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RESEARCH ARTICLE

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Characterization and visualization of industrial excess heat for different levels of on-site process heat recovery

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Summary

Increased utilization of industrial excess heat (or waste heat) can reduce primary energy use and thereby contribute to reaching energy and climate targets. To estimate the potential availability of industrial excess heat, it is necessary to capture the significant heterogeneity of the industrial sector. This requires the development of methodologies based on case study assessments of individual plants, adopting a systematic approach and consistent assumptions. Since the recovery of excess heat for power generation or off-site delivery competes with internal recovery for on-site fuel savings, a well-founded approach should enable a comparison of the excess heat availability at different levels of internal process heat recovery. To determine the best solution for excess heat utilization for a given process, there is a need for easy screening of various options, while considering that some techniques require heat at a constant temperature while others can exploit a nonisothermal heat supply. This paper presents a new tool, the excess heat temperature (XHT) signature, for exploring the potential heat availability and trade-offs for excess heat utilization by weighting the heat according to predefined temperature levels and ranges. A set of reference conditions are defined, and an energy targeting approach is proposed that can be used for characterizing the Theoretical XHT signature, which represents the unavoidable excess heat that can be recovered after maximized internal process heat recovery and ideal integration of a power generation steam cycle. The Theoretical XHT signature is contrasted with the Process Cooling XHT signature, which represents the excess heat that can be recovered given the current design and operation of the process and its utility system. The XHT signature curves provide a consistent representation of the excess heat, enabling comparison between sites and aggregation of results from different case studies.

KEYWORDS

energy efficiency, excess heat, heat recovery, industrial plant, waste heat

1 | INTRODUCTION

Industrial excess heat is an important resource for reaching energy and climate targets, as recognized, for example, in the European Union (EU) Energy Efficiency Directive.[1] Excess heat recovered from industrial processes could be used as an energy source in other industrial plants or other sectors and thereby reduce the overall use of primary energy resources.[2,3]

Excess heat, also referred to as waste heat or residual heat, is defined in a variety of ways in the literature. An overview of different terms and definitions can be found in the final report of the IETS TCP Annex XV (Phase 1)—the International Energy Agency (IEA) international collaboration program in the area of industrial excess heat recovery.[4] This paper adopts the term "excess heat" unless specifically referring to definitions proposed by other studies.

Many published estimations indicate that there is a large potential for increased recovery and utilization of industrial excess heat.[5,6] Even in countries such as Sweden, where many industrial plants already deliver excess heat to district heating systems and other external heat sinks, studies indicate that there is still a large potential for increased utilization of industrial excess heat.[7] However, there are large uncertainties in the estimations, and significant differences between the estimated potentials,[8] as a result of the significantly different methods and assumptions used. Brueckner et al[9] reviewed the literature related to methods for estimation of regional excess heat potentials and suggested categorizing the methods according to their approach (top-down or bottom-up), scale, and data acquisition procedure.

Within an industrial process site, hot and cold utility use can be reduced by retrofitting the plant to increase the degree of heat recovery between the process streams, leading to a reduction of excess heat. Consequently, the objective of recovering excess heat from a process and exporting it to an external user competes with the objective of recovering heat within the process itself to reduce the use of primary energy on site (see, eg, Eriksson et al.[10]). The impacts on overall primary energy demand, as well as CO_2 emissions related to internal and external heat utilization, are highly dependent on the performance of process unit operations and the type of energy carriers. It is therefore typically not obvious whether it is better to use heat internally or externally. However, there is a theoretical limit for maximum internal heat recovery that can be determined based on detailed data for process stream heating and cooling demands. At this target value for minimum external utility demand, there will still be excess heat available from the process in most cases. This excess heat can be referred to as unavoidable[11] and can be recovered for external applications without affecting the potential for on-site fuel savings, and any increase in recovery of such unavoidable excess heat immediately translates into an improvement in the overall system energy efficiency.

Novelty Statement

A new tool, the excess heat temperature (XHT) signature, is proposed for exploring the potential availability and trade-offs for recovery of excess heat from an industrial process. The XHT signature provides a consistent approach to characterization of excess heat at different levels of internal heat recovery, which allows for comparison and aggregation of results from different case studies.

Many studies have mapped and estimated the availability of industrial excess heat on a regional or subsector level, based on site-specific information retrieved from publicly available databases. Such studies generally estimate the amount of excess heat as a fixed fraction of the primary energy consumption covered by fuel combustion. The primary energy consumption is in turn often estimated from reported CO_2 emissions, combined with country-specific emission factors,[12] or literature data for typical process characteristics of industrial subsectors.[13] The advantage of such methods is that they are based on data that are relatively simple to obtain. However, different methods lead to highly different results, as shown by, eg, Dénarié et al.[14] Furthermore, Miró et al[15] observed that many studies fail to report important assumptions such as the reference year of the data, the system boundaries of the analysis, and the excess heat temperature (XHT) levels considered. The bottom-up approach originally suggested by McKenna and Norman[13] and further developed by Hammond and Norman[16] has been adopted in several more recent studies such as the work of Miró et al.[17] Papapetrou et al[18] extended and updated the approach by adjusting the conversion factors suggested by Hammond and Norman[16] for the UK for the period 2000 to 2003 in order to be applicable for other EU countries in 2015. This was achieved by applying ratios reflecting differences and development of annual, country, and sector-specific energy intensity values. Bühler et al[19] also relied on thermal process-related CO_2 emissions to allocate excess heat estimations for different industrial subsectors to individual production sites. Their sectorial potentials for excess heat availability were estimated based on energy and exergy analysis, with an approach that relied heavily on access to comprehensive data for the distribution of fuels between different process categories and temperature levels in 22 Danish industrial sectors.[20]

In general, however, these methods do not consider the complete picture of the specific sites' process heating and cooling demands and cannot, therefore, be used to distinguish between more or less efficient internal use of heat. Bühler et al[19] state, for example, that "the use of actual energy use data or excess heat amounts obtained from site-specific analyses has the highest accuracy" for assigning excess heat amounts to a given production unit. However, due to limited availability of such information, they chose to use it only for validation in those few cases for which this was possible. Typically, most of the methods presented in the literature for estimating excess heat potentials consider the availability of heat from current processes and not how this amount could change as a result of future improvements in internal process heat recovery. Furthermore, although Bühler et al[19] investigated the effect of efficiency improvements on the availability of industrial excess heat, they considered generic energy-saving measures to be directly correlated to excess heat amounts and equally applicable across all sites within an industrial sector. Process layout, technology choices, age structure of equipment, degree of heat recovery within plants and between plants at large multi-process sites, etc., can differ substantially between specific sites, even within the same industrial subsector. As a result, there is a clear need for case study-based approaches to better capture the significant heterogeneity of the industrial sector. Such detailed assessments of individual sites are necessary for collecting data and process information for the development and validation of more generic models. Such approaches must be able to distinguish between avoidable and unavoidable excess heat. To make this distinction clear, one main challenge is identifying a unified definition of unavoidable excess heat.

