Industrial excess heat

Development and application of new methods for identifying and visualizing availability of industrial excess heat

A collaboration project between:
Chalmers University of Technology, Linköping University and Profu AB

WP2 FINAL REPORT

Matteo Morandin and Simon Harvey
Div. of Energy Technology
Dept. of Space, Earth and Environment
CHALMERS University of Technology

Elin Svensson
CIT Industriell Energi AB

Gothenburg, Sweden, April 2018

Preface

This work was conducted within the framework of the research project "Development and application of new methods for identifying efficient ways to use industrial excess heat". The project was conducted in collaboration between Chalmers University of Technology, Linköping University and Profu AB. Project funding was provided by the Swedish Energy Agency (project nr P42222). The project started in October 2016 and is planned to be completed by June 2019.

This report presents the main results obtained in Work Package 2 (WP2). The aim of WP2 was to develop of methods for identifying the availability of industrial excess heat. The technological as well as economic and environmental aspects of excess heat utilization are investigated in greater detail in other work packages.

The activities carried out in WP2 built largely upon discussions and results from previous projects by Karin Pettersson and Matteo Morandin at Chalmers. WP2 focused mainly on the development of energy targeting methodologies and tools for quantifying and characterizing industrial excess heat and their application to some industrial processes that are particularly relevant in Sweden. The study about Kraft mills was conducted in collaboration with Igor Cruz, a PhD student at Linköping University.

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Introduction

This report discusses and illustrates the importance, and difficulty, of distinguishing between different types of industrial excess heat based on how heat is currently recovered and utilized within an industrial process and how the internal energy efficiency of the plant can be improved.

The report proposes a methodology for characterising industrial excess heat, that allows to distinguish between avoidable and unavoidable excess heat. The excess heat temperature signature curve (XHT signature) is proposed as a tool for visualizing the temperature characteristics of the excess heat availability. Different assumptions about internal heat recovery levels are used to generate a Theoretical XHT signature, representing the characteristics of excess heat assuming ideal internal heat recovery, and a Process Cooling XHT signature, representing the characteristics of excess heat based on the temperature-heat load profile of process streams that are currently being cooled by utility.

Furthermore, an energy targeting approach is introduced which is used to estimate power generation targets and excess heat availability from six Swedish Kraft pulp and paper mills. The results obtained from the case study mills are then used as input for a regression analysis that is used to estimate sector-wide potentials for power generation and excess heat availability.

1 Definitions and assumptions

This chapter discusses important assumptions about system boundaries as well as the type of data required to conduct an analysis of industrial excess heat potentials, for different definitions thereof.

1.1 System boundaries

According to a definition by the International Energy Agency (IEA), industrial excess heat refers to any source of heat from an industrial process that is cooled by water or air and finally dispersed into the environment (Berntsson and Åsblad, 2015). Heat from cogeneration plants is implicitly excluded from this definition since heat is an actual product and not a by-product in excess.

It is also important to provide an appropriate definition of an industrial process. This term generally refers to the set of buildings, equipment units, and materials that are required for large-scale production of basic commodities. This work focuses on the energy-intensive process industry. When looking more closely at an industrial site, it is also possible to make a distinction between process streams and utility streams as well as between different processes located at the same site. To properly address methods and analysis tools for assessing potential amounts and characteristics of industrial excess heat, it is therefore necessary to define the boundaries that separate a process from its surroundings.

A first type of boundary that needs to be considered is the administrative boundary of the company owning a given industrial process. This is particularly important for cases where it may be difficult to physically distinguish different processes in physical/spatial terms such as in the case of industrial clusters. It can also be useful to consider such administrative boundaries when collaborations already exist between companies regarding common management of energy and raw materials, since this might motivate including a number of industrial processes within a common system boundary.

Within the company boundary at a given industrial site, the “process” can be identified as the set of equipment units, material and energy streams of which the size, design and operation strictly depend on the manufacturing of materials, chemicals or fuels (e.g. steel, cement, paper, motor vehicle fuels, plastics, milk, fine chemicals). It is not uncommon to distinguish between multiple processes even when they are within the same company boundary and at a given site. For instance, a pulp and paper mill may consider a saw mill as a separate process even if it is owned by the same company and is located at the same site. Similarly, a refinery may refer to fluid-catalytic cracking and hydrogen production unit as different processes. Since such parts of the same site might present a certain degree of energy integration (e.g. via a common utility system), referring to such parts as different processes is misleading, and it is therefore proposed to consider such parts within the same process boundary.

1.2 Types of excess heat

Within an industrial process site, some equipment is often used only for providing utilities in support of the production of the plant products. Hot and cold utility use, such as the use of steam or cooling water, can be reduced by retrofitting the plant to increase the degree of heat recovery between the process streams without affecting the production of the main products. The resulting increase in process energy efficiency leads to a reduction of excess heat. This is an issue that has led to the definition of different types of excess heat such as avoidable or unavoidable excess heat (Bendig et al., 2013). For an overview of different types and definitions of excess heat, the reader is also referred to the final report from Task 1 of the IEA IETS Annex XV: “Industrial Excess Heat Recovery – Technologies and Applications” (Berntsson and Åsblad, 2015). Ultimately, this topic highlights the need to define reference conditions for quantifying and characterising the excess heat from a given industrial process. This can be illustrated by the following example. Suppose a boiler is used to provide low-pressure steam to an industrial process and suppose that the boiler is oversized compared to the actual process steam demand and some low-pressure steam is used most of the time to deliver heat to a district heating system. Strictly speaking, this heat is not related to process operation, but rather a co-product. From a system perspective, this would be equivalent in terms of resource utilization to producing the same amount of district heat in a stand-alone boiler. Conversely, suppose that in a similar process, the steam produced by the boiler is completely utilized by the process, but the same quantity of district heat is produced by using heat available from the process at low temperatures, and which would be otherwise discharged to the environment. From a system perspective, the export of this excess heat creates a marginal reduction in resource utilization for heat production elsewhere. The latter case leads to reduced global resource usage, which should be promoted by appropriate policy instruments.[1] Currently, in Sweden, existing policy instruments make no distinction between the above two cases and the amount of industrial excess heat delivered is the result of business opportunities.

Finding a way to distinguish between different degrees of energy efficiency in industry is necessary to overcome also the issue of finding an appropriate measure of the environmental impact of increased recovery of industrial excess heat. Currently, in Sweden, heat produced by combustion of biofuels can be labelled as “environmentally-friendly” and therefore favoured in the market by environmentally aware consumers (Naturskyddsföreningen, 2013). Conversely, excess heat from process industries that rely primarily on fossil fuels and fossil feedstocks is not eligible for such labelling, regardless of whether such heat actually leads to an increased resource efficiency in the system, which consequently results in a general market disadvantage.[2] However, in the new guidelines presented by the Swedish Environmental Protection Agency for calculating the greenhouse gas (GHG) emissions reduction benefits of investments aiming at reducing GHG emissions in municipalities and industry, it is clearly stated that excess heat from industry can be assumed to be emissions free, regardless of the fuels and feedstocks used (Naturvårdsverket, 2017). Similarly, when accounting for environmental impact of district heating production, no GHG emissions are allocated to industrial excess heat (Svensk Fjärrvärme, 2012).

The above discussion establishes clearly that it is important – and difficult – to be able to distinguish between different types of excess heat according to how energy is managed at an industrial plant. The recently introduced requirement for conducting energy audits in energy intensive industry in Sweden provides an excellent opportunity for improving the effectiveness of energy analysis tools, in particular regarding characterisation of industrial excess heat.

To be able to identify the excess heat from the process itself, it is suggested to include within the system boundary of the study only those equipment units, material and energy streams that are strictly involved in the manufacturing process and to exclude therefore utility units such as the heat production units and distribution systems (e.g. boiler and steam system). This distinction is not really a technological one and is furthermore case specific. For instance, a compressor that is used to compress a mixture of reactants before a reactor is part of the process and the heat from

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[1] Note: The example is still simplified. In the latter case, while steam is used in the process, and district heating is produced by process cooling at lower temperatures, this might still be an inefficient system if the excess heat is not unavoidable. If the process steam consumption can be reduced by internal heat integration, thereby saving fuel at the industrial plant, the district heating production still comes at the expense of fuel use. While this is a more efficient production of heat than, for example, a heat-only boiler, alternative district heating production based on, for example, excess heat from other plants might be favourable.

2 See criteria 1.1 and 3.1 in (Naturskyddsföreningen, 2013:2) which limit the amount of non-renewable fuel as heat source to 10% and exclude industrial excess heat for ”bra miljöval” labelling if the industrial process is not based on renewable feedstock.

intercooling stages can be considered as a potential source of excess heat. A closed-loop compression heat pump that is used for process heating purposes is instead considered part of the utility system and excluded from the accounting of potential excess heat sources. Similarly, combustion can be a substantial part of the process (e.g. cement industry) and not only used for steam production as in a steam boiler.

1.3 Process data

To assess the amount and temperature profile of excess heat from a given industrial process, data about excess heat sources needs to be available or otherwise estimated using appropriate assumptions such as via benchmark data or models.

The accuracy of the estimate is clearly affected by the quality of the data available. In the following discussion, some major causes of uncertainty are highlighted.

THE TIME FACTOR

An industrial process seldom operates at steady-state conditions. A process typically undergoes structural changes due to expansions and retrofits, and process operation changes over time and can be better described by a sequence of different steady-state conditions separated by periods of transient behaviour.

The availability of excess heat changes therefore over time. An accurate estimate of industrial excess heat must account for variation over time. This is particularly important for applications in which energy storage is technically difficult or too costly to implement to enable excess heat recovery and utilization. A typical case is a district heating system in which the heat demand typically varies depending on time of the day and seasonal weather conditions, and in which heat storage could be needed to balance excess heat availability with the heat demand.

Since data about temperatures and load of industrial excess heat sources are generally quite scarce, it is often necessary to conduct on-site measurement campaigns. Unless an advanced site-wide on-line measurement system can be used to retrieve data for specific periods of distinct process operation, it is necessary to collect data that satisfactorily represents the most typical operating conditions, which should be close to nominal conditions.

For process industries, typical operation is usually close to full nominal process capacity. For this reason, corresponding heat loads are often sufficient to represent with good details the excess heat availability. In addition, process industry tends to maximize production over the year and plant load factors over 90% are not uncommon.

LEVEL OF DETAIL OF PROCESS DATA

According to some definitions of industrial excess heat such as "heat (bound in liquids, gases, or hot materials) generated in an industrial process and currently not used internally in the processes" (Broberg Viklund, 2015), or heat "that cannot be used directly in the industrial process" (Grönkvist, et al., 2008) or "the heat content of all streams (gas, water, air, etc.) which are discharged from an industrial process at a given moment" (Berntsson and Åsblad, 2015), industrial waste heat or excess heat is simply heat dissipated to the environment. These definitions do not clearly consider the temperature profile of the heat and its possible use and re-use. According to such definitions, excess heat from a process can be determined simply by collecting the heat loads of all process coolers and possible also of process streams discharged directly to the environment (e.g. to atmosphere or sewage).

In principle, the temperature of the available excess heat could be considered by mapping not only the heat loads, but also the temperature levels of the cooling media, e.g. cooling water and air. Even more relevant would be to map the temperatures of the process streams being cooled, since this is the temperature level that is actually available for utilization. However, the amount and temperature levels of industrial excess heat from a process will change when changing the degree of internal heat recovery for a given mode of plant operation (see also Section 1.2). To be able to distinguish between different degrees of process energy efficiency, more process data are therefore required to be able to assess the potential for heat integration within the process and how this affects the excess heat availability.

In this context it is useful to make a distinction between what is sometimes referred to as “black box”, “grey box” and “white box” approaches (see e.g. Hackl, et al., 2010). In a “black box” approach, excess heat characteristics are described solely based on existing utility loads and temperature levels, such as the flow and temperature of cooling water at the outlet of process coolers. A “white box” approach, on the other hand, allows the amount and temperature of unavoidable excess heat to be determined based on all process stream data (temperatures and heat loads and their variation) assuming ideal internal heat recovery in the process. The intermediate “grey box” approach characterizes excess heat on the basis of the actual temperatures and heat loads of process streams in existing coolers, as opposed to the “black box” approach in which only the utility side is represented. However, only data about process coolers are used and the potential for increased process-to-process heat exchange is not considered. Consequently, the “grey box” approach does not provide the possibility to estimate the degree of internal heat recovery within the process.

To be able to assess what can be characterised as efficient excess heat, that is, excess heat from an internally energy efficient process, a white box approach is therefore advisable.

However, as discussed by Méchaussie (2018), the white box approach requires much more time and involves more difficulties for data extraction than the grey box approach, while commonly resulting in proposed retrofits that will rarely be feasible in practice due to safety, space, distance and economic constraints. The grey box approach, on the other hand leads, by definition, to heat recovery designs based on intermediate utility systems, which is more likely to be feasible since they are less likely to affect site operability. For these reasons, she argues, the grey box approach can be motivated as a default level of detail (Méchaussie, 2018).

In this report, a targeting methodology is proposed that enables the visualization of industrial excess heat characteristics as identified by a theoretical approach corresponding to the “white box” level of detail, as well as an approach based on current utility requirements resembling the “grey box” level.

2 Methods and tools

This chapter presents the methods and tools used in this report for characterizing industrial excess heat. These include the description of the energy targeting method and a tool for characterizing and visualizing industrial excess heat by its availability at different temperature levels.

2.1 Energy targeting method for quantifying excess heat availability from an industrial process

The minimum amount of energy that has to be spent in a given system to sustain the main system task is often referred to as the energy target. In thermal systems, this is referred to as the minimum energy requirement (MER). Energy targeting is the procedure by which the MER heating and cooling targets are established.

Pinch Analysis is used in this work as the energy targeting tool. As defined by Klemes and Kravanja (2013), heat integration based on pinch analysis "examines the potential for improving and optimising the heat exchange between heat sources and sinks in order to reduce the amount of external heating and cooling, together with the related cost and emissions". It is a powerful method largely used to improve heat integration within industrial sites or clusters with significant thermal power consumption, see for example Tjoe and Linnhoff (1986) and Hackl et al. (2011). Pinch analysis provides insights on the theoretical temperature profile as a function of heat flow for the industrial system, showing at which temperatures heat could be supplied to and removed from the process under conditions of maximum internal recovery, as well as the order of magnitudes of the heat exchanges. An important parameter for pinch analysis is the minimum allowable temperature difference for heat exchanging. This parameter is generally referred to as ΔT_{min}, and it captures the trade-off between capital costs for heat recovery equipment and operating costs related to utility. Secondly, pinch analysis provides targets for energy consumption reduction, via the difference between the minimum energy requirements resulting from the energy targeting calculations and the actual energy consumption. Finally, pinch analysis provides curves that contain visual information about the real temperatures and heat loads to be delivered by the utility system, as well as highlighting heat pumping opportunities.

A pinch analysis tool called MAT4PI developed at the division of Energy Technology was used in this work to estimate the maximum amount of excess heat that can be recovered from a process at the highest temperature possible.

As mentioned previously, the objective of recovering heat from a process and exporting it competes with the objective of recovering heat within the process itself. The MER condition of a given industrial process is therefore a very relevant reference condition to be able to distinguish between excess heat that could be re-used internally within the process, and heat which is truly in excess.

Such reference conditions for the process should be representative of maximum, ideal internal heat recovery. This is defined as the theoretical situation in which heat recovery is possible between all process thermal sources and thermal sinks without limitations and with $\Delta T_{min} = 0\,°C$. The resulting excess heat can be referred to as truly unavoidable excess heat, given that the choice of $\Delta T_{min} = 0\,°C$ in effect corresponds to neglecting capital costs for heat recovery equipment when establishing heat recovery targets. In practice, internal process heat recovery is never maximized to this extent, as a result of process operational constraints and capital costs for achieving heat recovery. If all of the resulting excess heat is exported to an external heat sink, it is not possible to achieve maximum process energy efficiency and overall energy efficiency gains must account for alternative sources of heat in the recipient system.

Note that in other definitions of potentials for industrial excess heat, the term theoretical is often used to denote the physical availability of heat, typically defining this as heat above ambient temperature that is bound in a medium (see e.g. Brueckner, et al., 2014). This theoretical potential is, according to this categorization, assumed to represent the maximum availability and put as an upper bound to the technical and economic potential, which also consider whether it is actually possible to extract the heat, whether there is any potential use, and whether this utilization would be economically feasible. In contrast, the definition of "theoretical excess heat" used in this report refers to ideal, maximized heat recovery within the process site, which means that the availability of heat for external use will in fact be reduced. Consequently, in this work, "theoretical" cannot be used interchangeably with "maximum". In fact, maximizing external excess heat utilization may imply utilizing process heat sources in a less efficient way compared to increasing heat recovery within the process site. To summarize, in this report theoretical is used to indicate "unavoidable" excess heat which can be lower in quantity and temperature level compared to the maximum potential for excess heat given current design of the heat recovery system.

2.2 Excess Heat Temperature signature

The temperature profile of the excess heat that is available from a given process is indicative of the quality of the excess heat since it typically determines its possible use and its economic value. This information can be represented by aggregating all the heat sources that are currently being cooled by utility in a process according to their temperature level.

If a white box approach is adopted (see Section 1.3), the theoretical reference condition of maximum process heat recovery can be represented by the process Grand Composite Curve (GCC)for ΔT_{min} = 0°C. The excess heat temperature profile corresponds to the portion of the GCC below the pinch point (or below the pinch point at the lowest temperature if the process has multiple pinch points).

An example of such a GCC and the corresponding profile of the theoretical excess heat is shown in Figure 1. Note that the GCC in this example contains several heat pockets (shaded with grey). The theoretical excess heat profile is determined by an envelope of the GCC if there are heat pockets.

