



**KTH Industrial Engineering
and Management**

Introducing Additional Heat Storage to the Hässelby CHP Plant

A case study on economic and ecological benefits
achievable with heat storage in a deregulated
electricity market

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Bachelor of Science Thesis

KTH School of Industrial Engineering and Management

Energy Technology EGI-2011-069BSC

SE-100 44 STOCKHOLM

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Approved	Examiner Catharina Erlich	Supervisor Anders Nordstrand
	Commissioner	Contact person

ABSTRACT

This paper deals with the cogeneration plant in Hässelby, Sweden and the district heating grid of north-western Stockholm. Before the background of the complex system of plants connected to the district heating grid and a volatile electricity market, the paper shows possible ways to optimise production at the Hässelby cogeneration plant by introducing additional heat storage. The pursued idea is to use heat storage to maximise electricity production during electricity peak price hours and store the excess heat for later supply. At the same time, heat storage can also be used to minimise production from more expensive heat plants. The situation is analysed by using the modelling and simulation software *energyPRO*. Based on the present value method, the evaluation implies a good investment potential for enlarging the existing heat storage. The conducted sensitivity analysis shows that the present value increases with growing storage capacity. The highest obtained present value is about 12,500,000€.

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NOMENCLATURE AND ABBREVIATIONS

Abbreviation/Sign	Description	Unit
CHP	Combined Heat and Power	
DH	District Heating	
EB	Electric Boiler	
B	Boiler	
EO5	Fuel Oil Number 5	
VAT	Value Added Tax	
MCP	Market Clearing Price	
EUA	European Union Allowance	
ETS	European Union Emission Trading Scheme	
TES	Thermal Energy Storage	
LHTS	Latent Heat Storage System	
PCM	Phase Change Material	
NHPC	Net Heat Production Costs	
c_p	Specific Heat	Wh/kgK
m	Mass	kg
P_{el}	Electricity Output	W
P_{heat}	Heat Output	W
Q	Heat flow	W
Q	Heat	Wh
V	Volume	m^3
α	Electricity ratio	-
ΔT	Temperature Difference	K
ρ	Density	kg/m^3
ω	Fuel efficiency	%

1. INTRODUCTION

In the public debate the Combined Heat and Power Production (CHP Production) is often referred to as a key element on the way to achieve international energy efficiency and carbon emission reduction goals. This is powerfully illustrated by Chris Goodall who dedicated one chapter in the popular scientific bestseller “Ten technologies to fix energy and climate”¹ to CHP. It is safe to say, that the CHP technology’s superior fuel efficiency make a substantial contribution towards climate protection. Furthermore several research projects, such as e-energy, Fenix and DESIRE, have shown that cogeneration can help to integrate fluctuating renewable energy sources like photovoltaic and wind power. The required flexibility of productions can be obtained by connecting CHP plants to heat storage units. Alongside with benefits for the electric grid as a whole, also the CHP plant operator can directly benefit from the volatile electricity prices.

2. PROBLEM AND GOAL DESCRIPTION

The northern European countries have formed the common electricity market Nord Pool. Electricity prices on this market are subject to great fluctuations. Therefore, the electricity production in power plants is more lucrative during certain time periods. Hence, it appears to be a profitable strategy for CHP plants to produce electricity in those lucrative hours, store the excessive heat in a heat storage unit and discharge the heat to the connected district heating grid during less profitable hours of production. Today, the Hässelby plant is completely controlled by the need of heat and only produces electricity as a side-product. This inflexible setup makes it impossible to benefit from time periods with high prices. The currently installed heat water tanks with a volume of combined 6600m³ water can store about 300MWh, which is enough to store the output of ca. 1.5 hours of operation and thereby does not provide the necessary degree of freedom.

This project will determine the techno-economic and ecologic premises the existing Hässelby CHP plant presents to install an additional heat storage unit. The question this report aims to answer is:

Can the current production of electric and thermal energy at the Hässelby cogeneration plant be improved by installing additional heat storage?

To be able to answer this question, the current situation at the plant, the market situation and heat storage technologies will be analysed and presented.

¹ (Goodall, 2008)

3. BACKGROUND

The following background literature study will give an overview on relevant topics that will help to answer the above posed question.

3.1. THE HÄSSELBY CHP PLANT

The combined heat and power plant (CHP plant) Hässelby was in 1959 the first plant built for the combined production of heat and power in Stockholm. The plant is situated in the western part of Stockholm at the shore of the lake Mälaren. From the beginning the plant was fired with coal and fuel oil and gradually replaced distributed small oil fuelled boilers. Between 1994 and 1996 three out of the four existing boilers were refitted to fire wood pellets. The fourth boiler, with a capacity of 160 MW of electricity production, was long-time conserved in 1999. In the following years the wood-pellet firing capacity was increased so that in the year 2000 the Hässelby plant was almost totally converted to bio-fuel. The plant is operated by Fortum AB who owns the plant together with the city of Stockholm. (Fortum Corporation, 2009)

Today the plant produces about 900 GWh of district heat per year for about 60,000 households in the western part of Stockholm and 260 GWh/a of electricity (AB Fortum Värme samägt med Stockholms stad, 2010a). The Hässelby plant is a base load unit that supplies the district heating (DH) grid of Hässelby, Vällingby, Järvafältet and Sollentuna with heat. Part of the Hässelby DH grid is also the plant in Akalla, which is operated as a peak demand and backup plant. Since 2004, Hässelby's DH grid is connected to Järfälla's DH grid and via the so called UVA transmission line to the DH grid of Sigtuna and Upplands Väsby. This DH grid includes the wood chips fuelled Brista CHP plant and is therefore often referred to as the "Brista grid". The connection allows a transfer of about 400 GWh heat per year from the Brista plant to the Hässelby grid. (AB Fortum Värme samägt med Stockholms stad, 2009)

3.1.1. TECHNICAL SPECIFICATIONS

The Hässelby CHP plant consists of a cogeneration unit that is fuelled with wood pellets and fuel oil and has a production capacity of 215 MW of heat and 75 MW of electricity as well as a, now long-time conserved, oil fuelled condensing unit of 160 MW. The cogeneration unit includes three boilers (B1-B3) with a connected turbine (T1-T3) each. The Hässelby CHP has an overall fuel efficiency of 81% and an α -value of 0.37 (Haglund & FortumAB, 2011). Furthermore there are three electric boilers EP1-EP3 with a total output of 57 MW heat and three water-based (single phase) heat storage tanks with a capacity of 2,200 m³ each. The wood pellets are stored in a depot with a capacity of 10,000 t by the port where the fuel is unloaded by crane from bulk freighters (Johanson, 2011). (AB Fortum Värme samägt med Stockholms stad, 2009)

3.1.2. PEAK LOAD AND BACKUP PLANTS

The Hässelby CHP is part of Fortum's PoD Nordväst Stockholm (Swedish abbreviation for "production and distribution northwest"). Figure 3-1 gives an overview on the district heating grid (DH) of the PoD Nordväst, its plants, the area supplied with DH and the main grid-connections. Marked with large red dots are the CHP plants in Hässelby and Brista, marked with smaller red dots are the back-up plants in Akalla, Vilunda and Valsta. The extern feed-in plants in Rotebro, Järfälla and Arlanda are marked with grey dots. The total length of the DH grid is 264 km. The total volume of water is 34,000 m³ water. Whereas the plants in Vilunda and Valsta are designated back-up for the Brista CHP, Hässelby has the operational responsibility over Akalla and the electric boilers located at the plant area in Hässelby (Fortum AB; Heat Scandinavia, 2011). The backup in Vilunda, however, also plays an important role in the Hässelby grid. Since Hässelby only has a very limited influence on the operations in Brista and Valsta, those will not be considered in this project. For further information on Brista and its back-up please consult (Fortum AB; Heat Scandinavia, 2011) or my fellow students' on-going projected concerning the operations at the Brista plant.

The back-up plant Akalla actually consists of several elements: three oil-fired boilers (B1-B3) with a maximum heat output of 75 MW each, two electric boilers (EB1 and EB2) with an output of 37.5 MW each and a 5 MW heat pump with a COP² of 1.59 (Haglund & FortumAB, 2011). B1 and B2 are fuelled with number 5 fuel oil (Eo5) and the B3 is fuelled with biogenic pine tar oil. Currently Fortum also experiments with other fuels like "Finbio", a biogenic fuel oil, and "Biofett", a biogenic greaslike fuel, in Akalla's B1 and B2 (Johanson, 2011). Those fuels are increasingly replacing the conventional fuels in the plant in Akalla. Localised in Akalla is also a central absorption chiller that supplies some local consumers with district cooling. (AB Fortum Värme samägt med Stockholms stad, 2010c)

The Vilunda back up plant has four boilers with a pooled output of 117 MW. The first boiler can be operated with wood pellets or fuel oil. When operated with fuel oil it has an effect of 22 MW. The second, third and fourth boiler are fuelled with heavy fuel oil EO5. Boiler two and three have an output of 35 MW each, whereas the Boiler 4 is smaller and has an output of 12 MW. (AB Fortum Värme samägt med Stockholms stad, 2010b)

² COP is the abbreviation for Coefficient of Performance, the ratio of the heat-output to the supplied work in heat pumps.

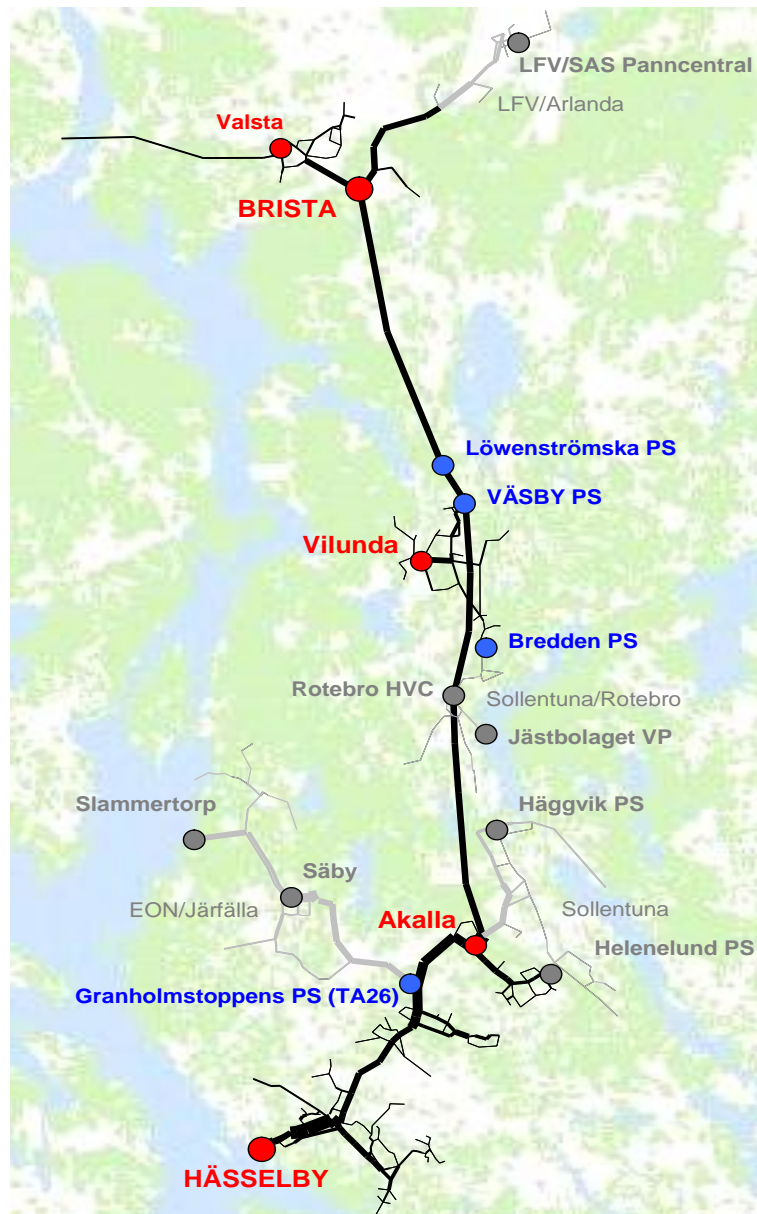


FIGURE 3-1 OVERVIEW ON FORTUM'S PRODUCTION AND DISTRIBUTION GRID NORTHWEST STOCKHOLM (FORTUM AB; HEAT SCANDINAVIA, 2011) (LARGE RED DOTS: CHP PLANTS IN HÄSSELBY AND BRISTA, SMALLER RED DOTS: BACK-UP PLANTS IN AKALLA, VILUNDA AND VALSTA, GREY DOTS: EXTERN PLANTS IN ROTE BRO, JÄRFÄLLA AND ARLANDA)

3.1.3. ENVIRONMENTAL ASPECTS OF THE CURRENT OPERATIONS

As previously mentioned, the main fuel at the Hässelby CHP plant is wood pellets. Fuel oil is used during start-up procedures and as reserve and supplement fuel to compensate for problems with the wood pellets or to increase the steam production. During normal operations the most important aspects are the emissions of carbon dioxide (CO₂) and carbon monoxide (CO), nitrogen oxides (NO_x), dust, ammonia (NH₃) and sulphur oxides (SO_x). The total amount of air emissions in the year 2008 can be seen in Table 3-1 (AB Fortum Värme samägt med Stockholms stad, 2009)

TABLE 3-1 TOTAL EMISSIONS FROM THE HÄSSELBY CHP PLANT IN 2008 (AB FORTUM VÄRME SAMÄGT MED STOCKHOLMS STAD, 2009)

	Emissions
CO2 from fossil fuel	3278.38 t
CO2 from biogenic fuels	411735 t
CO	245 t
NOx	287 t
Dust	4.9 t
NH3	4.0 t
SOx	1.4 t

Table 3-2 clearly shows that the vast majority of the emissions of the currently much debated climate gas CO2 originate from burning the biogenic fuel wood pellets. Since wood pellet is a biogenic fuel this emission can be considered climate neutral. Fortum claims that the use of wood pellets instead of coal as fuel saves about 388,000 tons of CO2 emissions annually (Fortum Corporation, 2009, p. 11). These savings correspond to about 0.75 % of the total Swedish emissions of CO2 (Index Mundi, 2010).

TABLE 3-2 CO2 EMISSIONS BY FUEL FROM HÄSSELBY CHP PLANT (AB FORTUM VÄRME SAMÄGT MED STOCKHOLMS STAD, 2009)

Fuel	Emission CO2 [t]	Share of Total [%]
Wood Pellets	411735,0	99,21
Fuel Oil EO5	3225,0	0,78
Fuel Oil EO1	53,0	0,01
Liquified Petroleum Gas	1,21	0,0003
SUM	415014,21	100,00

When considering the overall emissions caused by the operation of the Hässelby CHP, the emissions that arise from the transportation of the fuels, the combustion residues (ashes) and other consumables need to be taken into account. Values for these can be seen in the Table 3-3. The proportion between emissions from transport to emissions from operations is less than 1 to 100 (cf. Table 3-1).

TABLE 3-3 EMISSIONS FROM TRANSPORT (AB FORTUM VÄRME SAMÄGT MED STOCKHOLMS STAD, 2009)

	Fuel	Ashes	Consumables	Total
CO2	3696 t	7 t	4 t	3707 t
NOx	95 t	0.06 t	0.034 t	95.1 t
SOx	31.7 t	0	0	31.7 t

Those low amounts of emissions are achieved by using low emitting cargo shipping with bulk carriers, regardless of the partly long transport distance from surrounding Swedish areas, the Baltic States, Portugal or Canada (Johanson, 2011). The ashes from the Hässelby CHP still contain combustible

elements and are therefore transported to the Brista plant where the remaining energy content is utilised (Johanson, 2011).

During normal operations, the most important emissions from Akalla are carbon dioxide (CO₂), nitrogen oxides (NO_x), dust and sulphur oxides (SO_x) (AB Fortum Värme samägt med Stockholms stad, 2010c). The total amount of emissions in the year 2009 can be seen in Table 3-4. The emissions from transport are significantly higher than those for Hässelby per delivered ton of fuel, since the transport is carried out with tank trucks that cause higher emissions per tonne-kilometre (Nätverket för Transporter och Miljön, 2010). The absolute emissions are, however, considerably lower than the emissions from operations and transport at the Hässelby plant.

TABLE 3-4 TOTAL EMISSIONS FROM THE AKALLA BACK-UP PLANT IN 2009 (AB FORTUM VÄRME SAMÄGT MED STOCKHOLMS STAD, 2010C)

	Direct Emissions	Emissions from transport
CO₂ from fossil fuel	5654 t	2062 t
CO₂ from biogenic fuels	26682 t	
NO_x	26.1 t	52.9 t
Dust	3 t	
SO_x	24.4 t	17.6

An overview of inherent emissions and other vital properties of the most important fuels used in Hässelby and Akalla can be found in the following Table 3-5.

TABLE 3-5 ENERGY CONTENT, PRICE AND INHERENT EMISSIONS OF THE IMPORTANT FUELS AT THE HÄSSELBY CHP AND THE AKALLA BACK-UP PLANT (CALCULATION BASED ON (AB FORTUM VÄRME SAMÄGT MED STOCKHOLMS STAD, 2009; AB FORTUM VÄRME SAMÄGT MED STOCKHOLMS STAD, 2010C))

	Wood pellets	Pine tar oil	Fuel Oil Eo5 ³
Energy content [MWh]	4.81/t	9.69/Nm ³	10.74/Nm ³
Price [€/MWh]	28.38 ⁴	40.18 ⁵	25.70 ⁶
Price [€/t or €/Nm³]	135.51	389.34	276.02
CO2 [kg/MWh]	0.0	0.0	333.7
Nox [g/MWh]	244.8	168.1	577.1
SOx [g/MWh]	1.1	203.8	246.2
Dust [g/MWh]	4.0	5.4	79.7
CO2 [kg/t or Nm³ fuel]	0	0.0	3584.2
NOx [g/t or Nm³ fuel]	1177.5	1629.1	6197.8
SOx [g/t or Nm³ fuel]	5.2	1974.4	2644.6
Dust [g/t or Nm³ fuel]	19.0	52.3	856.4

3.1.4. STRATEGY OF OPERATIONS

The CHP's Hässelby and Brista account for the base heat delivery in the north-western DH grid of Stockholm. Since the Brista CHP has lower production costs than Hässelby, Brista takes over heat production for the entire DH grid during the summer months, with exception for a six week long period for physical examination and inspection of the plant. Without exception, the operation of all producing units has to be planned in order to supply the grid's heat demand at all times. (Johanson, 2011)

The operation of the backup plants is managed from either Brista or Hässelby. Hässelby bears responsibility for the backup boilers and the heat pump in Akalla, whereas Brista bears responsibility for the backup production at Vilunda, Valsta and Rotebro. It is furthermore Hässelby's responsibility to control and regulate the pressure in the DH grid. The heat storage tank can be charged from Hässelby and Brista CHP. At temperatures below -10°C, is not used. During summer a completely uncharged tank is pursued. In addition to the heat storage tank's acting as heat storage, it also plays an important role in pressure regulation processes. A fully charged heat storage tank therefore implies that no pressure regulation in the grid takes place. (Fortum AB; Heat Scandinavia, 2011).