Some authors define waste heat as equal to unavoidable excess heat,[11,21,22] although their exact definitions vary in some respects. Ammar et al[21] define waste heat as heat for which on-site recovery is not economically viable and thus emphasize the competition between external and internal heat utilization in economic terms. Both Bendig et al[11] and Oluleye et al[22] instead define waste heat as the heat that remains after theoretical maximum heat recovery, assuming an appropriate value for the minimum temperature difference for heat exchange $\Delta T_{\min}$. Bendig et al[11] express this in terms of exergy and consequently consider that the heat could be converted to work in an ideal heat engine cycle. Oluleye et al,[22] on the other hand, define industrial waste heat as "the sum of the residual heat rejected from the process on a site and residual heat rejected from the site utility system designed to satisfy the energy demand …" They thereby acknowledge that industrial process sites normally have a central utility system with cogeneration capacity that is designed to satisfy the process heating demands and cogenerate electric power while maximizing the utilization of the fuel energy content and that this commonly leads to large amounts of residual heat from the utility system. Kapil et al propose a method for cogeneration targeting and assessment of the potential for on-site recovery or upgrading of low-grade heat[23] or for over-the-fence heat deliveries.[24] Similar to Oluleye et al,[22] Kapil et al define waste heat as the low-grade heat that remains after maximized total site heat recovery.

There is clearly a need to define a set of reference conditions for ideal, theoretical heat recovery and maximized energy efficiency within an industrial site that can be used for quantifying and characterizing the excess heat. However, there are many technical and economic barriers to retrofitting industrial plants to achieve theoretical targets for process heat recovery.[25,26] As also observed by Klemeš et al,[27] recent developments in the area of methods for integration of excess heat utilization technologies are mainly based on theoretical targeting approaches, and there is a lack of studies that consider system limitations and appropriate process representations. It is therefore interesting to compare excess heat availability at various levels of internal process heat recovery, ranging from the theoretical to the current level. This has been done, for example, by Morandin et al,[28] who mapped the excess heat available for district heating from a petrochemical cluster. In addition to the current cooling profile of the cluster, a possible future scenario was also considered in which 50% of the purchased fuel fired for generating hot utility for process heating purposes is saved through improved total site heat recovery. In later work, Eriksson et al[29] targeted the capital costs required for collecting and delivering excess heat from the petrochemical cluster at different levels of heat recovery. In such studies, one case of particular interest and importance is to map the amounts of process heat removed at different temperatures in existing process coolers, as presented by, eg, Andersson et al.[30] Woolley et al[31] proposed another example of a methodology, which considers only (some of) the current sources of excess heat, in an otherwise comprehensive framework for assessing the excess heat recovery options.

Recovery and utilization of industrial excess heat can be achieved through various heat recovery technologies (see, eg, Jouhara et al[32] for a comprehensive review of commonly used, state-of-the-art technologies with an evaluation of their operation and performance). It is worth noting that many technologies have a heat demand at constant temperature (eg, for evaporation in a heat pump or organic Rankine cycle), while other applications are better suited for matching with a varying temperature heat supply (eg, district heating). Depending on the amount of heat available in different temperature ranges and whether the heat is available at constant temperature or not, different utilization technologies could be more or less suitable in terms of energy efficiency, economic, and environmental benefits. There is, therefore, a need for new methods that enable easy screening of possible excess heat utilization options under various assumptions about the level of internal process heat recovery in order to identify the best trade-off or combination of different options for a given process. There is also a need for a consistent way of characterizing and visualizing the availability of excess heat in a way that can represent a combination of utilization options and enable straightforward comparisons and aggregations of different sites. The Waste Heat Profile suggested by Oluleye et al[22] achieves some of these objectives but is only constructed for one level of on-site heat recovery and, furthermore, only represents excess heat at isothermal temperature levels.

The aim of this paper is to present a new graphical tool for representing the excess heat available from a given industrial process considering a combination of potential excess heat utilization options. The proposed XHT signature provides a consistent way of characterizing and visualizing the temperature characteristics of excess heat from an industrial process and its integrated utility system. The aim is furthermore to propose an energy targeting approach that can be used to estimate targets for power generation and determine the XHT signature for different levels of internal heat recovery within the process site. The paper suggests reference conditions that can be applied to determine theoretical targets for power generation and unavoidable excess heat availability, which can be used to generate a Theoretical XHT signature. In contrast, a Process Cooling XHT signature is also proposed that represents the characteristics of excess heat based on the temperature-heat load profile of process streams that are currently cooled by utility.

The originality of this approach is thus the comprehensive methodological framework for screening combinations of options for industrial excess heat utilization at an industrial process site. This includes the novel XHT signature for characterization and visualization of the XHT profile, which considers isothermal as well as nonisothermal heat availability, and enables consistent comparisons and aggregations between sites. The proposed framework also includes the systematic approach and necessary assumptions to determine the unavoidable excess heat availability (the Theoretical XHT signature). Finally, unlike most other methods reported in the literature, it also includes the possibility to consider various levels of on-site heat recovery and different process constraints ranging from the theoretical case of maximized on-site heat recovery to the case of recovering heat from existing process coolers.

The targeting approach and developed tools are described for a motivating pulp mill example. The pulp and paper industry is an important sector with respect to industrial energy use. With more than 5% of global industrial energy consumption, it is the fourth largest industrial energy user.[33] In some countries such as Sweden, the pulp and paper industry accounts for more than 50% of the total final industrial energy use.[34] As also acknowledged by the IEA, the high share of biomass use means that this sector can play an important role in providing fossil-free energy to other sectors, in the form of eg, excess heat.[33] Furthermore, combined production of heat and power (CHP) is recognized as an important energy efficiency technology in pulp and paper mills. This makes pulp mills suitable for illustrating the energy targeting approach suggested in this paper, which also accounts for potential opportunities for CHP. However, the tools and methods developed in this paper are applicable for all industrial sectors in which heating and cooling play a significant role. Certain characteristics of the tools proposed are better illustrated with examples other than the pulp mill. Therefore, a few complementary illustrations from other industrial plants are also included in the paper.

Preliminary versions of the XHT signatures and the energy targeting approach have previously been applied in a study presented at the Industrial Sustainable Energy Conference, where the concepts and ideas were first introduced and briefly summarized.[35] The present journal paper presents a significant extension of the methodological framework with regard to the motivation of the approach, the detailed and comprehensive description of tools and methods, and further insights into their interpretation and alternative applications.

2 | RELATED METHODS, CONCEPTS, AND KEY ASSUMPTIONS

2.1 | Pinch-based methods for targeting of industrial excess heat

One common method for assessment and identification of improvements in process heat recovery is pinch analysis.[36-38] The pinch method uses data for heating and cooling demands of the process streams and an assumed minimum temperature difference ΔT_{min} for heat exchange to determine the maximum internal heat recovery and minimum utility demands of the process. Bühler et al[39] used a case study to compare pinch analysis with different forms of exergy analysis and concluded that although more process improvement possibilities could be identified with the exergy-based methods, only some of these were possible to implement in practice. Furthermore, pinch analysis was regarded as relatively easy, and more importantly, as the easiest analysis method to communicate to nonscientific staff. Pinch-based methods provide a simple visualization of the potential for heat recovery within the process as well as between the process and a cogeneration system or an excess heat recovery technology or between different process plants within a total site.[40,41] For a review of the latest developments in applying pinch-based methods for integration of waste heat valorization technologies, see Section 2.6.2.2 of Klemeš et al[27].

