University of Southern Denmark

Integration of Refuse Derived Fuel in District Heating Systems

Analysis for Svendborg and Odense District heating systems

Rabbani, Raja Abid; Gabert, Melissa Carina; Gamborg, Filip; Pedersen, Morten R. ; Cimpan, Ciprian; Wenzel, Henrik

Publication date:
2016

Document version:
Final published version

Citation for pulished version (APA):
Rabbani, R. A., Gabert, M. C., Gamborg, F., Pedersen, M. R., Cimpan, C., & Wenzel, H. (2016). *Integration of Refuse Derived Fuel in District Heating Systems: Analysis for Svendborg and Odense District heating systems*. Centre for Life Cycle Engineering, SDU.

Go to publication entry in University of Southern Denmark's Research Portal

Terms of use
This work is brought to you by the University of Southern Denmark.
Unless otherwise specified it has been shared according to the terms for self-archiving.
If no other license is stated, these terms apply:

- You may download this work for personal use only.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying this open access version

If you believe that this document breaches copyright please contact us providing details and we will investigate your claim.
Please direct all enquiries to puresupport@bib.sdu.dk

Download date: 11. Jan. 2025

SDU LIFE CYCLE ENGINEERING

Abid Rabbani, Melissa C. Gabert, Filip Gamborg, Morten R. Pedersen, Cipri-an Cimpan & Henrik Wenzel

Integration of Refuse Derived Fuel in District Heating Systems

Analysis for Svendborg and Odense District heating systems

SYFRE WP4, November 2016

Synergi i fynske ressourcestrategier

Colophon

Title:
Integration of Refuse Derived Fuel in District Heating Systems - Analysis for Svendborg and Odense District heating systems

Authors:
Abid Rabbani,
Melissa C. Gabert,
Filip Gamborg,
Morten R. Pedersen,
Ciprian Cimpan
Henrik Wenzel

Publisher:
Centre for Life Cycle Engineering,
Department of Chemical Engineering, Biotechnology and Environmental Technology, Faculty of Engineering
University of Southern Denmark
Campusvej 55 DK-5230 Odense M
www.sdu.dk/lifecycle

Date:
2016-11-25

ISBN no.: 978-87-93413-07-8
EAN: 9788793413078

Please cite as:
Rabbani A., Gabert M.C., Gamborg F., Pedersen M. R., Cimpan C. & Wenzel H., 2015. Integration of Refuse Derived Fuel in District Heating Systems - Analysis for Svendborg and Odense District heating systems. SYFRE WP4 report. Centre for Life Cycle Engineering, University of Southern Denmark, Odense.

Contents

Executive Summary

This report presents an assessment of waste and district heating systems integration and analyses key parameters to highlight the competitiveness of Refused Derived Fuel (RDF) to other alternatives such as biomass boilers and heat pumps in district heating supply in future energy systems.

The results of this study demonstrate that RDF is economically attractive in energy systems already in the short-term, plus also in the long-term. It can compete with woodchip boilers and is a cost-efficient solution in district heating systems potentially in combination with heat pumps and heat storage. Overall, the analysed future system designs showed to reduce the heat prices of today significantly, if economics remain as expected.

Two different cases for RDF integration in the district heating system were analysed in this report, namely the cases of Svendborg and Odense district heating systems respectively. Though the cases are very different in terms of their scale of district heating supply, installed capacities, future framework conditions and methodologies to some extent, the deduced results for RDF prospects in Danish district heating system can be generalized. Both analyses show promising results for RDF boilers in the business case as well as socio-economically feasible within the simulated price ranges.

1.1 Prospects of RDF in the Svendborg Case

For the Svendborg case, the overall objectives were defined by the framework conditions pertaining to the fact that the present incineration plant is assumed due to reach its end of life by 2035. In addition, there are plans to expand the district heating network by 25% till 2020 and by 100% till the year 2035. Therefore, many different configurations of biomass, heat pumps and RDF boilers were formulated to identify the most appropriate solution.

For the time perspective of 2020 and under business economic considerations, the system with the existing incineration plant supplemented by 75% of rest capacity covered by a seawater heat pump and the remaining 25% covered by an additional RDF boiler proved to be most cost-efficient option in a business-economic perspective. The calculated heat price of this system is 290 DKK/MWh, which is around 36% lower than the heat price of the current system. The same scenario appeared to be the most suitable alternative in the socio-economic perspective, but with a socio-economic heat cost of 245 DKK/MWh.

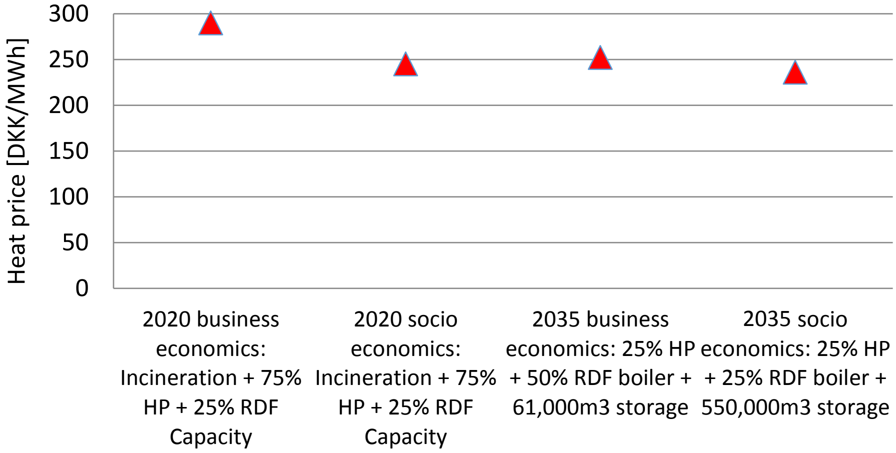

Figure 0.1: Business and socio-economic heat prices for 2020 and 2035 scenarios

When comparing the scenarios of 2035 with and without thermal storage, it can be seen that under all conditions studied, options including storage appear to result in lower heat prices. The reason for this lies in all cost categories as the storage decreases investment, operational cost as well as taxes and damage costs. Under business economics the combination of 25% capacity of heat pumps and 50% of RDF boilers plus a small storage of 61,000m^3 is to be preferred. In contrast under socio economics, or when heat pump electricity taxes are eliminated, it is the alternative consisting of 25% covered by heat pumps, 25% by RDF boilers and a large storage of 550,000m^3, that shows to result in the lowest heat cost. This is due to fact that if no heat pump taxes are applied, the heat pump can operate more often, therefore using the storage as seasonal storage. Hence, the storage is filled up during the summer months and emptied during winter months, together with direct production from boilers and heat pumps in winter.

In order to answer the question, whether RDF boilers can compete with biomass boilers, break-even prices for RDF in comparison to biomass boilers were determined. Higher prices than the current gate fee were found for almost all scenarios. In fact, RDF is competitive for all modelled scenarios with RDF gate fees ranging from 205 DKK/ton to 125 DKK/ton in 2020 from a business economics perspective. While socio-economically, the gate fees range is found to be within 268 DKK/ton to 195 DKK/ton. The breakeven prices in 2035 are found to be higher than to that of 2020 (see Figure 0.2). All prices are understood as break-even prices under which an RDF boiler is more cost-efficient than a wood chip boiler.

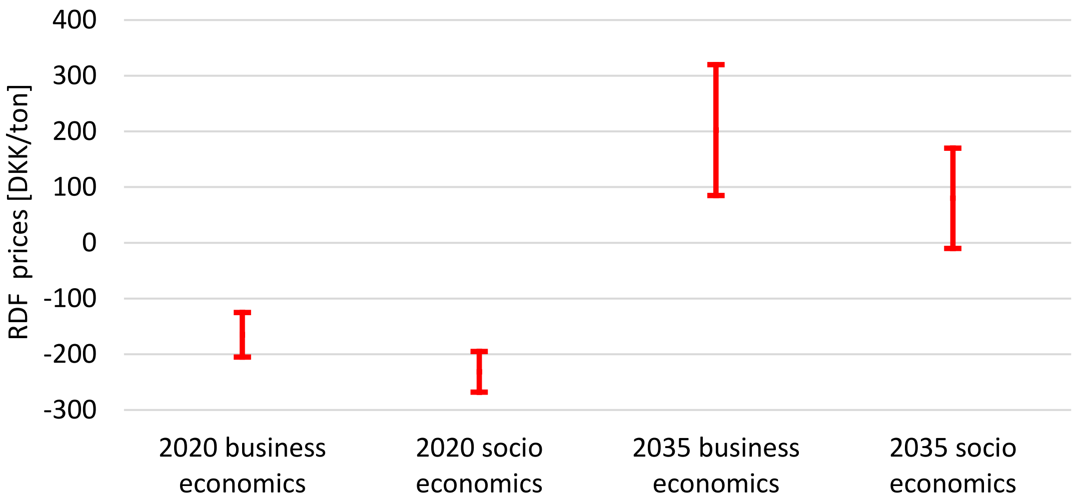

Figure 0.2: RDF breakeven price ranges for 2020 and 2035 scenarios in comparison to a wood chip boiler

1.2 Prospects of RDF in the Odense Case

In case of RDF integration in Odense district heating system, which is considerably a very large district heating system, a different approach was developed to look into RDF prospects. The modelling was done under the assumption that the coal fired CHP is anticipated to be converted into a wood pellet plant in 2025, while the Dalum wood chips CHP would be completely scrapped by then. In addition, the waste incineration plant was assumed to continue to run till the end of the simulated period. Keeping in view the size of coal-fired plant (575 MW_{th}) and potential sizes of RDF boilers, wood chip boilers and heat pumps, 75MW of both RDF and wood chip plant capacity and heat pump capacity was modelled in these scenarios.

Since the size of comparable alternatives is less than 10% of the total installed capacity of Fjernvarme Fyn, FVF, their influence in setting the heat price would be small. Therefore, the modelling was done as a partial analysis of the difference caused by installing the 75 MW boiler or heat pump respectively, and then calculating a yearly Present Net Worth of this investment to compare these alternatives and calculate the payback periods. Two variations of all scenarios have been run where the first is with electricity tax, biomass subsidy and waste tax as they are today. In the second variation the electricity tax has been reduced by 50% and biomass subsidy and waste tax have been completely removed. Moreover, additional simulations have been conducted for lower RDF gate fees/higher RDF prices to assess the economic performance of RDF boilers at such higher prices.

In accordance with a recent study conducted for Energistyrelsen, a modelling was done assuming a 50% increase in the current biomass price estimates, in order to reflect a global biomass market with highly increased demand for wood chips and pellets (see Figures 0.3 and 0.4).

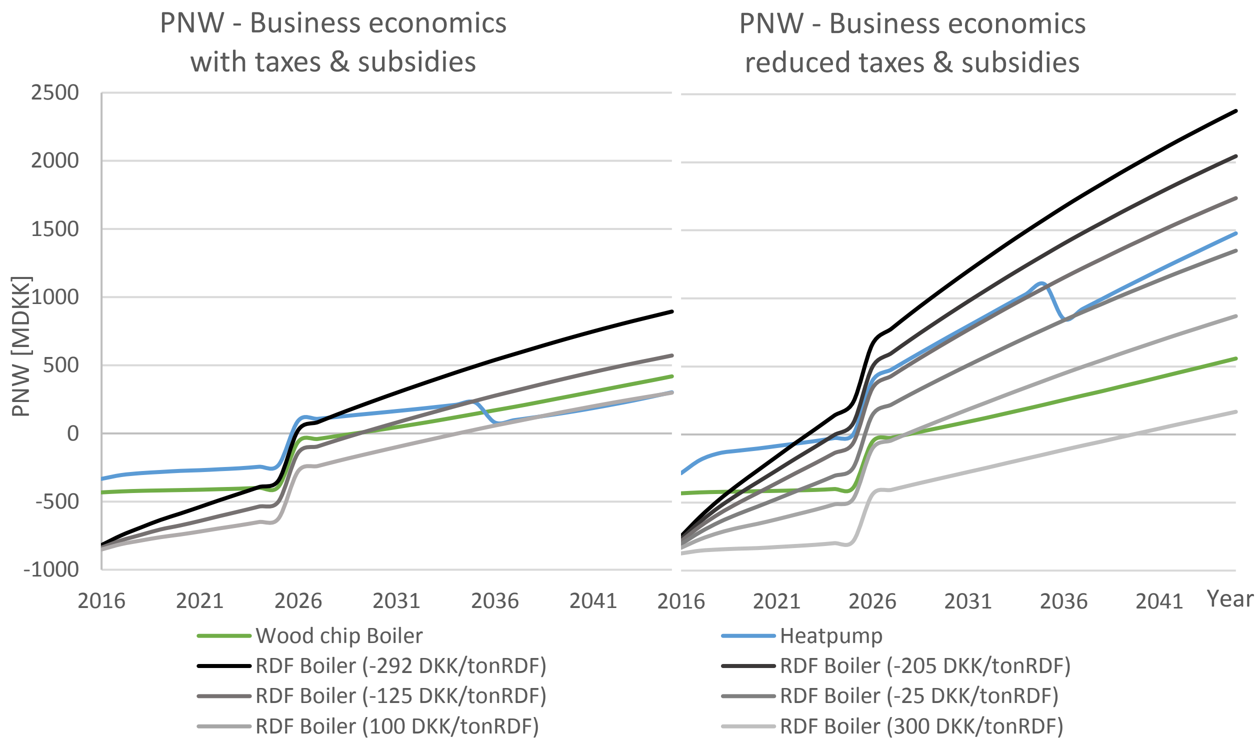

Figure 0.3: Comparison of business economic PNW for high biomass price scenario; a) with all taxes and subsidies, b) with ½ electricity tax, no waste taxes and no subsidies on biomass

In general, RDF boiler option has shown most promise even though with the highest investment cost (12 MDKK/ MW of heat produced) when compared to wood chip boiler (6 MDKK/ MW) and heat pump (5.2 MDKK/ MW). The RDF boiler economy is predominantly influenced by the RDF gate fees and investment savings in replacing coal-fired CHP to a smaller size wood pellet CHP. The highest gate fee simulated in our models is 292 DKK/ton, and if district heating companies are able to secure RDF import deals at higher gate fees, the RDF boiler option becomes even more attractive.

From today's business perspective, the return on investment is not substantial till 2025; therefore it would be beneficial if investment in RDF boiler is postponed until closer to investment in replacing coal-fired CHP to a wood pellet one. On the other hand, reduced electricity and waste taxes advocate an earlier investment in RDF boiler as the annual return on investment is quite high for this particular scenario.

It is important to mention that the sudden increase observed in the PNW in year 2026 in all the scenarios is due to the fact that the initial investment in 75 MW of RDF boiler, wood chip boiler and heat pump capacity in 2016 leads to a proportional saving of 75 MW capacity of wood chip CHP in the assumed conversion of the coal CHP to wood chip CHP in year 2026.

A typical conversion of coal plants to wood pellets fuel requires modified coal mills, additional storage silos and transport systems for the pellets. The lower calorific value of wood compared with coal increases the necessary fuel amounts to approximately double volume. In addition, the burners need modification or replacement all together and steam soot blowers to prevent ash formation and slag deposits in the boiler (Danish Energy Agency, 2016). By gauging these conversion needs, it is fair to assume that coal plant conversion to a reduced wood pellet plant size is achievable with linear cost savings. Nevertheless, further sensitivity analysis of the increase in PNW in Figure 0.4 reveals that the payback period for RDF boiler would increase by 5 years only if there were no such investment savings in year 2026 at all. And if this investment saving would be only 50%, this would result in delay of payback by 3 years.

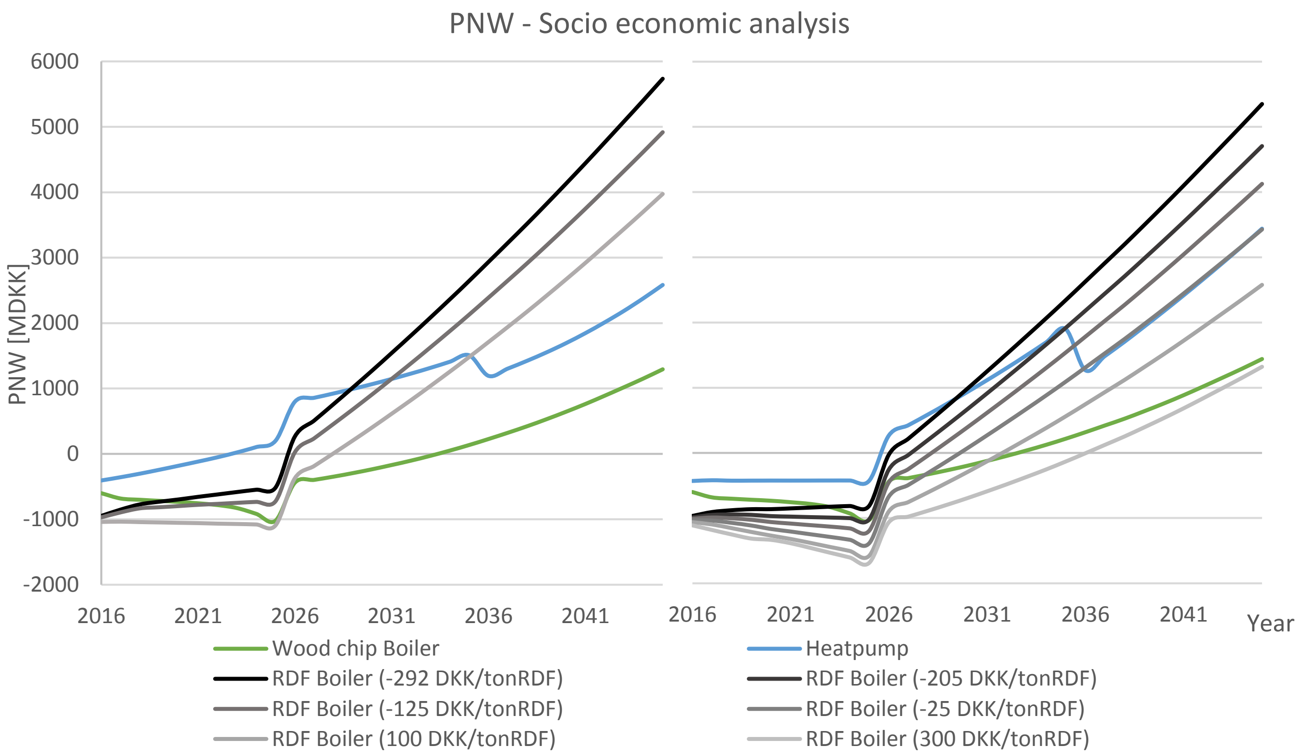

Figure 0.4: Comparison of socio economic PNW for high biomass price scenario; Left) with all taxes and subsidies, Right) with ½ electricity tax, no waste taxes and no subsidies on biomass. Note: Taxes and subsidies are only included in calculation of net heat production costs of energy production units in EnergyPRO simulation tool and not for socio economic payback calculations

From a socio-economic perspective, RDF boiler is competitive even at positive RDF prices. However, any investment in RDF and wood chip boiler would not return a considerable payback till 2026. The main reason being higher net production costs while competing with other biomass and coal fired CHPs till 2026. However, once the coal-fired CHP is replaced, RDF and wood chip boilers start to make profit, with RDF being the most attractive option due to its lower payback period. Heat pump alternative also shows similar developments, however would need reinvestment after 20 years, hence a reduction in PNW during that period. Therefore, it is implied that appropriate time for investment in a RDF boiler is after 2025, when the coal-fired CHP is either decommissioned or replaced with a wood pellet boiler.

Figure 0.5 exemplifies break-even periods for RDF boiler at different RDF prices for low and high biomass price scenarios in order to highlight the effect of increased biomass prices on the payback periods. It can be further deduced that the payback period will be shorter if investment in RDF boiler is delayed till 2025 for the reasons described above.

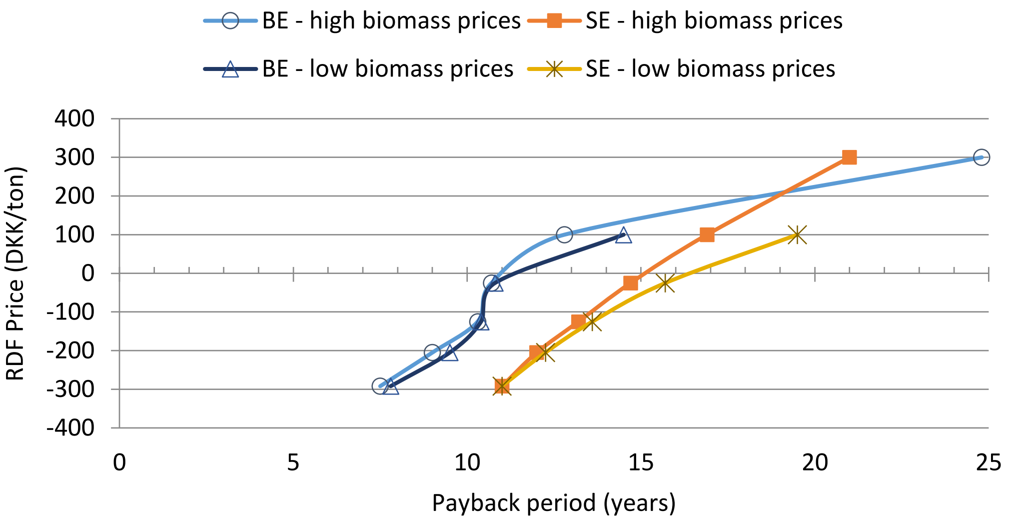

Figure 0.5: RDF boiler payback periods: Business Economic (BE) and Socio Economic (SE) paybacks for high and low biomass price scenarios with ½ electricity tax, no waste tax and no biomass subsidies (Taxes and subsidies are only included in calculation of net heat production cost in EnergyPRO)

1 Goal and Scope

Today, the recycling rate for household waste in Denmark is around 22% (The Danish Government, 2013). Rest of the waste is incinerated. Already in 1903, Denmark invested in a *combined heat and power plant* (CHP), which also functioned as its first district heating plant in Frederiksberg, Copenhagen area, and thereby made waste incineration more efficient by producing electricity and heat at the same time. The district heating grids that exist today are still in process to expand into suburbs. In these systems, CHP plants deliver hot water by means of waste heat to individual houses for space heating and hot water supply. Cooled water is then rotated back to the supplier to cool its plant. This circled use is already highly energy efficient, because it increases waste incineration plant efficiencies from around 25% electricity only production up to 100% heat and electricity production with flue gas condensation (Christensen, 2011).

However, the European Union‘s Waste Framework Directive 2008/98/EC Article 11 on Re-use and Recycling defines the goal of minimum 50% recycling of household waste (at least paper, metal, plastic and glass) by weight by 2020 (European Comission, 2008). Denmark as a member state, responded with a national resource strategy, which aims at 50% recycling of household waste rather than incineration by 2022 and 65% by 2035 (The Danish Government, 2013). These new directions imply difficulties for the existing district heating system, as in many regions in Denmark; heat is supplied from waste incineration plants.

Furthermore, Denmark is currently undergoing a fundamental change of its energy system by switching to 100% renewable energy sources in 2050, including fossil-free electricity and heat production (The Danish Government, 2011). This will create largely fluctuating energy prices in the future due to the fact that the biggest renewable energy source is wind energy in Denmark. Electricity from wind cannot be constantly produced but has cheap high peak hours and low production hours, which need to be intercepted by other backup sources. These sources need to be flexible, which means storable and for multi-purposes. Today one main backup source particularly for heating purposes is CHP plants. When fossil fuels are not allowed to be burned anymore and waste needs to be recycled instead of incinerated, on which backup sources can the system rely on in order to meet electricity and heat demands? These framework conditions lead to the need of adaptation and interaction of processes in both waste management and energy systems. As a consequence, the integration of the systems in relation to future framework conditions is to be analysed.

The purpose of this study is to investigate the feasibility of storable waste in a district heating system. Furthermore, it analyses key parameters to highlight the competitiveness of Refused Derived Fuel (RDF) to other alternatives such as biomass boilers and heat pumps in future energy systems. Henceforth, it is the aim to identify the optimum mix of heat sources for district heating system through techno-economic assessment of waste and energy system integration.

Two different cases for RDF integration in the district heating system are analysed in this report. Though both cases are very different in terms of their district heating sizes, installed capacities, future framework conditions and methodologies to some extent, the deduced results for RDF prospects in Danish district heating system can be generalized. For the first case, a small DH area is selected. This case is built on the Svendborg’ s waste incineration plant and district heating system and takes into account the future expansion plans of the grid. Svendborg is a medium sized city in Denmark, on the island of Funen. Additionally, governmental goals frame the scope of 50% recycling by 2020 and 65% by 2035. Given these timelines, some investigated scenarios are within the lifetime of the existing waste incineration plant, and the others beyond.

For the second case, Odense district heating system has been selected, which is considerably a very large district heating system, when compared to Svendborg. Presently, a substantial share of heat is supplied by the coal fired CHP, which would reach its end of life by 2025. The plans are to replace it by a wood pellet plant. Another unit; Dalum wood chips CHP would also run its lifetime by then and would be scrapped. In addition, the incineration plant would continue to run till the end of the simulated period. Keeping in view the size of coal-fired plant (575 MW_{th}) and potential sizes of RDF boilers and heat pumps, 75MW of plant capacity for different alternatives are modelled in these scenarios. Since the size of comparable alternatives is less than 10% of the total installed capacity of FVF, their influence in setting the heat price would be minimal.

Technical options, replacing the heat sources of today, are selected and modelled with use of the software energyPRO. This includes the integration of different sized heat pumps, biomass boilers and the comparative replacement with RDF boilers. Calculations are made in regard to the future energy market and its fluctuating prices of renewable energy sources. This will allow, together with a business economic and socio economic analysis, to assess the effects of different systems on the heat price and to find the most feasible solution under business costs and for society while meeting the recycling goals and heat demands. Furthermore, performing both economic analyses will enable to draw conclusions on the current tax system and show whether it inhibits the use of heat pumps in the future, or how it would need to be changed to make heat pumps economically more attractive. By including the comparison of biomass and RDF boilers in each scenario, it is possible to identify under which conditions RDF is competitive to biomass alternatives.

Economic gains of future waste import in Denmark are further exemplified by Ea Energianalyse (2016). In 2015, already 324,000tons of waste were imported to Denmark. Furthermore, they claim that the benefits of waste import will be even greater in the future. Economic benefits occur from other countries paying Denmark´s waste incineration plants to burn their waste and from import taxes. This makes imported waste an economically preferable fuel compared to biomass purchased by the waste incineration plants and reduces waste landfilling in the exporting countries. When the incineration plants are non-profit organizations, income from imported waste is also beneficial for the end-customers, since it lowers their heat price and garbage fees (Ea Energianalyse, 2016). Furthermore, the study states that Denmark will meet the goal of higher recycling rates on local waste by 2022 and even more in the following years. Imported waste is pre-treated in the exporting country before sent to Denmark (Ea Energianalyse, 2016). Therefore, the LHV of the waste is enhanced and it is allowed to be stored by law, making it flexible in use.

2 Methodology

This section describes the methodologies adopted in analyses of the two aforementioned cases. The energy system analysis header gives an introduction to the modelling software energyPRO and its modelling principles. Secondly, methods for business and socio economic analyses, performed in these studies are described.

2.1 Energy System Analysis

For the modelling and analysis of the energy system, the software energyPRO was chosen. This is an industry-standard simulation model for energy systems. Thus, it can be used for energy system analyses at a user-defined level by combining temporary and unit variables. EnergyPRO has been used in many energy system analyses within Europe. To name only some of these: Fragaki et al. (2008) made a sizing analysis on gas engines and storage for CHPs in the UK, Kiss (2015) modelled a city in Hungary to perform an analysis of the electricity and transport sector and Streckienė et al. (2009) investigated the feasibility of thermal stores in combination with CHPs in Germany.

According to Østergaard and Andersen (2016), energyPRO uses an optimization based on an analytical method. It creates a matrix consisting of the production units' times the number of time steps in the planning period. Then there is a priority number calculated for each cell in the matrix, which implies the order of the production. The priorities are applied in a non-chronological way, meaning that the lowest priority number is taken first when also considering restrictions in the energy store and transmission lines (Østergaard and Andersen, 2016). This means that energyPRO assigns the individual net production costs for each hour of the year to all production units and ranks them. Consequently, the priority of the production unit is derived from its net production costs. The lowest net production costs result in the lowest priority number or the highest priority.

Furthermore, energyPRO includes future hourly electricity prices in its calculations and is therefore an appropriate analysing tool for modelling future scenarios where heat pumps consuming electricity are included. Detailed information on the optimization procedures of energyPRO can be found in (Lund and Andersen, 2005).

2.2 Economic Analysis

Implementing economics in the modelling is a crucial instrument for energy system analyses since it allows energyPRO to minimize net production costs in the operation strategy. The aim of modelling the different scenarios is to compare them with each other in order to find the most economical feasible system for the given timelines. Hence, the economic analysis is essential for the system comparison. Two different approaches are adopted for both cases:

For the Svendborg study, the aim is to identify the most feasible option for future investments in the district heating system, which would constitute investments in capacities corresponding to the total size of the DH supply. Since Svendborg Fjernvarme is a non-profit organization, the calculation scheme is more reasonable to be based on the heat price that is given to the customers rather than on maximized profits. As a consequence, it has been decided to make an economic assessment by comparing heat prices from each system for the calculated optimization period of 2020 and 2035. Given the fact that heat pumps are included in the future scenarios, where significant taxes apply to, it has been further decided to calculate both business economic heat prices and socio economic heat prices.

For the Odense Case, Present Net Worth (PNW) method was employed for business and socio economic assessment of the modelled systems. Since the size of comparable alternatives is less than 10% of the total installed capacity of FVF, their influence in setting the heat price would be minimal. Therefore, a yearly PNW analysis was performed to compare these alternatives and calculate the payback periods for their respective investments. The PNW for the reference and alternative scenarios is calculated from the investment costs, O&M costs and corresponding cash flows in present values for each year. The break-even of the project is found when the PNW becomes positive. The average heat price for the given year for both the reference and the alternative model is calculated as the net cost divided by the annual heat demand.

2.2.1 Business Economic Analysis

For the business economic analysis, taxes were applied on all production units in the respective modelling. The cost inputs to the systems were:

- Electricity revenues from electricity export
- Investment costs (of the production units and the expansion of the grid)
- Operational expenditures (fuel costs, electricity import, fixed and variable operational costs, grid tariffs and system tariffs for electricity consumers)
- Taxes

Operational expenditures and total damage costs were found in the energyPRO calculations of the "Cash Flow Summary". The cost analysis was done the same way as for socio economics.

2.2.2 Socio Economic Analysis

Based on Danish Energy Agency (2016a), a reference project is needed for the socio economic analysis, which in these studies represents the baseline scenario of today. A common approach for a socio economic analysis is a *cost-benefit analysis* (CBA) (Barfod, 2015, Danish Energy Agency, 2016a). This applies however, to find the benefits of saved opportunity costs from an alternative with higher damage costs than the case. This means direct comparison with the reference scenario would be necessary. Following the cost related part of the CBA in Danish Energy Agency (2016a), the input data of this study consists of:

- Electricity revenues
- Investment costs
- Operational expenditures
- Damage costs

Electricity revenues, investment costs and operational expenditures are the same for business economic and socio economic modelling. All variable costs are included in the operation strategy of energyPRO, in order to operate the units with the lowest net production costs first. These are fuel costs, electricity imports, variable operational costs, grid and system tariffs and damage costs for the socio economic analysis. Damage costs are applied by using the emission coefficients and costs for each emission type.

