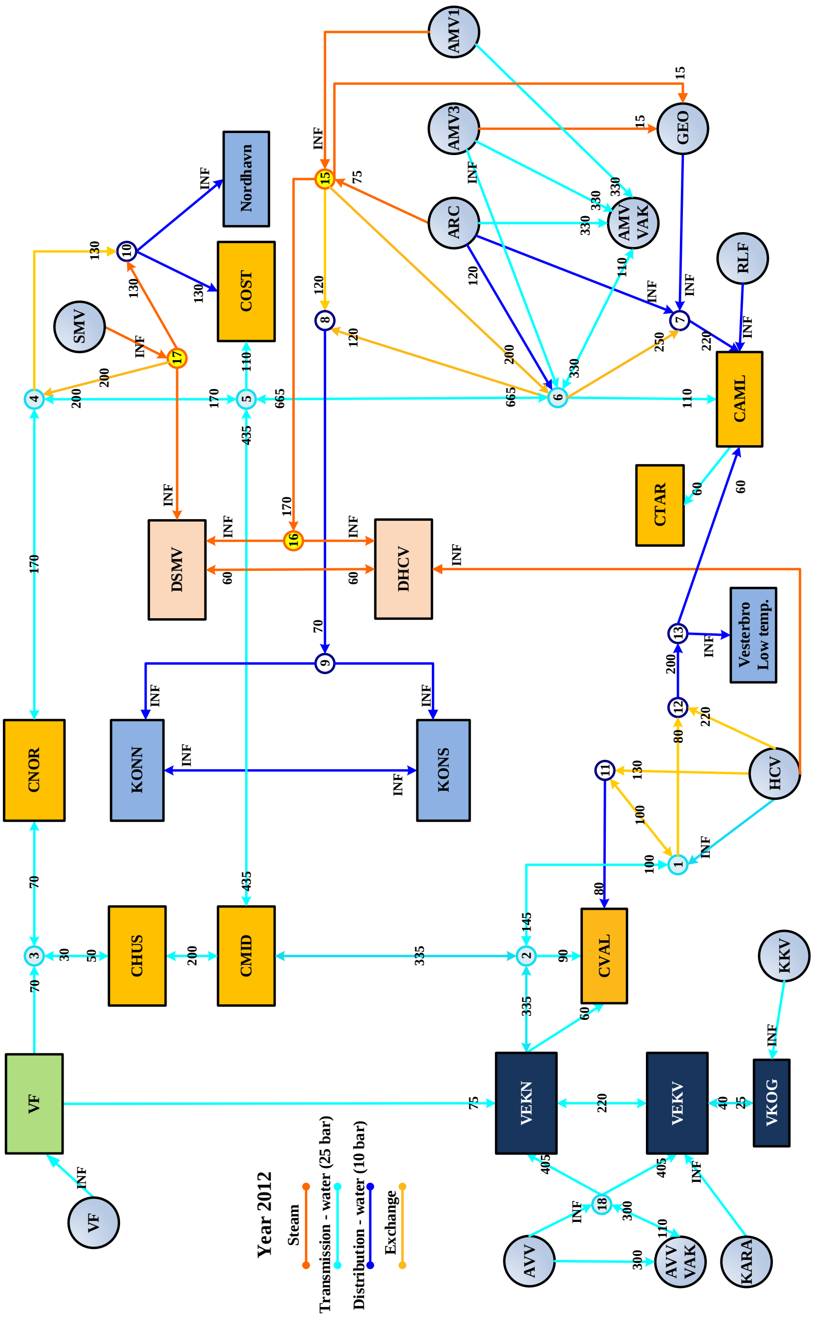


Figure 13.4: Structure and connections in the transmission grid of the Copenhagen area in 2012. See Table 13.2 and Table 2.1 for explanation of areas and generation technologies respectively. Circles represents production areas, and squares consumer areas. The colors of the consumer areas indicate which distribution company is responsible (see Table 13.2). (Original figure taken from VPH3 note about the heating network in the Greater Copenhagen area 2012 and 2025[22])

$$\min \quad \sum_{a,g,f} \left(C^{\text{fuel}}_{a,f} \sum_{t} V^{\text{con.,fuel}}_{a,g,t} \right) \tag{13.1a}$$

$$+ \sum_{a,g} \left(C^{\text{om,v.}}_{a,g} \sum_{t} V^{\text{gen.,el.}}_{a,g,t} \right) \tag{13.1b}$$

$$+ \sum_{a,g} C^{\text{om,f.}}_{a,g} G^{\text{cap.}}_{a,g} \tag{13.1c}$$

$$+ \sum_{r,r_x} \left(C^{\text{trans.,el.}}_{r,r_x} \sum_{t} V^{\text{trans.,el.}}_{r,r_x,t} \right) \tag{13.1d}$$

$$+ \sum_{c} \sum_{a \in \mathbb{A}_c, g} \left(\sum_{t,e} E_{g,e} V^{\text{con.,fuel}}_{a,g,t} C^{\text{tax,em.}}_{c,e} \right) \tag{13.1e}$$

$$+ \sum_{c,f,t} \left(\sum_{a \in \mathbb{A}_c, g} C^{\text{tax,fuel}}_{c,f} V^{\text{con.,fuel}}_{a,g,t} \right) \tag{13.1f}$$

The first term (13.1a) represents the fuel cost. The next two terms (13.1b) and (13.1c) are the variable and fixed O&M costs, respectively. The term (13.1d) is the transmission cost of electricity. Cost of taxes on emissions and fuels is formulated in (13.1e) and (13.1f) respectively. The objective function is then subject to (s.t.) the constrains:

$$\text{s.t.} \sum_{a \in \mathbb{A}_r} \sum_{g} V^{\text{gen.,el.}}_{a,g,t} + \sum_{r_x} \left(V^{\text{trans.,el.}}_{r_x,r,t} - V^{\text{trans.,el.}}_{r,r_x,t} \right) = D^{\text{el.}}_{r,t}, \quad \forall\ r, (r_x \in \mathbb{R}_x), t \tag{13.2}$$

$$\sum_{g} V^{\text{gen.,heat}}_{a,g,t} = D^{\text{heat}}_{a,t}, \quad \forall\ a, t \tag{13.3}$$

$$V^{\text{trans.,el.}}_{r,r_x,t} \leq L^{\text{trans.,el.}}_{r,r_x} \eta^{\text{trans.,el.}}_{r,r_x}, \quad \forall\ r, (r_x \in \mathbb{R}_x), t \tag{13.4}$$

$$V^{\text{trans.,heat}}_{a,a_x,t} \leq L^{\text{trans.,heat}}_{a,a_x} \eta^{\text{trans.,heat}}_{a,a_x}, \quad \forall\ a, (a_x \in \mathbb{A}_x), t \tag{13.5}$$

$$V^{\text{con.,fuel}}_{a,g,t} = \frac{V^{\text{gen.,el.}}_{a,g,t} + V^{\text{gen.,heat}}_{a,g,t} Z_g}{\eta^{\text{gen.}}_g}, \quad \forall\ a, t, (g \in \mathbb{G}^{\text{th.}}) \tag{13.6}$$

$$D^{\text{tech.,el.}}_{a,g,t} = \frac{V^{\text{gen.,heat}}_{a,g,t}}{\eta^{\text{gen.}}_g}, \quad \forall\ a, t, (g \in \mathbb{G}^{\text{e.h.}}) \tag{13.7}$$

The constraint (13.2) is the electricity production and consumption equation, balancing the supply and demand. The balancing of heat generation and demand is formulated in (13.3). The limitation of electricity and heat transmission is formulated in (13.4) and (13.5) respectively. Equation (13.6) gives the fuel consumption of the generation of electricity and heat. And equation (13.7) is the heat generation from electric heaters such as heat pumps.

13.8 Strengths and Weaknesses

One of Balmorel's biggest strengths is that it is open source, and therefore constantly being developed on. Balmorel has a number of add-ons that can be chosen depending on the required level of detail. It is built upon the optimisation modelling system GAMS, which is a high level modelling language for mathematical programming problems[54]. This makes Balmorel a power-full optimisation model, but at the same time makes it rather complex for new users to learn. Its interface is code and it consists of a lot of separate files. Another energy model like PLEXOS, which is a market modelling and simulation software also built upon mathematical programming, has a user-friendly desktop interface[49]. This makes PLEXOS more user-friendly than Balmorel, but PLEXOS is usually a closed commercial piece of software, which means that it can be modified and developed by the individual user only to limited degree[35].

STREAM is another energy model with a user-friendly interface. This model is build upon MS Excel, which makes it very easy to use. It is very easy and quick to set up scenarios in STREAM, and in contrast to Balmorel it can not only model the electricity and heat, but also the transport and industry sectors. A weakness of STREAM is that it considers the whole system as a single isolated region. This means that heat could be produced in Jutland and used on Sjælland. STREAM is not an optimisation model, and the output is a snapshot of the whole year. Balmorel has the advantage that it can split the system into regions and areas, and that it optimises each timestep during the year.

There are a number of reasons for why Balmorel is chosen as the model for this study.

- It is a strong model that allows to analyse both the electricity and district heating market.
- The level of detail of Copenhagen's electricity and district heating market is already rather high. It is possible to split the heat demand into different district heating areas and connect these with transmission lines.
- Balmorel is not a 'black box', which means that it is possible to model Balmorel to the project's needs. Which will be necessary for this study.
- The fact that it is an optimization model making it possible to find the best solution under given constrains. It provide results on an hourly basis, which is necessary for analysing a specific technology's (e.g. a heat pump) influence and operation.

14

Building of Scenarios

14.1 Scenarios

As mentioned before there are three main questions that could be interesting to investigate.

1. Is integration of heat pumps in the district heating system competitive?
2. What impact does seasonal dependent COP versus constant COP have on results?
3. Is it best to connect heat pumps to the distribution or the transmission grid?

To answer these questions, four scenarios are set up. All four scenarios are analysed for the years 2013 and 2025.

REF - Reference

- No heat pump integration

FCOP - Fixed COP

- Heat pump integration
- Fixed COPs and full load capacities
- Connected to the distribution grid

VCOP_DIS - Variable COP (distribution grid)

- Heat pump integration
- Time dependent COPs and full load capacities
- Connected to the distribution grid

VCOP_TRANS - Variable COP (transmission grid)

- Heat pump integration
- Time dependent COPs and full load capacities
- Connected to the transmission grid

14.2 Assumptions and Data

Most of the data used is already found collected and implemented in the model by Ea Energy Analyses. The key inputs and assumptions are listed below. Plots showing the key inputs are shown in Appendix G.

Fuel prices
Fuel price scenarios are from IEA's World Energy Outlook 2012[69].

CO_2 prices
The CO_2 prices are from scenarios made by Ea Energy Analyses in dialogue with the Danish Energy Agency. They are based upon a number of analyses mentioned in the DE Delft report made by de Bruyn et al. (2013)[14], and the prices used by the Ministry of Finance for their growth plan (Vækstplan.dk).

Taxes and subsidies
For 2013 the taxes are the historical ones. For the forecast is used practised Danish law where electricity subsidies are deflating over time, and taxes are kept constant.

Electricity demand
The forecast of the Danish electricity demand is from Energinet.dk[45].

District heating demand
The forecast of the district heating demands of the Greater Copenhagen areas are made by Ea Energy Analyses in dialogue with HOFOR, CTR and VEKS. The areas total heat demand can be seen in Figure 14.1. The areas annual demand for 2013 and 2025 can be seen in Figure 14.1.

The electricity prices are assumed unchanged by the integration of heat pumps in the system.

To improve the simulation time all of the Nordic Countries are not simulated every time[1]. Instead is applied an electricity price profile for 2013 and 2025 on to Eastern Denmark. For this to be possible some modifications in Balmorel have to be done, which are explained the the next chapter. The 2013 electricity price profile is the historical one from Nordpool Spot[94].

The 2025 electricity price profile is obtained by running an investment simulation in Balmorel with the Nordic Countries plus Germany. In the investments run, data from the Nordic Countries on decommissioning of plants and forecasts of electricity and heat demand[41], are used. Investments in coal plants are not allowed. To optimize the simulation time, the year of the investment simulation (2025) is split into four seasons and is time aggregated. The investments made in that simulation are then used as normal parameters (generation capacity, transmissions, etc.) in the second run, which uses the highest resolution so an hourly spot price throughout the year is obtained. In Figure 14.2 is shown the obtained price profile from the simulation.

Another thing that is done to optimize the simulation time (which can be very long when running unit commitment), is to only run a week in each month. The specific weeks are chosen from to the be the last week in each month. In Figure 14.3) the simulated weeks are shown. Considerations of to what extent the weeks are representative for the individual months have not been taken into account. By during this the simulation time is decreased from hours to around 10 minutes. The results are afterwards modified to show the yearly or monthly values.

The standard network analysed is the one showed in Figure 13.4 for 2013, and for 2025 it can be seen in Figure G.4 on page 143.

[1] which takes hours

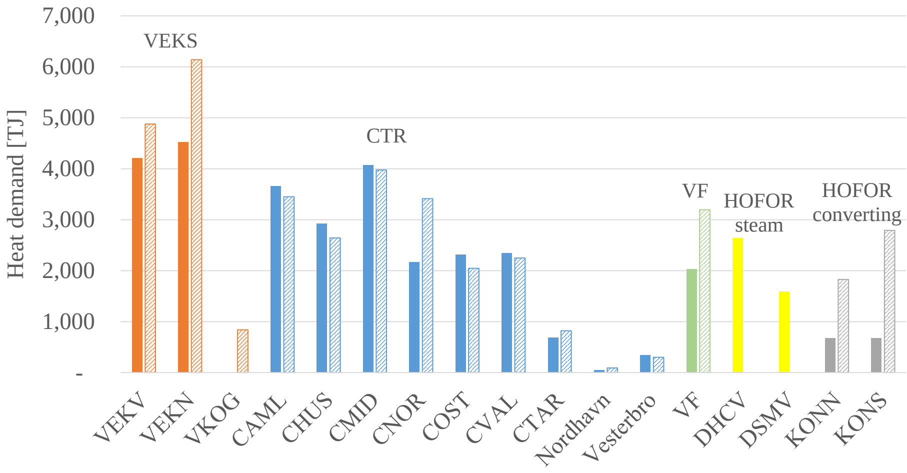


Figure 14.1: Heat demand in 2013 (filled) and 2025 (shaded). The steam areas are converted to water based district heating before 2025 and the demand is moved to the HOFOR converting areas. Køge (VKOG) will have a not negligible heat demand in the future.

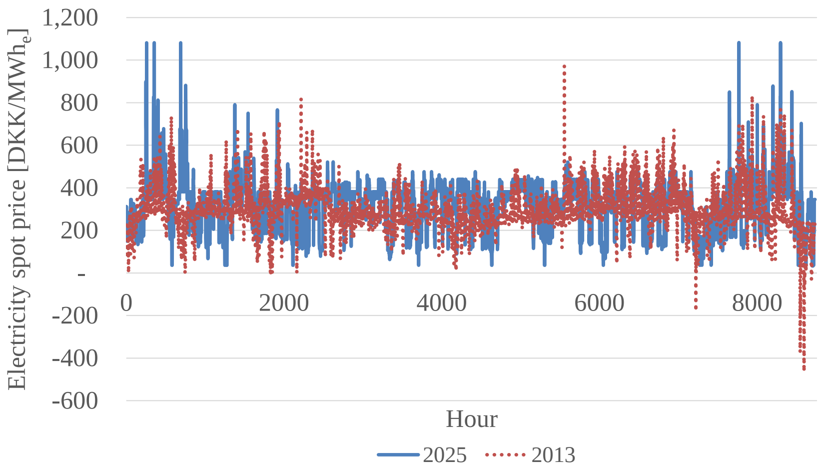


Figure 14.2: Electricity price profile for 2013 and 2025. The 2013 profile is from Nordpool Spot[94], and the 2025 profile is obtained with Balmorel simulation with investments in the Nordic Countries. The prices in 2025 is more fluctuating, due to higher wind capacity in the 2025.

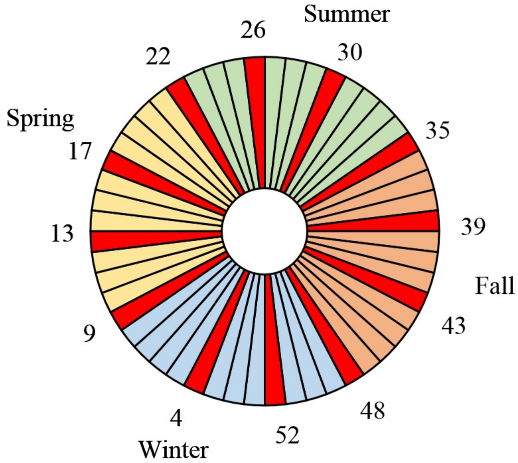


Figure 14.3: Visualisation of the weeks simulated.

Table 14.1: Distribution of heat pumps in the district heating system of Copenhagen.

Area	**Heat pump type**	**Capacity [MW_{th}]**
CAML	Sewage water	60.0
CVAL	Sewage water	27.0
CHUS	Drinking water	4.5
VEKV	Drinking water	4.5
VF	Drinking water	4.5
CAML	Sea water	70.0
COST	Sea water	90.0
Total		**260.5**

14.3 Implementation of Heat Pumps

From the investigation of the potentials in Part I Potential Heat Sources in the Copenhagen Area it was found that it is possible to install 3×4.5 MW_{th} drinking water heat pumps, 27 MW_{th} and 60 MW_{th} sewage water heat pumps at Damhusåen and Lynetten respectively, and in theory infinite capacity at Amager and Nordhavnen. Nordhavnen has a very low demand (see Figure 16.1), so it is assumed that the heat pump can provide heat for the COST (Østerbro) distribution grid.

In Figure 14.4 the duration curves for areas CAML and COST (Amager and Østerbro) are shown. For a heat pump to be economic feasible around 4000 FLH is expected[21, 103]. Assuming that the marginal individual heat pump should at least have the possibility of 4000 FLH, gives capacities of 130 MW_{th} in CAML, and 90 MW_{th} in COST when connected to the distribution grid. Connected to the transmission grid do not have this limitation, but to make the comparison more simply the same capacities are chosen as for the distribution grid. This gives the area distribution of heat pumps shown in Table 14.1. It is important to notice that this is the total amount of heat pump capacity installed in the area, and could consist of a number of individual heat pumps.

The sea water heat pumps are chosen to be based on the 'far' obtained sea water, i.e. the sea water pumped in from a 12 km pipe in Øresund in winter time and near coast in summer

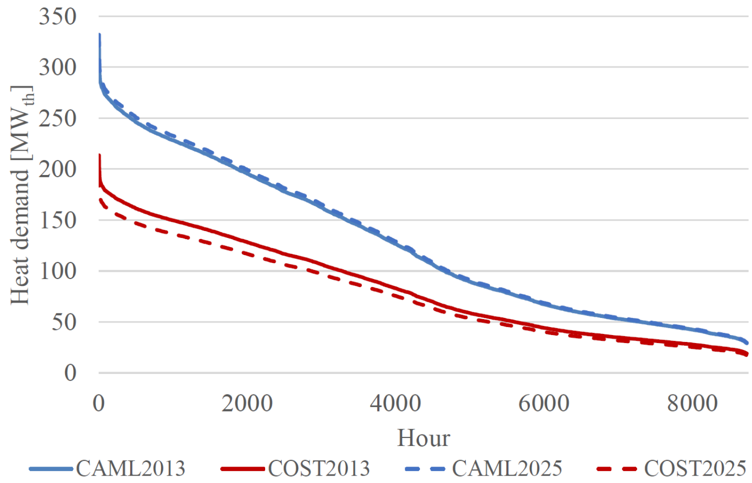


Figure 14.4: Heat duration curve of CAML and COST in 2013 and 2025.

Table 14.2: Heat pump parameters in Balmorel. The COPs are for the fixed COP scenario (FCOP), for the variable COP scenarios the COPs shown in Figure 10.1 are used. Variable costs are from Karlsson & Meibom (2008)[75].

Technology/Source	COP	Variable cost [DKK/MWh_{th}]
Sewage water	3.2	9.0
Drinking water	3.1	9.0
Sea water	2.9	9.0

time. The reason is that this heat pump can operate all year around, and security of supply is weighted higher than a higher yearly average COP.

The COPs of the heat pump technologies for the fixed scenario are chosen as the yearly COP weighted by demand (see Table 10.1), and for the variable scenario the seasonal COP shown in Figure 10.1 are used. The COPs are calculated with an optimum decrease of source water from Bäckström (1940)[8], where the potentials often are calculated from a larger decrease. In the system modelling it is assumed that the whole heat pump capacity of a technology have the same seasonal COPs, e.g. the 27 MW_{th} installed heat pump capacity at CVAL all have the same seasonal COPs.

The variable costs are assumed the same as in the study made by Karlsson & Meibom (2008)[75]. The parameters are shown in Table 14.2.

15

Modelling in Balmorel

15.1 Modelling Time Dependent Operation of Generation Technologies

In Balmorel generation technologies' fuel efficiencies are fixed, i.e. it is just a scalar for each technology. The capacities can be changed in Balmorel, for instance to apply outages, but an actual seasonal full load capacity can not easily be be applied. These operation parameters are as described before not fixed in reality. For a heat pump the COP mainly depends on the evaporating and condensing temperature, which of course changes during the year depending on the source and system. For a thermal power plant the efficiency also changes depending on the inlet temperature of the sink (cooling of steam, i.e. district heating water). To apply this application to Balmorel a time dependent operation add-on, `TimeDepOp`, is modelled.

The add-on consist of a number of different files which can be seen in Appendix H with an explanation of where to include these in the Balmorel model. The changes in the equations is actually very simple. The equations (15.1) and (15.2) are the modified versions of equation (13.6) and (13.7). The only differences are that the generation fuel efficiencies now are time dependent parameters.

$$V^{\text{con.,fuel}}_{a,g,t} = \frac{V^{\text{gen.,el.}}_{a,g,t} + V^{\text{gen.,heat}}_{a,g,t} Z_g}{\eta^{\text{gen.}}_{g,t}}, \quad \forall\, a, t, (g \in \mathbb{G}^{\text{th.}}) \tag{15.1}$$

$$D^{\text{tech.,el.}}_{a,g,t} = \frac{V^{\text{gen.,heat}}_{a,g,t}}{\eta^{\text{gen.}}_{g,t}}, \quad \forall\, a, t, (g \in \mathbb{G}^{\text{e.h.}}) \tag{15.2}$$

There is of course a lot more to it, but in principle it is that simple. Implementing it in Balmorel is the hard part. Here it have to be assured that the add-on does not interfere with the rest of the model. This is done by defining a new parameter to all technologies, which gives the option to become operational time dependent or not (Appendix H.2 and H.3). For the capacities Balmorel already has a parameter that decrease the capacity by the given value of the parameter. This parameter is redefined so it also contains the heat pump's seasonal full load capacity (Appendix H.4), and that it still defines outages and other decreases of the capacity. The t in (15.1) and (15.2) contains in Balmorel both seasons and timesteps, so depending on the user-input this have to be modified so it works for all seasons and all timesteps (Appendix H.3 and H.4). The actual modelling in the Balmorel equations should only implement the technologies chosen to be operational time dependent, both for existing and new (invested) thermal and heat pump units (from Appendix H.5 to H.8).