In this context, it is useful to make a distinction between "black box," "grey box," and "white box" approaches.[42] In a black box approach, excess heat characteristics are described based solely 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 considered. However, the potential for increased process-to-process heat exchange is not considered. To be able to assess the availability of excess heat from an internally energy-efficient process, a white-box approach is therefore advisable. However, as discussed by Méchaussie,[43] data extraction necessary for the white-box approach is very time-consuming, and often leads to retrofit proposals that are rarely feasible in practice due to safety, space, distance, and economic constraints. The grey-box approach, on the other hand, considers only heat recovery opportunities that can be achieved through existing utility systems, which are more likely to be feasible since they are less likely to affect site operability. For these reasons, Méchaussie argues that the grey-box approach can be motivated as a default level of detail.[43]

In this paper, a pinch-based 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.

One of the main tools of pinch analysis is the grand composite curve (GCC), which can be used for visualizing the energy flow interface between the process and utility system.[36,37] With a white-box approach, the theoretical reference condition of maximum process heat recovery can be represented by the process GCC for $\Delta T_{min} = 0°C$. However, conventional pinch analysis tools are not suitable for representing excess heat availability from an existing process at different levels of process heat recovery. This motivated the development of a set of additional advanced pinch curves.[44-46] The major difference between the conventional pinch curves (ie, composite curves and the GCC) and the advanced composite curves is that the advanced curves include information about the existing heat exchanger network.

The advanced curves show not only the potential savings that would result from reduced temperature differences in the system but also the placement of heaters and coolers with respect to temperature, as well as the theoretical upper and lower temperatures for heating and cooling. The theoretical upper temperature for cooling is of particular interest for assessing excess heat potentials, as is the actual current cooling temperature profile. The advanced curves are plotted as real temperatures and not shifted temperatures. The three advanced curves that are most interesting for representing the process cooling demand in an excess heat perspective are presented in Table 1 and illustrated in Figure 1.

The actual cooling load curve (ACLC) provides a good visualization of the temperature profile of excess heat available from the current system, assuming that no changes are made to the existing process-to-process heat recovery system. The theoretical cooling load curve (TCLC), on the other hand, shows the highest possible temperatures at which excess heat could be extracted if the hot utility demand would remain constant, but the heat exchanger network is retrofitted allowing a new value of $\Delta T_{min,HX}$ in the network (see Nordman and Berntsson[46] for a detailed description of how to construct this curve). In principle, the TCLC includes heat from a utility system that is designed to produce more hot utility than the theoretical minimum heating demand of the process and will,

TABLE 1 Advanced composite curves of relevance for estimating excess heat potentials

CUC	Cold utility curve	A composite curve of the utility streams in existing coolers.
ACLC	Actual cooling load curve	A composite curve of the parts of process streams that are cooled by utility in existing coolers. This generally also includes process effluent streams with heat content that could be recovered.
TCLC	Theoretical cooling load curve	A composite curve showing the highest possible temperature at which cooling could be supplied if the process would have the same utility requirement as the existing process, but a smaller $\Delta T_{min,HX}$ for new heat exchange would be allowed compared with the value $\Delta T_{min,global}$ corresponding to the current utility requirements of the system.

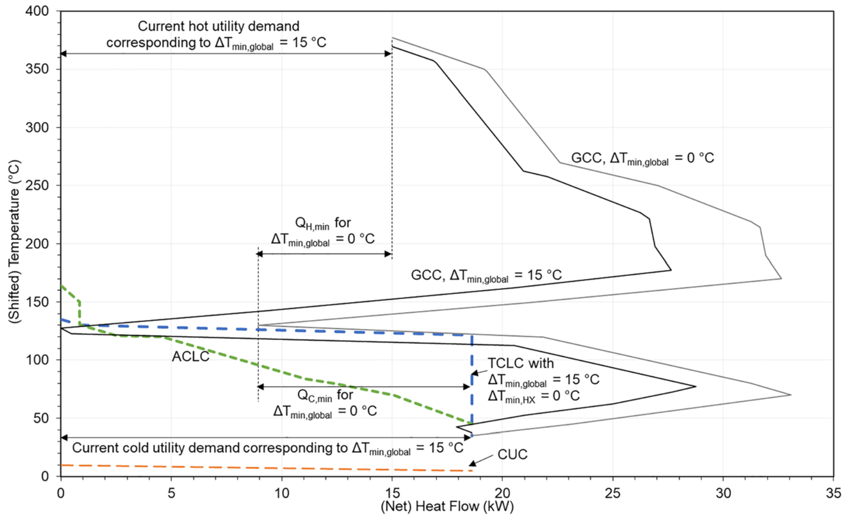

FIGURE 1 Advanced composite curves for a process below the pinch together with the grand composite curve (GCC) corresponding to the current utility demand of the process, and an ideal GCC constructed with $\Delta T_{\min} = 0$ °C. Note that the advanced curves are plotted as heat flows at real temperatures, whereas the GCCs are plotted as net heat flows at shifted temperatures [Colour figure can be viewed at wileyonlinelibrary.com]

therefore, be in excess if internal heat recovery within the process is increased. The TCLC suffers, however, from some ambiguities with respect to its construction and interpretation, such as allocation of streams above/below the pinch. Furthermore, there is no clear description of how the temperature level of the utility should be included in situations with several hot utilities nor of how cogeneration potentials are affected by exploiting the excess heat potential indicated by the TCLC.

This paper proposes a new systematic method to target and visualize the excess heat considering the integration between process and utility systems. The method enables visualization of excess heat at different levels of process heat recovery and utility integration. A further contribution is the targeting and visualization of integrated steam cycles and their effect on temperatures and amounts of excess heat.

2.2 | High-temperature excess heat and opportunities for combined heat and power generation

In energy-intensive industrial processes, it is not uncommon that excess heat is available at very high temperatures because of the need to cool product streams from high-temperature thermochemical conversion processes or chemical reactions. This also includes the combustion of various by-products in process furnaces or steam boilers, such as refinery gas in oil refineries, and blast furnace gas and other off-gases from iron and steel manufacturing processes. Steam boilers fuelled with off-gases that would otherwise be flared, or combustion processes that are inherently related to process unit operations (eg, lime kilns in the cement industry or pulp industry) need to be regarded as integral parts of the production process. The process recovery boiler of the Kraft pulping process, which is used for the illustrative example in Section 4, is one such example. The recovery boiler, which is fuelled by black liquor, is the main steam production unit, but it is also the heart of the mill's chemical recovery cycle and is, therefore, a necessary part of the core production process. The heat released by the black liquor combustion in the recovery boiler is thus an unavoidable source of very high-temperature heat.

Excess heat recovery is often achieved by raising steam and then generating work by steam turbine expansion. In such cases, it is relevant to estimate the cogeneration target, ie, the amount of shaft power that can be produced by steam expansion while still being able to satisfy the process heat requirement. In this work, it is assumed that the proposed targeting procedure can be applied to generate excess heat profiles for different assumptions about the utility system. A clear distinction can thus be made between unavoidable heat production due to high-temperature heat sources from the production process, and heat production in utility boilers, which can be reduced by better process heat recovery. Furthermore, a theoretical case is defined in which fuel minimization in utility boilers is prioritized over maximized cogeneration efficiency.

3 | THE XHT SIGNATURE

In this work, the availability of excess heat is characterized according to discrete temperature intervals. This results in a temperature profile referred to as the XHT signature (XHT signature), which is constructed by aggregating the available excess heat at predefined temperature levels and temperature intervals.

