Biomass and waste incineration CHP: the co-benefits of primary energy savings, reduced emissions and costs

F. Levihn & C. Nuur
Department of Industrial Economics and Management, Royal Institute of Technology (KTH), Sweden

Abstract

Energy utility companies face trade-offs in navigating through today's environmental challenges. On the one hand they face intense political, social and environmental pressures to move towards adopting energy systems that incorporate the use of renewable energy resources. By making this transition they would contribute to carbon reduction and mitigate climate change. On the other hand, they need to coordinate their resources and become efficient when investing in new plants or upgrading existing production systems. This paper seeks to address the gains that utility companies can make when replacing older fossil fuel base- plants with efficient *combined heat and power* (CHP) plants. We discuss the system effects from the changes in production of other units when new plants are constructed. Using one of the largest energy utility companies in Sweden, Fortum, as an empirical point of departure, we analyzed the company's transition from using coal and hydrocarbons to an increased use of renewables and waste incineration CHP. Our analysis was based on comprehensive production data on CO_2, SO_x and NO_x emissions. Our findings suggest that primary energy consumption drops when older and less efficient fossil plants are substituted for new efficient CHP plants; this drop includes the effect on the remaining production. The benefits in terms of primary energy savings might be even greater than what are achieved in meeting the goal of climate change abatement through reduced CO_2 emissions; NO_x and SO_x emissions are decreased with new biomass CHPs. Waste incineration CHP increase NO_x and SO_x emissions, when there is less fossil fuel to replace after the use of biomass is extended. In both cases, economic efficiency increases as costs are reduced.
Keywords: district heating, environmental impact, primary energy consumption.

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1 Introduction

The expansion of biomass and waste incineration *combined heat and power* (CHP) production within *district heating* (DH) systems is generally regarded as environmentally friendly. However, it is not free from emissions. In particular, the *sulfur oxides* (SO_x) and *nitrous oxides* (NO_x) emissions make the greatest impact on the local environment [1].

The political and academic discussions on climate change have put the impact of NO_x and SO_x on the local environment in the shadow of the impact of *carbon dioxide* (CO_2) emissions [2]. This was also evident by the investment patterns of utility companies, where it has been shown that costs followed by CO_2 emissions are the major evaluation criteria [3]. At the same time, air quality issues are aggregated by many green initiatives which focus on CO_2 reductions, which is why air quality implications need to be addressed [4]. Drawbacks in terms of air pollution have, for example, been claimed for biofuels relative to their fossil counterparts [2].

Energy systems are complex and interconnected and the introduction of new technologies or the construction of new plants have an effect on the existing production. In the case of waste incineration in France, it has been shown that 25% of present plants contribute to reducing air pollution and less than 2% to reducing climate-change-related emissions [5]. In the *carbon capture and storage* (CCS) technology, if the technology was added to an existing production system a small impact on air pollution were found, but a greater reduction would be obtained if CCS were combined with the *integrated gasification combined cycle* (IGCC) technology [6]. According to this study, the importance is which type of production is replaced and that climate change abatement and reduction of air pollution most often go hand in hand for the CCS related technologies. It has also been claimed that a 15% reduction in CO_2 emissions from the EU15 would have positive spillover effects on *sulfur dioxide* (SO_2) and NO_x emissions, which would be reduced 25% and 8%, respectively [2].

Energy utility companies face trade-offs in navigating today's environmental challenges. There are profound political, social and environmental pressures on them to move toward adopting energy systems that incorporate the use of renewable energy resources.

This paper seeks to address the gains utility companies can make when they substitute efficient CHP plants for older fossil fuel-based plants. We discuss the system effects from the changed production of other units when new plants are constructed and the *primary energy* (PE) savings that could be attained. Using one of the largest energy utility companies in Sweden, Fortum, as an empirical point of departure, we analyzed its transition from coal and hydrocarbons to an increased use of renewables and waste incineration CHPs. Our analysis was based on comprehensive operational data on CO_2, SO_x and NO_x emissions that we obtained in collaboration with the firm. The main contribution of this study is to show the effect of an increased application of biomass and waste incineration CHP in a district heating system with a mix of fossil and renewable production

by posing the following question: What are the effects of a new bio-mass-based CHP unit and a new waste incineration CHP within a DH system, as regards PE consumption, CO_2, SO_x and NO_x emissions, respectively?