³ Average value calculated from B1 and B2 in Akalla

⁴ Price including transport, excl. tax (SCB, 2011)

⁵ (OPUS Stockholm, 2011)

⁶ Price for industrial clients, excl. taxes. (Energimyndigheten, 2010)

The start-up of backup boilers in Akalla and Vilunda is planned with regard to their start-up and specific production costs. To optimise the start-ups of Akalla's B3, the boiler is kept warm in time periods in which need for backup production is expected. It is also a stated aim to always start up boilers fuelled with biogenic fuels before those driven with fossil fuel. (Fortum AB; Heat Scandinavia, 2011)

3.2. COMBINED HEAT AND POWER

Combined Heat and Power (CHP), or cogeneration, refers to the simultaneous production of mechanical energy, which in most cases is used to produce electric energy, and useful heat in power stations or smaller heat engines. Whereas conventional power stations release waste heat to the environment as a side-product of electricity generation, CHP plants capture the by-product heat to supply process heat or to supply a district heating grid (DH grid) with hot water for residential heating purposes.

Typical thermal power stations convert 28-58% of the primary energy of the fuel into useful electric energy (Erdmann & Zweifel, 2008). Thus, a substantial part of the primary energy is released to the environment. An overview of modern state of the art power plants, their fuel efficiency and an estimate of fuel costs per produced amount of electric energy is given in Table 3-6.

TABLE 3-6 TYPICAL PROPERTIES OF MODERN POWER PLANTS (ERDMANN & ZWEIFEL, 2008)

	Fuel efficiency ω [%]	Fuel costs [EUR/MWh _{el}]
Steam turbines		
Hard coal (700 MW)	38 – 46	25 - 30
Lignite (700 MW)	25 – 43	19 - 23
Gas turbine (200 MW)	28 – 37	75 - 100
Gas and Steam Combined Cycle (300 MW)	>58	50 - 55

CHP plants in contrast to common power plants use about 80-90% of the energy supplied by the fuel (Erdmann & Zweifel, 2008, p. 318; Umweltbundesamt, 2009). It is however important to notice that CHP production does not only utilise waste heat, but also decreases the electric fuel efficiency. That is why CHP plants have a smaller output of electric energy per supplied unit of fuel energy than conventional power plants.

In extraction plants, where the amount of extracted steam can be regulated according to the demand - in contrast to other plants with a fixed ratio between heat and electricity production- the relationship between thermal and electric fuel efficiency may look like presented in Figure 3-2. The figure illustrates that the electric fuel efficiency is decreased by extracting useful heat from the CHP plant. At the same time, the energetic output of useful heat that is considerably greater than the loss

in electricity production. The figure shows that the example plant could either produce 58 units of electric energy in pure electricity production mode, 100 units of heat energy in pure heat production mode or for example 51 units of electric energy and 32 units of heat energy in extraction mode per 100 units of fuel energy supplied. In extraction mode the overall fuel efficiency thereby sums up to 83%.

Whereas the electric and thermal fuel efficiency give a comprehensive understanding of the benefits of cogeneration, the operation point is generally defined by the ratio between generated electrical power (P_{el}) and the heat flow (\dot{Q}). This ratio is called *electricity ratio* or *power to heat ratio* or more commonly α -value or σ -value:

$$\alpha = \frac{P_{el}}{\dot{Q}} \tag{3-1}$$

A high α -value characterises a high output of electric power. A infinite ($\alpha=\infty$) value stands for pure electric power production, whereas a zero ($\alpha=0$) value stands for pure heat production. Common CHP plants have α -values between 0.4 and 0.9 (Hell, 1985). In most CHP plants α can be modified within certain boundaries to adapt the production to outer conditions and demands.

CHP plants can be operated to meet a local heat demand (heat driven operation) or to maximise the output of electric energy (electricity driven operation). The lowest energy losses and thereby the highest overall efficiency are achieved at heat operated CHP's (Erdmann & Zweifel, 2008). Nevertheless, electricity-driven operation can, due to significantly higher prices for electric energy, sometimes be more attractive seen from an economic perspective (Erdmann & Zweifel, 2008).

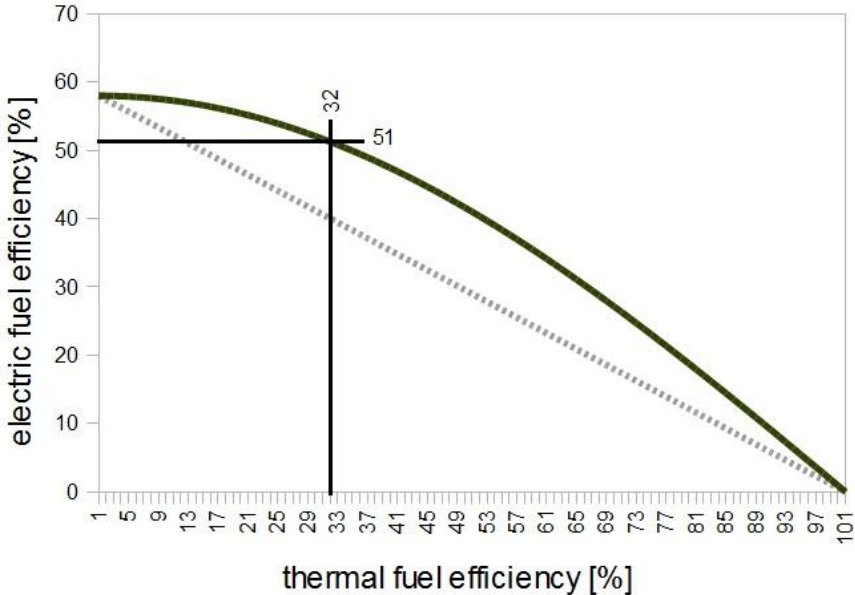


FIGURE 3-2 ENERGETIC BENEFITS OF CHP FOR A COMBINED CYCLE PLANT WITH STEAM EXTRACTION FOR HEAT PRODUCTION (DATA SOURCE: (ERDMANN & ZWEIFEL, 2008))

The possible savings of combined heat and power production are often illustrated as in Figure 3-3. The shown case promises 36% primary energy and 59% CO₂ savings⁷. It is important to notice that such comparisons are based on the following assumptions:

- i. The CHP plant can always cover the heat- and electricity demand and all of the produced heat is consumed.
- ii. The different fuels used in the presented system have the same heating quality and price.
- iii. The system with the separated production represents operating and existing technology whereas the CHP plant represents the state of the art technology not yet implemented in all power plants.

These assumptions promote the savings of the CHP plant. With different, more unfavourable, assumptions the CO₂ savings are still estimated to 17% (Dittmar & Erdmann, 2010). These more unfavourable assumptions mainly include the effect of a lower demand for heat in summer, and the different fuels and their properties (Dittmar & Erdmann, 2010). The amount of primary energy saved when using cogeneration instead of separate production is generally estimated to 10- 30% (Sperlich, 2006; Horlock, 1987; Bejan & Tsatsaronis, 1996).

The concept of combined heat and power generation can be realised with a variety of conventional and unconventional fuels and heat sources. There are successful implementations with fossil fuels, such as natural gas, coal or fuel oil, as well as with renewable energies, such as biogas, bioethanol, wood pellets or wood chips, or other energy sources, like urban waste or solar heat (Horlock, 1987). There are also a few reported cases where the cogeneration concept has been implemented at nuclear power plants, e.g. the Agesta reactor that supplied the DH grid of Stockholm's suburb Farsta between 1963 and 1974 (Csik & Kupitz; Foskolos, 2007), or the nuclear power plant Lubmin, in former GDR, that provided the city of Greifswald with DH (Wittkopf-Schade, 2007).

Not only can the concept of cogeneration be implemented with a variety of fuels, but also for a wide range of plant capacities. So called MicroCHP (usually less than 5kW_e) and MiniCHP (5-500 kW_e) plants are usually installed in houses or smaller businesses to cover the local demand for heating and electricity (Harrison, 2009). The generated electricity is then also often sold back into the electric power grid (Harrison, 2009). The projected installation of 100,000 "at home power plants"⁸ by the power supply company "Lichtblick" and the car manufacturer "Volkswagen" in European households is probably the biggest planned implementation of MiniCHP's. The natural gas fuelled MiniCHP's have

⁷ $36\% = (1 - 1000\text{kWh}) / (944\text{kWh} + 622\text{kWh})$; $59\% = (1 - 200\text{kg}) / (316\text{kg} + 166\text{kg})$

⁸ German: „ZuhauseKraftwerk“

an output of 19kW_e and $32\text{ kW}_{\text{thermal}}$ and shall supposedly be able to replace two nuclear power plants while providing heat to cover the local demand (Lichtblick ZuhauseKraftwerk GmbH, 2010).

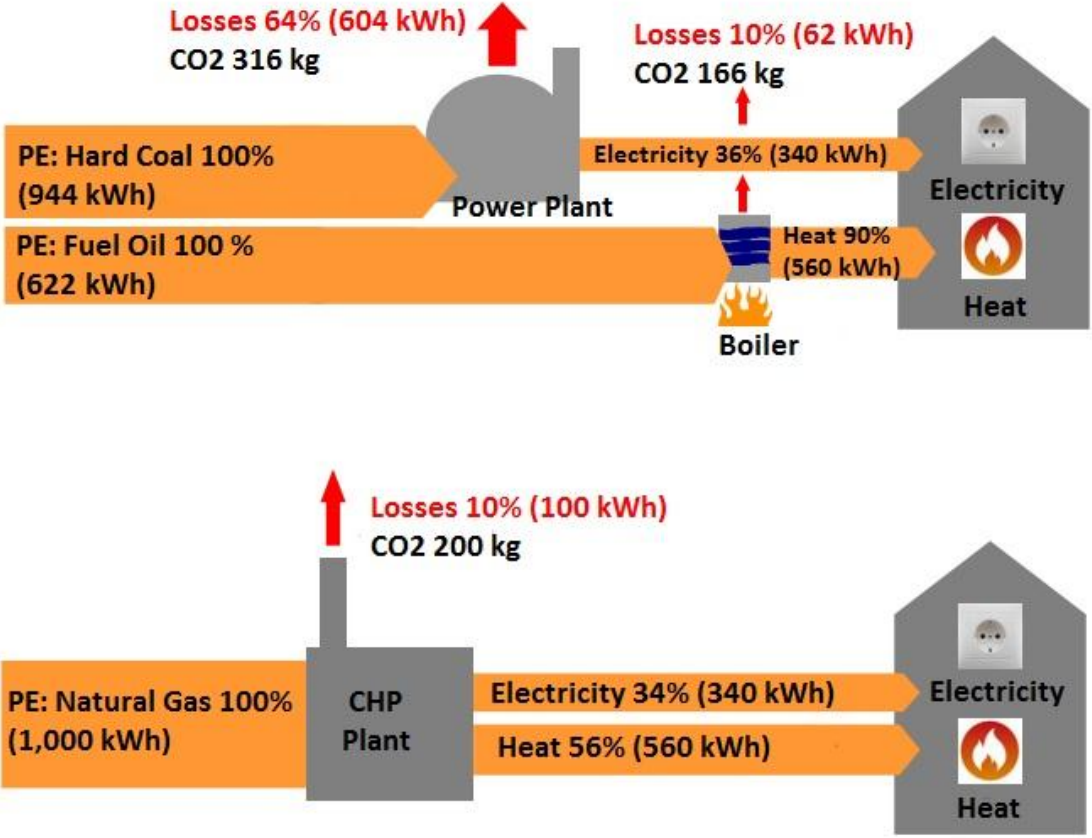


FIGURE 3-3 WIDELY USED ILLUSTRATION OF PRIMARY ENERGY (PE) AND CO2 EMISSION SAVINGS OF CHP PLANTS (DATA SOURCE: (DITTMAR & ERDMANN, 2010))

3.3. ECONOMIC FOUNDATIONS

The economic foundation of the operation at Hässelby CHP are expenses for fuel, staff, buildings and machine maintenances, taxes, fees, certificates etc. on the one hand and revenues from the sale of district heating, electricity and green certificates on the other. In order to sustain operation in the long term, revenues should naturally always exceed the expenses. The following sections give an overview on the Electricity and the District Heating (DH) market properties and present specific taxes related to the production of heat and electricity. Considerations about general taxes, such as VAT or corporate taxes, and standing charges are not subject of this thesis, since they do not have an influence on operational optimisations.

3.3.1. ELECTRICITY MARKET

An electricity market consists of a local distribution grid with producers, retailers and consumers. The grid is a requirement to make transactions between the producers and consumers possible. What is more, an electricity market enables competition between market participants. The local distributor Håsselby CHP is a producer in the multinational grid covering Sweden, Norway, Denmark, Finland and Estonia called Nord Pool. The Nord Pool is a liberalised electricity market where retailers trade energy related products, such as electric energy and European Union Allowance (carbon emission certificates), based on competitory principles. Trade transactions can be made on three different markets: (NASDAQ OMX Group, 2010)

- The futures and forwards market, for energy products with deliveries for the next weeks, days and years.
- The spot market (day-ahead market), where electric energy for the next days 24 hours is bought and sold.
- The intraday market where electric energy for up to one hour before distribution is traded.

The electricity spot prices at Nord Pool are determined through an auction for each delivery period within the next day - a timeframe of 12 to 36 hours ahead. After the close of trading at 12:00 noon, with all market participants bids placed, the spot price is set. All demand and supply offers are sorted by price into an aggregated demand and supply set, also called *Merit Order*. A simplified example of a merit order demand and supply set is shown in Figure 3-4. The intersection point of the aggregated supply set and the demand curve forms the market clearing price (MCP) and the amount of traded energy. All demand left of the intersection point is satisfied to the MCP and all suppliers left of the intersection point get paid the MCP, independent of the price they demanded during the auction. In hours with a low demand (off-peak demand) the MCP is low and only power plants with low marginal costs, like wind turbines and nuclear energy plants, can sell their energy and power plants with higher marginal costs are taken off the grid for the traded period. In high demand hours (Peak demand) the MCP increases and also power plants with relatively high marginal costs can go into production and sell electric energy (Erdmann & Zweifel, 2008, pp. 303-305)

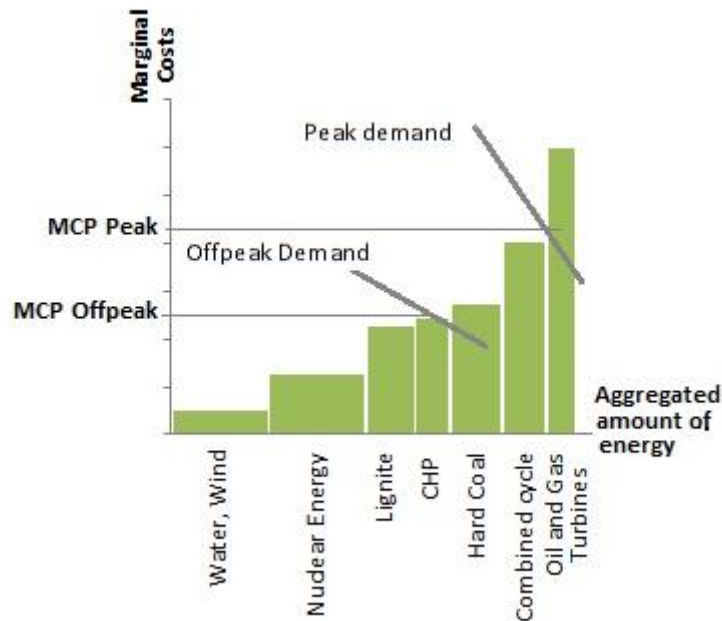


FIGURE 3-4 MERIT ORDER AND MARKET PRICING IN THE ELECTRICITY SPOT MARKET

In order to prevent grid congestions and imbalances, the Nord Pool grid is divided into a number of geographical bidding areas. Market participants place their demand or supply bids for the bidding area they are physically connected to. Transmission between different bidding areas is traded separately. At present the Nord Pool grid is divided into ten bidding areas that mostly correlate with the geographic area of the Transmission System Operators. Hence Sweden (SE), Finland (FI) and Estonia (EE) each form one national bidding area, whereas Denmark is separated into areas west (DK1) and east (DK2) of the Great Belt. Furthermore Norway is divided into five areas (NO1 to NO5), although the number of areas and their expanse change at times. (Nord Pool Spot AS, 2011)

The development of prices in five selected bidding areas can be seen in Figure 3-5. Exceptionally high prices over 200 €/MWh (in 2010 up to 506 €/MWh, SE 22.02.2010) are treated as outliers and are removed for the benefit of a higher resolution at lower prices. Although the prices correlate over periods of time and between certain groups of areas, e.g. NO1, SE and FI, more than with other, large price differences can occur on the spot market. This can for example be called forth by insufficient market mechanisms or transmission lines. Whereas e. g. the bid area DK1 had relatively constant prices, the Swedish area price shows distinct fluctuations and seasonally higher prices in winter.