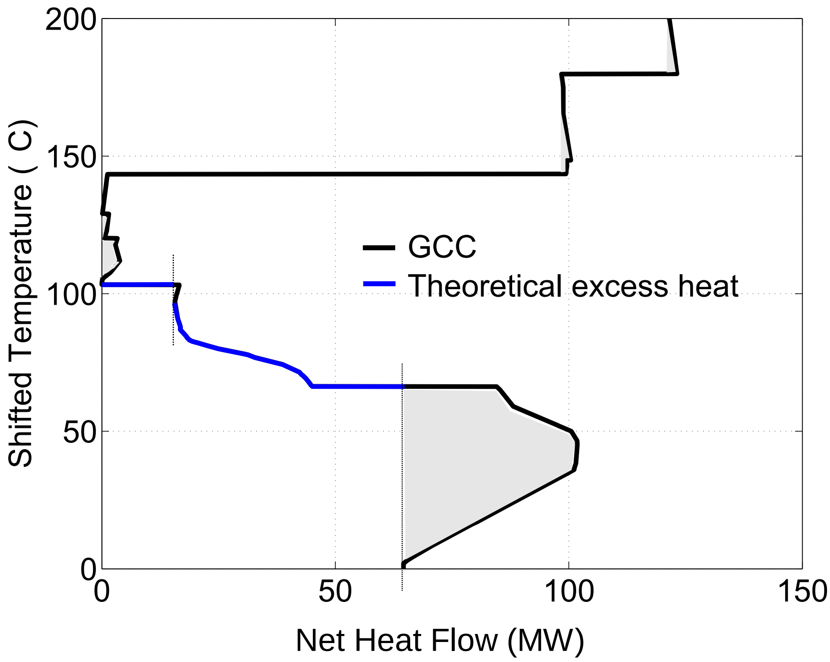

Figure 1: Example of GCC and resulting excess heat profile (ΔT_{min} = 0°C).

To estimate the maximum potential of excess heat that can be recovered from the process under the actual conditions set by the existing process design, it is, in principle, sufficient to consider the current process cooling demands in process coolers with the process streams' temperature and heat loads. However, in general, technical and economic conditions not only limit the heat recovery between process thermal sources and sinks but also between excess heat sources and possible excess heat recovery technologies (e.g. hot water system, organic Rankine cycle, etc.). As a result, a graphical procedure whereby all excess heat sources are aggregated into one single curve is not always relevant. For this reason, the excess heat recovery potential for specific site and technology conditions should be estimated by evaluating on a case by case basis the integration of the utilization technology according to the practical limitations that exist in each case. Still, an aggregated value of the excess heat utilization potential is desirable to be able to compare the availability of excess heat from different processes or different types of industries but also to compare this excess heat availability based on current process cooling demands with the theoretical excess heat profile.

In this work, excess heat availability is characterized according to discrete temperature intervals. Independently of how the amounts of excess heat are quantified for a given process (unavoidable or avoidable), excess heat can still be characterised with a temperature profile, which is hereafter referred to as the Excess Heat Temperature Signature (XHT signature). This profile is constructed by aggregating the available excess heat at and between different temperature levels. It is proposed that suitable temperature levels representing relevant excess heat utilization technologies are chosen based on the purpose of specific case studies. In this report, the temperature categories shown in Table 1 have been used consistently. These temperature categories are inspired by the temperature ranges reported from a Norwegian study in the final report of Task 1 in the IEA IETS Annex on Industrial Heat Recovery (Berntsson and Åsblad, 2015), but additional temperature ranges have been added. Note especially that excess heat available at constant temperature is also considered, which is useful for estimating opportunities for integration of phase changing processes, such as evaporation (e.g. steam raising, heat pumping, etc.) or liquefaction (e.g. thermal storage).

Table 1: Categories of excess heat according to temperature levels

Excess heat category	Temperature range	Notation
Very high temperature	Above 250°C	x_{10}
	250°C - 250°C	x_9
High temperature	250°C - 140°C	x_8
	140°C - 140°C	x_7
Medium temperature	140°C - 100°C	x_6
	100°C - 100°C	x_5
Low temperature	100°C - 60°C	x_4
	60°C - 60°C	x_3
Very low temperature	60°C - 40°C	x_2
	40°C - 40°C	x_1
Extremely low temperature	40°C - 25°C	x_0

The advantage of using the XHT signature compared to the GCC is a more immediate reading of the maximum values of various levels of excess heat. Also, XHT signatures from different plants at a large site can be aggregated into one curve to provide a total picture of the excess heat from a set of plants whereas the aggregation of multiple GCCs implies that all the included process streams of different plants can be arranged in an optimal way to maximize excess heat utilization which can lead to an overestimation of the potentials that can be achieved in practice.

To construct the XHT signature, the maximum availability of excess heat is estimated following a priority order according to descending temperature intervals (i.e. maximize excess heat in the highest temperature category first). The discretization of the excess heat temperature profile causes some details about temperature levels to be lost not only because the availability of excess heat can vary substantially within the assumed intervals but also because the way higher temperature excess heat is prioritized affects the amount of lower temperature excess heat. Ultimately, therefore, only an economic analysis can be used to estimate the best utilization of excess heat.

In order to determine the XHT signature, the amount of excess heat in the different categories were optimized case by case to maximize the following objective function:

$$f = x_1 + 2 \cdot x_2 + 3 \cdot x_3 + 4 \cdot x_4 + 5 \cdot x_5 + 6 \cdot x_6 + 7 \cdot x_7 + 8 \cdot x_8 + 9 \cdot x_9 + 10 \cdot x_{10}$$

where x_1 to x_{10} denote the amounts of heat available in the different excess heat temperature intervals as defined in Table 1.

The weighting factors in the objective function should be chosen such that excess heat availability in the higher temperature level categories is valued higher than the same amount available in the lower temperature categories. It is important to note that other weights in the objective function would lead to different solutions (shape of the XHT signature curve) and might be more relevant depending on the purpose of the excess heat study. Alternative weighting factors could be the average temperature or the average Carnot factors in the temperature level category. Another option would be to consider a less detailed excess heat profile with only isothermal excess heat categories, in which case the amount of excess heat at different levels can be maximized independently (compare also to the approach of Waste Heat Profiles suggested by Oluleye et al. (2016)).

The Theoretical XHT signature can be determined once the process GCC is available and illustrated graphically as shown in Figure 2 for the same GCC as shown in Figure 1. The figure shows clearly that the XHT signature neglects the particular details of the process thermal cascade. Furthermore, the choice of weighting factors used in the objective function (see Table 1) leads for this specific example to neglecting the isothermal excess heat at 100°C in order to maximize the excess heat availability between 60 and 100°C.

For the process considered to generate Figure 2, data was also available regarding the process cooling demand under current process conditions. This information can be used to construct what will hereafter be called the Process Cooling XHT signature. The Process Cooling XHT signature is shown in Figure 3 where the Theoretical XHT is also shown for comparison.

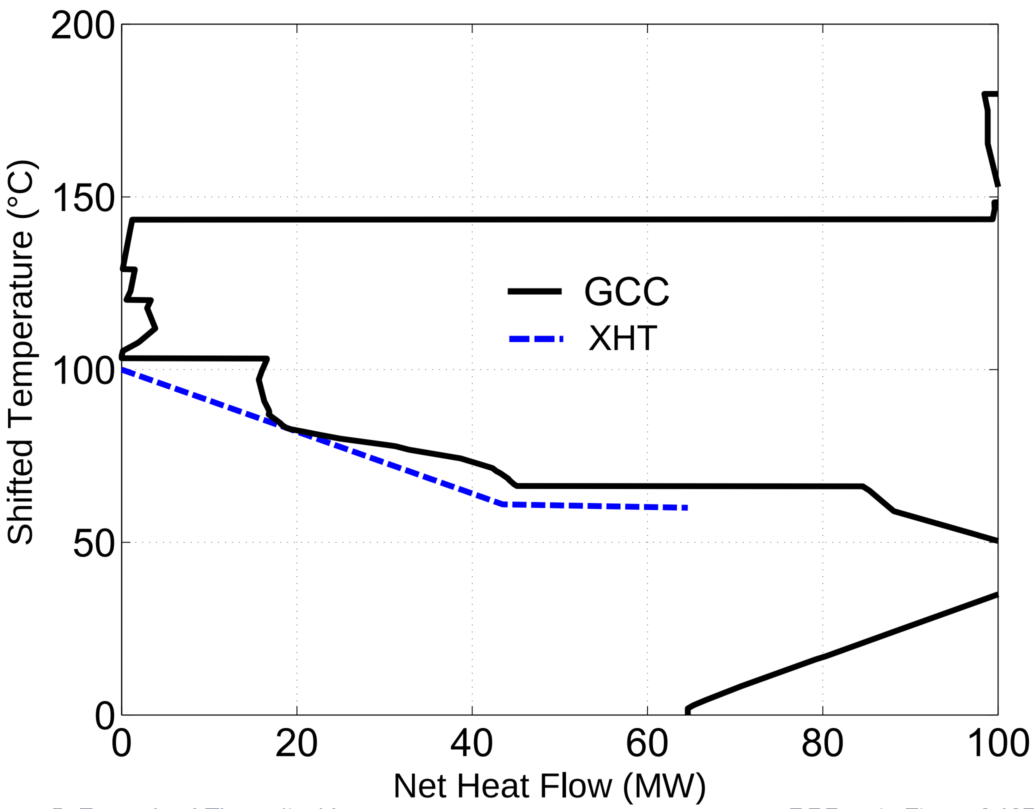

Figure 2: Example of Theoretical XHT signature estimated from the process GCC as in Figure 1 (ΔT_{min} = 0°C).

The Process Cooling XHT signature is different from the Theoretical XHT signature, which represents the unavoidable excess heat from the process. For the Process Cooling XHT signature it is assumed that the degree of heat integration in the process is not changed, and typically, it is also assumed that all streams that are currently cooled by utility can be used as heat sources for external excess heat utilization. While this is likely to be more realistic than the ideal heat integration assumed in the theoretical case, there might still be technical barriers to collecting all this heat. Consequently, excess heat targets based on the Process Cooling XHT signature should be interpreted as a maximum potential for excess heat with the current design of the heat recovery system and is typically also defined by a number of "theoretical" assumptions on a case-by-case basis.

The Process Cooling XHT signature usually differs from the Theoretical XHT signature. The amount of excess heat that can be recovered in practice does not necessarily exceed the theoretical potential. There are two underlying competing factors that determine the difference between the process cooling and Theoretical XHT signature profiles. On the one hand, the degree of internal process heat recovery that is actually implemented in the process is less than (or at most equal to) the theoretical ideal heat recovery, which creates larger cooling needs and therefore usually larger excess heat availability. On the other hand, larger temperature differences are also required in practice (recall that the Theoretical XHT profile assumes that ΔT_{min} = 0°C for all types of heat exchanging, i.e. process-to-process and process-to-utility), which limits the potential for recovery of excess heat at a given temperature level.

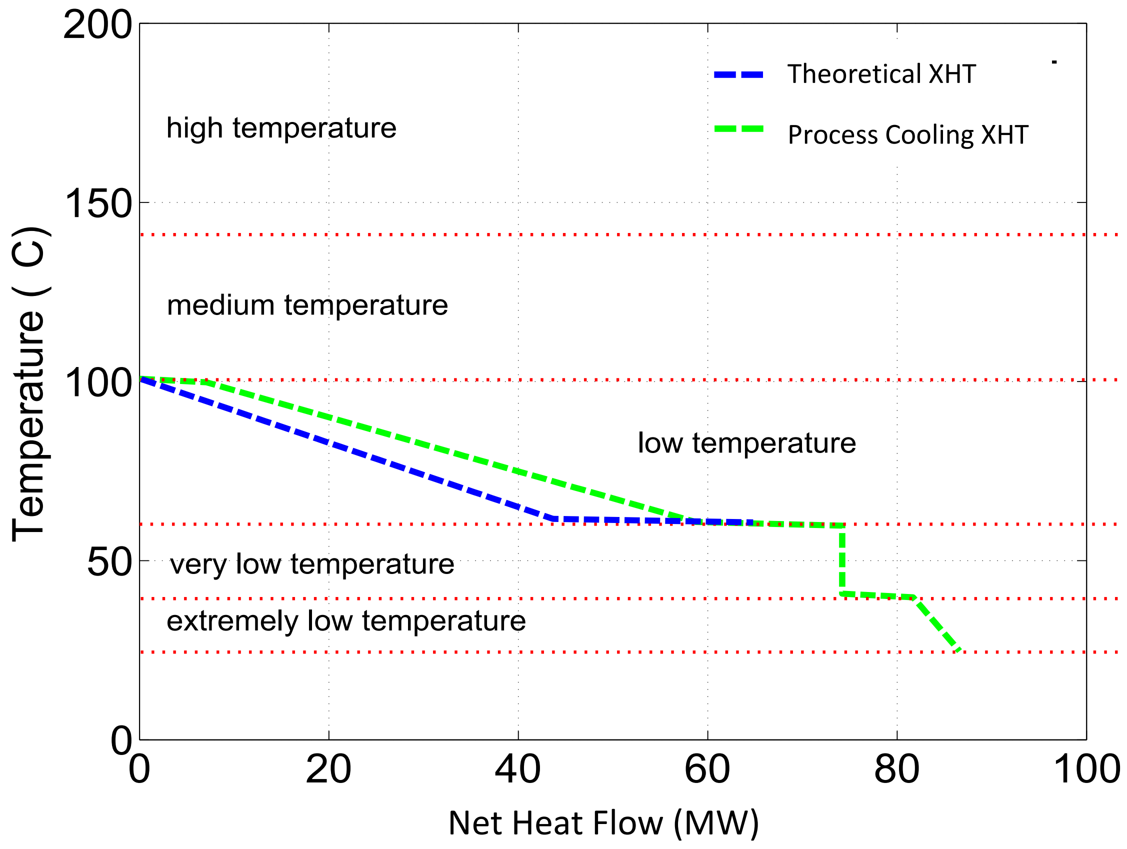

Figure 3: Examples of Theoretical and Process Cooling XHT signatures for a given process.

In conclusion, it is proposed to use the XHT signature to differentiate between more or less efficient utilization of excess heat. The Theoretical XHT signature can be used to determine the maximum amount of excess heat that can be recovered without limiting the potential for further internal process heat recovery. It is the opinion of the authors of this report that this excess heat should be eligible for policy incentives for promoting efficient excess heat utilization. To be able to implement such policies, it is, however, necessary to collect and analyse all thermal stream data from a process, which may be a significant practical limitation.

2.3 Targeting power generation via steam turbine expansion by using high temperature excess heat

In energy intensive industrial processes, it is not uncommon that excess heat is available at very high temperatures, that is at temperatures above 250°C, for instance because of the need to cool product streams from high temperature thermochemical conversion processes. One of the most common applications of excess heat recovery in such cases is to recover the excess heat to raise steam and then generate power by means of steam turbine expansion. This is a particularly relevant technology since most process plants include a steam network to collect and distribute heat around the process. In such cases, it is relevant to estimate the so-called cogeneration target, that is, the amount of shaft power or electricity that can be produced by steam expansion while still being able to produce the required amount of steam for process heating in a highly efficient way.

In this project, a linearized model of a steam network with multiple steam headers was developed to estimate the power generation target. Such models are based on decomposition of the steam system in elementary cycles. The decomposition allows to express energy balances simply as linear functions of the steam mass flow rates once pressure and temperature of steam headers are defined. Steam raising and steam condensation can be included in the overall system thermal balance and in various types of constraints.

3 Temperature levels and availability of excess heat from Swedish Kraft mills

3.1 Introduction

The pulp and paper sector is the main industrial sector in Sweden. Among the different types of mills, most of the pulp and paper production occurs in Kraft type mills.

Pulp and paper mills consume large quantities of biomass feedstock. In Kraft mills, part of the biomass is also used for production of heat and electricity, which is mainly used in the process itself. The heat and electricity produced are eligible for classification as renewable energy services since the energy source almost entirely originates from biomass in the form of black liquor, bark or sawdust. The renewable electricity certificate scheme introduced in Sweden in 2003 has contributed to a substantial increase in production of electricity in pulp and paper mills. Figure 4 shows the declared (gross) electricity production versus biofuel[3] utilization in Swedish mills in 2015 according to a database provided by the Swedish Forest Industries Federation (Skogsindustrierna, 2003-2015). The linear trend between biofuel usage and electricity production is quite distinct, especially for Kraft mills.

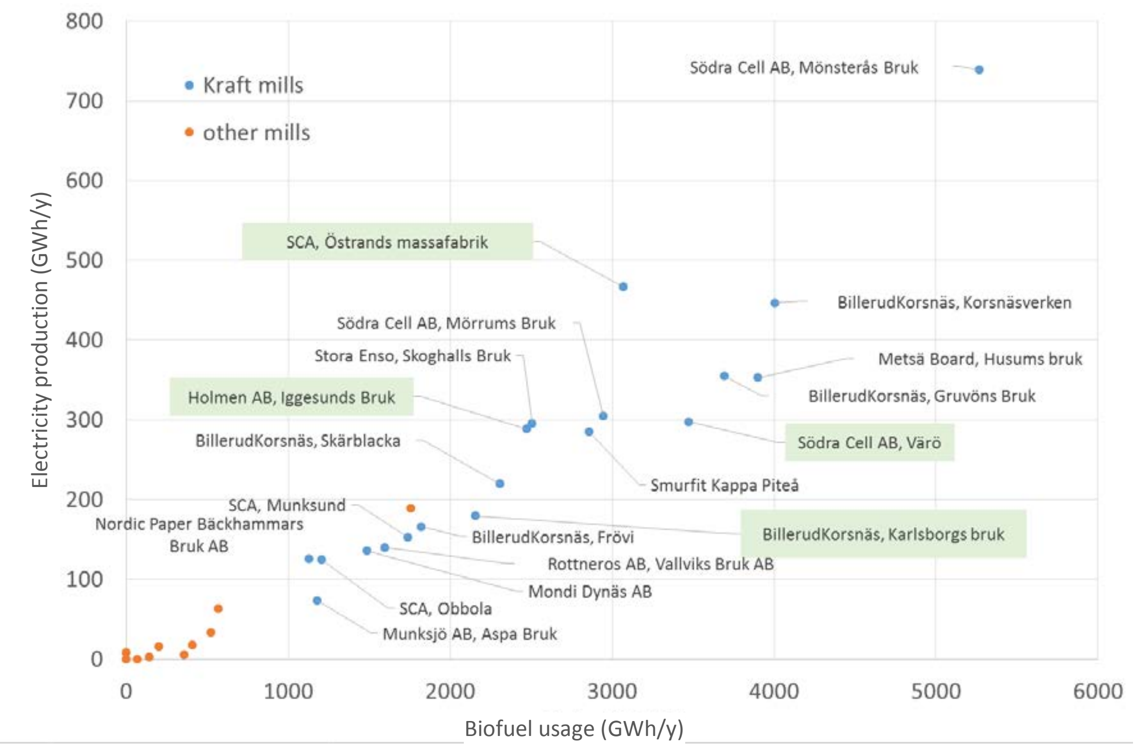

Figure 4: Electricity production vs Biofuel usage in Swedish pulp and paper mills according to 2015 year data (Skogsindustrierna, 2003-2015).