In order to analyse the competiveness of biomass and RDF, the socio economic analysis was further used to find the maximum prices of RDF that can compete with biomass. Here, the term "breakeven" refers to a certain price of RDF, under which the heat prices of the compared RDF and biomass scenario equalize (see a schematic explanation in Figure 2.1). The breakeven price of RDF was found by stepwise increasing the standard gate fee until the heat price of the RDF scenario matched the heat price of the same-sized biomass boiler scenario.

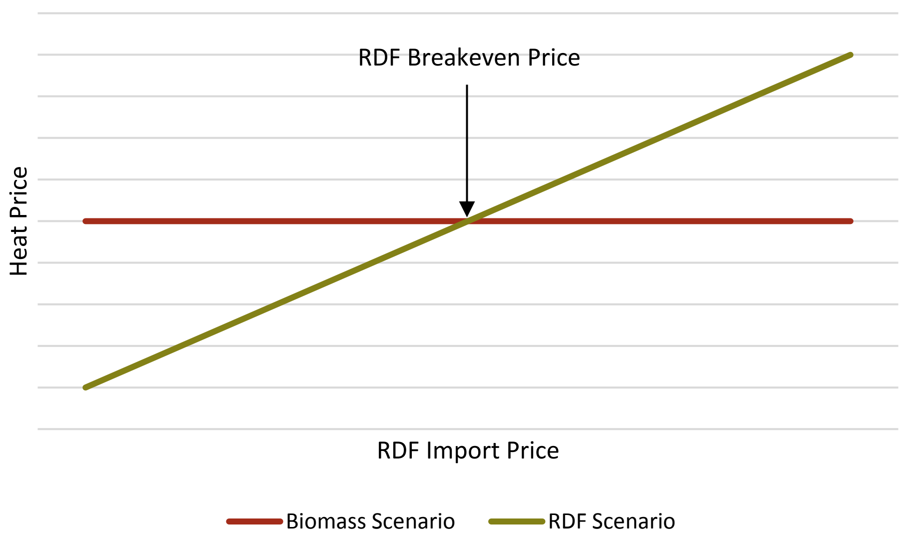

Figure 2.1: Scheme of RDF Breakeven Price

The same technique was also applied to find RDF breakeven prices under business economic conditions.

3 Key Assumptions and Background data

3.1 Electricity Prices

Historical electricity prices for 2014 and 2015 were given by Energinet.dk. In contrast to that, estimated electricity prices had to be taken for the future scenarios. In case of 2035, Energinet.dk has made simulations, including future assumptions regarding production of electricity, gas and heat, prices of fuels, CO_2 and electricity as well as external relations (Hansen, 2014). Derived from 2035 prices, prices for each year were found by interpolating 2015 and 2035 prices while considering the estimated different increase of wind and solar capacity installed from 2015 to 2020 and from 2020 to 2015, by Energinet.dk (2015).

The slopes for these periods can be seen in (Figure 3.1), where slope 2015-2020 equals to m_1 and slope 2020-2035 equals to m_2, P stands for price.

Henceforth, the electricity prices in 2020 were calculated with Equation 3.1:

Equation 3.1: Electricity Prices 2020

$$P(2020) = P(2015) + (2020 - 2015) * \frac{m_1}{m_1 + m_2} * \frac{P(2035) - P(2015)}{(2020 - 2015) * \left(\frac{m_1}{m_1 + m_2}\right) + (2035 - 2020) * \left(\frac{m_2}{m_1 + m_2}\right)}$$

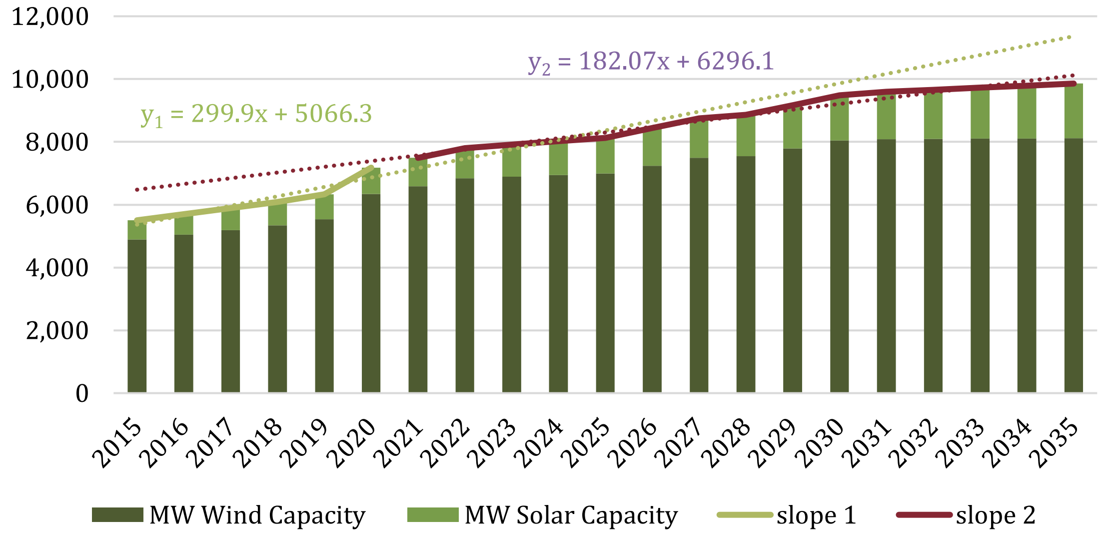

Figure 3.1: Estimated Development of Wind and Solar Capacity Installed in Denmark

3.2 CO2 Quota prices

CO_2 quota prices follow the projections of the EA analysis (Ea energianalyse, 2016), which are based on the IEA long term projections. The price development can be seen in Figure 3.2.

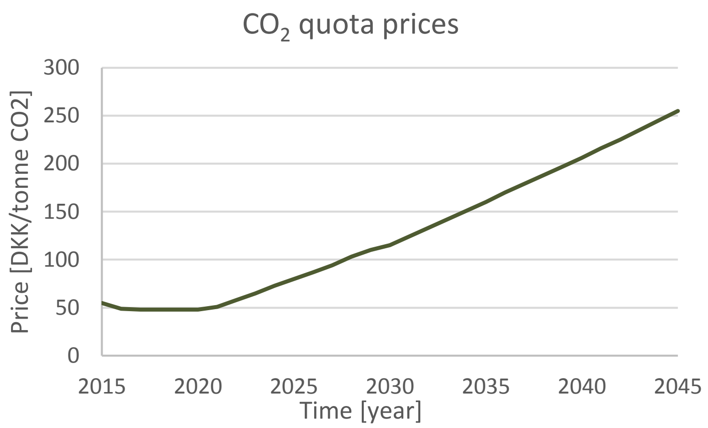

Figure 3.2: CO_2 quota price projections

3.3 Fuel Prices

The prices for fuels were taken from Energinet.dk (Energinet.dk, 2015). Waste prices are negative, since the waste incineration plant receives money for burning the waste. The values were collected from DH companies. The price for household waste represents the average price excluding taxes, which DH companies receive from all relevant municipalities. The price for imported waste is based on the maximum gate fee for waste treatment in Denmark specified by Watkins et al. (2012).
In case of heat pumps, the “fuel price” correlates to the hourly electricity price of the spot market for imported electricity.

3.4 Investment and Operational Costs

The costs for investing in the modelled production units were mainly gathered from Danish Energy Agency and Energinet.dk (2015). Costs for the seawater heat pump were taken for large heat pumps with a water heat source (Danish Energy Agency and Energinet.dk, 2015).

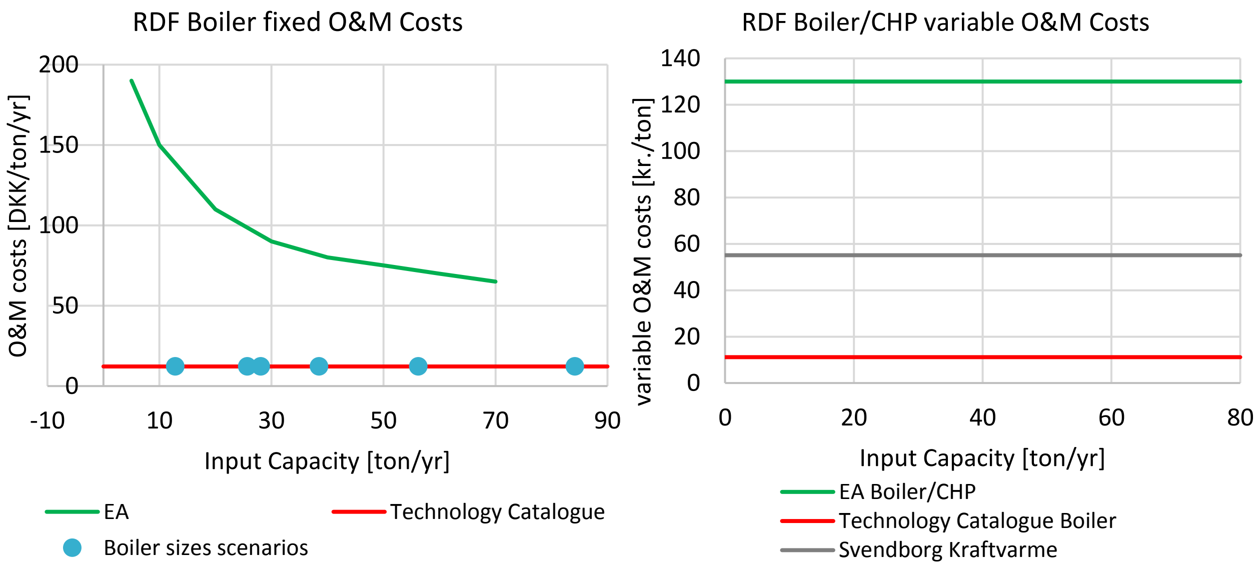

Figure 3.3: Comparison of RDF boiler O&M costs from different data sources

For the Svendborg case, costs of the incineration plant and the flue gas heat pump were given by Hansen (2016a), Hansen (2016b). RDF boiler investment and O&M costs were taken from technology catalogue (Danish Energy Agency, 2014). On the other hand, RDF boiler investment and O&M costs for the Odense case were taken from (Ea Energianalyse, 2016). The cost difference in the data sources is further exemplified in the Figures 3.3 and 3.4.

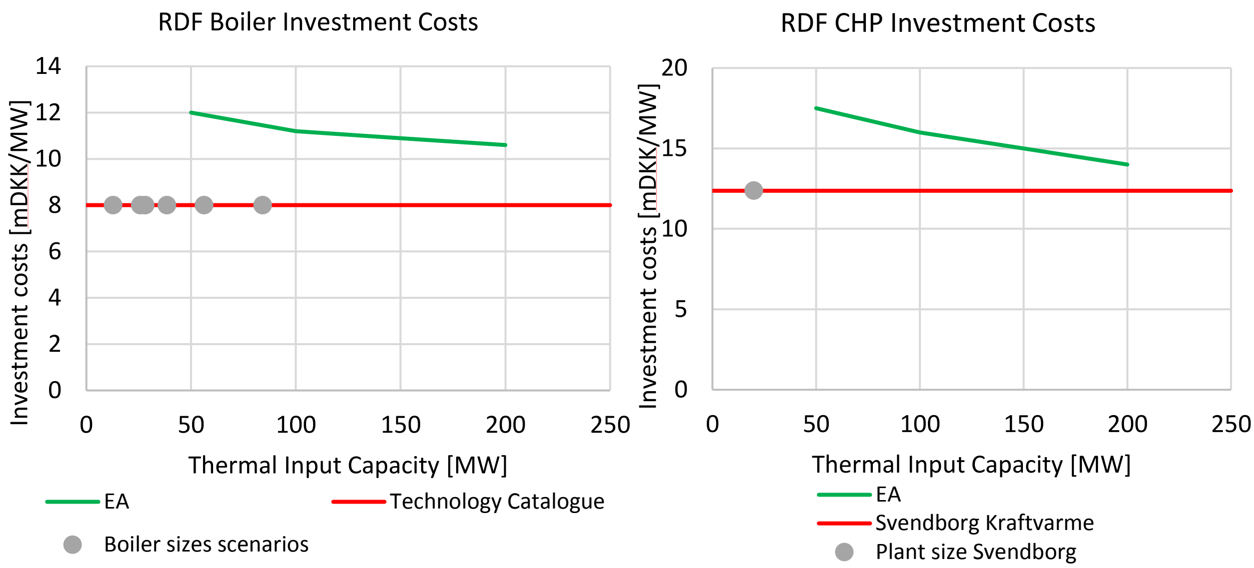

Figure 3.4: Comparison of RDF boiler investment costs from different data sources

3.5 Emission Coefficients

In order to perform a socio economic analysis as part of the economic assessment, emission coefficients were taken from Danish Energy Agency (2014a), Danish Energy Agency (2016a) and included in the energyPRO models. The increase of these data sets was used to interpolate the coefficients from 2015 to 2045 for the respective cases. CO_2 emissions are fuel dependent, while the other emissions are plant dependent. As an exception, CO_2 emissions do not apply to electricity consumption as they are already considered in the spot market electricity prices (Danish Energy Agency, 2016a). Start-up use of natural gas to pre-heat the waste incineration oven was not considered in the modelling. Furthermore, the same waste emission coefficients were used for the incineration plant and the RDF boiler in the future scenarios because of no better data available on RDF boilers.

3.6 Damage Costs

Socio economic damage costs are costs to the society due to emissions causing climate and health problems. The costs of carbon emissions, sulphur dioxide and nitrogen oxides were taken from Energinet.dk (2015). They include an increase of carbon emissions over the next years. CH_4 was calculated with a GWP of 25 CO_2 equivalents and N_2O with a GWP of 298 CO_2 equivalents (IPCC, 2007). Damages from particulate matter were supplied by Danish Energy Agency (2016a) and are based on large combustion plants.

Table 3.1: Damage Costs (Energinet.dk, 2015, Danish Energy Agency, 2016a)

Emission	CO_2	CH_4	N_2O	SO_2	NOx	$PM_{2,5}$
Unit	per ton	per kg	per kg	per kg	per kg	per kg
DKK 2015	51.00	1.28	15.20	11.50	26.40	22.00
DKK 2020	126.00	3.15	37.55	11.50	26.40	22.00
DKK 2035	253.00	6.33	75.39	11.50	26.40	22.00

3.7 Taxes and Tariffs

Taxes were applied for the modelling under business economic conditions. These include taxes on fuel emissions, special taxes on waste and taxes on electricity (“Elvarmeafgift”), PSO tariff and grid and system tariffs. The latter two tariffs apply to both business and socio economic models.

3.7.1 Fuel Taxes

An energy tax applies to the natural gas engine, -boiler and oil boiler, which is calculated per fuel consumption (PwC, 2015b). The same applies to carbon emission taxes for these production units, except that no CO_2 tax is applied on bio-oil and CH_4 taxes are only to consider in terms of the natural gas engine (PwC, 2015b). However, production units that supply combined heat and power can get a refund on CO_2 and energy taxes (Frandsen, 2016). Therefore, the share of the fuel used for electricity production has to be determined. This can be done on the basis of either heat production (V-formula factor 1.2) or electricity production (E-formula factor 0.67) (SKAT, 2014). Consequently, according to the application of the reimbursement by SKAT (2014), the E-formula reimbursement was used for the reference scenarios.

In regards to waste incineration & RDF boilers, CO_2 taxes per amount of CO_2 release and SO_2 costs per fuel consumption are incurred. Moreover, a surcharge tax and waste to heat tax (Danish “tillægsafgift” and “affaldsvarmeafgift”) is to be used on the heat production and a landfilling tax on the amount of ash residues from the burning process. According to Hansen (2016c), around 20% of the waste input end as ash at Svendborg Kraftvarme, which are landfilled and therefore taxed. Additionally, an excess heat tax is to be paid on heat being rejected from all heat producing units. On biomass only NOx taxes apply today (PwC, 2015b). For all future scenarios price growth index has been used and adapted to the years till 2045.

3.7.2 Electricity Taxes and Tariffs

Electricity consuming units like the heat pump have different taxes

Table 3.2: Taxes Electricity (Ea Energianalyse 2015, Skatteministeriet 2016, DEA 2016b, Dahlquist, 2016b)

	Elpatron, COP < 1.8	PSO	El. to heat	Grid and system tariff
	DKK/MWh heat	DKK/MWh el.		
2015	212.00	225.00	380.00	71.00
2020	222.00	186.65	395.00	126.00
2035	252.00	139.86	440.00	291.00

The PSO tariff stands for Public Service Obligations and is very sensitive to changes in the actual spot prices and has to be analysed with care in the modelling.

In this study, given PSO tariffs from 2015 and prospected ones for 2016 by Dahlquist (2015a), Dahlquist (2016b) were used to calculate the basis PSOs of today. According to Danish Energy Agency (2016b), Lorenzen (2016), Sekretariatet for afgifts- og tilskudsanalysen på energiområdet (2016), it is more obvious that the expenses of the PSO tariff will decrease over the next years following predictions until 2025. Moreover, the tax ministry discusses whether a restructuring of the PSO tariff would be more advantageous to push the support of renewable energy. PSO expenses could potentially be paid with household taxes rather than a separate tariff (Sekretariatet for afgifts- og tilskudsanalysen på energiområdet, 2016). However, it has not finally been decided how to adjust this payment. Consequently, an average PSO tariff was used in the modelling. Grid and system tariffs are also paid by electricity consumers to Energinet.dk (Ea Energianalyse, 2015). Future values were again interpolated from 2015 and 2016 prices (Dahlquist, 2016a). However, these tariffs were grouped with operational expenditures in the economic analysis as they apply to both, business and socio economic approach.

4 Case of Svendborg

Svendborg is a medium-sized city, located in the south-east of Funen, Denmark. It is therefore a coastal area, split into two main parts by Svendborgsund, a sub-canal of the big belt dividing the islands Funen and Sealand. Svendborg has around 27,000 inhabitants today (Danmarks Statistik, 2016).

4.1 Svendborg District heating system

The district heating network in Svendborg was already established in 1952 and has been expanded since that time (Svenborg Fjernvarme, 2015). Svendborg Fjernvarme is the supplier of district heating in Svendborg. In 2014, Svendborg Fjernvarme had a total heat production of around 170,000 MWh, which is equivalent to 10,000 households. However, not all households are connected to the grid today, so there is still space for expansion (Madsen, 2014). The heat source distribution is presented in Figure 4.1. This comprises mainly the incineration plant, delivering 61.2% of today´s district heating demand, by burning local waste and a bit of woodchips (accounting for 1.2%). Additionally, the smallest portion of heat is purchased from a crematorium (accounting for 0.3%). In addition to the purchased heat, Svendborg Fjernvarme is burning bio oil and natural gas in its own boilers, accounting for 20.8% and 13.7% respectively, and is producing heat together with electricity from gas engines (2.7%) (Madsen, 2014).

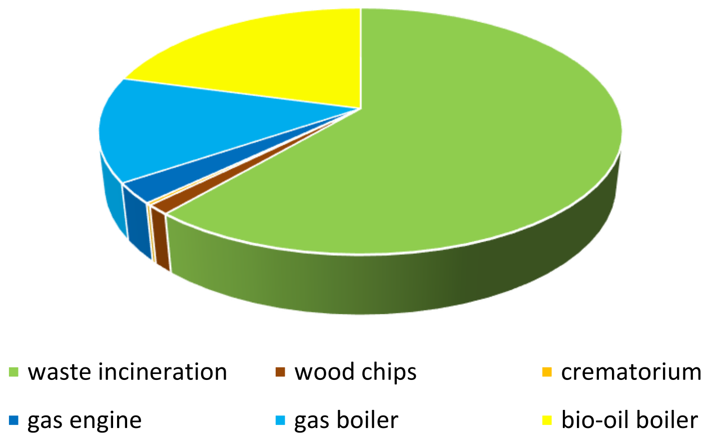

Figure 4.1: Heat Source Distribution of Svendborg Fjernvarme

The utilization of the mentioned heat sources in monthly heat production over the year 2014 is displayed in Figure 4.2. It can be seen that during the summer, almost all demand is supplied by the waste incineration plant (light green) while in the winter months, large shares of heat are delivered by the gas and oil boiler.

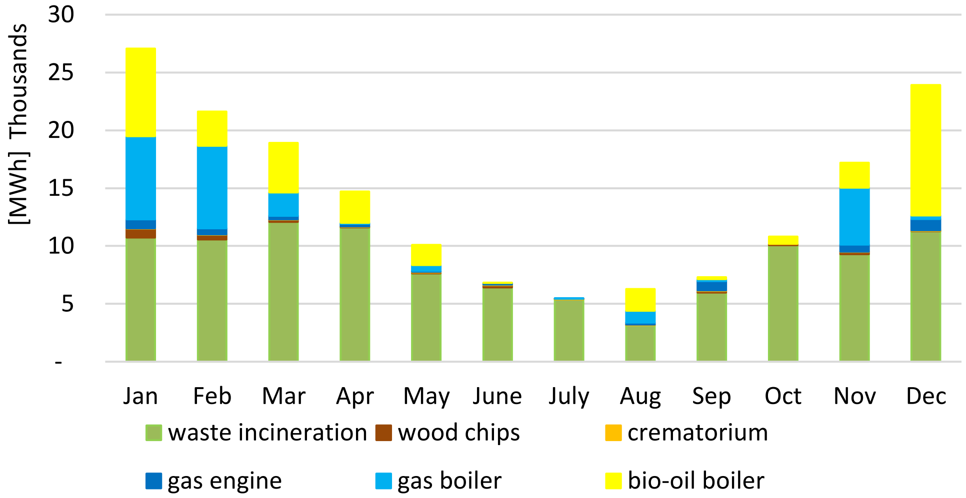

Figure 4.2: Heat Production Svendborg Fjernvarme 2014

Following the framework of future energy and waste system changes, the district heating system will have to change and adapt to the local circumstances. This means that the part of heat supply from local waste incineration will decrease significantly due to higher recycling rates and the use of natural gas will be completely phased out at some point as the energy policy switches to the use of renewable energy instead. Consequently, a high share of heat production has to be covered by other heat sources. At the same time, the district heating network is planned to grow in future to supply more households with heat, which tightens the issue even more.

4.1.1 Svendborg Kraftvarme

Svendborg Kraftvarme is a company, operating the waste incineration plant in Svendborg. It receives different types of waste from Svendborg municipality as well as other municipalities (Cimpan et al., 2015b) and is producing heat and electricity from that. It is handling 52,000 tons of waste and biomass per year (Svendborg Kraftvarme, 2015). Furthermore, Svendborg Kraftvarme is the key heat supplier of Svendborg Fjernvarme, as described before. The capacity of the plant can be varied between a minimum of 55% and 100%. Whereas 55% capacity of the plant is almost identical to the minimum demand of heat in the summer, when electricity production is at its maximum at the same time (Hansen, 2016c). This is needed to reduce taxes for cooling excess heat away during months of low heat demand and is possible due to adjustments in the controlling and grate system.

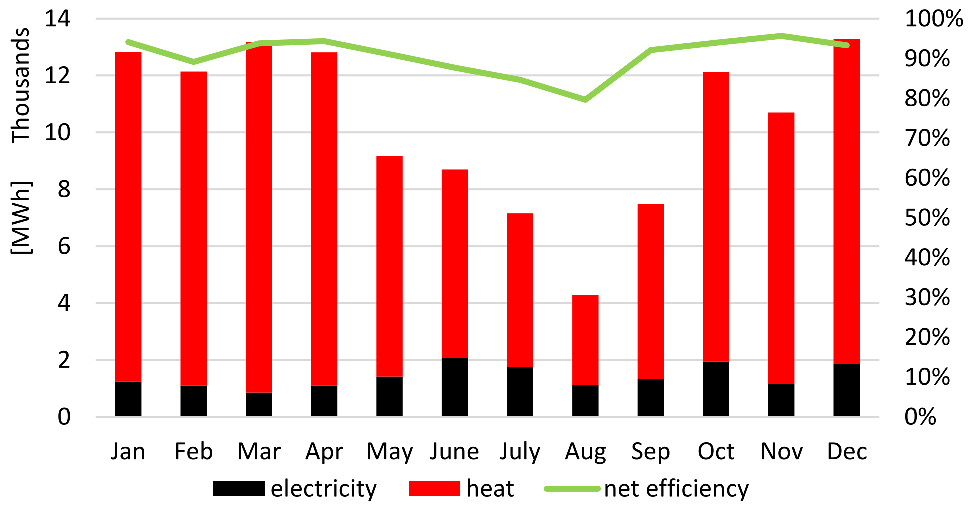

Figure 4.3: Electricity/Heat Production Svendborg Kraftvarme and Net Efficiency in 2014

Figure 4.3 exhibits the monthly heat and electricity production of the plant, together with its net efficiency for the year 2014, which are derived from fuel input and net output. The plant has a maintenance stop for one week in May and two to three weeks in August, which shifts the production in these months slightly to the next months. During this time, received waste can be stored for about one week in a silo and up to four weeks in a slag storage location (Hansen, 2016c).

Furthermore, a flue gas heat pump is currently being installed under the DEA initiative for large scale heat pump implementation, which will provide an additional capacity of 3.6 MW_{heat} output (Wittrup, 2015). Consequently, waste plays a significant role in the heating system of Svendborg in the short-term. Whether it can also take an important place in the long-term perspective needs to be answered in the study.

4.1.2 Heat Demand

In order to determine the future heat demand, Svendborg Fjernvarme's expansion plans were taken into consideration. The heat demand of the expansion areas was calculated by Svendborg Fjernvarme considering the building size and the heat demand per square meter for different years of construction (Madsen and Joensen, 2016). Figure 4.4 shows the current district heating area and the adjusted expansion area. In total, the expansion area has a heat demand of 133,209 MWh per year (Madsen and Joensen, 2016). The households of the expansion area are connected to the natural gas grid and therefore use mainly natural gas today.

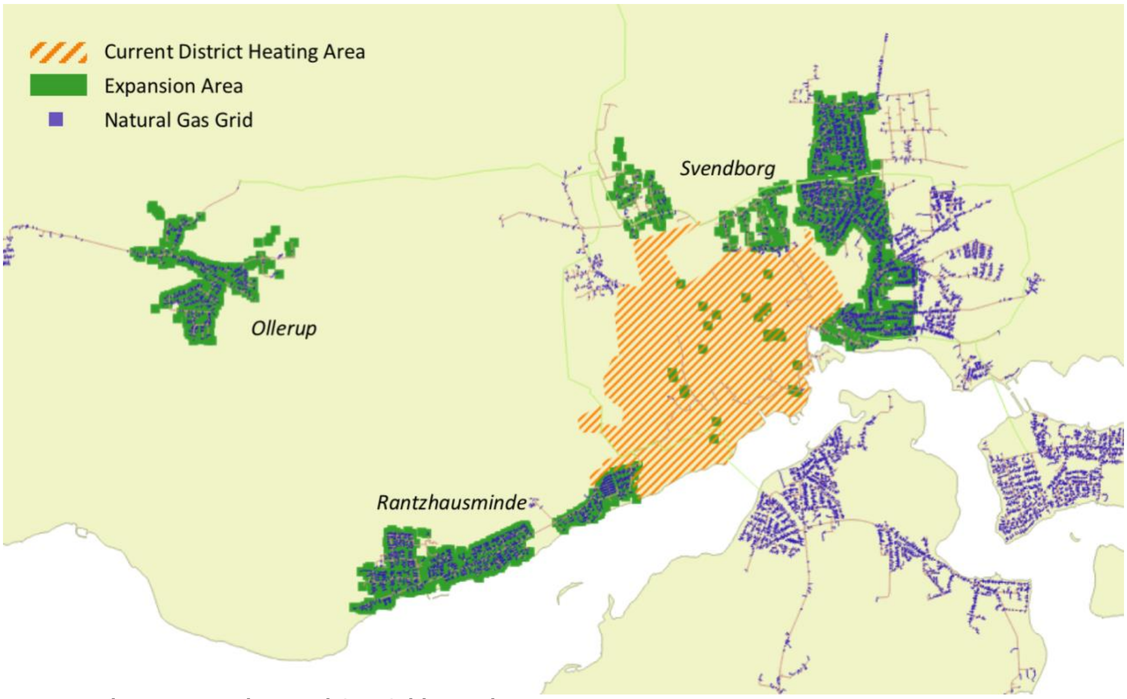

Figure 4.4: Expansion Areas and Natural Gas Grid Location

The fuels that are used today in the buildings of the expansion area can be seen in Figure 4.5. Similar data collection was done in 2010 by Statens Byggeforskningsinstitut Aalborg Universitet (2010).

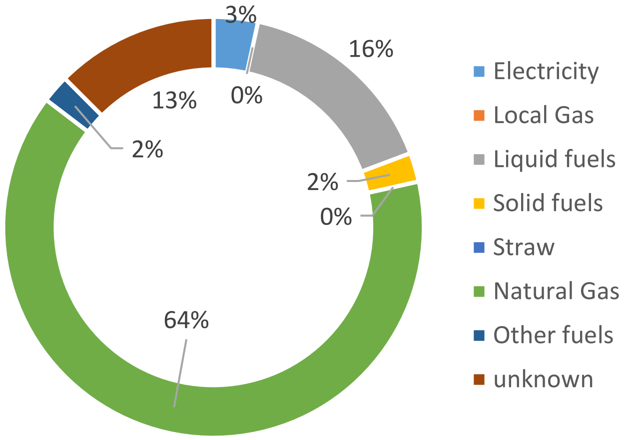

Figure 4.5: Fuel Distribution Expansion Area by Svendborg Fjernvarme (Madsen and Joensen, 2016)

One could expect, electricity boilers would not be replaced, since they become more attractive in future when a larger installed wind capacity leads to hours of low electricity prices on the market in windy hours. However, this only counts for some hours in the year; while in general, it is assumed that electric heating is less competitive than district heating, also due to tax burdens.

In 2020, the expansion of the grid is expected to be maximum 25% of the here described expansion area. Given this fact, the heat demand for 2020 is calculated by adding the current heat demand and 25% of the expansion demand, which sums up to 167,752 MWh. Grid losses were determined by using estimations according to Madsen (2016b):

- 18 MWh/m/yr in 2014
- 17 MWh/m/yr in 2020
- 15 MWh/m/yr in 2035

When 18 MWh/meter losses correspond to 21% losses, 17 MWh /meter correspond to 20% losses of the total heat production in 2020, resulting in 41,502 MWh. Hourly values were again received by using the heat production profile of Odense Fjernvarme.
For the year 2035, total expansion is assumed and therefore 100% of the expansion demand was added to the 2014 demand, resulting in 267,659 MWh. Grid losses correspond now to 15 MWh/m, calculated to 18% of the total heat production, resulting in 56,776 MWh.

4.2 Waste Amounts

The following section focuses on determining which share of waste fuel in the future scenarios is local waste and what has to be imported when local recycling goals are to be met.