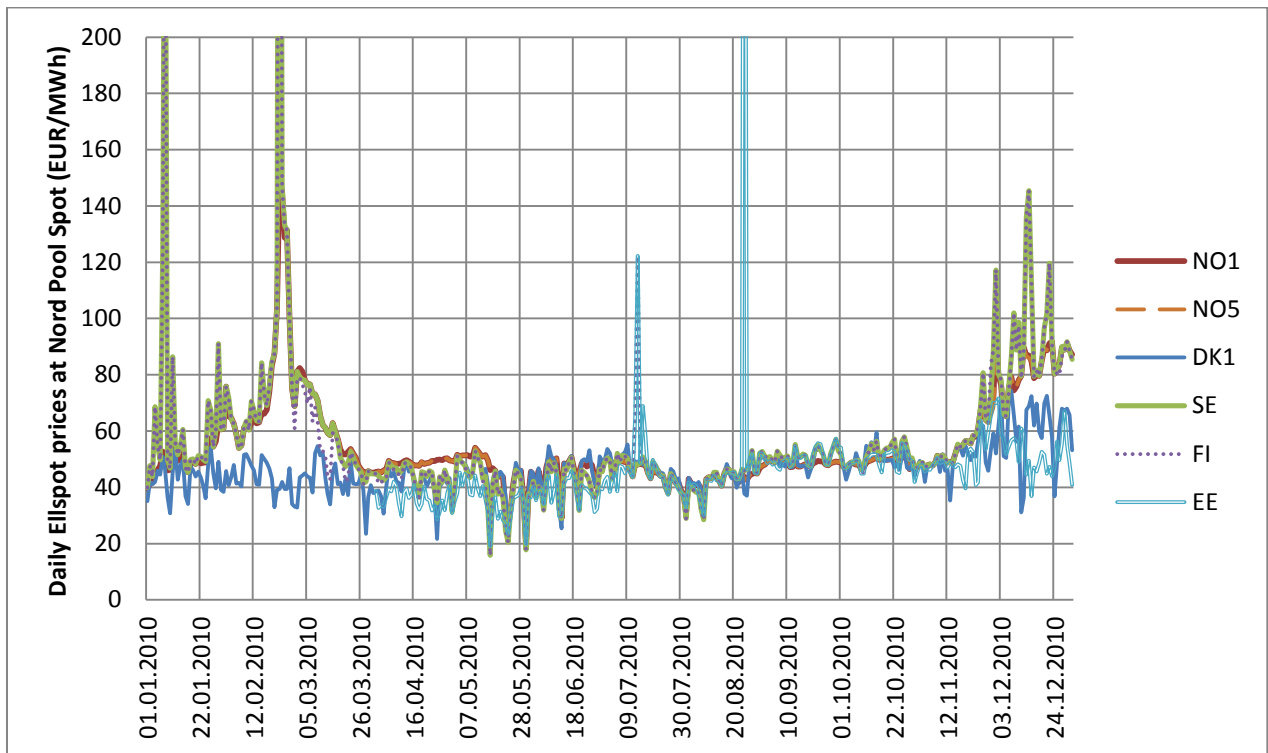


FIGURE 3-5 DAILY ELSHOT PRICES AT NORD POOL SPOT FOR A SELECTION OF BIDDING AREAS IN 2010 (DATA SOURCE: (NORD POOL SPOT AS, 2010)

Price fluctuations do not only occur over the course of days, but also within days. Figure 3-6 gives an insight into intraday fluctuation using the Elspot price for the Swedish bidding area for the first week in June 2009. There are often two peaks to be seen: around 12:00 and 18:00. Prices during the night are notably lower. These regularly fall to below 50% of the peak price of the day during the early morning hours around 03:00. The fluctuations do not always look as periodic as shown in Figure 3-6, but they always occur.

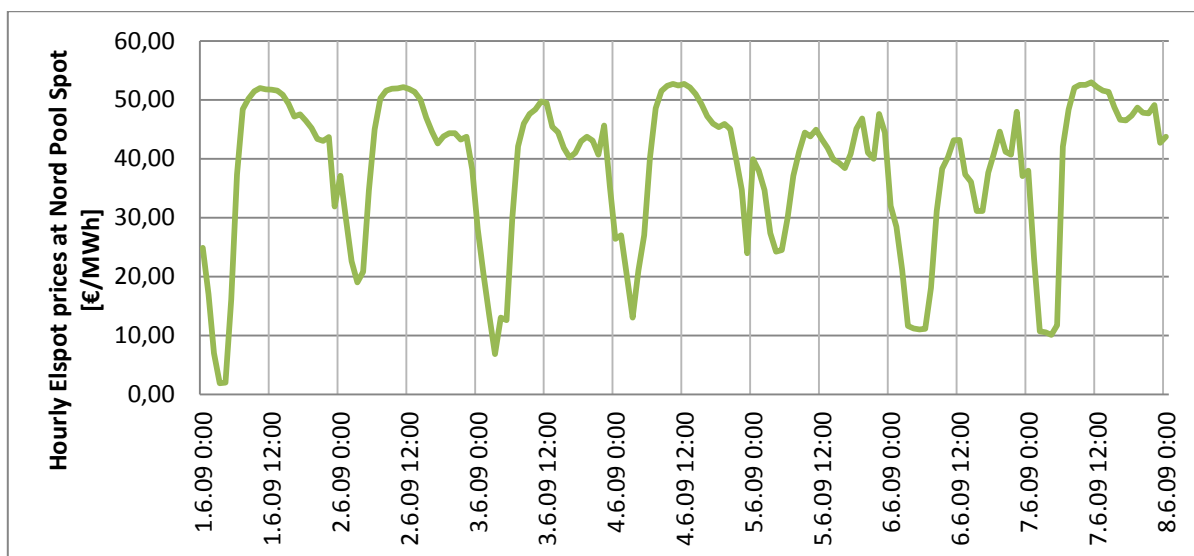


FIGURE 3-6 HOURLY ELSHOT PRICES AT NORD POOL SPOT FOR THE BIDDING AREA SWEDEN (SE)

3.3.2. DISTRICT HEATING MARKET

District heating markets are local markets. They are characterised by the missing competition between district heat suppliers on the one hand and the competition to alternative technologies that supply heat, for example heat pumps, pellet boilers or electric heating, on the other hand. In Sweden, district heating accounts for about half of the domestically used heat (Fortum AB, 2010). The price for different heating alternatives is shown in Figure 3-7. It is important to notice that the presented figures are calculated costs including production costs and standing charges. The first three columns illustrate how the price for district heating can differ between two DH grids: DH in Gnesta, in the Stockholm area, is the most expensive and nearly twice as high as Luleå in northern Sweden with the lowest prices. Also Stockholm has relatively high prices. It is interesting to see that the price for all fossil fuels and also some biogenic fuels like wood pellets have increased significantly over the last years (Energimarknadsinspektionen, 2007). DH prices on the other hand do not show this substantial increase, which lets DH currently appear to be the most cost efficient alternative for domestic heating purposes. This relation is very much dependent on connection costs to the DH grid. Houses with an unfavourable location to the DH grid may be rendered with a wood pellets boiler or a heat pump as most efficient heating alternative. The local price differences in heating with DH can be explained as a combination of several local circumstances, e.g. the used fuel, customer density and their proximity to the heat plant, efficiency of the heat production etc.

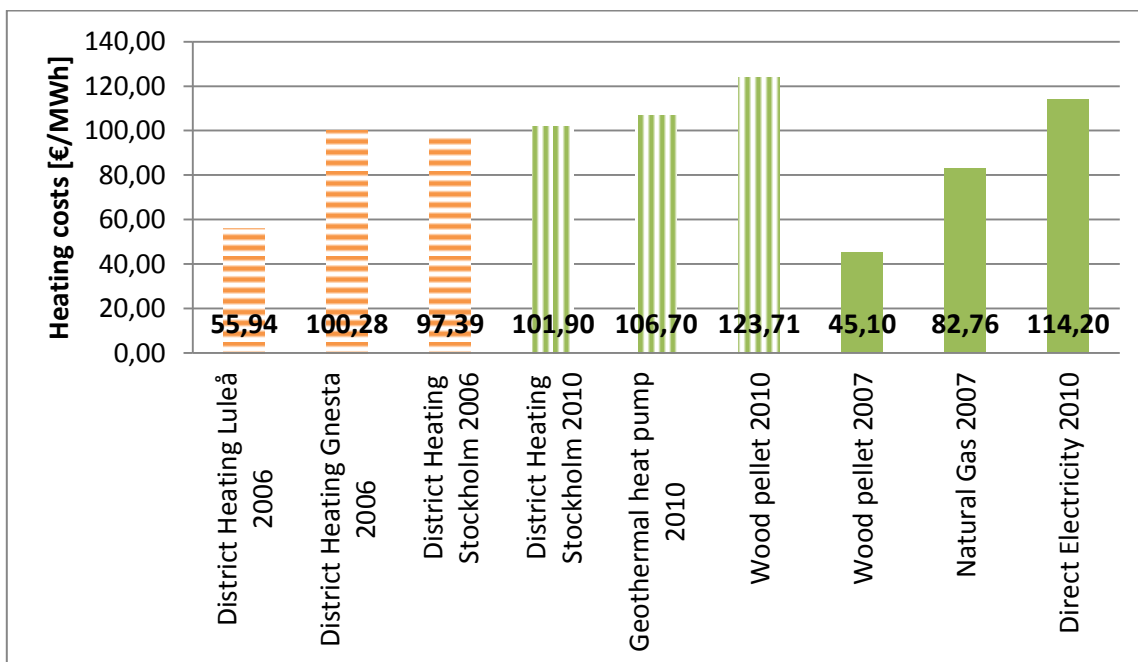


FIGURE 3-7 HEATING COSTS FOR DIFFERENT FUELS WITH LOCAL DIFFERENCES AND DEVELOPMENT OVER TIME (DATA SOURCE: ORANGE CHEQUERED: (ENERGIMYNDIGHETEN, 2007), GREEN STRIPED (FORTUM AB, 2011), GREEN UNICOLOURED (ENERGIMARKNADSINSPEKTIONEN, 2007))

The heat demand in DH grids can be described by the superposition of two effects: Seasonal and daily variations. Seasonal variations can be linked to the average ambient temperature, although the

base demand of about 20% for water heating is generally not influenced thereby. The ratio between peak demand on cold days in winter and summer days can be up to 14:1 (Stadtwerke Bielefeld GmbH, 2005). Above a daily average temperature of 17°C space heating is normally not needed anymore at all and the demand for heating above the base load diminishes significantly (Stadtwerke Bielefeld GmbH, 2005). This correlation is clarified in Figure 3-8. It shows the model used by the municipal heat supplier in Munich, Germany. The base demand of about 415 kWh/month is constant over the year, whereas the demand for space heating peaks in the winter month January.

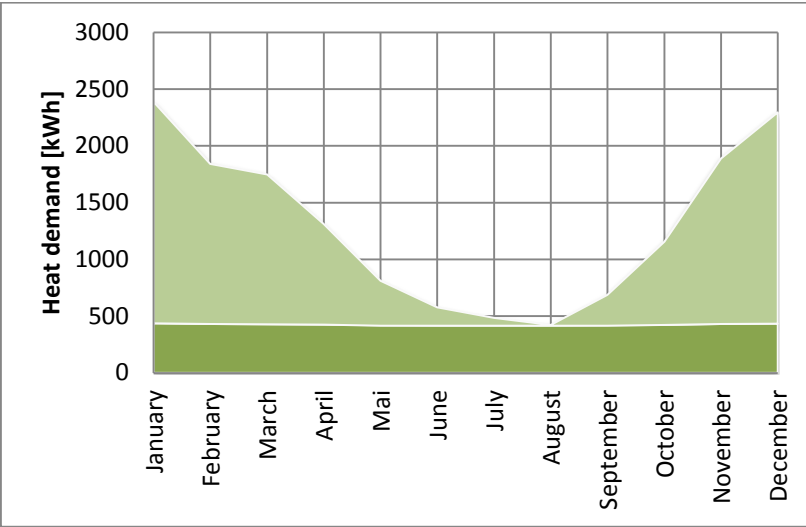


FIGURE 3-8 HEATING DEMAND MODEL FOR A MIDSIZED HOUSEHOLD IN MUNICH, GERMANY (DATA SOURCE: (STADTERKE MÜNCHEN, 2010)

Daily variations can amount to about 30 % of the average heat flow. An example of the varying heat demand in a DH grid is shown in Figure 3-9. It shows the low demand during night-time and a peak demand at 09:00 as well as a lower peak in the evening. An additionally increased demand can also occur on Mondays, depending on the amount of facilities that are not used over the weekend, e.g. schools and offices, and have to be warmed up in the beginning of the week (Stadtwerke Bielefeld GmbH, 2005).

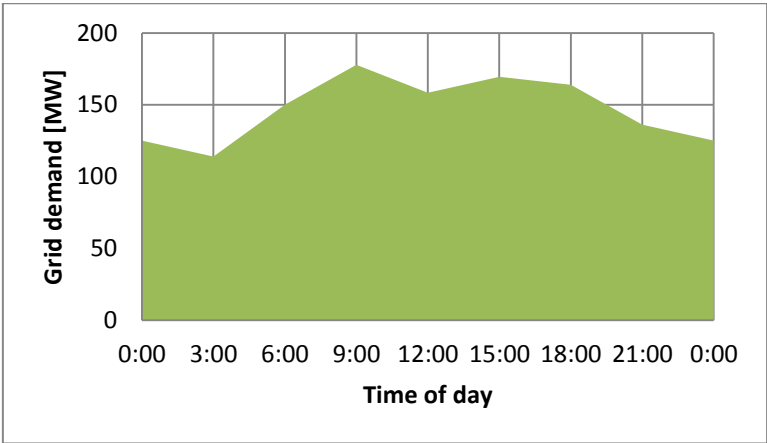


FIGURE 3-9 DH GRID HEAT DEMAND ON A WORKING DAY IN JANUARY; BIELEFELD, GERMANY (DATA SOURCE: (STADTWERKE BIELEFELD GMBH, 2005))

Based on past experiences, Fortum has developed a calculation model to predict the grid’s heat demand. An illustration of the relationship between ambient temperature and heat demand, divided into usable energy and heat losses and a table for some chosen temperatures is shown in Figure 3-10. It can be seen that the heat demand can be described with two linear functions, one for ambient temperatures under 10°C and one for temperatures above 10°C. The illustration also shows the rather constant heat loss over the temperature range. At an ambient temperature of 20°C heat losses stand for 30.1 % of the overall demand. At lower temperatures this share decreases to 4.1 % at -20°C.

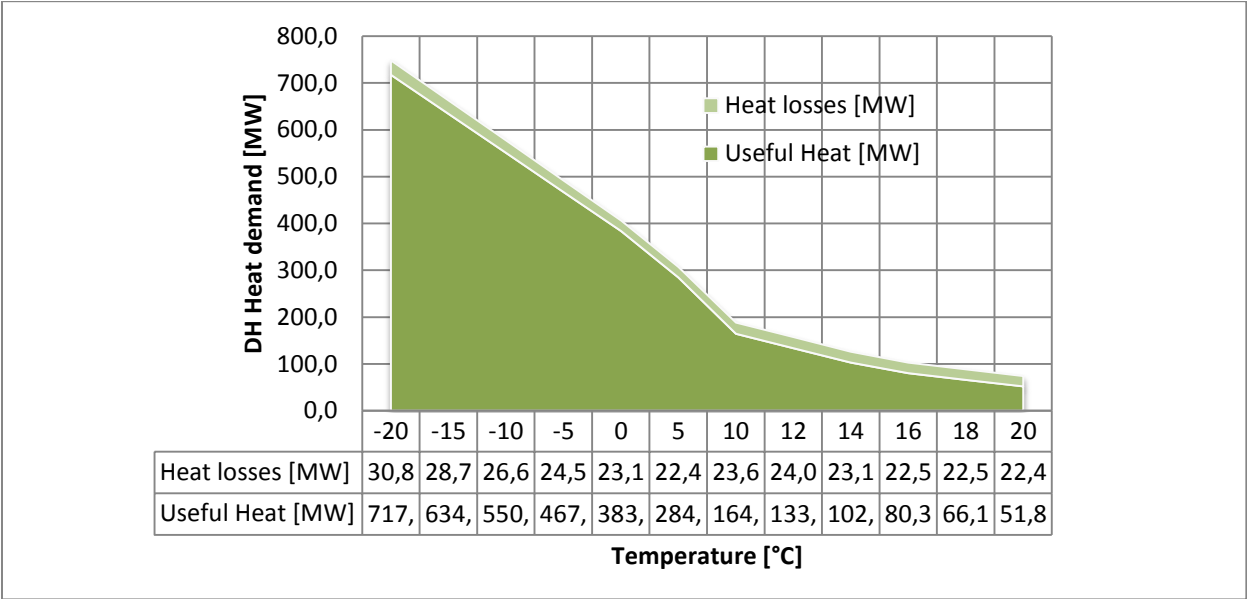


FIGURE 3-10 GRID DEMAND FOR THE DH GRID NORTHWEST STOCKHOLM AS A FUNTION OF THE AMBIENT TEMPERATURE

3.4. TAXES, FEES AND CERTIFICATES

By imposing taxes and fees on emissions and fuel consumption Swedish and European government agencies have a significant influence over the gross price for production of heat and electricity from different fuels. Taxes and fees are economic tools to discourage emissions and the use of fuels that cause high amounts of emissions and encourage e. g. better fuel gas clean-up systems or the switch to other energy sources. Certificates are another market economic tool to balance higher production costs of renewable energy sources against conventional, fossil fuels. Some of the presented economic tools are specific for Sweden, e.g. the green certificates, others have an equivalent in other national economies, e.g. the tax on sulphur emissions and some of the tools are initialised by an international agency, e.g. the emissions trading system.

3.4.1. FEE ON NITROGEN OXIDE EMISSIONS (KVÄVEOXIDAVGIFT)

The fee on emissions of nitrogen oxides (NO_x) is collected from all incineration plants with an output of more than 25GWh (Naturvårdsverket, 2010). It amounts to 50 SEK/kg (about 4.80€/kg⁹) of NO_x emissions (Lagerstedt, 2010). The majority of the fees are paid back to the fee payers. The exact amount of the repayment is calculated according to the fee payers' share of energy production. In 2006 the repayment amounted to 8.94 SEK/MWh (0.85€/MWh) produced energy. By that industries with low specific emissions of nitrogen oxide benefit.

First of all the fee on nitrogen oxide emission is always a cost for the operator of power plants, but specific emission of NO_x below average will actually grant an extra income.