To be able to distinguish between excess heat at different levels of internal process heat recovery, two different

XHT signatures are required: the *Theoretical XHT signature* that represents the unavoidable excess heat corresponding to the theoretical, maximum internal energy recovery of the process and the *Process Cooling XHT signature* that represents the current availability of excess heat corresponding to the current utility requirements of the process. The Theoretical XHT signature corresponds to an envelope curve below the process GCC constructed with $\Delta T_{min} = 0°C$. Accordingly, it is determined adopting a white-box approach (see Section 2.1). To determine the Process Cooling XHT signature, a grey-box approach is adopted in which the actual sources of cooling with their temperature and heat loads are mapped. This corresponds to identifying the XHT signature based on the ACLC instead of the GCC of the process.

In reality, various technical and practical barriers, such as geographical distance between heat sources and sinks and time-variations in heat supply and demand, limit the heat recovery not only between process heat sources and sinks but also between excess heat sources and possible excess heat recovery technologies. As a result, a targeting approach by which all excess heat sources are aggregated into one single curve will typically not represent the true feasible excess heat potential. However, this kind of aggregated characterization of the excess heat utilization potential is desirable to be able to compare the availability of excess heat from different processes or different type of industries or to compare the excess heat availability of a given site under different assumptions about the internal process heat recovery, that is, to compare the Process Cooling XHT signature with the Theoretical XHT signature.

3.1 | Construction of the XHT signature

The XHT signature is constructed by aggregating the available excess heat at and between predefined temperature levels (eg, 60-100°C, isothermal at 100°C, 100-140°C, and isothermal at 140°C, >140°C). Note that excess heat can be considered both between specified supply and return temperatures and at constant temperature levels, which is useful for estimating opportunities for integration of phase-changing processes, such as evaporation (eg, steam raising and heat pumping) or liquefaction (eg, thermal storage).

In order to construct the XHT signature, the amount of excess heat in the different categories is optimized to maximize the following objective function:

$$f = w_{T1} \cdot x_{T1} + w_{T2} \cdot x_{T2} + w_{T3} \cdot x_{T3} + \ldots + w_{Tn} \cdot x_{Tn} \qquad (1)$$

where T1 to Tn denote the chosen temperature categories from the lowest to the highest temperature, x_{T1} to x_{Tn} are the amounts of heat available in the respective temperature interval, and w_{T1} to w_{Tn} are weighting factors that determine the priority of excess heat according to its temperature level.

Since excess heat at higher temperature has a higher quality than excess heat at lower temperatures, 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 (ie, $w_{T1} < w_{T2} < \ldots < w_{Tn}$). Possible appropriate choices of the weighting function values are further discussed in Section 3.3.

An example of an XHT signature matched against a process GCC is shown in Figure 2. This XHT signature was constructed using temperature categories of T1 = 60°C isothermal, T2 = 60°C-100°C, and T3 = 100°C isothermal, and with weighting factors $w_{60} = 4$, $w_{60-100} = 5$, and $w_{100} = 6$.

3.2 | Interpretation of the XHT signature

The XHT signature represents the processes that could utilize the excess heat, which could be a combination of different options. Consequently, the XHT signature profile can be seen as representing a cold utility that needs to be matched against the process cooling demand.

One advantage of using the XHT signature compared with the GCC is a more immediate reading of the amount of excess heat available at various temperature levels. Furthermore, XHT signatures from different plants at a large site can be aggregated into a single curve to provide an overview of the excess heat from a set of plants. This is in contrast with the aggregation of multiple GCCs, which

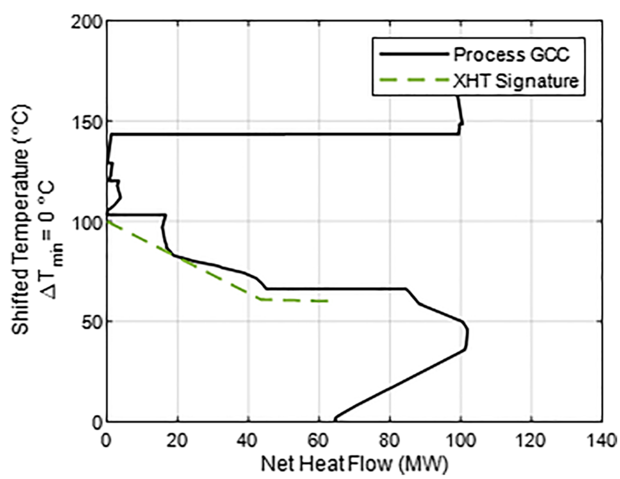

FIGURE 2 Construction of Theoretical excess heat temperature (XHT) signature from process grand composite curve (GCC) [Colour figure can be viewed at wileyonlinelibrary.com]

implies that all the included process streams from different plants can be arranged in an optimal way to maximize excess heat utilization, which in turn can lead to an overestimation of the potentials that can be achieved in practice.

It is also possible to compare different XHT signatures within the same chart, eg,:

- XHT signatures representing different sites,
- XHT signatures representing situations before and after a process retrofit, or
- XHT signatures resulting from different assumptions about heat recovery or steam cycle integration.

The Theoretical XHT signature can be used as a tool in energy audit studies or for formulating appropriate policy instruments for energy-efficient excess heat utilization. It is, therefore, necessary to introduce a methodology to appropriately define a theoretical reference for the XHT signature. For this purpose, a methodology for targeting the Theoretical XHT signature is proposed in Section 4.

3.3 | Selection of temperature intervals and weighting factors

Inevitably, the discretization of the XHT profile causes some details about temperature levels to be lost not only because the availability of excess heat can vary substantially within the selected intervals but also because the way higher temperature excess heat is prioritized affects the amount of lower temperature excess heat (see, eg, Figure 2). It is therefore important to choose the temperature categories and the weighting factors carefully so that they represent as accurately as possible the temperature requirements of the excess heat utilization options considered and the trade-off between using heat for the competing options.

The temperature levels should be chosen to represent relevant excess heat utilization technologies based on the purpose of specific case studies. For example, if district heating is the targeted recovery option, the supply and return temperatures of the district heating system should be used as boundary values for the temperature categories. Figure 3 shows the Process Cooling XHT signature corresponding to a subsystem of the water and air coolers of a petrochemical cracker plant. The temperature categories (60°C isothermal, and 60°C-100°C or 60°C-90°C) represent excess heat utilization for a heat pump and for district heating, respectively. In this case, the choice of target temperature for the highest temperature interval has a significant impact on the trade-off between the two utilization options.

The choice of weighting factors in the objective function in Equation 1 also affects the XHT signature. For example, the weighting factors used to generate the XHT signature shown in Section 3.1, Figure 2 cause the isothermal heat at 100°C to be neglected in order to maximize the excess heat recovery between 60 and 100°C. Another example that demonstrates the importance of the choice of weighting factors is shown in Figure 4. In this example, weighting factors of $w_{60} = 4$, $w_{60-100} = 5$, $w_{100} = 6$, $w_{100-140} = 7$, and $w_{140} = 8$ have been used. This results in a comparatively high prioritization of heat between 60 and 100°C, which is achieved at the expense of a larger flow of isothermal heat at, eg, 100°C. Ideally, the weighting factors should be chosen to represent the economic value of the excess heat, which would depend on the utilization option considered for a given temperature interval. Since this type of information is often lacking, or the utilization option not clearly specified, more generic weighting factors can be considered, such as the average temperature or the average Carnot factors in the temperature level category.