15.2 Modelling Distribution Areas

So far it is only possible to connect a generation technology to the transmission grid in the Greater Copenhagen model. Meaning that a technology placed in an area (see Figure 13.4) can produce heat to this area and all other areas that are connected to this.

A heat pump connected to the distribution area shall only be able to supply heat to this area, so some new 'isolated' areas that can function as distribution areas are needed. This new area is then connected to the old area with an one-way distribution line with infinite capacity and no loss. Then depending on the scenario the heat pump can be placed in the new distribution area or in the old area connected to the transmission grid.

In Figure 15.1 a modified version of the previous showed network (Figure 13.4) is shown. All the demand information, i.e. yearly heat demand and demand profiles have been shifted from the original area (e.g. VF) to the new distribution area (e.g. VF_DIS). The modelling in Balmorel can be seen in Appendix I.

15.3 Apply a Fixed Price Profile to a Region

For improvement of the simulation time a fixed electricity price profile is applied to the region (Eastern Denmark). To do this the Balmorel add-on `X3V` is modified. The `X3V` makes it possible to import/export from/to a 3rd country outside the geographic of Balmorel. The add-on can already apply a shifted electricity price profile depending on a net import/export. In the first simulation it uses an applied electricity price profile to calculate and log the shadow price. In the second run this shadow price is used to shift the profile to match the net import/export.

A fixed electricity price profile is needed, so the shadow prices used for shifting the price profile simply needs to overwritten. An infinite transmission between the two regions (Eastern Denmark and the fictive 'Profile-land') will ensure equalization in term of prices. This is made as a new option in the add-on so it can be used by others to validate future models with historical data. The changes in the `X3V` add-on files are highlighted in Appendix J.

15.4 Modelling of Scenarios in Balmorel

To make it easier to simulate the different scenarios some modifications in the model is made. By using '$if' statements throughout the model, it is possible to control all scenario changes from the option file (`balopt.opt`). These modifications makes it a lot quicker to run each scenario, because time on making the scenario changes is minimized, and it reduces the risk of making typing errors. The modelling of Balmorel can be seen in Appendix K.

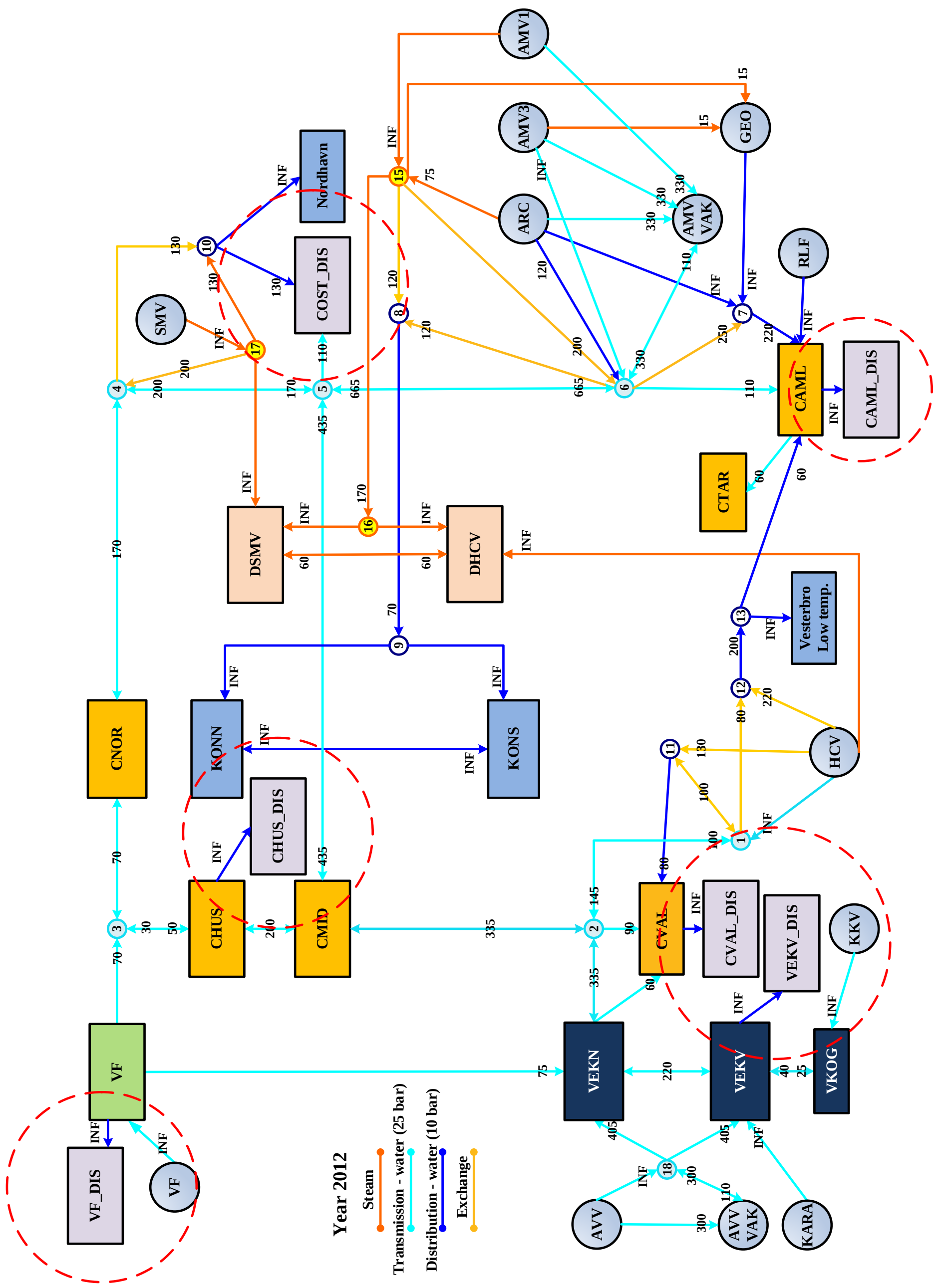


Figure 15.1: Visualisation of the implementation of distribution areas in Balmorel. The red circles indicate the areas added. Demand and demand profiles from the original areas (e.g. VF) are moved to these areas (e.g. VF_DIS), and connected to the original areas with a one-way distribution connection. The modelling in Balmorel can be seen in Appendix I

16

Validation of the District Heating Set-up in Balmorel

The first step in using any kind of model is to validate it with other studies or historical data. The Balmorel version used has a rather detailed description of the district heating network in Greater Copenhagen. Historical data from 2012 is chosen to validate this description. The idea is to compare the historical heating production from each power plant with the Balmorel results. This is done by first isolating Eastern Denmark from the rest of the world. Now it is only electricity generation technologies on Sjælland that can produce and supply electricity to Eastern Denmark. Then a historical electricity price profile from 2012 is applied onto Easter Denmark. CHP plants in Greater Copenhagen will now operate with respect to this electricity price profile, i.e. produce electricity and heat depending on market price. This will influence the production of heat on CHP plants and thereby on the whole district heating network in Greater Copenhagen.

16.1 Assumptions and Historical Data for Validation

To set up the operation of the different power plants in 2012 the operational informations from the power plants yearly statement on environmental impact are used[2, 36, 37, 38, 83, 102, 118] , together with confidential information about average failure and outage percentage of the plants in 2012 supplied from Varmelast.dk[1]. The only not confidential outage is from Vattenfall's yearly statement on environmental impact on Amagerværket, where it is mentioned that AMV1 was out in May 2012, plus it had problems with the straw boiler during the year[118].

Two units are modelled as combination technologies, AVV2 and AMV1.

1. AVV2 which consist of a multi fuel boiler, a biomass boiler using straws, and two gas turbines using natural gas. The multi fuel boiler is the primary boiler, and this can use gas, oil and wood pellets, but uses mainly wood pellets.

2. AMV1 is a CHP unit using wood pellets as fuel. It has bypass valves making it possible to use the AMV1 as a heat only unit in the situation of low electricity prices and high heat demand. AMV1 is not a combination technology, but is modelled as such to represent the bypass.

[1] This data are confidential and will not be shown in this thesis.

Table 16.1: Fuel prices and taxes on fuels used for heat production (see note about taxes in Appendix B) in 2012. CO_2 price was DKK 7.5 per tonne[70].

Fuel	Fuel prices [DKK/GJ]	Taxes on fuel for heat [DKK/GJ]	CO_2 tax [DKK/GJ]	Source
Natural gas	60	67	3	[46]
Coal	21	73	5	[25]
Fuel oil	107	71	4	[25]
Light oil	125	70	4	[24]
Municapality waste	0	58	2	[24]
Straw	34	0	0	[24]
Wood	34	0	0	[24]
Wood waste	0	0	0	[24]
Biogas	46	0	0	[24]
Wood pellets	57	0	0	[24]

There are assumed no transmission losses, and a transmission cost of DKK 0.32 per MJ. The fuel prices, and taxes on fuel and CO_2 are listed in Table 16.1. The area specific demands for 2012 are shown in Figure 16.1.

16.2 Validation of Balmorel Set-up 2012

The 2012 heat price weighted by consumption quantity found in Balmorel is 466 DKK/MWh. The 2012 historical prices in this area were 459 DKK/MWh weighted by population[2]. The heat production found in Balmorel from each plant is compared with historical productions in Figure 16.2.

The production distributed between the plants is overall comparable with the historical distribution. The production from the waste-to-energy (ARC, KAR, VF) plants found by Balmorel, is very close to the actual production in 2012 (around ±7%). The total production found from the AVV units is close to the historical production (around +8%), but the competition between AVV2 and AVV1 is a bit of. The reason could be that AVV2 in 2012 still used some natural gas in its main boiler, whereas the main boiler in Balmorel is using pure wood pellets. The price of wood pellets are assumed to be lower than the price of natural gas, and there is no tax on CO_2 emission on wood pellets, which all yields a higher production on AVV2.

The heat production from HCV is historical twice as high as found in Balmorel. The reason could be due to forced production to the steam grid. For security of supply reasons there has to be two steam producing plants in operation if the steam demand is over 83 MW_{th}[93]. Here all steam producers on Amager (AMV1 and ARC) counts as one, because they are connected to the same steam transmission line (often called the tunnel). ARC is more or less a must run unit, because it uses waste as fuel. Thereafter AMV1 is the cheapest, which in practise mean that the tunnel will supply base load. In Figure 16.3 a duration curve is shown, illustrating when HCV and SMV are forced to operate due to legislation. The HCV unit and the SMV units all are around 70 MW_{th}. Assuming that their minimum load is 50%, this gives a total forced production of 0.5 PJ. The total heat production from these units already exceeds this production. Which suggest that the extra production on the model is not because of forced production.

In the model HCV is in competition with both AMV (through the tunnel) and AVV (through

[2]Heat prices is from Energitilsynet[48] and population numbers are 2005 statistics from Statistics Denmark[112] (see calculations in Appendix A.5)

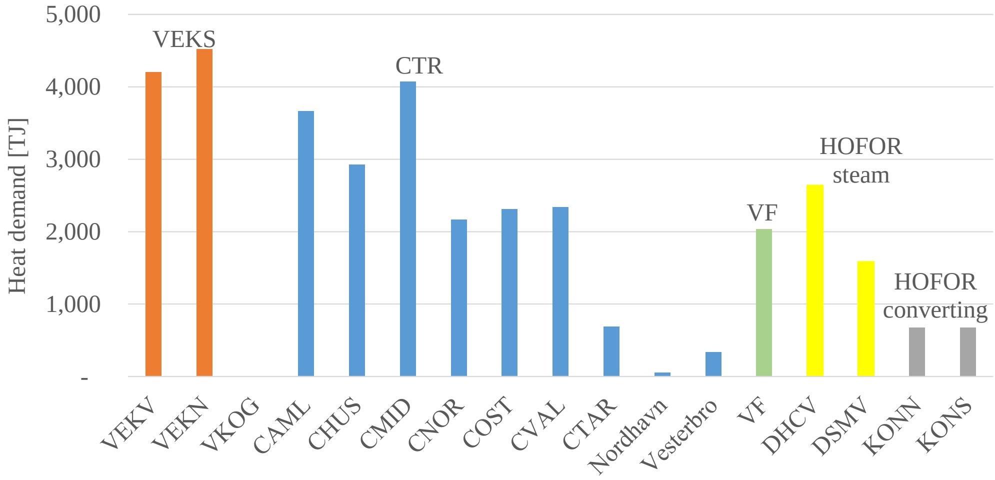


Figure 16.1: Demand of heat in Greater Copenhagen in 2012. The district heating in Køge (VKOG) is set to zero in 2012, because the connection to Køge was not constructed in 2012.

VEKN). Whereas SMV only compete with AMV. This suggest that the modelling of AVV–VEKN–HCV transmission is not completely representative. The AVV units produces 1.1 PJ more in the model, whereas HCV produce 1.6 PJ less.

The network description in the model seems to catch the total yearly productions distributed onto units. There maybe is a small misrepresentation in the transmission connections between HCV and AVV. This is not considered as crucial, mainly due to the fact that HCV will be decommissioned in 2015. This will, of course, have a small impact on the 2013 simulations.

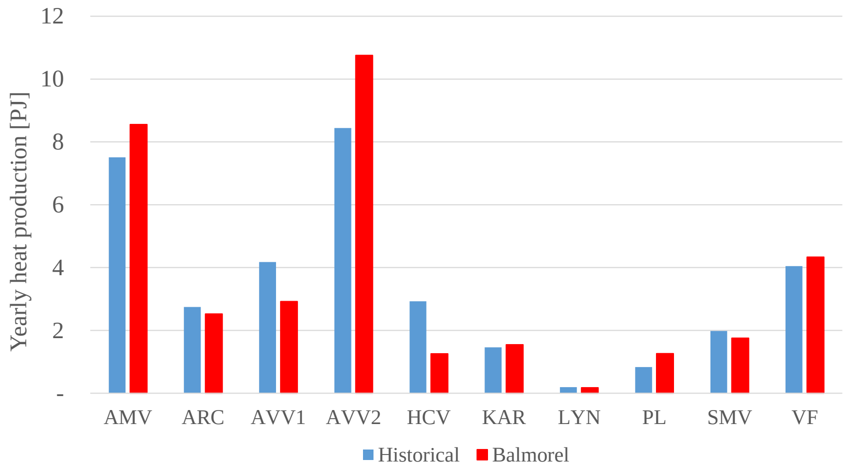


Figure 16.2: Comparison between historical and modelled production of heat.

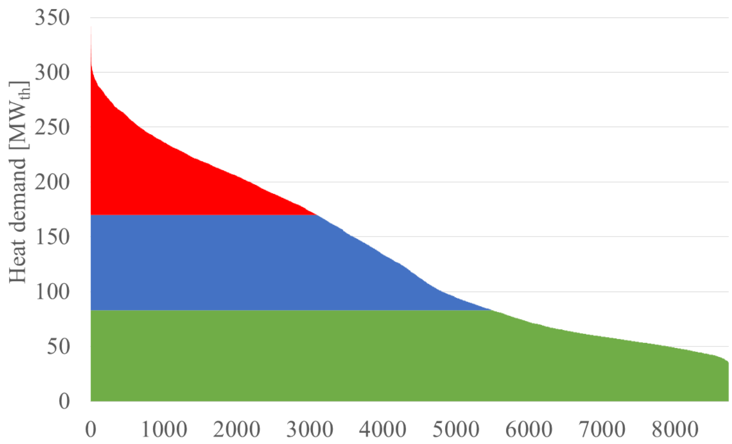


Figure 16.3: Steam duration curve showing the supply from AMV1, ARC, HCV and SMV. Green: The connection from AMV1 and ARC (the tunnel) can and is allowed to supply the demand alone. Blue: The connection from AMV1 and ARC can, but is not allowed to supply the demand alone. Therefore SMV or HCV have to run on minimum load due to regulation. Red: AMV1 and ARC can not supply the demand (tunnel max. is 170 MW_{th}), so SMV and/or HCV have to operate to supply demand.

17

Results on the Modelling

In this chapter the results from the scenario modellings will be presented. The results will be shown and explained, but not comment on in detail. The comments and discussions will be done in the next chapter. The last section in this chapter is presented a sensitivity analyses of the production by the heat pumps.

17.1 Scenario Results for 2013

In Figure 17.1 are shown the total heat productions distribution between units for the 2013 reference and the three scenarios. The reference peak load (PL, SMV and HCV) production counts around 7% of the total production (this number has historical been around 10% to 20%). In Figure 17.2 the differences between the reference year and the other scenarios are plotted. This figure shows from what units the heat pumps displace production. All in all the heat pumps connected to the distribution grid have a yearly heat production of around 3 PJ, and around 2.3 PJ when connected to the transmission grid.

The full load hours of the individual heat pumps are shown in Figure 17.3. The heat pumps connected to the distribution grid (FCOP2013 and VCOP_DIS2013) have around 3500 FLH. The heat pumps connected to the transmission grid only have around 2500 FLH, and in some cases only around 2000 FLH. Especially the sea water heat pumps have a very low number of full load hours in the 2013 scenarios. In Figure 17.4 is shown the full load hours for the 2013 VCOP_DIS scenario compared with the same scenario, but with half of the sea water heat pump capacity. The full load hours for the sea water heat pumps only increases around 3%.

The monthly productions from each technology (sewage, drinking and sea water) are shown in Figure 17.5. The monthly productions are calculated from the weekly production results in each month and multiplied with $52/12 = 4.333$. The distribution grid connected heat pumps with fixed COP (FCOP) and variable COP (VCOP_DIS) follow each other most months. An exception is for sewage water heat pumps in May. Here the heat pumps with variable COP produce twice the the amount compared to the ones with fixed COP. In Figure 17.6(a) it can be seen that the sewage water heat pumps displace production from the AMV1 unit in the VCOP scenario compared to the FCOP in May.

The heat pumps connected to the transmission grid produce a lot less compared to the ones connected to the distribution grid. Especially in the months February, March, and November the productions are significantly lower. In the summer time there is not much difference, and in June the sea water heat pumps actually produce more when connected

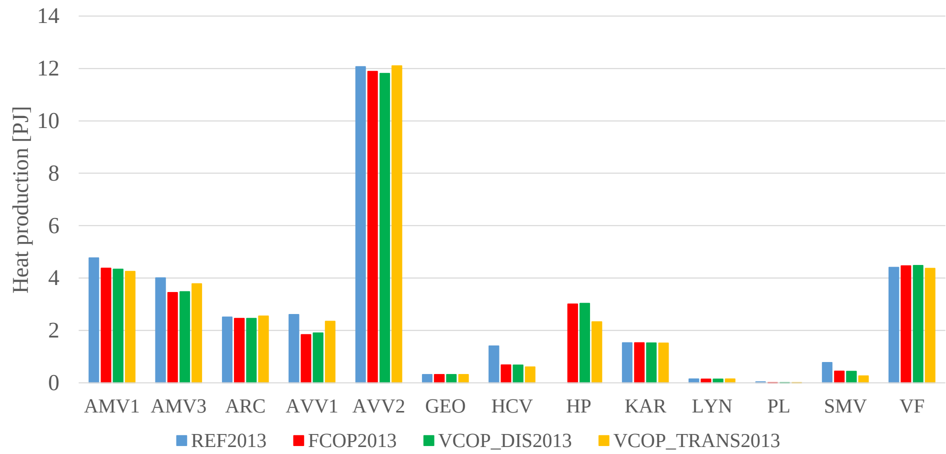


Figure 17.1: Heat production by unit in **2013**.

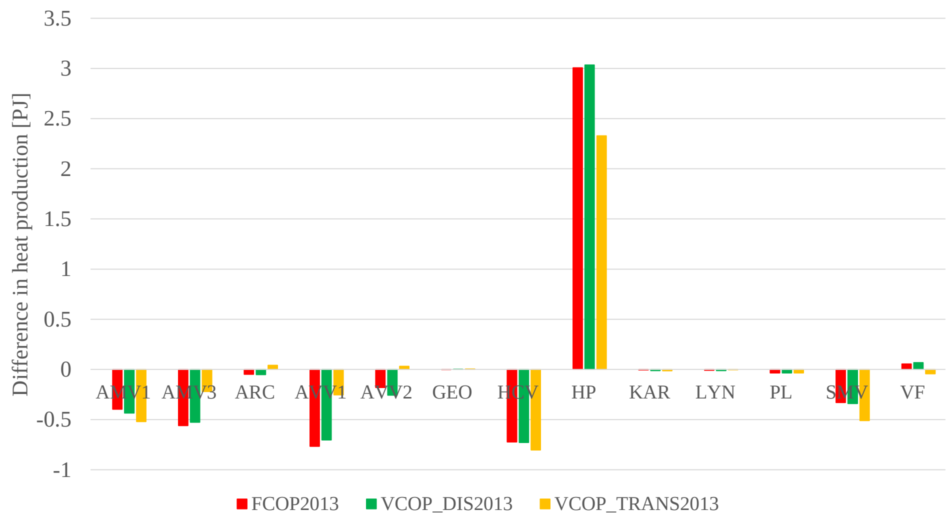


Figure 17.2: Difference in production from reference in **2013**.

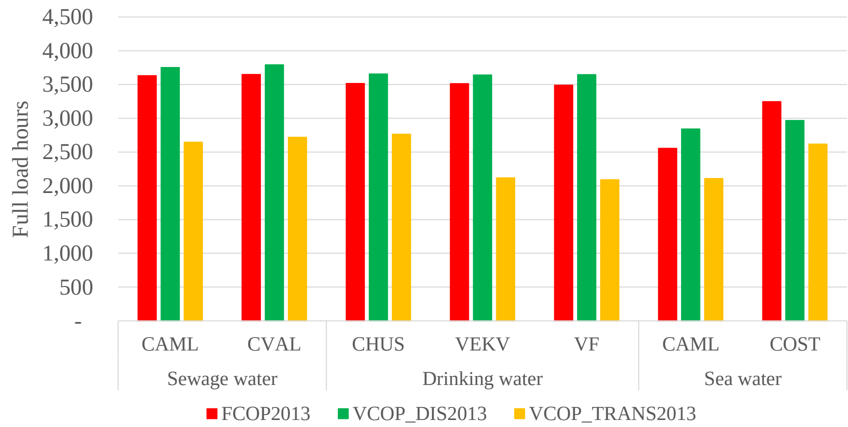


Figure 17.3: Full load hours for the heat pumps in **2013**.