3.4.2. TAX ON SULPHUR EMISSIONS (SVAVELSKATT)

The emission of sulphur created by burning solid fossil fuels and peat are taxed at 30 SEK per kg (2.85€/kg) of sulphur. Fluid fuels are taxed at 27 SEK per m³ (2.57€/m³) for every weight-percent of sulphur in the fuel. Fuels with a sulphur content of less than 0.05 % are not taxed and a sulphur content of 0.05-0.2% is rounded to 0.2%. (Lagerstedt, 2010)

This tax is mainly relevant for fossil fuels and will add to the specific production costs of plants running on fossil fuels.

3.4.3. CARBON DIOXIDE AND ENERGY TAX (KOLDIOXIDSKATT OCH ENERGISKATT)

The production of otherwise already taxed electricity is normally not taxed with carbon dioxide or energy taxes. Nevertheless, a fixed amount is taxed for an estimated internal consumption of electrical energy. Fuels that are used for heat production are taxed different than those used to produce electricity. Therefore, the operator of a multifuel cogeneration plant has to bookkeep the different fuels as a raw material for either heat or electricity production. In 2010 heating fuels were taxed with 15 % of the full carbon dioxide tax (2011: 7 %). The full carbon dioxide tax amounts to 1.10 SEK/kg (0.10 €/kg) carbon dioxide in 2011. Biofuels and peat are not taxed at all. (Lagerstedt, 2010)

Since the tax on internal consumption is an estimated lump sum, this tax does not have an influence on the strategic specific production costs. Only the heating with fossil fuels is influenced by those taxes.

3.4.4. GREEN CERTIFICATES (GRÖNA CERTIFIKAT)

Green certificates (or renewable energy certificates) are a market based method to support electricity production from renewable energy sources (Motiva, 2009). That is necessary, because the production of electricity from renewable sources is more environmentally, but has higher costs than the production from conventional sources (Maria Holm; IVA, 2003, p. 20).

⁹ Calculated with the average exchange rate in 2009: 10.50SEK : 1€ (SIX Telemekurs, 2011)

For every produced megawatt-hour (MWh) of electricity from renewable sources, the operator is granted one green certificate. The consumer, respectively the power supply company, on the other hand is obligated to own a certain amount of green certificates relatively to the consumed amount of electricity in a year. This is called the quota requirement¹⁰. For every missing certificate the consumer is charged with a fee higher than the price for a certificate (150% of the average price of the gone year) (Maria Holm; IVA, 2003). Production from following energy resources entitles to green certificates (Energimyndigheten, 2010).

- Wind power
- Solar Power
- Wave Power
- Geothermal energy
- Biofuels according to the law on green certificates (2003:120)
- Hydroelectric Power (new construction, small-scale and extension of existing plants)
- Peat in Cogeneration plants

When the green certificate law was initiated in 2009, the quota requirement was 7.4 % and was planned to increase to 16.9 % in 2010. The quota requirement thereby mirrors the official aim of the Swedish legislation to increase the share of electricity production from renewable energy sources. A more detailed outline of the planned development of the official quota requirement is presented in Figure 3-11. (Maria Holm; IVA, 2003)

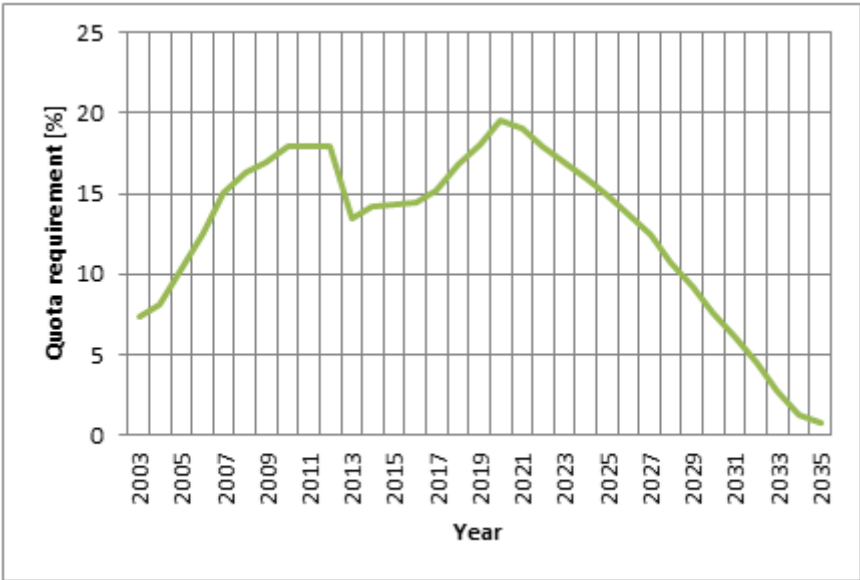


FIGURE 3-11 PLANNED DEVELOPMENT OF THE SWEDISH QUOTA REQUIREMENT FOR GREEN CERTIFICATES (DATA SOURCE: (ENERGIMYNDIGHETEN, 2010))

¹⁰ The company „AB Fortum Värme samägt med Stockholm’s stad” which owns and operates the Hässelby CHP for example held 228.081 certificates in 2010 to fulfil this quota requirement (Energimyndigheten; Svenska Kraftnäts statistik, 2011).

The price for the certificates is determined by the market mechanisms of supply and demand. It is therefore set by both the trading strategies of the companies involved and the production costs from renewable resources (Andersson, 2003). Some of the major influences on the certificate price are (Andersson, 2003):

- International demand for electricity from renewable resources, e.g. the Netherlands
- Market saturation
- Current price for electricity
- Weather conditions (esp. wind and solar radiation)
- Filling level in the waterpower reservoirs
- Price for biofuels
- Transaction partners

For the first trading period price boundaries were set by the legislation. In 2003 the lower boundary was 60 SEK/certificate (5.70 €/certificate). The upper boundary is set by the expected average price of the year and the 150% rule of penalty payments. Statistically the price is very volatile. This is very well illustrated in Figure 3-11.

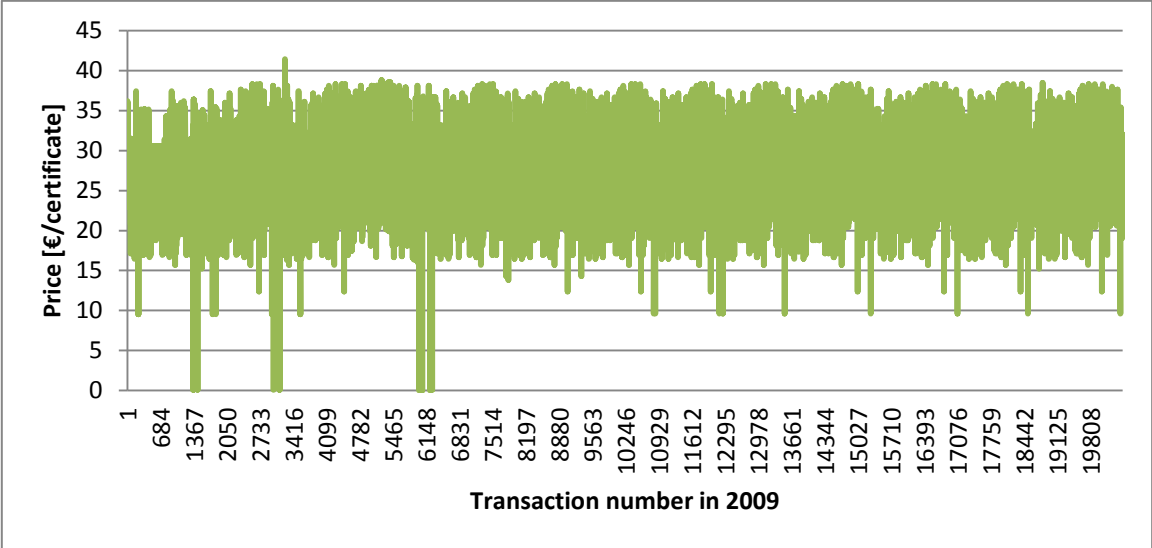


FIGURE 3-12 PRICE FOR GREEN CERTIFICATES IN 2009 (DATA SOURCE: (SVENSKA KRAFTNÄTS KONTOFÖRINGSSYSTEM; ENERGI MYNDIGHETEN, 2010)

It is important to notice that transactions are not made in regular time intervals, but often as contracts between two market participants. Therefore, in certain time periods many transactions are registered in one minute of a day and in other periods only one registration is made in a whole week. The Figure 3-13 gives a better understanding of the amount of traded certificates per month and the average price per certificate in the time between April 2003 and April 2009. In 2009 the average price of a green certificate was 27.92€ (calculation based on: (Svenska Kraftnäts kontoföringsystem; Energimyndigheten, 2010)).

For the time being green certificates are only traded among 624 Swedish companies and municipalities (Energimyndigheten; Svenska Kraftnäts statistik, 2011). With the beginning of the next

trading period in January 2012 also Norwegian market participators will join the trading system and enlarge the market, thus perhaps stabilising the certificate price (Ebenå & Energimyndigheten, 2011). The trading with green certificates creates an extra income to the producers of electricity from renewable sources. Every produced unit of energy is worth the retail price of the electric energy itself and a subsidy from the sales of the granted green certificates. The specific costs for electricity from conventional costs will in contrast be increased by the product of cost for a certificate and the required quota.

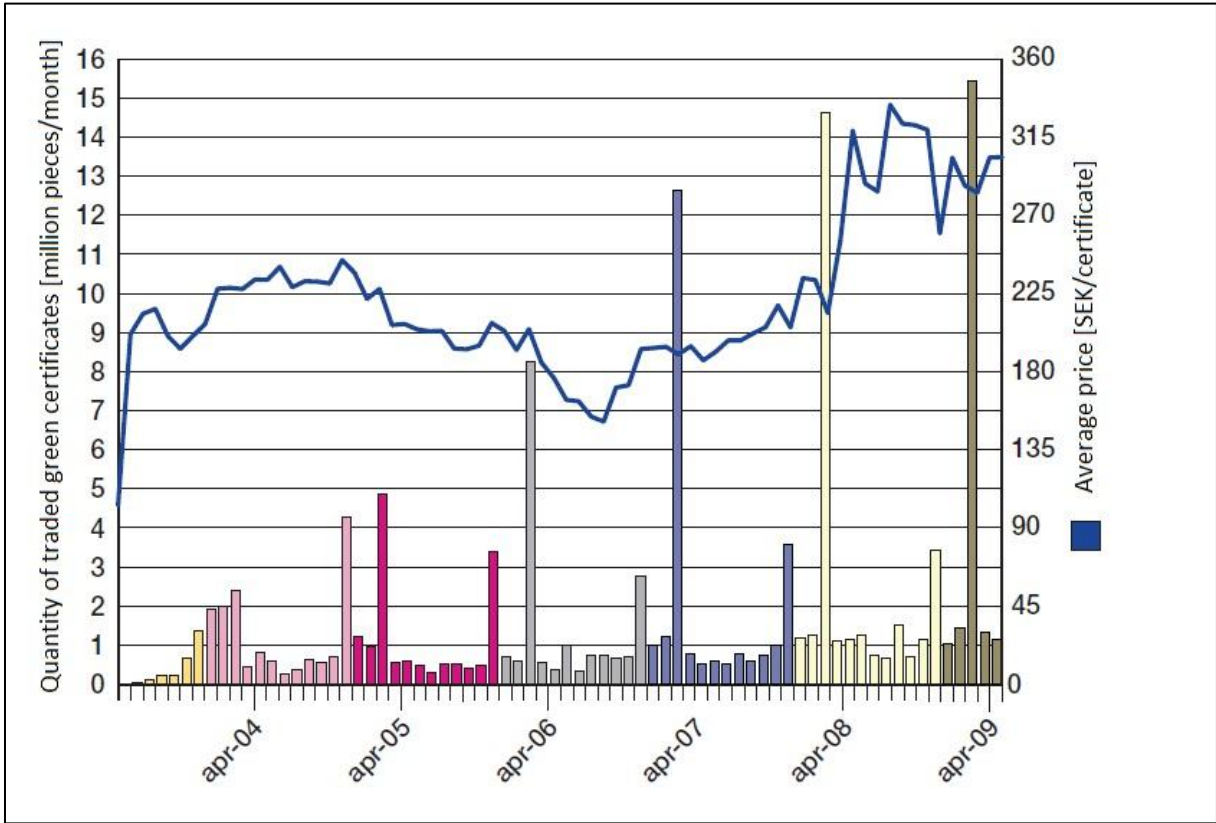


FIGURE 3-13 QUANTITY OF TRADED GREEN CERTIFICATES AND AVERAGE PRICE BETWEEN APRIL 2003 AND APRIL 2009 (STATENS ENERGIMYNDIGHET, 2009)

3.4.5. (CARBON DIOXIDE) EMISSIONS TRADING

When confronting the global economic dimensions of the greenhouse gas problematic, the development of efficient strategies to reduce the emission of the most important greenhouse gas carbon dioxide is of special importance. It makes sense to implement reduction measures in the order of their growing specific reduction costs. To fulfil the reduction goals laid down in the Kyoto protocol the European Union on October 13th, 2008 gave out the EU-directive 2003/87/EG. The directive laid the foundations for the EU-wide trade of carbon dioxide emission permits (also called European Union Allowance (EUA)) beginning in 2005 (Wagner, 2004; Erdmann & Zweifel, 2008).

In the beginning of every trading period the EU sets out a maximum amount (cap) of allowed carbon dioxide emissions and allocates emission permits. One EUA embodies the right to discharge one

tonne of carbon dioxide into the environment and all market participants are required to hold an amount of permits equivalent to their emissions at the end of every trading period (Wagner, 2004). Companies holding a too small amount of permits have to pay a penalty of currently 100 €/EUA and buy the missing amount of permits in the next trading period (Umweltbundesamt, 2011). Market participants are all operators of industrial or power plants with a heat excess of 20 MW or more (Wagner, 2004). The first trading period went from January 2005 until December 2007, the following trading will last longer: Period II: January 2008- December 2012, Period III: January 2013 – December 2020 (The Committee on Climate Change, 2008).

The EU emission trading directive dictates the primary means of allocation to be open auctions. Categorically all EUA's needed for the electricity production are to be purchased at those auctions. Other industries, however, are allocated with free permits. The amount of free EUA's is orientated on EU-wide product specific emission standards – so called Benchmarks. The amount of free allocations is planned to decrease from 100 % in 2005 to a maximum of 80 % in 2013, 30 % in 2020 and no free permits after 2027. Exceptions are made for industries that are afflicted by the so called “carbon leakage”, that means they would have competitive disadvantages on the global market due to high costs for EUA's. (Umweltbundesamt, 2011)

The European Union Emission Trading Scheme (ETS) is a cap and trade system and enables the market to choose and deploy the most cost efficient reduction measures necessary to fulfil the emission goals. Reduction measures that are more expensive than a EUA will not be deployed. The system can therefore be considered effective. (Erdmann & Zweifel, 2008)



FIGURE 3-14 PRICES FOR EMISSION ALLOWANCES AUGUST 2008 - APRIL 2011 (EUROPEAN ENERGY EXCHANGE AG, 2011)

Although it was planned to start in January 2005 the trade with EUA's started with delay, due to technical problems, in August 2008. The first year 362 million EUA's, worth € 7.2 billion (Point Carbon, 2006), were traded at the market and the price grew steadily to about 30 €/t in March 2006. After an announcement of additional free allocations the price then fell steadily to € 0.10 at the end of the trading period. This is a good example for a long market, where the supply of EUA's exceeds the demand (Erdmann & Zweifel, 2008). Since the start of the second trading period, the price has

been comparatively stable on a level of about € 14.50. The described development is also illustrated in Figure 3-14.

3.5. THERMAL ENERGY STORAGE SYSTEMS

Thermal energy storages (TES) are systems that enable the collection and preservation of excess heat for later utilisation. Practical problems where TES systems are often installed are solar energy systems and other systems where heat availability and utilisation periods do not coincide. The three basic types of TES systems are *sensible heat storage*, *latent heat storage* and *thermochemical heat storage*. (Dincer, 2002)

- Sensible TES systems store heat by changing the temperature of a storage medium such as water, bricks or thermal oils.
- Latent heat storage systems utilise the heat of fusion that is needed or released when a storage medium changes phase by melting or solidifying. ,
- Thermochemical energy storage is based on chemical reactions in inorganic substances. (Thermochemical energy storage is not yet applied on a larger scale and will therefore not be discussed in full length in this thesis.)

For comparison, some typical data for relevant storage materials are given in Table 3-7. Except for the obvious data, e.g. specific storage mass and volume and price, the selection of TES is greatly dependent on the required storage time period, e.g. day-to-day or seasonal, and outer operating conditions.

TABLE 3-7 TYPICAL DATA OF HEAT STORAGE MATERIALS (HASNAIN, 1998)

Property	Sensible Heat Storage		Phase Change Materials	
	Water	Rock	Organic	Inorganic
Latent heat of fusion [Wh/kg]	#	#	52	644
Specific heat [Wh/kg*K]	1,17	0,28	0,56	0,56
Density [kg/m³]	1000	2240	800	1600
Specific storage mass [kg/MWh]¹¹	5760	24120	1910	1566
Specific storage volume [m³/MWh]¹	5,76	10,8	2,38	0,97

¹¹ At $\Delta T=10K$

3.5.1. SENSIBLE HEAT STORAGE

The amount of heat that can be stored in a mass m is given by

$$Q = m * c_p * \Delta T = \rho * c_p * V * \Delta T \quad (3-1)$$

with c_p being the specific heat of the material. Sensible heat storages can furthermore be divided into *Liquid media storages* and *solid media storages*.

3.5.1.1. LIQUID MEDIA STORAGE

Liquid media storage materials are for example water, saltwater, thermal oils or molten salts. The main properties of a number of liquid media storage materials are given below.

3.5.1.1.1. WATER STORAGE

As can be seen in Table 3-7 water has outstanding heat storage properties. It is furthermore inexpensive and no object to chemical reactions, but evaporates over a temperature of 100°C. Water is therefore considered to be one of the best storage media, esp. at low temperatures. It can store energy over a wide temperature range between 0°C and 100°C and store 117 kWh of heat energy over this range (cf. Table 3-7 and equation (3-1)). Water is also a transport medium of energy, in form of steam inside power plants as well as liquid in radiator systems for space heating. Subsequently water is the most widely used storage medium in space heating, solar and industrial TES. For large scale TES, storage in aquifers¹² is considered. (Hasnain, 1998)

An elaboration on technical details follows in the section “Technical specifications of water based thermal energy storage systems”, page 32.