4.2.1 Local Waste

Data on incinerated waste of today was given by Svendborg Kraftvarme. This includes different waste categories: household waste, commercial, industrial and biomass, and was 50,286 tons in 2014 (Hansen, 2015). However, in order to follow the objective of this study, higher recycling rates needed to be included, which only affect the household waste. Following, data on household waste was taken from Cimpan et al. (2015b). The data is a collection of waste amounts per type of waste separately collected in each municipality on Funen in 2013 (see Figure 4.6). It also states how much residual waste of each municipality is incinerated at Svendborg Kraftvarme. This is 100% for the municipalities of Ærø and Langeland, 15% for Faaborg-Midtfyn and 27% for Nyborg.

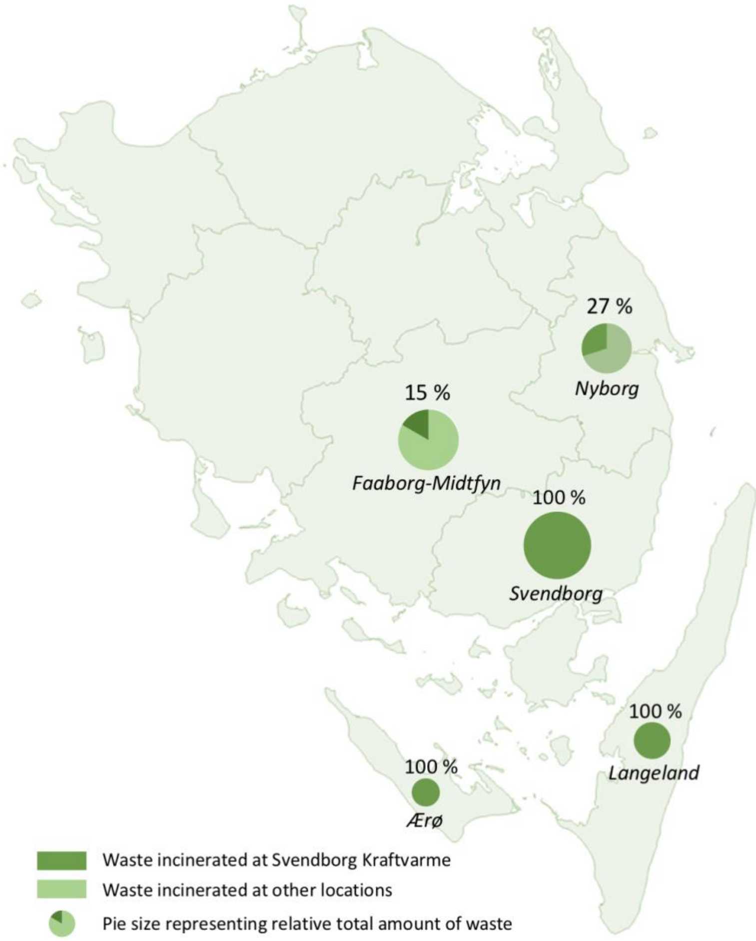

Figure 4.6: Waste Inputs to Svendborg Kraftvarme, based on Cimpan et al. (2015b)

The total waste amounts and shares of waste incinerated at Svendborg Kraftvarme are assumed to be the same in future. In order to apply 50% recycling in 2020 and 65% in 2035, the KISS tool (*Karbon Implications of waste Sorting Systems*) was used to find the final residual leftovers to be incinerated. Thus, for the calculations, optimized source separation efficiencies were used and monostream collection of biowaste in single-families (plus multi-families for 65% recycling) was added as long as the aimed recycling rates were achieved. The total amount of local waste to be incinerated in 2020 (50% recycling) was calculated to 17,555tons with a *lower heating value* (LHV) of 8.8 GJ/ton. The calculated results for the year 2035 were not used in the modelling, since they constituted only a fraction of the waste incineration capacity, instead only imported waste was used for the waste boilers in 2035.

4.2.2 Imported Waste

Imported combustible waste in the form of RDF was used to complement the fuel for the baseload production and was fully used for peak load production. Moreover, it is assumed that the availability of imported RDF from European countries is unlimited for the size of Svendborg´s heating demand and has an average LHV of 13 GJ/ton (Cimpan et al., 2015a).

4.3 Scenarios

The reference scenario of Svendborg district heating system is modelled for the year 2014. In the scenarios of 2020, the incineration plant is still expected to operate and supplemented by the flue gas heat pump. The heat demand in 2020 was adjusted to include 25% of the expansion area additionally to the current heat demand. On this basis, energyPRO calculates the maximum heat capacity needed in the system. It refers to the peak hour of the demand profile and is 70.7 MW in 2020. After subtracting the incineration plant´s capacity from the maximum capacity needed to meet the heat demand, the left capacity was calculated and defined to be covered by a heat pump plus either a biomass or a RDF boiler. To identify whether an RDF boiler can compete with a biomass boiler, all other system variants remained the same. The Heat Pump (HP) size was set with 25%, 50%, 75% and 100% of the left capacity in order to compare the economics of different heat pump sizes later on. The boilers were dimensioned to complement the final demand, i.e. with 75%, 50%, 25% and 0% respectively to the heat pump.
In 2035, the incineration plant was assumed to be phased out and therefore heat pump and boilers had to cover the whole heat demand. The same percentages were used for the dimensioning of the units using the maximum capacity needed (here 109.9 MW) to meet the current demand and 100% of the expansion demand.
Additionally, storage scenarios were modelled. Again heat pump and boiler capacity were predefined while the storage size was adjusted until the heat demand was covered. The scenarios including storage are:

- 25% heat pump and 50% boiler plus storage
- 50% heat pump and 25% boiler plus storage
- 25% heat pump and 25% boiler plus storage
- 50% heat pump plus storage

An overview of the modelled scenarios is presented in Table 8.5 for 2014 and 2020 and in Table 8.6 for 2035 in appendix. In the diagrams, the energy in- and outflows depict the maximum capacity of the production unit or the sum of all units of this type (i.e. four oil boilers are shown as one total boiler). All flows are given in MW. Figure 4.7 shows the flowchart of the baseline scenario for 2014.

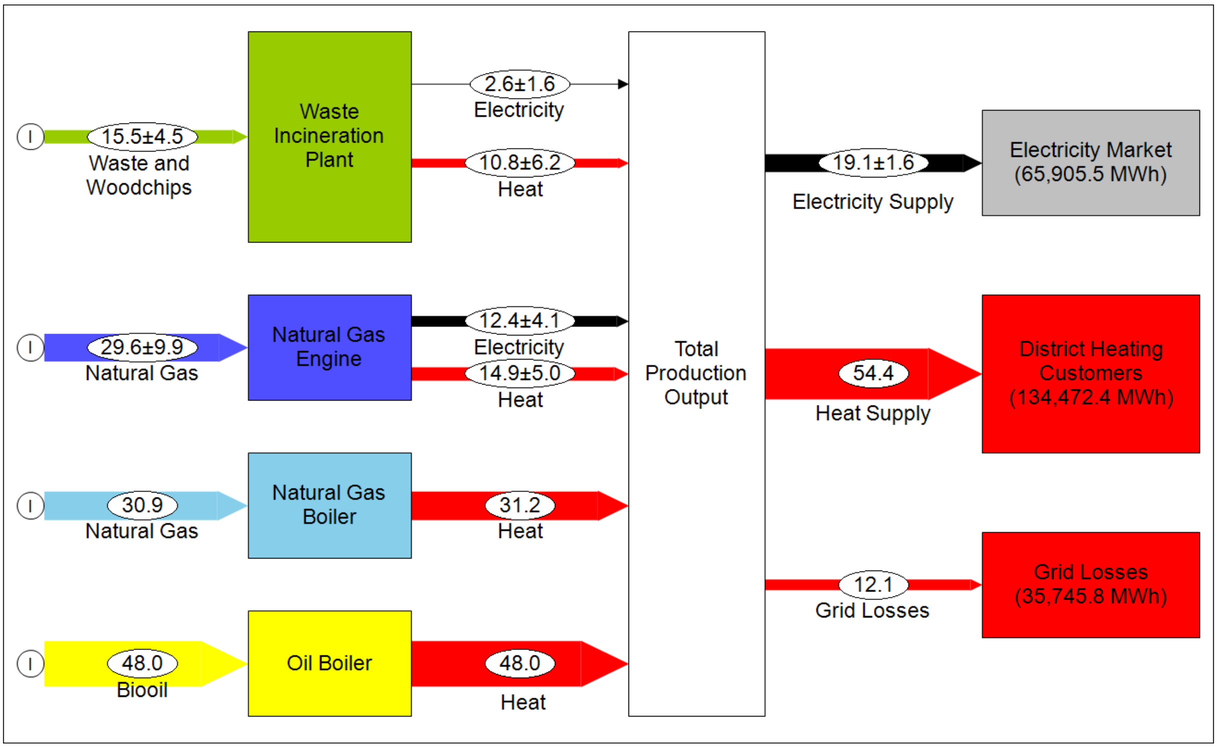

Figure 4.7: Flowchart 2014; Baseline scenario

The incineration plant can produce maximum outputs of 13.8 MWh_{heat} and 4.2 MWh_{el} when electricity prices are high and up to 17 MWh_{heat} and 1 MWh_{el} when electricity prices are low. Additionally, the plant can operate from a minimum capacity of 55% load to 100% load. In order to reduce excess heat taxes, Svendborg Kraftvarme aims to run the plant on minimum heat output during the summer months, where the heat demand is low. The baseload operation of 55% minimum input has an efficiency of 80%. This results in 4.6 MW_{heat} and 4.2 MW_{el} output (Hansen, 2015). On the other side, when the heat demand is high, peak load production is needed, which is in total 20 MW fuel input producing 17 MW_{heat} and 1 MW_{el} with an efficiency of 90%.

4.3.1 Scenarios 2020

In the 2020 scenarios, the incineration plant has an additional flue gas heat pump. This is why a small electricity input to the incineration plant is needed to run the flue gas heat pump. Furthermore, the waste input is now split into mixed waste, representing local household waste, and imported RDF. The varying electricity inputs to the heat pump occur from the different COPs over the year when the source temperature changes. Moreover, the heat demand includes 25% of the expansion areas on top of the 2014 demand with grid losses of 20%.

Figures 8.1 and 8.2 in appendix, show system configurations comprising of incineration plant, heat pump and biomass boilers with different plant capacities for the year 2020.

4.3.2 Scenarios 2035

Scenario 2035 only consists of heat pump and RDF or biomass boiler. Oil and natural gas boilers are assumed to be phased out by then. Moreover, the incineration plant will reach its end of life before 2035. Thus, heat pump and the boiler cover the increased heat demand, which is calculated by the current demand plus 100% of the expansion areas' demand. Grid losses in this case are calculated with 18% of the total heat production.

Additionally, storage is also included in 2035 scenarios. Boiler and heat pump both produce to the storage. In all storage-including scenarios, the optimization period in energyPRO starts from the 1st of May instead of the 1st of January. The reason is better modelling possibilities of the seasonal storage, as the storage is then empty at the beginning of the optimization period and can be filled up in the first months during the summer to supply heat for the entire winter season.

Figures 8.3 and 8.4 in appendix, express system configurations of heat pump and biomass/RDF boilers with storage for the year 2035.

4.4 System Analysis

In the following sections, the results of the system analysis and economic analysis are presented and discussed. Results of the system analysis refer to the production profiles of the scenarios, depending of the priority of each operation unit, calculated by energyPRO. Some example figures are explained in this report, while the rest of the results can be found in (Gabert, 2016). The results of the economic analysis are described by comparing the heat price of each system with the other alternatives of the time line and the reference system of today. Additionally, the heat prices are shown if breakeven prices of RDF were used in the calculations. Furthermore, sensitivity analysis for heat pump without electricity taxes and PSO tariff are presented.

4.4.1 2020 Scenario

Incineration Plant, HP and Biomass

First, the results of the scenario 2020 with 25% heat pump and 75% biomass boiler capacity in addition to the incineration plant are described. Under business economic considerations (see Figure 4.8); the heat pump is the peak load unit in most hours, as it is more expensive than the biomass boiler. This is due to its high taxes. It is therefore only running in the peak load hours from end of January until beginning of February.

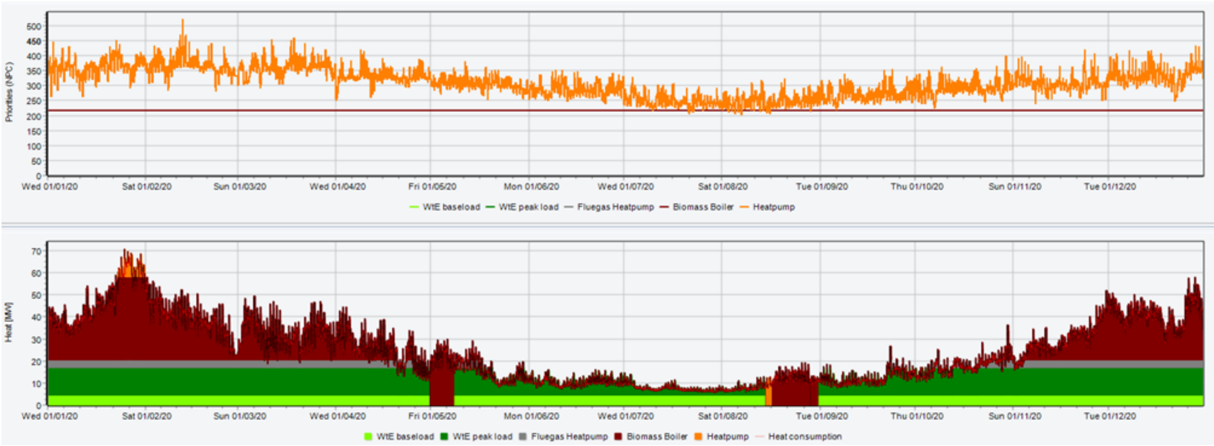

Figure 4.8: Results 2020 25% HP + Biomass (Business Economic Modelling)

Contrary to that, under socio economic costs (see Figure 4.9), the heat pump is preferable to the biomass boiler and is only overbid in a few high electricity hours.

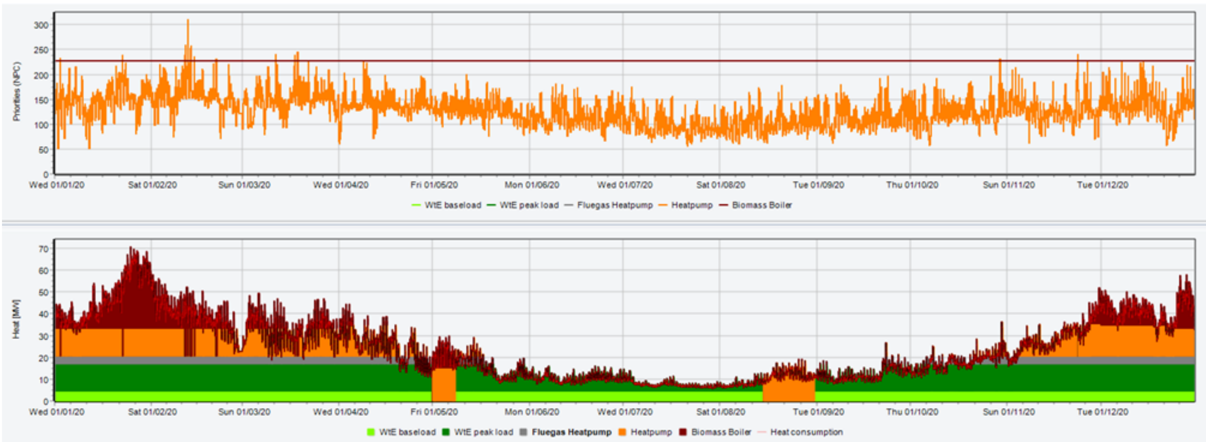

Figure 4.9: Results 2020 25% HP + Biomass (Socio Economic Modelling)

4.4.2 2035 Scenarios

2035 HP and Biomass

The first scenario includes a heat pump capacity of 25% and a biomass boiler capacity of 75%. Under business economics, the biomass boiler shows cheaper net production costs than the heat pump in most hours of production. This explains why the heat pump operates in peak hours as before in 2020 and during the summer also in some cheap electricity hours (see Figure 4.10).

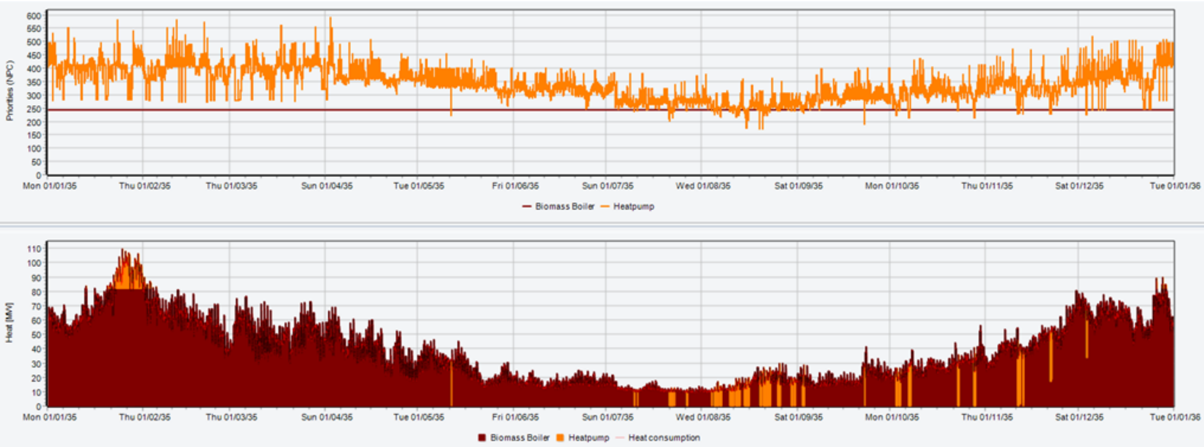

Figure 4.10: Results 2035 HP 25% + Biomass (Business Economic Modelling)

This effect changes again when only socio economics are considered. Here, the heat pump priority is most of the time higher than the one of the boiler. Only in some expensive electricity hours, biomass takes over (see Figure 4.11).

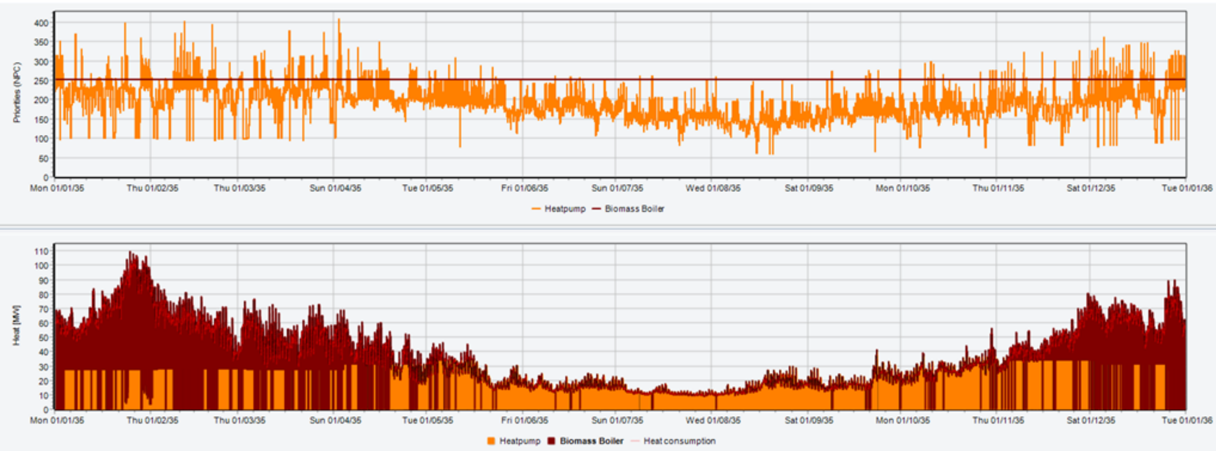

Figure 4.11: Results 2035 HP 25% + Biomass (Socio Economic Modelling)

The same effect can be seen when the heat pump capacity is increased to 50% and 75% and boiler capacities are reduced respectively.

2035 HP, Biomass and Storage

The first scenario in Figure 4.12 shows the production of 25% heat pump and 50% biomass boiler capacity with a 61,000m^3 storage under business economic conditions. It can be seen that in the beginning of the optimization period, 1st of May, the heat storage is filled with overproduction of the biomass boiler. In the summer months from mid of July until mid of November, the heat pump is operating from time to time when electricity prices are low enough. From the beginning of December, when the demand is much higher, the biomass boiler runs continuously, together with a flexible supply from the heat pump and the storage.

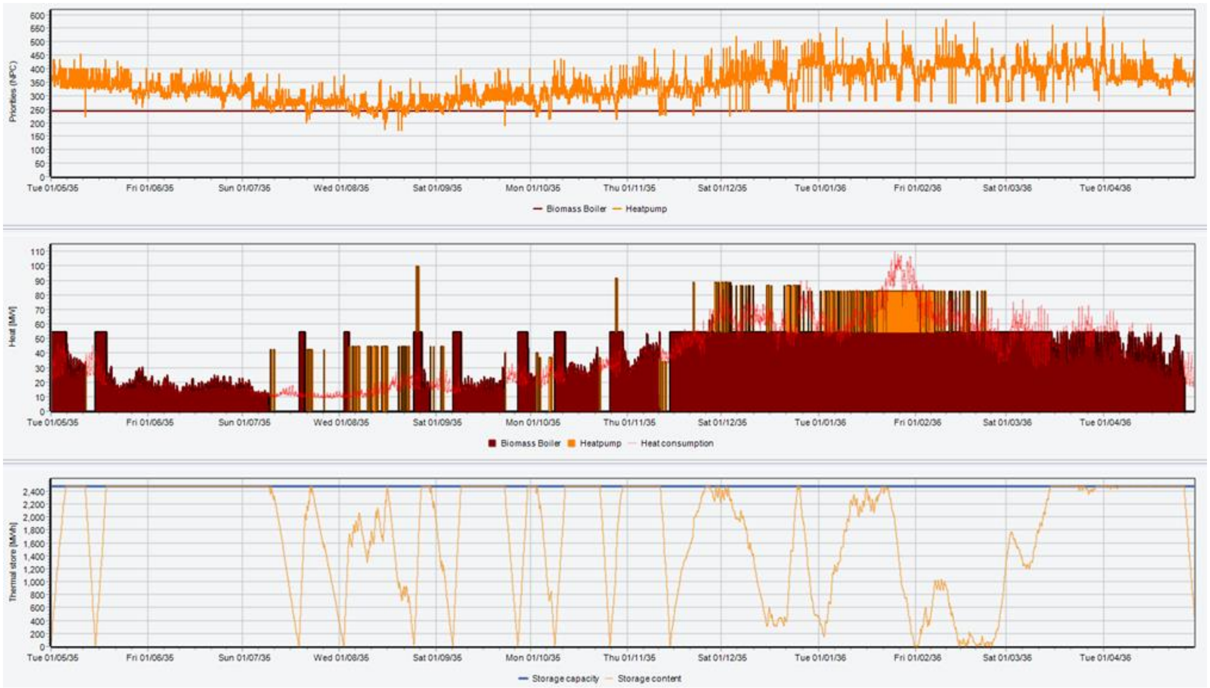

Figure 4.12: Results 2035 HP 25% + Biomass 50% + Storage (Business Economic Modelling)

Looking at Figure 4.13, from a socio economic perspective, the heat pump is most of the time prioritised and runs therefore flexibly over the whole year by using the storage to balance electricity price fluctuations. The black lines appear from the very short operation up- and down-times of the heat pump, which are not able to distinguish in this view of the entire year. The highly flexible production of the heat pump increases the turnover frequency of the storage. Further, the graph of the storage content shows that it is less often emptied completely.

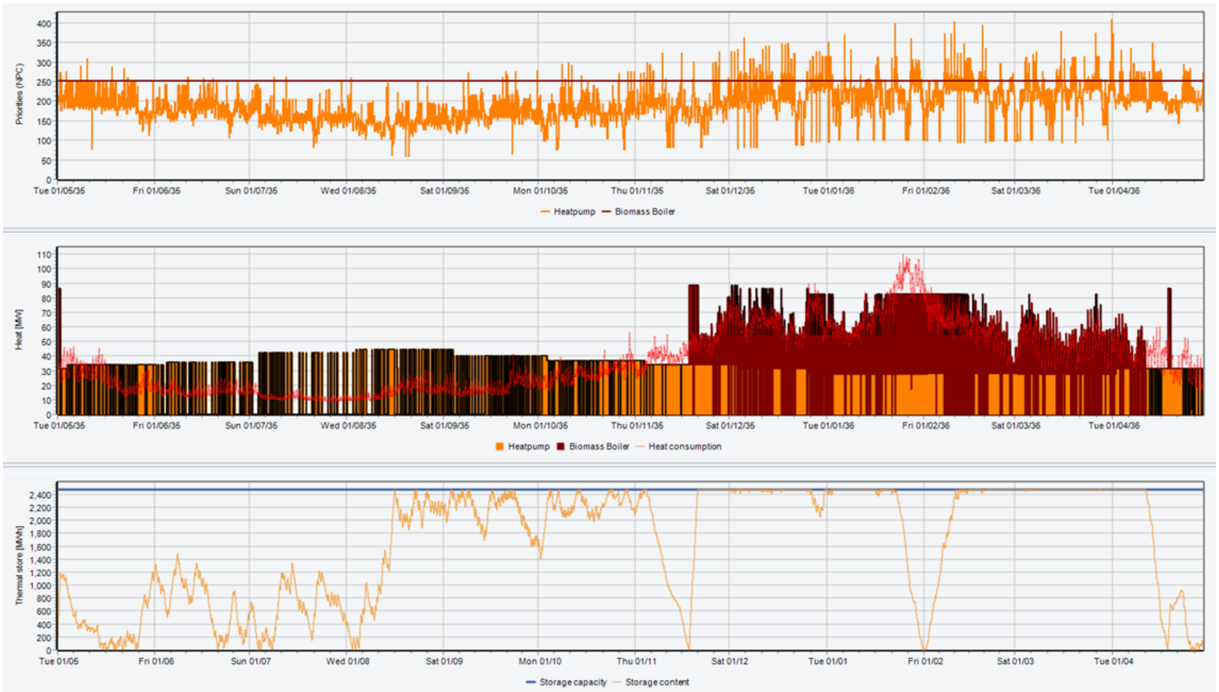

Figure 4.13: Results 2035 HP 25% + Biomass 50% + Storage (Socio Economic Modelling)

4.5 Economic Analysis

4.5.1 Business Economic Analysis 2020

Figure 4.14 shows the comparison of business economic heat prices for the scenarios in 2020. Electricity revenues in the bars result from constant electricity production of the incineration plant as the only electricity producer in the system. The total electricity production in the figure represents the maximum production from the baseload unit.

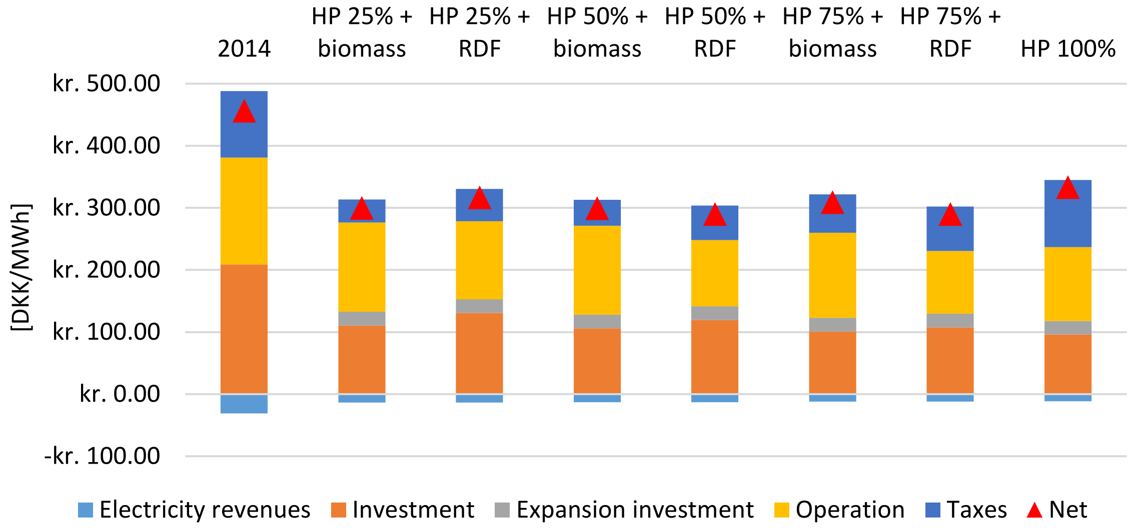

Figure 4.14: Business Economic Heat Prices 2020

All systems for 2020 show a lower heat price than the baseline scenario with 457 DKK/MWh. Overall the business economic results show, that total investment costs decrease with the reduction of the boiler size, and taxes increase in proportion to the heat pump's capacity. The lowest taxes occur in the system of 25% heat pump and biomass, while the highest ones occur in the system of 100% heat pump.

Comparing the boiler alternatives, RDF has lower operational costs but higher investment costs and taxes. The lower operational costs occur from the negative fuel prices compared to costs for biomass. The higher investment costs are caused by the RDF boiler itself, which is more complex than a biomass boiler, due to its flue gas cleaning system. Higher taxes on RDF are mainly caused by CO_2 taxes, but also the surcharge and waste to heat tax, while only NOx taxes apply to the biomass scenarios. Higher investment costs and taxes make RDF systems more expensive than biomass in the 25% heat pump scenarios. However, in the other two system configurations (50% and 75% heat pump), RDF becomes competitive to biomass. The scenario with 75% heat pump capacity and RDF appears to have the lowest heat price with 290 DKK/MWh. The breakeven prices for RDF under business economic calculations are presented as adjusted system heat prices in Figure 4.15, varying from -205 DKK/ton to -125 DKK/ton RDF.

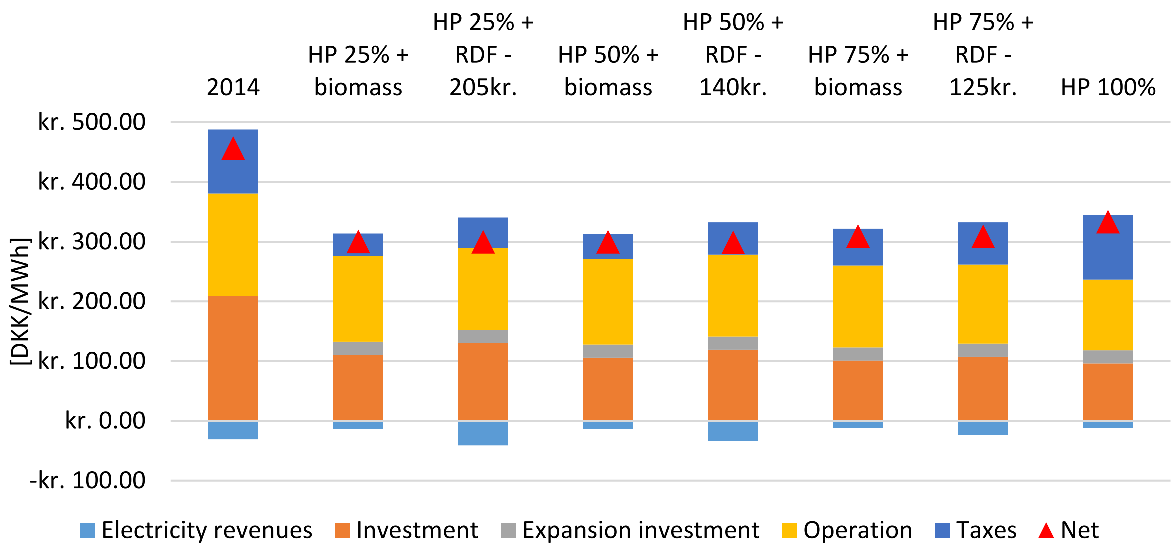

Figure 4.15: Business Economic Heat Prices 2020 Including RDF Breakeven Prices

4.5.2 Socio Economic Analysis 2020

In Figure 4.16, the socio economic heat prices of all scenarios of 2020 are shown in comparison to 2014. Overall, the socio economic analysis shows fewer differences between the scenarios and between the boiler alternatives. This is because the damage costs carry a smaller share of the heat prices and are less sensitive to the unit/fuel type than the taxes.