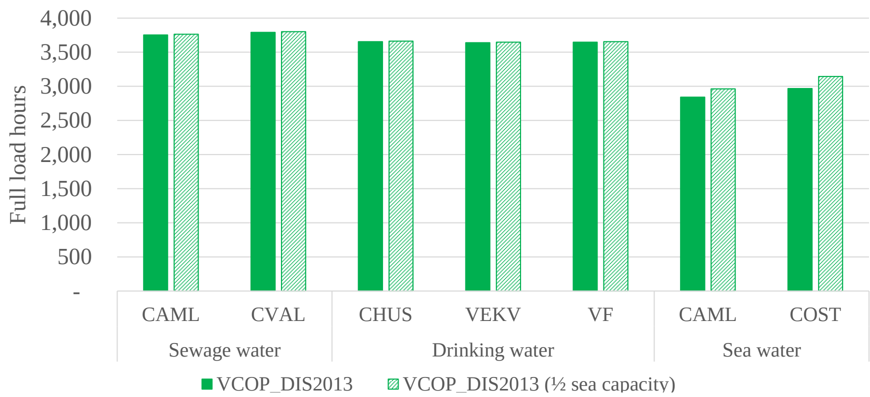


Figure 17.4: Full load hours for VCOP_DIS2013 scenario with all and half of the sea water capacities listed in Table 14.1.

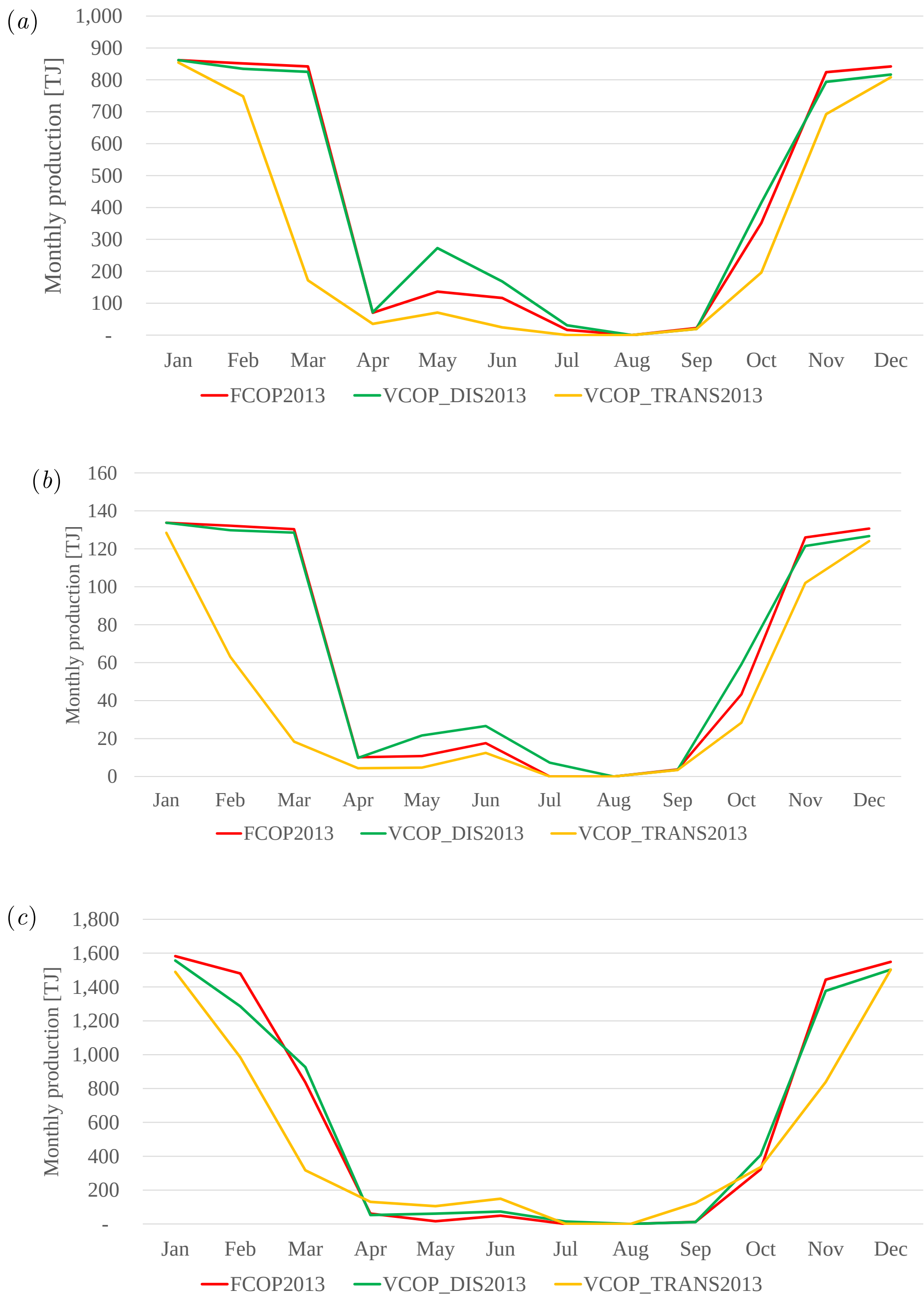


Figure 17.5: Total monthly production in **2013** for heat pumps using (a) **sewage water**, (b) **drinking water**, and (c) **sea water**.

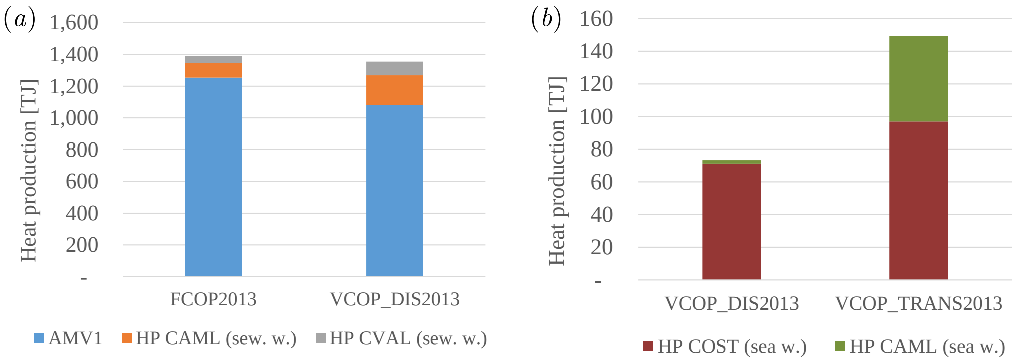


Figure 17.6: (*a*) Heat production from AMV1, and the sewage water heat pumps in CAML and CVAL in **May 2013**. (*b*) Production of heat from sea water heat pumps in **June 2013**.

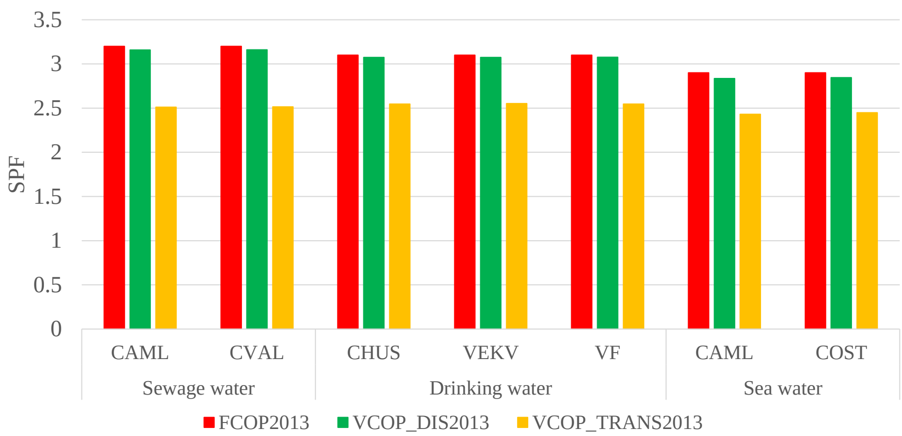


Figure 17.7: The heat pumps SPF in **2013**.

to the transmission grid. The production from the two sea water heat pumps in June can be seen in Figure 17.6(*b*). It is particularly the heat pump at CAML that get an extra production when connected to the transmission grid.

The seasonal performance factor (SPF) is the ratio of the total yearly heat production over the total electricity consumption[1]. The SPF for 2013 for each heat pump is shown in Figure 17.7. For the distribution grid connected heat pumps the SPF is around 3, where it is around 2.5 for the heat pumps connected to the transmission grid.

[1]See equation (9.2) on page 50.

17.2 Scenario Results for 2025

In Figure 17.8 the heat production for each unit for the different scenarios is shown. The peak load production counts around 5% of the total heat production in the REF scenario. The differences in heat production compared to the reference are shown in Figure 17.9. In 2025 the heat pumps mainly displace peak load (PL) production, and production from AMV1. The total heat production by heat pumps is around 3.3 PJ when connected to the distribution grid, and 2.6 PJ when connected to the transmission grid.

The full load hours for the heat pumps are shown in Figure 17.10. The heat pumps connected to the distribution grid gets in most cases around 4000 FLH. The exceptions are the sea water heat pumps and the drinking water heat pump connected to the VEKV grid. From Figure 17.11 it is seen that in February the production is extremely low for the particular heat pump connected to the VEKV area.

The heat pumps connected to the transmission grid gets around 3000 full load hours for sewage water and drinking water heat pumps. The sea water heat pump gets around 2500 full load hours. The drinking water heat pump in VEKV connected to the transmission grid only have around 2000 full load hours. The lower production when connected to the transmission grid can also be seen in Figure 17.12. In the figure is shown the monthly heat production from the different heat pump technologies. In most cases they have a peak in March, May, and August. The transmission grid connected heat pumps' production are lower for all months. All heat pumps seems to be out of operation in July.

The heat pumps SPF is shown in Figure 17.13. All heat pumps connected to the distribution grid have a SPF of around 3, whereas the it drops to 2.5 when the heat pumps are connected to the transmission grid.

In Figure 17.14 the displaced units (see Figure 17.9) monthly production in 2025 for the REF and VCOP_DIS scenarios are shown. In the winter month the heat pumps displace peak load, whereas in the summer months they displace load from the CHP units.

17.3 Sensitivity Analyses of Scenario Results

In Figure 17.15 a sensitivity analyses of the heat pumps heat production is visualized. The parameters; biomass prices, electricity prices, and total installed heat pump capacity[2] are increased and decreased by 50%. In Figure 17.16 the monthly production for the analyses is shown. A decrease in the electricity price or an increase in the biomass price by 50% will in both cases give a 70% increase in heat production from heat pumps. An increase in electricity prices by 50% will on the other hand only decrease the production by 30%. By installing 50% more heat pump capacity in the system the total heat production by heat pumps only increases by 30%. Meaning that the average amount of full load hours drops from 4000 FLH to 3500 FLH. The extra capacity is only used in the winter time (see Figure 17.16). If the biomass prices decreases by 50%, then the heat pumps are completely out of operation in the summer months.

[2]All heat pump units have been added or subtracted 50% of their capacity.

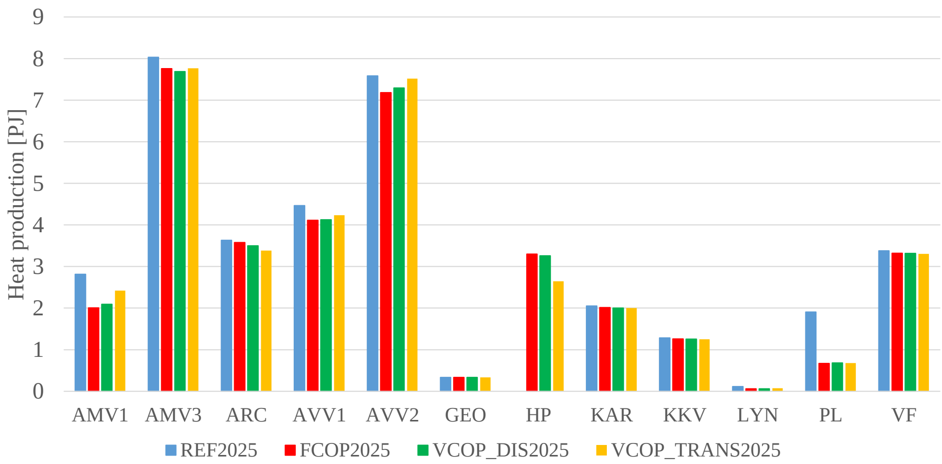


Figure 17.8: Heat production by unit in **2025**.

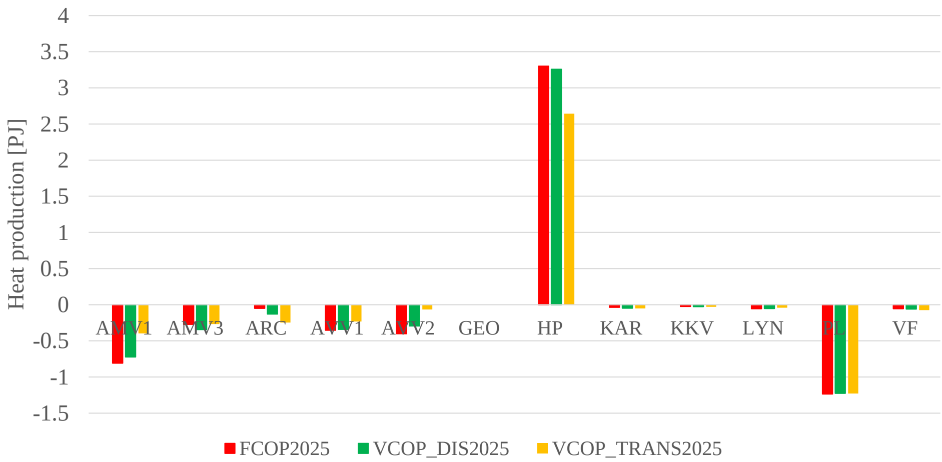


Figure 17.9: Difference in heat production from reference (REF) in **2025**.

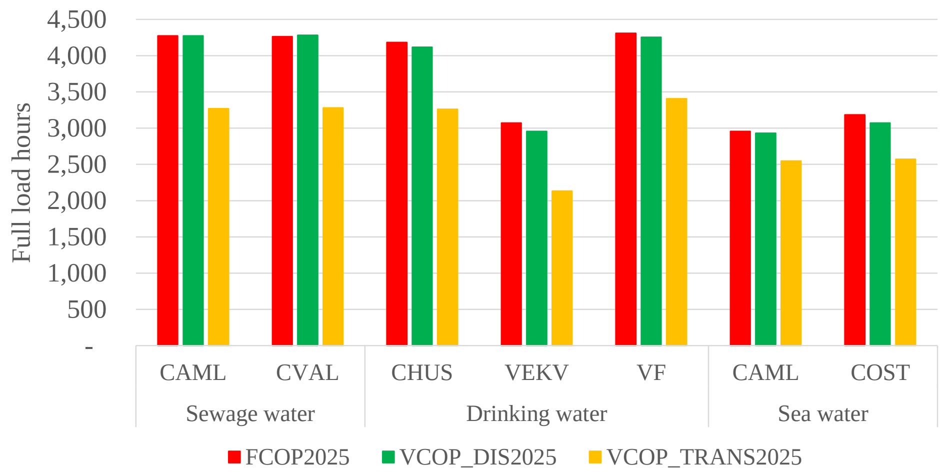


Figure 17.10: Full load hours for the heat pumps in **2025**.

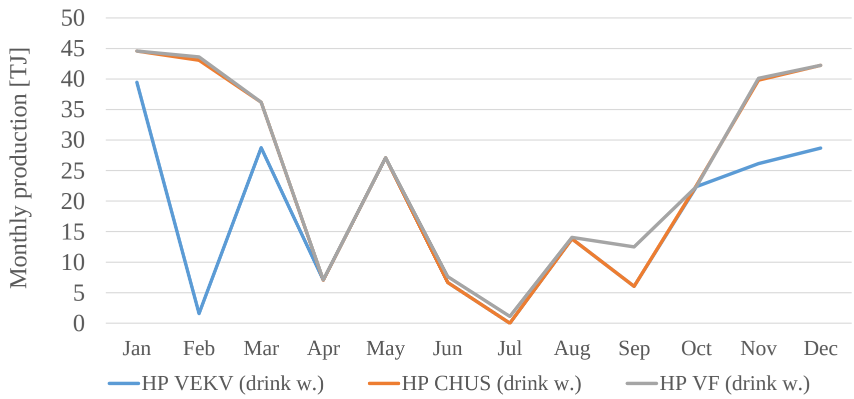


Figure 17.11: Total monthly heat production for the individual **drinking water** heat pumps in **2025** for the VCOP_DIS scenario.

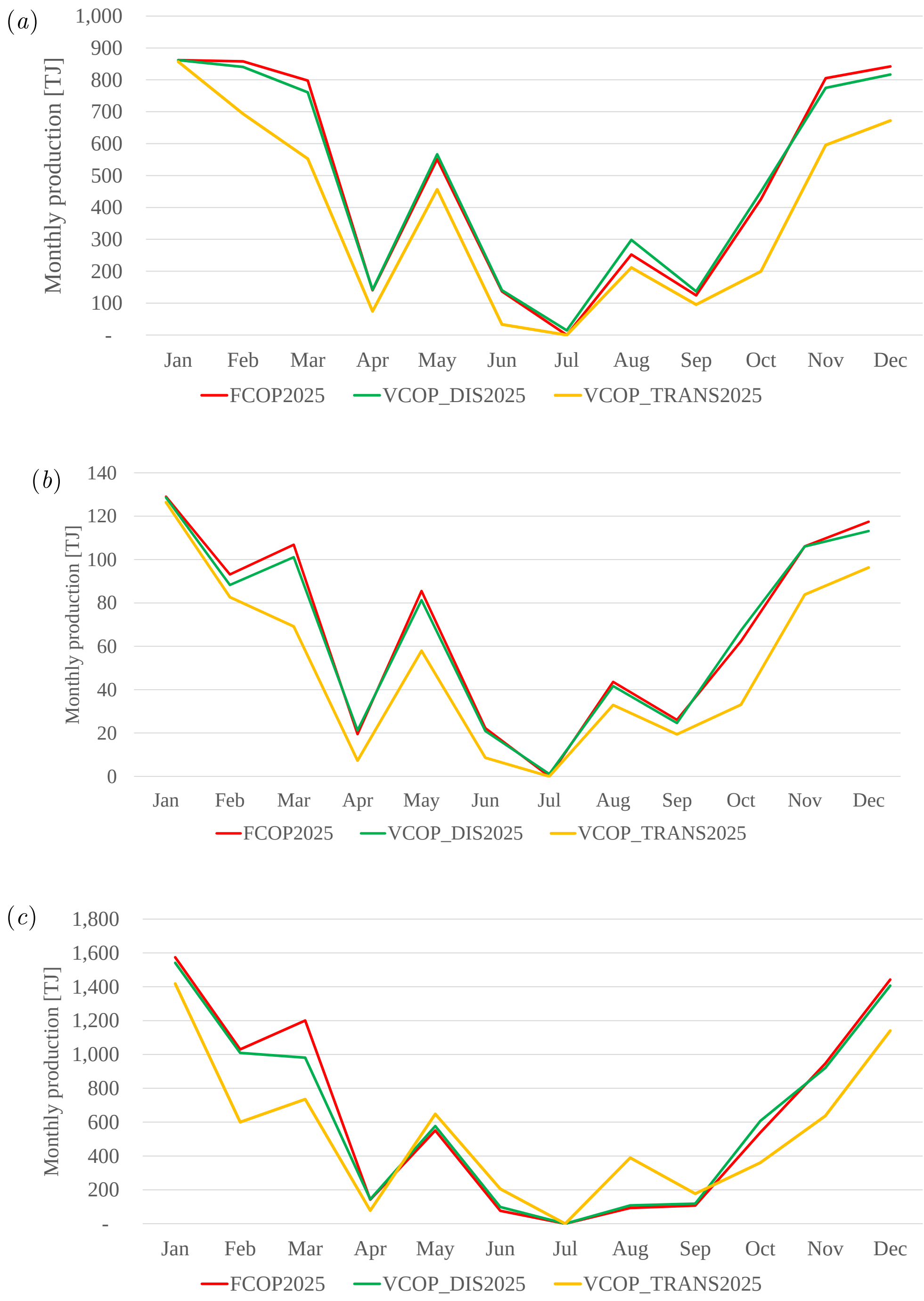


Figure 17.12: Total monthly heat production in **2025** for heat pumps using (a) **sewage water**, (b) **drinking water**, and (c) **sea water**.

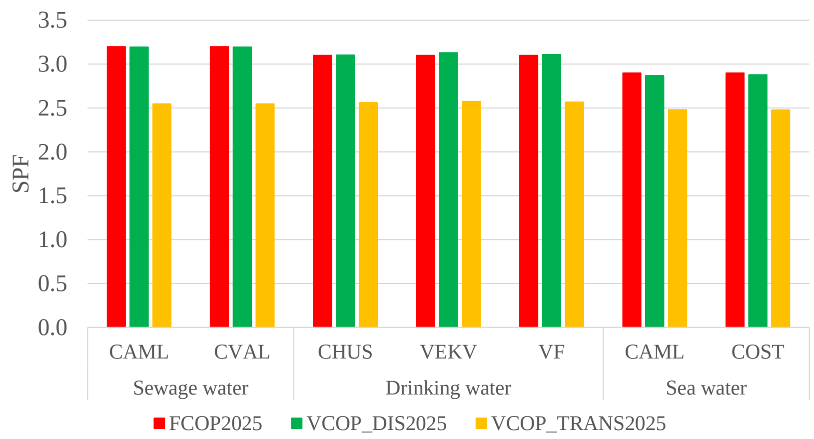


Figure 17.13: The heat pumps SPF in **2025**.

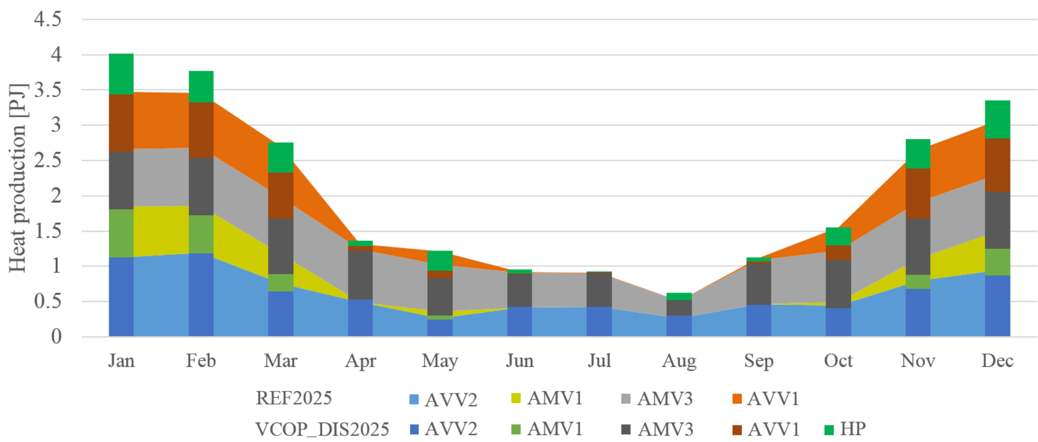


Figure 17.14: The heat production from heat pumps and the competitive units (without peak load) in **2025**. The bars show the production from the CHP units and heat pumps in the VCOP_DIS scenario, whereas the area plot shows the production from the CHP units in the 2025 reference (REF2025). In January and February the CHP units in the scenarios produces approximately the same as in the reference, which means that the extra production from the heat pump is displacing peak load. In October the heat pumps mainly displace production from the AMV units. In May the heat pumps are displacing production from all units.