3.5.1.1.2. STORAGE IN OTHER FLUIDS

Especially for applications with temperatures over 100°C other storage fluids, such as thermal oils and molten salts, are utilised. They have significantly lower specific heats, but allow operation temperatures over 100°C. Thermal oils can be used for applications with temperatures up to 350°C. Molten salt storages, such as sodium hydroxide (melting point: 320°C), can be used for temperatures ranging from 350°C to up to 800°C. In turn those materials are expensive and demand maintenance expenses in order to avoid chemical instabilities and corrosion. (Hasnain, 1998)

The heat exchange from heat source to storage medium and storage medium to consumer is usually handled with a fluid-to-fluid heat exchanger. This can either be an extern component or the storage tank can be built with pipes in which the working fluid of the heat source, often steam, circulates.

¹² Aquifers are large underground geological formations that hold water; often sand or pebbles.

3.5.1.2. SOLID MEDIA STORAGE

Materials used in solid media storages are often rocks, concrete, sand, bricks or metals. They can be used for low as well as high temperature applications do not pose challenges in terms of chemical instability. The material with the highest specific storage volume is cast iron. It is, however, an expensive material and rocks or bricks are commonly preferred. Depending on the used solid material a wide range of working temperature, theoretically from below zero to up to 1000°C. Solid media storages with rocks and pebbles as storage medium are constructed as a loosely packed rock bed within an insulated container. The individual pieces have a diameter of 1cm to 5cm, with growing size of the pieces for longer store-extract cycles. Energy is stored by leading heated air or water through the rock pile, the stored energy is extracted by forcing a colder working fluid through the heated layer of rock. To increase the heat exchange between the working fluid and the storage medium the rock bed can be fluidised. Solid media TES are frequently used to store solar heat. Furthermore various residential heat recovery ventilation systems use solid media to store heat in rotating heat exchangers. (Hasnain, 1998)

3.5.2. LATENT HEAT STORAGE

Latent heat thermal energy storage (LHTS) is a developing technology that builds on the effect that phase transition of material can store a lot of energy while maintaining a constant temperature (Hamada & Fukai, 2005). For example is the same amount of energy needed to melt 1kg of ice as is needed to warm the same amount of liquid water 80 K. This way a large amount of energy can be stored in a relatively small mass of material. The working materials, *called phase change material* (PCM), are specially designed to undergo a phase change (mostly solid to liquid, but also liquid to gas) in certain temperature ranges. The PCM is usually placed in long and thin tubes (to increase the heat exchange surface) piled in an insulated container. To store heat a hot working fluid is forced through the intermediate space between the tubes, the PCM melts or evaporates, thereby storing latent and also some sensible heat. When recovering heat from the LHTS a cold working fluid is forced through the storage container, absorbing heat from the solidifying or condensing PCM. (Hasnain, 1998)

3.6. TECHNICAL SPECIFICATIONS OF WATER BASED THERMAL ENERGY STORAGE SYSTEMS

The most commonly used TES are water-based single phase storage tanks. The technology is at an advantaged stage of technology and there are a variety of different models on the market (Hasnain, 1998). Water is, as mentioned before, an excellent heat storage material; it has a high specific heat, is chemically stable, widely available, inexpensive and non-hazardous. The following sections will give an overview on basic technical principles, physical and economic aspects.

3.6.1. TECHNICAL PRINCIPLE

The fundamental structure and most important elements of a water-based TES tank are shown in Figure 3-15. Heat storage units consist of the following elements (EVH GmbH, 2005):

- The cold water valves are used for feeding and extracting cold water. They are evenly distributed over the cross section and configured to avoid turbulences and guarantee a layer of 0,5m at the ground of the tank to ensure a minimal thermal expansion of the base plate.
- The hot water valves are the inlet and drain for the hot water stream. The valves sit on a floating device that ensures a turbulence and cavitation free flow. The inlet flow always has to be regulated to a maximum of 98°C. Therefore a mixer tap is installed on the inlet pipe.
- The pressure reliefs ensure safe pressure conditions in the tank, esp. during charging and discharging procedures. Further safety installations, such as the temperature probes, control temperature and pressure and the flow in drain and inlet pipes
- The outer shell is insulated to minimise heat losses and the resulting water down-welling at the inside surface.

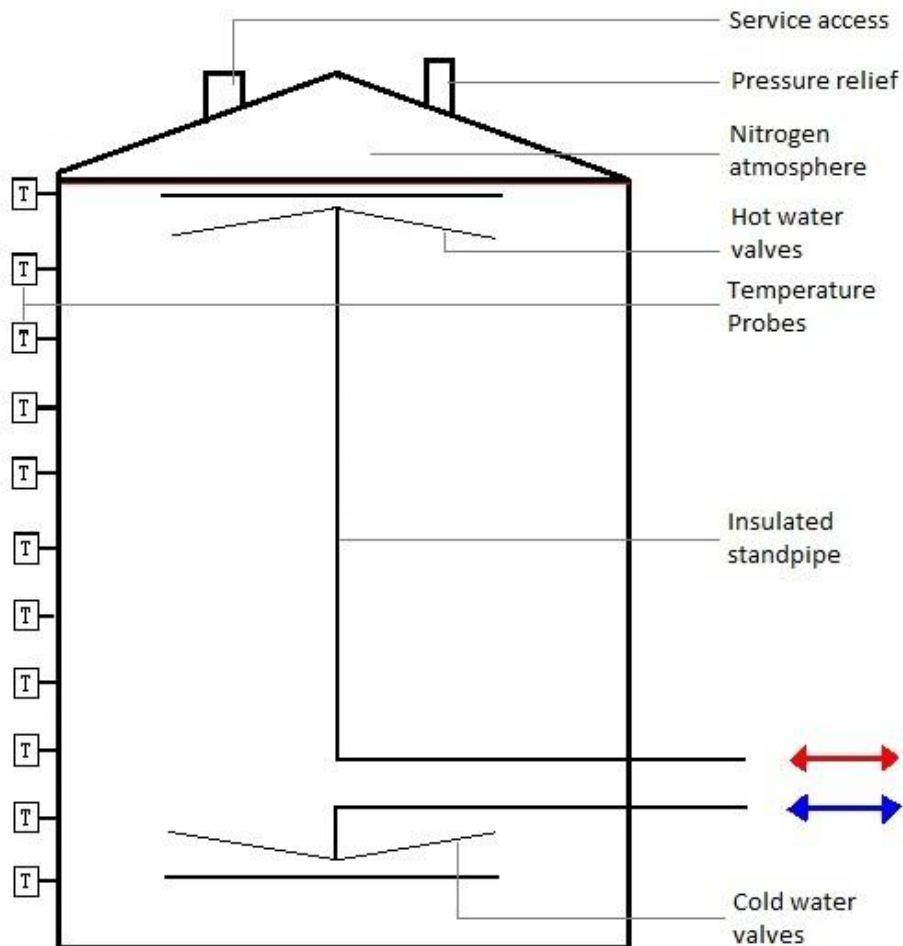


FIGURE 3-15 FUNDAMENTAL STRUCTURE OF A VERTICAL WATER-BASED HEAT STORAGE TANK (DE WIT, 2007, P. 3)

To avoid turbulences, mixing and other internal streams in the tank is important to achieve a maximum heat storage capacity with a given storage tank. Mixing disturbs the water stratification that normally divides a cold water layer in bottom of the tank and a hot water layer above with a mixing layer in between. An undisturbed tank can maintain a high temperature difference ΔT between the layers, which guarantees high storage capacity (cf. equation (3-1)). (de Wit, 2007)

3.6.2. PHYSICAL ASPECTS

Water storage tanks can be manufactured from a wide selection of materials, whereas reinforced concrete, steel, aluminium and fiberglass are most common. A minimum of heat losses is desirable and can be achieved by minimizing and insulating the tank's surface.

The optimal relation between surface and volume could be obtained by making the storage tank spherical. Due to operational considerations a cylindrical geometry is preferred. The best surface to volume relation for cylindrical bodies is achieved with a 1:1 ratio between diameter and height. However, since the mixing apparatus in tanks has a constant height and therefore occupies a smaller volume in slim tanks, tanks with a higher diameter-to-height ratio are preferred. The insulation has

to withstand temperatures up to 100°C, therefore mineral fibres such as rockwool is used. (de Wit, 2007, p. 5)

The following Figure 3-16 gives an example on expected heat losses for a tank insulated with different thicknesses of rockwool. The tank has a height-to-diameter relation of 1 and contains water at 80°C; the ambient temperature is 0°C. The significantly higher losses for thinner layers of insulation are obvious. The figure also shows that heat losses, compared to the energy content are very small. An example tank with 10,000 m³ storage volume and 200 mm insulation can contain up to 470 MWh of energy and only loose about 0.0075 % or 35 kWh of its energy content per hour.

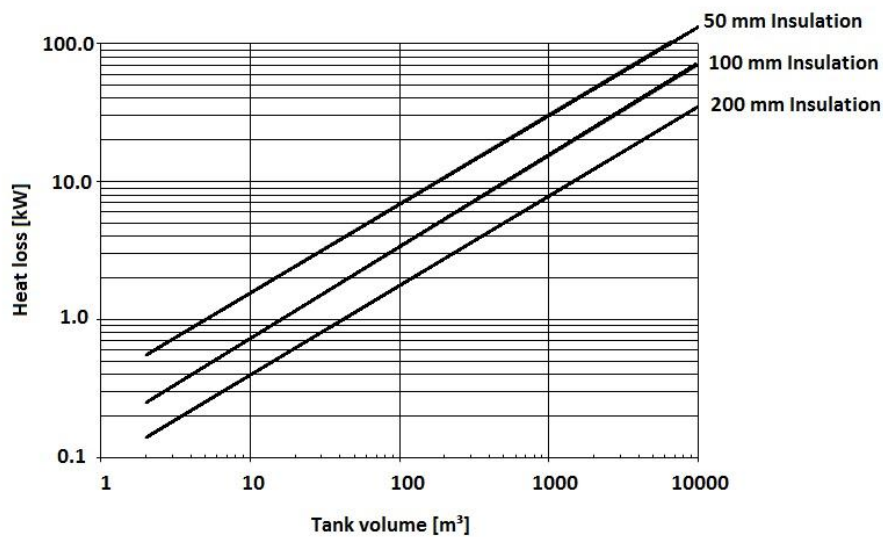


FIGURE 3-16 HEAT LOSS THROUGH SURFACE FOR A TANK WITH DIFFERENT INSULATIONS (DE WIT, 2007, P. 12)

3.6.3. ECONOMIC ASPECTS

In the following Figure 3-17 an estimation of erection costs for a free standing insulated steel tank is presented. The figure illustrates well that the specific erection costs decrease considerably with an increasing size. For example may the costs of 1000 m³ tank be calculated to 150,000-250,000 €, whereas a tank with the tenfold capacity will cost only about two to three times more.

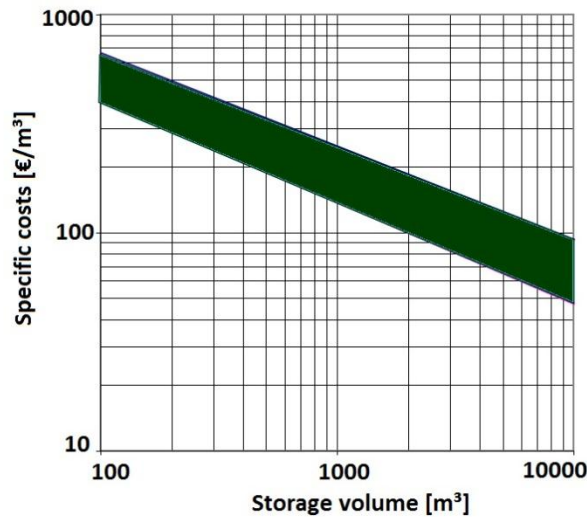


FIGURE 3-17 SPECIFIC ERECTION COSTS FOR AN INSULATED FREE-STANDING STEEL HEAT STORAGE TANK

4. OPTIMISATION OF CHP PLANT OPERATIONS WITH HELP FROM HEAT STORAGE SYSTEM

The installation of a thermal energy storage unit (TES unit) is generally considered to be a cost-effective way to improve the operational behaviour of CHP plants. Heat storage facilities enable CHP plant operators to uncouple the production of electricity and the supply of DH. In a liberalised electricity market, the production can hence be planned to benefit from high prices during peak demand hours. The surplus heat produced in those hours can be stored and satisfy the heat demand during hours with lower electricity prices. Furthermore, TES can be used to store heat for an expected peak of heat demand that exceeds the power output of the CHP plant. Thereby a start-up of backup plants with substantially higher production costs per produced unit of heat energy is avoided. Similarly heat can be delivered to the grid from a previously charged TES, while the CHP plant is rendered unavailable for short times, as during minor service or repair procedures. Even other reasons, such as turning off smaller plants over nights and weekends to save personnel costs, could motivate the cyclical supply from the TES unit only. As summarised above TES units can have several advantages. Hence, a variety of scientific papers have been published in which the benefits of adding heat storage to CHP plants and other operational impacts. The following chapter is a review on a number of relevant papers and publications.

The paper “Heat Accumulators in CHP Networks” by Gustafson and Karlsson (Gustafsson & Karlsson, 1992) is a case study of the CHP in Malmö, Sweden. The DH system consists of several elements illustrated; the used model is illustrated in Figure 4-1. The model determines the possibilities to store heat from off-peak to peak-load times. To evaluate those possibilities a mixed integer program is used. The optimization model covers the time of a year that is divided into 12 months; every month is than subdivided into a high and a low electricity price period. As well the demand of the DH grid as

the prices are constant for time periods of at least 14 days. Fluctuations in this data are not considered. The authors come to the conclusion that under the given circumstances, esp. cheap heat from the coal fired heat plant and the garbage incineration plant, the purchase of a heat storage tank is not profitable. Assumed that the storage was an existing device, it would have a present value of about 4,800,000 €, or generate an income of about 260,000 € per year. The optimal size of the accumulator is calculated to 2744 MWh, this can be set into relation to the CHP plant with a maximal output of 120 MW. According to the calculation model, a utilization of the heat storage tank is only lucrative between November and April.

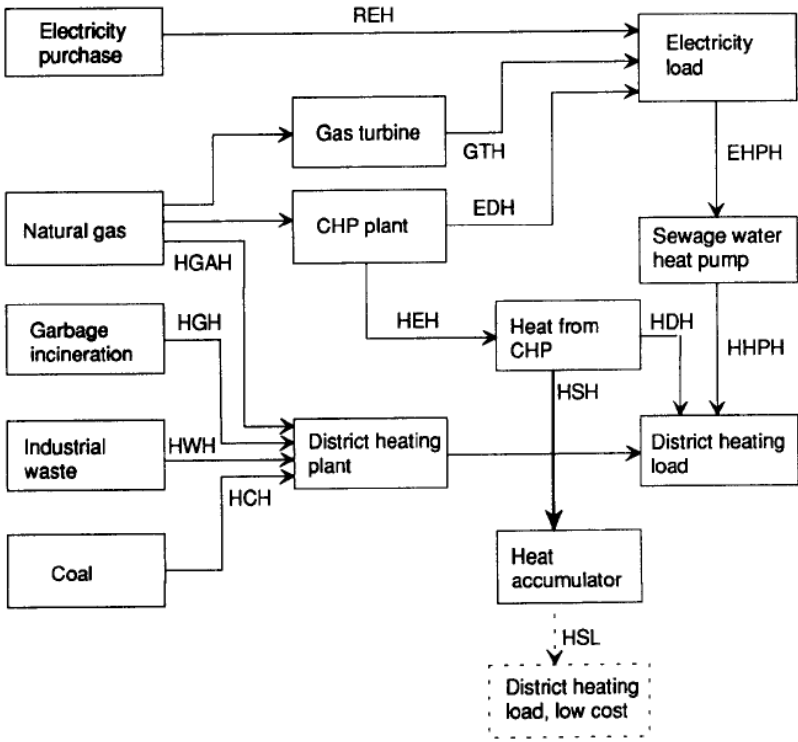


FIGURE 4-1 GRAPHICAL PRESENTATION OF THE MODEL USED IN (HEAT ACCUMULATORS IN CHP NETWORKS, 1992)

The paper “Cost minimization for a local utility through CHP, heat storage and load management” (Henning, D., 1998) studies a fictional municipal energy system including heat storages and determines the most cost-effective way to satisfy the assumed demand. Electricity prices and demand data are taken from a case study of the national Swedish energy system to guarantee authentic simulation data. The data create a fully deterministic simulation model. A linear optimization program is used to simulate a whole year, where some winter weekdays and certain peak days are divided into time steps of 4 hours. The author concludes by proposing a woodchips fuelled CHP plant and some heat pumps as optimal solution for the demand of the fictional municipality. All production units in this model are given the possibility to store heat in the storage tank. The heat storage in this set-up is used to cover heat demand peaks, enable the CHP to produce electricity although there is no current demand of heat and to store heat from the heat pumps that are operated at low price hours in the night rather than in daytime with higher electricity prices. At

lower electricity prices and in a scenario where the CHP plant electricity production is paid, the exact production costs of electricity biomass-fired heat-only boilers are calculated to be the most cost-effective solution.

Also in “Combined heat-and-power plants and district heating in a deregulated electricity market” (Rolfman, 2004), a municipal energy system with a CHP plant, storage and back-up boilers is studied. In this case the municipal energy system of the city of Linköping, Sweden is modelled. An outline of the optimisation model is shown in Figure 4-2. As storage a hot-water accumulator and storage in the building stock is being considered.