[3] The term ”biofuel” is used here to indicate all type of biomass derived fuel used in the mill as energy source, i.e. excluding the part of the wood that is used for pulp production. This is a direct translation of the term ”biobränsle” reported in statistics by (Skogsindustrierna, 2003-2015).

The export of some amount of excess heat from pulp and paper mills to district heating systems is also common in Sweden. However, the relation between sold excess heat and biofuel usage for different sizes and types of mill is less apparent than for electricity, see Figure 5. This may depend on several factors, such as~~-~~:

- Location: the export of excess heat depends on the demand for heat from nearby industries or district heating systems and differs significantly from case to case.
- Type and size of mills: although the Kraft process is rather standardized, steam demand and excess heat differ substantially between mills depending on the production of market pulp, paper or paperboard and their quality as well as on the performance level of key process units such as the multi-effect evaporator, digester, etc.
- Hot process water consumption: hot water is used in several parts of the pulp making process. Water utilization can vary substantially between different processes, reducing in this way the amount of excess heat at sufficiently high temperatures.

Note that some excess heat from the pulp and paper process is sometimes exported to a nearby sawmill, often located at the same site or on a neighbouring site. It is not always clear whether this excess heat export is reported as sold heat.

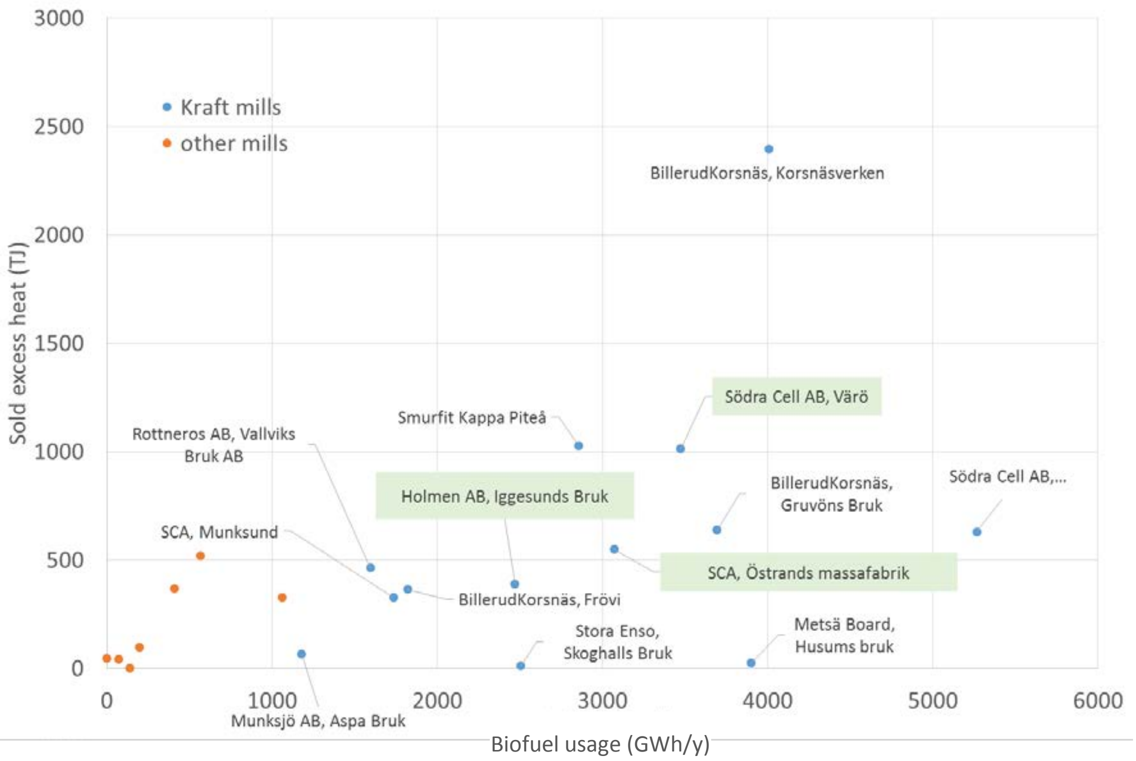

Figure 5: Sold excess heat vs biofuel usage in Swedish pulp and paper mills based on 2015 year data (Skogsindustrierna, 2003-2015).

This work presents an attempt to characterize the excess heat availability from Kraft mills, based on detailed process data collected mainly during M.Sc. thesis projects conducted at the division of Heat and Power Technology at Chalmers University of Technology. The names of the mills for which data were retrieved are highlighted in green in Figure 4 and Figure 5. In addition, data about typical pulp and paper mills were obtained the FRAM (Future Resource Adapted Pulp Mill) project, one of the largest collaborative projects conducted in Sweden for defining technology benchmarks for the pulp and paper industry. More specifically, mill specifications were extracted from FRAM report 9 related to bleached market Kraft pulp mills (Delin, et al., 2005a) and FRAM report 10 related to integrated fine paper mills (Delin, et al., 2005b).

With the data available, it was possible to define a theoretical reference condition of maximum process heat recovery. However, it was not possible to retrieve data about the actual cooling demand of each mill and therefore the Process Cooling XHT signature curve was estimated based on assumptions about the technical constraints for energy integration in pulp mills and assumptions about the mill energy system (see Section 3.4).

The characterisation of the excess heat from Kraft mills was conducted together with the estimation of the power generation targets since large amounts of excess heat at high temperatures are obtained by black liquor combustion in the Kraft process which are effectively converted into power via steam expansion in steam turbines.

Based on the results from the analysis of the six mills, regression functions using pulp and paper production rates as predictor variables were built to predict the power production targets as well the amount and characteristics of excess heat from the entire Swedish Kraft mill park

3.2 Mill case studies

The main data about the mills used as case studies are shown in Table 2. Most data about pulp and paper production as well as energy usage and export were retrieved from Miljödatabasen (Skogsindustrierna, 2003-2015) for the same reference year as the study during which process thermal data were collected.

These mills may have undergone substantial revamping and retrofit since the year the data were collected. The data about SCA Östrand in particular are representative of a new expansion that was planned in year 2015. In this case, data were obtained by quotations and interaction with mill process experts and therefore may be affected by a larger error compared to the other cases (this case is also referred to as “reconstructed Östrand mill”).

Data about so-called typical market and integrated mills were generated in the FRAM project by process flowsheet simulation and are representative of typical (or “average”) Scandinavian mills with significantly lower performance compared to benchmark reference mills.

Together, these mills provide a quite good representation of the Kraft mill park in Sweden.

Table 2. Overview of Kraft mill study cases. Data taken from Miljödatabasen (Skogsindustrierna, 2003-2015) with the exception of the FRAM mills (Delin et al., 2005a,b).

Company	**Södra**	**SCA**	**Holmen**	**Billerud-Korsnäs**	**FRAM type pulp mill**	**FRAM type int. mill**
Location	Värö	Östrand	Iggesund	Karlsborg	-	-
Data type	Mostly measure-ments	Quotations and models	Mostly measure-ments	Mostly measure-ments	FRAM models	FRAM models
Data year	2012	2015	2013	2010	-	-
Pulp prod. (kt/y)	419	900 (+95)	347	272	327	385
Market pulp (kt/y)	419	900 (+95)	50	151	327	0
Paper/board (kt/y)	0	0	381	151	0	512
Biofuel (GWh/y)	3035	na	2327	1952	1975	2594
Fossil fuel (GWh/y)	31	na	66	48	0	0
El. prod. (GWh/y)	358	na	155	224	259	523
Sold heat (GWh/y)	91	na	0	0	0	0
Process thermal data reference	Bood and Nilsson, 2013	Ahlström and Benzon, 2015	Isaksson, et al., 2013	Eriksson and Hermansson, 2010	Axelsson, et al., 2006	Axelsson and Berntsson, 2008

3.3 Process boundaries

The recovery boiler, the lime kiln, bark and oil boilers, the steam system, and the secondary heating system are integral parts of the energy systems of Kraft mills. Following the rationale whereby industrial excess heat should be quantified as excess heat available from a process only and should not originate from the utility units, it is important to define the heat sources that are to be excluded from the analysis in the case of Kraft mills. Hereafter, some equipment units that are typically found in pulp and paper mills are discussed with respect to their potential role as excess heat sources.

Recovery boiler and lime kiln

In the recovery boiler of Kraft mills, black liquor is combusted for recovery of energy and regeneration of cooking chemicals. The recovery boiler is a critical part of the Kraft process and is therefore considered as a part of the process itself, and its size is defined by the amount of black liquor being processed. Similarly, the lime kiln is another critical part of the Kraft chemical cycle and is therefore also considered as being part of the process. While heat in flue gases is mainly used to produce high pressure steam, excess heat can be further recovered at lower temperature levels, typically via a scrubber system for flue gas cleaning or simply by cooling and condensation of flue gases from which hot water can be produced.

BARK AND OIL BOILERS

The amounts of bark and oil that are utilized for extra steam production in a mill are solely dependent on the mill energy balance. These boilers should therefore be regarded as part of the utility system and not as process excess heat sources for assessing the theoretical availability of excess heat. In practice, these boilers are often utilized to obtain an optimal balance between combined production of electricity and heat to the process. When all the steam produced in the recovery boiler is fed to a turbine, the low-pressure steam obtained at the back-pressure turbine outlet may not be sufficient to cover the mill's steam demand. There are therefore two alternatives: either high pressure steam is reduced directly, by-passing the turbine expansion, or extra steam is produced in a bark boiler or an oil boiler (sometimes referred to as "power boiler"). The latter option is in fact a way to maximize fuel utilization for combined production of heat and power. In addition, export of bark or saw dust is not always economically viable and their combustion on-site remains in practice the only option. For the above reasons, bark and oil boilers might be included in the mill energy balance when assessing the excess heat availability from current process cooling since they are highly justified for production of electricity.

STEAM SYSTEM

The high temperature heat available from combustion of black liquor generates a large excess of heat at high temperature which is recovered for combined production of electricity and heat. This is thermodynamically the most efficient way to use the combustion heat. A steam turbine system should also be considered as an integral part of the mill. The steam system should, however, strive for maximum power generation, provided that no extra fuel is burned for steam production other than black liquor and that the process steam demand is satisfied. Cases in which low-pressure steam is used for export of district heating are not uncommon. In such cases, low-pressure steam could instead, as in this work, be considered for further expansion in a condensing turbine stage when possible. Note, however, that the condensing turbine stage should, in a theoretical, high energy efficiency scenario, only be considered provided that no extra fuel is burned for steam production other than black liquor. Using low-pressure steam for district heating while at the same time burning extra fuel (e.g. bark) in a steam boiler, should not be considered for the theoretical case, since such excess heat is in fact avoidable.

SECONDARY HEATING SYSTEM

Warm and hot water are used in various parts of the pulp production process. Generally, production of warm and hot water in process coolers is maximized and process parameters adjusted according to the availability of hot and warm water. Because of different degrees of closure of the water systems, the consumption of fresh water varies substantially between different mills and is one of the reasons why it is difficult to predict general characteristics of excess heat from Kraft mills even though the process technologies do not differ substantially from case to case. The warm and hot water system is generally referred to as the secondary heating system in pulp and paper mills. However, a large share of the water is not only used for heating purposes, but also as process water in the pulp production process, for example for pulp washing. Nevertheless, a certain mass flow rate is simply recirculated in the secondary heating system and used as a source of low temperature process heating. This part of the warm and hot water system can be seen as an intermediate utility system. As long as warm and hot water are produced using process excess heat, possible sources of excess heat in the secondary heating system can be included in the assessment of excess heat from pulp and paper mills. However, in order to characterize the theoretical excess heat availability for a mill, it is advisable to consider among the process thermal data only the production of the water used directly as process water in the pulp process (that is equivalent to the amount of make-up water heated from the temperature at which the make-up water is available up to the temperature at which the water is utilized in the pulp process).

3.4 Step-wise approach for targeting of power generation and excess heat in the studied Kraft mills

Due to the presence of high temperature excess heat from black liquor combustion in Kraft pulp mills, the XHT signature was characterized considering that a steam turbine system is also present and configured for maximum power generation.

The combined production targets for power and heat depend on the useful heat available from biofuel combustion and on the amount of steam required by the process. In this work, these targets were estimated using a mathematical programming framework. In principle, however, the steps required can be illustrated graphically, and can be listed as follows:

1. Characterization of available high-temperature heat from black liquor combustion in the recovery boiler (red line in Figure 6).
2. Description of net process heating and cooling demands for the rest of the pulp mill processes.

   When considering the theoretical case, this step corresponds to construction of the process GCC assuming a minimum temperature difference for heat exchange of zero degrees (blue line in Figure 6).

   For construction of the Process Cooling XHT signature, the current utility requirements of the process should be considered instead. In this case, the GCC is replaced by a representation of the actual heating and cooling demands of the process at different temperatures.
3. Background/Foreground analysis using split GCCs for black liquor combustion heat and process heating demand (Figure 6)

   This analysis shows if the heat content from the combustion of black liquor is sufficient to cover the heating demand of the process. When the split GCCs show that there is more heat available from the black liquor than what is required by the pulping process, this means that there is a potential for power generation in an integrated steam cycle without the use of additional fuel. This is the case for the example shown in Figure 6.

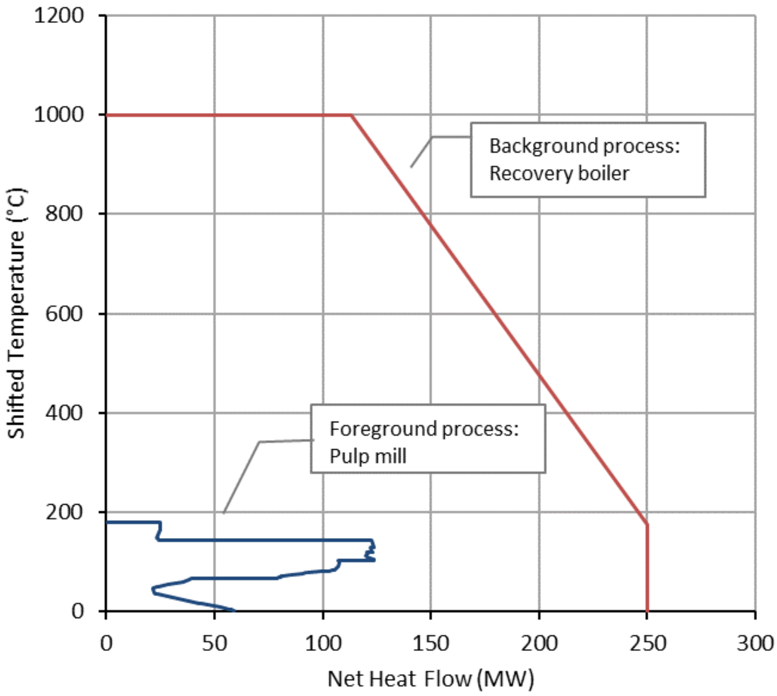

Figure 6. Background/foreground analysis using split GCCs of the heat from black liquor combustion in the recovery boiler and the rest of the pulp mill processes

4. Integration of a steam turbine cycle between the black liquor combustion heat from the recovery boiler and the net process heating demand (Figure 7).

   The integration of a steam turbine cycle is illustrated in another background/foreground graph using split GCCs. In this case, the pulp mill process and the black liquor combustion heat from the recovery boiler is combined into a single GCC that forms the background. The steam cycle is represented as another GCC in the foreground.

   The highest level of fuel utilization can be obtained with a back-pressure turbine where the low-pressure steam is sufficient to cover the process steam demand. In practice, such perfect steam balance seldom occurs and either steam is available in excess, which opens the opportunity for a condensing turbine stage, or steam is directly reduced to lower pressure by-passing the turbine.

   For the example shown in Figure 7, steam is available in excess. The figure to the left illustrates the case of pure back-pressure turbine operation, which leads to an excess of low-pressure steam that could be delivered as excess heat to an external user. The figure to the right illustrates the case where a condensing turbine is also added to the system. This way, the excess of steam is utilized for additional power generation. Note that this system design not only limits the amount of excess heat available as steam from the steam turbine cycle, but also reduces the amount of excess heat available from the pulp mill process, since this heat is used for heating the condensate from the turbine condenser up to feedwater temperature.