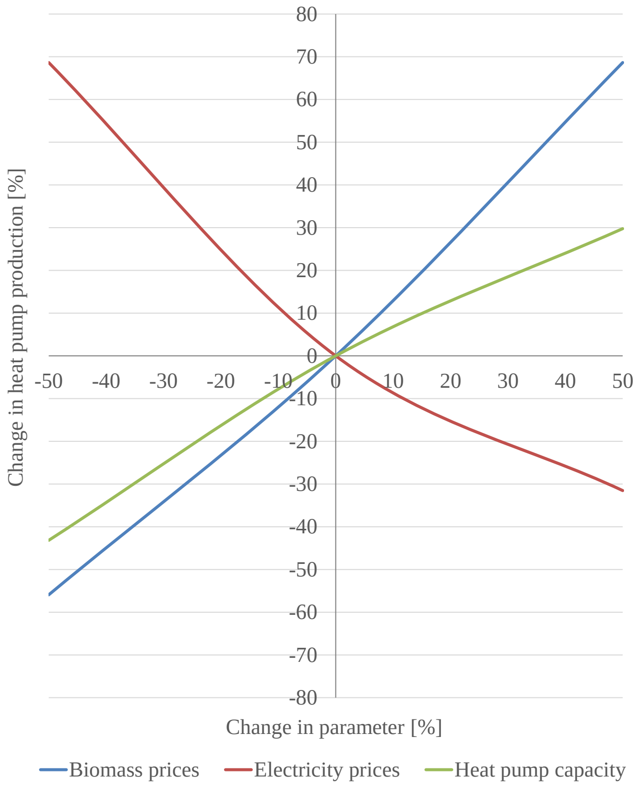


Figure 17.15: Sensitivity analyses of the results of the total heat pumps production for the **2025** VCOP_DIS scenario.

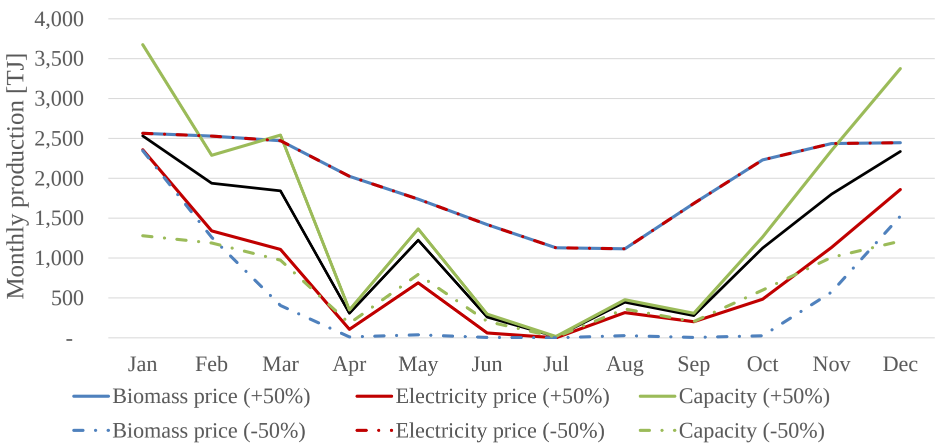


Figure 17.16: Sensitivity analyses for the total monthly heat production from all heat pumps in **2025**. The black line is the original VCOP_DIS scenario results.

18

Discussion of the Modelling

In this chapter the Balmorel model and scenario results are discussed.

18.1 Method Discussion

The VEKS distribution areas in the model (VEKV and VEKN) are in reality split into a lot of smaller distribution areas. The the CTR area description is better, but an area as CNOR still consist of three distribution areas in reality. So the risk is that the heat transmissions between the real areas is not captured probably. And more importantly for this study, a heat pump connected to a distribution area, is supplying to a larger area than it in practice would.

To decrease the simulation time, it was chosen to only simulate one week in each month. These weeks where chosen to be the last week in each month, not taking into consideration if this week were representative for the month or not. This can, of course, give a number of problems. If the electricity price is very different in that week compared to the rest of the month, then the heat production from heat pumps will be very different. In Balmorel is used an outage sheet, which provides power plants with planned and forced outages. These outages will have an extra huge impact when only simulating certain weeks.

The 2025 simulation is based upon a number of assumptions and forecast. The forecasts and scenarios are found from reliable sources, such as IEA and the Danish Energy Agency, but prediction is difficult, and especially about the future (which is nicely illustrated in Figure 18.1).

18.2 Scenario Discussions – 2013

The heat pumps displaces mainly production from expensive units such as SMV and HCV, that are so expensive that they can be considered as peak load in the model. Thereafter production by CHP plants are displaced. A heat pump is expected to produce when electricity is low, where a CHP plant will try to decrease its overall production, if possible, when the electricity price is low. This would help equalizing the energy balance in a future fluctuating electricity market.

The heat pump connected to the distribution grid gets around 3000 FLH to 3500 FLH. This is significantly higher than found in the study made by Ommen et al. (2013)[96]. They made a model for investigation of larger heat pumps connected to the district heating network of Copenhagen. They found that connecting 300 MW_{th} of heat pump capacity in the

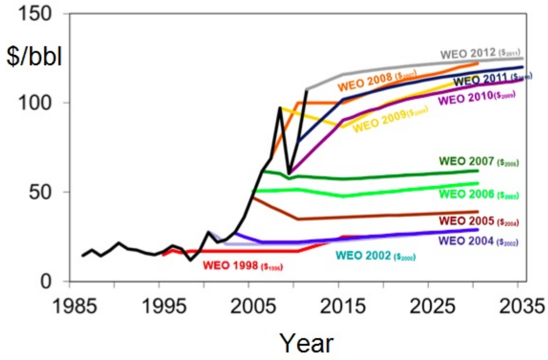


Figure 18.1: IEA WEO forecast of oil prices from 1998–2012 plotted with the actual market price. (Original figure from: [82])

2011 district heating system gave a heat pump 1400 hours of operation with an average load of 228 MW_{th} (yields approximately 1000 FLH). The differences could either be that they make socio economical calculations, or, they use private economical calculation, it could be because the energy taxation changed at new year 2013 (see e.g. Appendix B).

Connecting the heat pumps to the transmission grid decreases the number to approximately 2000 FLH to 2500 FLH. The reason is the lower COP. The sewage and drinking water heat pump connected to the distribution grid all have around 3500 FLH, whereas the sea water heat pumps only has 3000 FLH. The reason is not because to much heat pump capacity at COST and CAML is installed, which Figure 17.4 clearly shows. So it is simply because the COPs for the sea water heat pumps are lower than the COPs for drinking and sewage water heat pumps.

Whether 3000 FLH to 3500 FLH are high enough will depend on the investment cost of the heat pump, and the future heat price (i.e future revenue). A simple economical calculation [1] gives around 2000 FLH. Which makes the results of around 3000 FLH profitable. In another study of the district heating system of Copenhagen done in Balmorel, they find that the model invested heat pumps have around 3000 FLH to 3300 FLH[21]. First conclusion is that it seems to be economical feasible with today's taxation legislation[2] (DKK 406 per MWh_e). With the tax legislation before 2013 (DKK 688 per MWh_e) the same calculation gives almost 6000 FLH.

There is no significantly differences between the fixed and variable COP scenarios when they both are connected to the distribution grid. Consequently, previous heat pump studies made in Balmorel with a fixed COP, still holds. The reason probably is that the COP does not change much over time. The COP only changes with a few percentage from one week to the next due to the inertia the temperature of the source water. If instead the analyses was to be made on residential air source heat pump, then the COP could change significantly from day to night. For such a study it would be relevant to use hourly COPs.
On the other hand there are big differences in the results between connecting the heat pumps to the transmission and to the distribution grid. The reason is not because they are connected to different grids, but mainly due to the fact that the COP is lower when connected to the transmission grid. Consequently all previous heat pump studies made in Balmorel (or other energy models) possibly have used a too high COP (of course depending on assumed

[1] Assuming a COP of 3, life time of 15 year, investment cost of DKK 2.2 mill. per MW_{th}, electricity price of DKK 300 per MWh_e, fuel tax of DKK 406 per MWh_e, and heat price of DKK 380 per MWh_{th} (neglecting inflation and discount rate).

[2] See note about energy taxes in Appendix B.

technology development).

The SPF is around 3 and 2.5 for the heat pump connected to the distribution and transmission grid respectively. For sea and lake heat pumps these are usually between 2.4 and 3.3[56]. The SPF is the COP weighted by heat production, so one would expect them to be near the COP weighted by demand as listed in Table 10.1, which is also the case.

18.3 Scenario Discussions – 2025

The heat pumps displaces mainly peak load production ($\sim$ 1.2 PJ) in the winter time, and in the summer time they displaces some production from ($\sim$ 1.0 PJ) from CHP plants when the electricity price is low. This is also what is expected and hoped for by implementing the heat pumps in the district heating system. In the future the electricity prices is expected to fluctuate more due implementation of indispatchable and inflexible renewable sources, such as wind. By implementing heat pumps CHP plants are not forced to be in operation when electricity prices are low, just to supply heat. The heat production from heat pumps are also much more fluctuating during the year 2025 (Figure 17.12) than 2013 (Figure 17.5).

The heat produced by heat pumps in March and May 2025 (see Figure 17.14) displace production by CHP plants. The reason is that the electricity prices in March and May are very low as can be seen in Figure 18.2. This gives a high heat production from heat pumps in March and May, as can be seen in Figure 17.12. The production from heat pumps are highly dependent on the electricity price, which also can be concluded from the sensitivity analyses in Figure 17.15. If the electricity price increases with 50%, then the heat production from heat pumps decreases with 30%. If the electricity prices on the other hand decreases by 50%, then they increase their production by 70%. This is also the reason why all heat pumps are out of operation in July.

The full load hours for drinking and sewage water heat pumps are around 4000 FLH, when connected to the distribution grid. Except for sea water heat pumps and the drinking water heat pump connected to VEKV. For the sea water heat pumps the reason is the high electricity price in February (see Figure 18.2), and a much lower peak in August, than the other technologies. The lower peak in August seems to have something to due with the demand in the distribution grid.

Drinking water heat pumps in VEKV has a very low production in February. The electricity prices are high in February 2025, but the price does not seem to have any effect on the drinking water heat pumps connected to the other grids. The reason is that VEKV is well connected both to another grid (VEKN), but also directly to AVV and KARA. When electricity prices are high, AVV will run as much as possible. KARA, which is a waste-to-energy plant, is more or less a must run unit. This is not the case for the heat pump connected to the VF distribution grid. The VF grid is isolated, and only has the VF plant and some peak load capacity. The heat pump will therefore operate as base load. The same is the case at CHUS. The heat pump is the only direct connected unit, beside a peak load boiler. Both the heat pumps in the VF and CHUS grid gets over 700 hours of operation in February, whereas the heat pump in VEKV only gets 35 hours.

The sensitivity analyses shows that the heat production from heat pumps are highly dependent on the biomass and electricity prices. Increasing the biomass prices or decreasing the electricity prices by 50% both give an increase in heat production by 70%. What one need to bear in mind is that in the 2025 a lot of the Danish electricity production probably will come from biomass, meaning that if the prices of biomass increases, then the electricity prices will increase as well. Not necessarily as much, but it will increase. The model have fixed the electricity price profile, so the electricity prices will not be influenced on the biomass prices.

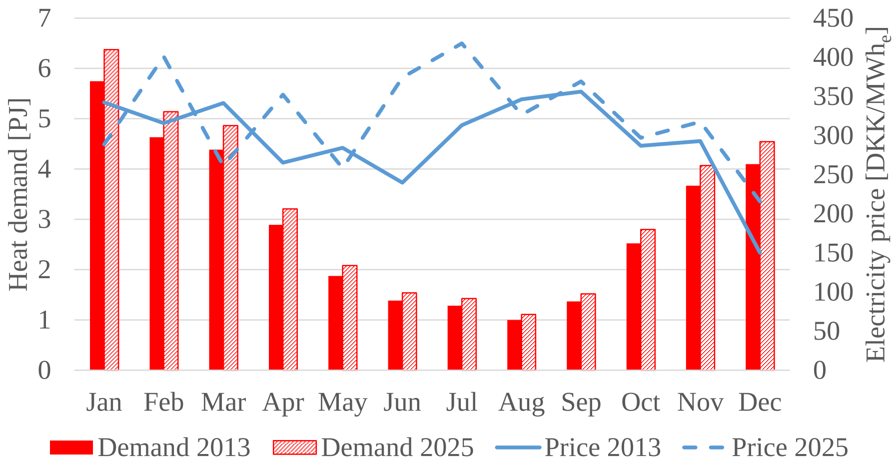


Figure 18.2: The heat demand and electricity prices for 2025.

Installing extra heat pump capacity in the already used locations will not give a proportional amount of extra heat production. Increasing the capacities with 50% only gives 30% extra production. Consequently the amount of full load hours will drop. To find the optimal heat pump capacity in an area one have to estimate the number of full load hours the marginal heat pump unit get.

18.4 Summary

To answer the three questions listed in the previous chapter:

1. Is integration of heat pumps in the district heating system competitive?

   Yes! After the new legislation in 2013 the heat pumps are competitive on the district heating market. In the 2013 simulation they get 3500 FLH and in 2025 they get 4000 FLH, which according to quick estimations is more than enough to be economical feasible.

2. What impact does seasonal dependent COP versus constant COP have on results?

   Not much! The monthly production depends very highly on the COP, but the values of COP in the investigated heat pumps do not vary sufficiently over the year. For investigations of air source heat pumps it could be of relevance.

3. Is it best to connect heat pumps to the distribution or the transmission grid?

   Distribution grid! The number of full load hours of the heat pumps decrease drastic when connected to the transmission grid, due to the lower COP.

Discussion & Conclusion

19

Discussion

In 2032 AVV1 and AMV3 are expected to be decommissioned. This leaves a gap of around 700 MW_{th} in Copenhagen. What this gap should be filled with is an open question. Going for CO_2 neutrality, then it can in practice only come from biomass or heat pumps. This study shows implementing 260 MW_{th} to different distribution grids will be economical feasible. The number of full load hours the gets are 3000 FLH to 4000 FLH, which should be enough according to estimations and experiences from other studies. The 260 MW_{th} is set by two limits, one being the potential of sewage water and drinking water, and another being the assumed capacity that the two distribution grid connected to the sea water heat pumps can obtain. For getting closer to the 700 MW_{th} it is necessary to connect the heat pumps to the transmission grid.

19.1 Connecting the Heat Pumps to the Transmission Grid

Connecting the heat pumps to the transmission grid instead of the distribution grid decreases the number of full load hours of the heat pump drastic. The reason is the very high temperature in the transmission grid, which yields a lower COP of the heat pumps. If the COP of the heat pumps could get on the same level as the heat pump connected to the distribution grid, then they would get at least the same amount of full load hours.

It would be favourable if the heat pumps could be connected to the transmission grid. This is due to the fact that most big sources are near the sea (e.g. sea water and sewage water), and it therefore would not be possible to supply inland areas with heat from heat pumps, if not they are connected to the transmission grid. In the future getting a higher COP with newer technologies (water vapour compression or hybrid heat pumps) might be possible.

Another suggestion for increasing the COP of the heat pump connected to the transmission grid could be to lower the temperatures in the transmission grid. Lowering the temperatures in the transmission grid would have a number of challenges. If the transmission forward temperature is decreased, then the mass flow have to be increased with the same factor to supply the same amount of heat. A decrease of the transmission temperature around 20% (from ca. 100°C to ca. 80°C), will increase the mass flow by 25%. Alternatively the return temperature have to be decreased together with the forward temperature, so ΔT_{dh} is constant. Lowering the forward temperatures of the transmission grid, will consequently also lower the temperatures in the distribution grid. Due to the fact that all residential radiators have been designed to the given temperatures, they will as a consequence work more purely. Whether lowering the temperature in the transmission grid is a possibility seems to be an entire study in itself.

Another idea could be to operate the heat pump with a constant temperature lift all year around, e.g. 55°C to 90°C (ΔT_{dh}=35°C), and then boost the extra 10°C to 20°C with a boiler running on biogas or biomass. Looking purely at the fuel (e.g. biogas and electricity) prices for this booster systems, and compare it with a stand alone heat pump taking the full temperature lift, then the booster system will be competitive if the electricity price is twice the price of the boiler fuel (see Appendix A.6). The average electricity price in 2012 was DKK 270 pr. MWh, and the only fuels there were below half of this price were coal and waste. Meaning that even though the COP decrease drastic when connecting to the transmission grid, it will still be a better idea than only pre-heating it with a heat pump and boosting it with a boiler. Here is of course not taken CO_2 prices, taxes and extra investments, but these will overall point in the same direction as the conclusion already given. Overall it is expensive to connect a heat pump to the transmission grid, but the question is if there is an alternative?

19.2 Possibilities in Other Cities

There are other more obvious locations in Denmark for utilization of for instance sea water in a heat pump. One of these is Helsingør, where the depth just a few hundreds meter from the coast is 40 m. Here they have an infinite heat source, that is just as easy to utilize as drinking or sewage water. Another place is the bay of Sønderborg, which is over 27 m deep.

Sewage water can be used as source in most cities. The drinking water will depend on how centralised there intake of water is. Air could be a possibility in inland areas where utilization of source water is not possible. This should be at less populated areas or industrial area, where noise pollution is not a problem.

20 Conclusion

In this study three main concerns of heat pump integration in the Copenhagen district heating system have been investigated: (I) the potential sources, (II) the feasible heat pump technologies, and (III) the impact on the system of integrating heat pumps to the transmission and distribution grid.

Of the six natural heat sources investigated three is found to be feasible in the Copenhagen district heating system. These are sewage water, drinking water, and sea water. A total of around 87 MW_{th} can be connected to sewage water facilities, and around 14 MW_{th} can be connected to drinking water facilities. The sea water potential is found to be almost infinite, but there are some challenges with pumping, piping, and freezing of water. For the sea water utilization two possible options is found: taking the water near coast all year around, or in winter time taking the water from deep sea around 12 km from the coast. The deep sea option is assumed to be the better of the two. The reason is that the temperature at the deep sea (under the thermocline) is around 5°C in winter time, where near coast water has a high risk of freezing. From analyses of the demand in the near coast distribution areas it was estimated that a total capacity of 160 MW_{th} of sea water heat pump could be implemented in the system. The potential of sea water as heat source was found to be highly dependent on the hydrography of the system analysed.

The current most suitable heat pump technology for the district heating system, is found to be an ammonia two-stage compression heat pump, heating the district heating water in a tandem system. The operational thermodynamic calculations of such a heat pump connected to the distribution grid yields a COP of around 2.8 to 3.1 in winter time, and a COP of 3.2 to 3.6 in the summer time. Sewage water gives the highest COP due to high source temperature, and sea water give the lowest. Connecting the heat pumps to the transmission grid gives a much lower COP of around 2.5 in winter time and 2.9 in summer time, for all sources.

A program, COPcalc, for calculating COPs and seasonal/hourly capacities has been developed. These operational data can be implemented in Balmorel, where a better representation of heat pumps has been modelled. This new representation can analyse the impact of seasonal variations of COP, and it enables the model to implement heat pumps in the distribution grids. The seasonal variation in COP is not found to have any significant impact on the overall result. This is mainly because the COP do not vary sufficiently throughout the year.

Implementing the heat pumps with respect to capacity and location depending on the sources, yields around 3500 full load hours for the heat pumps connected to the distribution grids in 2013, and around 4000 full load hours in 2025. When connected to the transmission grid the number decreases by around 1000 full load hours for both years. The heat pumps mainly displace peak load production in winter time, and heat production by combined heat and power plants in summer time. The integration of heat pumps is found to be economical feasible already today, and in 2025.

21

Future Work

21.1 Field Study of Utilization of Sea Water

As mentioned utilization of sea water in a heat pump in Copenhagen is not straight forward. The temperatures of the water near coast is to cold during winter, but maybe due to stratification of the water it is still possible to utilize tom heat at the bottom. The water at deep sea is never too cold, but is maybe too expensive to implement and operate.

A field study have to be made to get some actual data on the temperatures and flows in the near coast water around Copenhagen. Plus make some research on the technical feasibility of pumping/suction of water from a 12 km distance.

21.2 Case Studies on Drinking and Sewage Water Heat Pumps

It would be relevant to conduct a case study on how to implement heat pumps to the two different facilities; drinking water and sewage water. Cases considering different approaches of type of heat pump, and implementation evaporator in the process.

21.3 Investigation of More Suitable Heat Pump Technologies

This study have been chosen to be based on an ammonia two-stage compression heat pump. A whole study could be made upon analysing the pros and cons for different types of heat pumps. Heat pumps, like the water vapour compression heat pump, and the hybrid heat pump, could be interesting to analyse with the ammonia heat pump used in this study. Especially considering the poor COP the ammonia heat pump when connected to the transmission grid (110°C).

Bibliography

[1] Advansor (2013). 'compHEAT - Varmepumper til industri og fjernvarme Grøn strøm giver lavere varmepriser.', 2013-11-12.
Website: `http://www.advansor.dk/litteratur/produktblade/`

[2] Amager Ressourcecenter (2013); *ARC - Miljøredegørelse 2012.* Yearly statement on environmental impact.

[3] Andersen, H. (2013); *WorldClassHub & Corporate Social Responsibility.* Presentation at Kuben Management by Head of Department of Asset Management & Energy at Copenhagen Airport Hans Andersen about energy efficiency, management and cooperation.

[4] Arp, K. (2013). 'Private telephone conversation and mail exchange with Engineer Kim Arp, Frederikshavn Forsyning.', 2013-11-12.

[5] Arp, K. (2013); *Varmepumpe på spildevand Frederikshavn Forsyning A/S.* Presentation of heat pumps in Frederikshavn owned by Forsyningen Frederikshavn.

[6] Assur, A. (1958); 'Composition of sea ice and it tensile strength.' In 'Arctic sea ice,' pages 106–138. Division of Earth Science.

[7] Bach, B. (2014). 'COPcalc download site.', 2014-03-16.
Website: `http://goo.gl/kXwN1f`

[8] Bäckström, M. (1940); *Economic optimum problems in connection with refrigeration.* Generalstabens litografiska anstalts förlag.

[9] Bäckström, M. (1970); *Kylteknikern.* Almiqvist & Wiksell.

[10] Barrow, H., 'A note on frosting of heat pump evaporator surfaces.' *Journal of Heat Recovery Systems*, 5:(1985) 195–201.

[11] Beck, S. & Collins, R. (2008). 'Moody diagram.', 2013-12-06.
Website:
`http://upload.wikimedia.org/wikipedia/commons/8/80/Moody_diagram.jpg`

[12] Bejan, A.; George, T.; & Moran, M. (1996); *Thermal Design & Optimization.* Wiley.

[13] Boyce, P., 'The application of noise criteria to domestic air-to-water heat pumps.' *Applied Acoustics*, 17:(1984) 1–19.

[14] de Bruyn, S.; Nelissen, D.; & Koopman, M. (2013); *Carbon leakage and the future of the EU ETS market - Impact of recent developments in the EU ETS on the list of sectors deemed to be exposed to carbon leakage.* April. CE Delft.

