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AVAILABILITY OF EXCESS HEAT FROM THE SWEDISH KRAFT PULPING INDUSTRY

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1 SUMMARY

An approach for estimating national targets for industrial excess heat recovery based on detailed analysis of data from case studies followed by regression analysis is proposed and applied to the Kraft pulping industry in Sweden. According to the resulting estimates, there is a large potential for increasing the excess heat utilization from the Swedish pulp and paper mills. The suggested methodology provides a more detailed picture of industrial excess heat availability in the Swedish pulp and paper industry and could be applied to other sectors and regions.

Key-words: industrial excess heat, pulp and paper industry, unavoidable excess heat, regression analysis

2 INTRODUCTION

Industrial excess heat is an important resource for meeting energy efficiency and climate goals. In Sweden, many industrial plants deliver excess heat to district heating systems and other external users. However, there is still a large potential for further utilization of industrial excess heat (see e.g. Broberg Viklund et al., 2012). Methods for estimating excess heat potentials can be characterized according to their approach (top-down or bottom-up), scale, and data acquisition (Brueckner et al., 2014). Furthermore, recovering heat from a process and exporting it competes with reusing the heat within the process itself. The most accurate way to estimate the excess heat potential of a specific site requires detailed process data of heating and cooling demands, and considers the distinction between avoidable and unavoidable excess heat (see e.g. Bendig et al., 2013). On a regional or national scale, however, it is not realistic to base estimations of excess heat potentials on detailed assessments of each individual plant. There is, consequently, a need for better tools to estimate the potential for increased excess heat utilization. This work proposes an approach for estimating national targets for industrial excess heat recovery. The approach is applied to the Kraft pulping industry in Sweden, and a detailed analysis of data from six case studies is used to estimate a sector-wide potential using regression analysis.

3 ENERGY IN THE SWEDISH KRAFT PULPING SECTOR

The pulp and paper sector is a major industrial sector in Sweden, representing about half of the national industrial energy use. Figure 1 (LEFT) shows the declared gross electricity production versus biofuel usage (black liquor, bark, and other wood residues) in Swedish mills in 2015, according to data 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.

Excess heat export from pulp and paper mills to district heating systems is common in Sweden. However, the correlation between sold excess heat and biofuel usage for different sizes and types of mill is less pronounced than for electricity, see Figure 1 (RIGHT). Possible reasons for this include geographical location, type and size of mill, and hot process water consumption. It is common that some excess heat from the pulp and paper process is exported to a nearby sawmill, but it is not always clear whether this excess heat export is reported as sold heat.