2 The south/central Stockholm district heating system

Stockholm has two large DH networks. In an average year, the south/central Stockholm DH system produces about 9.7 TWh of heat and 1.7 TWh of electric power. The system consists of many production units that use different kinds of technologies and fuel. The base load production is mainly based on CHP from waste incineration, biomass and coal. Middle load production is based on a combination of CHP, electric *heat pumps* (HP) and *heat only boilers* (HOB). The middle load uses a combination of biomass, waste incineration and electricity as fuel. Peak load is mainly based on fossil and bio oil. Even though the fossil oil equals 1500 MW in installed capacity, it is only responsible for the production of 0.08 TWh annually.

The main actor of the Stockholm DH systems is *AB Fortum Värme samägt med Stockholms stad* (Fortum Värme), a utility firm which has a market share of 80% of heat delivered within the region. It is a subsidiary owned jointly with the Municipality of Stockholm and the Finish-based multinational utility Fortum group. Fortum Värme is a multi-utility firm that in addition to providing DH provides district cooling, waste disposal through waste incineration, electric power production and energy services. Peak production is dispersed around the Stockholm region and the major plants of the south/central network analyzed in this study are as follows):

- Hammarbyverket, which was constructed in 1986, has one of the largest HP capacities in the world. This production plant is an integrated part of the highly profiled “green” area of Hammarby Sjöstad, which has been marketed as the “residential area” of the future and has bio oil and electric HOBs installed.
- Värtaverket is one of the largest production systems for district heating and cooling in Europe. The plant is located close to the end users and in the northeast of the city, and has a seaport. To reduce the use of coal and oil and increase the share of renewables within production, a large scale biomass CHP unit called KVV8 is under construction at Värtaverket.
- Högdalenverket is located in the southern suburbs and is mainly based on waste incineration CHP, although bio oil HOBs are available for peak production. There are plans to construct a large waste incineration CHP plant to be ready by 2015, thereby, expanding the capacity for waste management within the region.

3 Methodology

The calculations in this study were conducted with the aid of Optima, investment optimization software. Many different software programs might be used in this type of studies (e.g., MARKAL, MARTES, HEATSPOT). However, for our

purposes Optima was the ideal software because Fortum Värme uses it and granted access to the software and different technical parameters. Data was adopted for the present production in the south/central Stockholm DH system, together with data on future investment.

3.1 Optima

The system analyzed is described using an annual load duration curve based on the empirical details of production in the system. Thus, Optima is similar to the HEATSPOT/EUROPSOT model (see, e.g., [7–9]). Variable operational costs together with technical parameters were used to establish merit order and an energy balance. The technical parameters were based on actual production data.

All variable costs were allocated to heat generation, with revenue from power sales and policy incentive mechanisms added where applicable. Fixed costs were handled separately and did not affect the energy balance or merit order. While this might be inappropriate for free-market systems, it is suitable for optimizing a monopoly, such as a DH system in which one firm bears all costs.

3.2 Source of calculation and allocation methods

The technical data used for calculations was based on actual operational data. To ensure reliability of the calculations, the results were compared to environmental reports regarding Värtaverket [10] and Högdalen [11]. PE consumption was calculated according to the Swedish Heat Market Committee [12], which defines the accounting principles to be used within the sector. It is worth noting this means that calculations of PE were made according to the standard accounting principles of the DH industry in Sweden.

All costs are presented in Swedish crowns (SEK). At the time of writing, EUR 1 was approximately SEK 9. MSEK represents millions of SEK. SO_x and NO_x emissions are discussed as *metric tonnes* (t), CO_2 emissions in thousand metric tonnes or *kilotonnes* (kt). The emissions were calculated for the whole network including production from other actors in addition to Fortum Värme; these are presented as "other" in the tables. PE consumption was calculated only in relation to Fortum Värme's production.