[15] Chang, K.-c.; Baik, Y.-j.; Kang, B.-c.; Yoon, H.-k.; Kim, H.-j.; & Lee, H.-s., 'Simulation and preliminary experimental study on the sea water source tandem heat pump.' *OCEANS 2012 MTS/IEEE - YEOSU.*

[16] Chemical Engineering (2013). 'Chemical Engineering Plant Cost Index (CEPCI).', 2014-03-17.
Website: `http://business.highbeam.com/408261/article-1G1-339746176/chemical-engineering-plant-cost-index`

[17] Christensen, S. W. & Markussen, M. M. (2010); *Industiel varmegenvinding med CO2- og NH3-baserede varmepumper.* MSc thesis at the Technical University of Denmark.

[18] City Council of Copenhagen (2013); *KBH 2025 Klimaplan - En grøn, smart og CO2-neutral by.*

[19] Cloutier, M. (2001); 'Chapter 10: Refrigeration Cycles.' In 'ME 372 Thermodynamics,' University of Nevada, Reno.
Website: `http://web.me.unr.edu/me372/Spring2001/RefrigerationCycles.pdf`

[20] Coker, A. K. (2007); *Ludwig's applied process design for chemical and pretrochemical plants - Chapter 0: Rules of thumb: Summary.* 30 cm. Elsevier, 4 edition.

[21] CTR - HOFOR - VEKS (2013); *Scenarieanalyser - Baggrundsrapport til VPH3.* december. Confidential report from Ea Energy Analyses.

[22] CTR - HOFOR - VEKS (2013); 'VPH3 - Varmenettet i Hovedstanden 2012 og 2025.' *Technical report.*

[23] CTR - Københavns Energi - VEKS (2009); *Data for teknologier til produktion af varme - Baggrundrapport til Varmeplan Hovedstaden.* November.
Website: `http://www.varmeplanhovedstaden.dk/files/otherfiles/0000/0048/Baggrundsrapport_om_teknologier_ekstern.pdf`

[24] Danish Energy Agency (2011); *Forudsætninger for samfundsøkonomiske analyser på energiområdet.* April.

[25] Danish Energy Agency (2013). 'Energipriser og -afgifter.', 2014-02-18.
Website: `http://www.ens.dk/info/tal-kort/statistik-nogletal/energipriser-afgifter`

[26] Danish Energy Agency (2014). 'Udbud af drejebog til store varmepumper i fjernvarmesystemer.', 2014-03-27.
Website: `http://www.ens.dk/energistyrelsen/aktuelle-udbud/udbud-drejebog-store-varmepumper-fjernvarmesystemer`

[27] Danish Meteorological Institute (2013); *Temperature data of the sea at Nordhavn.* Data of the sea temperature near Copenhagen provided by Bent Vraae Jørgensen, DMI.

[28] Danish Meteorological Institute (2014). 'Vejrnormaler - Vejrdata 2001-2010.', 2014-01-16.
Website: `http://www.dmi.dk/vejr/arkiver/normaler-og-ekstremer/klimanormaler-dk/vejrnormal/`

[29] Danish Ministry of Climate; Energy and Building (2012); *Aftale mellem regeringen (Socialdemokraterne , Det Radikale Venstre , Socialistisk Folkeparti) og Venstre , Dansk Folkeparti , Enhedslisten og Det Konservative Folkeparti om den danske energipolitik 2012-2020.* The Danish parliaments energy agreement 2012.

[30] Danish Ministry of Environment (2009). 'Bekendtgørelse om fastsættelse af miljømål for vandløb, søer, kystvande, overgangsvande og grundvand - Bilag 2.E.', 2014-02-11.
Website: `https://www.retsinformation.dk/forms/R0710.aspx?id=127762`

[31] Danish Ministry of Environment (2011). 'Bekendtgørelse om vandkvalitet og tilsyn med vandforsyningsanlæg: Bilag 1 - Kvalitetskrav til drikkevandets hovedbestanddel. BEK nr 1024 from 31/10/2011.', 2014-30-01.
Website: `https://www.retsinformation.dk/forms/r0710.aspx?id=138647`

[32] Danish Ministry of Environment (2012). 'Bekendtgørelse om jordvarmeanlæg: §10 stk. 8. BEK nr 1312 from 21/11/2013.', 2014-02-02.
Website: `https://www.retsinformation.dk/Forms/R0710.aspx?id=158936#Kap4`

[33] Dansk Fjernvarmes Geotermiselskab (2014). 'Geotermisk anlæg - Amager.', 2014-01-29.
Website: `http://www.geotermi.dk/showpage.php?pageid=5156#GDA`

[34] Danske Vandværkers Forening (1998); *Indledende reapport om vandkvalitet i ledningsnet*. DVF Vejledning nr. 17.

[35] Deane, P. & O Gallachóir, B. (2013); *Quantifying the Impacts of National Renewable Electricity Ambitions using a North-West European Electricity Market Model*. Research paper from University of College Cork Ireland.
Website: `http://energyexemplar.com/wp-content/uploads/publications/North-WestEuropeanElectricityMarketModel.pdf`

[36] Dong Energy (2013); *Avedøreværket - Miljøregnskab 2012*. Yearly statement on environmental impact.

[37] Dong Energy (2013); *H.C. Ørsted værket - miljøregnskab 2012*. Yearly statement on environmental impact.

[38] Dong Energy (2013); *Svanemølleværket - Miljøregnskab 2012*. Yearly statement on environmental impact.

[39] Duer, A.-C. (2014). 'Private telephone conversation with Anne-Christine Duer, Ministry of Environment.', 2013-02-18.

[40] Ea Energianalyse (2009); 'Afgifter på varmepumper til fjernvarme.' *Technical report*.

[41] Ea Energy Analyses (2012); *Energy Policy Strategies of the Baltic Sea Region for the Post-Kyoto Period*. Prepared for the Baltic Sea Region Energy Co-operation (BASREC).

[42] Emerson Climate Technologies (2010). 'Vilter single screw ammonia heat pumps - Harness your heat... don't reject it.', 2014-03-16.
Website: `http://www.emersonclimate.com/europe/Documents/Brands/Vilter/ProductBrochures/Brand_Vilter_Brochure_HeatPump.pdf`

[43] Emerson Climate Technologies (2012); *Vilter Single Screw Compressors - For Industrial Refrigeration*. Brochure about Vilter screw compressors with technical data.

[44] Emerson Electric (2010); *The World's Best Compressors for Industrial Refrigeration - Single screw ammonia heat pumps*. Brochure about Vilter screw compressor use in large ammonia heat pumps.

[45] Energinet.dk (2012); *Energinet.dk's analyseforudsætninger 2012-2035*. Dok. 29494/12, sag. 12/427.

[46] Energinet.dk (2014). 'Neutral gaspris.', 01-02-2014.
Website: `http://energinet.dk/DA/GAS/Produkter-og-handel/Transmissionstarif-prisblad/Sider/Neutralgaspris.aspx`

[47] Energinet.dk - Energistyrelsen (2012); *Technology data for energy plants - Generation of electricty and district heatin, energu storage and energy carrier generation and conversion.*

[48] Energitilsynet (2012). 'Fjernvarmepriser.', 2014-02-18.
Website:
`http://energitilsynet.dk/varme/prisstatistik/pr-18-december-2012/`

[49] Energy Exemplar (2014). 'PLEXOS Integreated Energy Model.', 2014-02-28.
Website: `http://energyexemplar.com/software/plexos-desktop-edition/`

[50] European Commission (2013); *Køebhavn - Europas Grønne Hovedstad 2014.* Den Europæiske Unions Publikationskontor.

[51] Frijns, J.; Hofman, J.; & Nederlof, M., 'The potential of (waste)water as energy carrier.' *Energy Conversion and Management*, 65:(2013) 357–363.

[52] Friotherm (2005). 'Värtan Ropsten – The largest sea water heat pump facility worldwide, with 6 Unitop 50FY and 180 MW total capacity.', 2013-01-13.
Website: `http://www.friotherm.com/webautor-data/41/vaertan_e008_uk.pdf`

[53] Friotherm (2007). '5 Unitop 50FY heat pump / chiller units simultaneously generate 90 MW heat energy and 60 MW chilled water.', 2013-11-17.
Website:
`http://www.friotherm.com/webautor-data/41/katri_vala_e012_uk.pdf`

[54] GAMS (2013). 'The GAMS System.', 2014-02-14.
Website: `http://www.gams.com/`

[55] GNS Science (2014). 'Shell and tube heat exchanger.', 2014-02-10.
Website:
`http://www.gns.cri.nz/Home/Learning/Science-Topics/Earth-Energy/Extracting-the-Heat/Heat-Exchangers/Shell-and-tube-heat-exchanger`

[56] Granryd, E.; Ekroth, I.; Lundqvist, P.; Melinder, Å.; Palm, B.; & Rohlin, P. (2011); *Refrigerating Engineering.* Royal Institute of Technology, KTH.

[57] Grundfos (2012); *Grundfos Data Booklet: NB, NBE, NK, NKE - Single-stage end-suction pumps according to EN 733.* Data catalogue of Grundfos pumps single-stage end-suction pumps.
Website: `http://www.industrialwaterequipment.co.uk/pdf/nb-nk-nke.pdf`

[58] Grundfos (2013). 'Nu er fjernvarmen i Bjerringbro på køl.', 2013-12-28.
Website: `http://dk.grundfos.com/cases/find-case/nu-er-fjernvarmen-i-bjerringbro-p-k-l.html`

[59] Grundfos Research and Technology (2006); *Centrifugalpumpen.* GRUNDFOS Management A/S.

[60] Grüner, S. (2013); *Hourly temperature data from Lynetten sewage treatment plant in the periods 2011 and 2012.* Excel file: "Temp RL afløb 2011-2012.xls".

[61] Grüner, S. (2013); *Store, eldrevne varmepumper til fjernvarme.* Presentation at HOFOR about heat pumps in VPH3.

[62] Hedegaard, K. & Münster, M., 'Influence of individual heat pumps on wind power integration – Energy system investments and operation.' *Energy Conversion and Management*, 75:(2013) 673–684.
Website: `http://linkinghub.elsevier.com/retrieve/pii/S0196890413004743`

[63] Henriksen, T. (2013). ‘Private telephone conversation and mail exchange with Engineer Torben Henriksen, ICS Energy.’, 2014-01-30.

[64] Hoffmann, K. & Pearson, D. F., ‘Ammonia Heat Pumps for District Heating in Norway - a case study.’ *The Institute of Refrigeration*, pages 1–8.

[65] HOFOR (2013); *Fra damp til vand - København afvikler den dampbaserede fjernvarme.*

[66] HOFOR (2013); *VPH3 - Lavtemperatur fjernvarme.* Presentation at HOFOR about low temperature district heating.

[67] ICS Energy (2011). ‘Neatpump - Industrielle højtemperatur varmepumper.’, 20141-01-23.
Website: `http://www.icsenergy.dk/PDF/Neatpump/PraesentationafICSEnergyogNeatpump2011.pdf`

[68] ICS Energy (2013). ‘Trendsættende projekt med varmepumper fra ICS.’
Website: `http://www.icsenergy.dk/PDF/Industripumper/CASE_Bjerringbro_Varmevaerk_Grundfos.pdf`

[69] IEA (2012); *World Energy Outlook 2012.* International Energy Agency.

[70] Investing.com (2014). ‘Carbon Emissions Historical Data - 2012 monthly view.’, 18-03-2014.
Website:
`http://www.investing.com/commodities/carbon-emissions-historical-data`

[71] Jensen, L. G. (2012). ‘Kom tæt påDTU’s nye vindtunnel.’, 2012-02-02.
Website:
`http://ing.dk/infografik/kom-taet-pa-dtus-nye-vindtunnel-129603`

[72] Jensen, U. A. & Lomstein, E. (2011); *Spildevand - drift af biologiske anlæg.* Course material for Education of construction and industryl. Course 44943, Biological cleanig of sewage water.

[73] Jeppesen, J. P. (2013); *Hydrografien i Øresund.* Presentation by Marin Biologist Jens Peder Jeppesen, University of Copenhagen, about hydrography and flows in Øresund.

[74] Jeppesen, J. P. (2013). ‘Private telephone conversation and mail exchange with Marine Biologist at The Øresund Aquarium, Jens Peder Jeppesen.’, 2013-11-22.

[75] Karlsson, K. & Meibom, P., ‘Optimal investment paths for future renewable based energy systems—Using the optimisation model Balmorel.’ *International Journal of Hydrogen Energy*, 33:(2008) 1777–1787.
Website: `http://linkinghub.elsevier.com/retrieve/pii/S0360319908000888`

[76] Klootwijk, M. & Jacobsen, L. H. (2013); *Heat pumps in Dutch district heating.* Presentation by Energie Total Projects and GEO about ATES integration in district heating networks.

[77] Københavns Energi (2003). ‘Vandspejlet.’, 2014-02-02.
Website: `http://www.sansebio.dk/lib_6.htm`

[78] Koch, J. (2013). ‘NOx-afgift koster 250 mio. kroner i tabt eleksport.’, 2013-12-25.
Website:
`http://www.danskenergi.dk/Aktuelt/Indblik/NOXafgiftTabtEksport.aspx`

[79] Krak (2013). ‘Krak Sea Maps.’, 2013-12-08.
Website: `http://map.krak.dk/`

[80] Krøyer, K. (2009). 'Nu kører Danmarks første kæmpe-varmepumpe påbillig møllestrøm.', 2014-03-26.
Website: http://ing.dk/artikel/nu-korer-danmarks-forste-kaempe-varmepumpe-pa-billig-mollestrom-102000

[81] Lindstrom, H. O., 'Experiences with a 3.3 MW heat pump using sewage water as heat source.' *Journal of heat recovery systems*, 5:(1985) 33–38.

[82] Ludwig Bölkow Systemtechnik (2013). 'Ölpreisprognosen der IEA World Energy Outlook (WEO) 1998 bis 2012.', 2014-03-26.
Website: http://nicolashoening.de/user/iea-outlook-1000.jpg

[83] Lynettefællesskabet I/S (2013); *Miljøberetning 2012*. Yearly statement on environmental impact from Lynetten and Damhusåen cleaning facilities.

[84] Lynettefællesskabet (2013). 'Renseprocessen.', 2014-02-03.
Website: http://www.lyn-is.dk/Bes%C3%B8gscenter/Renseprocessen.aspx

[85] MacAller, S. A. (2013); *Potential for Heat Recovery from Danish Drinking Water Supply*. MSc thesis at the Technical University of Denmark.

[86] Madsbøll, H.; Minds, G.; & Koren, A. (1995). 'Water as refrigerant. Operation experience from a 2 MW water chiller and an 0.6 MW heat pump plant.', 2014-02-10.
Website: http://xqw.dk/work/fg51/work1/20121003130728959.pdf

[87] Marfelt, B., 'Lufthavn tjener millioner ved at lagre varme og kulde.' *Ingeniøren*.

[88] Mathiesen, B. V.; Blarke, M. B.; Hansen, K.; & Connolly, D. (2011); 'The role of large-scale heat pumps for short term integration of renewable energy: Case study of Denmark towards 50% wind power in 2020 and technology data for large-scale heat pumps.' *Technical report*, Department of Development and Planning, Aalborg University.

[89] McGovern, J. (2011); 'Technical Note: Friction Factor Diagrams for Pipe Flow.' *Technical report*, Dublin Institute of Technology - School of Mechanical and Transport Engineering.

[90] Minea, V. & Chiriac, F., 'Hybrid absorption heat pump with ammonia/water mixture – Some design guidelines and district heating application.' *International Journal of Refrigeration*, 29:(2006) 1080–1091.
Website: http://linkinghub.elsevier.com/retrieve/pii/S0140700706000600

[91] Moody, L. F., 'Friction Facotrs for Pipe Flow.' *Transactions of the A.S.M.E.*

[92] Münster, M.; Morthorst, P. E.; Larsen, H. V.; Bregnbæ k, L.; Werling, J.; Lindboe, H. H.; & Ravn, H., 'The role of district heating in the future Danish energy system.' *Energy*, 48:(2012) 47–55.

[93] Nielsen, M. N. (2012); *Minimumsproduktioner, varmhold og reserveforhold i det nordlige og sydlige dampområde*. Note concerning operational aggrement for the steam network in Copenhagen. Københavns Energi (HOFOR).

[94] Nord Pool Spot (2013). 'Data download page.', 2013-01-04.
Website: http://www.nordpoolspot.com/Market-data1/Downloads/Historical-Data-Download1/Data-Download-Page/

[95] Nørrevang, A. & Meyer, T. J. (1968); *Danmarks Natur - Havet*. Politekens Forlag.

[96] Ommen, T.; Markussen, W. B.; & Elmegaard, B., 'Heat pumps in district heating networks.' *CoolEnergy.dk 2013 conference*.

[97] Pearson, A. (2013); *District Heatpumps & Rivers of Gold.* Presentation in the conference ATMOsphere Europe 2013.

[98] Pearson, S. F., 'Ammonia Refrigeration Systems.' *ASHRAE.*

[99] PlanEnergi (2013); 'Udredning vedrørende varmelagringsteknologier og store varmepumper til brug i fjernvarmesystemet.' *Technical Report November*, PlanEnergi, Teknologisk Institut, GEO, and Grøn Energi.

[100] Poulsen, C. S.; Andreasen, M. B.; Pedersen, S. V.; Hansen, H. J.; Hauritz, P.; Radisch, N.; Sandberg, S.; Thøgersen, L.; Sørensen, I.; & Bjørn, H. (2010); *Varmepumper med lodrette boringer som varmeoptager.* Elforsk-projekt j.nr. 342-066.

[101] Ravn, H. F.; Hindsberger, M.; Petersen, M.; Schmidt, R.; Bø g, R.; Grohnheit, P. E.; Larsen, H. V.; Munksgaard, J.; Ramskov, J.; Esop, M.-R.; Klavs, G.; Galinis, A.; Paprocki, R.; Wawrzyszczuk, M.; & Gloukhov, A. (2001); *Balmorel: A Model for Analyses of the Electricity and CHP Markets in the Baltic Sea Region.* Balmorel Project, 2001.

[102] Roskidle Forbrændingsanlæg (2013); *Grønt regnskab for 2012.* Yearly statement on environmental impact.

[103] Rygaard, S.; Lauritzen, P.; Hjortbak, G.; Lundfald, A.; Hetley, J.; Togeby, M.; Engstrøm, S.; Bregnbæk, L.; & Werling, J. (2010); *Kombination af vindkraft og varmepumpe til Varmeplan Århus.* Report about wind and heat pump cooperation in Århus made by AffaldVarme Århus, Nordjysk Elhandel, Vindenergi Danmark, and Ea Energy Analyses.

[104] SKAT (2013). 'Ændring af afgiftssatserne påfossile brændsler pr. 1. februar 2013 - forsyningssikkerhedsafgift.', 2013-11-26.
Website: `http://www.skat.dk/SKAT.aspx?oId=2091005&vId=0`

[105] SKAT (2013). 'Afgiftens størrelse for målt udledt NOx til luften Standardsatser for energiprodukter.', 2013-12-25.
Website: `http://www.skat.dk/SKAT.aspx?oID=1946602`

[106] SKAT (2014). 'E.A.4.3.9 Afgiftslempelse for fjernvarme (el-patronordningen).', 2014-02-04.
Website: `https://www.skat.dk/SKAT.aspx?oId=2061609`

[107] Skovrup, M. J. & Jakobsen, A. (2003); *Calculations on a standard refrigeration cycle - Household refrigerator example.* Note in DTU refrigeration course.

[108] Smith, C. E. (2013). 'Worldwide Pipeline Construction: Crude, products plans push 2013 construction sharply higher.', 2014-03-06.
Website: `http://www.ogj.com/articles/print/volume-111/issue-02/special-report--worldwide-pipeline-construction/worldwide-pipeline-construction-crude-products.html`

[109] Sørensen, E., 'Varmepumpe og vindmøller giver billig fjernvarme.' *Maskinmesteren*, Energi:(2010) 34–35.

[110] Sørensen, S. N. (2011); 'Grundvandskøle- og varmeanlæg (ATES) status og erfaringer.' *Technical report*, Enopsol ApS.

[111] Star Refrigeration (2014). 'Neatpump - The natural choice.', 2014-03-26.
Website: `app.timelog.com/eaea/default.asp?login=true`

[112] Statistics Denmark (2005). 'PNR1: Key figures by region.', 2014-02-18.
Website: `http://www.statistikbanken.dk/statbank5a/default.asp?w=1366`

[113] The Engineering Toolbox (2014). 'Refrigerants - Ozone Depletion (ODP) and Global Warming Potential (GWP).', 2014-01-29.
Website: `http://www.engineeringtoolbox.com/Refrigerants-Environment-Properties-d_1220.html`

[114] Thornberg, D. (2013); *Daily sewage water flow at Lynetten in the period 1996 to 2013.* Data proviede by Manager at Copenhagen Wastewater Innovation, Dines Thornberg.

[115] Tredal, J. E. (2014). 'Privat telephone conversation with Engineer at Grundfos Jens Erik Tredal about feasible pump technologies for sea water.', 2014-03-25.

[116] University of Copenhagen (2013). 'Øresund facts.', 2013-11-17.
Website: `http://www.oresundsakvariet.ku.dk/videnom/oeresundfacts/`

[117] Varmelast.dk (2013). 'Fjernvarmenettet - tre integrerede fjernvarmesystemer.', 2013-11-11.
Website: `http://varmelast.dk/varmenet.html`

[118] Vattenfall (2013); *Amagerværket - Grønt regnskab 2012.*

[119] Woods, D. R. (2007); *Rule of Thumb in Engineering Practice.* Wiley.

Appendix

A

Calculations for Assumptions

A.1 Calculation of NPSH of Water Pump

The NPSH_A is calculated from

$$\text{NPSH}_\text{A} = \frac{(p_\text{atm} + \rho_\text{water} g H_\text{surf} - \Delta p_\text{fric}) - p_\text{vapour}}{\rho_\text{water} g}. \tag{A.1}$$

Here p_atm is the atmospheric pressure, ρ_water is the density of the water, g is the acceleration due to gravity, H_surf is the vertical location of the pump in respect to the water surface, Δp_fric is the pressure drop due to friction, and p_vapour is the saturation pressure of the water.

To calculate the pressure drop in a $L = 12,000$ m pipe the Darcy–Weisbach equation[89] is used:

$$\Delta p_\text{fric} = f_\text{D} \frac{L}{D} \frac{\rho_\text{water} v^2}{2}, \tag{A.2}$$

where f_D is the Darcy friction factor, D is the diameter of the pipe, and v is the flow velocity. For a circular pipe with diameter, D, and mass flow, $\dot{m}$, the velocity can be expressed by,

$$v = \frac{4\dot{m}}{\rho \pi D^2}. \tag{A.3}$$

And the Darcy–Weisbach equation can be rewritten to:

$$\Delta p_\text{fric} = f_\text{D} \frac{L}{D^5} \frac{8\dot{m}^2}{\rho \pi^2} \tag{A.4}$$

Assuming that the diameter is between 10 cm to 50 cm gives a Reynold number ($\text{Re} = \rho_\text{water} v D / \mu_\text{water}$) in the order of 10^{-6}. Assuming a smooth pipe the friction factor is found from the Moody digram[91] (see Appendix C) to $f_\text{D} = 0.01$.