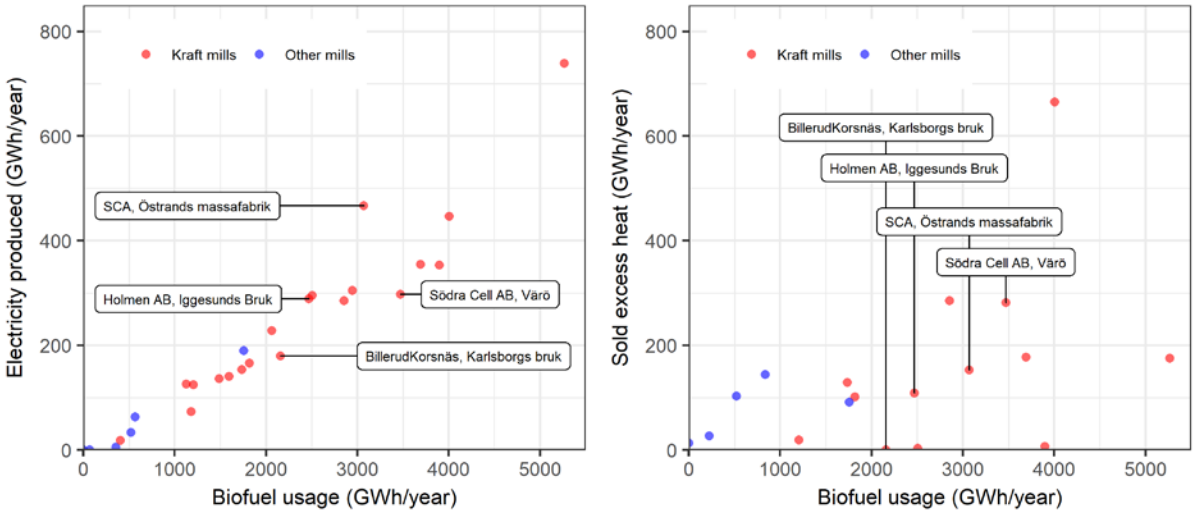

Figure 1: LEFT: Electricity production vs biofuel usage in Swedish mills 2015. RIGHT: Sold excess heat vs biofuel usage in Swedish mills 2015 (Skogsindustrierna, 2003-2015).

Table 1: 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)

Mill	Södra Cell Värö	SCA Östrand	Holmen Iggesund	Billerud-Korsnäs Karlsborg	FRAM type pulp mill	FRAM type int. mill
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*

4 METHODOLOGY

4.1 Case studies - Pulp and paper mills

Detailed process data collected in earlier studies was used to characterize the excess heat availability from four different Kraft mills, indicated by name in Figure 1. In addition, benchmark data about typical mills were obtained from the FRAM (Future Resource Adapted Pulp Mill) project. Benchmark mill specifications were extracted for bleached market Kraft pulp mills (Delin et al., 2005a) and integrated fine paper mills (Delin et al., 2005b). Table 1 lists the main data for the case study mills. Some mills have undergone substantial revamping since the data were collected. The SCA Östrand mill planned for a new expansion in 2015, and the 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.

4.2 Targeting of power generation and characterization of excess heat availability

Given the large amounts of high temperature excess heat from black liquor combustion in Kraft pulp mills, excess heat availability was characterized considering that the mills are equipped with a steam turbine system designed 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, according to the steps described below.

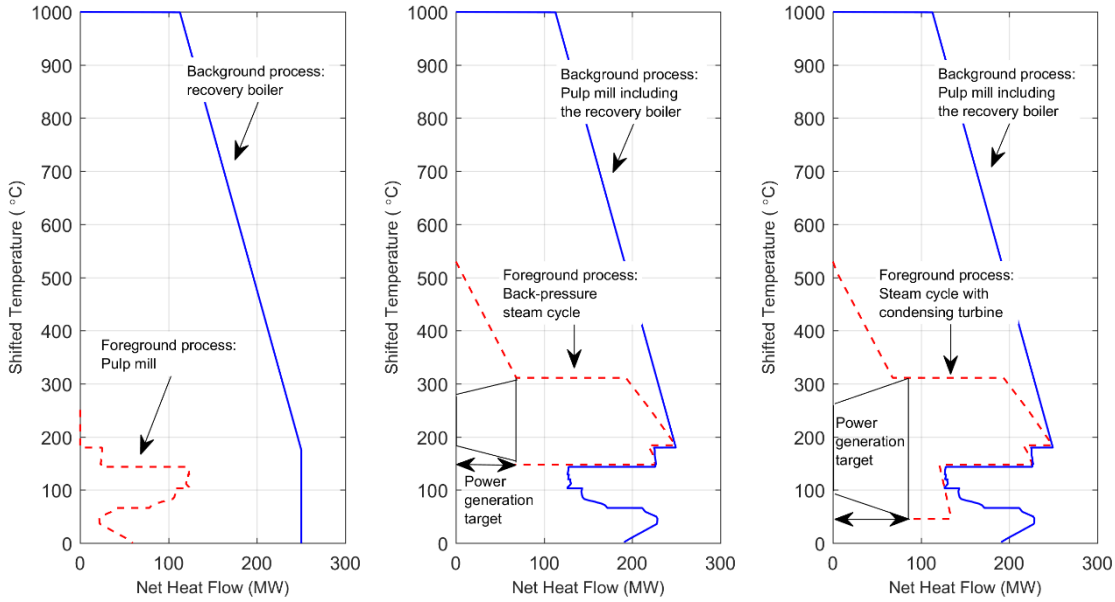

Figure 2. LEFT: Background/foreground analysis using split GCCs of the heat available from black liquor combustion in the recovery boiler and the net heating demand of the process. CENTER: Integration of a back-pressure turbine cycle with the pulp mill process using heat from the recovery boiler. RIGHT: Back-pressure and condensing turbine operation.