Another option would be to consider a less detailed XHT signature profile with only isothermal excess heat categories, in which case the amount of excess heat at different levels can be maximized independently (compare also with the approach of Waste Heat Profiles suggested by Oluleye et al[22]).

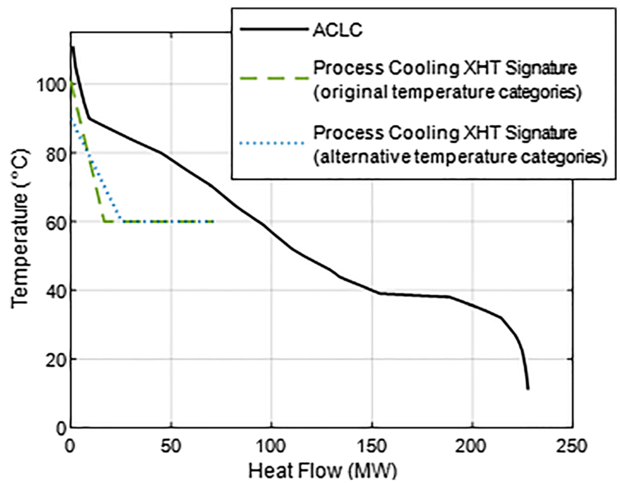

FIGURE 3 Actual cooling load curve (ACLC) related to a petrochemical cracker plant and the corresponding Process Cooling excess heat temperature (XHT) signature curves for two different target temperature values for heat recovery for district heating purposes. Original temperature categories: 60°C isothermal and 60°C-100°C. Alternative temperature categories: 60°C isothermal and 60°C-90°C. Minimum temperature difference for excess heat recovery: 10 °C [Colour figure can be viewed at wileyonlinelibrary.com]

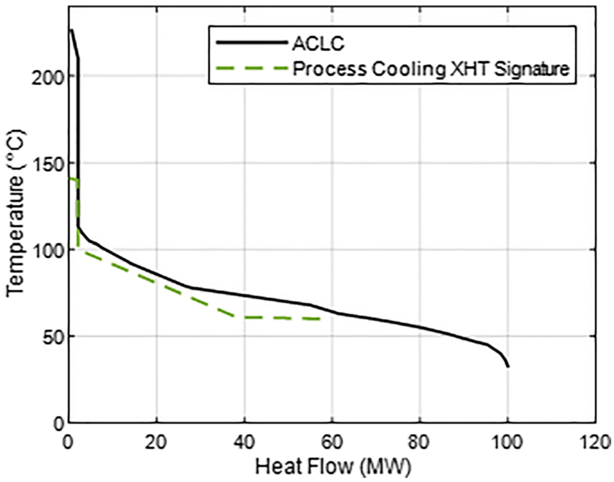

FIGURE 4 Actual cooling load curve (ACLC) of a polyethylene plant and its Process Cooling excess heat temperature (XHT). Minimum temperature difference for excess heat recovery: 5 °C [Colour figure can be viewed at wileyonlinelibrary.com]

4 | ENERGY TARGETING APPROACH FOR ESTIMATING THE THEORETICAL XHT SIGNATURE

In principle, the Theoretical XHT signature can be targeted against the process GCC, as illustrated in Figure 2. As discussed in Section 2.2, many industrial processes have large amounts of high-temperature excess heat available from exothermic chemical reactions or incineration of by-products. When there is such high-temperature excess heat available at a process site, the Theoretical XHT signature can be determined by adopting an energy targeting approach, in which the industrial plant is assumed to be equipped with an ideally integrated steam turbine cycle. Furthermore, the steam cycle is assumed to be designed for maximum power generation such that the process heat demand is also satisfied. To be consistent with the assumptions about theoretical, ideal conditions, state-of-the-art performance characteristics should be assumed for the energy conversion system, eg, boiler outlet steam conditions and turbine isentropic efficiencies.

The combined production targets for power and heat depend on the useful heat available from fuel combustion and on the amount of heat required by the process.

The targeting is performed according to the following priority order:

1. minimize fuel use;
2. maximize power generation; and
3. maximize excess heat.

This priority order implies that the value (economic or environmental) of reduced fuel usage is assumed to be higher than that of power generation. Other priority orders could be motivated depending on the prices and emissions associated with different energy carriers, see also Section 6.

4.1 | Steps required for energy targeting

The steps required to estimate the power and excess heat targets according to the stated priorities are outlined below. The targets are most easily established using a mathematical programming framework. In principle, however, the steps can be illustrated graphically. The figures illustrating the procedure all relate to a typical Swedish Kraft market pulp mill.

4.1.1 | Step 1. Characterization of available high-temperature combustion heat

The combustion heat available is determined by the amount of fuel being processed that has no other use than combustion on site (eg, black liquor, refinery gas, and process off-gases). This amount depends on the production rate of the industrial processes, and if not combusted on site, its energy content is typically wasted through eg, flaring. Additional boilers, fuelled with imported fuel or by-products that could otherwise be exported, are regarded as part of the utility system and not as necessary parts of the process itself. The dotted line in Figure 5 represents the high-temperature heat from the combustion of black liquor in the pulp mill example. Note that the high temperature of radiation heat is represented at a constant temperature of 1000 °C. The outlet flue gas temperature is set to 175 °C, a typical value for existing recovery boilers.

4.1.2 | Step 2. Description of process heating and cooling demands for the foreground production processes

For this step, information about process heating and cooling demands for all process streams are collected and analyzed in order to determine the net heating and cooling demands (Q_{Hmin} and Q_{Cmin}) for an ideally integrated process assuming a specified value for the minimum temperature difference for heat exchange. Here, we define a theoretical case by assuming a ΔT_{min} of 0°C. The resulting net heating and cooling demands can be visualized as a GCC. In Figure 5, the process GCC (solid line) is shown as a foreground curve against the background process represented by the recovery boiler, which means that the GCC is mirrored (see also Step 3).

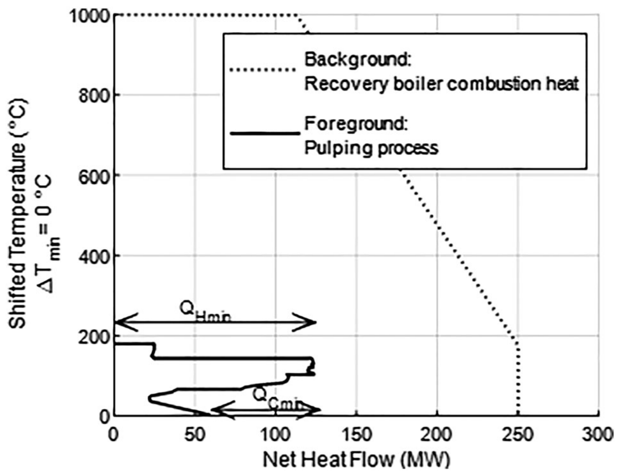

FIGURE 5 Background/foreground analysis using split grand composite curves (GCCs) of the heat available from black liquor combustion in the recovery boiler and the rest of the production process. The production process is represented by its GCC, ie, considering the net heating demand of the process after ideal process heat recovery for $\Delta T_{\mathrm{min}} = 0°C$

4.1.3 | Step 3. Background/Foreground analysis using split GCCs

To analyze whether the heat content from the combustion of internal fuel is sufficient to cover the heating demand of the process, the two curves representing the available heat (from Step 1) and the process heat demand (from Step 2) are drawn separately, but in the same chart, and with one of the curves mirrored. If the background/foreground analysis using the split GCCs indicates that there is more heat available from the combustion of internal fuels than is required by the industrial process, there is a potential for power generation without the use of additional fuel. This is the case for the example shown in Figure 5. Additional fuel is only considered when targeting the Theoretical XHT signature if the heat from internal fuels is insufficient to cover the process heating demand.