A.2 Calculation of Air Temperature in Evaporator

Frosting is when water vapour in the air freezes in the pipes and fines the evaporator. For this to happen the pipes and fines have to be below 0°C, thus the refrigerant have to be below 0°C ($\Delta T_\text{eva} < 0$°C). According to Granryd et al. (2011)[56, table 8.68] the optimum mean log temperature difference, (A.5), of a forced convection air cooler is $\Delta T_\text{lm,eva} = 5.5$°C, and the optimum decrease of the air source is $\Delta T_\text{source} = 3$°C. This yields a temperature of

$T_{\text{air,in}} < 7°\text{C}$. Meaning that if the air temperature is below 7°C there is a risk of frosting to happen on the pipes and fines.

$$\Delta T_{\text{lm,eva}} = \frac{(T_{\text{air,in}} - T_{\text{eva}}) - (T_{\text{air,out}} - T_{\text{eva}})}{\ln\left(\frac{T_{\text{air,in}} - T_{\text{eva}}}{T_{\text{air,out}} - T_{\text{eva}}}\right)} \tag{A.5}$$

A.3 Estimation of Volume Flow in Compressor

Assumed evaporator temperature of $T_{\text{eva}} = 0°\text{C}$. Ammonia quality between $x = 0.3$. No super heating (i.e. density of inlet flow to evaporator is found at $x = 1$). The density is then found to be $\rho = 1.1$ kg/m^3.

The mass flow of the refrigerant needed in an evaporator for utilizing $\dot{Q} = 1$ MW of heat is;

$$\dot{m} = \frac{h|_{x=1} - h|_{x=0.3}}{\dot{Q}}, \tag{A.6}$$

which gives $\dot{m} = 0.7$ kg/s. And by using the density to find cubic meter per hour we get $\dot{V} = 1180$ m^3/h.

A.4 Estimation of Condenser Price

The heat transfer area of the condenser is found to be around 400 m^2. The price of a heat transfer area for a titanium tube-in-shell condenser is around DKK 185,000 per m^2[1]. This gives a condenser price of the 12 MW$_{\text{th}}$ (first tandem step) sea water heat pump of around DKK 11 mill[2].

A.5 Calculation of Heat Prices in Copenhagen in 2012

Heat prices is from Energitilsynet[48] and population numbers are 2005 statistics from Statistics Denmark[112].

[1] Calculated from \$700 per m^2 from 'Rule of Thumb in Engineering Practice'[119], with CEPCI index 524[16], and a titanium correlation factor of 9.

[2] Using a size dependency of $n = 0.71$ (size^n)[119].

Post no.	Heat price [DKK/MWh]	Population
2000	380	318,432
2300	514	185,252
2600	329	23,036
2605	339	20,350
2610	357	36,888
2620	410	25,892
2625	413	5,245
2630	441	32,744
2635	307	20,604
2650	372	49,371
2670	320	34,788
2680	472	16,116
2730	805	35,933
2765	544	10,516
2800	1220	38,602
2820	292	21,136
2840	710	15,097
2860	277	28,589
2970	501	19,522

Population	
Total	938,113
Heat price [DKK/MWh]	
Standard average	474
Weighted average (by population)	459

A.6 Calculation of Fuel Prices for Boosting the Forward Temperature

```
TH1=110
TH2=90
Tr=55
TL=10

dThp=TH2-Tr
dTb=TH1-TH2
dTtot=TH1-Tr

COP1=(273+TH1)/(TH1-TL)*0,65
COP2=(273+TH2)/(TH2-TL)*0,65
eta=0,95

Pel=1
P_ratio=Pel/Pf

Eco_ratio = Pel/COP1/(dThp/dTtot*Pel/COP2+dTb/dTtot*Pf/eta)
```

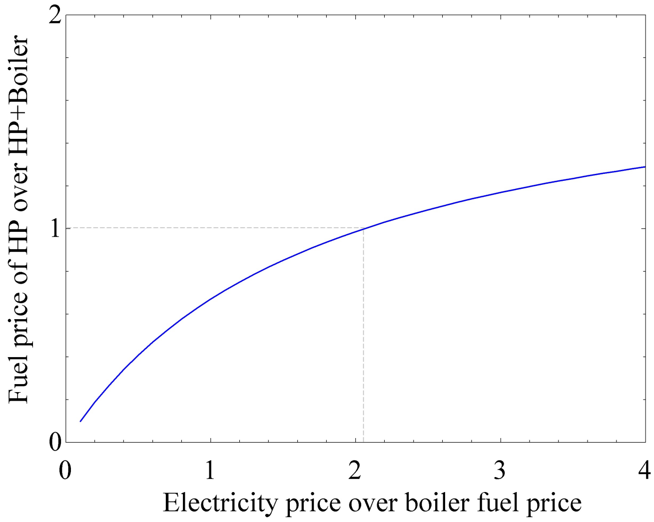


Figure A.1: Comparison of prices of supplying to the transmission grid directly with a heat pump, and by pre-heating with a heat pump and boosting the water with a boiler.

B

Note about Energy Taxes

The taxes and tariffs in Denmark has an important influence on the economical perspective of heat pumps in district heating networks. In Denmark there is overall four political reasons to apply a tax to a service or consumption. The four is listed in an report made by Ea Energy Analyses (2009)[40];

Taxes with environmental benefits
: Taxes on acts that aggravates the environment. Could for instance be CO_2 and NO_x taxes on emission.

Taxes with security of supply benefits
: Tax on a product to regulate it to be sure that there is enough of it in the future.

Taxes as a mean to enhance something
: Tax on a product to enhance the benefits of substituting this with another product. For example taxes on fossil fuels to improve the economical benefits of renewable energy.

Taxes for governmental economical profit
: Taxes wit simple mean to get money into the state treasury. These taxes should not regulate in any way, so here the task is to distribute the equally. Often companies can subtract these taxes from their accounts. The tax on electricity can be considered as such a tax.

Energy taxes constitute about 11% to 13% of the total tax system in Denmark. In 2012 the energy taxes summed up to DKK 34 bill., plus DKK 6 bill. in emission taxes (see Table B.1). The heat producers can choose between two taxation options; tax on the fuel input or fixed tax on the heat output (tax limit).

As standard the tax is on the fuels. Meaning if a boiler produce heat for district heating, then the tax is on the used fuel. If electricity is used for heating taxes is also here on the production of heat, where the production of electricity is tax free. Taxes is first applied on the consumption stage for electricity, due to the fact that electricity is a commodity that is traded with between countries and it would therefore be anticompetitive to put taxes an production. This does not include environmental taxes as CO_2, SO_2, and NO_x[40, 78, 104], which is put on all production including that of electricity.

From 1st of January 2008 there have been a limit on the energy taxation on the heat output. This is important when considering heat pumps. And especially important after the tax relief in 2013 (as seen in Table B.2 and Figure B.1).

Table B.1: Danish revenue of taxes on energy and emissions in mill. DKK. (Source: [105])

	2008	2009	2010	2011	2012
Energy taxes					
Coal	1,471	1,576	2,450	2,418	2,473
Electricity	8,697	8,792	10,204	11,989	11,155
Natural gas	3,799	3,555	4,418	4,429	4,005
Oil	8,763	8,953	9,086	9,252	9,098
Gasoline	8,876	8,736	8,132	7,719	7,457
Taxes on emission					
CO_2	5,076	5,019	5,757	5,897	5,676
SO_2	86	71	47	47	45
NO_x			189	202	443
Total [mill. DKK]	**36,768**	**36,702**	**40,283**	**41,953**	**40,352**

Table B.2: Taxes on electricity used for heat in 2012 and 2013. (Source: [106])

	2012	2013
Tax limits [DKK/MWh]		
Energy tax limit	215	215
CO2-tax limit	48	48
Total tax limit	**263**	**263**
Electricity taxes [DKK/MWh]		
Energy tax	517	233
Additional tax	61	62
Energy saving contribution	6	6
Distribution contribution	40	40
Energy saving tax	64	65
Total elelectricity taxes	**688**	**406**

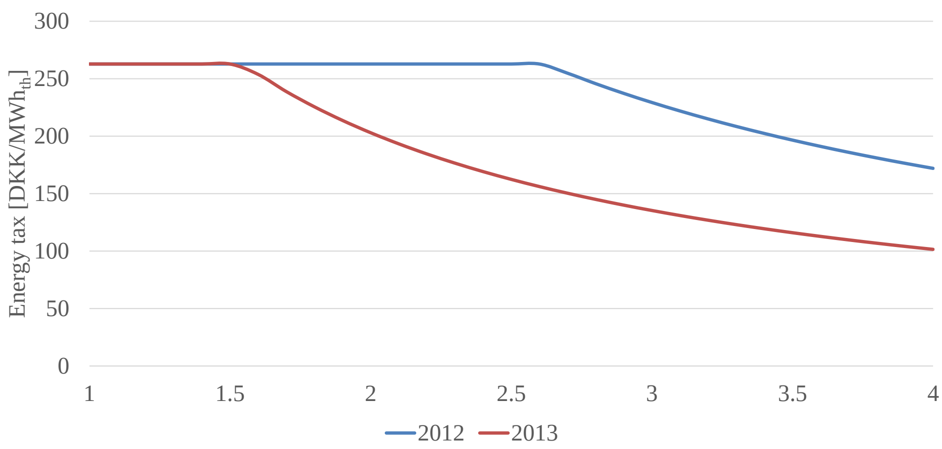
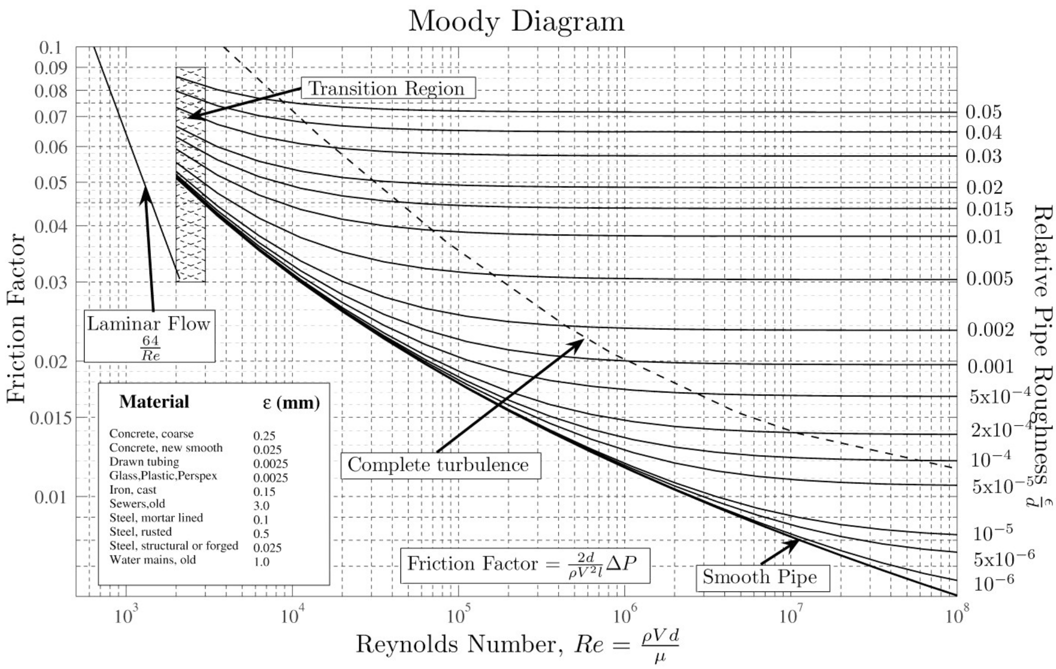


Figure B.1: Energy taxes on electricity depending on COP. A COP of 1 is equal a direct electric heater.

C

Moody Diagram



Source: [11]

D

Thermodynamic Equations in EES

D.1 Equations and Macros in COPcalc

```
"!COPcalc equations for design of heat pumps"
"Bjarne Bach, 2014"

"COP, Cap [MW] "

"Definition of cells to use in Excel"
cells$=CONCAT$('A2:C';STRING$(SS+1))

"Refrigerant (ammonia)"
R$='R717'
S$='NaCl'

"List values of return temp., subcooling and utilized heat from source"
dT_subcool=StringVal(dTsc$)
dT_s=StringVal(dT_s$)

"Evaporation temperature"
Te=Ts-dT_s-dTp_e

"Pinch on condenser"
dTp_c=Tc-(Tdh-(qc[4]-qc[3])/Q_dot_c*(Tdh-Tdh[2]))


"Heat capacity of source (water at 1 bar)"
C=C_w/10
cp_s=cp(S$;T=Ts;C=C)
T_s_freez=FreezingPt(NaCl;C=C)

"Heat from source"
Q_dot_s=m_dot_s*cp_s*dT_s

"Pressure of district heating"
p_dh=10

"Saturation and intermediate pressure"
p[1]=P_sat(R$;T=Te)
p[4]=P_sat(R$;T=Tc)
p_m=sqrt(p[1]*p[4])
p_r1=p_m/p[1]
p_r2=p[4]/p_m

"Screwcompressor isentropic efficiency relation (from Grandryd et al. (2011), eq:7.29b)"
eta_sC=0,7
k=1,3
vi=2,5
pii=vi^k
eta_sC1=eta_sC*(p_r1^((k-1)/k)-1)/(pii^((k-1)/k)-(k-1)/k*pii^(-1/k)*(pii-p_r1)-1)
eta_sC2=eta_sC*(p_r2^((k-1)/k)-1)/(pii^((k-1)/k)-(k-1)/k*pii^(-1/k)*(pii-p_r2)-1)
```

```
"! The equations below are for the cycle calculations"

"State 1 - After Evaporator"
T[1]=Te+0,01
h[1]=enthalpy(R$;T=T[1];P=p[1])
s[1]=entropy(R$;T=T[1];P=p[1])

"State 2 - After first Compressor"
s_2s=s[1]
p[2]=p_m
h_2s=enthalpy(R$;S=s_2s;P=p[2])
h[2]=(h_2s-h[1])/eta_sC1+h[1]
T[2]=temperature(R$;H=h[2];P=p[2])

"State 3 - Heat loss before second compressor"
T[3]=Tdh[1]+dTp_hx
p[3]=p_m
h[3]=enthalpy(R$;T=T[3];P=p[3])
s[3]=entropy(R$;T=T[3];P=p[3])

"State 4 - After last Compressor"
s_4s=s[3]
h_4s=enthalpy(R$;S=s_4s;P=p[4])
h[4]=(h_4s-h[3])/eta_sC2+h[3]
T[4]=temperature(R$;H=h[4];P=p[4])

"State 5 - After Codensor"
T[5]=Tc-dT_subcool
p[5]=p[4]
h[5]=enthalpy(R$;T=T[5];P=p[5])

"State 6 - After Valve"
h[6]=h[5]
p[6]=p[1]
T[6]=temperature(R$;H=h[6];P=p[6])
x[6]=quality(R$;H=h[6];P=p[6])

"! The equations below are for output to diagram"

"COP calculation"
COP=round(((h[4]-h[5])+(h[2]-h[3]))/((h[2]-h[1])+(h[4]-h[3]))*1000)/1000

"Mass flow of refrigerant"
Q_dot_e=Q_dot_s
Q_dot_e=m_dot*(h[1]-h[6])

"Compressor work"
W_dot_1 = m_dot*(h[2]-h[1])
W_dot_2 = m_dot*(h[4]-h[3])

"Heat from condenser"
Q_dot_c=m_dot*(h[4]-h[5])

"Mass flow DH"
Q_dot_tot=m_dot*(h[2]-h[3])+m_dot*(h[4]-h[5])
Q_dot_tot=m_dot_dh*cp_dh*(Tdh-Tdh[1])
cp_dh=cp(water;T=Tdh;P=p_dh)

"UA values for Condenser and Evaporator (simple dT)"
"dTc=((Tc[4]-Tdh[4])-(Tc[1]-Tdh[3]))/ln((Tc[4]-Tdh[4])/(Tc[1]-Tdh[3]))"
exp(((Tc[4]-Tdh[4])-(dTp_c))/dTc1)=((Tc[4]-Tdh[4])/(dTp_c))

exp(((dTp_c)-(Tc[1]-Tdh[3]))/dTc2)=((dTp_c)/(Tc[1]-Tdh[3]))

qc[4]-qc[3]=UA_c1*dTc1          "UA value for de-super heat"
qc[3]=UA_c2*dTc2                      "UA value for condensing"


exp(((Ts[1]-T[1])-(Ts[2]-T[6]))/dTe)=(Ts[1]-T[1])/(Ts[2]-T[6])
Q_dot_e=UA_e*dTe

dThx=T[3]-Tdh[1]
m_dot*(h[2]-h[3])=UA_hx*dThx

"Output in MW"
Q_hp_MW=Q_dot_tot/1000


"! The equations below are for the plots"
```

```
"For plot ph"
h[7]=h[1]
p[7]=p[1]

"For plot QT sew (eva)"
qr[1]=0
qr[2]=m_dot*(enthalpy(R$;P=p[1];X=1)-h[6])
qr[3]=qr[2]+m_dot*(h[1]-enthalpy(R$;P=p[1];X=1))
Tr[1]=T[6]
Tr[2]=Tr[1]
Tr[3]=T[1]
qw[2]=0
qw[1]=Q_dot_e
Ts[1]=Ts
Ts[2]=Ts-dT_s

"For plot QT dh (ex)"
qx[1]=0
qx[2]=m_dot*(h[2]-h[3])
Tx[1]=T[3]
Tx[2]=T[2]
qdh[1]=0
qdh[2]=m_dot*(h[2]-h[3])
qdh[2]=m_dot_dh*cp_dh*(Tdh[2]-Tdh[1])

"For plot QT dh (con)"
qc[4]=qc[3]+m_dot*(h[4]-enthalpy(R$;P=p[4];X=1))
qc[3]=qc[2]+m_dot*(enthalpy(R$;P=p[4];X=1)-enthalpy(R$;P=p[4];X=0))
qc[2]=m_dot*(enthalpy(R$;P=p[4];X=0)-h[5])
qc[1]=0
Tc[4]=T[4]
Tc[3]=temperature(R$;P=p[4];X=1)
Tc[2]=temperature(R$;P=p[4];X=0)
Tc[1]=T[5]
qdh[3]=0
qdh[4]=m_dot*(h[4]-h[5])
Tdh[3]=Tdh[2]
Tdh[4]=Tdh

"Interval of the axis"
Q_plot_e_max=Q_dot_e*1,1
Q_plot_e_interval=round(Q_dot_e/4/1000)*1000
T_plot_e_min=T[6]-1,5
T_plot_e_max=Ts+1
T_plot_e_interval=1 "round((T_plot_e_max-T_plot_e_min)/4)"

Q_plot_hx_max=m_dot*(h[2]-h[3])*1,1
Q_plot_hx_interval=round(m_dot*(h[2]-h[3])/4/100)*100
T_plot_hx_min=round(Tdh[1]*0,8)
T_plot_hx_max=T[2]*1,3
T_plot_hx_interval=round((T[2]-Tdh[1])/4/10)*10

Q_plot_c_max=Q_dot_c*1,1
Q_plot_c_interval=round(Q_dot_c/4/1000)*1000

T_plot_c_min=round(Tdh[3]*0,8)
T_plot_c_max=T[4]*1,2
T_plot_c_interval=round((T[4]-Tdh[3])/4)
```

D.2 Extra Equations for the Design Phase

```
Ts=StringVal(Tsource$)
Tdh=StringVal(Tdh$)
dTp_e=StringVal(dTp_e$)
dTp_c=StringVal(dTp_c$)
Tdh[1]=StringVal(Tdh_ret$)
dTp_hx=2


$export 'C:\COPcalc\bin\UA_values.dat' UA_c2 UA_e UA_hx
```

D.3 Extra Equations for the Off-design Phase

```
$import 'C:\COPcalc\bin\UA_values.dat' UA_c2 UA_e  UA_hx

$ifnot ParametricTable
Ts=StringVal(Tsource$)
Tdh=StringVal(Tdh$)
Tdh[1]=StringVal(Tdh_ret$)
$endif
```

D.4 Macro for Running Single Run

```
Solve
UpdateGuesses
```

D.5 Macro for Running Seasonal Run

```
Solve
UpdateGuesses
EXCEL.OPEN(FileNameData$)
EXCEL.COPY(cells$)
Paste Parametric 'COP'  R1 C1
SolveTable 'COP' Rows=1..SS
Copy ParametricTable 'COP' R1 C4 R8760 C5
EXCEL.Range('D2:D2')
EXCEL.Paste
EXCEL.Range('D1:D1')
COPY Equations L2 C1:L2 C4
EXCEL.Paste
EXCEL.Range('E1:E1')
COPY Equations L2 C6:L2 C13
EXCEL.Paste
EXCEL.FileSaveAs(FileNameData$)
AlterValues  'COP'  COP  Rows=1..8760  Clear
AlterValues  'COP'  Ts  Rows=1..8760  Clear
AlterValues  'COP'  Tdh[1]  Rows=1..8760  Clear
AlterValues  'COP'  Tdh  Rows=1..8760  Clear
HideWindow Parametric
```

E

Simple Model of Heat Pump System

```
****************************************************************
*      Simple heat pump and heat storage with price profile    *
*      Bjarne Bach (s080494)                                   *
****************************************************************


****************************************************************
*        Definition of sets and parameters                     *
****************************************************************

Sets
t 'hour number' /h1*h8736/
;

Scalars
L_hp_min 'Min. prod. of heat pump per hour [kW]'               /0.1/
L_hp_max 'Max. prod. of heat pump per hour [kW]'               /3/
L_hs_min 'Min. charge/discharge of heat storage pr hour [kW]' /0.01/
L_hs_max 'Max. charge/discharge of heat storage pr hour [kW]' /3/
L_hs_min 'Min. level of heat storage [kWh]'                    /0.1/
L_hs_max 'Max. level of heat storage [kWh]'                    /4/
L_init   'Initial level of heat storage'                       /0.5/
eff_hs   'Effectivity of ch. and dch. in heat storage'         /0.99/
;

Parameters
* Data input
D(t)    'Heat demand in hour t'
/
$include '../data/heat_demand.inc'
/

C(t)     'Electricity price in hour t'
/
$include '../data/elec_price.inc'
/

COP(t)     'COP of heat pump to hour t'
/
$include '../data/COP_yhourly.inc'
/
;



****************************************************************
*        Definition of decision variables                      *
****************************************************************


Positive variables
```

```
V_hp(t)           'Production of heat pump in hour t [MW]'
V_hs_dc(t)        'Production from heat storage (discharge) [MW]'
V_hs_c(t)         'Production to heat storage (charge) [MW]'
V_hs(t)           'Level in heat storage [MWh]'
;

Binary variables
onoff_dc(t)       'Discharging = 1'
onoff_c(t)        'Charging = 1'
onoff_hp(t)       'Heat pump on = 1'
;

Free variable
cost         'Total production costs'
;


*****************************************************************
*        Definition of equations                                *
*****************************************************************

Equations
eq_costs          'Total costs'
eq_demand(t)      'Supply-demand equilibrium'
eq_p_min(t)       'Minimum generation level'
eq_p_max(t)       'Maximum generation level'
eq_Lhs_initial(t)'Initial level of storage'
eq_Lhs_level(t)   'Heat storage level'
eq_Lhs_min(t)     'Minimum level heat storage'
eq_Lhs_max(t)     'Maximum level heat storage'
eq_hsdc_min(t)    'Minimum discharge'
eq_hsdc_max(t)    'Maximum discharge'
eq_hsc_min(t)     'Minimum charge'
eq_hsc_max(t)     'Maximum charge'
eq_onoff_HS(t)    'Discharge/charge'
;

*****************************************************************
*        Formulation of  model                                  *
*****************************************************************

eq_costs .. cost =e= sum(t,V_hp(t)*c(t)/COP(t));
eq_demand(t) .. V_hp(t) + V_hs_dc(t) - V_hs_c(t) =e= D(t);
eq_p_min(t) .. V_hp(t) =g= L_hp_min*onoff_hp(t);
eq_p_max(t) .. V_hp(t) =l= L_hp_max*onoff_hp(t);
eq_Lhs_initial(t)$(ord(t)=1) .. V_hs(t) =e= L_init;
eq_Lhs_level(t)$(ord(t)>1) .. V_hs(t) =e=
              V_hs(t-1) + V_hs_c(t-1)*eff_hs - V_hs_dc(t-1)/eff_hs;
eq_Lhs_min(t) .. V_hs(t) =g= L_hs_min;
eq_Lhs_max(t) .. V_hs(t) =l= L_hs_max;
eq_hsdc_min(t) .. V_hs_dc(t) =g= L_hs_min*onoff_dc(t);
eq_hsdc_max(t) .. V_hs_dc(t) =l= L_hs_max*onoff_dc(t);
eq_hsc_min(t) .. V_hs_c(t) =g= L_hs_min*onoff_c(t);
eq_hsc_max(t) .. V_hs_c(t) =l= L_hs_max*onoff_c(t);
eq_onoff_HS(t) .. onoff_dc(t)+onoff_c(t) =l= 1;

Model HP_simple /all/;
Solve HP_simple using mip minimizing cost;



*****************************************************************
*        Extraction of data                                     *
*****************************************************************
$include 'output.inc'
```

F

Generation Technologies in Copenhagen

The generation technologies of Greater Copenhagen in 2012/2013 and 2025 are shown in table on the next page.