1. *Characterization of high-temperature heat from black liquor combustion in the recovery boiler (blue line in Figure 2)*
   Black liquor is combusted in the recovery boiler for recovery of energy and regeneration of cooking chemicals. The boiler size is determined by the amount of black liquor being processed, which in turn depends on the production rate in the pulp digesters. Additional boilers, mainly fuelled with bark, are regarded as part of the utility system and not as necessary parts of the process itself.

2. *Description of net process heating and cooling demands for the rest of the pulp mill processes*
   Ideal, maximized internal process heat recovery is estimated from the process Grand Composite Curve (GCC) assuming a minimum temperature difference for heat exchange of 0°C (blue line in Figure 3). When characterizing the current availability of excess heat, actual utility requirements of the process should be considered instead. In this case, the GCC is replaced by a representation of the current heating and cooling demands of the process at different temperatures.

3. *Background/Foreground analysis using split GCCs for black liquor combustion heat and net process heating demand*
   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 is required by the pulping process, there is a potential for additional power generation without the use of additional fuel. This is the case for the example shown in Figure 2 (LEFT).

4. *Integration of a steam turbine cycle between the black liquor combustion heat from the recovery boiler and the net process heating demand (Figure 2)*

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

Maximum fuel utilization can be achieved with a back-pressure turbine where the low-pressure outlet steam is sufficient to cover the process steam demand. In practice, steam is either available in excess, which opens the opportunity for a condensing turbine stage, or steam is directly reduced to lower pressure, by-passing the turbine. In the latter case, it might be justified to increase the steam production and back-pressure power generation, by firing additional bark in a boiler. This opportunity is considered for the assessment of excess heat availability under current utility requirements. However, for the theoretical heat integration case, minimized fuel use is prioritized.

For the example shown in Figure 2, steam is available in excess. The figure in the centre illustrates pure back-pressure turbine operation and 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 added to the system. This way, the excess of steam is utilized for additional power generation. Note that this system design does not only limit 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.

5. *Characterization of excess heat availability for processes with integrated steam cycle (Figure 3)*

In this work, the availability of excess heat is characterized according to discrete temperature intervals. The resulting temperature profile is referred to as the excess heat temperature signature curve (*XHT signature*), which is constructed by aggregating the available excess heat at pre-defined temperature levels and temperature intervals. Two different signatures can be constructed: The *Theoretical XHT signature* represents the unavoidable excess heat, corresponding to theoretical, maximum internal process energy recovery, assuming a minimum temperature difference of 0°C for all heat exchangers. The *Process Cooling XHT signature* represents the current availability of excess heat.Figure 3 shows the estimated Theoretical XHT signatures for Södra Värö, assuming that a steam cycle with an additional condensing stage is integrated with the process.