4.1.4 | Step 4. Integration of a steam turbine cycle

Steam turbine cycle integration is illustrated in a background/foreground graph using split GCCs (see Figure 6). In this case, the process heating demand and the fuel combustion heat release are combined into a single background GCC. The steam cycle is represented by an additional GCC in the foreground.

Maximum fuel utilization can be achieved with a back-pressure turbine, where the extraction pressures match the pressure levels of the process steam demands and the extraction flows for the low-pressure outlet steam as well as the medium-pressure extraction steam exactly cover the process steam demand. In practice, steam is either available in excess, which opens the opportunity for a condensing turbine stage, or steam must be directly reduced to lower pressure, by-passing the turbine. In the latter case, it would be justifiable to increase the steam production and back-pressure power generation, by firing additional fuel (eg, imported fuel or generated fuel that could otherwise be exported) in a boiler. However, for the theoretical heat integration case required for a systematic, consistent definition of the XHT signature, minimized fuel use is prioritized. This also implies that for a process without excess internal fuel, no cogeneration will be assumed for the construction of the Theoretical XHT signature.

For the example shown in Figure 6, steam is available in excess. The figure to the left 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. In 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

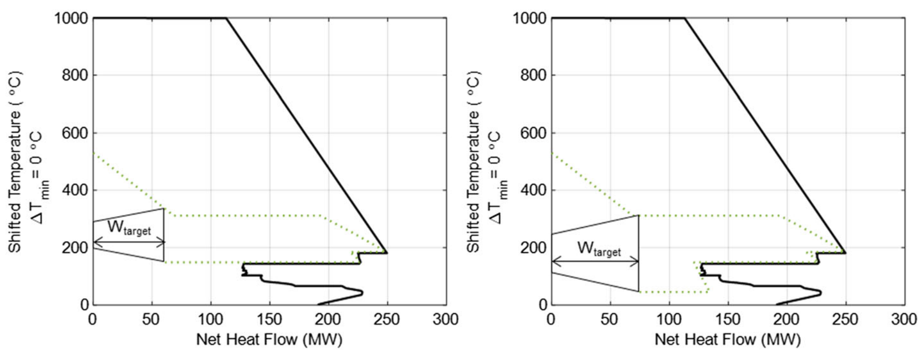

FIGURE 6 Split grand composite curve representation of a steam turbine cycle integrated with the pulp mill process using heat from the recovery boiler. Solid black line: Background representing the pulp mill process including the recovery boiler. Green dotted line: Foreground representing the integrated steam cycle. The turbine symbol indicates the power generation target (W_{target}). (left) Back-pressure operation only. (right) Back-pressure and condensing turbine operation [Colour figure can be viewed at wileyonlinelibrary.com]

available from the production process, since this heat is used for heating the condensate from the turbine condenser up to feedwater temperature.

4.1.5 | Step 5. Characterization of excess heat availability

Finally, the availability of excess heat for the ideally integrated processes can be characterized by the XHT signature as defined in Section 3.

The Theoretical XHT signature is matched against the net cooling demands of the integrated production process and steam utility system, ie,, against the GCC of the integrated processes. Figure 7 shows an estimated Theoretical XHT signature for the example mill, assuming that a steam cycle with an additional condensing stage is integrated with the process, as illustrated in the right-hand figure in Figure 6.

The Theoretical XHT signature in Figure 7 was targeted for predefined temperature intervals of 60°C-100°C, 60°C isothermal, 40°C-60°C, and 40°C isothermal. The weights in the objective function (1) were chosen as the average Carnot factors for the respective temperature interval. The weights and temperature categories are for illustrative purposes only. For a specific application, the excess heat utilization options should determine which temperature intervals to apply, as well as their weighting factors.

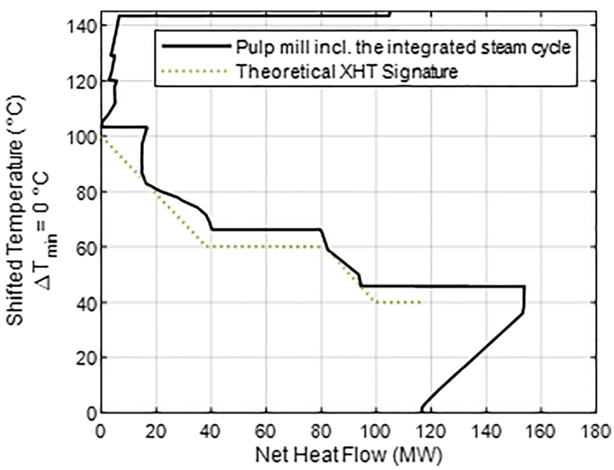

FIGURE 7 Theoretical excess heat temperature (XHT) signature based on the net cooling demand represented by the grand composite curve (GCC) of the integrated pulp mill process, recovery boiler, and steam cycle. The minimum temperature difference of 0°C is valid for the GCC as well as for matching of the GCC and the Theoretical XHT signature [Colour figure can be viewed at wileyonlinelibrary.com]

4.2 | Linear programming implementation of targeting approach

To complete Steps 1–5, a linear programming model of a steam network with multiple steam headers was developed, which enables automated integration of steam cycles with maximized power generation, and generation of the XHT signature. The model is based on the decomposition of the steam systems in elementary single-pressure cycles. The decomposition allows expressing the energy balances as linear functions of the steam mass flow rates once pressure and temperature of steam headers are defined.

With such a mathematical model, Steps 4 and 5 can be 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 of a linear combination of power generation and excess heat amounts at different temperature levels, where the weighting factor for power generation is very large compared with the coefficients for excess heat.

5 | THE PROCESS COOLING XHT SIGNATURE

The Process Cooling XHT signature is matched against the composite curve representing the actual cooling demand of the process and its utility system, that is, the process ACLC. Figure 8 shows the ACLC and the Process Cooling XHT signature of the pulp mill example. Figure 9 shows in the same diagram the Theoretical and the Process Cooling XHT signatures for the example pulp mill.

As shown in Figure 9, the Process Cooling XHT signature approximately matches the shape of the Theoretical XHT signature. However, the excess heat availability at and above 60°C is larger in the Process Cooling XHT compared with the Theoretical XHT, which is a direct consequence of less heat recovery and lower energy efficiency in the real mill compared with the idealized theoretical case. This illustrates that, in practice, industrial excess heat in a specified temperature range often exceeds the theoretical target, which represents the limit of highly efficient excess heat utilization.