Besides the technologies listed each consumption area is supplied with a peak load boiler of 1000 MW_{th} in the model. This peak load is a lot more than in reality, so is only a model fix, to sure that demand can be met. In 2012/2013 these boilers run on light oil, and in 2025 they are assumed to run on biomass.

Two heat accumulators is present in the 2012/2013 system, one at Avedøreværket with a storage capacity of 1980 MWh_{th} and on at Amagerværket of 750 MWh_{th}. In 2025 it is assumed that 14 GWh_{th} extra heat storage has been build.

Table F.1: Generation technologies in Greater Copenhagen area in 2012/2013 and 2025. The capacities are in MW_e for back-pressure and extraction, and in MW_{th} for heat-only boilers. (Source: [23])

Area	**Plant ID**	**Type**	**Fuel**	**Co-firing fuel**	**2012/13 [MW]**	**2025 [MW]**
ARC	AMF1_3-ST-B7	Backpressure	Municipality waste	-	24	0
ARC	AMF4-HO	Heat-only boilers	Municipality waste	-	36	0
ARC	AMF5_6-ST-B1	Backpressure	Municipality waste	Wood	0	43
AMV1	AMV1-ST-E1-WP	Backpressure	Wood pellets	-	64	64
AMV3	AMV3-ST-E0-CO	Extraction	Coal	-	250	0
AMV3	AMV3-ST-E1-WP	Extraction	Wood pellets	-	0	250
AVV	AVV1-ST-E0-CO	Extraction	Coal	-	250	0
AVV	AVV1-ST-E1-WP	Extraction	Wood pellets	-	0	250
AVV	AVV2-ST-E1-WP	Backpressure	Wood pellets	Gas/Straw	442	442
HCV	HCV7	Backpressure	Natural gas	-	75	0
HCV	HCV8	Backpressure	Natural gas	-	23	0
HCV	HCV8-t	Heat-only boilers	Natural gas	-	53	0
KARA	KARA34-HO	Heat-only boilers	Municipality waste	-	28	0
KARA	KARA5-ST-B9	Backpressure	Municipality waste	Wood	14	14
KARA	KARA6-ST-B1	Backpressure	Municipality waste	Wood	0	19
KKV	KOEGE-ST-B7	Backpressure	Wood	-	0	9
KKV	KOEGE-ST-B8	Backpressure	Wood	-	0	17
RLF	LYNETTEN	Heat-only boilers	Municipality waste	-	10	10
SMV	SMV7	Backpressure	Natural gas	-	67	0
SMV	SMV7-t	Backpressure	Natural gas	-	13	0
VF	VF1_2-G-HO	Heat-only boilers	Municipality waste	-	48	0
VF	VF5-ST-B9	Backpressure	Municipality waste	Wood	17	17
VF	VF6-ST-B0	Backpressure	Municipality waste	Wood	22	22
					1,436	**1,157**

G

Balmorel Inputs

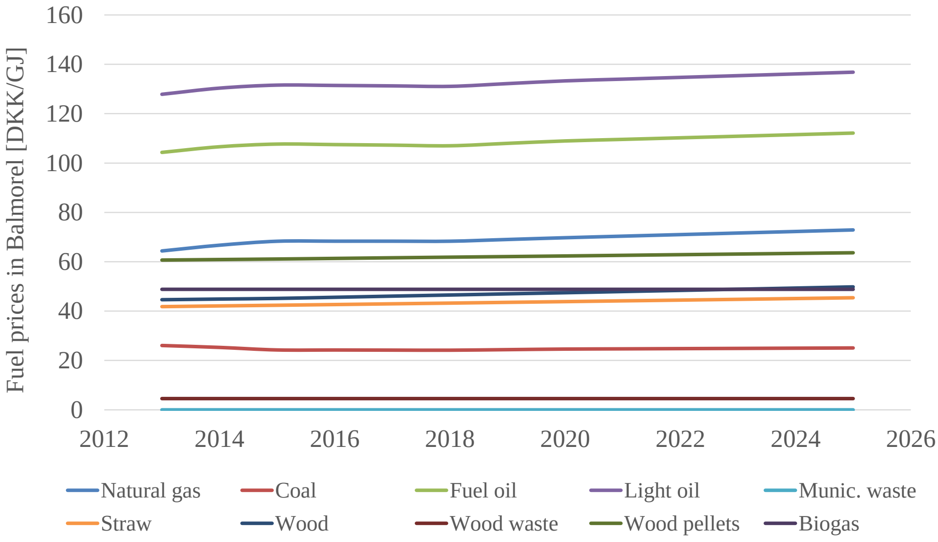


Figure G.1: The fuel prices in Balmorel is from the IEA WEO 2012[69].

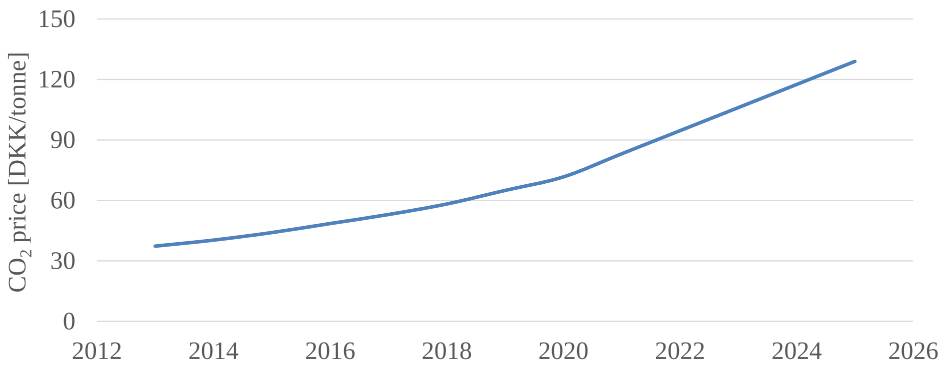


Figure G.2: The CO2 prices in Balmorel is from a scenario made by Ea Energy Analyses in dialogue with the Danish Energy Agency.

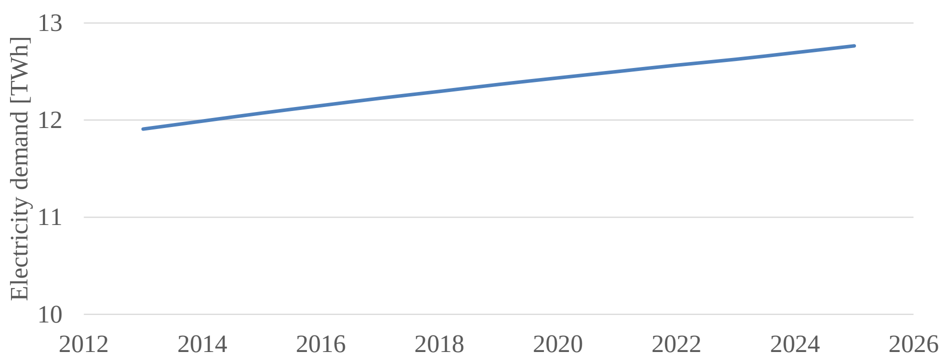


Figure G.3: The forecast of the Danish electricity demand is from Energinet.dk[45].

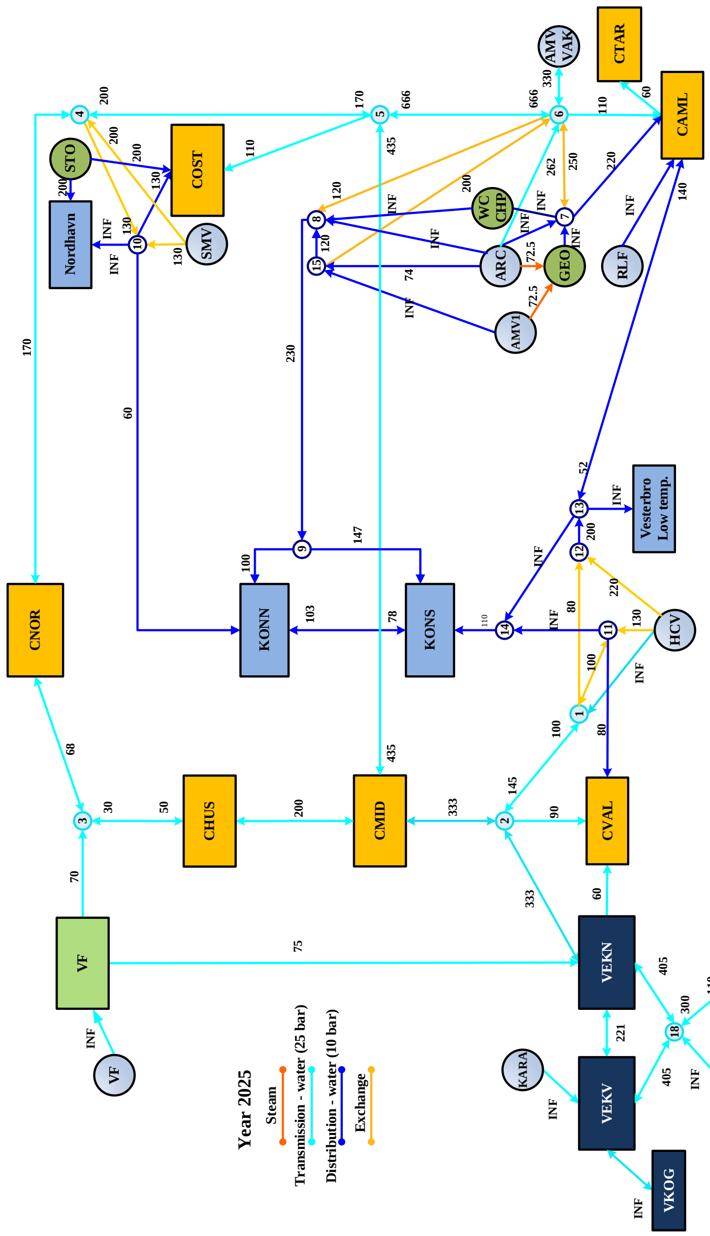


Figure G.4: Structure and connections in the transmission grid of the Copenhagen area in 2025. See Table 13.2 and Table 2.1 for explanation of areas and generation technologies respectively. Circles represent production areas, and squares consumer areas. The colors of the consumer areas indicate which distribution company is responsible (see Table 13.2). (Original figure is from VPH3 note about the heating network in the Greater Copenhagen area 2012 and 2025[22])

H

Balmorel Modelling of Add-on for Making the Operation Time Dependent (`TimeDepOp`)

H.1 Making the Add-on Option in Balmorel's Option File (`balopt.opt`)

```
* TIMEDEPOP makes the operation (capacity and efficiency) time dependent.
$Setglobal TIMEDEPOP yes
```

H.2 Modelling the Technology Dataset (`tech.inc`)

Applying an extra element `GDTDO` to the set `GDATASET`. If `GDTDO` equals 1, then the generation technologies capacity and efficiency will be time dependent. If not `GDTDO` equals 1, then it will run as a normal generation technology.

```
* Time dependent operation add-on to Balmorel.
  GDTDO          'Time dependent oparation (effeciency and capacity) (0/1)'
```

An example of implementing a technology is shown below (compressed example). The three heat pumps are all set to have time dependent operation, where as the boiler don't.

```
TABLE    GDATA(GGG,GDATASET) 'Technologies characteristics'
          GDTYPE  GDFUEL  GDCV   GDCB   GDFE   GDOMFCOST0  GDOMVCOST0  GDTDO
HP_sew     5       17      0      0      3.2    1.8         0.30        1
HP_drink   5       17      0      0      3      1.8         0.30        1
HP_sea     5       17      0      0      3      1.8         0.30        1
Boiler     4       2       0      0      0.9    80          2
```

H.3 Defining the Time Dependent Efficiencies (`TimeDepOp_eff.inc`)

```
*------------------------------------------------------------
* TimeDepOp add-on to make the operation efficiency of a technology
* time depended.
* Bjarne Bach 2014-01-06
*
* This file creates a SET of technologies with time dependent
* operation and includes the technologies time dependent
* efficiencies.
*
*------------------------------------------------------------

Set IGTDO(G) 'Set of tech. with time dependent operation';

IGTDO(G) = YES$(GDATA(G,'GDTDO') EQ 1);

PARAMETER GDTDOE_S(GGG,SSS) 'Time dependent operation efficiency'
/
$include '../../%COREDATAFOLDER%/data/TDO/TDOeff_HPsew.inc';
$include '../../%COREDATAFOLDER%/data/TDO/TDOeff_HPdrink.inc';
$include '../../%COREDATAFOLDER%/data/TDO/TDOeff_HPsea.inc';
/
;


PARAMETER GDTDOE(GGG,SSS,TTT) 'Time dependent operation efficiency'
/
*$include '../../%COREDATAFOLDER%/data/TDOeff_AMV3.inc';
/
;

GDTDOE(G,SSS,TTT)$GDTDOE_S(G,SSS)=GDTDOE_S(G,SSS);
```

This file shall be included just after the definition of the parameter containing the generation data (`GDATA`). In `balmorel.gms` (Balmorels main file) include the highlighted line;

```
PARAMETER GDATA(GGG,GDATASET)  'Technologies characteristics'
$if EXIST 'tech.inc' $INCLUDE 'tech.inc';
$if not EXIST 'tech.inc' $INCLUDE '../../%COREDATAFOLDER%/data/tech.inc';

* Time dependend efficiency of gen. tech.
$ifi %TIMEDEPOP%==yes $include '../../base/addons/TimeDepOp/TimeDepOp_eff.inc';
$ifi not %TIMEDEPOP%==yes GDATA(G,'GDTDO')$(GDATA(G,'GDTDO')=1)=0;
```

The last line resets all technologies to normal (not time dependent) if the add-on is not chosen in the `balopt.opt` file.

H.4 Defining the Time Depending Capacities (`TimeDepOp_cap.inc`)

```
*------------------------------------------------------------
* TimeDepOp add-on to make the operation of a technology
* time depended.
* Bjarne Bach 2014-01-06
*
* GTDOC uses the GKDERATE parameter to make the capacity
* time dependent.
*------------------------------------------------------------


PARAMETER GDTDOC(GGG,SSS) 'Time dependent operation capacity (normalized)'
/
$include '../../%COREDATAFOLDER%/data/TDO/TDOcap_HPsew.inc';
$include '../../%COREDATAFOLDER%/data/TDO/TDOcap_HPdrink.inc';
$include '../../%COREDATAFOLDER%/data/TDO/TDOcap_HPsea.inc';
/
;

* If nothing else is given, then design capacity is constant throughout the year
GDTDOC(G,SSS)$(IGTDO(G) and not GDTDOC(G,SSS))=1;
```

```

* Redefining GKDERATE.
GKDERATE(IA,G,SSS,TTT)$IGTDO(G)= (GKDERATE(IA,G,SSS,TTT)*GDTDOC(G,SSS))$IGTDO(G);
```

This file shall be included just after the inclusion of profiles and outages (`var2001.inc`). In `balmorel.gms` (Balmorels main file) include the highlighted line;

```
$if EXIST 'var2001.inc' $INCLUDE 'var2001.inc';
$if not EXIST 'var2001.inc' $INCLUDE '../../%COREDATAFOLDER%/data/var2001.inc';

* Time dependent capacity for technologies.
$ifi %TIMEDEPOP%==yes $INCLUDE '../../base/addons/TimeDepOp/TimeDepOp_cap.inc';
```

H.5 New Term on Fuel Consumption Equation for Existing Thermal Units (`TimeDepOp_eq_thermal.inc`)

```
*-----------------------------------------------------------
* For time dependent operation efficiency for existing units.
* Bjarne Bach 2014-01-20
*
* Extra line to the fuel consumption rate calculated on existing
* units QGFEQ.
*-----------------------------------------------------------

+(VGE_T(IA,G,IS3,T)/(GDTDOE(G,IS3,T)*GEFFDERATE(IA,G)))$(IGNOTETOH(G) and IGE(G)
                     and GDATA(G,'GDTDO')=1)
+(GDATA(G,'GDCV')*VGH_T(IA,G,IS3,T)/((GDTDOE(G,IS3,T)-1$(GDATA(G,'GDFUEL')=19
                     and IGETOH(G)) )*GEFFDERATE(IA,G)))$(IGH(G)
                     and GDATA(G,'GDTDO')=1)
```

This term shall be included in the equation `QGFEQ(IA,G,IS3,T)$IAGK_Y(IA,G)` with the lines highlighted below.

```
* Fuel consumption rate calculated on existing units.
QGFEQ(IA,G,IS3,T)$IAGK_Y(IA,G) ..
     VGF_T(IA,G,IS3,T)
  =E=
     (VGE_T(IA,G,IS3,T)/(GDATA(G,'GDFE')* GEFFDERATE(IA,G)))$(IGNOTETOH(G)
                                            and IGE(G)
                                            and GDATA(G,'GDTDO')=0)
* Katja 2012-11-27: reformulation of geotermal, only additional heat from steam
* heatpumps are counted in vgh
   +(GDATA(G,'GDCV')*VGH_T(IA,G,IS3,T)/((GDATA(G,'GDFE')-1$(GDATA(G,'GDFUEL')=19
                                  and IGETOH(G)) )*GEFFDERATE(IA,G)))$(IGH(G)
                                  and GDATA(G,'GDTDO')=0)
$ifi %UnitComm%==yes $include '../../base/addons/unitcommitment/qgfeqadd.inc';
* Time dependent efficiency of existing thermal plants.
$ifi %TIMEDEPOP%==yes $include '../../base/addons/TimeDepOp/TimeDepOp_eq_thermal.inc';
;
```

H.6 New Term on Fuel Consumption Equation for New Thermal Units (`TimeDepOp_eq_thermal_new.inc`)

```
*-----------------------------------------------------------
* For time dependent operation efficiency for new units.
* Bjarne Bach 2014-01-20
*
* Extra line to the fuel consumption rate calculated on existing
* units QGFEQ.
*-----------------------------------------------------------

```

```
+(VGEN_T(IA,G,IS3,T)/(GDTDOE(G,IS3,T)*GEFFDERATE(IA,G)))$(IGNOTETOH(G) and IGE(G)
                     and GDATA(G,'GDTDO')=1)
+(GDATA(G,'GDCV')*VGHN_T(IA,G,IS3,T)/((GDTDOE(G,IS3,T)-1$(GDATA(G,'GDFUEL')=19
                     and IGETOH(G)) )*GEFFDERATE(IA,G)))$(IGH(G)
                     and GDATA(G,'GDTDO')=1)
```

This term shall be included in the equation QGNFEQ(IA,G,IS3,T)$IAGK_Y(IA,G) with the lines highlighted below.

```
* Fuel consumption rate calculated on existing units.
QGNFEQ(IA,G,IS3,T)$IAGK_Y(IA,G) ..
     VGFN_T(IA,G,IS3,T)
  =E=
     (VGEN_T(IA,G,IS3,T)/(GDATA(G,'GDFE')* GEFFDERATE(IA,G)))$(IGNOTETOH(G)
                                                    and IGE(G)
                                                    and GDATA(G,'GDTDO')=0)
* Katja 2012-11-27: reformulation of geotermal, only additional heat from steam
* heatpumps are counted in vgh
   +(GDATA(G,'GDCV')*VGHN_T(IA,G,IS3,T)/((GDATA(G,'GDFE')-1$(GDATA(G,'GDFUEL')=19
                                         and IGETOH(G)) )*GEFFDERATE(IA,G)))$(IGH(G)
                                         and GDATA(G,'GDTDO')=0)
$ifi %UnitComm%==yes $include '../../base/addons/unitcommitment/qgfneqadd.inc';
* Time dependent efficiency of existing thermal plants.
$ifi %TIMEDEPOP%==yes $include '../../base/addons/TimeDepOp/TimeDepOp_eq_thermal_new.inc';
;
```

H.7 New Term on Fuel Consumption for Existing Electric Heat Pumps (`TimeDepOp_eq_hp.inc`)

```
*---------------------------------------------------------------------
* Time dependend COP of electric heat pump tech.
* Bjarne Bach 2014-01-05
*
* Extra term in the electricity consumption for existing heat pumps.
*---------------------------------------------------------------------

+(VGH_T(IA,IGETOH,IS3,T)/GDTDOE(IGETOH,IS3,T))$(GDATA(IGETOH,'GDTDO')=1)
```