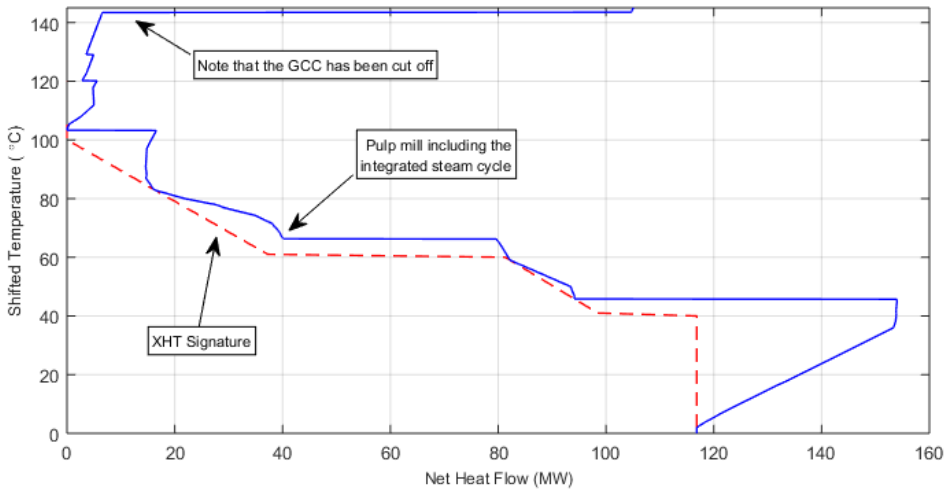

Figure 3. Estimated XHT Signatures based on the net cooling demand represented by the GCC of the integrated pulp mill process, recovery boiler and steam cycle.

4.3 Data and assumptions for the mill study cases

The net useful heat available for steam production from black liquor combustion was estimated based on data for the FRAM mills, 6.046 MWh per air-dried tonne of pulp (Delin et al., 2005a). Bark feed to the bark boiler was estimated by subtracting the estimated black liquor from the reported value of total biomass fuel consumption (see Table 1). No steam was considered to be produced from fossil fuel. Theoretical maximum process heat recovery was estimated based on the thermal stream data for the case study mills. However, data about the actual heat exchanger network including process heaters and coolers are scarce and incomplete and it was not possible to define the actual cooling demand of each mill. Instead, the Process Cooling XHT signature curve was estimated based on assumptions about the current mill heat recovery as well as layout and operability limitations.

The heat generated by black liquor and bark combustion is used for power generation and low and medium pressure steam is used for process heating. The power generation depends on turbine inlet steam conditions, which are determined by the properties of the high-pressure (HP) boiler steam. In the theoretical case, the assumed steam properties for HP steam are representative of state-of-the-art recovery boiler technology (100 bar, 530°C). For the estimation of the Process Cooling XHT signature, steam values corresponding to the Iggesund mill (80 bar, 480°C) were used. The back-pressure turbine isentropic efficiency was assumed to be 0.85 for the theoretical integration case and 0.75 for the assessment considering existing turbines. Low and medium steam pressure values were determined on a case by case basis with the objective of maximizing power generation. The condensing turbine option was considered only if the extra power produced by the condensing stage is greater than 10 MW. The assumed isentropic efficiency for the condensing stage was 0.9 and 0.85 for the theoretical and current systems, respectively. Steam reduction was modelled as separate steam production at 16 bar.

4.4 Regression analysis

Based on the analysis of the six mills, linear regression functions based on reported pulp and paper production rates were used to predict the power production targets as well as the availability of excess heat from the entire Swedish Kraft mill park. For excess heat, a regression analysis was conducted using eq. (1) for each of the temperature levels that were used to represent the XHT signature. Excess heat was assumed to be used primarily for district heating applications, which requires excess heat temperature levels above 60°C. Constant mill production was assumed, reflecting the process conditions when thermal stream data were collected.

$$Excess\ heat\ (\text{GWh/y}) = k + m \cdot Market\ Pulp\ (\text{kADt/y}) + n \cdot Paper\ (\text{kADt/y}) \qquad \text{(eq. 1)}$$

5 RESULTS

5.1 Theoretical heat integration in the studied mills

When establishing the theoretical potential for internal heat recovery within the mill, no other sources of primary heat than the recovery boiler are considered, and ideal heat integration is considered with ΔT_{min} = 0°C. Furthermore, heat transfer is assumed to be possible directly between the recovery boiler flue gases and the pulp and paper process. The theoretical heat integration target is visualized for two of the studied mills in Figure 4.

The split GCC analysis indicates that the heat available from black liquor combustion is substantially larger and at a sufficiently high temperature to cover the process heat demand without the need to use additional fuel. Furthermore, there is a much larger excess of heat from black liquor combustion in the market pulp mills than in integrated pulp and paper mills. Market pulp mills have a substantial potential for 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.