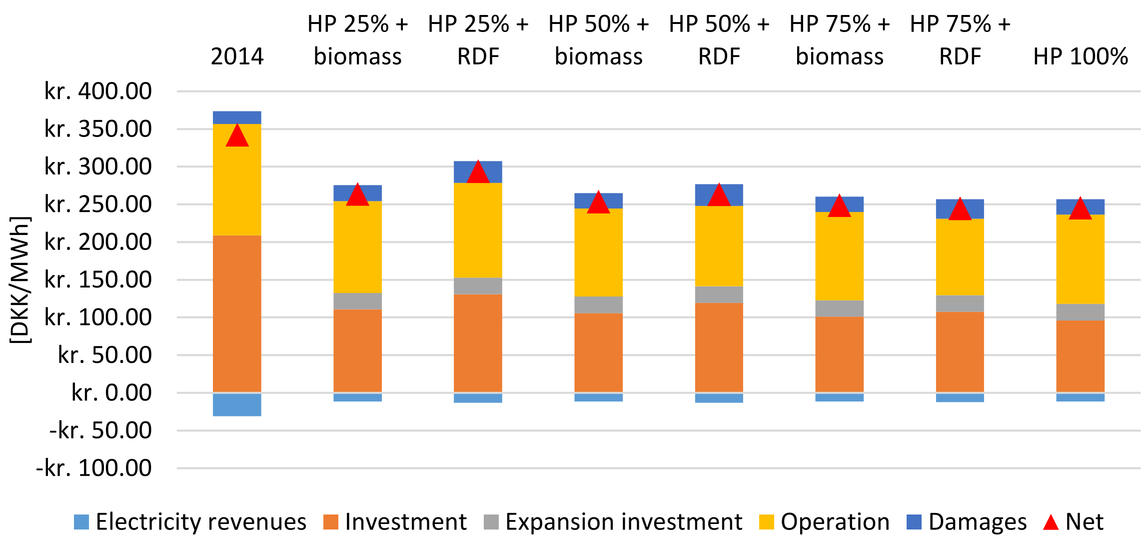

Figure 4.16: Socio Economic Heat prices 2020

The scenario with 75% heat pump and a RDF boiler has the lowest net price of 245 DKK/MWh. The highest heat prices of 2020 have the scenarios of 25% heat pump and RDF or biomass with 294 DKK/MWh and 264 DKK/MWh respectively. Higher damages in the RDF scenarios mainly occur from higher CO_2 emissions on RDF compared to no CO_2 emissions on biomass. The break-even import prices of RDF vary from -268.2 DKK/ton to -195 DKK/ton (see Figure 4.17)

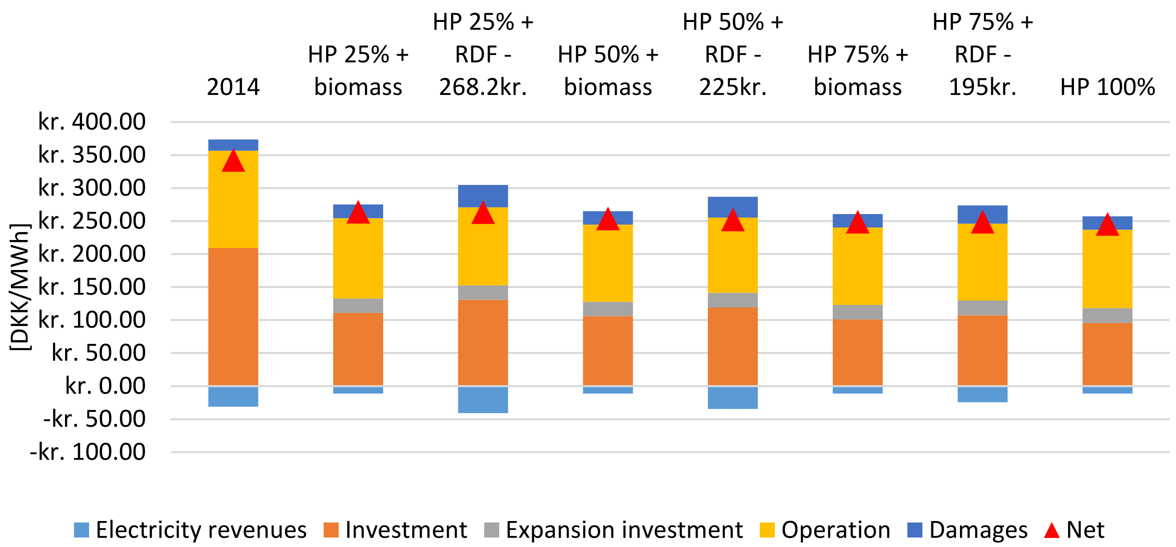

Figure 4.17: Socio Economic Heat Prices 2020 Including RDF Breakeven Prices

When comparing all 2020 scenarios with changed RDF prices, the system with 100% heat pump capacity becomes the most feasible one with a heat price of 246 DKK/MWh.

4.5.3 Business Economic Analysis 2035

In the 2035 systems, no revenues are subtracted from electricity sales, because the incineration plant has been phased out. Larger differences in business economic heat prices are observed when comparing the 2035 alternatives (see Figure 4.18) with the ones of 2020.

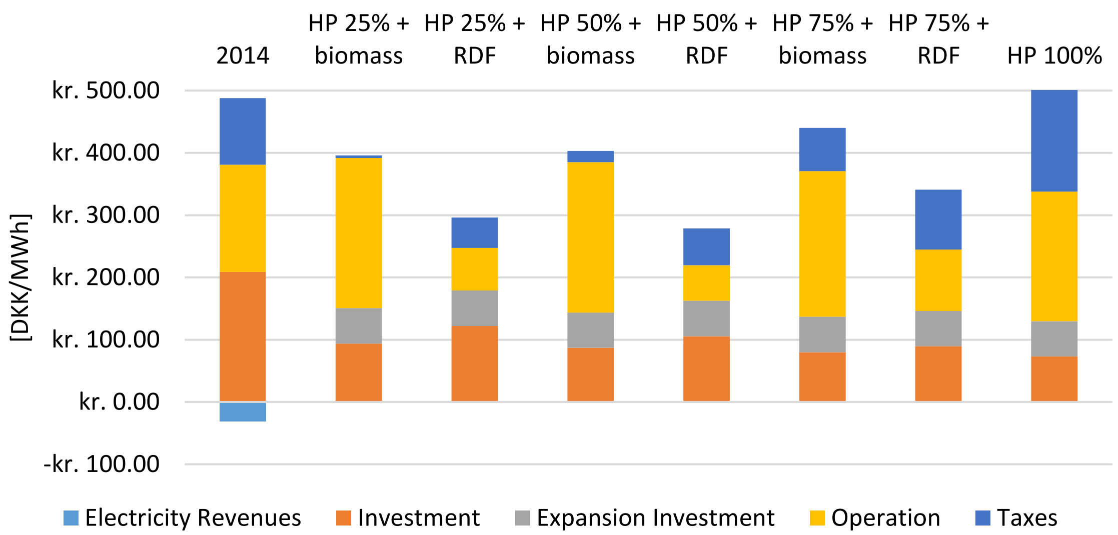

Figure 4.18: Business Economic Heat Prices 2035

System taxes and tariffs increase with the increase of the heat pump size. Additionally, fuel costs of biomass in 2035 and revenues from RDF import differ very much, which is to see in the high differences of operational costs. This results in the lowest heat price for the system of 50% heat pump capacity and 50% RDF with 279 DKK/MWh. In comparison, the largest heat price occurs in the 100% heat pump scenario with more than 501 DKK/MWh. The breakeven RDF prices and the new heat price constellations are shown in Figure 4.19.

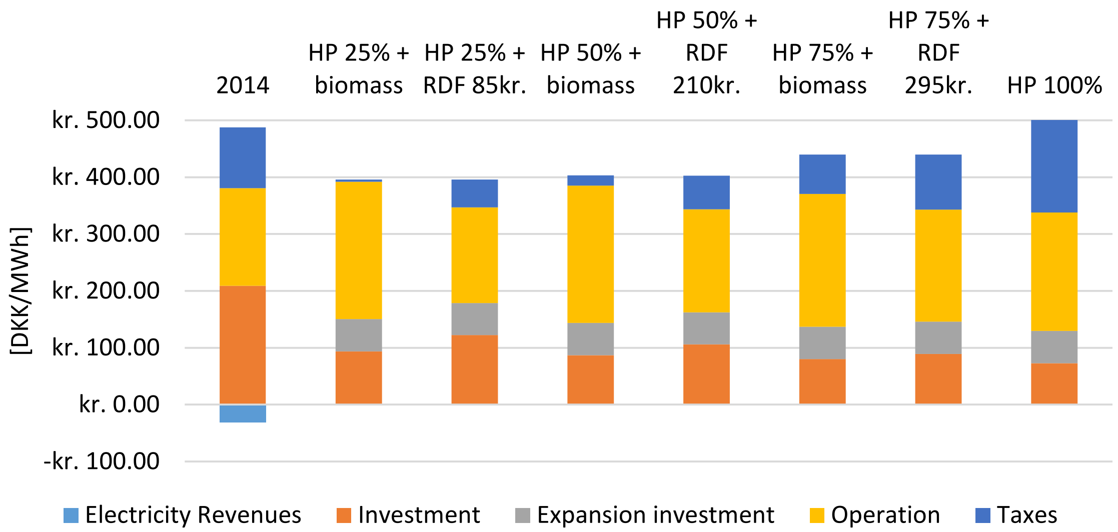

Figure 4.19: Business Economic Heat Prices 2035 Including RDF Breakeven Prices

The breakeven prices differ from 85 DKK/ton to 295 DKK/ton. The lowest heat price here has the same scenario of 25% heat pump and 75% RDF boiler with 396 DKK/MWh and a price of 85 DKK per ton imported RDF.

4.5.4 Socio Economic Analysis 2035

Figure 4.20 shows the socio economic heat prices for all 2035 scenarios in comparison to the heat price in 2014.

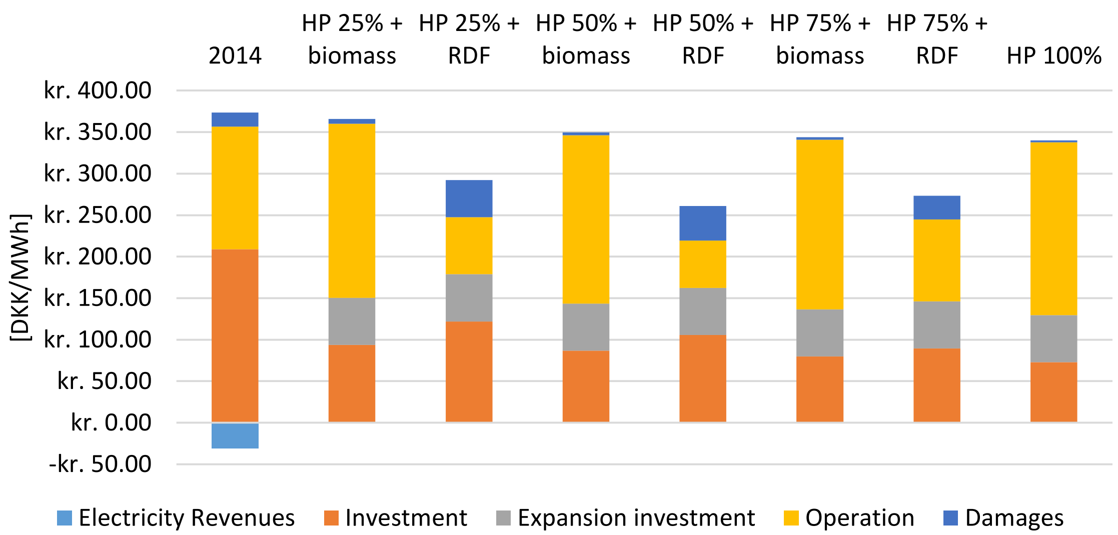

Figure 4.20: Socio Economic Heat Prices 2035

The lowest price has the scenario with 50% heat pump capacity and RDF with 261 DKK/MWh. When this scenario is compared to 25% heat pump and RDF, it can be seen that investment costs, operational costs and damage costs are lower. However, the influence of damage costs is not as significant as taxes before. Lower damage costs are mainly caused by less CO_2 and NOx emissions with the increase of heat pump capacity. The breakeven prices vary from -10 DKK/ton to 135 DKK/ton (Figure 4.21).

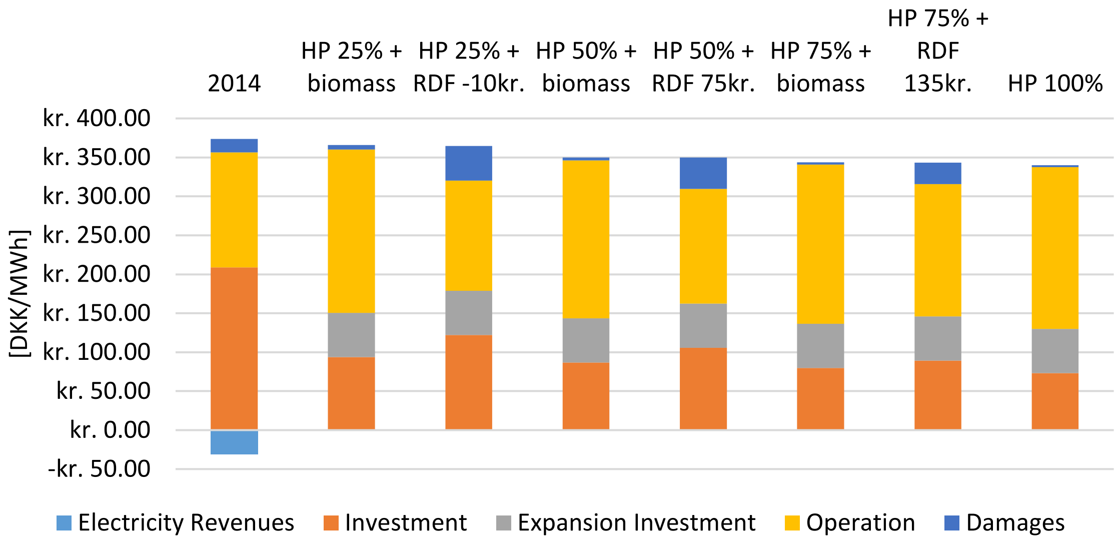

Figure 4.21: Socio Economic Heat Prices Including RDF Breakeven Prices

Taking into account these increased RDF prices, the cheapest scenario of this comparison is the system with 100% heat pump and a heat price of 340 DKK/MWh. This is caused by its very low damage costs, which can balance the otherwise higher operational costs.

4.5.5 Business Economic Analysis 2035 Including Storage

The results of business economic heat prices for scenarios of 2035 including storage are shown in Figure 4.22.

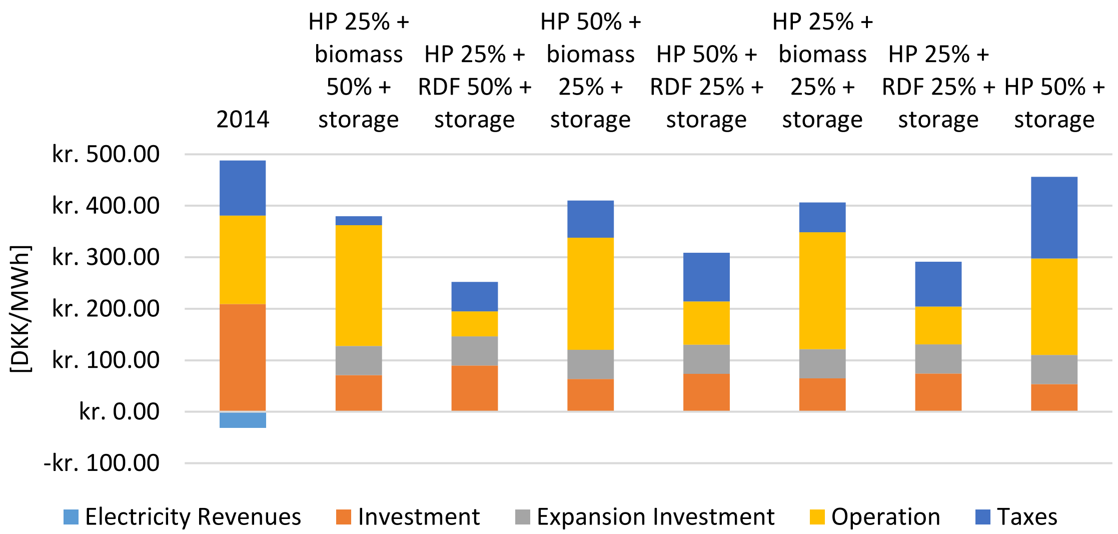

Figure 4.22: Business Economic Heat Prices 2035 Including Storage

Here, the system of 25% heat pump capacity together with 50% RDF boiler plus storage has the lowest heat price with 252 DKK/MWh. RDF prices that can compete with the heat price when bio-mass is used are shown in Figure 4.23. The import prices vary from 215 DKK/ton to 320 DKK/ton. The most feasible alternative is still the one with 25% heat pump capacity, 50% RDF boiler and the respective storage with a heat price of 379 DKK/MWh.

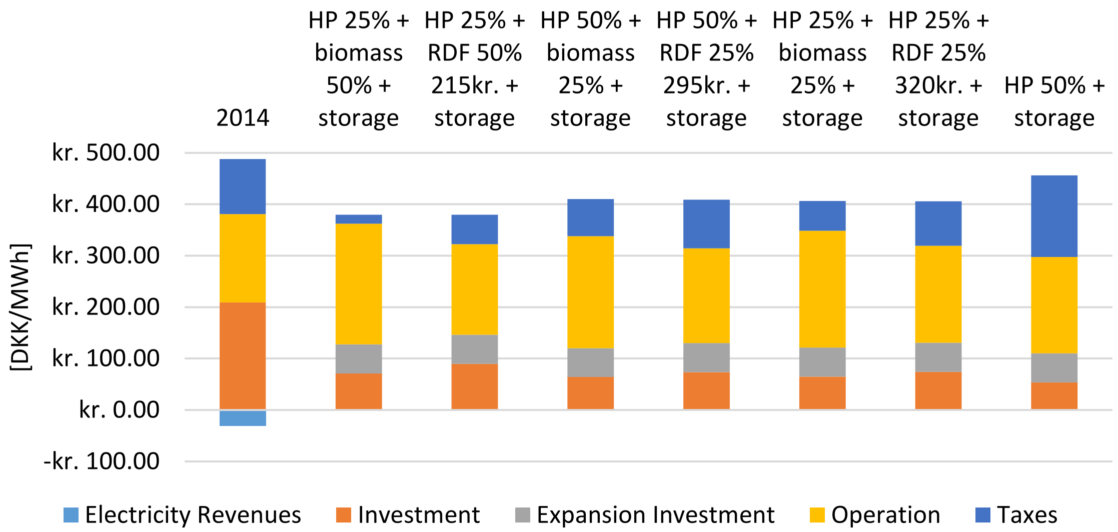

Figure 4.23: Business Economic Heat Prices 2035 Including Storage and Including RDF Breakeven Prices

4.5.6 Socio Economic Analysis 2035 Including Storage

Even bigger differences between the socio economic heat prices can be seen in the scenarios that include thermal storage. The cheapest alternative here is the scenario with a 25% sized heat pump and 25% RDF plus the biggest storage of all scenarios with a size of 550,000m^3, leading to a heat price of 236 DKK/MWh. Furthermore, this is the cheapest heat price of all 2035 scenarios with and without storage (Figure 4.24).

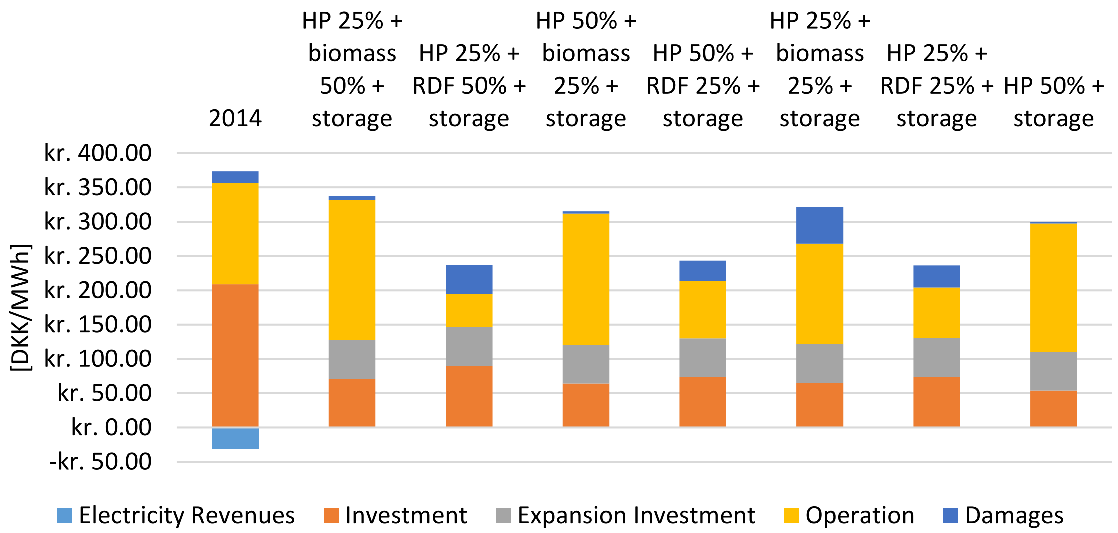

Figure 4.24: Socio Economic Heat Prices 2035 Including Storage

Figure 4.25 represents the heat prices when breakeven RDF prices were applied. The RDF prices range from 110 DKK/ton to 170 DKK/ton.

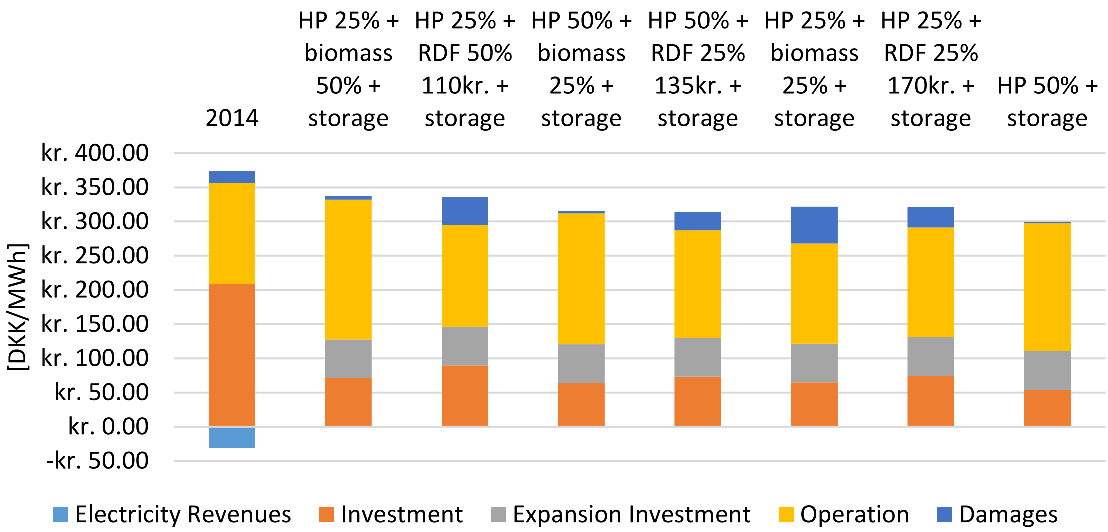

Figure 4.25: Socio Economic Heat Prices 2035 Including Storage and Including RDF Breakeven Prices

4.5.7 Elimination of PSO and electricity taxes

Due to fact that PSO tariffs are expected to decrease in the next decades (Danish Energy Agency, 2016b), it could be argued that electricity to heat taxes for heat pumps would be reduced instead of increased. In order to compare the standard scenarios with a radical “heat pump-friendly” scenario and to evaluate the sensitivity of PSO tariff and electricity taxes, all business economic modelling for 2035 scenarios was also done when eliminating these costs completely (Figure 4.26).

The figure demonstrates that the alternative system comprising of 50% heat pump capacity and RDF again appears to have the lowest heat price with 263 DKK/MWh. This is the best alternative under business and socio economic cost conditions. Hence, it indicates that following the estimated taxes and tariffs on heat pumps, results also in the best alternative for society within the investigated scenarios of 2035 without storage.

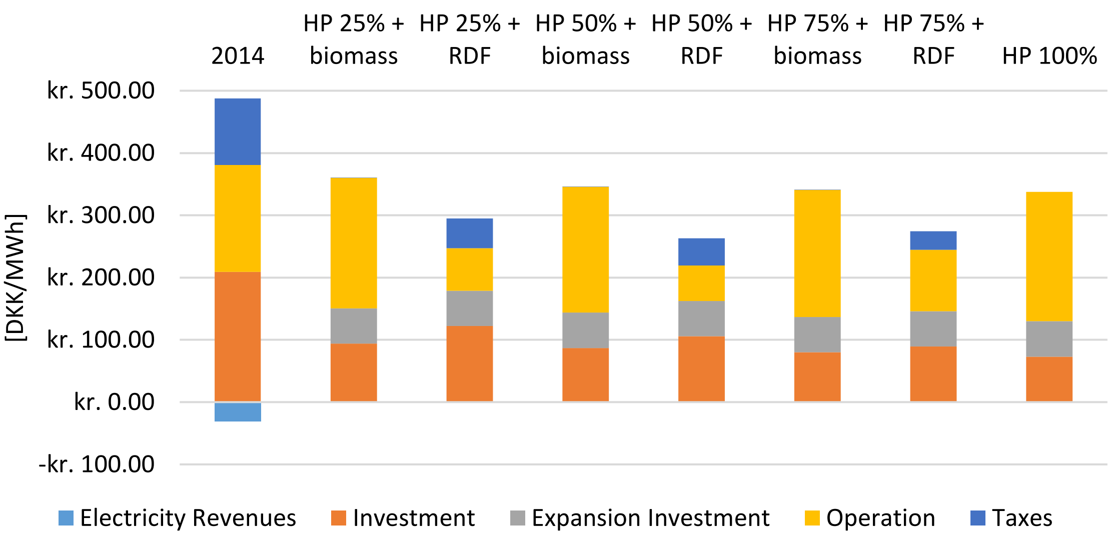

Figure 4.26: Business Economic Heat Prices 2035 without storage (Eliminated Heat Pump Taxes)

Figure 4.27 shows the results of heat prices when heat pump taxes and PSO are eliminated in the storage-including scenarios. The system with 25% heat pump and 25% RDF boiler capacity in combination with a large storage is the best alternative. This is also the most feasible scenario under socio economics with a heat price of 237 DKK/MWh here.

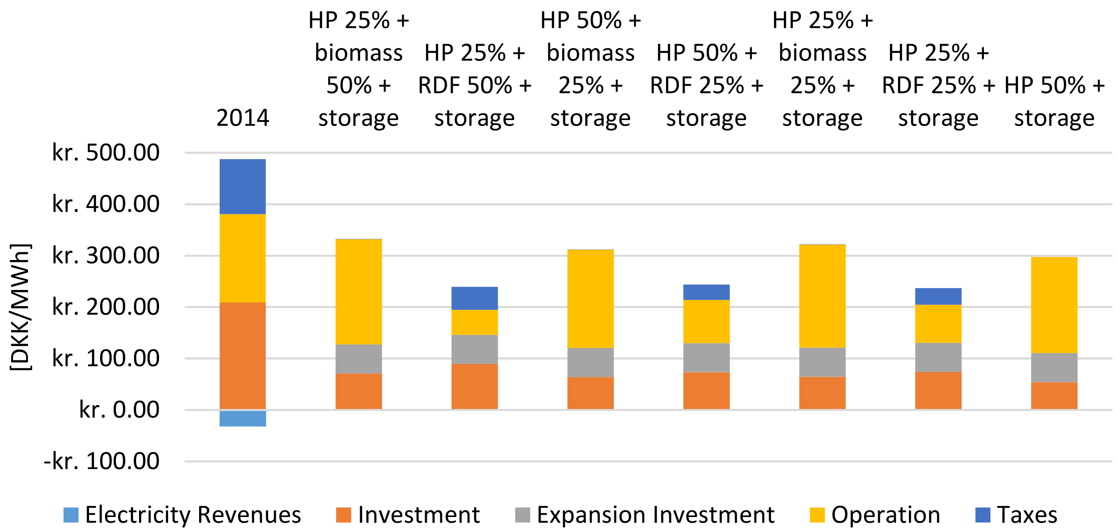

Figure 4.27: Business Economic Heat Prices 2035 Including Storage (Eliminated Heat Pump Taxes)

4.6 Summary

To summarize the findings, this section gives an overview of the heat prices of the scenarios that showed to be the most feasible option for 2020 first. Table 4.1 shows the best alternative when modelled under business economics and socio economics only, and when RDF prices were adjusted to the competitive price of biomass systems under business and socio economic conditions. Additionally, the total amounts of imported RDF are shown in the right column for each best alternative.

Table 4.1: Overview of Lowest Heat Prices 2020 Scenarios

2020			
	Heat Price [DKK/MWh]	Scenario	RDF Amounts [tons]
Business Economics	290.08	HP 75% + RDF	45,428.33
Business Economics Adjusted RDF Prices	298.55	HP 50% + RDF -140kr.	59,715.33
Socio Economics	244.79	HP 75% + RDF	45,428.33
Socio Economics Adjusted RDF Prices	245.66	HP 100%	31,417.93

Secondly, the same overview is given for all 2035 scenarios that were modelled without storage (see

Table 4.2). In addition, best alternatives were also found for business economic conditions, when heat pump taxes and tariff were eliminated completely. Here, the best scenario under business economics and adjusted RDF prices appears to have the largest amount of imported RDF i.e. 91,302 tons.

Table 4.2: Overview of Lowest Heat Prices and RDF Amounts in Scenarios of 2035 without Storage

2035			
	Heat Price [DKK/MWh]	Scenario	RDF Amounts [tons]
Business Economics	278.78	HP 50% + RDF	84,162.70
Business Economics Adjusted RDF Prices	395.69	HP 25% + RDF 85kr.	91,302.10
Business Economics Eliminated Electricity Tax and PSO	263.25	HP 50% + RDF	84,162.70
Business Economics Eliminated Electricity Tax and PSO and adjusted RDF Prices	337.72	HP 100%	-
Socio Economics	261.05	HP 50% + RDF	84,162.70
Socio Economics Adjusted RDF Prices	340.15	HP 100%	-

Finally, Table 4.3 shows the best alternatives with their amounts of RDF import for the scenarios of 2035 including storage.