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,

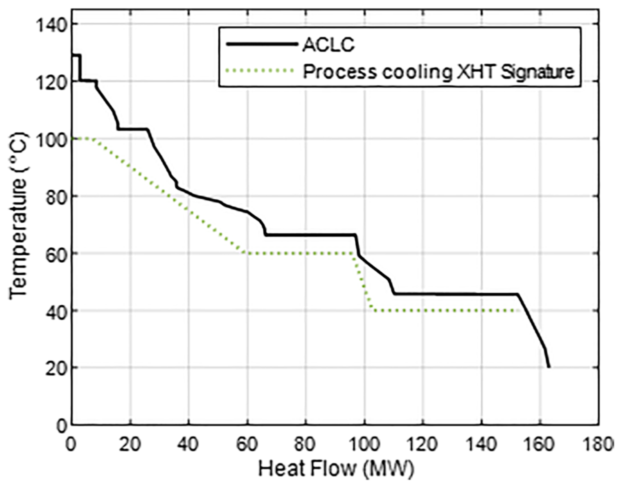

FIGURE 8 Process Cooling excess heat temperature (XHT) Signature based on actual cooling demand of the integrated pulp mill process and its utility system. $\Delta T_{\min} = 10$ °C [Colour figure can be viewed at wileyonlinelibrary.com]

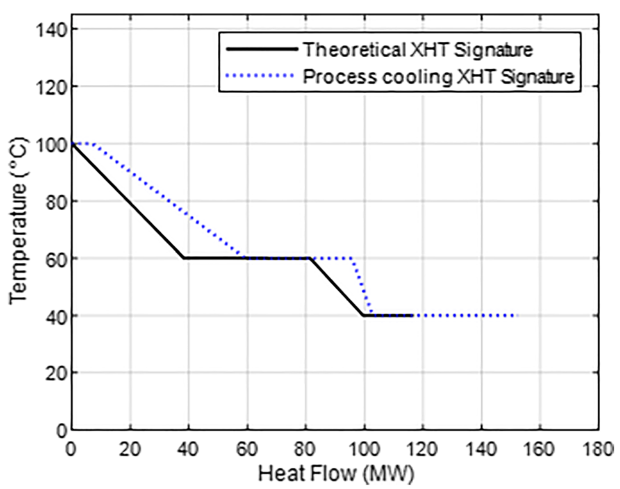

FIGURE 9 Theoretical and Process Cooling excess heat temperature (XHT) signatures for the example pulp mill [Colour figure can be viewed at wileyonlinelibrary.com]

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.

6 | TARGETING OF XHT SIGNATURES FOR DIFFERENT LEVELS OF INTERNAL PROCESS HEAT RECOVERY

As shown above, the Process Cooling XHT signature can be generated directly from the process ACLC, which only requires information about the process streams in all process coolers at a given site. However, even if there is stream data available that makes it possible to generate the process GCCs and target the ideal integration of steam turbine cycles to generate the Theoretical XHT signatures, there is commonly a lack of data regarding the existing heat exchanger networks at the sites. In these situations, it is sometimes necessary to apply the targeting approach described in Section 4, but instead of minimizing the fuel use, try to match the fuel consumption or total steam production to reported or measures values, and apply more realistic assumptions about, eg, conversion efficiencies and minimum temperature differences for heat exchange. In this way, the Process Cooling XHT signature can be estimated in a similar way to the Theoretical XHT signature.

In addition to the Theoretical and Process Cooling XHT signatures, other XHT signatures could be estimated that represent other levels of process heat recovery or alternative sizing criteria for integrated steam cycles.

Some possible variations of the XHT signature can be generated by applying the following alternative assumptions or combinations thereof:

a. Minimum temperature difference for heat exchange > 0°C
 In the targeting approach, a $\Delta T_{\min} > 0$°C can be applied to represent more realistic assumptions about the conditions for new heat exchangers. Different $\Delta T_{\min}$ contributions can be applied for heat exchange within the process, between the process and the steam utility system, and for heat exchange between the process and the excess heat utilization options represented by the XHT signature. In practice, if $\Delta T_{\min} > 0$°C is applied for the recovery of excess heat, the temperatures of the XHT signature must be shifted in the targeting procedure.
b. Actual instead of targeted process heating and cooling demands
 The targeting approach for estimating the integration of the steam utility system can be applied with current temperature-heat load profiles for the process cooling and heating demands (ie, the ACLC of the core production process and the corresponding actual heating load curve (AHLC), representing the process streams heated by utility in existing heaters) instead

of the targeted net heating and cooling demand profile (ie, the GCC). With respect to the excess heat available from the cooling of hot process streams, this is very similar to the Process Cooling XHT signature. However, while the Process Cooling XHT signature is also determined by the actual cooling demand, in addition, it also assumes the current design and operation of the steam boiler and turbine system; ie, it is matched against the ACLC representing the process cooling loads of the production process as well as of the utility system. This means that the Process Cooling XHT signature may include currently available residual heat from the utility system such as steam venting and hot flue gases from utility boilers, which may be reduced if the utility system is optimized. By instead applying the targeting procedure described in Section 4, a different XHT signature may be obtained due to a different sizing of the steam production units and steam turbine stages. In practice, this variation of the XHT signature is similar to the assumptions that would be applied in total site targeting, where heat recovery within single processes is assumed to be left unaltered, while the supply and use of utility are optimized (compare eg with Kapil et al[24]).

c. Maximized fuel utilization instead of minimized fuel use
   An alternative XHT signature can be constructed by assuming that fuel energy utilization should be maximized, which would mean that instead of minimizing fuel consumption in Step 3, the steam cycle integrated in Step 4 should be sized to exactly cover the process heating demand. Unless there is a surplus of high-temperature heat as in the illustrative example of the market Kraft pulp mill, this would lead to additional fuel use. In practice, this can be of interest especially if there is a low-cost fuel available and the value of power generation is high. This is commonly the case in the pulp and paper industry. The pulp and paper mills can use bark, which is a low-grade wood by-product from their process, as a low-cost fuel. Depending on national policy instruments, they might also be eligible for some sort of support for the production of electricity from renewable energy sources. In principle, the priority order used in the targeting procedure for reduced fuel use and increased power production could be determined by the emission consequences associated with changes in fuel and electricity balances, as well as by the prices for fuel and electricity. Note also that short- and long-term variations and geographical differences in the energy system, eg, in electricity prices, biomass markets, or marginal electricity production, may motivate different priorities at different mill locations and points in time.
d. Actual fuel use instead of minimized fuel use
   A special case of the XHT signature can be obtained by investigating what would be the maximum levels of excess heat if the fuel use is kept at current levels. This XHT signature is estimated by applying the energy targeting approach with the ideal process GCC, but instead of minimizing fuel use, maintaining the current fuel use as well as the same steam cycle specifications as in the existing system. The resulting XHT signature is similar in some respects to the TCLC.

In the future, major revamps of existing industrial plants can be expected if industry is to meet its climate targets. Possible measures range from significant energy efficiency projects to large-scale integration of bio-based processes or carbon capture. Such changes could drastically reduce the availability of excess heat for other purposes. In principle, XHT signatures can be generated to represent potential future excess heat profiles, for example, by basing the Process Cooling XHT signature on an ACLC representing the process cooling demands after a heat exchanger network retrofit or by basing the Theoretical XHT signature on a GCC representing the prospected new plant.

7 | DISCUSSION

The XHT signature can be used 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 on-site fuel savings.