4 Results and discussion

4.1 Värtaverket

Värtaverket is a large multi-utility production site. Constructed in 1903 outside the Stockholm city borders, the plant was originally constructed for producing electricity from coke and oil. It was expanded during the 1960s and 1970s with the introduction of large oil-fired CHP unit with two fossil oil HOBs. As Stockholm grew, Värtaverket found itself inside the city borders. By then, it was one of the largest thermal plants with electric boilers in the world. During the 1980s, HPs that used the thermal energy in seawater were installed; they had the

potential of supplying central Stockholm with DH from spring to early autumn. Today, Värtaverket has the largest installed HP capacity in the world.

Considerations for the local environment were of great importance in the 1970s when the operator of Värtaverket was choosing technologies for its future production. At this time, however, greenhouse gas emissions were in practice not considered an issue. For a new unit called KVV6, the *pressurized fluidized bed combustion* (PFBC), which is a clean coal technology [13]. PFBC made it possible to remove 95–99% of the SO_x and NO_x formed. Additional gas cleaning technologies enabled the removal of most of the particulate emissions and radioactive isotopes. The operation of the carbon stocks was one of the most important factors considered when the new plant was designed. Previous operations at the seaport, as well as open stockpiles, had affected the local environment negatively for decades. The solution was a closed automated fuel handling system from the seaport to two P-200 PFBC boilers. This prevented the spreading of dust in the harbor surrounding areas. An underground storage facility was built in the cavern under the plant, where it is possible to store 100,000 metric tonnes of carbon (half the annual consumption). From there, the coal is transported to a preparation facility where it is crushed and mixed with dolomite, limestone and water. The carbon paste is then used in the PFBC boilers. Today the combined production from Värtaverket is 3.3 TWh heat, 0.9 TWh electricity and 0.3 TWh district cooling.

The increased focus on climate change has resulted in a less positive view of coal power compared to that when KVV6 was constructed. To sustain competitiveness and to take into account local opinions, Fortum Värme took measures to reduce CO_2 emissions and the use of coal and other fossil fuels. One such measure is the installation of a new biomass *fluidized bed combustion* (FBC) unit called KVV8. While the PFBC technology is arguably well suited for the local environment, FBC technology is in some ways less so. Compared to FBC, PFBC is compact to start with. To comply with local building regulations, the new plant is currently being built in a pit to reduce the overall height of the plant. Further, a closed fuel handling system, similar to the system now used for KVV6 is under construction to reduce the impact of handling fuel on the local environment. An underground oil silo is available and could be transformed for storing biomass together with the existing 144 m chimney.

The economics of the investment are affected by different environmental legislation. Electricity prices are high enough to support the investment in CHP production. The taxes on fossil fuels and CO_2 emissions reduce the competitiveness of these resources. The DH production is also included within the trading sector of the *European Union emissions trading scheme* (EU ETS). Further, there are economic incentives for renewable electricity production through the Swedish green certificate system.

As KVV8 is introduced, it will affect the use of other production units. Some methods of production such as waste incineration will be less affected because fuel costs are negative. Other production units will be used less. Among these are KVV6, the HPs and other biomass CHPs and the HOBs. The effect is spread through the region.

Table 1: The effect on emissions and PE consumption from building the waste biomass FBC CHP plant KVV8 at Värtaverket.