Table 4.3: Overview of Lowest Heat Prices and RDF Amounts in Scenarios of 2035 with Storage

2035 + storage			
	Heat Price [DKK/MWh]	Scenario	RDF Amounts [tons]
Business Economics	252.06	HP 25% + RDF 50% + storage	85,776.60
Business Economics Adjusted RDF Prices	379.46	HP 25% + RDF 50% 215kr. + storage	85,776.60
Business Economics Eliminated Electricity Tax and PSO	237.27	HP 25% + RDF 25% + storage	63,577.60
Business Economics Eliminated Electricity Tax and PSO and adjusted RDF Prices	297.47	HP 50% + storage	-
Socio Economics	236.24	HP 25% + RDF 25% + storage	63,577.60
Socio Economics Adjusted RDF Prices	299.83	HP 50% + storage	-

5 Case of Odense

The district heating in Odense is provided by FVF, which is owned by Odense municipality, and has the purpose of providing "*the best possible heat supply at the cheapest possible price*" (Fjernvarme Fyn, 2016). It is a non-profit company, which means that the price of heat is set by taking the deficit for a period, divided by the amount of produced heat. This also means that the price varies with the production prices for the different production units that have currently been providing heat for that period.

In Odense, there are mainly two types of production units, boilers and CHP's. A boiler is the simplest production unit as it produces heat only, while CHP's produce both electricity and heat. CHP's can adjust their production of heat and electricity within a specified range. In this project only production on the back pressure line is considered for simplicity.

For CHP's the co-generation of electricity and heat means that the heat price is dependent on the electricity price. The price that they receive for the electricity produced effectively lowers the cost of producing heat. The complexity of this situation is illustrated in a fictional district heating area with a CHP, a boiler and a heat pump with imaginary costs of heat production, here shown as a function of the electricity price in Figure 5.1.

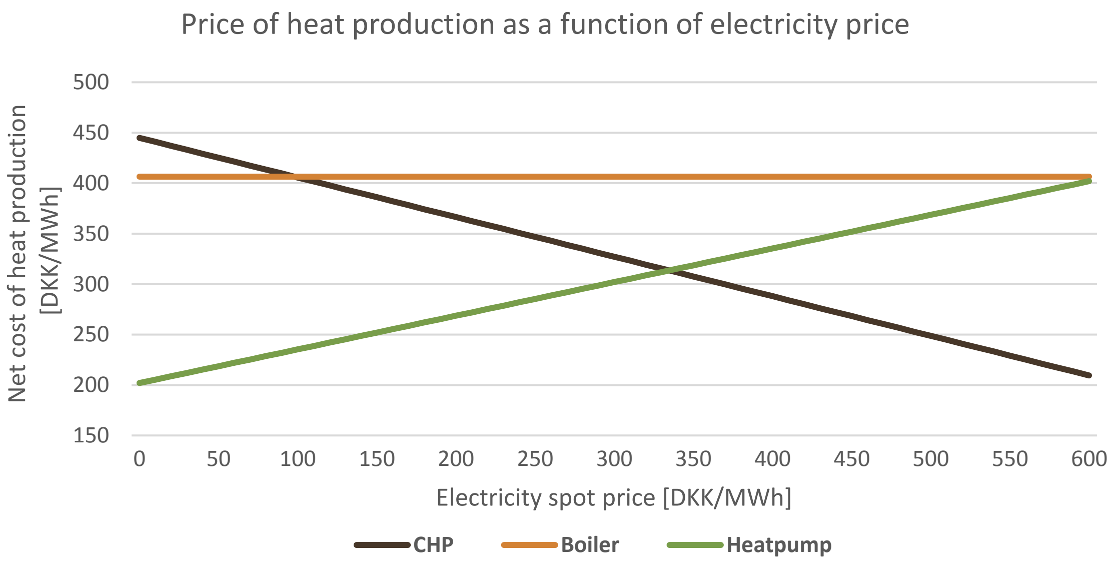

Figure 5.1: Fictional net prices of heat production as a function of electricity price for three types of production units

As the boiler does not produce or consume considerable amounts of electricity it is not affected by the electricity price. The price of the heat produced by the CHP on the other hand is clearly influenced by the electricity price. This can be seen on the downward sloping graph (blue) that shows how the price of heat decreases as the electricity price increase. In this example, the CHP becomes cheaper than the boiler at an electricity price of more than 100 DKK/MWh. The heat pump is also dependent on the electricity price but with the opposite effect than the CHP, since this unit utilizes electricity for the production of heat instead of producing electricity. Therefore, the price of heat increases as the electricity price increase. In here the heat pump is cheaper than the CHP and the boiler while the electricity price is below respectively 330 DKK/MWh and 600 DKK/MWh.

Practically this means that in order for the district heating supplier of this area to deliver the cheapest heat possible for the consumers he must be aware of the electricity prices. He must choose to operate the units with the lowest net cost of heat production.

If the electricity price is below 330 DKK/MWh the heat pump must operate. If this unit is unable to satisfy the heat demand one other or all units must operate as well. In this case if the electricity price is below 100 DKK/MWh the boiler is preferable and if the electricity price is above 100 DKK/MWh the CHP is most economical.

5.1 Production units in Odense district heating network

An overview of the largest production units in Odense district heating network and the most relevant specifications are listed in **Error! Reference source not found.**.

Table 5.1: Existing production units in FVF district heating network

	Bloc 7	**Bloc 8**	**ODV**	**Dalum CHP**	**Heat central natural gas**	**Heat central gasoil**
Type	CHP	CHP	CHP	CHP	Boiler	Boiler
Fuel	Coal	Straw	Waste	Wood chips	Natural gas	Gasoil
Max fuel input [MW]	1118	122	101	56	228	555
Max heat output	570	84	65	48	217	527
Max electricity output	380	31	19,5	6,5	N/A	N/A

Bloc 7 is by all means the largest production unit in the district heating network. ODV works as a baseload since FVF receives money for burning the waste. Also bloc 8 produce a large share of the heat at present due to the PSO-supported price for electricity production it receives until 2019 of 400 DKK/MWh, after which it changes to a subsidy of 150 DKK/MWh, Appendix B. The two heat centrals consist of several smaller boilers that work as peak-load units and produces only when the remaining units are unable to cover the demand.

5.2 Other heat suppliers

This consist of a list of minor heat suppliers such as industrial waste heat and external heat centrals. Furthermore, EMWTP already supplies heat to the district heating from the excess heat produced by a gas engine in the plant (Fjernvarme Fyn, 2015). This category is not described further or used in the model as it is considered a minor contributor (i.e. supplied only 3% of the heat production in 2015) and this contribution is not easily simulated or controlled. The actual distribution of FVF heat production in 2015 is illustrated in Figure 5.2.

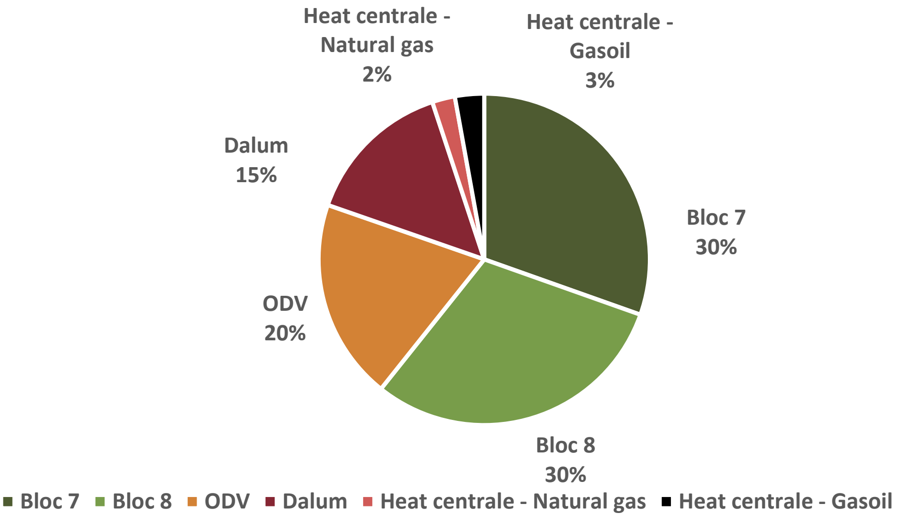

Figure 5.2: Distribution of FVF heat production of 2015

5.3 Heat storage

FVF also has storage capacity in the district heating network of 65.000 MWh. This can be filled with heat in periods when heat production price is low and later supply this heat to the consumers when the price of producing heat raises again.

5.4 Scenarios

The three different heat producing units, with an output of 75 MW, are modelled as added to the existing district heating system of Odense in each their scenario. The existing system and main assumptions about the future development are visualized in Figure 5.3.

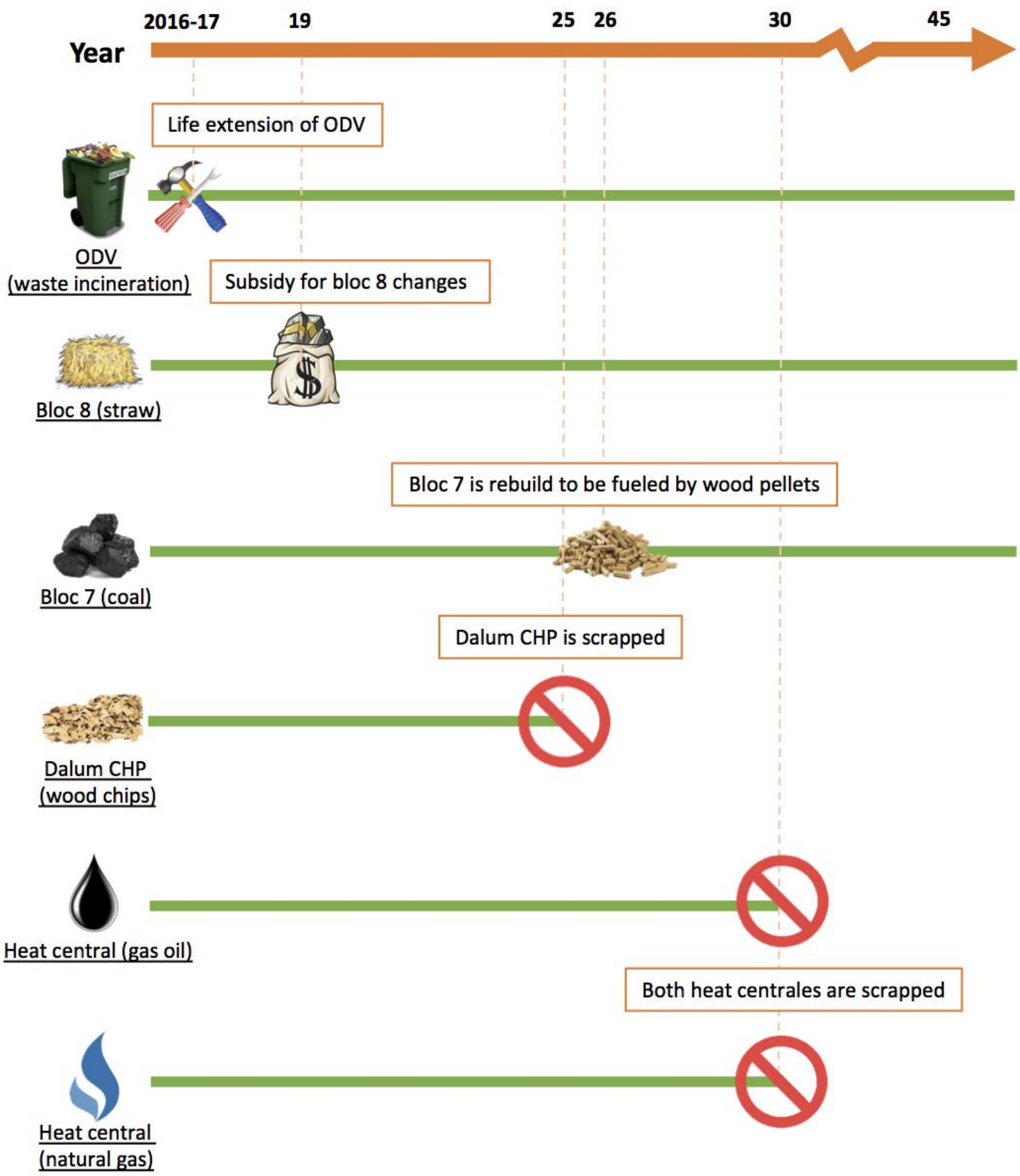

Figure 5.3: Odense district heating system

The coal-fired CHP (Bloc 7) gets a life time extension in the beginning of 2026 and is converted to run on wood pellets due to the government's vision of bringing down coal consumption by 60% and changing fuel type to biomass for larger plants (Energinet.dk, 2014). When Bloc 7 is changed in 2026, the capacity is reduced, due to the addition of the 75 MW heat producing unit in the system, so that the max heat output is reduced by 75 MW compared to the reference, which gives an investment saving in this year in relation to the reference scenario. The Heat central (Natural gas) and Heat central (Gasoil) are both assumed to be scrapped in 2030, but this does not really influence the modelling, as these units operate very seldom anyways. Dalum CHP will be scrapped in 2025 due to the plans of FVF. The incineration plant and straw CHP (Bloc 8) will most likely continue their operations till the end of the simulation period.

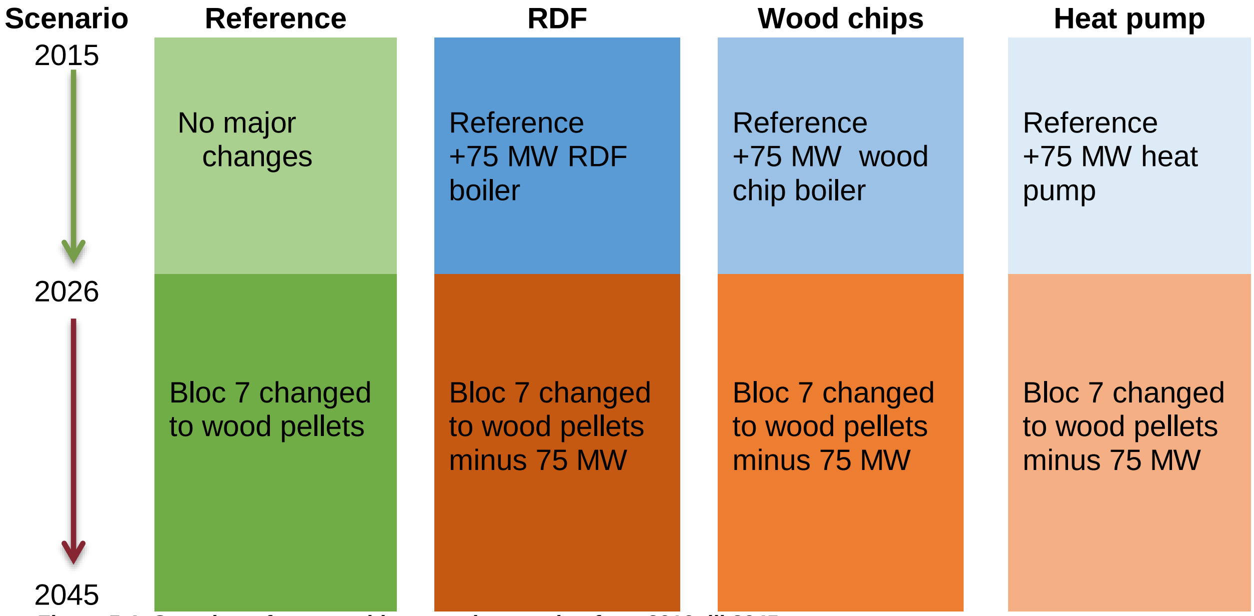

Figure 5.4: Overview of comparable scenarios starting from 2016 till 2045

Operation strategy

The operation strategy is a function of the net heat production cost (NPC) for each production unit and therefore determines at what time each plant should produce heat, depending on the electricity spot price. The heat demand of Odense should be met at a minimum production cost, and model simulates it by assigning highest priority to the plant with the lowest NPC and reducing the priority to the next plant with lower NPC until the heat demand is satisfied. For the purpose of understanding the above mentioned strategy, the operation strategy for RDF scenario in the year 2017 is exemplified in Figure 5.5.

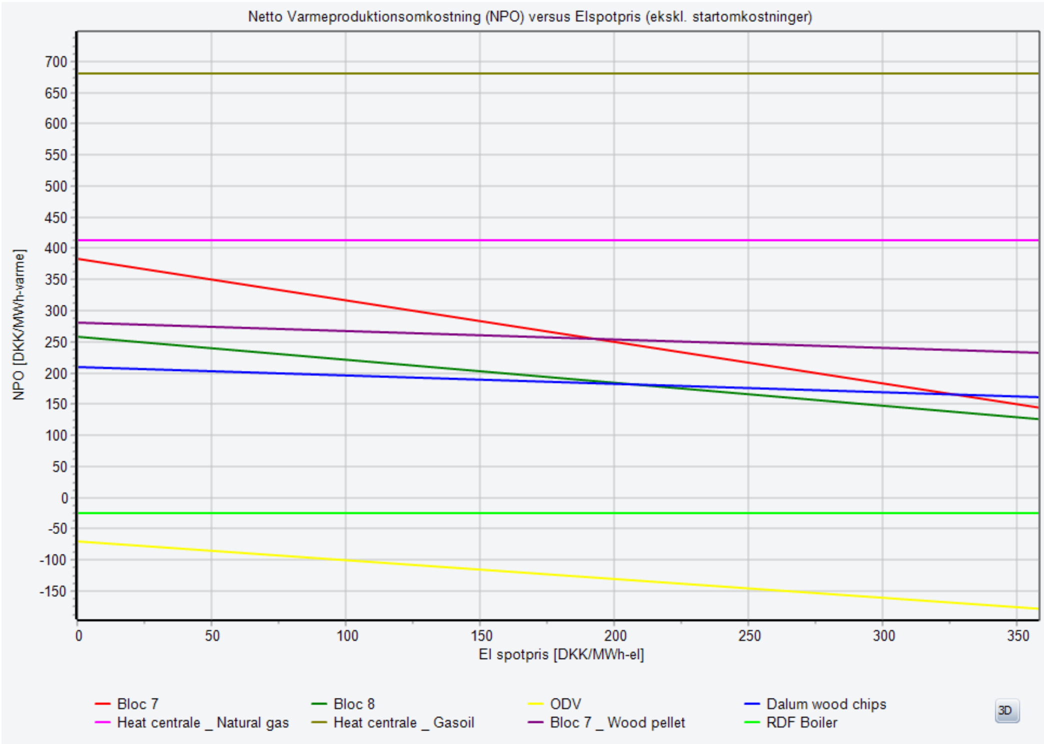

Figure 5.5: Operation strategy of 2017 of RDF scenario without any taxes or subsidies

Figure 5.5 shows that the NPC of the CHPs decline with increasing electricity spot prices. Bloc 7 is the CHP that decreases its NPC most, when electricity price increases, due to the large share of electricity production of the total capacity. Bloc 7 with wood pellets also demonstrates lower NPC with increasing spot prices, however not much when compared to coal-fired bloc 7. It is important to stress that these two CHP never produce at the same time, since it's the same CHP, but in different time periods. The operation strategy of Bloc 7 (wood pellet) is not valid until 2026, but is calculated by EnergyPro when simulating the 20 year period. The RDF boiler displays a constant NPC since it is not dependent on the spot price. Also, the NPC for RDF boiler is considerably lower than the other units due to the fact that fuel price (waste gate fee) is negative in this case. The waste incineration CHP (ODV) has the lowest NPC and is prioritized by the model to run as a base load. On the other hand, heat pump NPC would increase with the electricity price lowering its priority at higher spot prices (not shown in Figure 5.5 though).

5.5 System Analysis

Results of the system analysis are presented in this section and refer to the production profiles of energy suppliers, depending of the priority of each operation unit, calculated by energyPRO.

5.5.1 Reference scenario

The heat production under the reference scenario is presented in Figure 5.6, which shows production profiles of all units over the simulation period (2016-2045). The coal-fired plant (Bloc 7) supplies major share of the heat till 2025, and is converted to wood pellets after that. The Dalum wood chips boiler would also reach its end of life by 2025 and is scrapped at that point. The incineration plant continues to run with its maximum capacity throughout. Moreover, it can be seen that straw boiler's (Bloc 8) production is affected by the projected decrease in the coal and biomass prices till 2018.

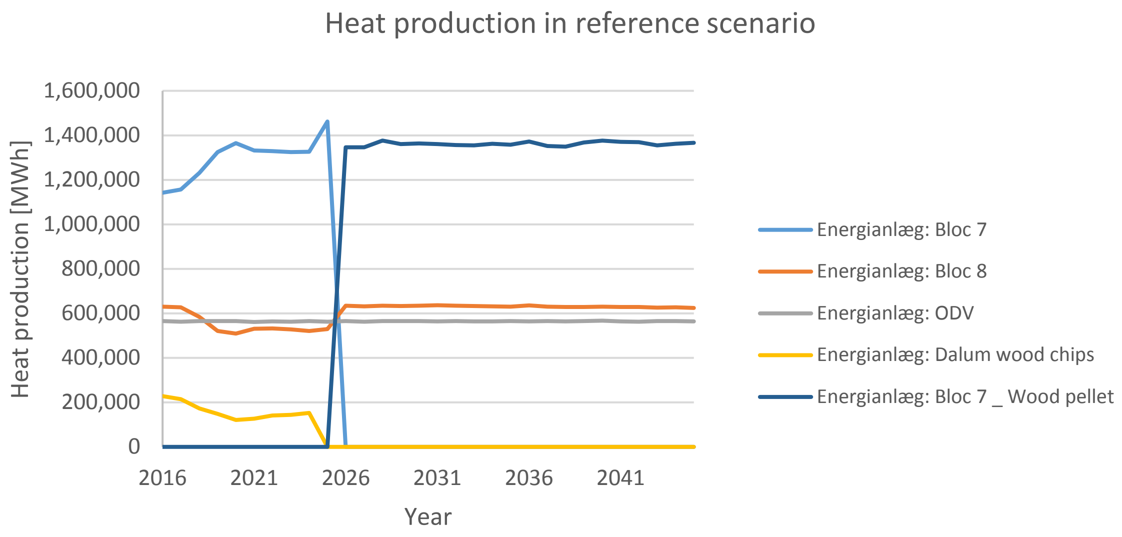

Figure 5.6: Heat production profile for reference scenario

5.5.2 Biomass & HP scenarios

The biomass scenario replaces 75 MW of rebuilt wood pellet CHP (Coal-fired till 2025) by a wood chips boiler. It can be also observed in the Figure 5.7, that lower prices of coal influence production of the wood chips boiler in the early years.

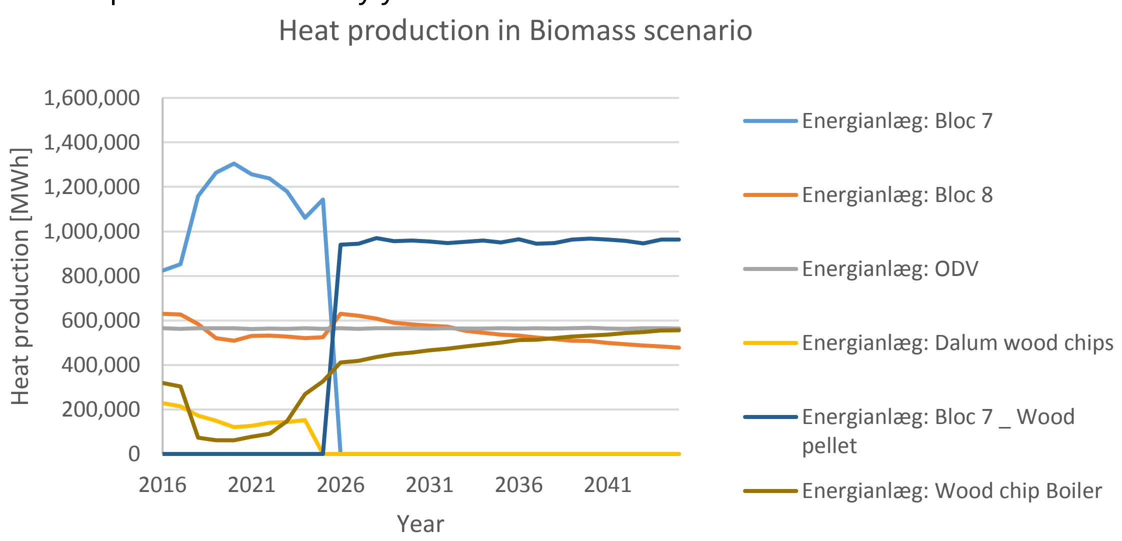

Figure 5.7: Heat production profile for biomass scenario

Similarly, for the Heat pump scenario, 75 MW of rebuilt wood pellet – CHP is replaced by heat pump.

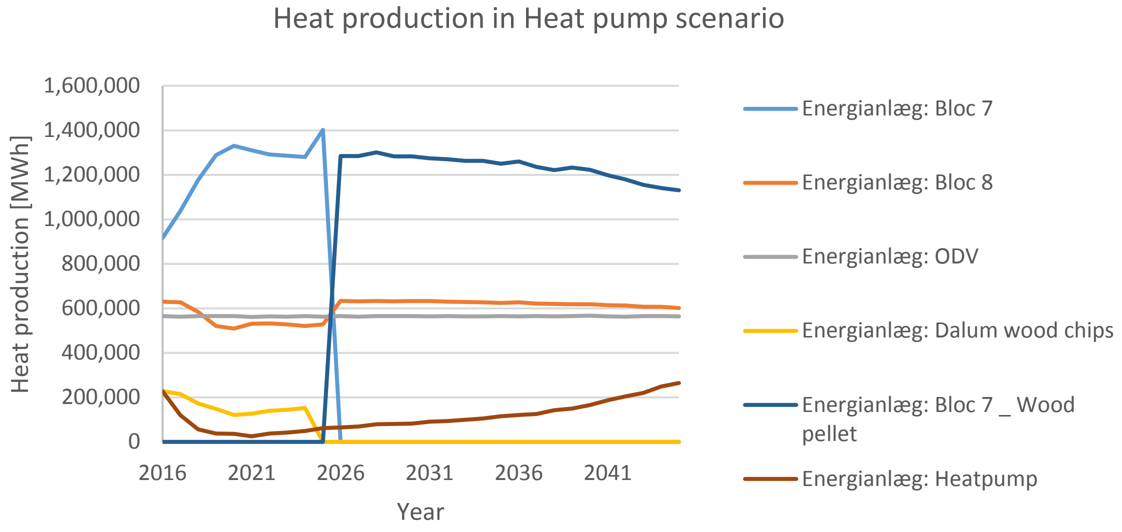

Figure 5.8: Production profile with heat pump alternative

5.5.3 RDF scenario

Figure 5.9 presents the alternative RDF scenario, where a 75 MW RDF boiler is added to the system in addition to the already operating incineration plant (ODV). The waste incineration is a base-load plant that produces at full capacity load almost the entire year. The downtime of the plant (2%) due to maintenance is ignored in the current simulations.

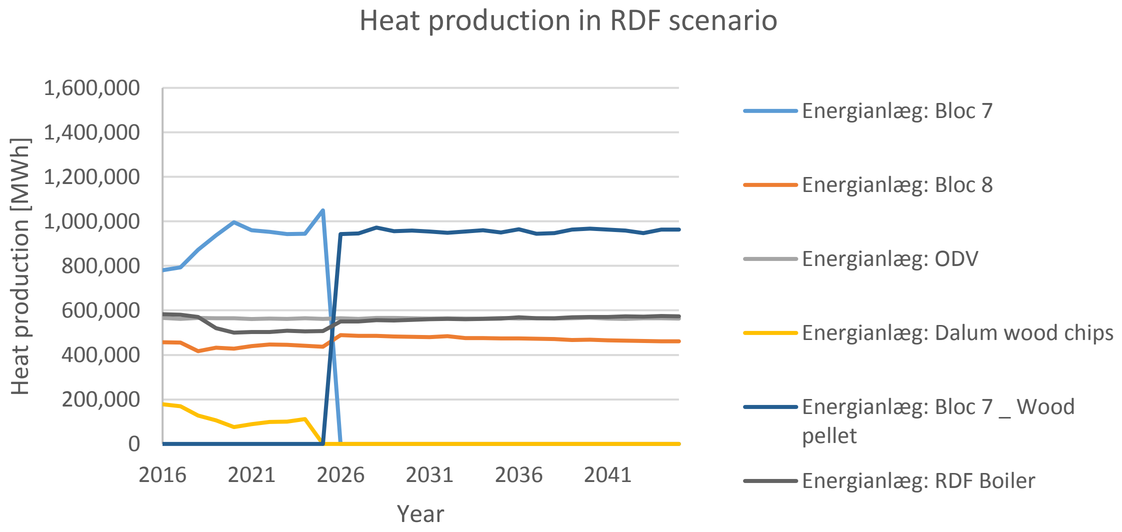

Figure 5.9: Heat production in RDF scenario

It can be seen that the RDF boiler displaces more production from the coal-fired Bloc 8 and straw CHPs. This is due to low fuel costs (292 DKK gate fees) when compared to biomass and electricity price for alternative wood chips boiler and heat pumps respectively. The effect of RDF gate fees on production profiles is presented in the Figure 5.10 below:

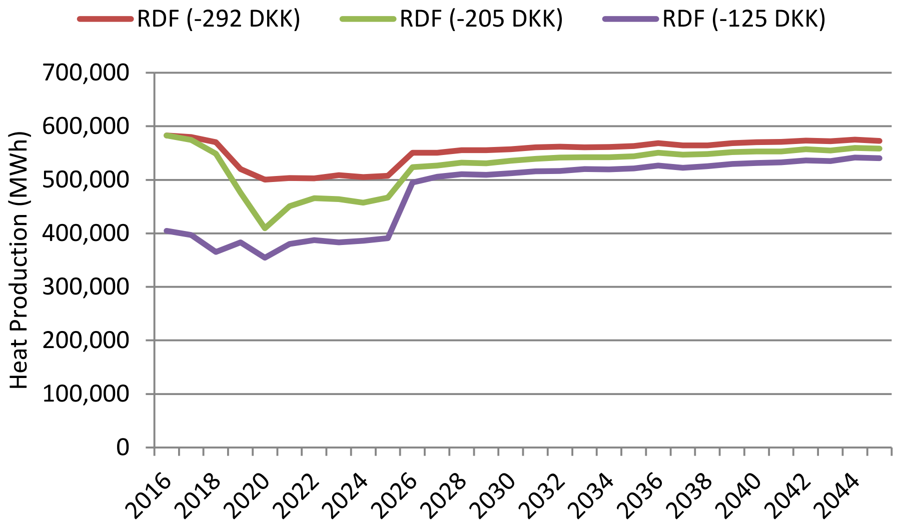

Figure 5.10: Heat production for different RDF prices

Based on the operation strategy and prioritization function of EnergyPRO, the yearly production for the RDF scenario (-292 DKK/ton) is simulated for the period 2016 – 2045. Figure 5.11 demonstrates yearly heat and electricity production for 2017. It can be seen that the incineration CHP operate throughout the year being the unit with lowest NPC. During summer, when the demand is at its lowest, ODV and RDF Boiler suffice the entire demand.