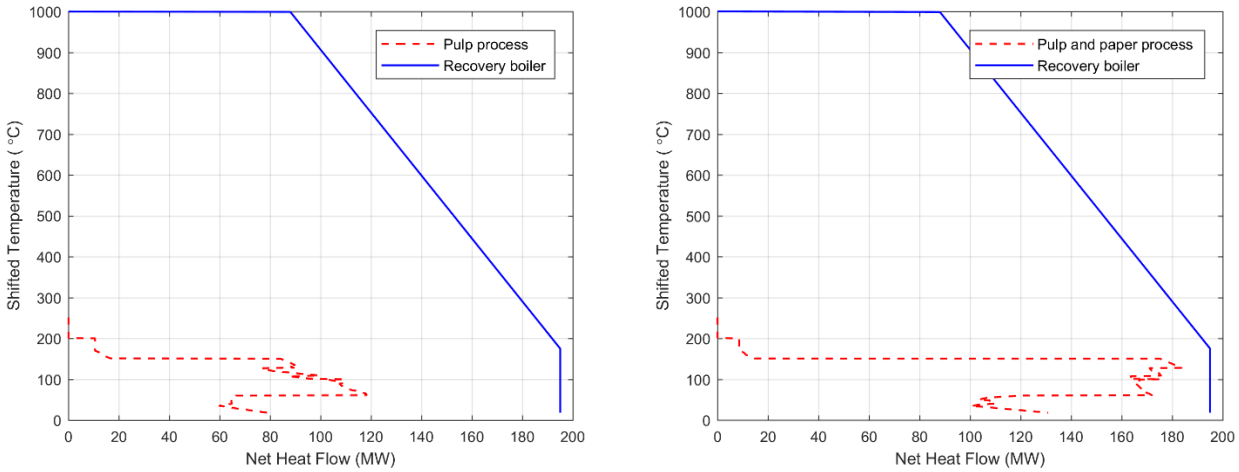

Figure 4: Split GCCs of the ideally integrated (ΔT_{min} = 0°C) process (dashed line) and the heat from black liquor combustion in the recovery boiler (solid line). Combustion heat available above 1000°C is shown as a horizontal line. LEFT: FRAM market pulp mill, RIGHT: FRAM integrated fine paper mill.

5.2 Excess heat availability in the studied mills

Figure 5 shows both XHT signatures for two of the studied mills. In most cases, the shape of the Process Cooling XHT signature is similar to that of the Theoretical XHT signature. However, the excess heat availability at medium to high temperature is lower for the theoretical case, due to increased heat recovery. This implies that excess heat from Kraft mills, e.g. for district heating application, can easily exceed the theoretical target which represents the limit of highly efficient excess heat utilization. Figure 6 presents a comparison between the six mills by showing the specific excess heat availability above 60°C. The specific excess heat is evaluated as a ratio between the total excess heat and the biofuel consumption.

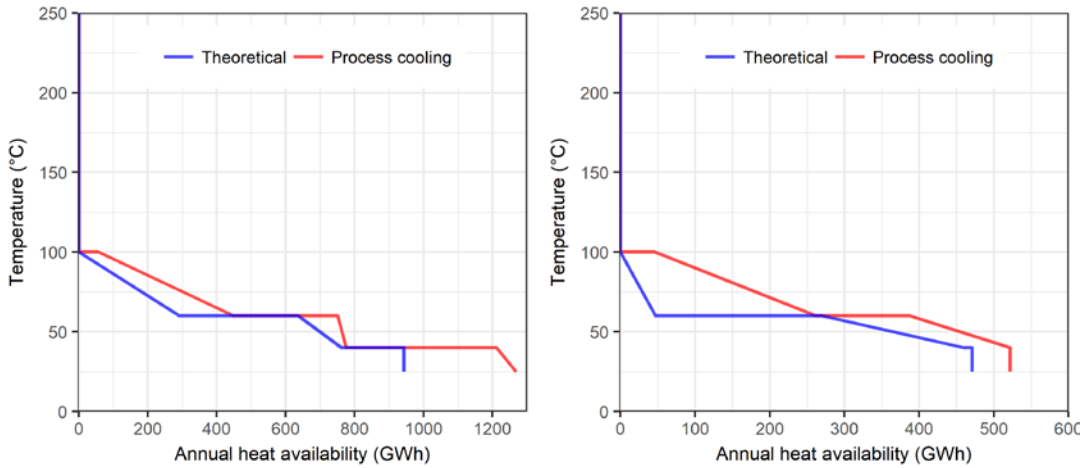

Figure 5. Estimated XHT signatures for Södra Cell Värö (LEFT) and Holmen Iggesund (RIGHT).