	[t]	*[t]*		*[kt]*	*[TWh]*
	NO_x	**SO_x**		**CO_2**	**PE**
Värtan	178	32			
Hammarby	-58	-5			
Högdalen	0	0			
Peak Production	-31	-16			
Other	-116	-12			
Total	-27 -2.0%	-1 0.6%		-158 -13.5%	-1.02 -20.6%

4.1.1 CO_2 and primary energy consumption

The combined effect of reduced production from the other units results in a net reduction of 158 kt CO_2 annually. This corresponds to a 13.5% reduction of the total CO_2 emissions resulting from the production of DH in Stockholm. The decrease is attributed to a reduced use of other production units, including the KVV6 and fossil oil HOBs. While one of the main goals is the reduction of CO_2, the PE consumption is in fact reduced more than 1 TWh, which corresponds to 20.6%. This decrease is attributed to the reduced use of other production units, including the HPs which do not contribute directly to CO_2 emissions.

Building KVV8 will also increase the production capacity and export of electric power from the south/central Stockholm DH system to the Nordic electricity network. The combined effect of an increased share of CHP to HOB production and decreased HP production, will increase the net electric power export from the DH system 0.64 TWh annually. This corresponds to an additional replacement of 1.24 TWh of PE used for the alternative electric power production.

4.1.2 Effect on NO_x and SO_x emissions

The reallocation of emission sources within the region from the suburbs to production close to the city center has an effect on NO_x and SO_x emissions. According to our calculations, the combined effect of the reduced production from KVV6 and new production from KVV8 increase NO_x emissions by 178 t annually at Värtaverket. However, because less NO_x is emitted elsewhere there is a net reduction of 27 t for the whole region. SO_x emissions were affected less in absolute numbers, and the total increase in SOx emissions is about the same as the decrease from other production. The chimney that is used for KVV6 and will be for the KVV8 is 144 m high and favorable wind conditions on average from southwest result in the highest concentrations dispersed at less densely populated areas or the sea [14]. Production at Hammarbyverket is less favored by the prevailing wind conditions, which is why a reduction in NO_x and SO_x has positive effects on the local environment for the southern part of the city.

4.2 Högdalenverket

In the 1960s, a general policy called "den Svenska linjen" (the Swedish line) was adopted. This called for an expansion of nuclear power and a development of nuclear weapons, independent of foreign countries. Between 1963 and1974, the first Swedish commercial nuclear reactor operated in the south of Stockholm (Ågesta) to produce electricity and to supply the southern suburbs with district heating.

In the 1960s, as the population grew, the need for waste disposal became urgent in the Stockholm region. In 1963, a decision was made to build a waste incineration plant in Högdalen and in the early 1970s two boilers became operational with a capacity to incinerate 15 t of household waste per hour. The plant was first connected to the DH network in 1979 during construction of the new waste incineration CHP and peak production HOBs.

The expansion and incremental development of the plant continued and in 1999 a FBC unit was added to burn industrial waste (PTP). In 2004, the latest waste incineration CHP unit was built, and today the plant incinerates around 700,000 t of household waste annually. To reduce the impact on the local environment, flue gas cleaning takes place in multiple steps consisting of electrical filtering, wet scrubbing, venturi and flue gas condensation. In total, the plant produces 3.6 TWh heat, 0.3 TWh electricity and 0.1 TWh of district cooling annually.

Currently, there are plans to expand Högdalen and add an additional waste incineration CHP unit called KVV7 or P7, which is scheduled to be operational in 2015. This unit is expected to add 0.6 TWh heat and 0.2 TWh electricity annually. The fuel cost for waste is negative because utilities with incinerators are paid for burning the waste. This places waste incineration plants high in merit order.

Table 2: The effect on emissions and PE consumption from constructing the waste incineration CHP plant KVV7.

	[t]	*[t]*		*[kt]*	*[TWh]*
	NO_x	**SO_x**		**CO_2**	**PE**
Värtan	-11	-2			
Hammarby	-13	-1			
Högdalen	77	13			
Peak Production	-6	-3			
Other	-46	-5			
Total	1 0.1%	2 1.2%		7 0.6%	-0.34 -8.7%

4.2.1 CO_2 and primary energy consumption

The construction of KVV7 will result in a slight increase in the CO_2 emissions resulting from production within the south/central Stockholm DH system. However, if KVV8 were not built, there would be a small decrease in CO_2

emissions. This would result from the reduction in coal- and oil-based production as the amount of biomass-based production increased. When it comes to PE, KVV7 results in a 0.34 TWh reduction in PE consumption, which is equal to a further reduction of -8.7%.