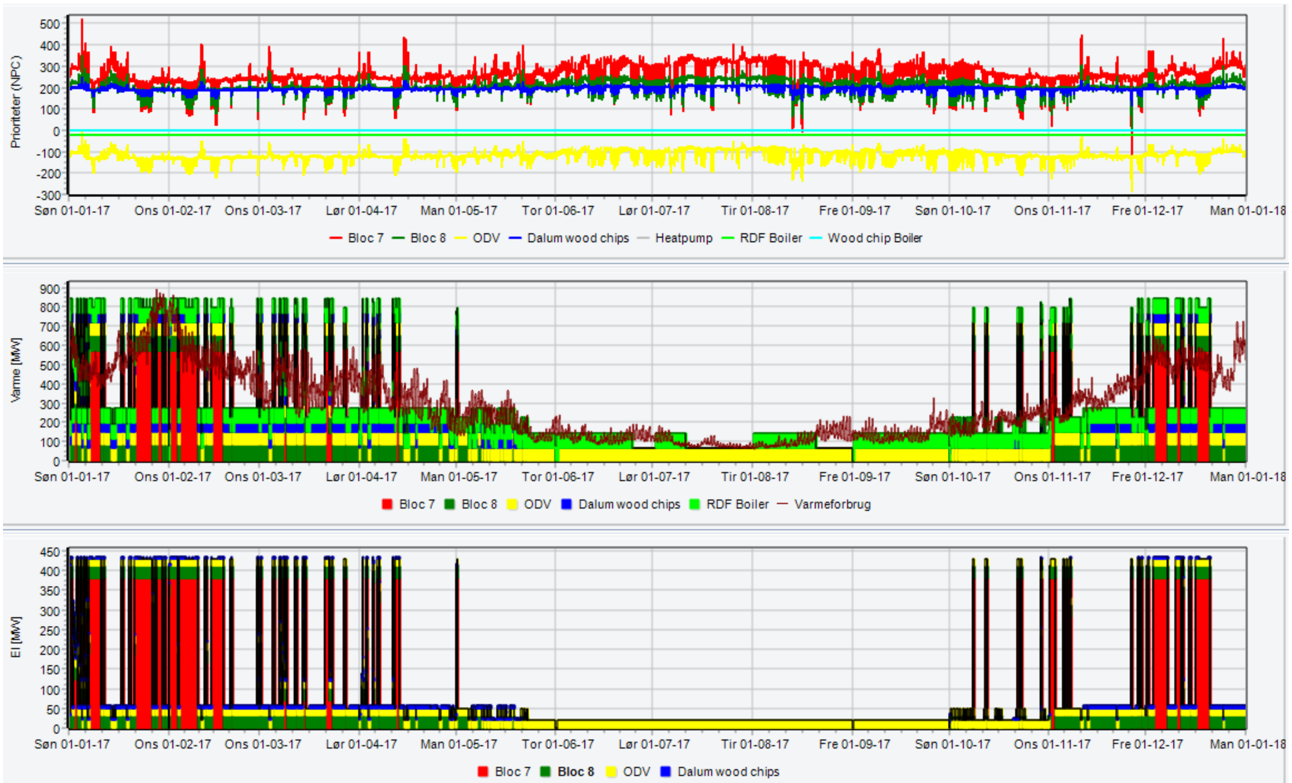

Figure 5.11: RDF Scenario Heat and electricity production profile for 2017

Production profiles for 2026 and 2035 can be found under the appendix Figures 8.4 and 8.5.

5.6 Economic Analysis

The economic analyses are conducted based on the simulations run in EnergyPro, which take into account the cost of production and other factors including taxes and subsidies. The results of these simulations, which include the operation hours based on the least production cost strategy, fuel consumption and cash flow budgets etc., make the basis for the economic analyses.

The Present Net worth (PNW) for the reference and alternative scenarios are calculated from the investment costs, O&M costs and corresponding cash flows in present values for each year. The break-even of the project is found when the PNW becomes positive. The average heat price for the given year for both the reference and the alternative model is calculated as the net cost divided by the annual heat demand.

5.6.1 Business Economics

From a business perspective, all the options demonstrate lower annual returns on investment till 2025 (see Figure 5.12 below). The main reason being higher net production costs while competing with other biomass and coal fired CHPs till 2025. The sudden increase in the NPW of all the scenarios can also be observed in the figure. This is due to the difference in investment cost of the given technologies in year 2016 of the model and the reduced investment cost in year 2026 for the conversion of bloc 7 to wood pellets and due to the reduction in the installed capacity thereafter. Heat pumps would also need reinvestment in 2035, hence a reduction in PNW during that period. Overall, the RDF boiler option returns the highest net worth when compared to heat pump and wood chips alternatives.

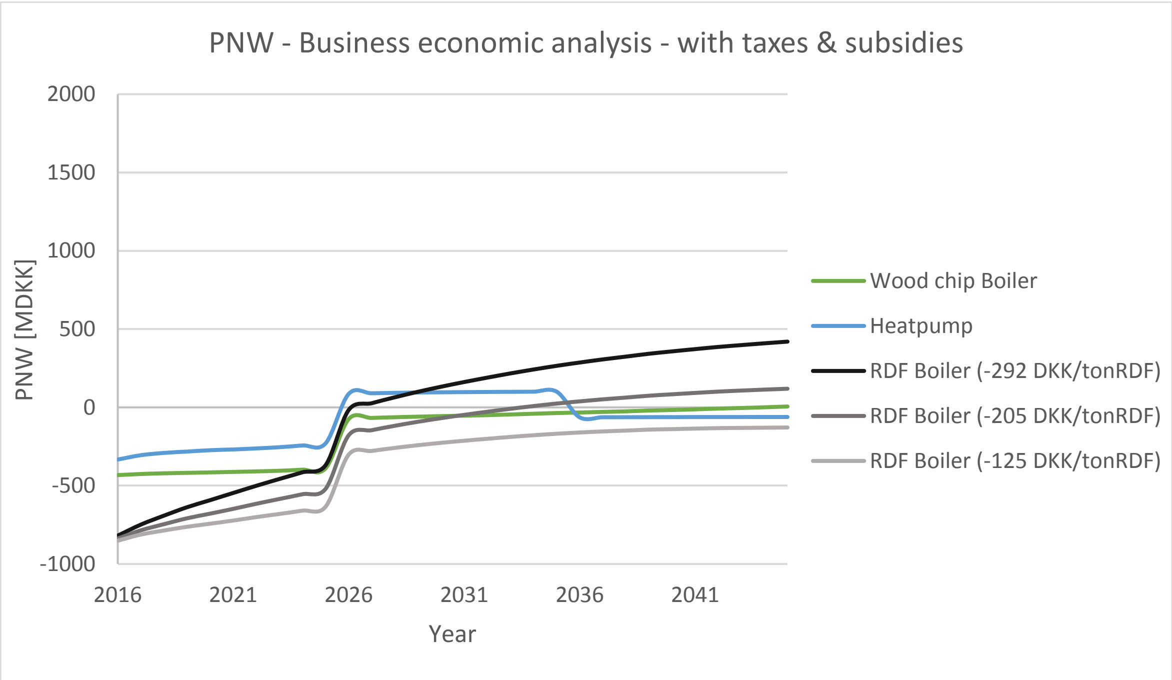

Figure 5.12: Business economics PNW with taxes and subsidies

Two variations of all scenarios have been run where the first is with electricity tax, biomass subsidy and waste tax as they are today. In the second variation the electricity tax has been reduced by 50% and biomass subsidy and waste tax have been completely removed. Moreover, additional simulations have been conducted for higher RDF prices/lower gate fees to assess the viability of such scenarios. The RDF boiler has the highest investment cost (12 MDKK/ MW of heat produced) when compared to wood chip boiler (6 MDKK/ MW) and heat pump (5.2 MDKK/ MW). However, the payback period is almost similar to these alternatives from a business perspective (break even in 11 years). Whereas, the case when electricity taxes are halved on heat pumps and waste taxes are removed along with biomass subsidies, RDF boiler payback period is reduced to 8 years.

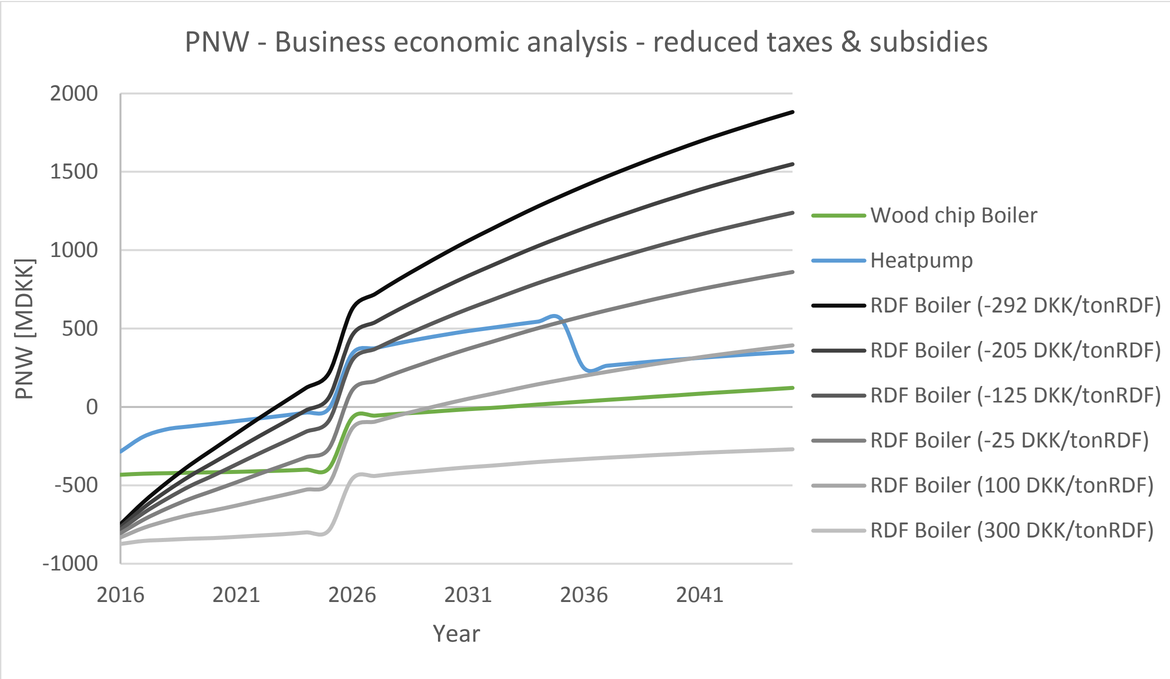

Figure 5.13: Business economics PNW with ½ electricity tax, no waste tax and no biomass subsidies

5.6.2 Socio Economics

The costs that are considered in this socio economic analysis is the total cost for the company, which is the investment costs, O&M costs, lost income from electricity sales and the fuel costs. These costs are considered because FVF is a nonprofit organization and are therefore directly paid by the society. Also the socio economic emission costs and tax distortion are included. The calculations are done by comparing the costs for the reference and the alternative models.

The operation cost for each plant and the emission of gases from production is obtained from the EnergyPRO simulations. The socio economic extra costs of the alternatives, compared to the reference model, are calculated by the extra investments, O&M, lost income from electricity production and extra fuel costs. These extra costs are multiplied by the net tax factor of 1.17. The tax distortion is computed as 20% of the energy taxes that is being avoided. After adding the extra emission costs, the present value (PV) of the amount is calculated for each year with a discount rate of 4%. Furthermore, the present net worth (PNW) is computed. From a socio economic perspective, the payback period is calculated to be 11 years with or without waste taxes. (See Figures 5.14 and 5.15).

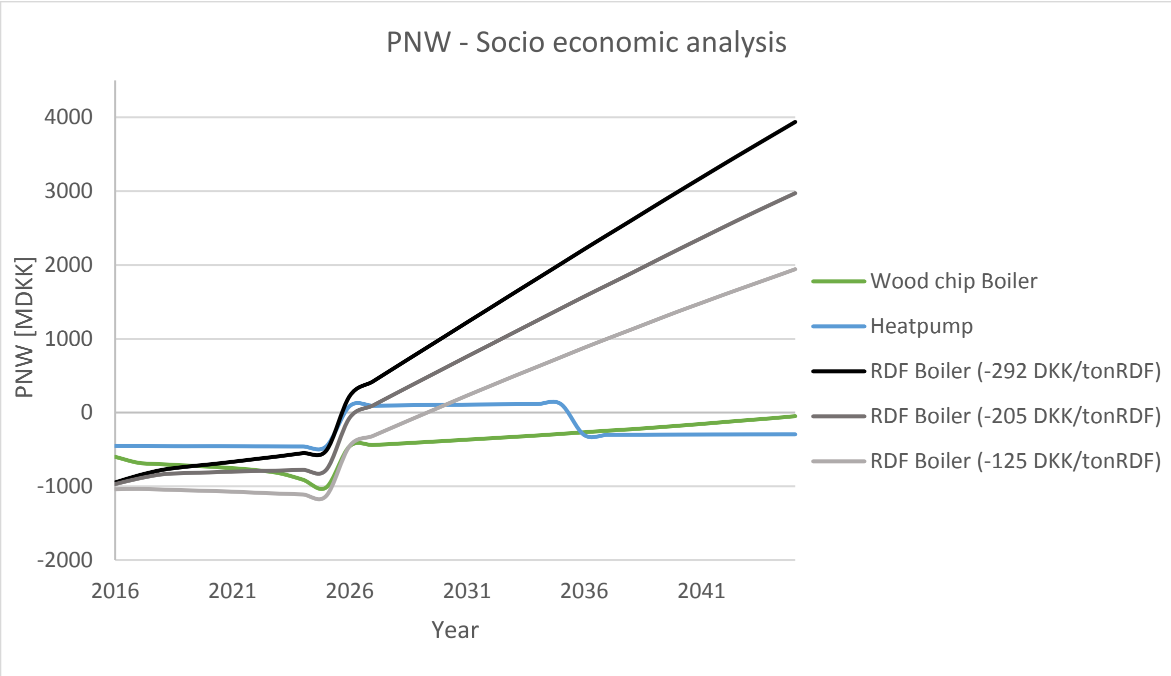

Figure 5.14: Socio-economics PNW with all taxes and subsidies. Note: Taxes and subsidies are only included in calculation of net heat production costs of energy production units in EnergyPRO and not for socio economic payback calculations

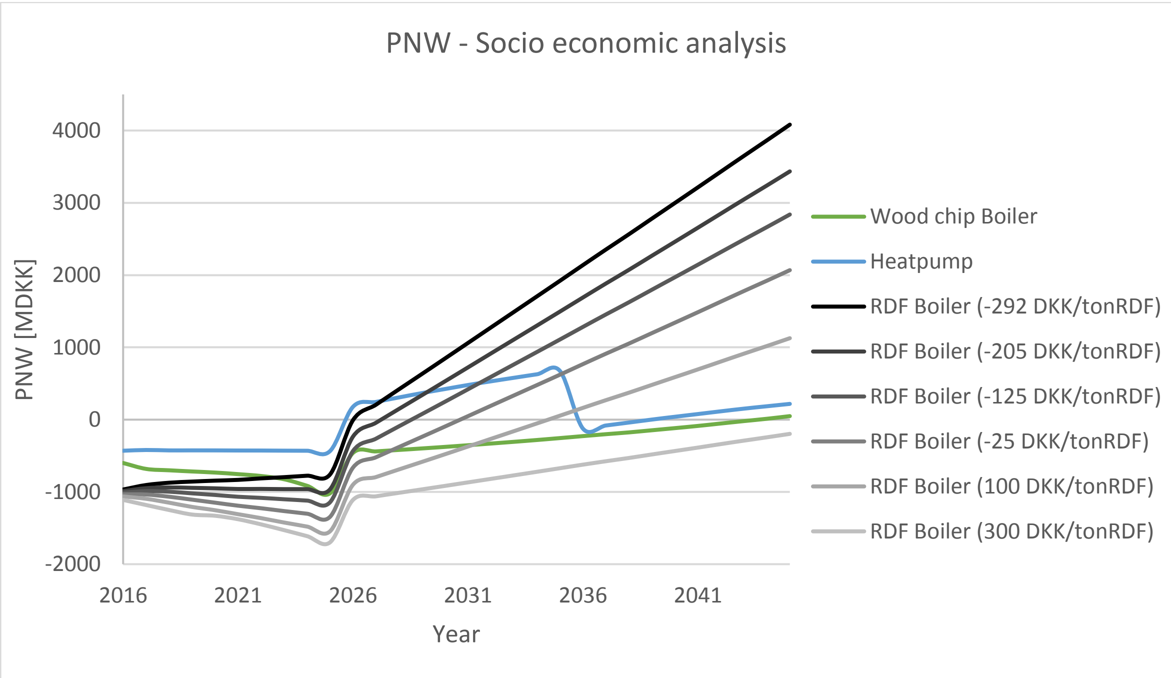

Figure 5.15: Socio-economics PNW with ½ electricity tax, no waste tax and no biomass subsidies (Taxes are only included in calculation of net heat production costs of energy production units in EnergyPRO)

5.6.3 Higher projected biomass prices

It is anticipated that biomass' use for energy purposes will increase considerably in the future and put more strain on the biomass supply, consequently raising the price (Ea Energianalyse, 2016). In accordance with a recent study conducted for Energistyrelsen, a modelling was done assuming a 50% increase in the current biomass price estimates, in order to reflect a biomass market with highly increased demand for wood chips and pellets. The original price projection and the increased price of wood pellets are visualized in Figure 5.165.16.

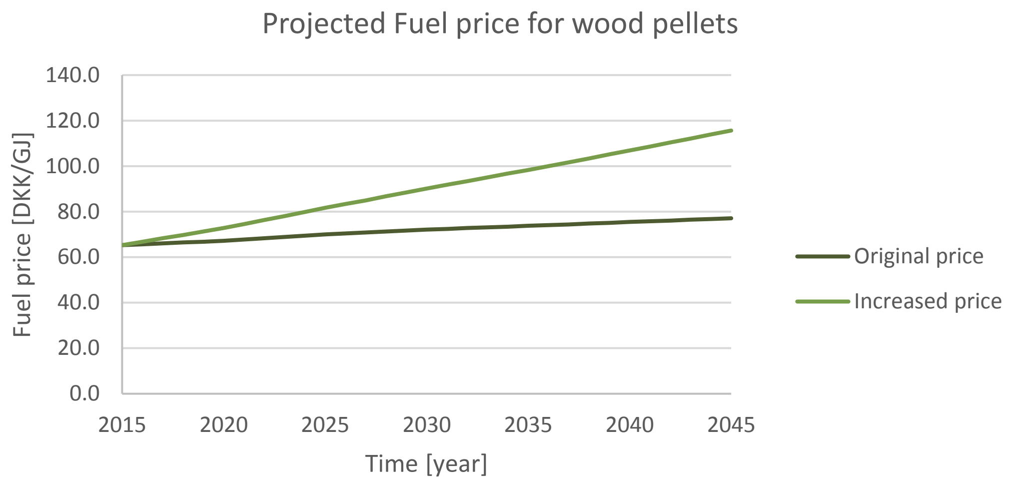

Figure 5.16 Projected wood pellet price and increased wood pellet price estimation

Figures 5.17 to 5.20 present the business and socio-economic net worth of all scenarios with updated biomass prices. RDF still remains an attractive option with the payback period of 11 years for the business economic model with all taxes at RDF price (-292 DKK/ton). However, the break-even period increases to 14 years and 19 years for RDF prices of (-205 DKK/ton) and (-125 DKK/ton) respectively.

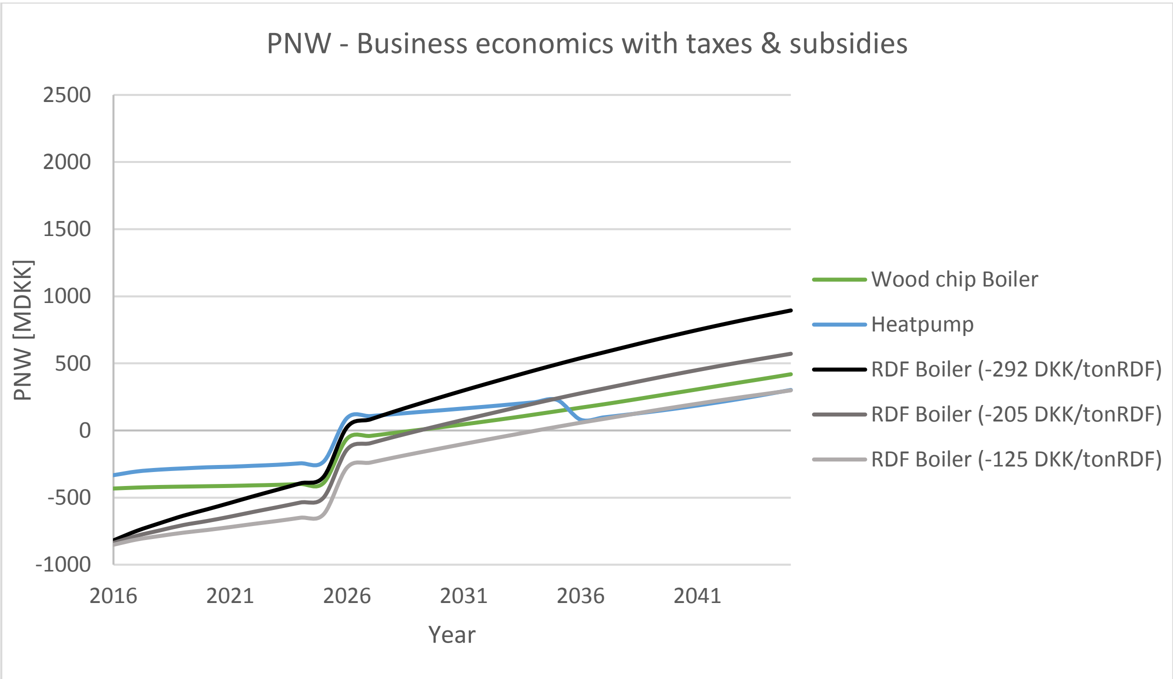

Figure 5.17: Business economics PNW for higher biomass price projections, including taxes and subsidies

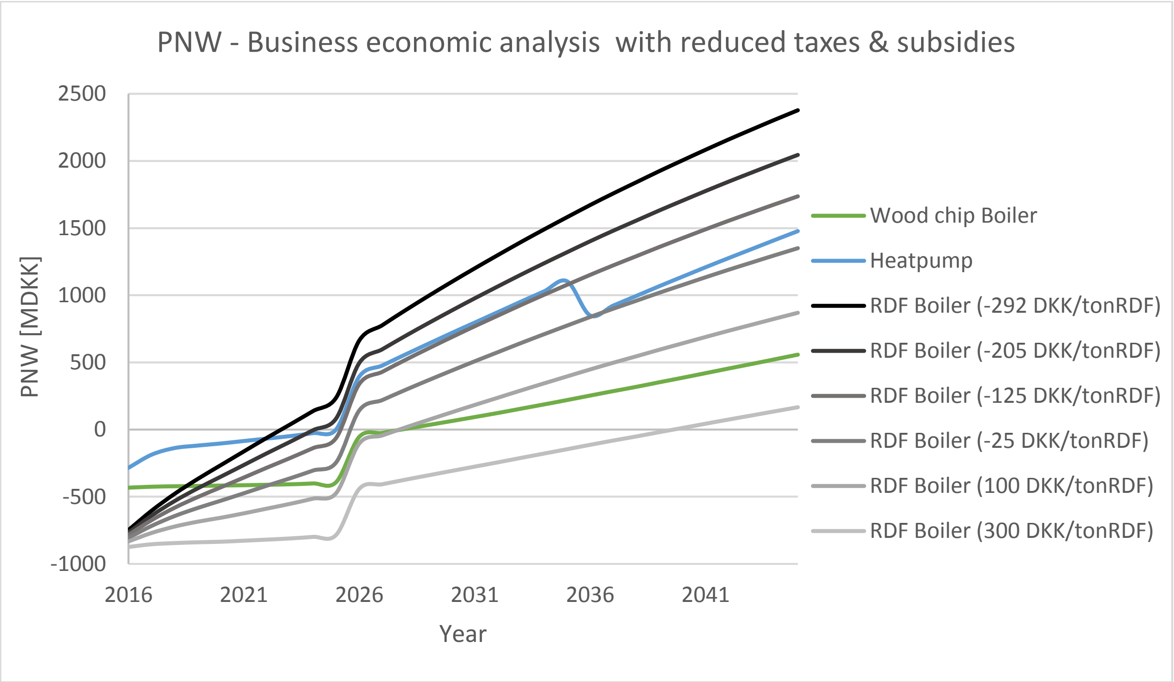

Figure 5.18: Business economics PNW for higher biomass price projections with ½ electricity tax, no waste tax and no biomass subsidies

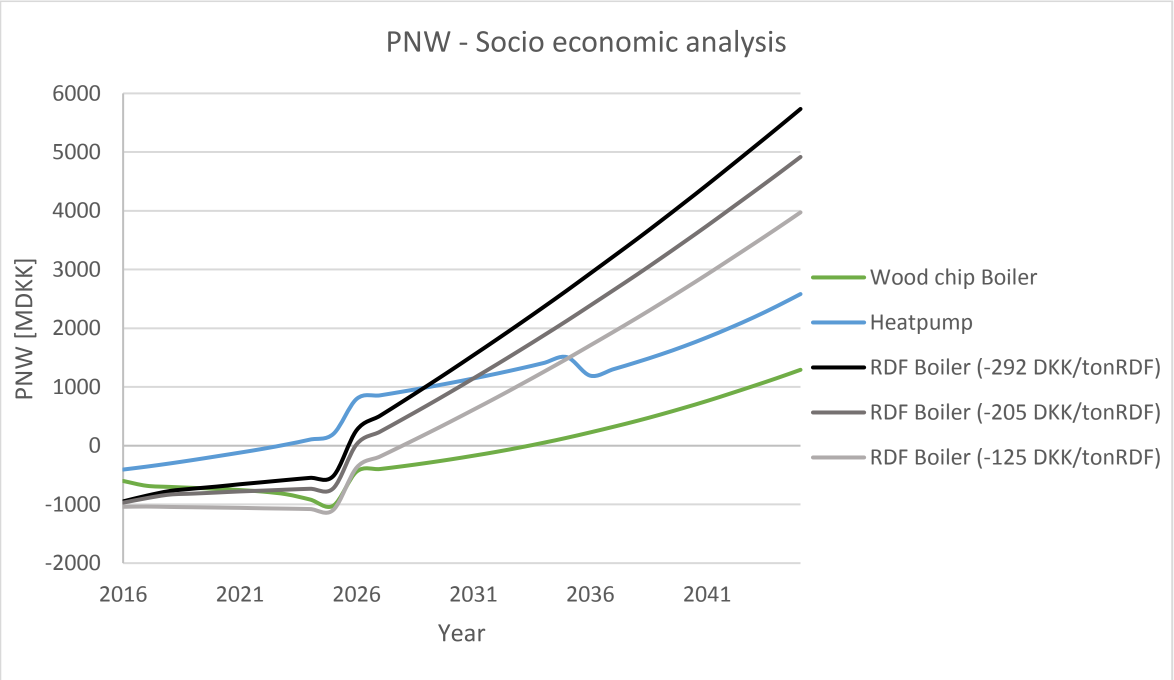

Figure 5.19: Socio- economics PNW for higher biomass price projections, including taxes and subsidies (Taxes and subsidies are only included in calculation of net heat production costs of energy production units in EnergyPRO)

Socio-economically, RDF is among the most attractive options with all taxes included, while still breaking even at 11 years at (-292 DKK/ton), but with the highest PNW over the long term. Payback for the highest simulated RDF price (300 DKK/ton) is calculated to be 28 years at halved electricity taxes and no biomass subsidies and waste taxes.

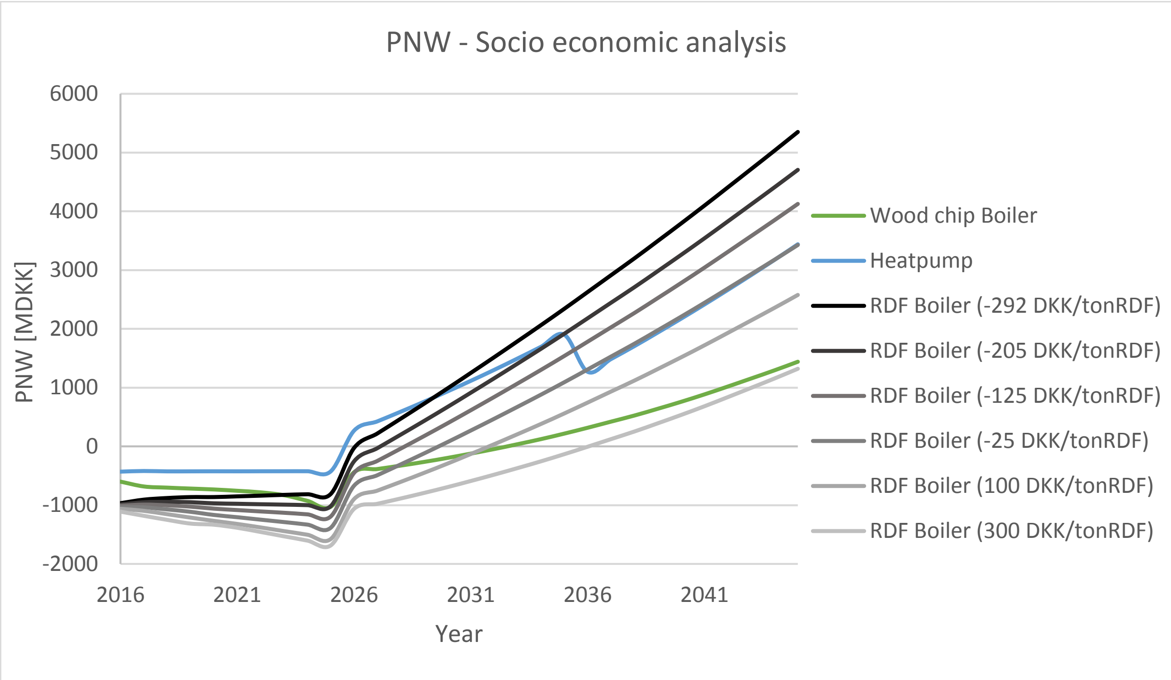

Figure 5.20: Socio- economics PNW for higher biomass price projections with ½ electricity tax, no waste tax and no biomass subsidies (Taxes are only included in calculation of net heat production costs of energy production units in EnergyPRO)

On the other hand, wood chips boiler option is rendered least profitable when compared to the other alternatives of RDF and Heat pumps for both business and socio economics. The main reason being higher net production costs while competing with other biomass and coal fired CHPs till 2025. Heat pumps would also need reinvestment in 2035, hence a reduction in PNW during that period. The RDF boiler demonstrates highest PNW in all scenarios at lowest gate fees (292 DKK/ton) with minimum payback period of 7.5 years and a maximum of 28 years within the simulated timeframe of this study.