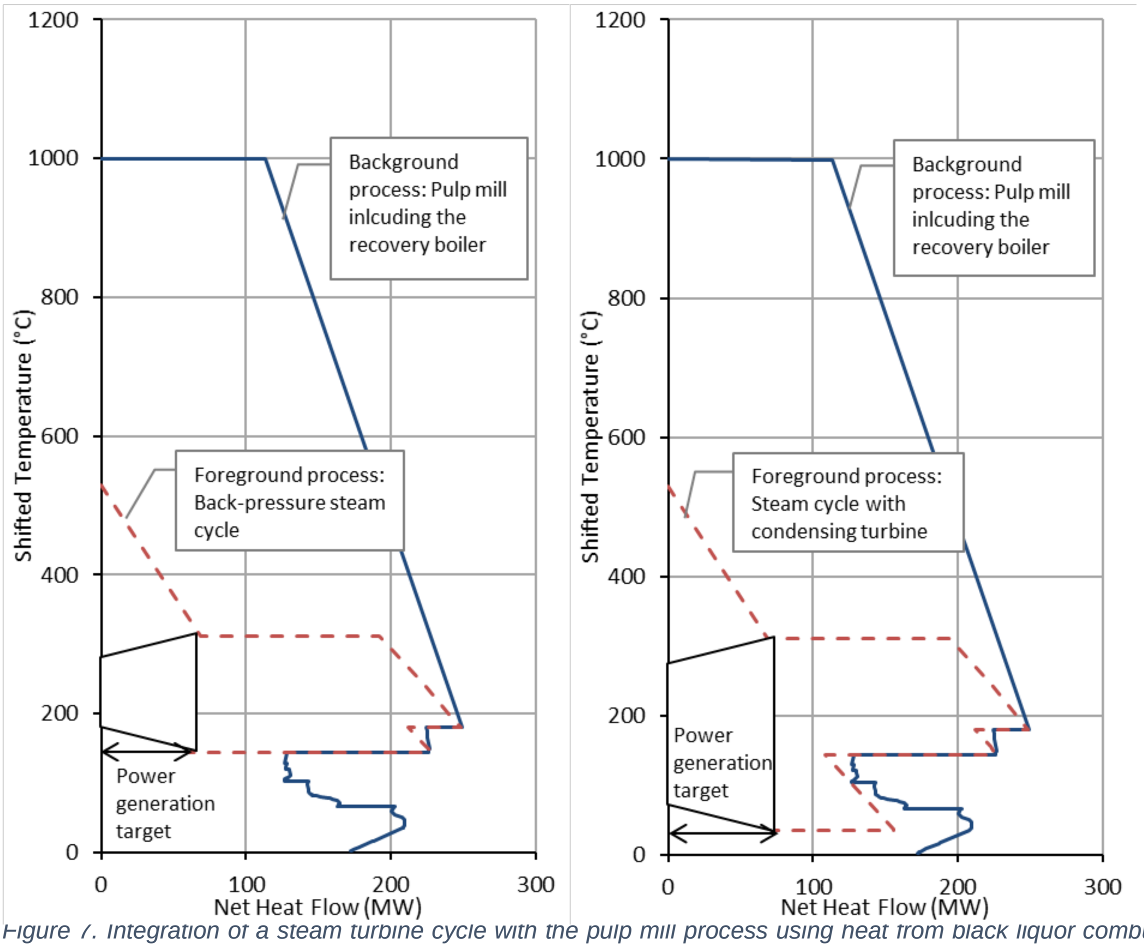

Figure 7. Integration of a steam turbine cycle with the pulp mill process using heat from black liquor combustion. LEFT: Back-pressure turbine operation only. RIGHT: Back-pressure and condensing turbine operation

5. Characterization of the XHT signature based on the process with the integrated steam cycle (Figure 8).

   In the final step, the characterization of available excess heat is made against the GCC representing the net heating and cooling demands of the total integrated processes of the pulp mill, the recovery boiler (and if necessary any complementary boilers) and the steam cycle. The XHT signature is fitted against this GCC to optimize the excess heat recovered at different temperature levels according the objective function presented in Section 2.2. Figure 8 shows the estimated XHT signatures for the example mill, assuming back-pressure turbine only (above), or assuming the presence of an additional condensing stage (below).

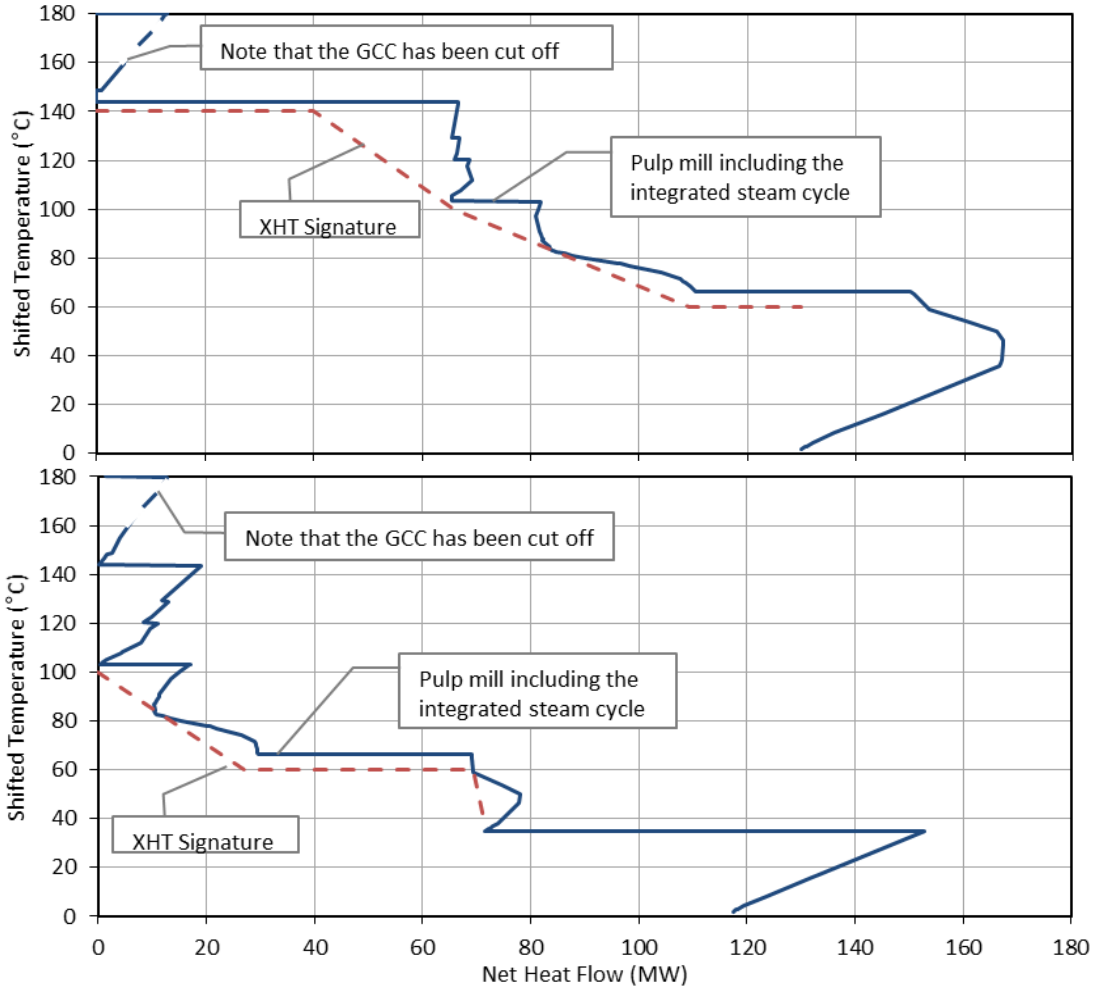

Figure 8. Estimated XHT Signatures based on the net cooling demand represented by the GCC of the integrated pulp mill process, recovery boiler and steam cycle. ABOVE: Back-pressure turbine only. BELOW: Back-pressure and condensing turbine stage.

To complete steps 1–5, the energy targeting methodology introduced in Section 2.1 was used. Following this methodology, Steps 4 and 5 were completed simultaneously, by solving a linear programming problem following the combined objective of maximum power generation *and* maximum excess heat export. In practice, a single objective function was considered that consists in a linear combination of power generation and excess heat amounts at different temperature levels, where the weighting factor for power generation is assumed to be very large compared to the coefficients for excess heat.

Data regarding, for example, the availability and heat content of black liquor, and steam data for the recovery boiler are presented in Section 3.5. This section also describes the assumptions made regarding internal process heat integration and whether or not to assume a condensing turbine in the assessment.

3.5 Assumptions and input data

All calculations were made considering average constant mill production which reflects the process conditions for which thermal stream data were collected in the various studies. Annual data obtained from Miljödatabasen (Skogsindustrierna, 2003-2015) were converted into loads or production rates considering a common plant capacity factor of 7838 hours/y as considered in the FRAM project (Delin, et al., 2005a).

The thermal stream data that were collected from the four existing mills are mainly the set of process heating and cooling demands. Data about the actual heat exchanger network including process heaters and coolers are scarce and not complete. To be able to characterize the excess heat currently available from process cooling, some further assumptions were made and simplified energy and mass balance models of equipment units were used.

ESTIMATION OF THE USEFUL HEAT FROM BIOFUEL COMBUSTION

The useful heat available from combustion of black liquor was estimated according to data from FRAM report 9 (Delin, et al., 2005a) for typical softwood market pulp mills (see Table 3). This is the heat that can be used for net production of steam after all the losses are considered, including the steam for soot blowing. Since there are not sufficient data available about the exact amounts of black liquor processed in each mill (only the total biofuel usage value is available in Miljödatabasen), the net useful heat available from black liquor combustion was estimated for each mill by calculating the amount of black liquor from the total pulp production[4].

The amount of biomass fed to the bark boiler under existing process conditions was estimated by subtracting the estimated black liquor from the reported value of total biofuel consumption (see Table 2). For simplicity, the extra useful heat from the bark boiler was estimated assuming the same efficiency as for the recovery boiler in Table 3.

Table 3: Recovery boiler assumptions (Delin, et al., 2005a).

Black liquor LHV	12.24 MJ/kg dry solids
Adiabatic temperature	1677 °C
Flue gas temperature	175 °C
Net useful heat	9.45 MJ/kg dry solids
Black liquor / pulp ratio	6.046 MWh/ADt

PROCESS HEAT INTEGRATION

As already mentioned, the theoretical process excess heat availability was defined as the remaining excess heat that can be recovered after implementation of ideal, maximized internal heat recovery within the industrial process. For such theoretical reference conditions, ideal heat integration is considered within the process, whereby heat can be exchanged between any system thermal sink and source with ΔT_{min} = 0 °C.

[4] Note that pulp production refers to the pulp produced from the wood via the Kraft process. This quantity may exceed the sold amount of market pulp when paper is also produced, unless extra market pulp is also imported.

In practice, due to economic and operability reasons, the actual excess heat available from a process may differ substantially from the theoretical conditions. Due to scarce or lacking data about the current design of the heat recovery system and process cooling in some of the mills, some assumptions about the current heat integration were made in order to model and estimate the current process cooling temperature-heat load profile. For example, it was assumed that hot process streams that are currently cooled by water could transfer heat to a secondary (intermediate) heating system with a minimum temperature difference ΔT_{min} of 5°C. In addition, layout and operability limitations were considered when estimating the Process Cooling XHT profile. Furthermore, according to these assumptions, direct process to process heat exchange is allowed only between thermal streams that are connected to the dryer operation (e.g. between fresh and humid air) while heat recovery between most of the process heat sources and sinks is achieved via a secondary heating system. Steam is used for covering the process hot utility demand.

STEAM TURBINES, STEAM NETWORK AND SECONDARY HEATING SYSTEM

In the mills, the heat generated by black liquor and bark combustion is used for power generation in steam turbines, while low and medium pressure steam is used for process heating.

The power generation depends on turbine inlet steam conditions, turbomachinery efficiency and on the type of steam turbines. Turbine inlet steam conditions, in turn, depend on the steam properties of the high-pressure steam generated from black liquor combustion in the recovery boiler. In the theoretical case, the steam properties were selected to be representative of a modern, newly built recovery boiler (100 bar, 530°C). This steam pressure is comparable to the specifications for the modernization of the SCA Östrand mill, while for example the Holmen Iggesund mill has a new recovery boiler with even higher pressure specification (110 bar) . For the estimation of the Process Cooling XHT signature, steam values were instead set to more moderate levels (80 bar, 480°C). Note that the development has been quite fast during the last decade. In the report from the FRAM project (Delin, et al., 2005a), the reference, best available technology mill assumed recovery boiler steam specifications of 80 bar, while the average type mill was modelled at 60 bar.

The low and medium steam pressure values were determined on a case by case basis by inspection of the process GCC with the objective of maximizing power generation.

In this work, a condensing turbine option was considered only if the extra power produced by the condensing stage is greater than 10 MW, a limit that was set somewhat arbitrarily to avoid unrealistically small turbine sizes. Steam reduction was modelled as separate steam production at 16 bar, a pressure that is high enough for process heating in all the considered cases.

In addition to the steam system, a warm and hot water system was also modelled to represent the mill secondary heating system when calculating the actual Process Cooling XHT profile. The water systems were modelled as two separate circulating thermal loops between 20°C and 60°C and 20°C and 80°C for warm and hot water respectively.

Table 4 provides an overview of the assumptions made for calculating the theoretical and process cooling-based XHT potentials. Note that small amounts of fossil fuel are also used in the mills. It is not possible to know the type and usage of the fossil fuel but since it is often used in the lime kiln, such amounts were included in the accountings of the total fuel consumption. However, no steam was considered to be produced from fossil fuel.

Table 4: Assumptions for estimation of excess heat and cogeneration power targets for Kraft mills.

	Theoretical XHT	Process Cooling XHT
Black liquor	6.046 MWh/ADt pulp	6.046 MWh/ADt pulp
Bark	-	Total biofuel – Black liquor
Fossil fuel usage	Included	Included
ΔT_{min} for heat exchanging	0°C	5°C
HP steam conditions	100 bar, 530°C	80 bar, 480°C
Turbine isentropic efficiencies	Back-press. turb: 0.85 Condens. turb stage: 0.9	Back-press. turb: 0.75 Condens. turb stage: 0.85
Condenser pressure	0.1 bar	0.1 bar
Additional steam production	-	16 bar
Secondary heating system	-	20 to 60°C and 80°C water

3.6 Theoretical heat integration and XHT availability

In this case, no other sources of heat than the recovery boiler are considered. Also, ideal heat integration is considered with ΔT_{min} = 0 °C. Heat transfer is assumed to be possible directly between the recovery boiler flue gases and the pulp and paper process.

Theoretical heat integration opportunities are highlighted for the six mills in Figure 9 to Figure 14. The reader is referred to Table 2 for an overview of the main characteristics and production volumes of these mills. In these figures, the GCC of the pulp and paper process is shown as a dashed line whereas the useful heat released from the recovery boiler is shown in bold. To reduce the extent of the y-axis, the combustion heat available above 1000°C is shown as a horizontal line.

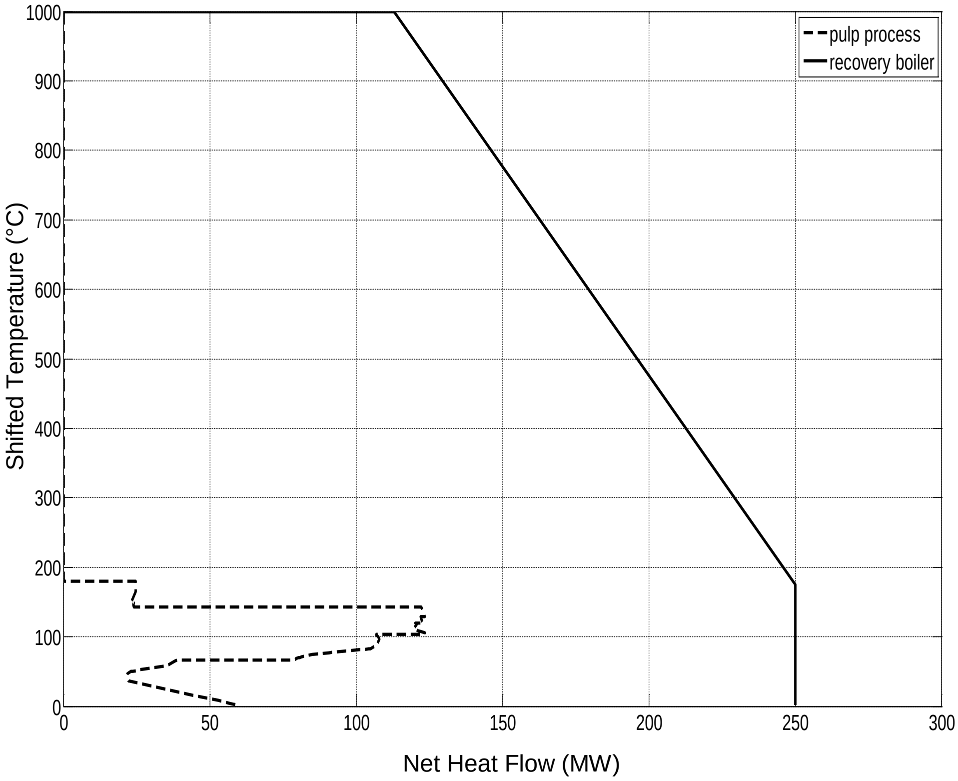

Figure 9: Theoretical GCCs of the process and of the recovery boiler at Södra Värö mill (ΔT_{min} = 0°C).

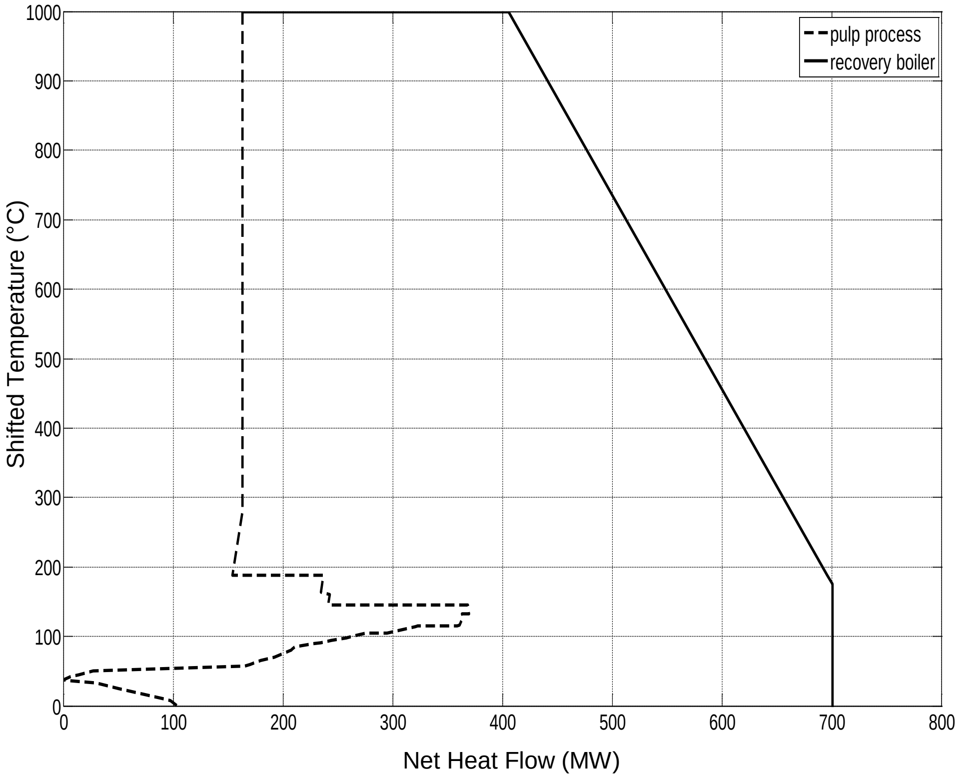

Figure 10: Theoretical GCCs of the process and of the recovery boiler at the reconstructed SCA Östrand mill (ΔT_{min} = 0°C).