4.2.2 Effect on NO_x and SO_x emissions

When KVV8 starts production, its SO_x and NO_x emissions will be transferred to less densely populated areas. With KVV7 the effect is the opposite. Even if Högdalenverket were situated in a less populated area compared to Värtaverket and KVV8, the emissions from its chimney would affect an area that is more populated than the area affected by KVV8. While the NO_x emissions will be increased locally by building KVV7, the increase is about the same as the decrease elsewhere in the region. There will be an increase in SO_x emissions at Högdalen, countered to some extent by reductions from the rest of the region, resulting in an overall increase of 1.2%.

4.3 Combined effect

While there are pros and cons with investing in new production, the combined effect of investing in KVV8 and KVV7 needs to be considered.

Table 3: The combined effect of the combined constructing the biofuel CHP plant KVV8 and the waste incineration CHP plant KVV7.

	[t]	*[t]*		*[kt]*	*[GWh]*
	NO_x	**SO_x**		**CO_2**	**PE**
Värtan	167	30			
Hammarby	-71	-6			
Högdalen	77	13			
Peak Production	-37	-19			
Other	-162	-17			
Total	-26 -1.9%	1 0.6%		-151 -11.4%	-1361 -27.5%

4.3.1 CO_2 and primary energy consumption

The increased proportion of biofuel and waste incineration CHPs compared to HOBs and coal- and oil-based production has had a positive impact on both climate change abatement and reduction in PE consumption. KVV8 will have a significant impact on climate change abatement in reducing the CO_2 emissions resulting from DH production within the Stockholm region by 13.5%. When KVV8 is constructed though, there will be less fossil production for KVV7 to replace. In the end, about the same amount of CO_2 will be replaced as would be introduced if KVV7 is constructed. The combined effect is an 11.4% reduction.

KVV8 replaces as much oil- and coal-based production so, when and if, KVV7 is constructed, there will be less to replace, which is why there would be a small increase in CO_2 emissions. If KVV7 is constructed before KVV8, it would

reduce CO_2 emissions, but then the reductions from KVV8 would be smaller, a result that is similar to [5]. From a PE consumption perspective, both units have a positive effect. According to our calculations, the two units combined would reduce PE by 1.36 TWh annually, which is a significant 27.5% reduction compared to the present PE consumption by Fortum Värme.

4.3.2 Effect on NO_x and SO_x emissions

While KVV8 reduces overall NO_x emissions, KVV7 reduces SO_x. In both cases, the emissions from Hammarbyverket are projected to decline, which will improve air quality for the southern part of Stockholm. The combined effect is a 1.9% reduction of NO_x spread across the region. The largest local increase is at Värtaverket; even though this plant is centrally located, wind conditions combined with the 144 m chimney disperse the emissions to less populated areas. For the whole region, NO_x is reduced by 26 t annually which corresponds to 1.9%. SO_X emissions on the other hand are increased by 1 t, corresponding to a 0.6% increase for the whole region.

4.4 Enabling capabilities and context

4.4.1 Economic

Constructing KVV8 and KVV7 is financially sound and will reduce production costs because of a number of factors. Starting with their capabilities, the production that will be replaced is, in both cases, more expensive. There must also be sufficient heat load for the higher fixed cost of CHP to be competitive relative the HOBs. The competitiveness is in turn a result of many contextual factors. Among them is the combined effect of fuel prices of alternative production and economic policy such as NO_x and electricity taxes, EU ETS and green certificates (favoring renewable electricity production). These affect both the future operation of KVV8 and KVV7 and the savings made when other production is operated at a slower rate. Thus the path dependent aspects of previous measures taken are highly relevant [15–16].