6 Conclusion

Two different cases for RDF integration in the district heating system were analysed in this report. Though both cases are very different in terms of their district heating sizes, installed capacities, future framework conditions and methodologies to some extent, the deduced results for RDF prospects in Danish district heating system can be generalized. Both analyses show promising results for RDF boilers in the business case as well as socio-economically feasible within the simulated price ranges.

6.1 Analysis of RDF in Svendborg DH System

For the Svendborg case, the overall objectives were defined by the framework conditions pertaining to the fact that the present incineration plant is due to reach its end of life by 2035. In addition, there are plans to expand the district heating network by 25% till 2020 and by 100% till the year 2035. Therefore, many different configurations of biomass, heat pumps and RDF boilers were formulated to identify the most appropriate solution.

For the time perspective of 2020 and under business economic considerations, the system with the existing incineration plant supplemented by 75% of rest capacity covered by a seawater heat pump and the remaining 25% covered by an additional RDF boiler proved to be best option. The calculated heat price of this system is 290 DKK/MWh, which is around 36% lower than the heat price of the current system. The same scenario appeared to be the most suitable alternative under socio economic aspects, but with a heat price of 245 DKK/MWh.

In Figure 6.1, the breakeven prices of RDF are given for 2020 when modelled under business economics. The results show that RDF is competitive to biomass for all scenarios with prices between -205 DKK/ton and -125 DKK/ton, depending on the heat pump size, whereas the second scenario of 50% heat pump capacity showed to have the lowest heat price in the 2020 comparison. The respective increase of the current gate fee is therefore between 63 DKK and 143 DKK.

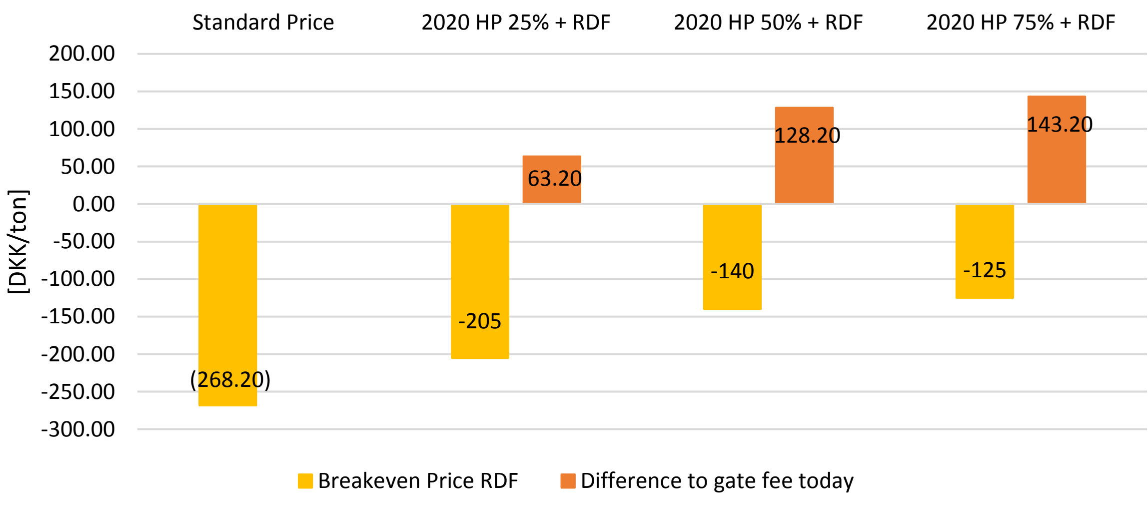

Figure 6.1: RDF Breakeven Prices 2020 under Business Economics

Figure 6.2 presents the same overview of breakeven RDF prices for 2020 from a socio economic perspective. Here, the prices are lower than before and therefore also the span of increase compared to the current gate fee is smaller. As a consequence, the RDF price would need to remain at -268.20 DKK/ton gate fee to compete with the compared biomass system of 25% heat pump capacity when considered under socio economic in 2020.

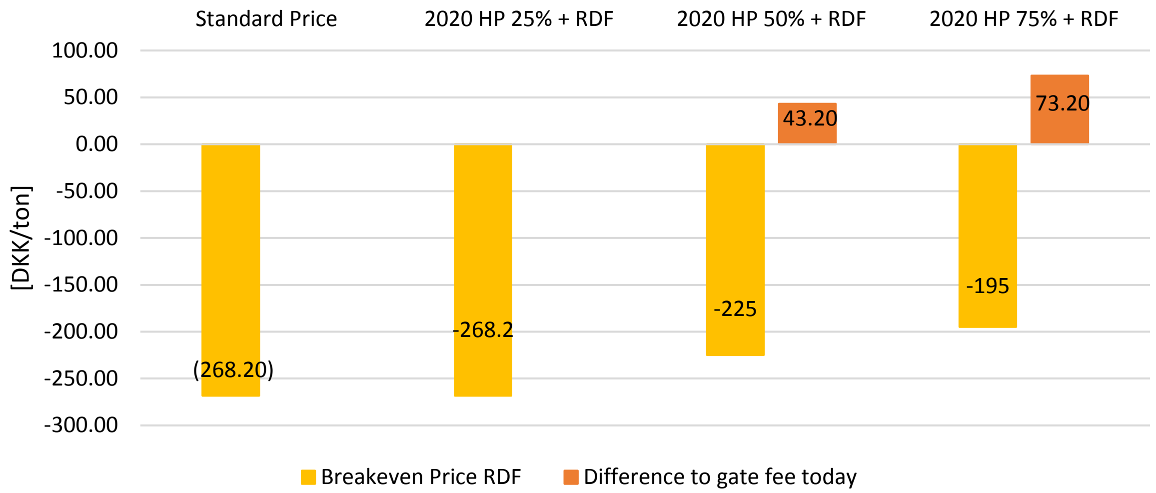

Figure 6.2: RDF Breakeven Prices 2020 under Socio Economics

In 2035, when the incineration plant has been phased out, the most viable system is the one with 25% capacity heat pump and 50% by an RDF boiler, supplemented by thermal heat storage of 61,000m³. This alternative shows the lowest heat price of 252 DKK/MWh within all 2035 scenarios that were investigated.

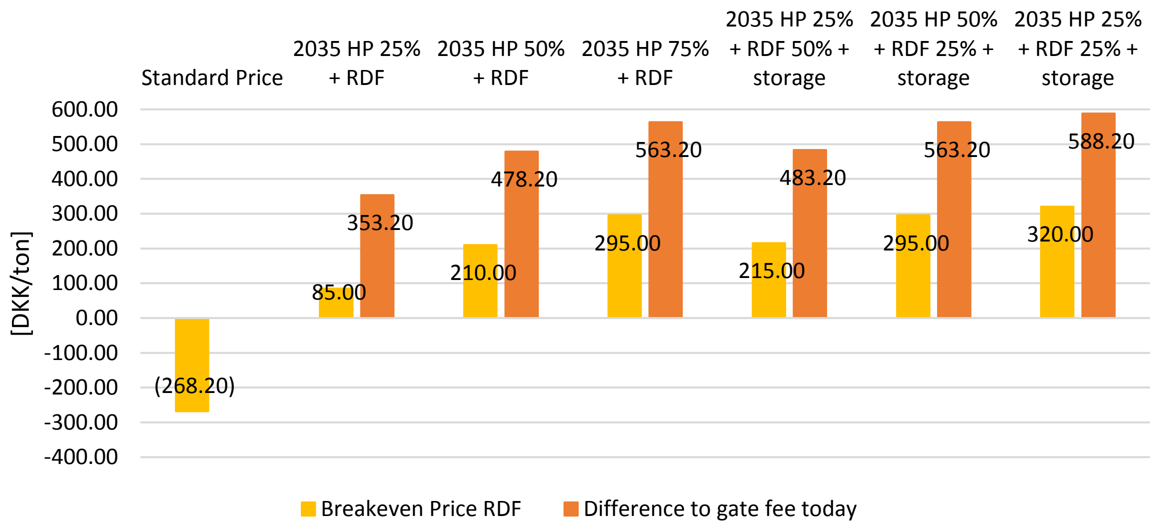

Figure 6.3: RDF Breakeven Prices 2035 under Business Economics

Nevertheless, if electricity taxes and PSO tariff were eliminated, the storage scenario of 25% heat pump capacity and 25% RDF boiler capacity, plus heat storage of 550,000m³ is preferable since its heat price is 237 DKK/MWh. This is again less than in the cheapest scenario under these conditions without a heat storage (50% heat pump and 50% RDF with a heat price of 263 DKK/MWh).

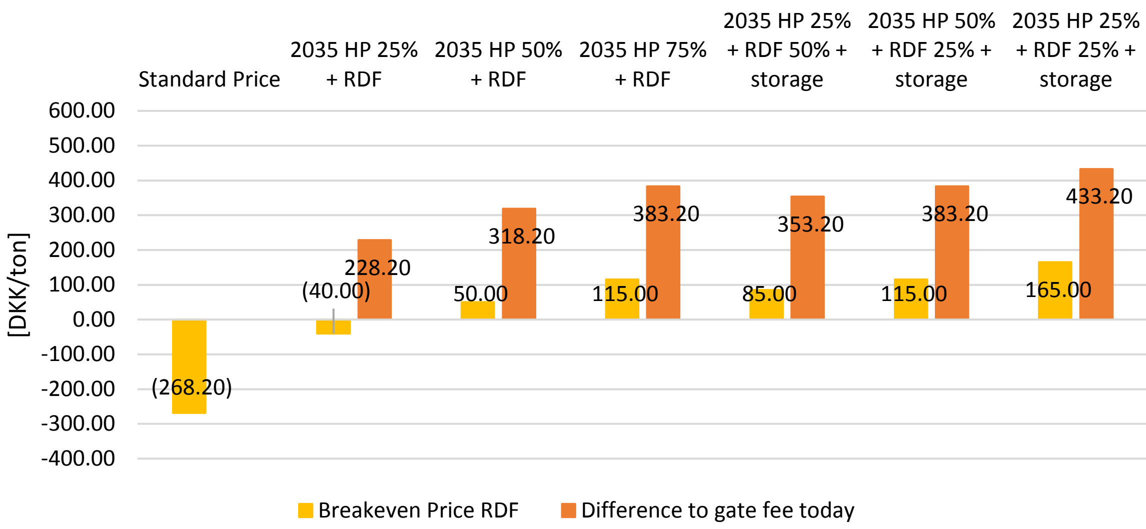

Figure 6.4: RDF Breakeven Prices 2035 under Business Economics (Eliminated Heat Pump Taxes)

From a socio economic perspective, this alternative is also the most appropriate, but with a heat price of 236 DKK/MWh and therefore slightly lower than under business economics. Break even prices under all 2035 socio economic scenarios show to be competitive to biomass with increased RDF prices compared to the current gate fee. The prices are a bit higher than before with eliminated heat pump taxes, as the prices of biomass systems are also slightly higher under socio economics.

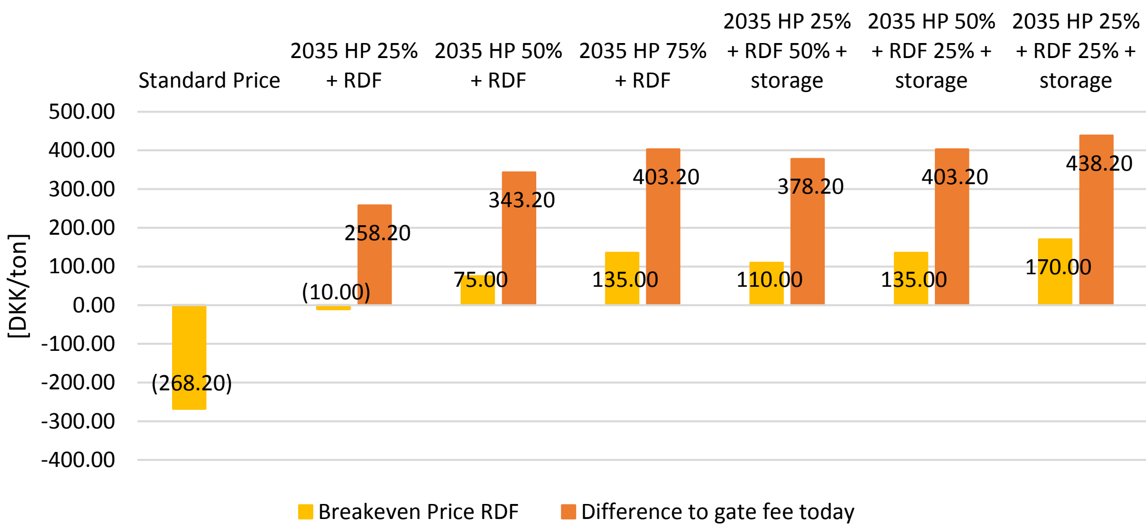

Figure 6.5: RDF Breakeven Prices 2035 under Socio Economics

When comparing the scenarios of 2035 with and without thermal storage, it can be seen that under all conditions studied, options including storage appear to result in lower heat prices. The reason for this lies in all cost categories as the storage decreases investment, operational cost as well as taxes and damage costs. Under business economics the combination of 25% capacity of heat pumps and 50% of RDF boilers plus a small storage of 61,000m^3 is to be preferred. In contrast under socio economics or when heat pump taxes are eliminated it is the alternative consisting of 25% covered by heat pumps, 25% by RDF boilers and a large storage of 550,000m^3, that shows to result in the lowest heat price. This is due to fact that if no heat pump taxes are applied, the heat pump can operate more often, therefore using the storage as seasonal storage. Hence, the storage is filled up during the summer months and emptied during winter months, together with direct production from boilers and heat pumps in winter.

6.2 Analysis of RDF in Odense DH System

In case of RDF integration in Odense district heating system, which is considerably a very large district heating system, a different approach was developed to look into RDF prospects. The framework conditions dictated that the baseload coal fired CHP is anticipated to be converted into a wood pellet plant in 2025, while the Dalum wood chips CHP would be completely scrapped by then. In addition, the incineration plant would continue to run till the end of the simulated period. Keeping in view the size of coal-fired plant (575 MW_{th}) and potential sizes of RDF boilers and heat pumps, 75MW of plant capacity for different alternatives was modelled in these scenarios.

Since the size of comparable alternatives is less than 10% of the total installed capacity of Fjernvarme Fyn, FVF, their influence in setting the heat price would be small. Therefore, a yearly Net Present Worth, PNW analysis was performed to compare these alternatives and calculate the payback periods for their respective investments. Two variations of all scenarios have been run where the first is with electricity tax, biomass subsidy and waste tax as they are today. In the second variation the electricity tax has been reduced by 50% and biomass subsidy and waste tax have been completely removed. Moreover, additional simulations have been conducted for lower RDF gate fees/higher RDF prices to assess the viability of such scenarios.

In accordance with a recent study conducted for Energistyrelsen, a modelling was done assuming a 50% increase in the current biomass price estimates, in order to reflect a biomass market with highly increased demand for wood chips and pellets (see Figures 6.6 and 6.7).

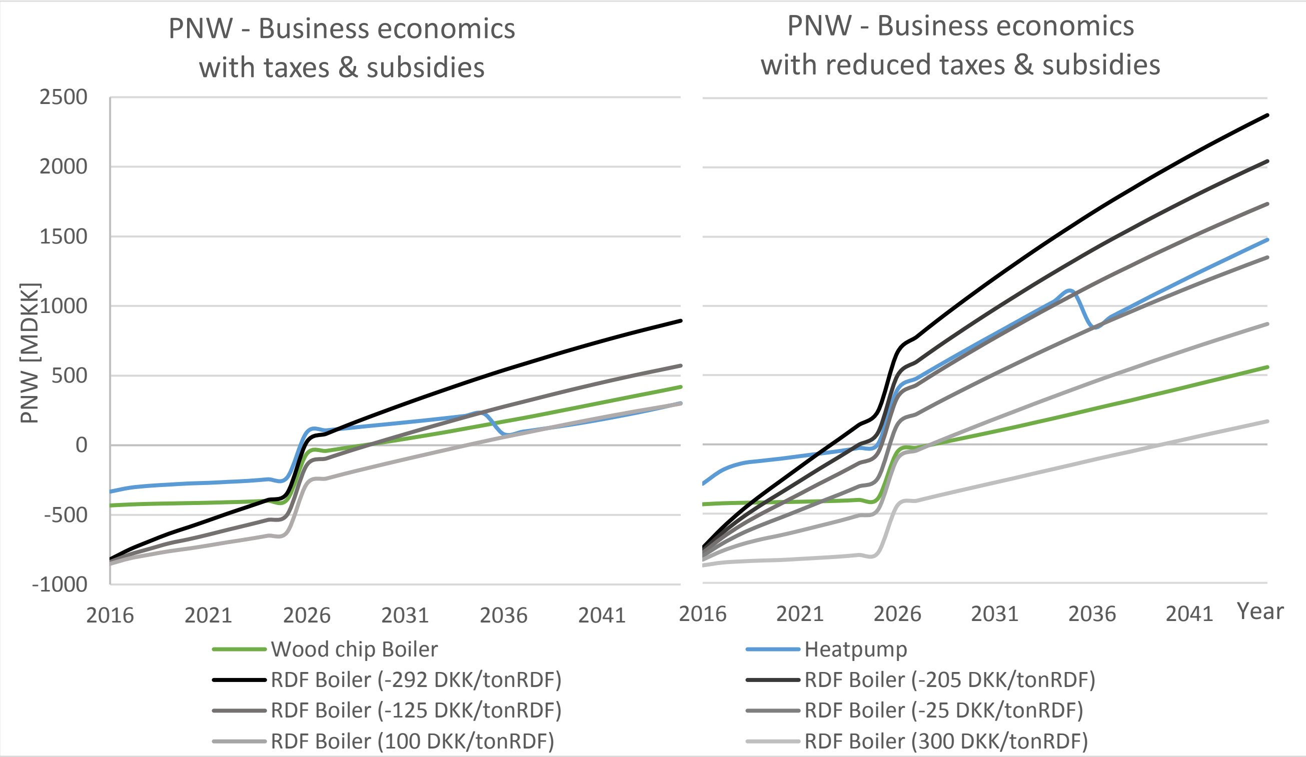

Figure 6.6: Business economic PNW for high biomass price scenario; a) with all taxes and subsidies, b) with ½ electricity tax, no waste taxes and no subsidies on biomass

In general, RDF boiler option has shown most promise even though with the highest investment cost (12 MDKK/ MW of heat produced) when compared to wood chip boiler (6 MDKK/ MW) and heat pump (5.2 MDKK/ MW). The RDF boiler economy is predominantly influenced by the RDF gate fees and investment savings in replacing coal-fired CHP to a smaller size wood pellet CHP. The highest gate fee simulated in our models is 292 DKK/ton, and if district heating companies are able to secure RDF import deals at higher gate fees, the RDF boiler option becomes even more attractive.

From today's business perspective, the return on investment is not substantial till 2025; therefore it would be beneficial if investment in RDF boiler is postponed until closer to investment in replacing coal-fired CHP to a wood pellet one. On the other hand, reduced electricity and waste taxes advocate an earlier investment in RDF boiler as the annual return on investment is quite high for this particular scenario.

It is important to mention that the sudden increase observed in the PNW in year 2026 in all the scenarios is due to the fact that the initial investment in 75 MW of RDF boiler, wood chip boiler and heat pump capacity in 2016 leads to a proportional saving of 75 MW capacity of wood chip CHP in the assumed conversion of the coal CHP to wood chip CHP in year 2026.

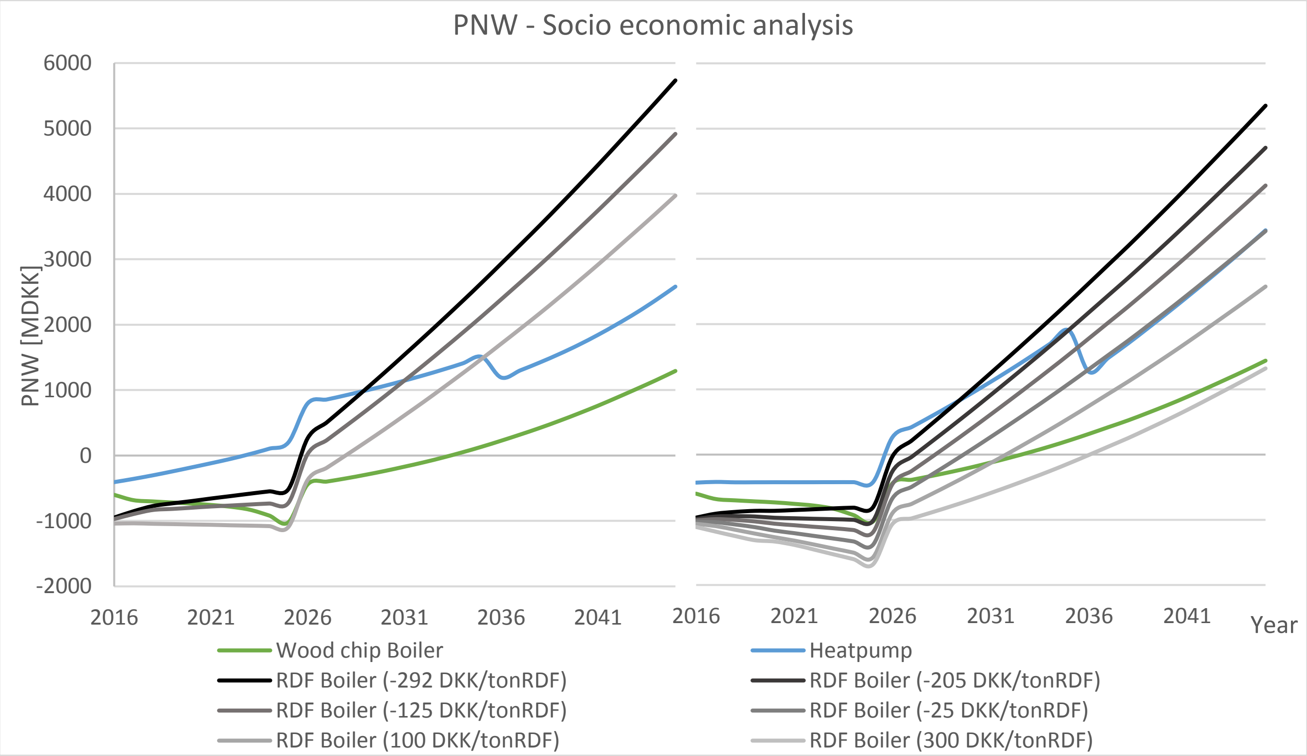

Figure 6.7: Socio economic PNW for high biomass price scenario; Left) with all taxes and subsidies, Right) with ½ electricity tax, no waste taxes and no subsidies on biomass. Note: Taxes and subsidies are only included in calculation of net heat production costs of energy production units in EnergyPRO simulation tool and not for socio economic payback calculations

A typical conversion of coal plants to wood pellets fuel requires modified coal mills, additional storage silos and transport systems for the pellets. The lower calorific value of wood compared with coal increases the necessary fuel amounts to approximately double volume. In addition, the burners need modification or replacement all together and steam soot blowers to prevent ash formation and slag deposits in the boiler (Danish Energy Agency, 2016). By gauging these conversion needs, it is fair to assume that coal plant conversion to a reduced wood pellet plant size is achievable with linear cost savings. Nevertheless, further sensitivity analysis of the increase in PNW in Figure 0.4

reveals that the payback period for RDF boiler would increase by 5 years only if there were no such investment savings in year 2026 at all. And if this investment saving would be only 50%, this would result in delay of payback by 3 years.

From a socio-economic perspective, RDF boiler is competitive even at positive RDF prices. However, any investment in RDF and wood chip boiler would not return a considerable payback till 2026. The main reason being higher net production costs while competing with other biomass and coal fired CHPs till 2026. However, once the coal-fired CHP is replaced, RDF and wood chip boilers start to make profit, with RDF being the most attractive option due to its lower payback period. Heat pump alternative also shows similar developments, however would need reinvestment after 20 years, hence a reduction in PNW during that period. Therefore, it is implied that appropriate time for investment in a RDF boiler is after 2025, when the coal-fired CHP is either decommissioned or replaced with a wood pellet boiler.

Figure 6.8 illustrates break-even periods for RDF boiler at different RDF prices for low and high biomass price scenarios in order to highlight the effect of increased biomass prices on the payback periods. It can be further deduced that the payback period will be shorter if investment in RDF boiler is delayed till 2025 for the reasons described above.

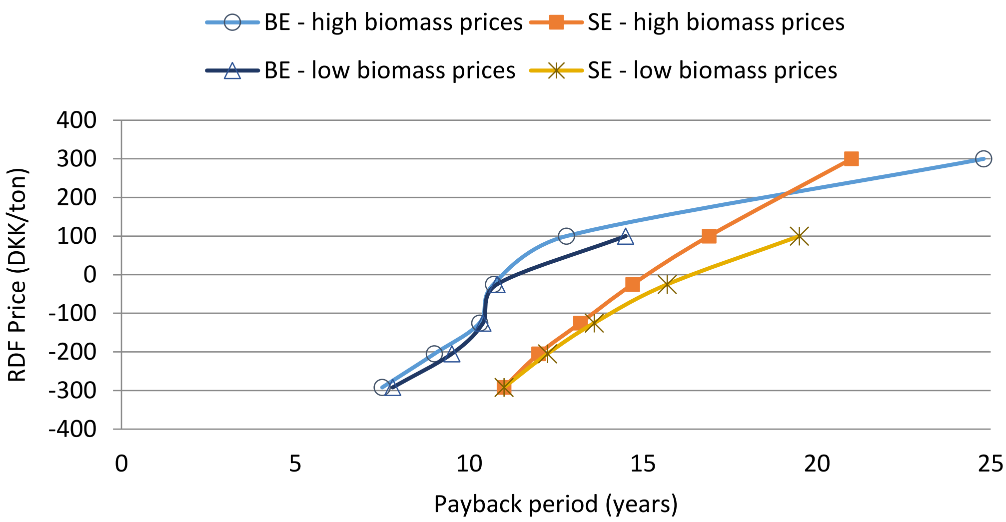

Figure 6.8: RDF boiler payback periods: Business Economic (BE) and Socio Economic (SE) paybacks for high and low biomass price scenarios with ½ electricity tax, no waste tax and no biomass subsidies (Taxes and subsidies are only included in calculation of net heat production costs of energy production units in EnergyPRO)

7 References

BARFOD, M. B. 2015. Socio-economic analysis in the transport sector. *In:* LELEUR, S. (ed.) 2 ed. Lyngby: Technical University of Denmark, Transport.

CHRISTENSEN, T. H. 2011. *Solid Waste Technology & Management,* Chichester, John Wiley & Sons Ltd.

CIMPAN, C., ROTHMANN, M., HAMELIN, L. & WENZEL, H. 2015a. Towards increased recycling of household waste: Documenting cascading effects and material efficiency of commingled recyclables and biowaste collection. *Journal of environmental management,* 157**,** 69-83.

CIMPAN, C., ROTHMANN, M. & WENZEL, H. 2015b. Material flow analysis, carbon footprint and economic assessment of alternative collection and treatment of domestic household waste from the region of Funen, Denmark. Odense: Centre for Life Cycle Engineering.

DAHLQUIST, L. J. 2016a. *Aktuelle tariffer og gebyrer* [Online]. Energinet.dk. Available: http://www.energinet.dk/DA/El/Engrosmarked/Tariffer-og-priser/Sider/Aktuelle-tariffer-og-gebyrer.aspx [Accessed 05/10 2016].

DANISH ENERGY AGENCY 2014a. Forudsætninger for samfundsøkonomiske analyser på energiområdet, December 2014. Copenhagen.

DANISH ENERGY AGENCY 2014b. Technology Data for Individual Heating and Energy Transport.

DANISH ENERGY AGENCY 2016a. Forudsætninger for samfundsøkonomiske analyser på energiområdet, April 2016. Copenhagen.

DANISH ENERGY AGENCY 2016b. Fremskrivning af omkostninger til PSO på baggrund af Energistyrelsens Basisfremskrivning 2015. Copenhagen.

DANISH ENERGY AGENCY AND ENERGINET.DK 2016. Technology Data for Energy Plants. The Danish Energy Agency.

DANSK KOMPETENCECENTER FOR AFFALD OG RESSOURCER 2016. Nyhed: Import af affald til danske affaldsforbrændingsanlæg steget 25 %.

EA ENERGIANALYSE 2015. Energiafgifter og -tilskud - Overblik og analyse. Copenhagen.

EA ENERGIANALYSE 2016. El, varme og affaldsforbrænding - Analyse af økonomi ved import af affald i et langsigtet perspektiv Copenhagen.

ENERGINET.DK 2015. Analyseforudsætninger 2015-2035. Energinet.dk.

EUROPEAN COMISSION 2008. Directive 2008/98/EC of the European parliament and of the Council of 19 November 2008 on waste and repealing certain Directives. *Official Journal of the European Union*.

FRAGAKI, A., ANDERSEN, A. N. & TOKE, D. 2008. Exploration of economical sizing of gas engine and thermal store for combined heat and power plants in the UK. *Energy,* 33**,** 1659-1670.

HANSEN, A. B. 2014. E.1 Scenarios of Future Electricity Production and Prices. Energinet.dk.

HANSEN, N. C. 2015. *RE: Svendborg kraftvarme data til energisystemet analyse.* Type to CIMPAN, C. & GABERT, M.

HANSEN, N. C. 2016. *RE: Svendborg kraftvarme data til energisystemet analyse.* Type to GABERT, M.

IPCC 2007. Climate Change 2007: Synthesis Report. *In:* PACHAURI, R. K. & REISINGER, A. (eds.). Geneva: IPCC.

KISS, V. M. 2015. Modelling the energy system of Pécs – The first step towards a sustainable city. *Energy,* 80**,** 373-387.

LUND, H. & ANDERSEN, A. N. 2005. Optimal designs of small CHP plants in a market with fluctuating electricity prices. *EnergyConversion and Management,* 46**,** 893-904.

ØSTERGAARD, P. A. & ANDERSEN, A. N. 2016. Optimal use of heat pumps in district heating systems – individual booster heat pumps vs central heat pumps. Aalborg: Aalborg University & EMD International.

PWC 2015a. Overblik over afgiftssatser i 2015 og 2016 - oversigten er ikke udtømmende. Copenhagen.

PWC 2015b. Samlet overblik over afregning og godt-gørelse af afgifter - Afgiftsvejledning 2016. Hellerup.

SEKRETARIATET FOR AFGIFTS- OG TILSKUDSANALYSEN PÅ ENERGIOMRÅDET 2016. Afgifts- og tilskudsanalysen på energiområdet - Delanalyse 2: Omkostninger til offentlige forpligtelser. Skatteministeriet.

SKATTEMINISTERIET. 2016. *Elafgiftsloven* [Online]. Available: http://www.skm.dk/skattetal/satser/satser-og-beloebsgraenser/elafgiftsloven [Accessed 05/04 2016].

STATENS BYGGEFORSKNINGSINSTITUT AALBORG UNIVERSITET 2010. Danske bygningers energibehov i 2050. Hørsholm: Statens Byggeforskningsinstitut.

STRECKIENĖ, G., MARTINAITIS, V., ANDERSEN, A. N. & KATZ, J. 2009. Feasibility of CHP-plants with thermal stores in the German spot market. *Applied Energy,* 86**,** 2308-2316.