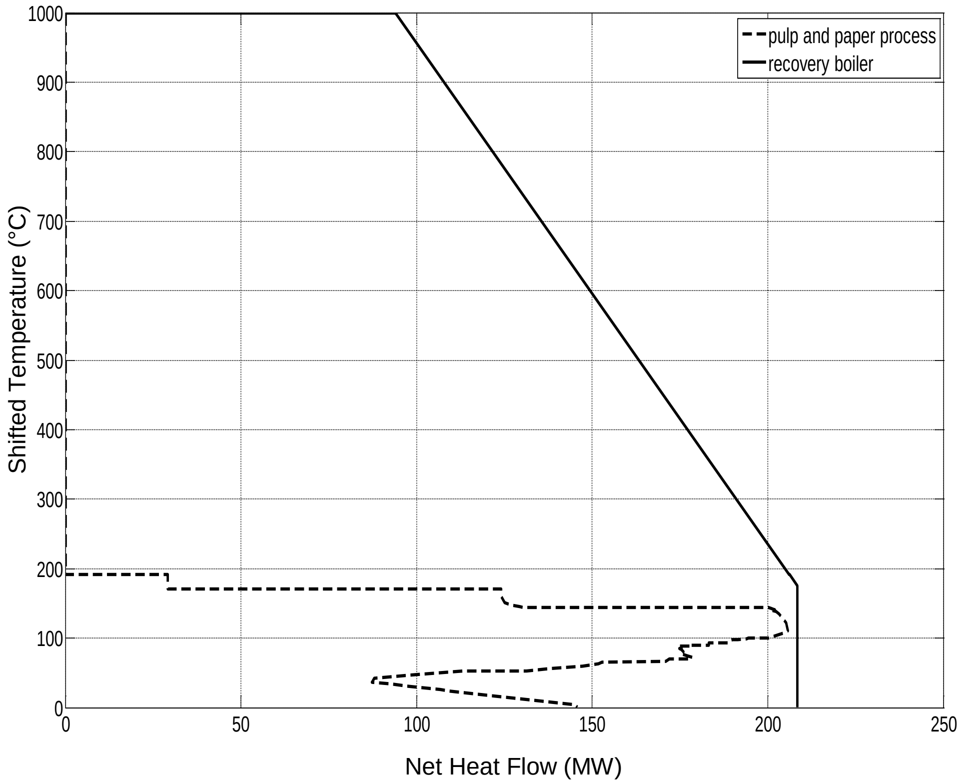

Figure 11: Theoretical GCCs of the process and of the recovery boiler at Holmen Iggesund mill (ΔT_{min} = 0°C).

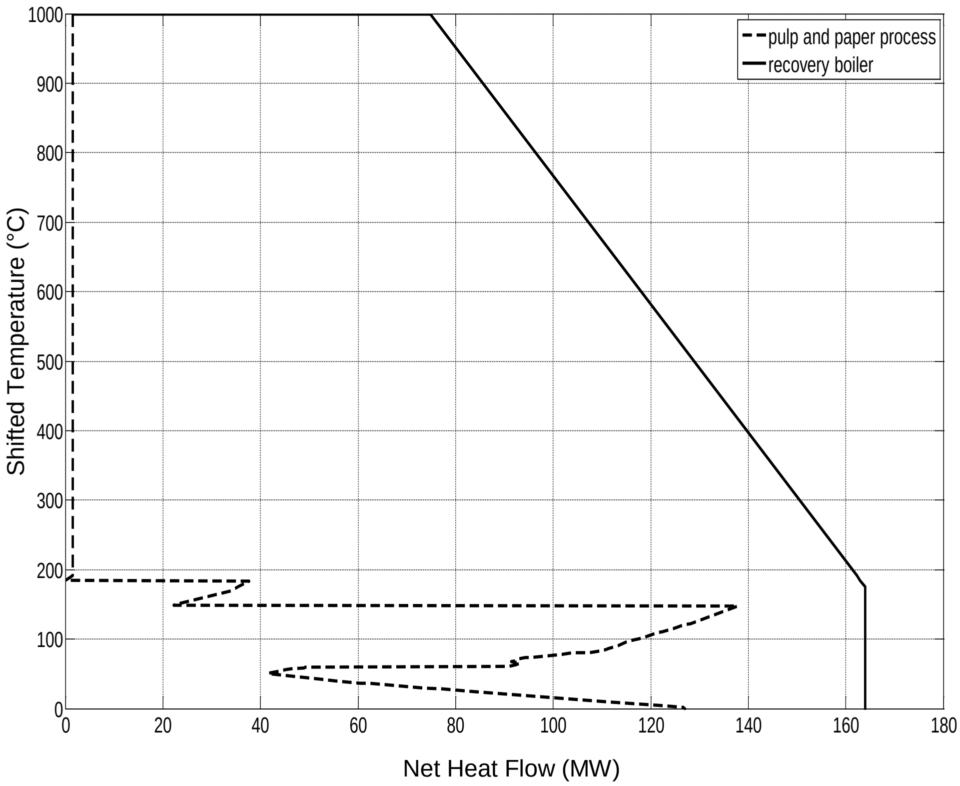

Figure 12: Theoretical GCCs of the process and of the recovery boiler at Billerud Korsnäs Karlsborg mill (ΔT_{min} = 0°C).

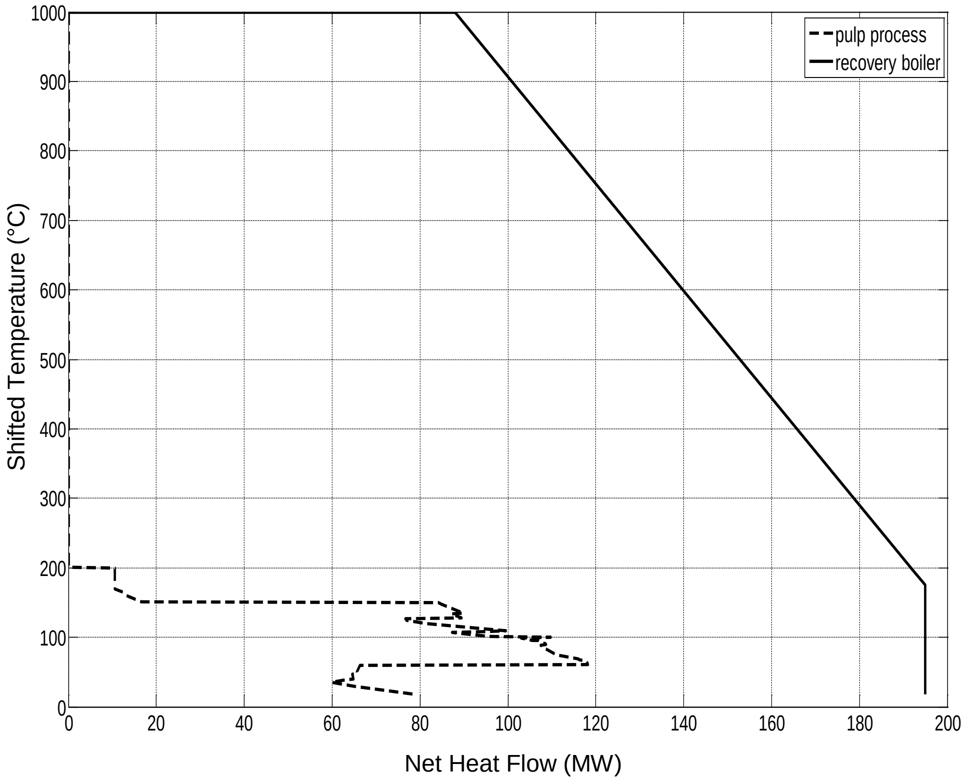

Figure 13: Theoretical GCCs of the process and of the recovery boiler of FRAM type market pulp mill (ΔT_{min} = 0°C).

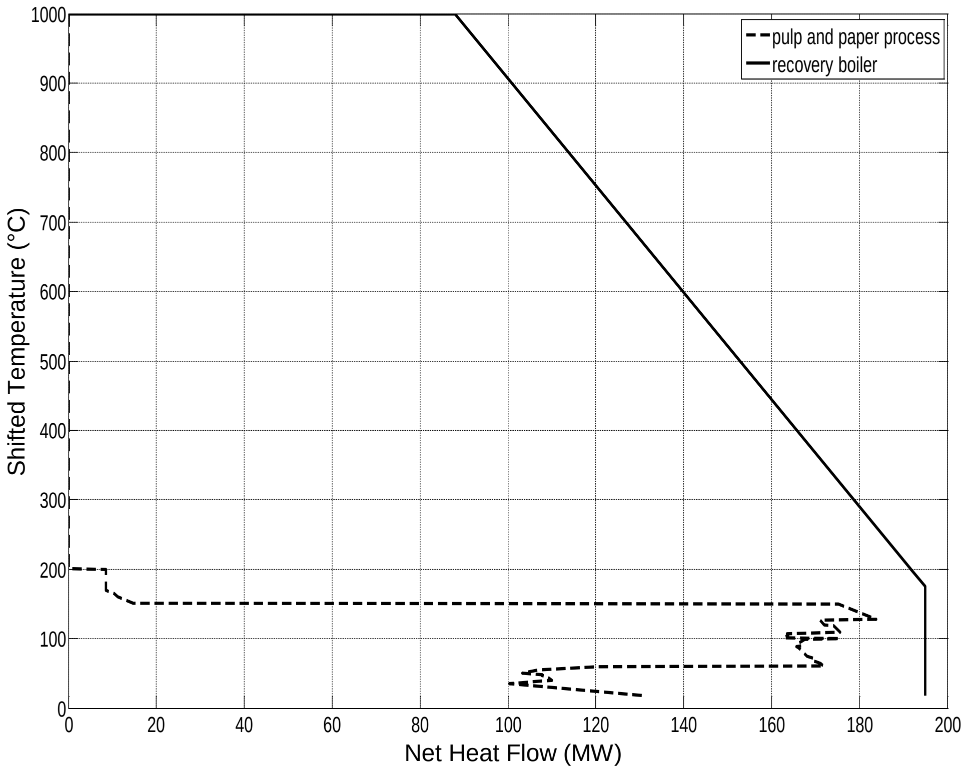

Figure 14: Theoretical GCCs of the process and of the recovery boiler of FRAM type integrated pulp and paper mill (ΔT_{min} = 0°C).

From these curves, it is also possible to obtain indications about the theoretical power generation targets and theoretical excess heat availability. In particular, the theoretical power generation cannot exceed the minimum horizontal distance between the process GCC and the recovery boiler GCC.

Some observations can be made:

- The heat available from black liquor combustion is substantially larger and at a sufficiently high temperature to cover all the process heat demand without the need to use additional fuel such as bark or oil.
- The process heat demand related to the heat available from black liquor combustion is much larger for integrated pulp and paper mills compared to market pulp mills. This difference is particularly pronounced when comparing the market pulp mills (Värö, Östrand, FRAM pulp mill) with the Iggesund mill and FRAM integrated mill where most of the pulp is used to produce paper on-site.
- In market pulp mills, the heat balance between process requirements and black liquor combustion allows substantial amounts of on-site power generation which highlights opportunities for a condensing turbine stage. Conversely, in the integrated pulp and paper mills, there might be the need for extra fuel combustion to obtain a well-balanced combined production of heat and power.
- The GCCs of all the pulp and paper processes are similar. The process heat demand occurs primarily at two temperature levels, the highest temperature level heat demand typically corresponding to heat demands in the bleaching and digesting stages and the lower to the evaporation plant. The lower section of most of the GCCs shows a pronounced heat pocket which is delimited by the heat demand of the warm and hot process water preparation.
- Although the process GCCs are similar, excess heat temperature and amounts are quite different even when comparing the different market pulp mills. The difference may be explained by higher energy efficiency of more recent process technologies (e.g. the reconstructed Östrand mill) compared to older mills. However, the substantially lower water demand and hot utility demand of the Östrand mill can also be a result of the quotations used to retrieve most of the process thermal data which may represent more optimistic figures compared to the data obtained from measurements in existing mills.

3.7 Power generation targets

Figure 15 shows the specific power generation targets for the six mills considered in this study, for both the theoretical case and considering current utility demands. This result is calculated by dividing the total power generation by the biofuel usage. The green bars show the specific power generation calculated using the data in Miljödatabasen (Skogsindustrierna, 2003-2015). Representing such targets in specific form allows to neglect the mill size factor when comparing different cases.

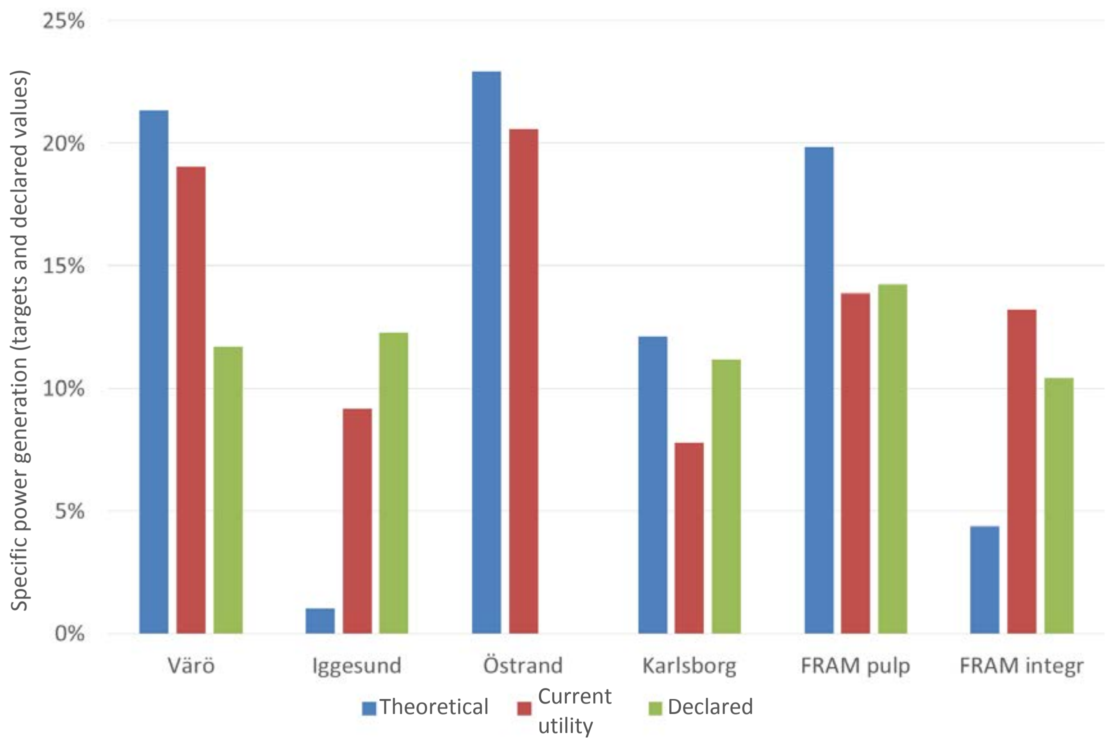

Figure 15: Specific power generation for the six Kraft mills, calculated as the ratio between power generation and total fuel usage, where the power generation is a target estimated based on theoretical or current utility demands, or is based on declared data (Skogsindustrierna, 2003-2015).

The following observations can be made:

- The specific theoretical power generation targets for market pulp mills are around 20% and less than 5% for the fully integrated pulp and paper mills.
- The difference in specific power generation targets between the theoretical and current utility scenarios is less pronounced. In the integrated pulp and paper mills, the observed difference is mainly caused by the fact that bark and oil boilers are used in practice to supplement the steam production from the recovery boiler. This is particularly the case for the fully integrated pulp mills (Iggesund and FRAM integrated mill). For these mills, the process heat demand substantially limits the power generation opportunities in the theoretical case in which external utility demand is minimized, and the recovery boiler is left as the only steam producer. For the market pulp mills, on the other hand, a reduction in power generation is observed from the theoretical case to the case based on current utility requirements, which is attributed to lower steam turbine inlet conditions and turbine performance parameters.
- With the exception of the Värö mill, the specific power generation calculated based on declared data of total yearly power generation and biofuel consumption is close to, or exceeds, the estimated targets based on current utility levels. This may indicate that the assumptions used in this study for the current utility requirements are rather conservative compared to the industrial practice or may not be representative of all the cases. In fact, the assumptions related to useful heat obtained from biofuel combustion are based on the FRAM softwood market pulp type mill for which very similar results were obtained. Note that the model of the FRAM market pulp mill does not consider a bark boiler. This may indicate that steam production and steam values in the current utility scenario underestimate the performances of actual bark and oil boilers.

More details about the total power production and the share of the back-pressure turbine and of the condensing turbine are shown in Table 5 and Table 6.

Table 5. Calculated theoretical power production targets.

Mill	Värö	Iggesund	Östrand	Karlsborg	FRAM pulp	FRAM integr.
Black liquor (MW)	323	269	694	210	252	258
Bark (MW)	-	-	-	-	-	-
Back-pressure turb. (MW)	40	3	66	26	37	11
Condensing turb. (MW)	29	0	95	0	13	0
Total power gen (MW)	70	3	162	26	50	11
Power-to-biofuel ratio	21%	1%	23%	12%	20%	4%

Table 6: Calculated power production targets based on actual utility usage.

Mill	Värö	Iggesund	Östrand	Karlsborg	FRAM pulp	FRAM integr.
Black liquor (MW)	323	269	694	210	252	258
Bark (MW)	64	46	128	39	0	73
Back-pressure turb. (MW)	38	29	60	20	35	44
Condensing turb. (MW)	36	0	111	0	0	0
Total power gen (MW)	74	29	171	20	35	44
Power-to-biofuel ratio	19%	9%	21%	8%	14%	13%

3.8 XHT signatures

The estimated XHT signatures of the six mills are shown in Figure 16 to Figure 21. The theoretical and process cooling based signatures are shown together for comparison. With the exception of the Karlsborg case, the Process Cooling XHT signature follows approximately the shape of the Theoretical XHT signature. However, the excess heat availability at medium to high temperature is lower for the theoretical case which is a direct consequence of increased heat recovery. This might be an indication that, in practice, excess heat from Kraft mills, e.g. for district heating purposes, can easily exceed the theoretical target which corresponds to maximum internal excess heat recovery.