Another enabling capability that strongly contributes to the operational costs of the two plants is the current infrastructure. Both units will be built at existing production sites. As a result, the costs are lower compared to what they would have been if the enabling infrastructure also needed to be constructed. Another important capability that will contribute to reduced costs is experience with handling the automated fuel handling process for KVV6; it will be valuable because a similar system is being implemented for KVV8.

4.4.2 CO_2

The financial performance of the two plants puts them high in merit order because the use of the coal and oil-based production capacity will be reduced. If they were too low in merit order, they would be replaced by oil and/or coal and the performance, from a CO_2 perspective, would be reduced. In other words, the relative operating cost is one of the key capabilities that determine the basis on which alternative production will be replaced.

Beylot and Villeneuve [5] discussed the importance of the fossil share of replaced production; it is also possible to further identify which circumstances define how much fossil production is replaced. Not only is the present production mix important, but how this translates into financial performance of the new production is also important. A performance that in turn is both dependent on internal capabilities as well as the external context.

4.4.3 Primary energy consumption

Climate change mitigation is strongly dependent on which alternative production that is replaced, but, in our case, PE consumption is even more strongly dependent on it. The financial performance of the new production unit and thus what alternative production would be replaced is most important. Production with a higher PE intensity such as coal- and oil-based production will be reduced by both KVV8 and KVV7. Additionally, the reduced use of electricity for heat production in the HPs and electric HOBs will further decrease PE consumption.

As the share of CHP increases in comparison to that of the HOBs, electricity production increases. There would be double effects because the amount of electricity consumed by electric HPs and HOBs would be reduced. This would vastly increase the impact of the new CHP in the south/central Stockholm DH network in terms of net electricity exported to the Nordic power grid. The resulting additional 0.8 TWh is significant. If the PE consumption of replaced Nordic electricity production is taken into account, the marginal PE saving are more than doubled. This would be significantly reduced if the new plants were to rank behind the HPs in merit order.

4.4.4 NO_x and SO_x

Both NO_x and SO_x emissions are dependent on which type of production is replaced. Thus, one key capability is the economic performance of the new production plant. For KVV8, the height of the present chimney is another advantage, which together with favorable wind conditions allow less pollution to affect densely populated areas. Another advantage is the reduced production from Hammarbyverket, which has a positive effect on the local environment of the southern parts of inner city in Stockholm. Given the present structure of the south/central DH-system in Stockholm, the effect on SO_X and NO_x emissions is rather small, why the geographical change to affected areas is of greater importance.

5 Conclusion

The impact of waste incineration and biomass CHP plants is strongly connected to existing production, which provides strong path dependency based on previous decisions and investments. The effect is also dependent on which existing production plant is replaced. In this paper, we have shown that the competitiveness of a new production plant is essential for what and how much of the present production is replaced when building new plants. This is based on a combination of enabling capabilities and the context of the two technologies.

If waste incineration and biomass CHP plants are able to replace coal and oil-based production, benefits in terms of reduced PE consumption and reduced CO_2 emissions would be realized. NO_x and SO_x emission levels are heavily dependent on which production is replaced. In the example of the Stockholm south/central DH network, the new biomass CHP plant KVV8 would reduce NO_x emissions, but have a small impact on SO_x. For the new waste incineration CHP unit KVV7, NO_x would only marginally be affected and SO_x would slightly increase. When the impact of both plants are combined, NO_x emissions are reduced within the system, but SOx emissions will be about about the same as before. As the source of the emissions is transferred within the region, there could be benefits because the prevailing wind conditions would allow air quality to improve in the southern part of the city. As the change to SO_x and NO_x emissions is rather small, it is instead more important to understand what areas, in relation to other production within the system, will be affected when biomass and waste incineration CHP production is expanded.

The construction of KVV8 reduces the amount of fossil-based production that KVV7 could replace, because KVV7 would slightly increase CO_2 emissions by 0.6%. In total, the combined effect of the plants is an 11.4% reduction of CO_2, a 27.5% reduction of PE consumption, a 6.6% reduction of SO_x emissions and a 1.9% reduction of NO_x emissions.

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