The specific availability of excess heat varies largely between the Kraft mills. However, the availability of excess heat for most of the cases is less than 15% of the biofuel energy supply, which is substantially below the 25% excess heat recovery level that has been suggested in generic studies assessing the potential of industrial excess heat levels for district heating applications (Persson et al., 2014).

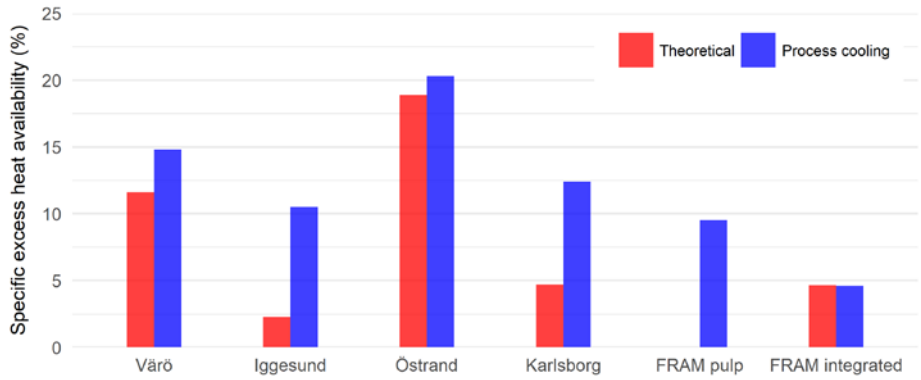

Figure 6: Estimated specific excess heat availability above 60°C in the six Kraft mills.

5.3 Results from the regression analysis

The availability of excess heat above 60°C was estimated for the six mills using (eq.1). The results are indicated in Figure 7 together with the standard deviation and the original estimates based on the detailed mill process data. Although the deviations are significant, the regression values agree quite well with the original values, at least for the real mills. The total excess heat above 60°C was extrapolated for the whole Swedish Kraft mill park using the above regression for all mills based on production data for 2015 (Skogsindustrierna, 2003-2015). The results indicate that there is a significant potential for increasing mill excess heat recovery, given that the theoretical target is about twice as much as the heat sold in 2015, and the 'process cooling' target is about three times larger than the sold heat in 2015. Figure 8 shows more details about each mill. There is no clear relation between amount of sold heat that is reported and the estimated excess heat potential. The theoretical excess heat potential is very small for small mills. This is an indication that the linear regression is not very accurate in this range. A more accurate prediction could be made with a more complex statistical analysis, provided that more data were available.