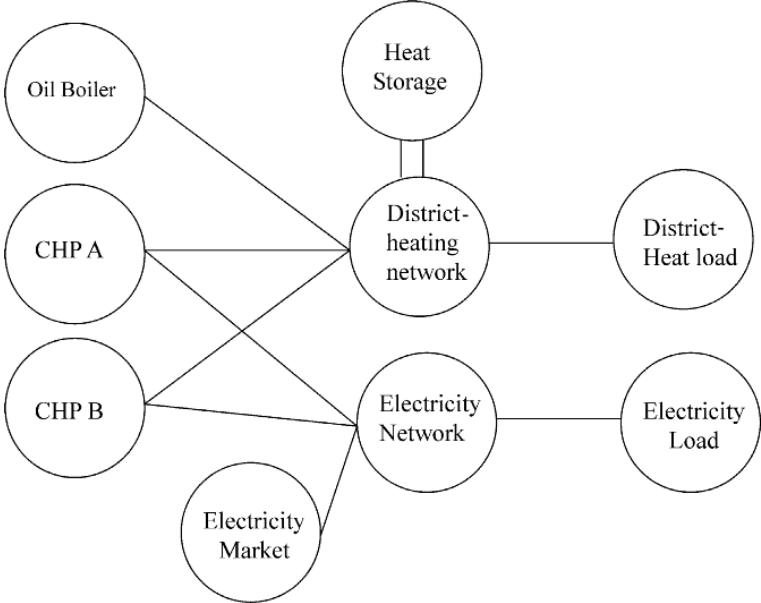


FIGURE 4-2 GENERAL FIGURE OF THE OPTIMISATION MODEL USED IN (ROLFSMAN, 2004)

TABLE 4-1 SELECTED TECHNICAL DATA AND COSTS FOR THE CHP PLANTS AND THE BACK-UP OIL FIRED BOILER IN LINKÖPING (ROLFSMAN, 2004)

	CHP A	CHP B	Oil-fired boiler
Cost [SEK/MWh] ^a	178	48 ^b	346
Heat Power [MW]	201	90	360
Electricity Power [MW]	59	47	–
Electricity/heat ratio	0.29	0.52	–
Efficiency	0.92	0.82	0.85

^a Tax included.

^b This cost is very low because the mixture includes refuse which has a negative cost.

The situation is analysed with a mixed integer linear-programming model and a simple forecast-model for the price on the Nordic electricity market. The paper is unique in the aspect that the planning horizon for the operational strategy is set on the coming 24 hour period of the next day. This is based on the horizon the presentation of the Nord Pool spot prices imply. It is the aim of the calculations to determine the investment potential and optimal size of heat storage. To do so, the

system is simulated both with and without heat storage. The increased income from selling electricity to high spot prices and the decreased costs for back-up heat are summed up and can be calculated with the present value method to an investment potential. Instead of calculating the exact benefits for the whole considered period of 20 years, the situation of 1996 is assumed to prevail those 20 years. The year 1996 can therefore be considered the base case. With an interest rate of 5 % the present value of having heat storage is calculated to about 1,200,000€. A sensitivity analysis to investigate the effect of two cases is also implemented. The first case is a trend of increasing fuel and electricity prices, and the price increase is set to 3%. Calculations show in this case, that the present value of a TES system rises to ca. 1,560,000€, an added value of 360,000€. The second examined case is a scenario with more volatile electricity spot prices. This case is implemented by multiplying the spot prices of the time period between 21:00 and 06:00 with the factor 0.9, thereby decreasing the price at night, and multiplying the spot prices between 06:00 and 21:00 with the factors 1.1 and 1.2 (factor 1.1 for time periods 06:00-09:00, 12:00-15:00 and 18:00-21:00 and factor 1.2 for time periods 09:00-12:00 and 15:00-18:00), thereby increasing the price differences from day to night. This case generates a total present value of ca. 3,800,000€, a triplication compared to the base case. The maximum utilisation of the simulated TES was 784 MWh. This can be set into relation to the maximum heat production capacity of the CHP plants of 291 MW¹³.

5. THE MODELLING SOFTWARE ENERGYPRO

The producers of *energyPRO* advertise the program as “the most advanced and flexible software package for making a combined technical and economic analysis of multi-dimensional energy projects” (EMD International A/S, 2010). The modelling software is specialised on combined techno-economic analysis of cogeneration projects and other energy related projects with a combined supply of heat (process and district heat), cooling and electricity. *EnergyPRO* has been used to simulate different marketing and operation strategies for cogeneration plants in conjunction with the possibilities and difficulties generated by a liberalised electricity market. Based on a wide range of data, different possible types of energy conversion units, external conditions, demand profiles, tariffs, specific emissions, revenue possibilities and other inputs the software gives a detailed output on operational strategies, economic numbers and emissions for an arbitrary time period. (EMD International A/S, 2010)

Based on an entirely deterministic scenario, *energyPRO*'s algorithms calculate the most cost-effective operational strategy by identifying the most favourable time-periods of production and start-up (in

¹³ This number is particularly interesting, since Hässelby and Brista have a combined maximum heat production of 308MW, which is about the same capacity as in the discussed model.

contrast to an intuitive hour-by-hour chronological approach). As a consequence all new production is always checked in order to not disturb already planned productions, thereby verifying the made planning. The number of time periods can be adjusted by the length of calculation steps, which can be chosen as time intervals ranging from 10 minutes to 1 hour. (EMD International A/S, 2011)

For further information on *energyPRO* please consult the user's guide (User's Guide energy PRO, 2011) or the website <http://www.emd.dk/energyPRO/Frontpage> with further references, tutorials and other possible applications.

6. THE MODEL

A graphical layout of the created model that has been used in this project can be seen in Figure 6-1. It can be interpreted as an energy flowchart. The fuels on the left hand side with arrows indicating the mass flow to the energy conversion units, which in this case are the Hässelby CHP plant and the back-up boilers in Akalla and Vilunda. The numbers displayed on the arrows represent the maximal energy flow into the respective conversion unit. Red arrows emerging from a unit denote a heat flow and black arrows stand for a flow of electric energy. Also the arrows are labelled with the maximum flow from the respective unit. All heat flows coming from the conversion units end at the components that embody heat sinks, the grid's heat demand and heat losses. The heat supplied by the CHP unit can also be blown off to the environment or be stored in a heat storage. The Nordic Electricity Market is connected to the Hässelby CHP and the Akalla heat pump. The arrows indicate that the CHP delivers electric energy to the market and the market delivers to the heat pump. The supply of electric energy to the Akalla heat pump also can be covered by the Hässelby CHP.

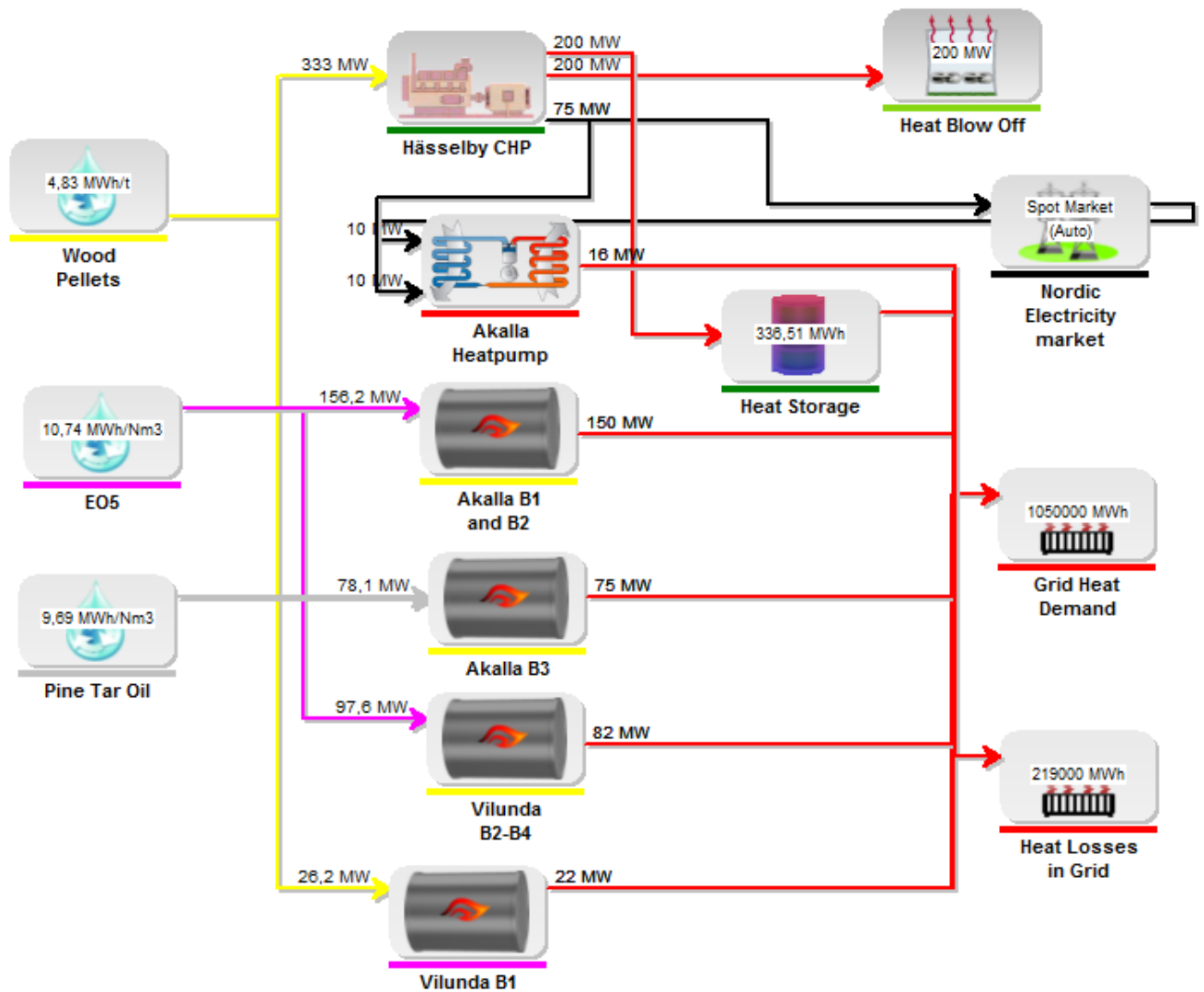


FIGURE 6-1 GRAPHICAL LAYOUT OF THE MODEL USED IN THIS THESIS

6.1. INPUT

In this section all input data that are part of the calculations are reviewed and completed with their origin and role in the model.

6.1.1. TIME SERIES

Time series are of special importance in *energyPRO*. They consist of set values specified by a day and time and can be accessed from other points in the program with variables that change over time. In the simulation for this thesis a time series for a modified temperature and a time series with the Nord Pool electricity spot price are used as input.

6.1.1.1. MODIFIED TEMPERATURE TIME SERIES

The modified temperature series is used to calculate the grids heat demand. The basis is a time series that gives the daily average ambient temperatures obtained from (temperatur.nu, 2011). In order to

simulate the diurnal fluctuations in heat demand that were described in Figure 3-8, page 23, these temperatures were modified by a pattern of up to 4°C higher temperatures at night, rendering the wanted effect of lower demand at night, and up to 4.5°C lower temperatures at daytime, leading to higher demand in those hours. The result of this superposition can be seen in Figure 6-2. The average daily temperature is marked with red circles and the modified temperature with blue stars.

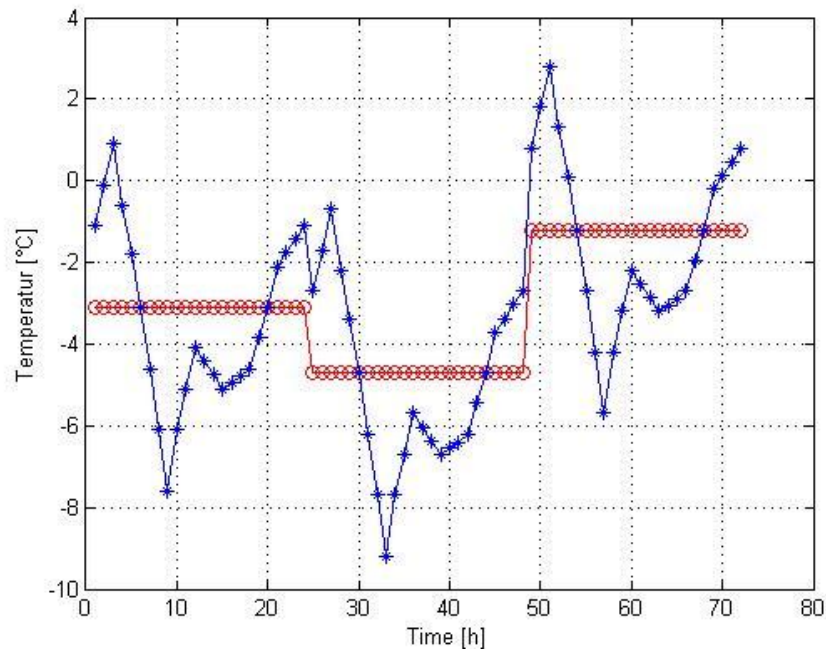


FIGURE 6-2 MODIFIED TEMPERATURE PROFILE FOR THE FIRST 72 HOURS OF 2009

6.1.1.2. HEAT LOSS TEMPERATURE

This time series regulates the heat losses of the DH grid. Over a daily temperature of 16 °C it is set to 0 and below that temperature it is linearly dependent of the ambient temperature. This way Hässelby CHP only has to account for heat losses in time periods when it is actually delivering heat to the grid. More about this connection in section 6.2, page 46.

6.1.1.3. NORD POOL SPOT PRICE TIME SERIES

The prices saved in the Nord Pool spot time series set the price for selling electric energy from the CHP plant and buying electric energy to supply the heat pump in Akalla. The values for the time series are illustrated in Figure 3-6, page 21. The spot prices influence the operation, because they indirectly decrease the CHP's heat producing costs and determine the system's income from trading electricity.

6.1.2. FUELS

The fuels used in these simulations are wood pellets, heavy fuel oil number 5 (Eo5) and Pine Tar Oil. In this sheet of energyPRO, their energy content per metric ton (t) or standard cubic meter (Nm³) is

set. They are 4.83 MWh/t wood pellets, 10.74 MWh/Nm³ fuel oil Eo5 and 9.69 MWh/Nm³ Pine Tar Oil (cf. Table 3-5).

6.1.3. DEMANDS

Demands are the values that have to be supplied at any cost. In this simulation those demands are the DH demand and the associated heat losses. Total values of 1150 GWh for the DH demand and 100 GWh for the heat losses are set here. Those total values descend from the total energy demand in the north-western DH grid of Stockholm in 2009 minus the supply delivered from the Brista CHP plant. More about this assumption is found in section 6.2. The DH demand is considered to depend linearly on the modified temperature time series. The reference temperature, which marks the highest temperature of production, is 16°C. The reference temperature corresponds to the temperature at which Brista can supply the whole DH grid by itself (cf. Figure 3-10). The same applies on the heat losses. These are much less depended on the ambient temperature and therefore have their own time series that implies the heat losses here that are given in Figure 3-10. Also there are no heat losses over 16°C because the Hässelby CHP plant is turned off above that temperature and no heat losses can occur.

6.1.4. ENERGY CONVERSION UNITS

The energy conversion units used in this simulation can be seen in Figure 6-1. In this sheet of energyPRO, the used fuel, their capacity and efficiency is set. An overview on the input is given in Table 6-1.

TABLE 6-1 SUMMARY OF THE SIMULATED HEAT CONVERSION UNITS (HAGLIND & FORTUMAB, 2011, P. 10)

Energy conversion unit	Fuel	Input [MW]	Output [MW]	Efficiency [%]
Hässelby CHP plant	Wood Pellets	333	200 MW heat + 75MW el	82.5
Akalla Heat Pump	Electricity	10	16	159
Akalla Boiler 1 and 2	Fuel Oil EO5	156,2	150	96
Akalla Boiler 3	Pine Tar Oil	78,1	75	96
Vilunda Boiler 1	Wood Pellets	26,2	22	84
Vilunda Boiler 2 to 4	Fuel Oil EO5	97,6	82	84
Heat Blow Off	Heat	200	0	0

6.1.5. STORAGES

The only heat storage used in this simulation is a water based single phase TES. The heat storage tank is characterised by the following data. For the first simulations the given volume is 6600 m³ and has thereby the same capacity as the already existing unit. The difference in temperature is given by the normal output temperature of 95°C in the DH grid and the normal return temperature of 45°C (Johanson, 2011). At an estimated utilization of 80 % a storage capacity of 306 MWh heat energy can be obtained. The possible utilization is decreased by effects such as mixing layers and reserve

capacity (cf. section 3.6). Storage losses are also accounted for. It is assumed that the heat storage tank is insulated with 200mm of mineral rock wool that has a thermal conductivity of 0,036 W/m²K. The ambient temperature has an influence on the heat loss and is given by the modified temperature time series.

6.1.6. ELECTRICITY MARKET

The electricity market of this simulation is the Nordic Electricity Market with the Nord Pool spot prices of 2009. Values for this time series can be seen in Figure 3-6.

6.1.7. ENVIRONMENT

Input under this point are specific emissions of CO₂, NO_x and SO₂. The data used can be seen in Table 3-5. They are used to calculate the total emissions of a specific operation strategy but do not have any influence on the strategy itself.

6.1.8. ECONOMY

Since the operation will be optimised to deliver heat to the lowest net heat production costs, the input in this section has great influence on the total optimisation result. Expenditures for fixed costs, such as costs for loans or personnel, and general taxes are not part of the model. The results will therefore not describe the real profits of operations.

6.1.8.1. REVENUES

Revenues from the operation come from three sold products: District heating, electric energy and green certificates.

The price for DH energy is assumed to be constant at 101.90 €/MWh over the analysed time period. This price resembles the average price for DH in Stockholm 2010 for the year 2010, as seen in Figure 3-7. The actual price is of less importance. Since the DH demand will be satisfied in any case, no optimisation based on this price will be done.

The revenues from selling electric energy on the spot market are based on the above described time series for Nord Pool spot prices. The spot price has great influence on the Net Heat Production Cost (NHPC), since they decrease the specific NHPC of the CHP with the amount that is paid for the “side-product” electric energy.

Payments for the trade of green certificates have the same effect on the NHPC as the income from the spot market. Every produced unit of electric energy is worth more the price for one certificate, which in this case amounts to constant 27.92 € per certificate. The extra income from green certificates encourages the heat production in the CHP.