SVENDBORG KRAFTVARME. n.a. *Velkommen til Svendborg Kraftvarme A/S* [Online]. Available: http://svendborgkraftvarme.dk [Accessed 12/09 2016].

THE DANISH GOVERNMENT 2011. Energy Strategy 2050 - from coal, oil and gas to green energy. Copenhagen: The Danish Ministry of Climate and Energy.

THE DANISH GOVERNMENT 2013. Danish Resource Strategy: Denmark without waste, Recycle more - incinerate less. The Environmental Protection Agency.

WATKINS, E., HOGG, D., MITSIOS, A., MUDGAL, S., NEUBAUER, A., REISINGER, H., TROELTZSCH, J. & VAN ACOLEYEN, M. 2012. Use of Economic Instruments and Waste Management Performances. Paris: Bio Intelligence Service.

WITTRUP, S. 2015. Nu etableres 10 stora varmepumper i fjernvarmen. *Ingeniøren.* Ingeniøren.

8 Appendix

8.1 Data on Energy Conversion Units

Table 8.1: Production units data (Danish Energy Agency and Energinet.dk 2015, Hansen 2015, Madsen 2016a)

NG engine		
Input max. load	39.5	MW
Design output 1	19.8	MW_{heat}
	16.5	MW_{el}
Input min. load	19.7	MW
Design output 2	9.9	MW_{heat}
	8.3	MW_{el}
Net efficiency	0.92	
Lifetime	20	yr
Min. load	0.50	
NG boiler		
Input	30.9	MW
Output	31.2	MW_{heat}
Net efficiency	1.01	
Lifetime	30	Yr
Oil boiler		
Input	48.0	MW
Output	48.0	MW_{heat}
Net efficiency	1.00	
Lifetime	20	Yr
Woodchip boiler		
Input one unit 2020	11.6	MW
Output one unit 2020	12.5	MW_{heat}
Input one unit 2035	25.4	MW
Output one unit 2035	27.4	MW_{heat}
Net efficiency	1.08	
Lifetime	20	yr
LHV woodchips	10.05	GJ/ton
RDF boiler		
Input one unit 2020	12.8	MW
Output one unit 2020	12.5	MW_{heat}
Input one unit 2035	28.1	MW
Output one unit 2035	27.4	MW_{heat}
Net efficiency	0.98	
Lifetime	20	yr
LHV RDF	13	GJ/ton
Incineration plant		
Design input	20.0	MW
Max. load design output 1	13.8	MW_{heat}
	4.2	MW_{el}
Max. load design output 2	17.0	MW_{heat}
	1.0	MW_{el}
Min. load design output 1	4.6	MW_{heat}
	4.2	MW_{el}
Min. load design output 2	7.8	MW_{heat}

	1.0	MW_{el}
Construction year	1999	
Lifetime	30	years
Running hours 2014	7,984	h/yr

Table 8.2: Data Flue Gas Heat Pump (Hansen, 2015, Danish Energy Agency and Energinet.dk, 2015, Hoffmann, 2014)

Flue gas heat pump		
Construction year	2017	
Design output	3.6	MW_{heat}
	14,400.0	MWh/yr
Design input	0.6	MW_{el}
COP	6.5	
Lifetime	20.00	yr

Table 8.3: Sea Water heat pump COP Values Calculated and from Johnson Controls (Linemann, 2016)

		Calculated	Johnson Controls	Deviation	Calculated	Johnson Controls	Deviation
	Source Temp. [°C]	**2020**	**2020**		**2035**	**2035**	
Jan	1.3	2.7	2.9	8%	3.1	3.1	-1%
Feb	2.1	2.7	2.9	7%	3.2	3.1	-3%
Mar	1.5	2.7	2.9	7%	3.1	3.1	-2%
Apr	7.9	3.0	3.1	3%	3.6	3.3	-8%
May	11.5	3.2	3.3	3%	3.9	3.7	-5%
Jun	13.3	3.3	3.3	-1%	4.1	3.7	-9%
Jul	19.3	3.8	3.5	-7%	4.8	3.9	-19%
Aug	21.2	3.9	3.7	-6%	5.1	4.1	-19%
Sep	17.5	3.6	3.5	-4%	4.6	3.9	-14%
Oct	14.2	3.4	3.3	-3%	4.2	3.7	-11%
Nov	11.1	3.2	3.3	4%	3.9	3.7	-4%
Dec	7.9	3.0	3.1	3%	3.6	3.3	-8%
Average	**10.7**	**3.2**	**3.2**	**1%**	**3.9**	**3.6**	**-9%**

Table 8.4: Data Seasonal Thermal Storage (Madsen, 2016d)

PTES		
Heat source	heat pump and boiler	
Temperature in the top	70.0[1]	°C
Temperature in the bottom	35.0[2]	°C
Utilization	100.0[3]	%
Minimum storage content	0.0	
Storage loss	0.0[4]	%

[1] Estimated supply temperature of Svendborg district heating by 2035 (Madsen, 2016d)

[2] Estimated return temperature of Svendborg district heating by 2035 (Madsen, 2016d)

[3] By utilization, energyPRO means the share of the tank that is filled with water. It was set to be 100% since no other information was available.

[4] Energy losses of the PTES were not included in this study due to missing information on the technology. The losses are however estimated to be not more than 5% and therefore would not have significant impacts.

8.2 Overview of analysed scenarios

Table 8.5: Overview Scenarios 2014 and 2020

2014 & 2020			
Scenario	**Fuel**	**Production unit**	**Max heat capacity in [MW]**
2014 baseline	Local waste	Incineration plant	17
	Natural gas	Natural gas boiler	31.2
	Natural gas	Natural gas engine	19.8
	Biooil	Oil boiler	48
2020 HP 25% + biomass	Local waste + RDF	Incineration plant	17
	Electricity	Flue gas heat pump	3.6
	Electricity	Heat pump	12.5
	Woodchips	Biomass boiler	37.6
2020 HP 25% + RDF	Local waste + RDF	Incineration plant	17
	Electricity	Flue gas heat pump	3.6
	Electricity	Heat pump	12.5
	RDF	RDF boiler	37.6
2020 HP 50% + biomass	Local waste + RDF	Incineration plant	17
	Electricity	Flue gas heat pump	3.6
	Electricity	Heat pump	25.1
	Woodchips	Biomass boiler	25.1
2020 HP 50% + RDF	Local waste + RDF	Incineration plant	17
	Electricity	Flue gas heat pump	3.6
	Electricity	Heat pump	25.1
	RDF	RDF boiler	25.1
2020 HP 50% + biomass	Local waste + RDF	Incineration plant	17
	Electricity	Flue gas heat pump	3.6
	Electricity	Heat pump	37.6
	Woodchips	Biomass boiler	12.5
2020 HP 50% + RDF	Local waste + RDF	Incineration plant	17
	Electricity	Flue gas heat pump	3.6
	Electricity	Heat pump	37.6
	RDF	RDF boiler	12.5
2020 HP 100%	Local waste + RDF	Incineration plant	17
	Electricity	Flue gas heat pump	3.6
	Electricity	Heat pump	50.1

Table 8.6: Overview Scenarios 2035

2035			
Scenario	**Fuel**	**Production unit**	**Max heat capacity in [MW]**
HP 25% + biomass	Electricity	Heat pump	27.4

	Woodchips	Biomass boiler	82.2
HP 25% + RDF	Electricity	Heat pump	27.4
	RDF	RDF boiler	82.2
HP 50% + biomass	Electricity	Heat pump	54.8
	Woodchips	Biomass boiler	54.8
HP 50% + RDF	Electricity	Heat pump	54.8
	RDF	RDF boiler	54.8
HP 75% + biomass	Electricity	Heat pump	82.2
	Woodchips	Biomass boiler	27.4
HP 75% + RDF	Electricity	Heat pump	82.2
	RDF	RDF boiler	27.4
HP 100%	Electricity	Heat pump	109.6
HP 25% + biomass 50% + storage	Electricity	Heat pump	27.4
	Woodchips	Biomass boiler	54.8
	Water	PTES	2,474 MWh
HP 25% + RDF 50% + storage	Electricity	Heat pump	27.4
	RDF	RDF boiler	54.8
	Water	PTES	2,474 MWh
HP 50% + biomass 25% + storage	Electricity	Heat pump	54.8
	Woodchips	Biomass boiler	27.4
	Water	PTES	2,515 MWh
HP 50% + RDF 25% + storage	Electricity	Heat pump	54.8
	RDF	RDF boiler	27.4
	Water	PTES	2,515 MWh
HP 25% + biomass 25% + storage	Electricity	Heat pump	27.4
	Woodchips	Biomass boiler	54.8
	Water	PTES	22,307 MWh
HP 25% + RDF 25% + storage	Electricity	Heat pump	27.4
	RDF	RDF boiler	54.8
	Water	PTES	22,307 MWh
HP 50% + storage	Electricity	Heat pump	54.8
	Water	PTES	20,858 MWh

Scenario 2020: Incineration plant and HP and Biomass

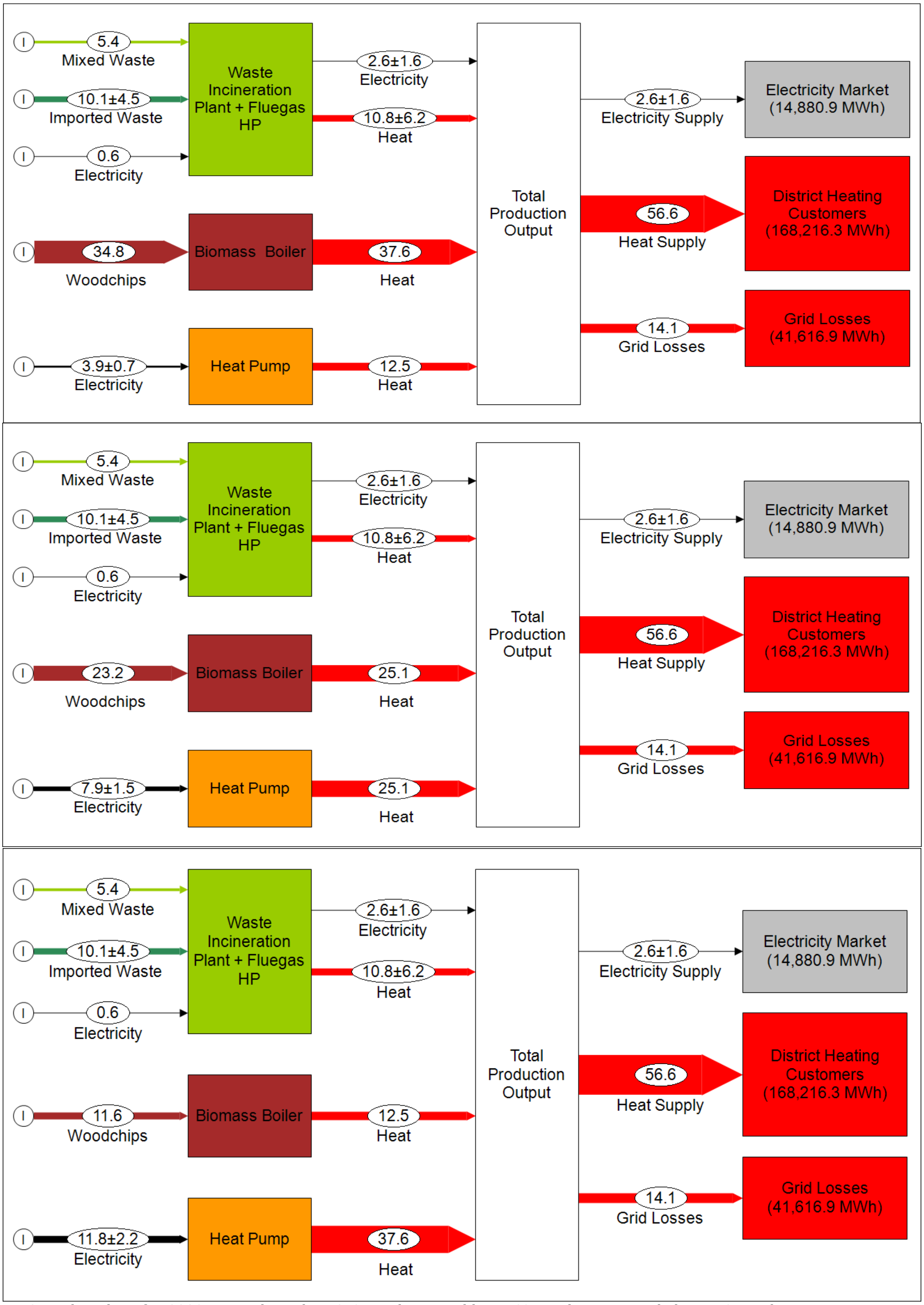

Figure 8.1: Flowchart for 2020 scenarios; a)HP 25% + Biomass, b)HP 50% + Biomass, and c)HP 75% + Biomass

Scenario 2020: Incineration plant and HP and RDF

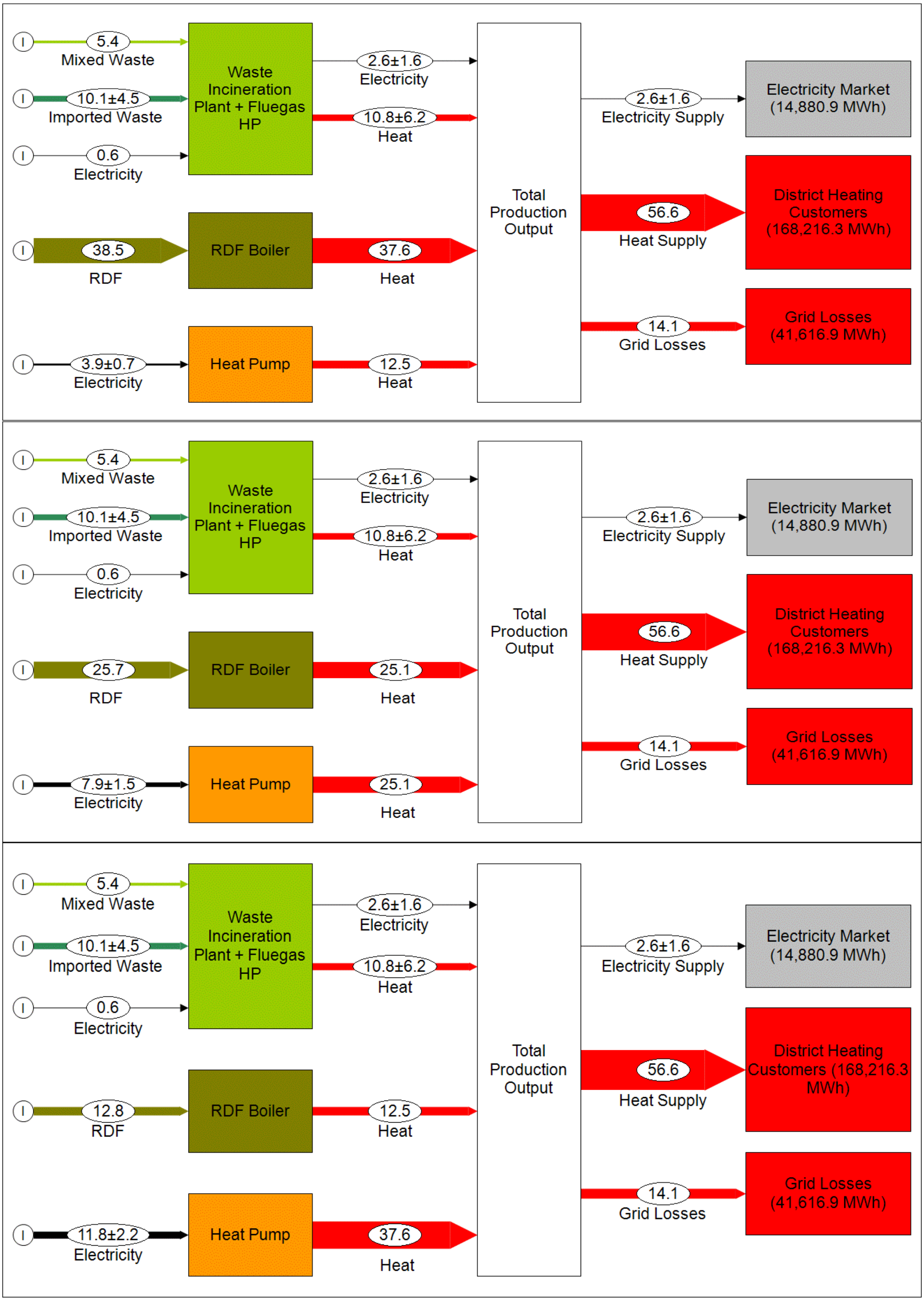

Figure 8.2: Flowchart for 2020 scenarios; a)HP 25% + RDF, b)HP 50% + RDF, and c)HP 75% + RDF boiler

Scenario 2035: HP and biomass/RDF boiler without storage

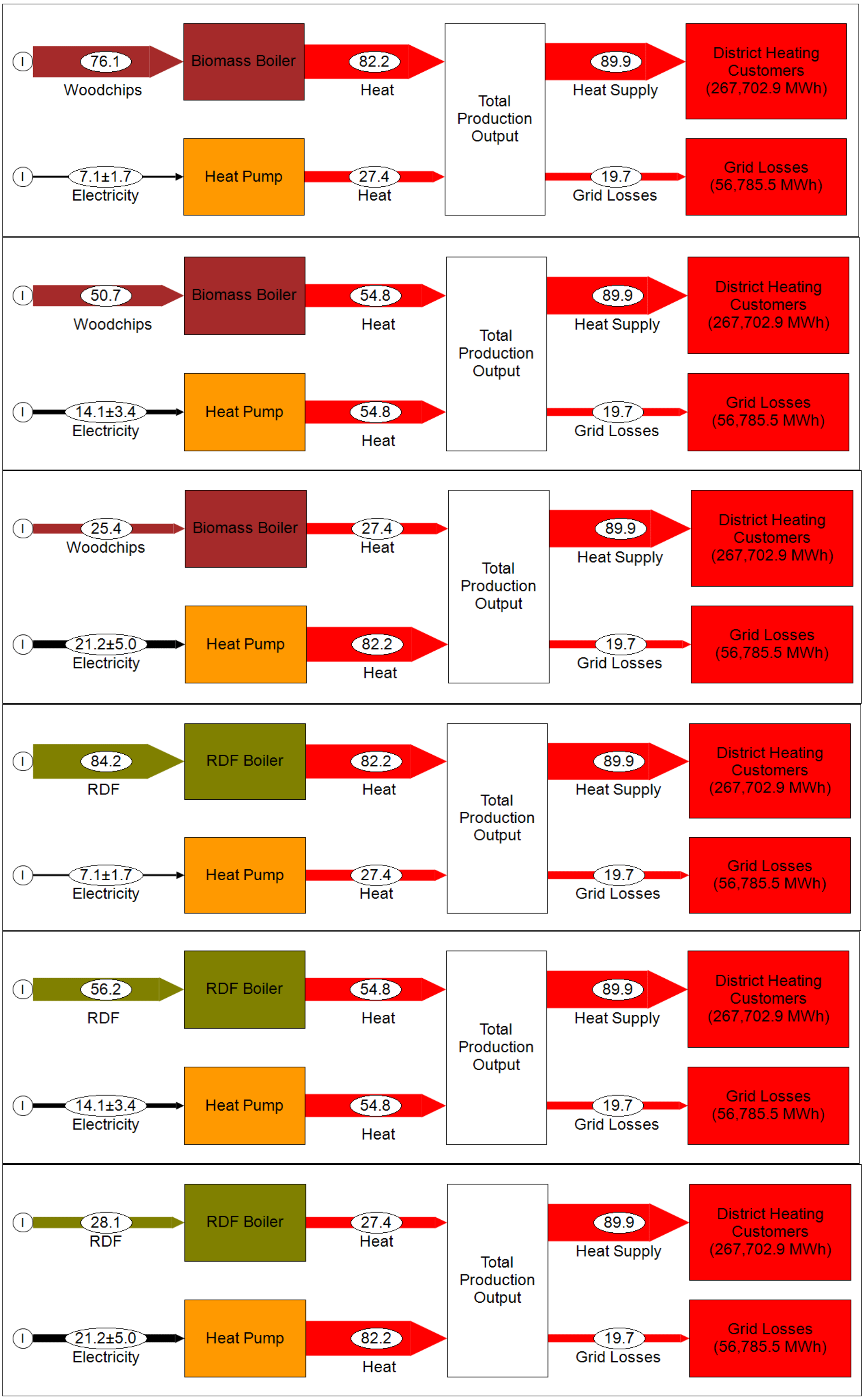

Figure 8.3: Flowchart for 2035 scenarios without storage; 25%, 50% & 75% HP with Biomass/RDF boiler

Scenario 2035: HP and biomass/RDF boiler with storage

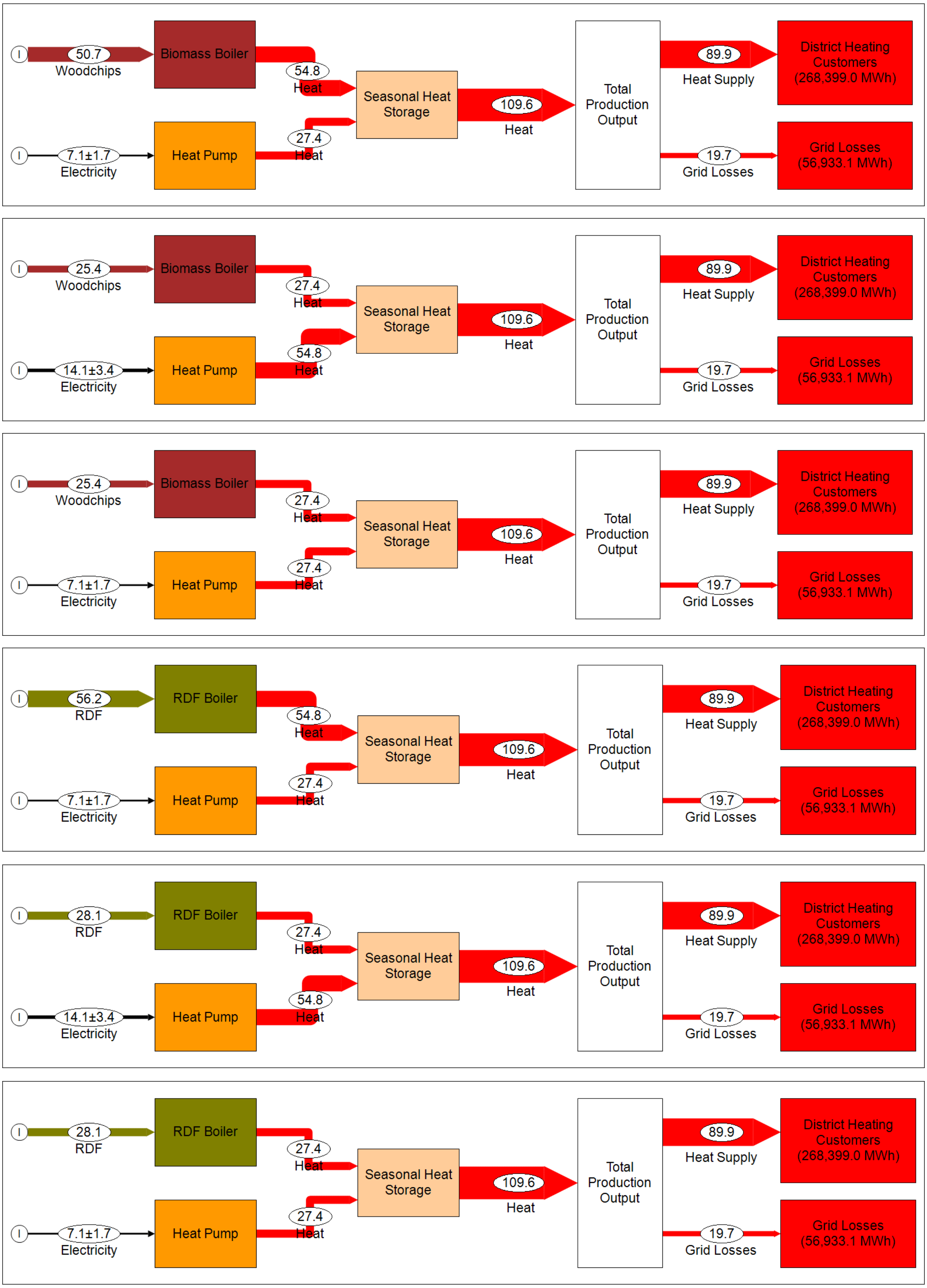

Figure 8.4: Flowchart for 2035 scenarios with storage; 25%, 75% & 50% HP with Biomass/RDF boiler

8.3 Heat and Electricity production profiles for Odense Case

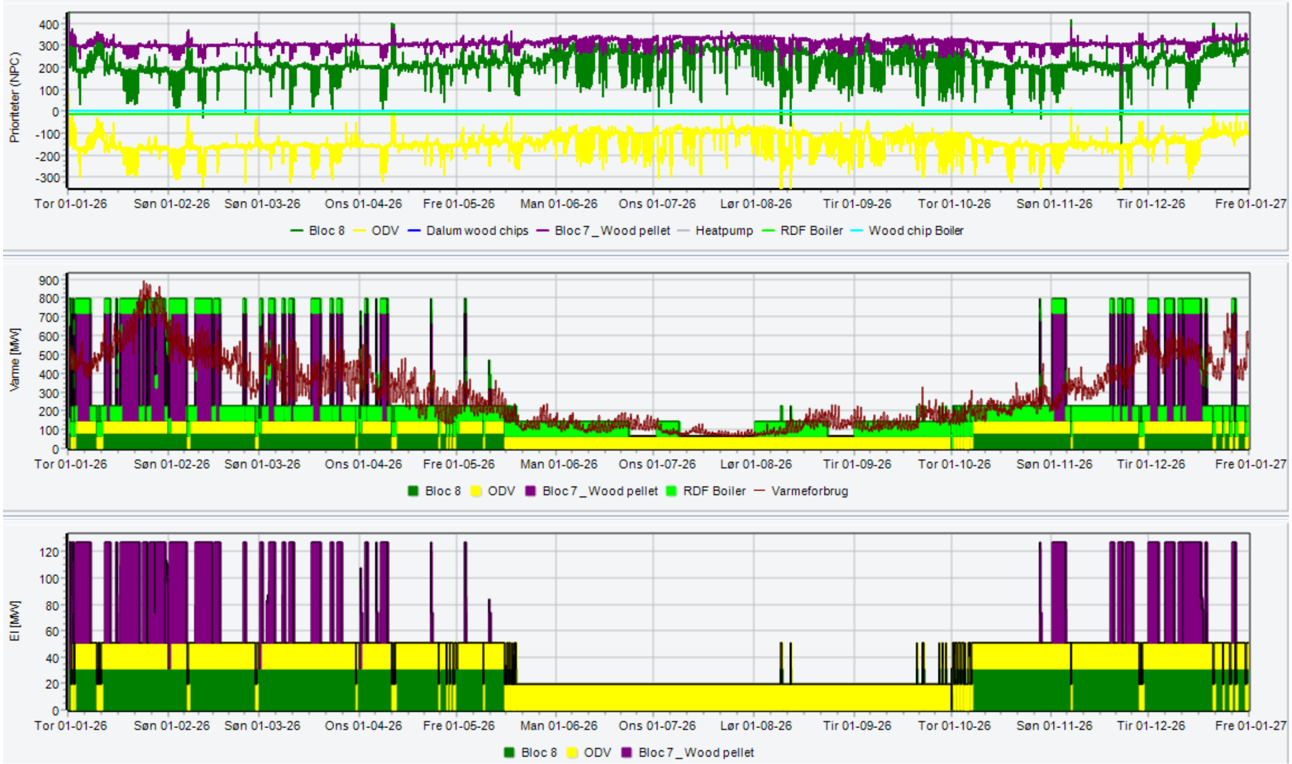

Figure 8.5: RDF Scenario yearly heat and electricity production for 2026

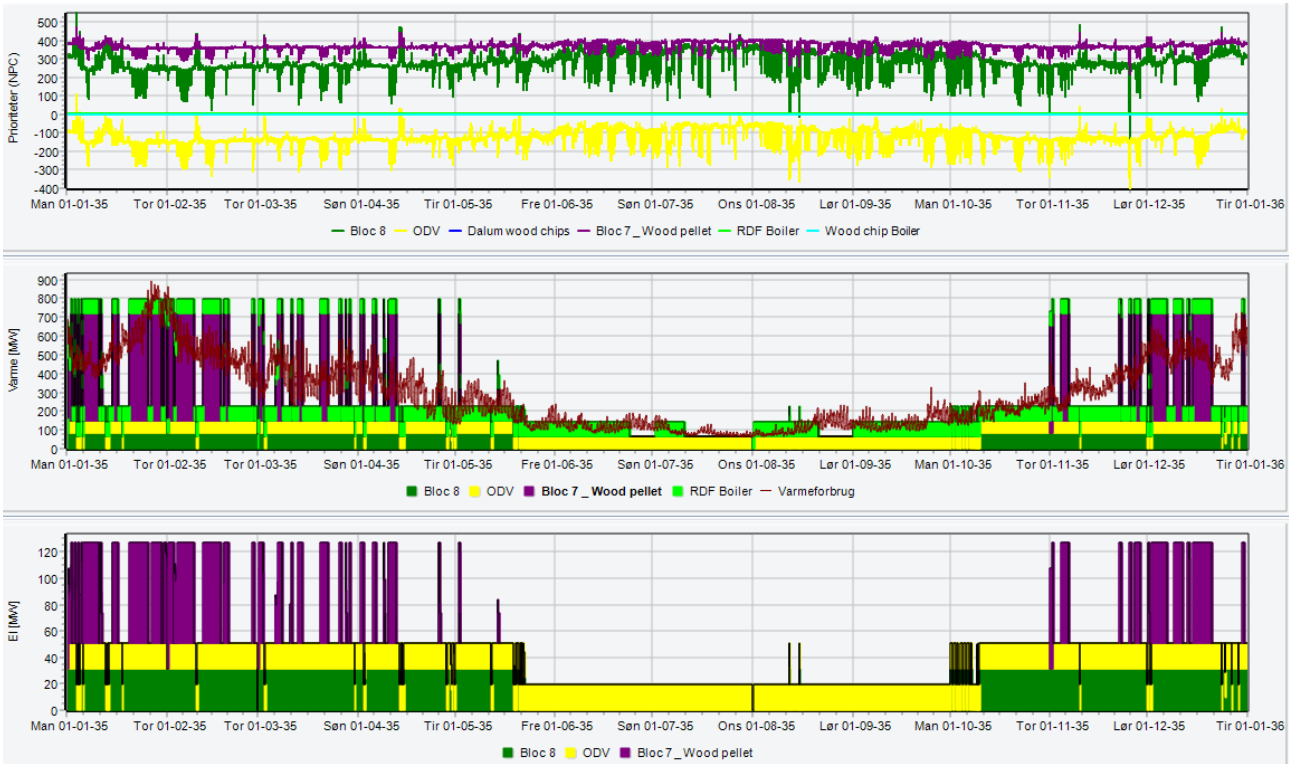

Figure 8.6: RDF scenario yearly heat and electricity production for 2035

ISBN 978-87-93413-07-8

SDU LIFE CYCLE ENGINEERING