The term shall be included in the equation describing electricity consumption by existing heat pump QGGETOH(IAGK_Y(IA,IGETOH),IS3,T) as highlighted below.

```
* Electric heat pumps:
* Katja 2012-11-27: Reformulation of geotermi
* The electricity use for geotermi heat production is set. Note! change from GDFE
* to 1/GDCB to be simmilar to other heat units"
QGGETOH(IAGK_Y(IA,IGETOH),IS3,T) ..
      VGE_T(IA,IGETOH,IS3,T)
   =E=
     (VGH_T(IA,IGETOH,IS3,T)/GDATA(IGETOH,'GDFE'))$((not GDATA(IGETOH,'GDFUEL')=19)
                                     and (not GDATA(IGETOH,'GDTDO')=1))
     +(VGH_T(IA,IGETOH,IS3,T) * GDATA(IGETOH,'GDCB'))$(GDATA(IGETOH,'GDFUEL')=19)
* Time dependent COP of existing heat pumps
$ifi %TIMEDEPOP%==yes $include '../../base/addons/TimeDepOp/TimeDepOp_eq_hp.inc';
;
```

H.8 New Term on Fuel Consumption for New Electric Heat Pumps (`TimeDepOp_eq_hp_new.inc`)

```
*---------------------------------------------------------------------
* Time dependend COP of electric heat pump tech.
* Bjarne Bach 2014-01-05
```

```
*
* Extra term in the electricity consumption for new heat pumps.
*------------------------------------------------------------------------

+(VGHN_T(IA,IGETOH,IS3,T)/GDTDOE(IGETOH,IS3,T))$(GDATA(IGETOH,'GDTDO')=1)
```

The term shall be included in the equation describing electricity consumption by new heat pump `QGNGETOH(IAGK_Y(IA,IGETOH),IS3,T)` as highlighted below.

```
QGNGETOH(IAGK_Y(IA,IGETOH),IS3,T) ..
      VGEN_T(IA,IGETOH,IS3,T)
   =E=
     (VGHN_T(IA,IGETOH,IS3,T)/GDATA(IGETOH,'GDFE'))$((not GDATA(IGETOH,'GDFUEL')=19)
                                         and (not GDATA(IGETOH,'GDTDO')=1))
     +(VGHN_T(IA,IGETOH,IS3,T) * GDATA(IGETOH,'GDCB'))$(GDATA(IGETOH,'GDFUEL')=19)
* Time dependent COP of existing heat pumps
$ifi %TIMEDEPOP%==yes $include '../../base/addons/TimeDepOp/TimeDepOp_eq_hp_new.inc';
;
```

I

Balmorel Modelling of Distribution Grids

I.1 Added to the File Containing All Sets (`sets.inc`)

Added to the sets `CCCRRRAAA`, `AAA(CCCRRRAAA)`, `AAA_GreaterCHP(AAA)`, `AAA_GreaterCHPAndSur(AAA)`, `KBHAREAS(AAA)`, and `RRRAAA('DK_E',AAA)`.

```
*Distribution areas
   DK_E_VF_DIS
   DK_E_VEKV_DIS
   DK_E_CVAL_DIS
   DK_E_CAML_DIS
   DK_E_CHUS_DIS
```

I.2 Added to the File Containing the Miscellaneous Profiles (`var2001.inc`)

Apply the heat demand profiles (`DH_VAR_T`) on the new distribution area.

```
* Distribution grids for heat pumps
DH_VAR_T('DK_E_VF_DIS',SSS,TTT)=DH_VAR_T('DK_E_VF',SSS,TTT);
DH_VAR_T('DK_E_VEKV_DIS',SSS,TTT)=DH_VAR_T('DK_E_VEKV',SSS,TTT);
DH_VAR_T('DK_E_CVAL_DIS',SSS,TTT)=DH_VAR_T('DK_E_CVAL',SSS,TTT);
DH_VAR_T('DK_E_CAML_DIS',SSS,TTT)=DH_VAR_T('DK_E_CAML',SSS,TTT);
DH_VAR_T('DK_E_CHUS_DIS',SSS,TTT)=DH_VAR_T('DK_E_CHUS',SSS,TTT);
```

I.3 Changes in the File Containing Annual Demand for Heat (`dh.inc`)

The areas;

```
   DK_E_VF
   DK_E_VEKV
   DK_E_CVAL
   DK_E_CAM
   DK_E_CHUS
```

are replaced with;

```
  DK_E_VF_DIS
  DK_E_VEKV_DIS
  DK_E_CVAL_DIS
  DK_E_CAML_DIS
  DK_E_CHUS_DIS
```

respectively.

I.4 Added to the File with the Heat Transmissions Capacities (`htrans.inc`)

Making a one way connection (`XHKINI`) from the original area to the new distribution area.

```
*BB: Distribution grid
XHKINI(YYY,'DK_E_VF','DK_E_VF_DIS')= INF;
XHKINI(YYY,'DK_E_VEKV','DK_E_VEKV_DIS')= INF;
XHKINI(YYY,'DK_E_CVAL','DK_E_CVAL_DIS')= INF;
XHKINI(YYY,'DK_E_CAML','DK_E_CAML_DIS')= INF;
XHKINI(YYY,'DK_E_CHUS','DK_E_CHUS_DIS')= INF;
```

J

Balmorel Modelling of Add-on for 3rd Country Import/Export (X3V)

The modifications to the Balmorel add-on X3V is highlighted in the code below.

J.1 Modelling of the Option File (x3v.opt)

```
* This is the options file for the price dependent electricity
* exchange with  third countries add—on.
* 1) In BB1 and BB2 there are two ways use the module.
*   A) An assumption that there is a fixed annual net import/export
*       to each specified 3rd country. This method also outputs a
*       parallel shift in prices from the 3rd country which ensures
*       this balance. The method is recomended for baseline
*       scenarios, i.e. the normal situation.
*   B) A parrallel price shift can be supplied as input, i.e. from
*       an execution of the A). This is recomended for analysing
*       abnormal years, i.e. dry or wet years in the Nordic region.
*   C) Option for validation of model. A fictive 3rd country supply
*       the region with a price profile and an infinite transmission
*       capacity. The price profile of the region will therefore be
*       the prices of the 3rd country.
* 2) For BB3 the only option is to use an exogenous parrallel shift
* in prices, i.e. one generated from 1A). This option file should
* be located either in the  base/addons/x3v directory or in
* working directory (most often where your project file is located.
* Balmorel searches the working directory first and otherwise
* defaults to base/addons/x3v.

* (January 2007 LB, January 2014 BB).

* Only one of the following options must be yes.

* X3VfxQ==yes indicates 1A) is selected.
$Setglobal X3VfxQ

* X3VfxP==yes indicates 1B) is selected.
$Setglobal X3VfxP

* X3VfxC==yes indicates 1C) is selected.
$Setglobal X3VfxC yes

* NOTE: BB3 disregards both options and runs as 2.

* The following distinguishes the name of the price shift input or
* output file. The path to the file is always
* '../../base/addons/x3v/data/X3V_%X3VPRICECASE%_BALSP.gdx'
```

```
* the filename will be 'X3V_%X3VPRICECASE%_BALSP.gdx'. If set to
* the empty string  the file name will be X3V__BALSP.gdx.
* (TIP: It can be usefull to set the X3VPRICECASE control option
* to %CASEID% or %COMPARECASE% when writing input to or loading
* input from, other model executions respectively.)

$Setglobal X3VPRICECASE Dummy


*-----------------------------------------------------------------
* The following contains only internal program code and no user
* options.
*-----------------------------------------------------------------

* In order to use the same control variables for BB1, BB2 and BB3
* some control variables are overwritten.
$ifi %BB3%==yes $Setglobal X3VfxP yes
$ifi %BB3%==yes $Setglobal X3VfxQ no
$ifi %BB3%==yes $Setglobal X3VfxC no

$ifi %X3VfxC%==yes $Setglobal X3VfxP yes
```

J.2 Modelling of the Add-on Sets File (x3vsets.inc)

```
*-------------------------------------------------------------------------

* The following concerns price-dependant electricity exchange to places
* outside the simulated area
*-------------------------------------------------------------------------

$ontext
Price dependent electricity exchange with places outside the simulated
geographical scope may be used together with the fixed electricity
exchange with third countries.
The price-quantity relationships are given as a piecewise step curve.
There are card(X3VSTEP)steps applied in simulation, and in the data
card(X3VSTEP0) steps
may be given. The length (MW) of each import step is X3VIMQ and X3VEXQ of
each export step.
The associated prices are X3VIMP and X3VIMP, respectively.
The prices are given on a yearly basis,
the value for the currently simulated year are held in IX3VPIM_Y and
IX3VPEX_Y. The exchange is assumed to be lossless and without transmission
cost.

The simulated price dependent electricity exchange transmission connections
are specified in the set X3VX.
$offtext


* The set of regions with which there can be price dependent electricity
* exchange:

SET X3VPLACE0 'Set of possible places w. price dependent elec. exchange data'
/
X3VPROFLAND 'Profileland'
*X3VGERMAN 'Germany'
*X3VPOL 'Poland'
*X3VFRANCE 'France'
/;


SET X3VPLACE(X3VPLACE0) 'Set of sim. places w. price depend. elec. exchange data'
/
X3VPROFLAND
*X3VGERMAN
*X3VPOL
*X3VFRANCE
/;

* The combinations of RRR and X3VPLACE that are to be simulated:

SET X3VX(RRR,X3VPLACE0) 'Simulated transm. lines for price depend. elec. exchange'
/
   'DK_E'.'X3VPROFLAND'
*    'DK_W'.'X3VGERMAN'
*    'DK_E'.'X3VGERMAN'
```

```
*   'SE_S'.'X3VGERMAN'
*   'SE_S'.'X3VPOL'
*   'GB_all_island'.'X3VFRANCE'
/;

*-------------------------------------------

* The following set RX3VSUBSTI indicates (by assigning YES) if elements in
* X3VPLACE0 is a substitute for a region in RRR. If it is, the price
* dependent exchange should only be used if the region is NOT included in
* a country in set C, i.e. the set RX3VSUBSTI(IR,X3VPLACE0) (where IR is a
* region in C) should be empty. The only function of the set RX3VSUBSTI is
* to help the user to avoid errors by printing an error message.

SET RX3VSUBSTI(RRR,X3VPLACE0) 'Substitutes in price depend. elec. exchange';
* RX3VSUBSTI(RRR,X3VPLACE)=NO; /* This is used if no substitutes*/
* Give the real information, if any:

*  RX3VSUBSTI('DE_R','X3VGERMAN')=YES;
*  RX3VSUBSTI('PL_R','X3VPOL')=YES;

* The set of steps on the price dependent electricity exchange curves.
* The same number of steps is assumed for the import and the export directions:

$ifi %X3VfxC%==yes $goto X3V_labelC1;
SET X3VSTEP0 'Steps for price dependent electricity exchange data'
    /X3VSTEP01*X3VSTEP04/;
$label X3V_labelC1;

* For constant price profile applied on region only one step i necessary
$ifi not %X3VfxC%==yes $goto X3V_labelC2;
SET X3VSTEP0 'Steps for price dependent electricity exchange data'
    /X3VSTEP01*X3VSTEP01/;
$label X3V_labelC2;

* The set of steps on the price dependent electricity exchange curve
* used in simulation (no exchange if empty, in this case use
* 'IX3VSTEP(X3VSTEP)=NO'):

SET X3VSTEP(X3VSTEP0) 'Simulated steps for price depend. elect.  exchange'
*    X3VSTEP(X3VSTEP0)=NO;
   /X3VSTEP01*X3VSTEP01/;
```

J.3 Modelling of the Data Import File (x3vdata.inc)

```
* LARS: Flyttet fra balmorel.gms
PARAMETER X3VPIM 'Price (Money/MWh) of price dependent exported electricity'
/
$INCLUDE '../../%COREDATAFOLDER%/data/X3V/x3vpim_DK_E_2012.inc';
$INCLUDE '../../%COREDATAFOLDER%/data/X3V/x3vpim_DK_E_2013.inc';
$INCLUDE '../../%COREDATAFOLDER%/data/X3V/x3vpim_DK_E_2025.inc';
/;

* This file contains:
PARAMETER X3VPEX 'Price (Money/MWh) of price dependent imported electricity'
/
$INCLUDE '../../%COREDATAFOLDER%/data/X3V/x3vpex_DK_E_2012.inc';
$INCLUDE '../../%COREDATAFOLDER%/data/X3V/x3vpex_DK_E_2013.inc';
$INCLUDE '../../%COREDATAFOLDER%/data/X3V/x3vpex_DK_E_2025.inc';
/;

* This file contains:
* PARAMETER X3VPEX "Price (Money/MWh) of price dependent exported
* electricity"

* LARS: Nyt
$ifi %X3VfxQ%==yes
PARAMETER X3VBAL(YYY,X3VPLACE0) 'Annual net-export to 3rd country MWh/year';

* Net exports assumed to be zero based on the assumption that competetative
* investments ensure long run equilibrium prices.
*$ifi %X3VfxQ%==yes X3VBAL(YYY,'X3VFRANCE')=-6500000;
*$ifi %X3VfxQ%==yes X3VBAL('2018','X3VFRANCE')=-6500000/10;

$ifi %X3VfxQ%==yes X3VBAL(YYY,'X3VPROFLAND')=0;

* Shadow price of balancing imports and exports according to annual values.
```

```
PARAMETER X3VBALSP(YYY,X3VPLACE0);
* Get shadow price of the annual balance constriant.
$ifi %X3VfxP%==yes execute_load
'../../base/addons/x3v/data/X3V_%X3VPRICECASE%_BALSP.gdx',X3VBALSP;

$ifi %X3VfxC%==yes  X3VBALSP(YYY,X3VPLACE0)=0;
```

J.4 Modelling of the Connections with 3rd Countries File (x3.inc)

```
* File X3.inc

* This file is part of the Balmorel model, version 2.11 Alpha (April 2004).

*--------------------------------------------------------------------------
* PARAMETER X3FX contains the annual net electricity export to third regions.
* Observe that it is not possible to specify a net export
* which is not consistent with the values in TABLE X3_VAR_T.

* Units: MWh
* For each new nuclear power plant in Finland, import from Russia is
* decreased by 3.5 TWh. New nucelar power plants introduced in 2017 and 2025

TABLE X3FX(YYY,RRR)  'Annual net electricity export to third regions'

              FI_R        DK_E
2010     -11000000
2011     -11000000
2012     -11000000
2013     -11000000
2014     -11000000
2015     -11000000
2016     -11000000
2017     -7500000
2018     -7500000
2019     -7500000
2020     -7500000
;

* LARS 20091201: Delete exchange Finnish fixed exchange with Russia if
* Russia is in simulation.
if(SUM(C$SAMEAS(C,'Russia'),1),
X3FX(YYY,'FI_R') = 0;
);


$ifi not %X3V%==yes $goto X3V_label1
*--------------------------------------------------------------------
* The following concernes price-dependant electricity exchange to
* places outside the simulated area
*--------------------------------------------------------------------

* Price (Money/MWh) for the price dependent electricity exchange.
* It will be assumed that prices should be positive.
* For import the prices should be increasing with ord(X3VSTEP0),
* for export the prices should be decreasing with ord(X3VSTEP0).
PARAMETER
X3VPIM(YYY,RRR,X3VPLACE0,X3VSTEP0,SSS,TTT) 'Price of price depend. imp. elec.';
PARAMETER
X3VPEX(YYY,RRR,X3VPLACE0,X3VSTEP0,SSS,TTT) 'Price of price depend. exp. elec.';

* Maximum quantity (MW) of price dependent electricity exchange per time segment:
PARAMETER
X3VQIM(RRR,X3VPLACE0,X3VSTEP0,SSS,TTT) 'Limit (MW) on price depend. elect. imp.';
PARAMETER
X3VQEX(RRR,X3VPLACE0,X3VSTEP0,SSS,TTT) 'Limit (MW) on price depend. elect. exp.';

* Forbindelse ml. Oestdanmark og Tyskland
*X3VQIM('DK_E','X3VGERMAN',X3VSTEP0,S,T)=550;
*X3VQEX('DK_E','X3VGERMAN',X3VSTEP0,S,T)=550;

* Forbindelse m. Danmark og Profileland
X3VQIM('DK_E','X3VPROFLAND',X3VSTEP0,S,T)=1000;
X3VQEX('DK_E','X3VPROFLAND',X3VSTEP0,S,T)=1000;

* Forbindelse m. Vestdanmark og Tyskland
```

```
*X3VQIM('DK_W','X3VGERMAN',X3VSTEP0,S,T)=1400;
*X3VQEX('DK_W','X3VGERMAN',X3VSTEP0,S,T)=1400;

* Forbindelse m. Sverige og Polen
*X3VQIM('SE_S','X3VPOL',X3VSTEP0,S,T)=600;
*X3VQEX('SE_S','X3VPOL',X3VSTEP0,S,T)=600;

* Forbindelse m. Sverige og Tyskland
*X3VQIM('SE_S','X3VGERMAN',X3VSTEP0,S,T)=400;
*X3VQEX('SE_S','X3VGERMAN',X3VSTEP0,S,T)=400;

*
* BB 20140104: Constant price profile applied on region
* (very large~inf. trans from 3rd country)
$ifi not %X3VfxC%==yes $goto label_X3V_trans
X3VQIM(RRR,'X3VPROFLAND',X3VSTEP0,S,T)=10000;
X3VQEX(RRR,'X3VPROFLAND',X3VSTEP0,S,T)=10000;
$label label_X3V_trans

$label X3V_label1
```

K

Modelling of Scenario in Balmorel

K.1 Added to Balmorels Option File (`balopt.opt`)

Making it possible to control the four analysed scenarios REF, FCOP, VCOP_DIS, VCOP_TRANS from the option file.

```
$Setglobal PROJECTID BB—VPH3

* Set REF, FCOP, VCOP_DIS, VCOP_TRANS
$Setglobal SCENARIO VCOP_TRANS
$Setglobal SIMULATEDYEARS 2025

$Setglobal CASEID '%SCENARIO%%SIMULATEDYEARS%'

* TIMEDEPOP makes the operation (capacity and efficiency) time dependent.
$ifi %SCENARIO%==VCOP_DIS $Setglobal TIMEDEPOP yes
$ifi %SCENARIO%==VCOP_TRANS $Setglobal TIMEDEPOP yes
```

K.2 Added to the Data File Containing Generation Technologies' Capacities (`gkfx.inc`)

The reference scenario REF shall not have heat pumps implemented. The scenarios FCOP and VCOP_DIS shall have heat pumps connected to the distribution areas. The scenario VCOP_TRANS shall have the same heat pumps as FCOP and VCOP_DIS, but connected to the transmission areas.

```
*BB: Heat Pumps in Copenhagen in 2013 and 2025
$ifi %SCENARIO%==REF $goto label_hp_ref

$ifi %SCENARIO%==VCOP_TRANS $goto label_hp_vcop1
*2013
GKFX('2013','DK_E_VF_DIS','HP_drink')   = 4.5;
GKFX('2013','DK_E_VEKV_DIS','HP_drink') = 4.5;
GKFX('2013','DK_E_CHUS_DIS','HP_drink') = 4.5;
GKFX('2013','DK_E_CAML_DIS','HP_sew')   = 60;
GKFX('2013','DK_E_CVAL_DIS','HP_sew')   = 27;
GKFX('2013','DK_E_CAML_DIS','HP_sea')   = 70;
GKFX('2013','DK_E_COST','HP_sea')       = 90;

*2025
GKFX('2025','DK_E_VF_DIS','HP_drink')   = 4.5;
```

```
GKFX('2025','DK_E_VEKV_DIS','HP_drink') = 4.5;
GKFX('2025','DK_E_CHUS_DIS','HP_drink') = 4.5;
GKFX('2025','DK_E_CAML_DIS','HP_sew')   = 60;
GKFX('2025','DK_E_CVAL_DIS','HP_sew')   = 27;
GKFX('2025','DK_E_CAML_DIS','HP_sea')   = 70;
GKFX('2025','DK_E_COST','HP_sea')       = 90;
$label label_hp_vcop1

$ifi not %SCENARIO%==VCOP_TRANS $goto label_hp_vcop2
*2013
GKFX('2013','DK_E_VF','HP_drink')   = 4.5;
GKFX('2013','DK_E_VEKV','HP_drink') = 4.5;
GKFX('2013','DK_E_CHUS','HP_drink') = 4.5;
GKFX('2013','DK_E_CAML','HP_sew')   = 60;
GKFX('2013','DK_E_CVAL','HP_sew')   = 27;
GKFX('2013','DK_E_CAML','HP_sea')   = 70;
GKFX('2013','DK_E_SMV','HP_sea')    = 90;

*2025
GKFX('2025','DK_E_VF','HP_drink')   = 4.5;
GKFX('2025','DK_E_VEKV','HP_drink') = 4.5;
GKFX('2025','DK_E_CHUS','HP_drink') = 4.5;
GKFX('2025','DK_E_CAML','HP_sew')   = 60;
GKFX('2025','DK_E_CVAL','HP_sew')   = 27;
GKFX('2025','DK_E_CAML','HP_sea')   = 70;
GKFX('2025','DK_E_SMV','HP_sea')    = 90;
$label label_hp_vcop2

$label label_hp_ref
```

K.3 Modelling of the Time Dependent Efficiency File (`TimeDepOp_eff.inc`)

Scenario modification of the parameter `GDTDOE_S(GGG,SSS)`. The COP of the heat pumps is different if is connected to the distribution or the transmission grid.

```
PARAMETER GDTDOE_S(GGG,SSS) 'Time dependent operation efficiency'
/
$ifi %SCENARIO%==VCOP_TRANS $goto label_eff_hp1
$include '../../%COREDATAFOLDER%/data/TDO/TDOeff_HPsew.inc';
$include '../../%COREDATAFOLDER%/data/TDO/TDOeff_HPdrink.inc';
$include '../../%COREDATAFOLDER%/data/TDO/TDOeff_HPsea.inc';
$label label_eff_hp1

$ifi not %SCENARIO%==VCOP_TRANS $goto label_eff_hp2
$include '../../%COREDATAFOLDER%/data/TDO/TDOeff_HPsew_trans.inc';
$include '../../%COREDATAFOLDER%/data/TDO/TDOeff_HPdrink_trans.inc';
$include '../../%COREDATAFOLDER%/data/TDO/TDOeff_HPsea_trans.inc';
$label label_eff_hp2
/
;
```

K.4 Modelling of the Time Dependent Capacity File (`TimeDepOp_cap.inc`)

Scenario modification of the parameter `GDTDOC(GGG,SSS)`. The maximum capacity of the heat pumps is different if is connected to the distribution or the transmission grid.

```
PARAMETER GDTDOC(GGG,SSS) 'Time dependent operation capacity (normalized)'
/
$ifi not %SCENARIO%==VCOP_DIS $goto label_cap_hp1
$include '../../%COREDATAFOLDER%/data/TDO/TDOcap_HPsew.inc';
$include '../../%COREDATAFOLDER%/data/TDO/TDOcap_HPdrink.inc';
$include '../../%COREDATAFOLDER%/data/TDO/TDOcap_HPsea.inc';
$label label_cap_hp1

$ifi %SCENARIO%==VCOP_DIS $goto label_cap_hp2
```

```
$include '../../%COREDATAFOLDER%/data/TDO/TDOcap_HPsew_trans.inc';
$include '../../%COREDATAFOLDER%/data/TDO/TDOcap_HPdrink_trans.inc';
$include '../../%COREDATAFOLDER%/data/TDO/TDOcap_HPsea_trans.inc';
$label label_cap_hp2
/
;
```

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