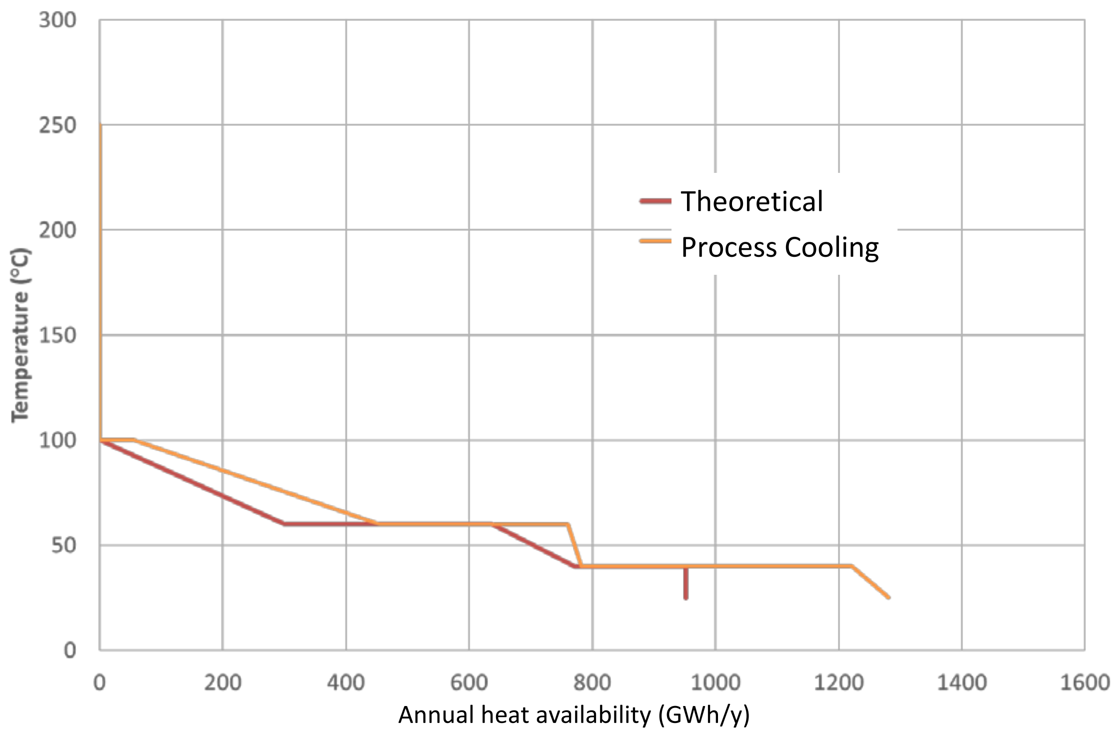

Figure 16: Estimated XHT signatures of the Södra Värö mill.

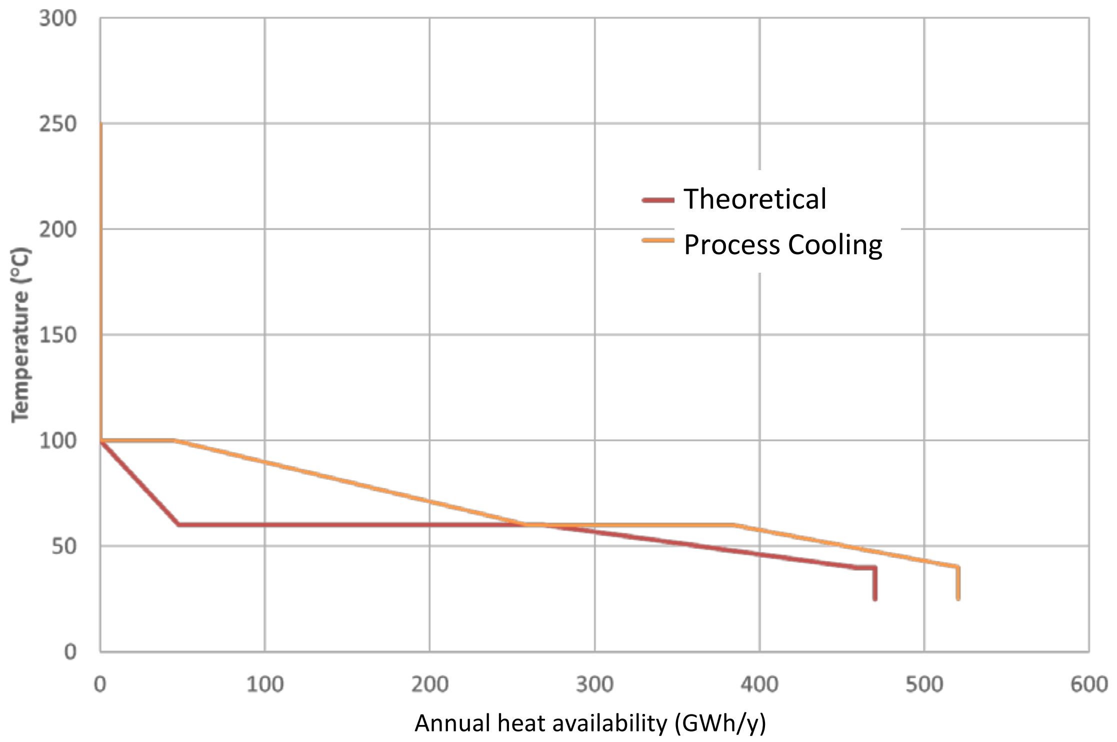

Figure 17: Estimated XHT signatures of the Holmen Iggesund mill.

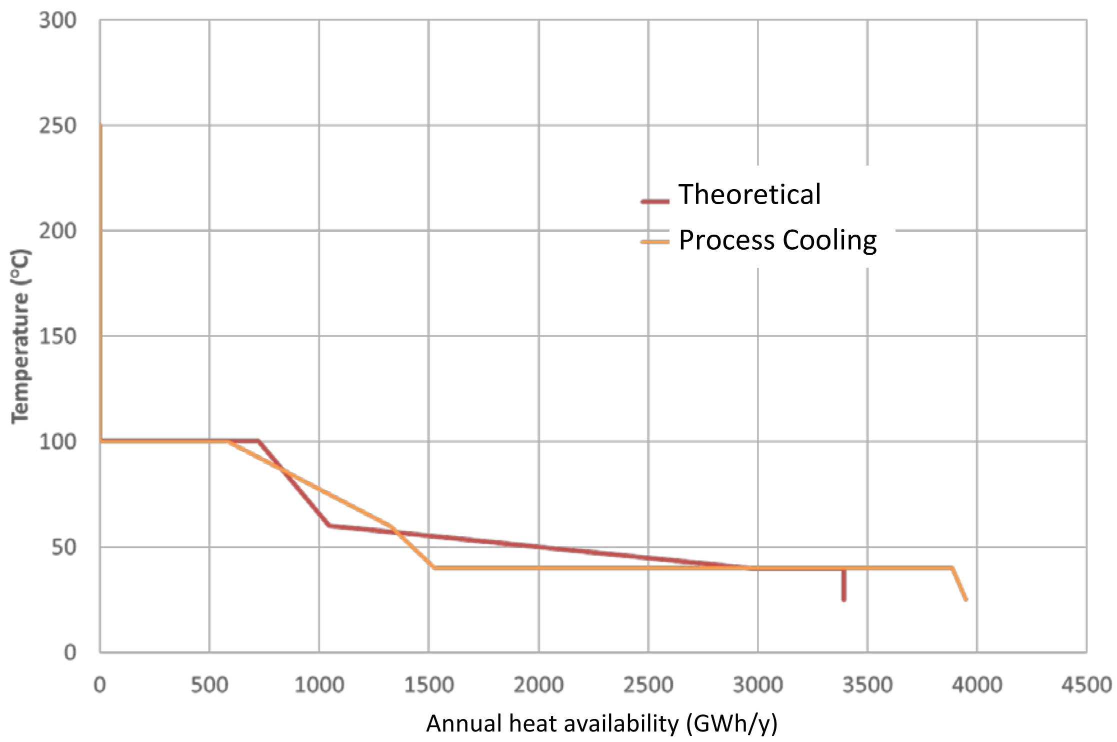

Figure 18: Estimated XHT signatures of the reconstructed SCA Östrand mill.

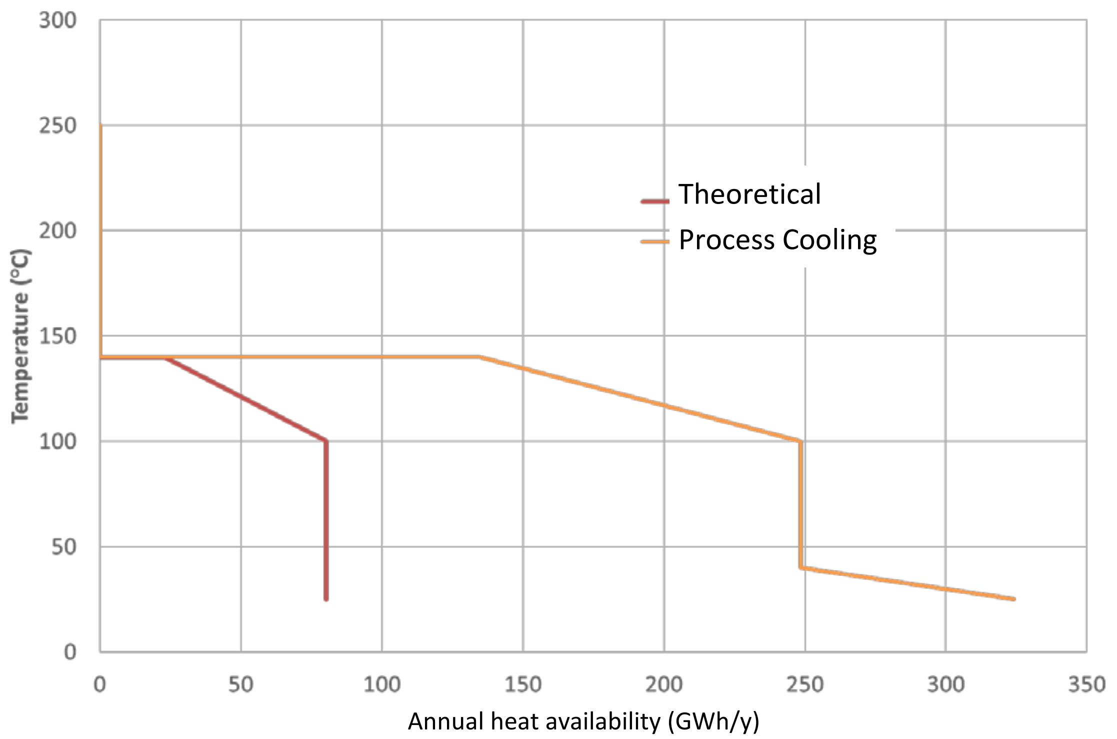

Figure 19: Estimated XHT signatures of the Billerud Korsnäs Karlsborg mill.

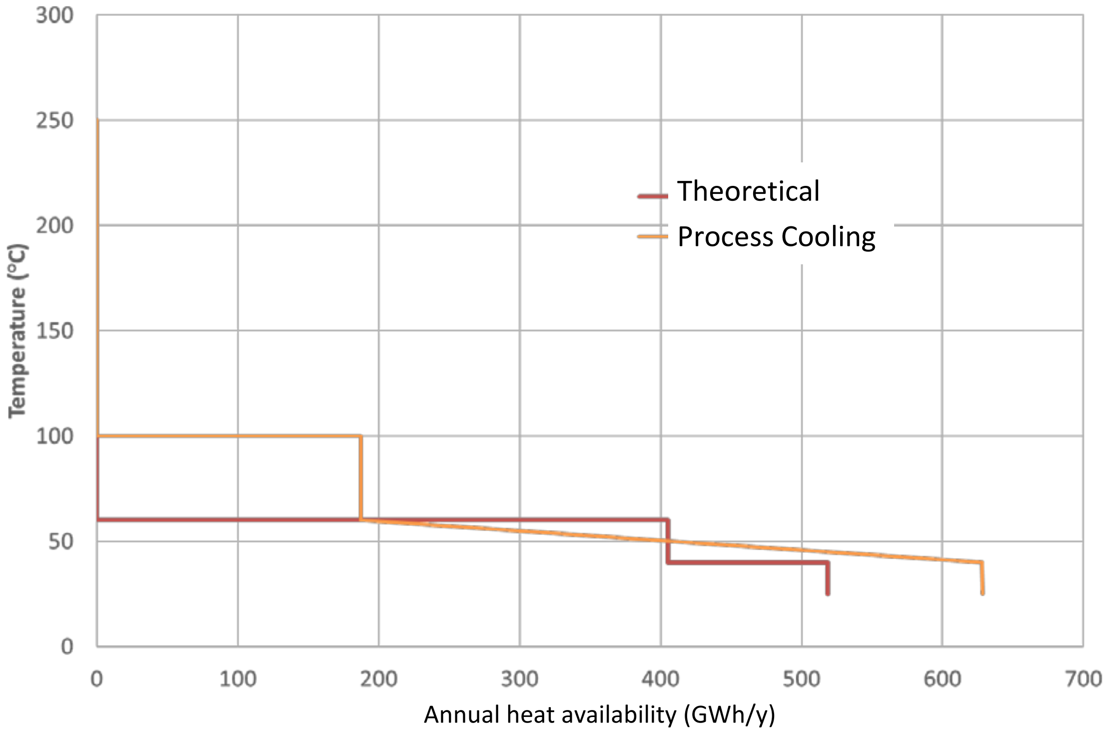

Figure 20: Estimated XHT signatures of the FRAM type pulp mill.

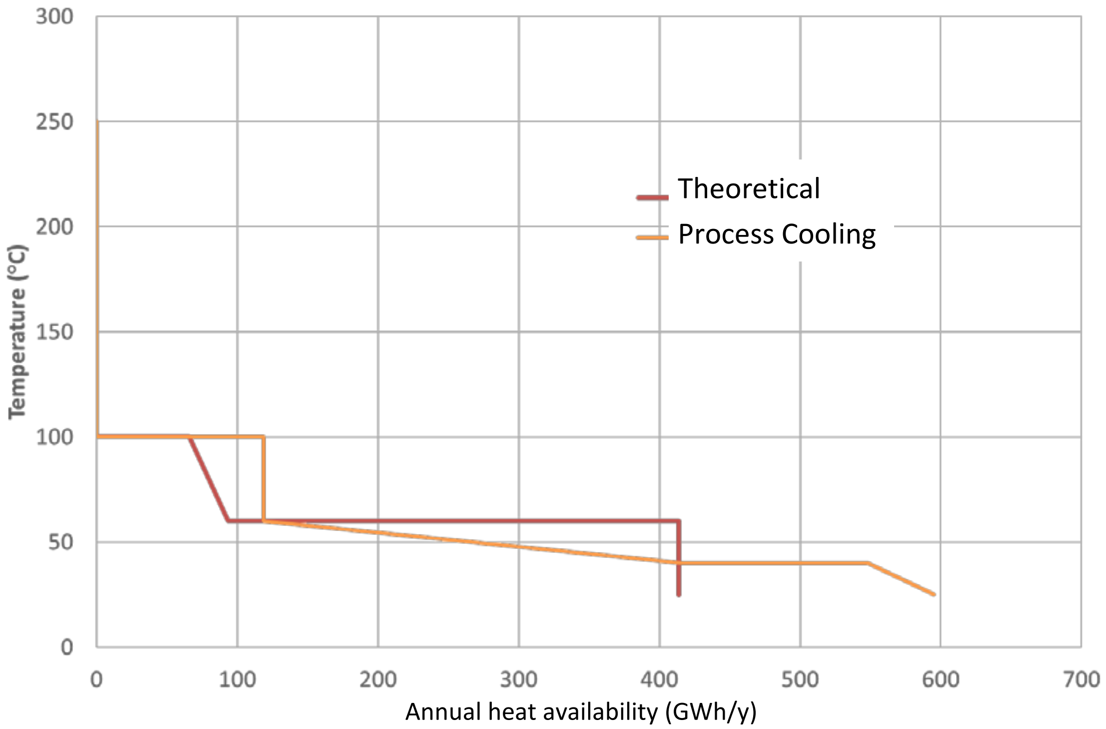

Figure 21: Estimated XHT signatures of the FRAM type integrated pulp and paper mill.

Figure 22 and Figure 23 present a comparison between the six mills by showing the specific excess heat availability above 60°C (low to very high temperature) and 25°C (all temperature intervals included), respectively. As for the specific power generation targets, the specific excess heat is evaluated as a ratio between the total excess heat available and the total biofuel usage.

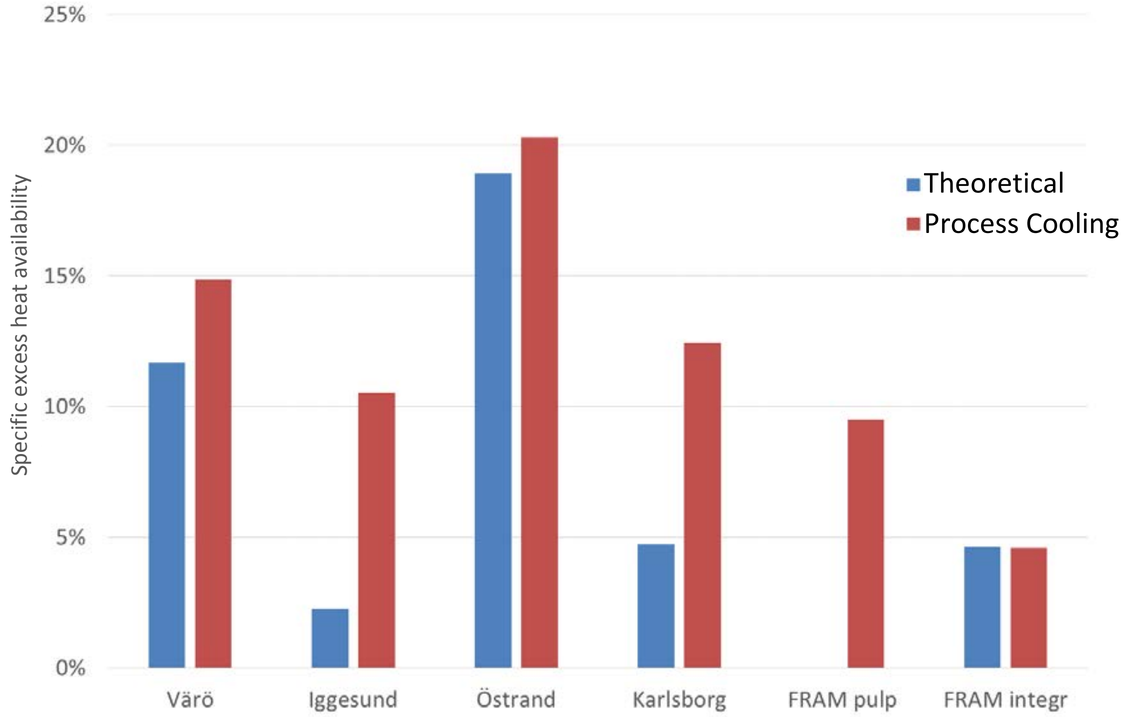

Figure 22: Estimated specific excess heat availability above 60°C in the six Kraft mills. Specific excess heat evaluated as ratio between excess heat and total biofuel usage.