6.1.8.2. OPERATION EXPENDITURES

Operation expenditures are fuel or plant specific. The sum of all expenditures associated with one plant and one fuel form the overall specific production costs of this unit. The fuel specific costs are the purchasing costs for the fuel itself and taxes and fees for the emission of carbon dioxide, sulphur oxide and nitrogen oxides. Plant specific costs are start costs that describe inefficiency of the operation related to the start procedure.

The applicable emission fees and taxes are summarised in Table 6-2. Further explanations to fees and tax regulations can be found in chapter 3.4, page 24.

TABLE 6-2 SUMMARY ON OPERATION EXPANDITURES ON ACCOUNT OF EMISSION FEES AND CERTIFICATES

Fuel	NOx-Emissions	Carbon-Emission	Sulphur-Emissions
Wood Pellets	5.61 €/t	-	-
Fuel Oil EO5	7.82 €/Nm ³	51.97 €/Nm ³ (EUA) + 53,76 €/Nm ³ Carbon dioxide tax	2.00 €/Nm ³
Pine Tar Oil	29.75	-	-

Start costs are added to the payment lines for each time a heat conversion unit is started. Such start costs influence the priority of a unit during the optimisation. The costs make it more undesirable to start a unit compared to expanding already started units or compared to taking heat from the storage. Start costs describe inefficiencies in the start-up procedure. It is assumed that those inefficiencies can be described as an amount of fuel that, during the start-up phase, is not converted into useful energy. Therefore the start-up costs are set by an estimated length of the start-up phase, the amount of fuel used and the fuel's price. Also wear on the plant is accounted for by this amount. The estimated start-up costs are presented in Table 6-3.

TABLE 6-3 ESTIMATED START-UP COSTS

Heat conversion unit	Start-up time	Start-up cost [€]
Hässelby CHP plant	1 h	9350
Akalla Heat Pump	10 min	100
Akalla B1 and B2	30 min	1100
Akalla B3¹⁴	5 min	0
Vilunda B2-B4	30 min	600
Vilunda B1	1 h	370

¹⁴ Akalla B3 is preheated during periods with expected start-ups.

6.2. ASSUMPTIONS

The presented model is a part of the DH grid of north-western Stockholm. It consists of energy conversion units and interacts with the environment by the input of fuels, emissions to the environment and the output of electric energy and heating energy. All flows over the system's boundary are accompanied by payments. Effects concerning the physical transport of fuels, combustion residues and energy are not part of the system. While creating the model, assumptions were made that let the model differ from reality. The following chapter describes those made assumptions.

- The presented model does not contain all the real units of Stockholm's DH grid. Since it is not the purpose of this model to optimise operations at the Brista CHP and the smaller plants dedicated to serve as back-up in the Brista grid, those units are not part of the system. Their importance in the grid has been accounted for by subtracting Brista CHP's yearly output from the heat demand of this model. This is possible because Brista CHP has significantly lower specific NHPC than other plants in the grid and is therefore operated as only base-load plant during summer. Production in Hässelby starts when the ambient temperatures fall under 16°C, which is the breakpoint under which additional heat production is needed in the grid.
- Other production units that are not presented in this model are electric boilers. They mainly serve as reserve in case of severe damage and loss of production in the other units. Production from these units is not necessary in the simulated year 2009.
- One of the most characteristic assumptions in models like these is made by assuming a total deterministic position. This assumption implies that all used input data and parameters are known over the whole analysed time period. This is of course not the case. Deterministic data is mainly assumed for the Nord Poll spot price of electric energy, ambient temperatures and thereby heat demand, and constant known fuel prices. There are, however, effective forecasting models in place that can give a sufficiently accurate forecast early enough to plan productions. The results obtained with deterministic models like this are said to give the optimal planning and maximum investment potential.

- Several assumptions concern the supply of district heating to the grid. The model does not take transportation effects into account. In a physical DH grid the delivery of a heat takes a certain period of time and therefore the future heat demand has to be forecasted and production has to supply heat demand before it actually occurs. Another effect of those delays could be a smoothing in the demand profile, since the hours of peak demand in different distance to the producing unit will have different delays and will create a broadened, but less sharp peak demand. It is furthermore put aside in this model that the 34,000m³ of water in the DH grid actually can serve as short term heat storage. This is already done today but cannot be simulated with the chosen simulation software.
- Concerning the trade of energy it is assumed that the entire selling price is profit, although there should be fees in place for transporting the energy. As a market participant Hässelby CHP's operator benefits from spot prices, but is not object to the merit order effect. The merit order effect dictates that place a bid below the MCP can trade their energy. It is certain that Hässelby CHP plant cannot always be able to place a bid under the MCP and could therefore be forced to bypass the generators in order not produce any electric energy. In these time periods there would of course not be any revenues from the selling, rendering a more expensive heat production in Hässelby.

7. OUTPUT REPORTS

After the calculation *energyPRO* presents a vast amount of diagrams and numbers. In the following chapter the most important output sheets and diagrams are discussed for a base case. The base case represents the current set up with a water based heat storage tank of 6600m³.

7.1. NET HEAT PRODUCTION COSTS

The most immediate result obtained with *energyPRO* is a diagram that illustrates the Net Heat Production Costs (NHPC) as a function of the Electricity Spot Price. Calculations are made considering all fuel-specific revenues and expenditures explained above. Figure 7-1 shows that the heat production costs of the Hässelby CHP plant decrease from initially ca. 37 €/MWh_{heat} at 0 €/MWh_{el} to 10 €/MWh_{heat} at 75 €/MWh_{el}. Above an Electricity Spot Price of 20 €/MWh production in the Hässelby CHP plant is most cost-efficient. Akalla Heat Pump is bookkept with costs of 0 €/MWh_{heat}, that is because it is assumed, that internal flow of electric energy from the producing Hässelby CHP is for free. In ascending order of constant costs come production from Akalla's Pine Tar Oil fuelled B3, the wood-pellets fired Vilunda B1 and with higher cost the Fuel Oil Boilers Akalla B1-B2 and Vilunda's Boiler B2-B4. These costs decide the order in which the units are started to cover the dynamic demand in the DH grid.

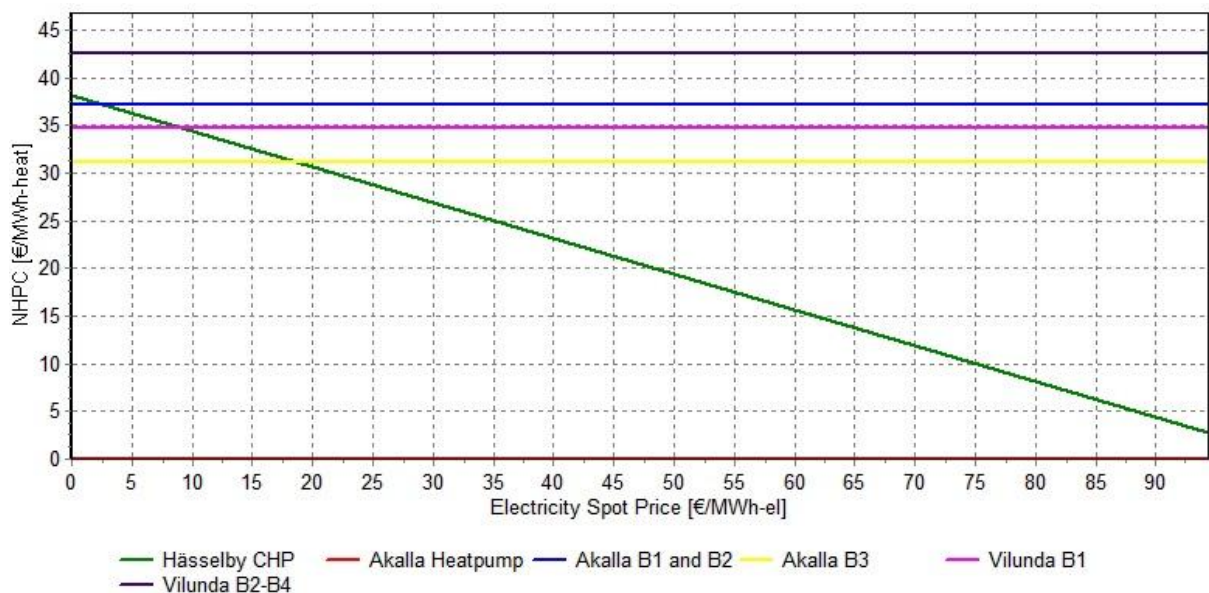


FIGURE 7-1 NET HEAT PRODUCTION COSTS AS A FUNCTION OF THE ELECTRICITY SPOT PRICE

7.2. PRODUCTION, GRAPHIC

The production graphic shows for a freely selectable time period the calculated optimal operational planning. There are graphs for the Electricity Spot Price, Heat Production and Demand, Electricity Production and filling level of the heat tank. The example in Figure 7-2 shows a 14day time period in January. The second graph shows how the heat demand under one day fluctuates around the maximal output of the CHP plant. In total it is slightly higher than the output so that back-up plants are started to supply the total demand. In the short periods with decreased demand the CHP is still operated on maximal output and the surplus heat stored in the heat storage. The stored heat is later

used to help to supply the again increased heat demand. Thereby the operation time of the backup plants is decreased.

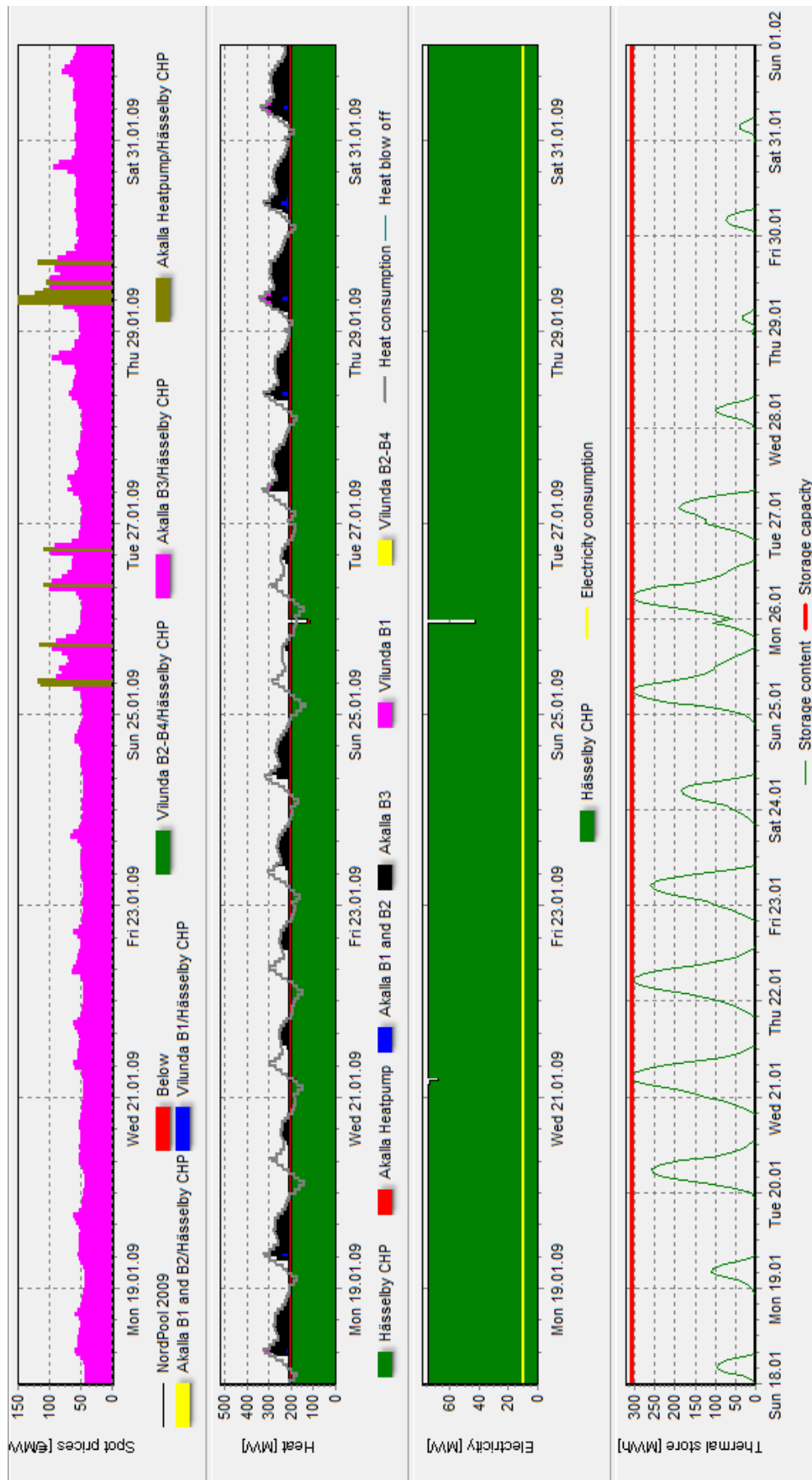


FIGURE 7-2 PRODUCTION GRAPHIC FOR THE TIME PERIOD 18.01. TO 01.02. , BASE CASE

7.3. ENERGY CONVERSION ANNUAL, MONTHLY AND SUMMARY

The following sheets give an overview on the energy conversion processes in the plant. In those sheets information about heat demand and heat production from the single units, electricity production, hours of operation and turn-ons can be found. Important figures that are obtained from these sheets are fuel consumption and operating hours. The monthly energy conversion sheet shows these figures broken down for every month. An example of a monthly energy conversion output sheet is attached as Figure 7-4. This figure shows for example how the heat production decreases rapidly in the summer month while the number of turn-ons increases.

7.4. ENVIRONMENT

The produced sheet here contains emissions coming from the utilization of different fuels. The Figure 7-3 is an example produced for the base case data.

Emissions	
	2009
CO2 [ton]	
Wood pellets	0
Pine Tar Oil	0
Eo5	10.153
CO2 Total	10.153
NOx [kg]	
Eo5	17.556
Wood pellets	390.686
Pine Tar Oil	16.744
NOx Total	424.986
SO2 [kg]	
Wood Pellets	1.725
Eo5	697
Pine Tar Oil	2.095
SO2 Total	4.517

FIGURE 7-3 CLIPPING FROM THE ENVIRONMENT OUTPUT DISPLAYING EMISSIONS ASSOCIATED TO THE USED FUELS, BASE CASE

Hässelby Cogeneration Plant
The District Heating Grid North-West Stockholm
Model for the Bachelor-Thesis "Introducing Additional Heat Storage to the Hässelby CHP Plant"
David Schröder
KTH 2011

Energy conversion, monthly

Calculate period: 01.2009-12.2009

	Total	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Heat demand [MWh]	1.200.000,0	200.078,1	177.372,4	166.296,2	84.135,7	47.468,8	31.985,3	4.450,8	6.920,9	31.255,9	124.246,3	120.074,0	205.715,4
Electricity produced by energy units [MWh]	357.376,4	55.123,1	50.311,6	53.506,2	27.438,1	13.855,6	9.441,5	868,6	1.370,4	8.940,4	42.103,8	40.382,2	54.035,0
Electricity consumed by energy units [MWh]	68.588,1	7.440,0	6.485,7	7.440,0	6.877,9	6.085,7	4.288,2	1.412,9	2.017,2	4.800,4	7.419,9	7.044,6	7.275,7
Delivered electricity Nordic Electricity market [MWh]	301.179,7	47.703,1	43.825,9	46.096,2	21.947,1	10.403,4	7.006,7	644,1	1.073,1	6.664,9	35.175,1	33.830,8	46.809,3
Peak [MW]	85.000	85.000	85.000	85.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	85.000	85.000
Received electricity Nordic Electricity market [MWh]	12.391,3	20,0	0,0	30,0	1.386,9	2.633,4	1.853,5	1.188,4	1.720,0	2.524,8	491,2	493,2	50,0
Peak [MW]	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Energy unit: Hässelby CHP	328.520,0	50.672,1	46.249,1	49.185,8	25.222,6	12.736,9	8.679,1	798,5	1.259,7	8.218,5	38.704,1	37.121,5	49.671,9
Fuel consum. [t]	1.586.751,4	244.746,4	223.383,3	237.567,5	121.825,2	61.519,0	41.920,2	3.856,7	6.084,4	39.695,5	186.940,9	179.296,9	239.915,3
Heat prod. [MWh]	953.003,8	146.994,8	134.164,2	142.683,2	73.166,3	36.948,4	25.177,3	2.316,3	3.654,3	23.841,1	112.276,8	107.585,8	144.093,3
Elec. prod. [MWh]	357.376,4	55.123,1	50.311,6	53.506,2	27.438,1	13.855,6	9.441,5	868,6	1.370,4	8.940,4	42.103,8	40.382,2	54.035,0
Turnons	243	3	1	4	35	46	31	17	19	35	23	24	5
Operating hours	5.921	742	672	741	565	394	274	66	65	291	699	673	739
Energy unit: Akalla Heatpump	109.055,1	11.829,6	10.312,3	11.829,6	10.935,8	9.676,2	6.818,3	2.246,5	3.207,4	7.632,6	11.797,6	11.200,9	11.568,4
Heat prod. [MWh]	68.588,1	7.440,0	6.485,7	7.440,0	6.877,9	6.085,7	4.288,2	1.412,9	2.017,2	4.800,4	7.419,9	7.044,6	7.275,7
Elec. consum. [MWh]	29	1	7	1	1	1	1	1	1	1	1	8	5
Turnons	29	1	7	1	1	1	1	1	1	1	1	8	5
Operating hours	8.684	744	651	744	718	738	712	744	736	712	742	706	737

FIGURE 7-4 MONTHLY ENERGY CONVERSION SHEET, 6600M³ HEAT STORAGE

7.5. CASH FLOW

The cash flow sheets give numbers that summarise revenues from selling heat, electricity and green certificates and expenditures for fuel purchase, fees, certificates and start-up costs. Like in the energy conversion sheet before, also here numbers can be presented monthly, as a summary or as financial key figures. The financial key figures are basically only the Net cash from operation. An example of a summarised cash flow sheet is presented in Figure 7-5. The monthly sheets present the same figures, only broken down to the single months.

7.6. INCOME STATEMENTS AND BALANCE SHEETS

Those sheets essentially contain the information seen in the sheets explained above. They are, however, presented in a form that is used in banks and tax related affairs.