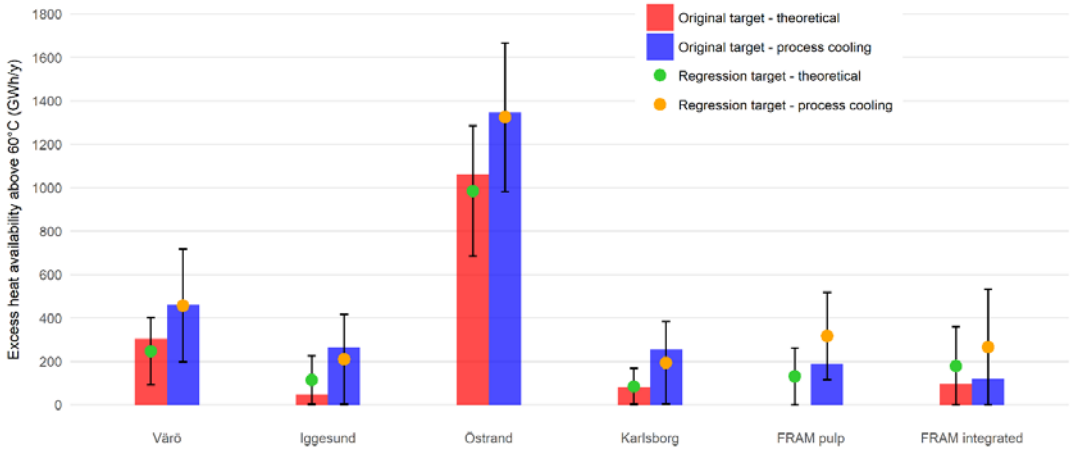

Figure 7: Estimated availability of excess heat above 60°C for the six Kraft mills (68% confidence interval for regressed values).

Finally, the results from the prediction of power generation targets indicate that the reported electricity generation in the mills is close to the target corresponding to theoretical maximum internal process heat recovery. However, a potential for increasing the power production by 20 to 30% is apparent when considering current heat recovery levels in the mills in which bark is used as a fuel for extra steam production above the theoretical minimum requirement.

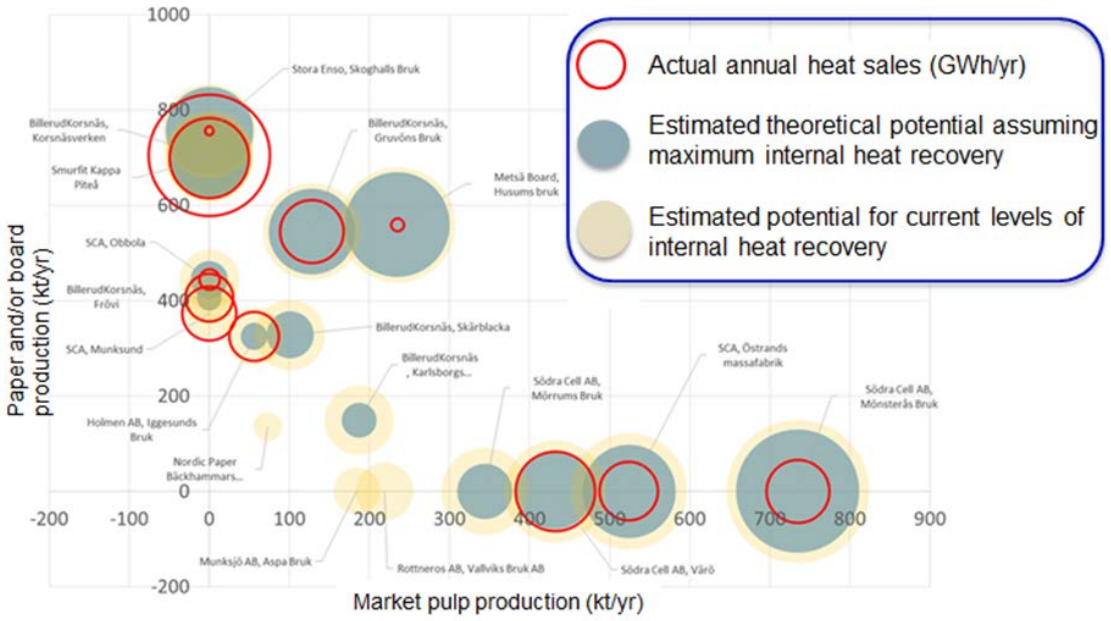

Figure 8: Availability of excess heat above 60°C from Swedish Kraft mills estimated based on 2015 production data, and sold heat according to declared data for the same year. Circle diameters proportional to heat deliveries and availability.

6 CONCLUSION

This paper proposed a bottom-up approach for estimating the availability and characteristics of excess heat from the Swedish pulp and paper industry. The results indicate that there is a large potential for increasing excess heat recovery in Swedish Kraft pulp and paper mills. The proposed approach based on detailed energy targeting studies for a selection of industrial plants should be possible to extend to other sectors and regions.

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