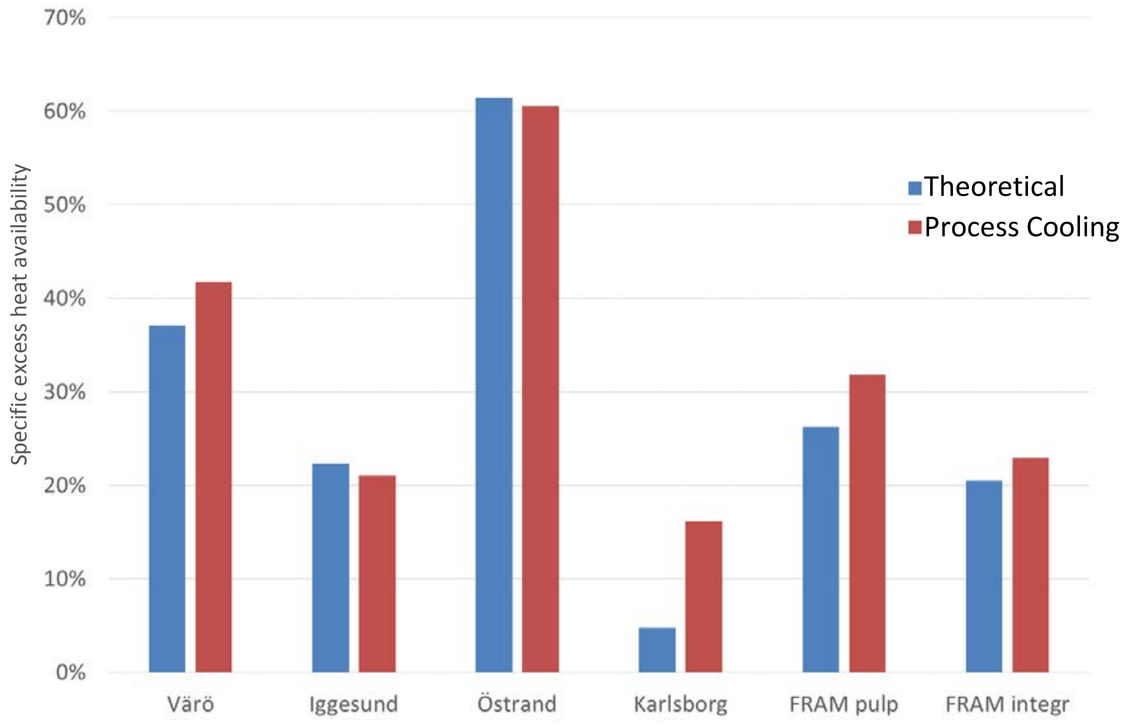

Figure 23: Estimated total specific excess heat availability (above 25°C) in the six Kraft mills. Specific excess heat evaluated as ratio between excess heat and total biofuel usage.

The following observations can be made:

- The total availability of excess heat varies largely between Kraft mills but is generally greater for market pulp mills than for integrated pulp and paper mills.
- The amount of excess heat available above 60°C is much less than the total excess heat availability; for most of the cases specific availability is lower than 15% of the biofuel energy supply. This figure is substantially below the 25% excess heat recovery level often considered in generic studies assessing the potential of industrial excess heat levels for district heating applications, see for example (Persson, et al., 2014).
- In the two real integrated mills (Iggesund and Karlsborg), the excess heat available above 60°C is much lower for the theoretical case, whereas this difference is not as pronounced for the real pulp mill cases (Värö and Östrand). This indicates that integrated mills could be more likely to deliver larger amounts of heat for external utilization than what would be possible if the mill had maximized its energy efficiency through ideal internal heat integration. In other words, they are more likely to deliver excess heat that is not “true” excess heat. On the other hand, the availability of excess heat from market pulp mills is greater than for integrated mills.
- The data for the reconstructed Östrand mill indicate again that much more excess heat could be obtained in modern mills. However, the data for this case is more uncertain than for the other mills since they were obtained from quotations and not from real measurements.
- The excess heat available from the FRAM type mills appear to be lower than from the real mills (even when neglecting the reconstructed Östrand mill). This is probably because the heat sources and sinks have been analysed in more detail in the FRAM project in comparison to the studies on real mills where data collection might be more limited for practical reasons. In other words, it can be expected that theoretical excess heat is overestimated for the four real cases while the process cooling excess heat availability is underestimated in the case of the FRAM type mills.

3.9 Power generation targets and excess heat availability from the Swedish Kraft mill park

An attempt was made in this work to estimate the power generation targets and excess heat availability from the whole Swedish Kraft mill park based on the data that were obtained from the six case studies and the general data available from Swedish mill statistics (Skogsindustrierna, 2003-2015).

For this purpose, a linear regression analysis was conducted based on the results obtained for the six study cases. To make the regression as significant as possible, only the market pulp and paper production rates were considered as predictor variables. The least square interpolation tool available in the MATLAB statistical toolbox was used for this purpose.

3.9.1 Power generation targets

The following regression function was postulated:

$$Electricity\ (\mathrm{GWh/y}) = a + b \cdot Market\ Pulp\ (\mathrm{kADt/y}) + c \cdot Paper\ (\mathrm{kADt/y})$$

The values of the coefficients estimated via least square interpolation are given in Table 7 together with their standard errors.

Table 7: Values of linear coefficients obtained for linear regression of power generation targets with standard deviations.

Case	a (constant)	b (Pulp coeff.)	*c* (Paper coeff.)
Theoretical target	-32.54 ± 54.75	1.314 ± 0.090	0.157 ± 0.154
Current utility target	-177.88 ± 84.74	1.550 ± 0.139	0.985 ± 0.238

The values of coefficient *c* are lower than the values of the coefficient *b* because integrated mills generally have a much lower power production potential compared to a pulp mill processing the same quantity of raw material. Furthermore, the difference is less pronounced in the current utility scenario compared to the theoretical case due to the consumption of extra fuel such as bark for production of power. Nevertheless, the magnitude of the standard deviations show that the prediction based on market pulp and paper production is affected by large uncertainty especially for fully integrated mills and especially in the theoretical case. Better predictions can be made for market pulp mills.

The power production targets were recalculated for the six mills based on the linear regression. The results are shown with dots in Figure 24 together with their standard deviations (68% confidence interval). In the same figure, the original estimates are also shown. Although the errors are quite large compared to the total values for the smaller mills, the central values of the regression are quite well in line with the original values.

With the regression function now available it is possible to estimate the total power production targets for all the Swedish Kraft mills given their Market pulp and paper production.

The total targets estimated based on the year 2015 data are shown in Figure 25 for the together with the total production based on declared values for the same year (Skogsindustrierna, 2003-2015).

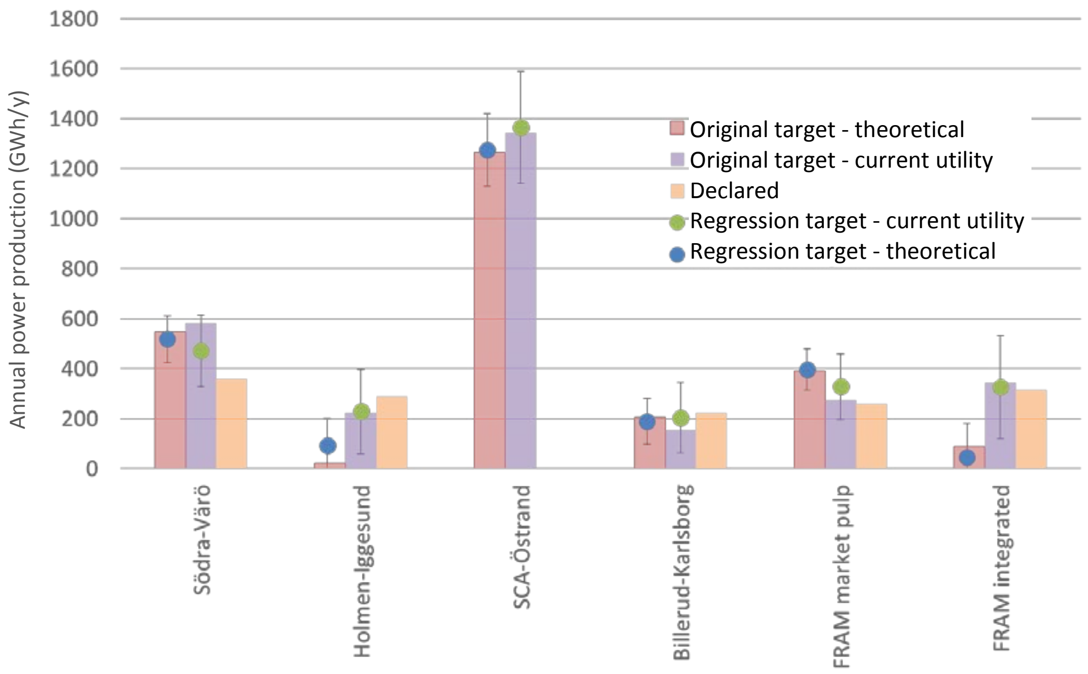

Figure 24: Total estimated power production targets of the six Kraft mills calculated based on the regression function and their original values.

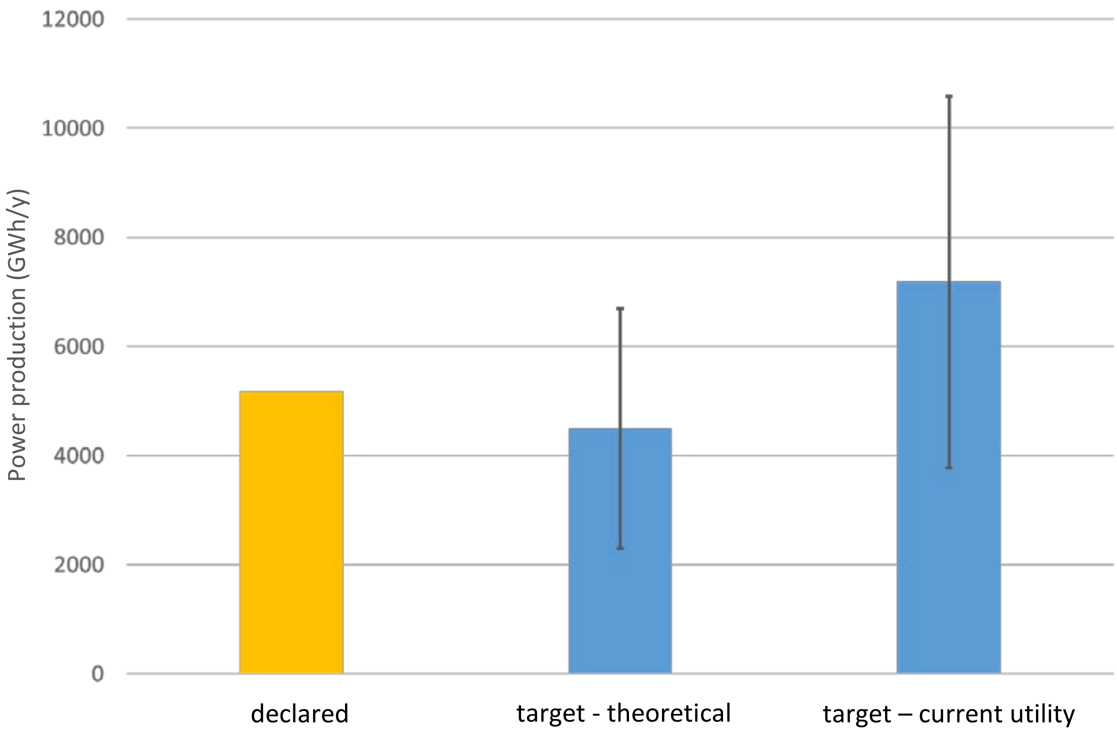

Figure 25: Total power production targets of the whole Swedish Kraft mill park based on year 2015 data and the actual total value of declared power production. Error bars indicate the 68% confidence interval.

Based on such estimates it is possible to conclude that the Kraft pulp and paper mills tend to maximize the generation of electricity, and their total observed production is close to the theoretical target. However, the potential for increasing the power generation by 20 to 30% is also apparent when considering the current utility scenario in which bark is also used for extra steam production.

The estimated targets together with declared data for each of the Swedish Kraft mills are shown in Figure 26. From the figure, it is possible to observe that integrated pulp and paper mills tend to produce more power than what is actually possible if only black liquor is used for steam production. At the same time, a potential increase in power generation also seems possible for most of the Kraft mills. However, some small mills seem to be able to produce more power than what was estimated. It should be pointed out that many other factors influence the power generation potential which are not taken into account in this study.

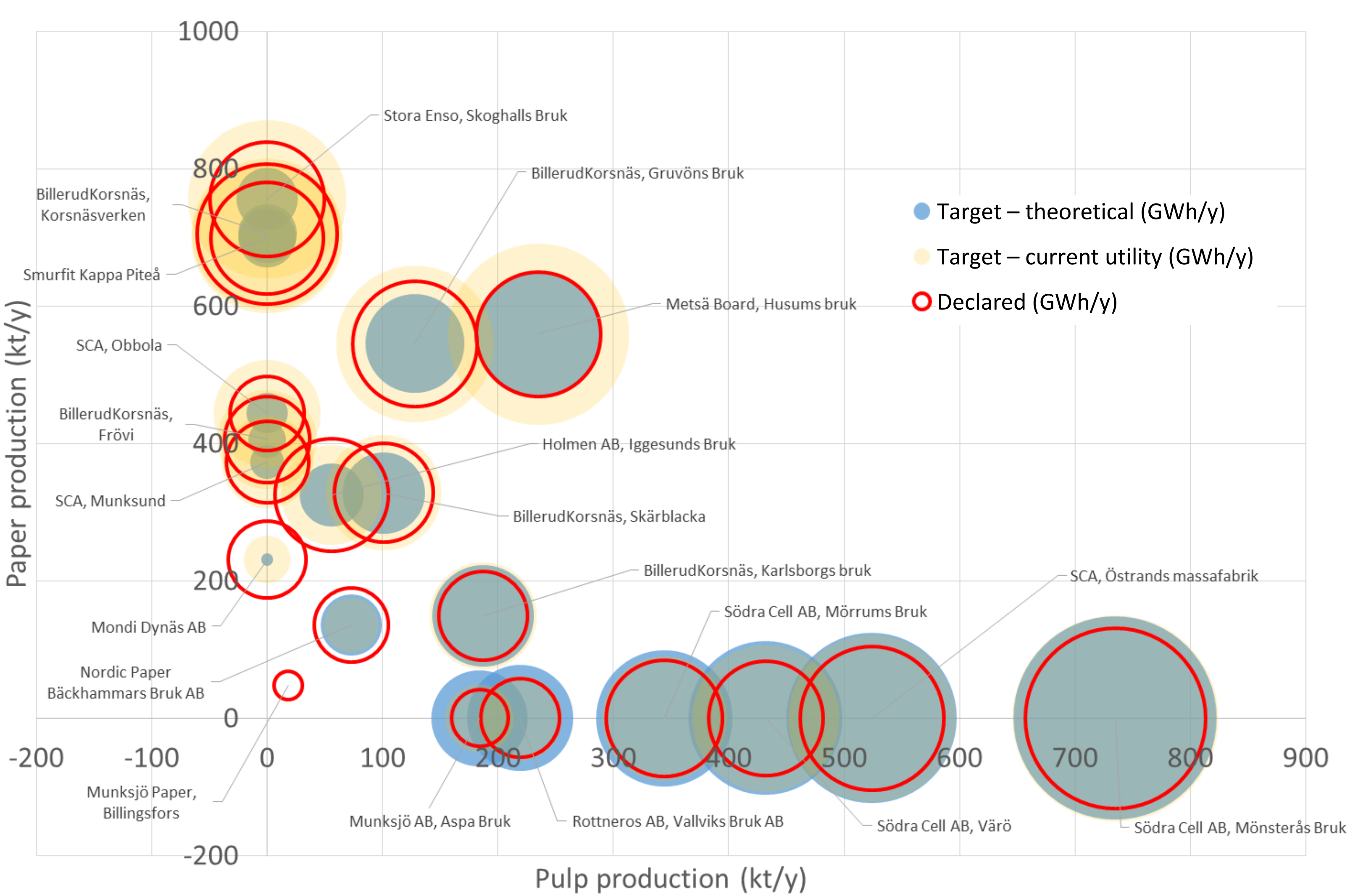

Figure 26: Power production targets for the Swedish Kraft mills estimated based on 2015 production data and declared power generation for the same year. Circle diameters proportional to power production in GWh/y.

3.9.2 Excess heat availability from the whole Swedish Kraft mill park

Similarly to what was done for the power generation targets, a regression analysis was conducted for the excess heat availability, with the only difference being that for excess heat a regression analysis was performed for each of the temperature levels used to represent the XHT signature.

The following regression function was postulated where the excess heat is the total excess heat available above a given temperature level:

$$Excess\ heat\ (\mathrm{GWh/y}) = k + m \cdot Market\ Pulp\ (\mathrm{kADt/y}) + n \cdot Paper\ (\mathrm{kADt/y})$$

The values of the coefficients are shown in Table 8 and Table 9 for the theoretical and current utility scenarios. Since no excess heat appears to be available above 140°C from any of the six Kraft mills considered in this study, no regression was performed for the intervals above this level.

The errors of such estimates are quite large, especially for the higher temperature intervals where the excess heat availability is more moderate. Higher values for the coefficient m (market pulp coefficient) are in line with the larger excess heat availability observed for market pulp mills compared to integrated mills.

The excess heat availability from the six Kraft mills were recalculated using the regression function with the coefficients estimated by least square interpolation.

The availability of excess heat above 60°C is shown in Figure 27 while the estimation of the total excess heat available (above 25°C) from the six Kraft mills is shown in Figure 28 together with the 68% confidence interval (standard deviation) and the original estimated values.