Cash Flow, summary

(All amounts in €)

	2009
Revenues	
Electric Energy Payments	20.466.523
District Heating Payment	84.067.503
Green certificates	8.408.936
Total Revenues	112.942.963
Operating expenditures	
Fuels	
Wood Pellets	44.961.218
Eo5	781.859
Pine Tar Oil	2.973.841
Fuels Total	48.716.918
Taxes, fees and certificates	
NOx CHP	80.366
SOx EO5	5.665
CO2 EO5	152.282
Carbon trade EO5	147.211
NOx Pine Tar Oil	1.863.347
NOx EO5	84.270
Taxes, fees and certificates Total	2.333.142
Startups	
Hasselby CHP	2.272.050
Akalla Heat Pump	2.900
Akalla B1 and B2	85.800
Akalla B3	0
Vilunda B2-B4	3.000
Vilunda B1	19.980
Startups Total	2.383.730
Total Operating Expenditures	53.433.789

FIGURE 7-5 CLIPPING FROM CASH FLOW SUMMARY, BASE CASE

8. INFLUENCE OF INSTALLING ADDITIONAL HEAT STORAGE

In the following chapter the operational influences of heat storage will be discussed. In order to achieve as clear results as possible a big heat storage unit with a capacity of 24,000m³ water has been chosen. This heat storage is about four times bigger than the existing one.

The first figure shows how the optimisation model chooses production hours in time periods with relatively low heat demand and a relatively highly volatile electricity spot price. Here, only a small fraction of the total output capacity of CHP plant is needed to cover the heat demand. It is not profitable to run the CHP plant in extraction mode and blow-off the heat in the heat blow-off. In order to maximise profit the time periods with the highest spot prices are chosen and the obtained heat is stored in the heat tank. During time periods with relatively lower spot prices the CHP plant is shut off and the hot water for the DH grid taken from the heat storage.

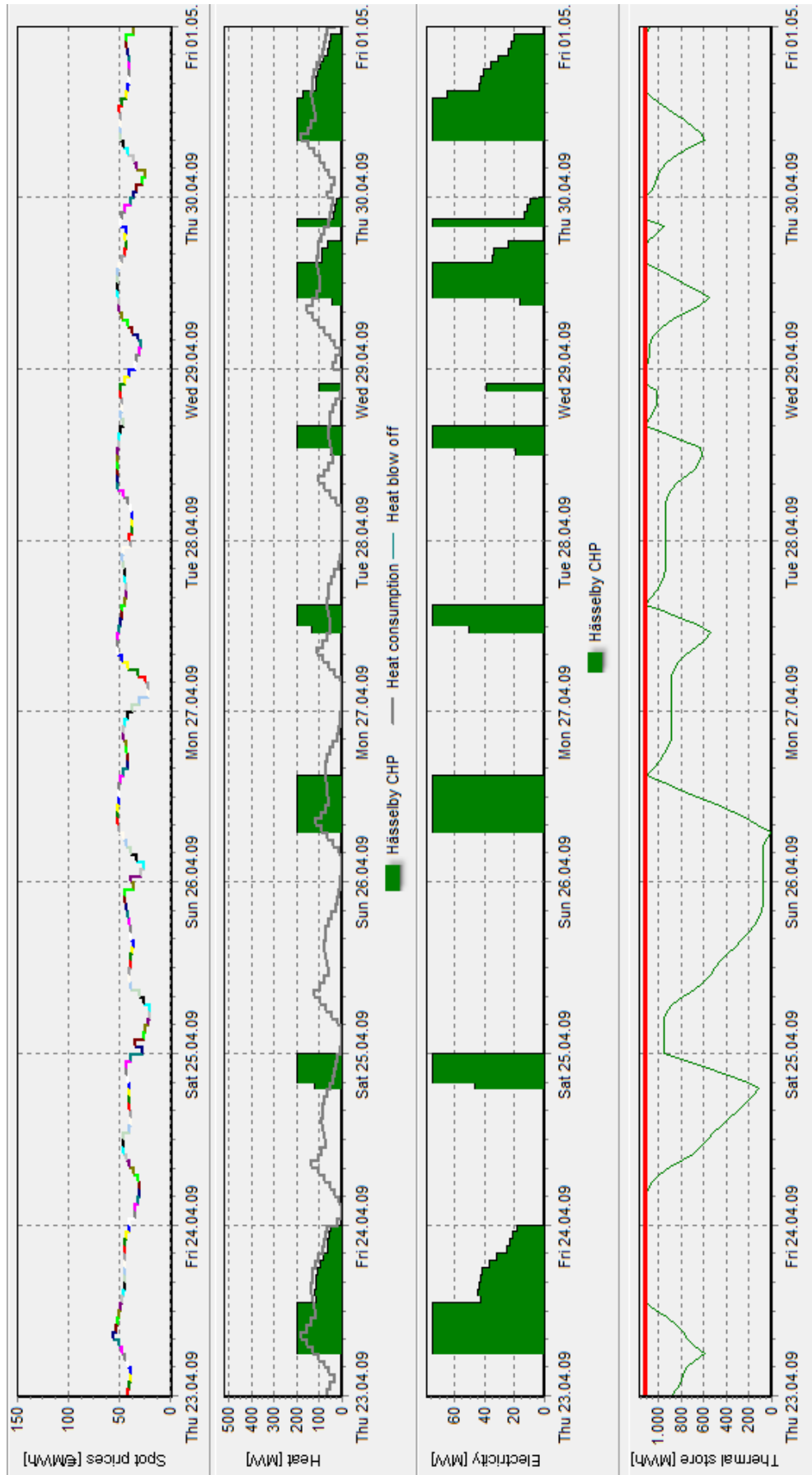


FIGURE 8-1 OPTIMISATION OF PRODUCTION IN TIME PERIODS WITH LOW HEAT DEMAND AND VOLATILE ELECTRICITY PRICE

The following figure shows how the heat storage tank is used to compensate for diurnal demand fluctuation around the maximal output of the CHP plant. The start-up of back-up plants is avoided by running the plant on full power output over the whole time period. During low demand hours the excess heat is stored in the heat storage. The stored heat is then used to cover demand peaks. In the end of the analysed time period the heat storage is completely uncharged, so that a back-up plant eventually has to be started. The started back-up plant is Akalla B3, fuelled with biogenic Pine Tar Oil. The start-up order is also illustrated in Figure 7-1. Other back-up plants given in the figure are in this time period not needed to cover the heat demand. In this time the utilisation of heat storage helped to avoid the start-up of more expensive back-up units.

The possibility to choose the best paying production hours and to avoid more expensive back-up plants results in a better economic result than under the same conditions except for smaller heat storage. Not included in these calculations are higher expenditures for the investments in bigger heat storage. Compared to the base case (6600m³ heat storage) an additional income of about 906,000€ was achieved. Significant environmental benefits in contrast could not be obtained. Only a saving of 2% from 10153 t of emitted carbon dioxide in the base case to 9942 t in this analysed case was obtained. The emissions of nitrogen oxide furthermore even increased and sulphur oxide emissions were reduced by 3.5%.

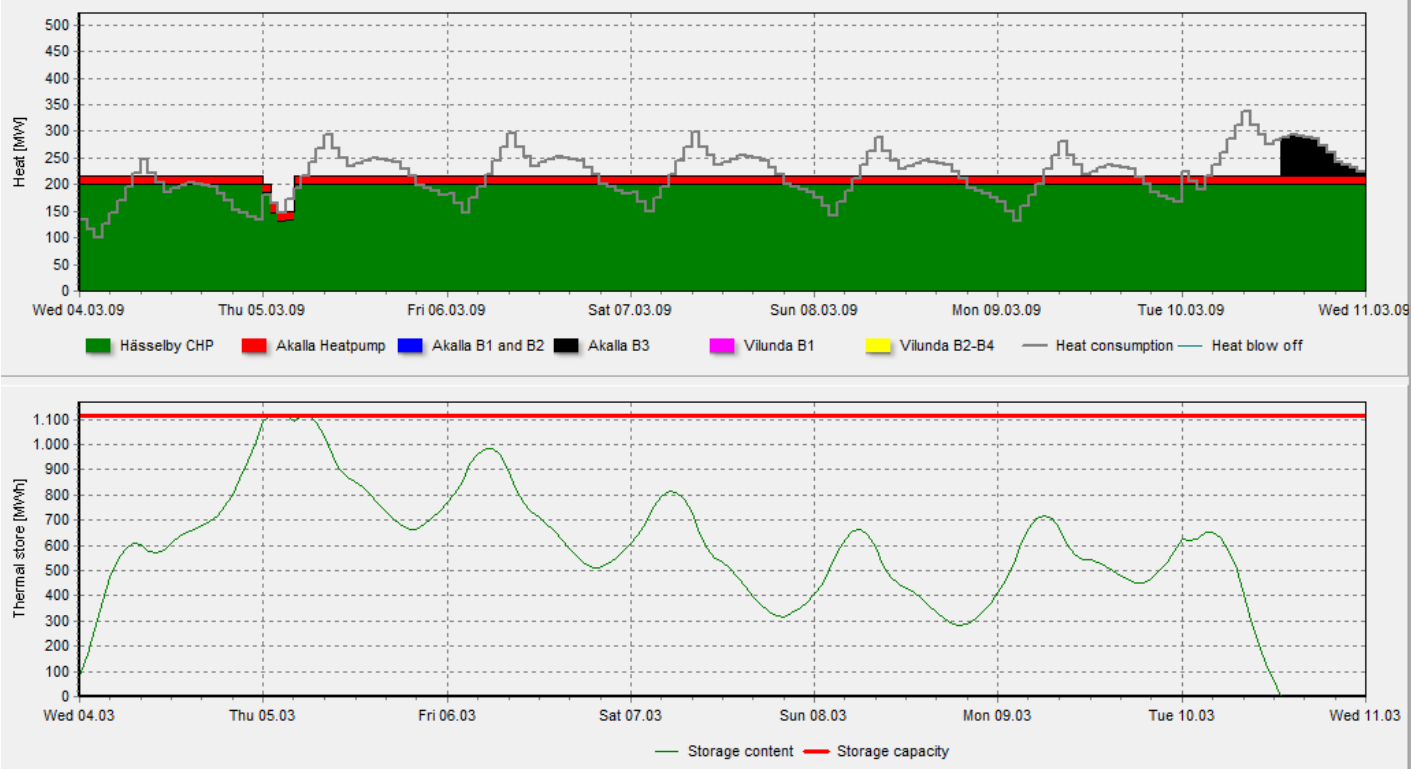


FIGURE 8-2 OPTIMISATION OF PRODUCTION IN TIME PERIODS WITH HEAT DEMAND FLUCTUATIONS AROUND THE MAXIMAL OUTPUT OF THE CHP PLANT

9. SENSITIVITY

The section above has shown that heat storage units can increase the income from operations. In the following sections this result will be validated by performing a sensitivity analysis. The analysis will test the sensitivity of the increased income towards the size of the heat storage.

Basis of the analysis are values obtained for a number of storage sizes. The values are presented in the tables Table 9-1 and Table 9-2.

In table the economic results of changing the heat storage volume is shown. The numbers indicate that the income increases with growing heat storage. It is shown that with growing heat storage, revenues from selling electricity and green certificates increase. At the same time costs for fuels and taxes decrease. The reason for that is a better utilisation of the CHP plant. With bigger heat storage the possibility to decouple production is bigger as well as production for a future peak demand is enabled. Fuel costs and taxes are decreasing because wood pellet is a relatively cheap fuel with low taxation.

TABLE 9-1 ECONOMIC SENSITIVITY TO STORAGE SIZE

Heat storage Volume [m ³]	Relative net cash ¹⁵		Revenues		Expenditures	
	Electricity [€]	Green Certificates [€]	Fuels [€]	Taxes, Certificates [€]		
0	-258,858	-3,225,888	-3,225,888	19,528,538	7,968,062	
6,600	0	0	0	20,466,523	8,408,936	
9,900	305,996	3,813,322	3,715,602	20,646,898	8,490,787	
13,200	590,776	7,362,251	7,231,957	20,750,804	8,540,315	
16,500	696,758	8,682,998	8,533,703	20,820,499	8,579,880	
20,250	814,283	10,147,595	9,981,026	20,884,808	8,606,032	
24,000	906,002	11,290,597	11,086,495	20,933,662	8,628,313	
30,600	1,025,005	12,773,612	12,531,977	20,997,010	8,656,576	

The present value method¹⁶ clarifies the benefits of an investment into heat storage. Figure 9-1 implies that the investment into heat storage has a growing present value. It can therefore be considered profitable to install an as big as possible heat storage to create additional income. Figure

¹⁵ Since the model does not contain any standing charges the calculated net cash amount is very high. That is why all net cash amounts are given as relative amounts to the net cash sum obtained with the base case.

¹⁶ The present value is a method to estimate the worth of future payments. Basis for this present value calculation is an estimated rate of interest of 5% and a span of 20 years.

9-1 is based on annual credit costs for the construction of a new heat storage tank and the net present value of an income stable on the same level as 2009 over the next 20 years.

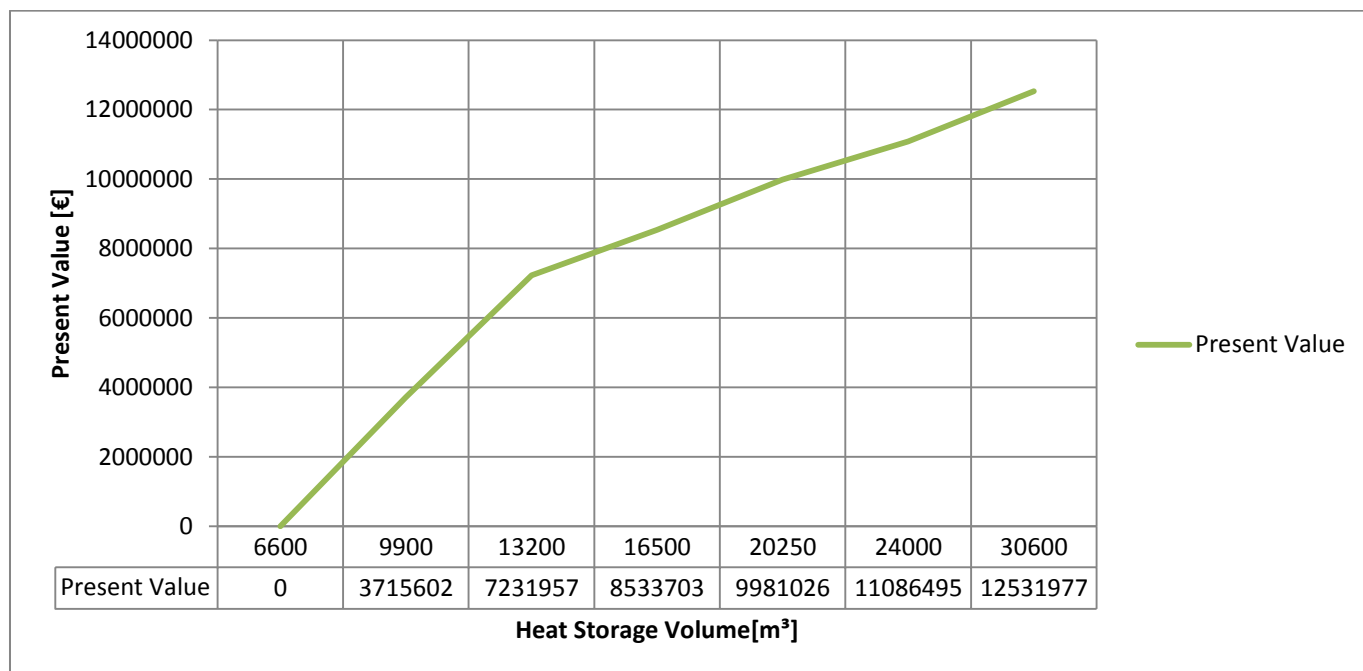


FIGURE 9-1 PRESENT VALUE AS A FUNCTION OF THE HEAT STORAGE VOLUME

The table shows the impact of alternating heat storage on fuel consumption and emissions to the environment. A clear development towards lower or higher emissions cannot be seen.

TABLE 9-2 FUEL CONSUMPTION AND EMISSION SENSITIVITY TO STORAGE SIZE

Heat storage Volume [m³]	Fuel Consumption				Environment - Emissions		
	Wood Pellets [t]	Fuel Oil EO5 [Nm³]	Pine Tar Oil [Nm³]	Electricity [MWh]	CO2 [t]	Nox [t]	SO2 [kg]
0	324950	2655	12536	68	9514	419504	4898
6600	331792	2832	10278	69	10153	424986	4517
9900	332773	2785	10027	68	9982	425436	4460
13200	333211	2808	9684	69	10063	425858	4438
16500	333656	2805	9759	68	10054	426163	4414
20250	334147	2775	9645	68	9964	426370	4386
24000	334577	2774	9524	68	9945	426672	4364
30600	335010	2774	9406	68	9942	426990	4342

10. CONCLUSION

The analysis in this report has conclusively shown that an investment into additional heat storage at the Hässelby CHP plant is beneficial. It enables the operator to decouple energy and heat production for a certain period of time, thereby rendering an additional income from producing in peak electricity spot price hours. Another demonstrated benefit of an enlarged heat storage unit is the possibility to store heat for future expected demand peaks. Thereby, the start-up of more expensive back-up plants can be avoided.

It is therefore safe to answer the introductory question: “Can the current production of electric and thermal energy at the Hässelby cogeneration plant be improved by installing additional heat storage?” with a yes.

10.1. THE MODEL’S PLAUSIBILITY

It is certainly open for discussion whether the obtained results could actually work in the existing cogeneration plant. Especially the simplifications to not consider general taxes and conduct calculations based on deterministic time series, provides some plausibility concerns. The obtained present values are certainly the highest achievable. In a real system with limited knowledge of future developments such increased income will not be reachable.

10.2. SUGGESTIONS FOR FUTURE WORK

This report does not go into details concerning the physical DH grid and the eventual possibility to implement dynamic strategies here. By using the circulating water as heat storages an improvement of operations could be obtained. Furthermore, an expansion of the model on all physically connected energy conversion units, esp. Brista CHP plant, might lead to completely new dynamic opportunities.

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