It can again be noted that the prediction based on the proposed regression is more accurate at lower temperatures while it is more difficult to predict the availability at higher temperatures. This is because less excess heat is available at higher temperatures and the variation between mills cannot be simply related to the production of market pulp or paper. Conversely, at lower temperatures, the cumulative amount of excess heat from higher temperature tends to even out the differences between mills and the correlation between excess heat availability and the size and type of mill becomes more pronounced.

Table 8: Values of linear coefficients obtained for linear regression of theoretical excess heat availability with their standard deviations (the sign “≥” corresponds to the excess heat available above the indicated temperature including the isothermal heat included at that temperature).*

Excess heat temp. interval	k (constant)	m (Pulp coeff.)	n (Paper coeff.)
>250°C	na	na	na
>140°C	na	na	na
≥ 140°C*	11.28 ± 12.13	0.00 ± 0.00	0.00 ± 0.00
>100°C	39.10 ± 42.10	-0.05 ± 0.07	-0.06 ± 0.12
≥ 100°C*	-324.24 ± 104.76	1.02 ± 0.17	0.83 ± 0.29
> 60°C	-338.92 ± 93.66	1.39 ± 0.15	0.90 ± 0.26
≥ 60°C*	21.98 ± 169.41	1.08 ± 0.28	0.63 ± 0.48
> 40°C	-807.68 ± 154.44	3.79 ± 0.25	2.60 ± 0.43
≥ 40 °C*	-854.34 ± 164.29	4.26 ± 0.27	2.68 ± 0.46
> 25°C	-854.34 ± 164.29	4.26 ± 0.27	2.68 ± 0.46

Table 9: Values of linear coefficients obtained for linear regression of excess heat availability assuming current utility levels with standard errors (the sign “≥” corresponds to the excess heat available above the indicated temperature including the isothermal heat included at that temperature).*

Excess heat temp. interval	k (constant)	m (Pulp coeff.)	n (Paper coeff.)
>250°C	na	na	na
>140°C	na	na	na
≥ 140°C*	65.67 ± 70.63	-0.08 ± 0.12	-0.11 ± 0.20
>100°C	121.24 ± 130.41	-0.15 ± 0.21	-0.20 ± 0.37
≥ 100°C*	-41.47 ± 139.95	0.60 ± 0.23	0.33 ± 0.39
> 60°C	-174.58 ± 128.01	1.49 ± 0.21	0.75 ± 0.36
≥ 60°C*	-10.95 ± 231.44	1.36 ± 0.38	0.46 ± 0.65
> 40°C	119.28 ± 142.46	1.43 ± 0.23	0.62 ± 0.40
≥ 40 °C*	-842.46 ± 136.59	4.76 ± 0.22	2.88 ± 0.38
> 25°C	-819.46 ± 130.40	4.80 ± 0.21	2.91 ± 0.37

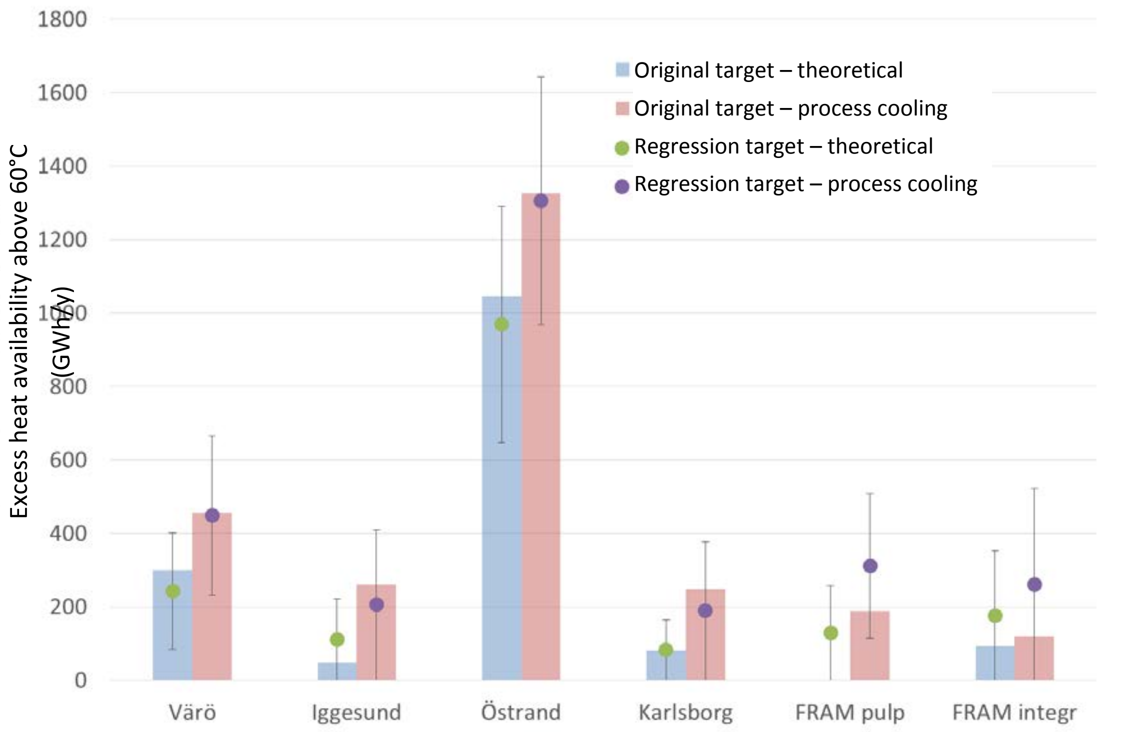

Figure 27: Estimated availability of excess heat above 60°C for the six Kraft mills (68% confidence interval for regressed values).

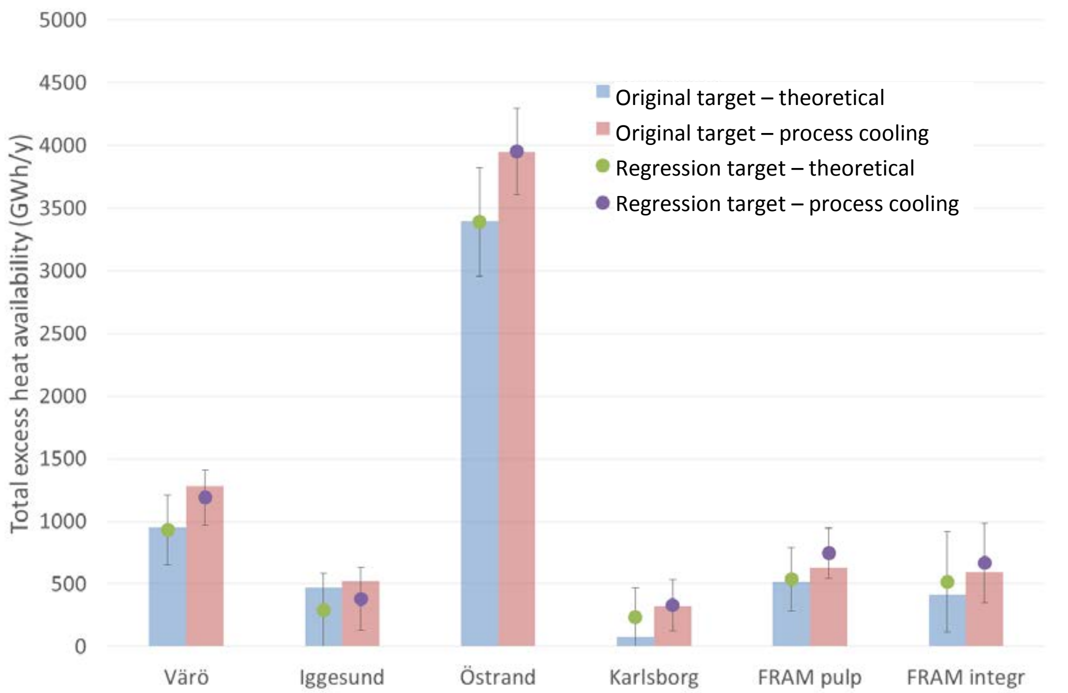

Figure 28: Estimated total excess heat availability (no lower temperature bound) for the six Kraft mills (68% confidence interval for regressed values).

Figure 29 shows the total excess heat above 60°C for the whole Swedish Kraft mill park estimated by extrapolating the above regression for all mills based on the reported production data for year 2015 (Skogsindustrierna, 2003-2015). According to these estimates, there is a large potential for increasing the excess heat utilization from the mills. In particular, the theoretical target, which represents the maximum amount of high efficiency excess heat, is about twice as much as the reported heat sales for 2015. The target based on current utility, which represents the maximum, practically viable, amount of excess heat that can be exported from the mills at current degree of internal process heat recovery, is about three times larger than the reported heat sales for 2015. Note that, implicitly, it was assumed that sold heat is primarily used for district heating applications, which is compatible with return temperature levels above 60°C.

More details about each mill are given in Figure 30. It is possible to see that, compared to the power production targets, the amount of sold heat from the mills is much less related to the estimated excess heat targets. Note also that the theoretical excess heat potential becomes very small or even negligible for small mills. This may seem rather counterintuitive if the assumption that the excess heat characteristic does not change so much with the size but rather with the ratio between market pulp and paper production holds true. This is instead an indication that the linear regression is not very accurate for representing the theoretical targets due to a large constant negative term (see Table 9). A more accurate prediction could be made with a more complex statistical analysis provided that more data are available.

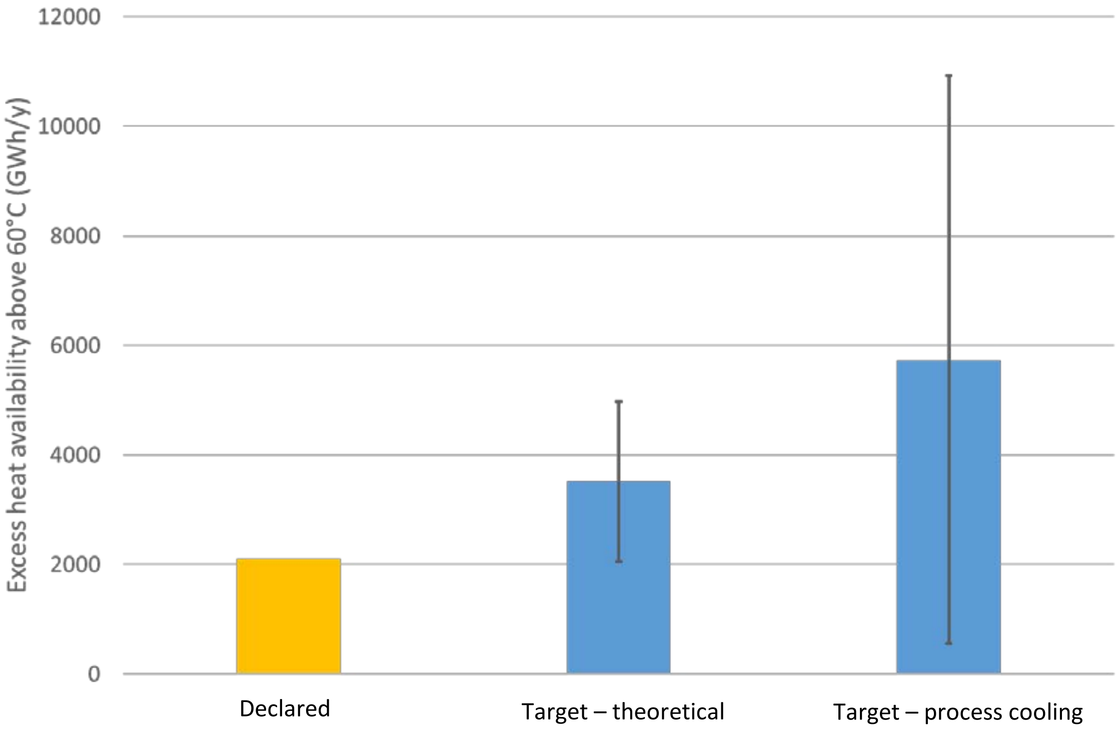

Figure 29: Estimated total excess heat availability above 60°C for the whole Swedish Kraft mill park (68% confidence interval).

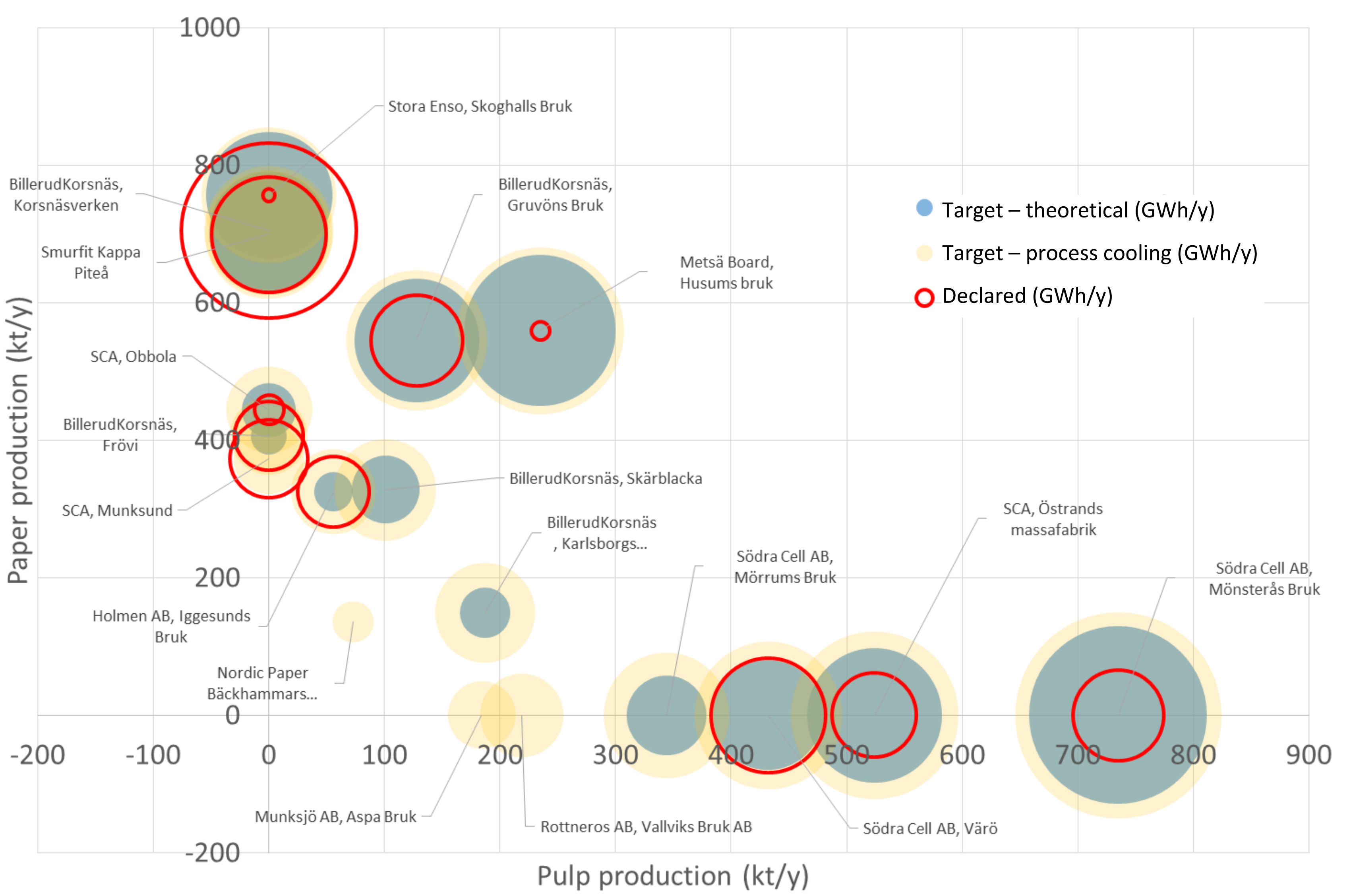

Figure 30: Availability of excess heat above 60°C from Swedish Kraft mills estimated based on 2015 data and declared data about sold heat for the same year. Circle diameters proportional to heat deliveries in GWh/y.

4 Summary and Conclusions

This report discussed and illustrated the importance, and difficulty, of distinguishing between different types of industrial excess heat based on how heat is currently recovered and utilized within the industrial process and how the internal energy efficiency of the plant can be improved.

In the report, a methodology for characterising industrial excess heat was proposed that allows to distinguish between avoidable and unavoidable excess heat. As a tool for visualizing the temperature characteristics of the excess heat availability, the excess heat temperature signature curve (XHT signature) was proposed. Different assumptions about internal heat recovery levels were used to generate a Theoretical XHT signature, representing the characteristics of excess heat assuming ideal internal heat recovery, and a Process Cooling XHT signature, representing the characteristics of excess heat based on the temperature-heat load profile of process streams that are currently being cooled by utility.

Furthermore, an energy targeting approach was introduced which was used to estimate power generation targets and excess heat availability from six Swedish Kraft pulp and paper mills. The results obtained from the case study mills were then used as input for a regression analysis that was used to estimate sector-wide potentials for power generation and excess heat availability.

Based on these estimates, it can be concluded that most Kraft pulp and paper mills already have an electric power production that is close to the target corresponding to maximum possible power generation assuming ideal internal heat recovery in the process and no additional fuel use. However, when considering the current level of heat integration in the process, and the fact that bark is used for extra steam production in addition to black liquor in most mills, a potential increase in power production is estimated to about 20 to 30%.

The prediction of excess heat availability from the Kraft pulp and paper sector based on the proposed regression is more uncertain than the prediction of the power generation potential. Especially for estimation of excess heat availability at higher temperature intervals, the errors of the estimates are quite large, which is explained by the relatively few data points, which required the use of a linear regression model. However, according to these estimates, there seems to be a large potential for increasing the excess heat utilization from Swedish Kraft pulp and paper mills. In particular, the theoretical target, which represents the maximum amount of excess heat in a highly internally efficient mill, is about twice the amount of heat sold in the studied year. The target based on current utility use, which represents the maximum amount of excess heat that can be exported from the mills at their current degree of internal process heat recovery, is about three times larger than the reported heat sales for the same year.

The results from the bottom-up assessment provide a detailed picture of industrial excess heat availability in the Swedish Kraft pulping industry, and the presented study illustrates a proposed energy targeting approach that could be extended to other sectors and regions.

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