Given the consistent, systematic way of defining the heat-temperature profile, another promising application of the XHT signatures is as a tool for systematic characterization of industrial excess heat from several sites, eg, as an input to estimations of regional or sector-wide excess heat potentials. This application of the XHT signatures has been previously demonstrated in a study targeting power generation and excess heat availability from the Swedish Kraft pulping industry.[35]

In order to be able to implement policies that distinguish between more or less efficient excess heat utilization, as well as to be able to estimate aggregated regional or sector-wide potentials based on detailed case studies, there is a significant need for more comprehensive data for process heating and cooling demand in the industrial process plants. To analyze individual sites or case studies, it is necessary to collect and analyze all thermal stream data from a process, which may be a significant practical limitation. Several studies conclude that lack of data for industrial process heating demands is a constraining factor in studies of industrial energy systems. For example, Rehfeldt et al[47] argue in their introduction that there is a need for more detailed (less aggregated) data for industrial energy end-use. Brueckner et al[9] conclude in their review of methods for estimation of industrial waste heat potentials that "lack of data is a very huge obstacle to the quantification and usage of the industrial waste heat," and Naegler et al[48] conclude that "A serious obstacle in this study is the difficulty to obtain reliable, up-to-date data for energy usage and PH [process heating] temperature levels on a national and industry branch level."

At Chalmers University of Technology, an extensive number of case studies of industrial sites have been carried out and used as a basis for research projects investigating the consequences of enhanced heat recovery, implementation of new process technology, industrial symbiosis in industrial clusters, etc. Recently, these data were compiled into a case study portfolio that includes detailed stream data for a large share of the largest emitting industrial sites in Sweden.[49] Other similar initiatives and/or future policy frameworks to obtain data for industrial heat use could lead to better data availability for bottom-up evaluations of industrial excess heat. This implies that there is a need to consider policies in the form of incentives or obligations to promote the acquisition and reporting of industrial process heat use. For example, mapping of process heating and cooling demands at different temperature levels could be done in connection with, or as part of, mandatory or voluntary energy audits. In particular, the mandatory energy audits required by large companies according to Article 8 of the EU Energy Efficiency Directive should be considered as a possible means to collect process data for excess heat assessments.

8 | CONCLUSION

This paper presented a new tool for characterization and visualization of excess heat availability from industrial process sites, called the XHT signature. This tool can be used to explore the potential heat availability for different heat utilization options that either have heat demands at specified constant temperature levels or between specified supply and target temperatures. By categorizing the available heat according to predefined temperature levels and intervals that are given different weighting factors, the XHT signature enables an initial estimation of how the heat should be distributed between different utilization options.

Since the XHT signature offers a consistent representation of XHT profiles, it is a very well-suited tool for comparison between different sites or cases. In particular, the XHT signature can be used to compare excess heat availability under different assumptions about heat recovery within a site. For example, a Theoretical XHT signature, representing the excess heat that can be recovered after the site's on-site process heat recovery and ideal steam cycle power cogeneration is maximized, can be compared with a Process Cooling XHT signature that represents the excess heat that can be recovered from process streams in existing coolers.

In this work, reference conditions and assumptions for the Theoretical XHT signature were defined. Furthermore, an energy targeting approach was proposed to determine this Theoretical XHT signature. The Theoretical XHT signature represents the maximum amount of excess heat that can be recovered without limiting the potential for further on-site primary heat savings and can, therefore, be used as a reference to differentiate between more or less efficient utilization of excess heat.

Finally, it is suggested that future studies apply the methodology and tools developed in this paper to determine industrial excess heat availability for different sites and use the results for bottom-up estimations of regional or sector-wide industrial excess heat potentials. However, this also requires further efforts in systematic collection of site-specific process data on industrial heating and cooling use. Future research could also further develop the idea of using the Theoretical XHT signature as a reference for characterizing unavoidable industrial excess heat in, eg, energy audits and support schemes for excess heat recovery and utilization.

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REFERENCES

1. European Parliament and Council of the European Union. Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC. *Off J Eur Union*. 2012;L 315:1-56. http://data.europa.eu/eli/dir/2012/27/oj
2. Sandvall AF, Börjesson M, Ekvall T, Ahlgren EO. Modelling environmental and energy system impacts of large-scale excess heat utilisation—A regional case study. *Energy*. 2015;79:68-79. https://doi.org/10.1016/j.energy.2014.10.049
3. Weinberger G, Amiri S, Moshfegh B. On the benefit of integration of a district heating system with industrial excess heat: An economic and environmental analysis. *Appl Energy*. 2017;191:454-468. https://doi.org/10.1016/j.apenergy.2017.01.093
4. Berntsson T, Åsblad A. Annex XV: Industrial excess heat recovery—technologies and applications: final report—phase 1.; 2015. IETS. https://iea-industry.org/app/uploads/annex-15-final-report-phase-1-appendix-1.pdf. Accessed February 19, 2019.
5. Panayiotou GP, Bianchi G, Georgiou G, et al. Preliminary assessment of waste heat potential in major European industries. *Energy Procedia*. 2017;123:335-345. https://doi.org/10.1016/j.egypro.2017.07.263
6. Forman C, Muritala IK, Pardemann R, Meyer B. Estimating the global waste heat potential. *Renew Sustain Energy Rev*. 2016;57:1568-1579. https://doi.org/10.1016/j.rser.2015.12.192
7. Broberg S, Backlund S, Karlsson M, Thollander P. Industrial excess heat deliveries to Swedish district heating networks: drop it like it's hot. *Energy Policy*. 2012;51:332-339. https://doi.org/10.1016/j.enpol.2012.08.031
8. Cornelis E, Van Bael J. How well can the potential of industrial excess heat be estimated? In: *Eceee Industrial Summer Study Proceedings*. Berlin, Germany; 2016. Vol 2016-Sept.:199-206.
9. Brueckner S, Miró L, Cabeza LF, Pehnt M, Laevemann E. Methods to estimate the industrial waste heat potential of regions—a categorization and literature review. *Renew Sustain Energy Rev*. 2014;38:164-171. https://doi.org/10.1016/j.rser.2014.04.078
10. Eriksson L, Morandin M, Harvey S. A feasibility study of improved heat recovery and excess heat export at a Swedish chemical complex site. *Int J Energy Res*. 2018;42(4):1580-1593. https://doi.org/10.1002/er.3950
11. Bendig M, Maréchal F, Favrat D. Defining "waste heat" for industrial processes. *Appl Therm Eng*. 2013;61(1):134-142. https://doi.org/10.1016/j.applthermaleng.2013.03.020
12. Persson U, Möller B, Werner S. Heat Roadmap Europe: identifying strategic heat synergy regions. *Energy Policy*. 2014;74:663-681. https://doi.org/10.1016/j.enpol.2014.07.015
13. McKenna RC, Norman JB. Spatial modelling of industrial heat loads and recovery potentials in the UK. *Energy Policy*. 2010;38(10):5878-5891. https://doi.org/10.1016/j.enpol.2010.05.042
14. Dénarié A, Muscherà M, Calderoni M, Motta M. Industrial excess heat recovery in district heating: Data assessment methodology and application to a real case study in Milano, Italy. *Energy*. 2019;166:170-182. https://doi.org/10.1016/j.energy.2018.09.153
15. Miró L, Brückner S, Cabeza LF. Mapping and discussing Industrial Waste Heat (IWH) potentials for different countries. *Renew Sustain Energy Rev*. 2015;51:847-855. https://doi.org/10.1016/j.rser.2015.06.035
16. Hammond GP, Norman JB. Heat recovery opportunities in UK industry. *Appl Energy*. 2014;116:387-397. https://doi.org/10.1016/j.apenergy.2013.11.008
17. Miró L, McKenna R, Jäger T, Cabeza LF. Estimating the industrial waste heat recovery potential based on CO_2 emissions in the European non-metallic mineral industry. *Energ Effic*. 2018;11(2):427-443. https://doi.org/10.1007/s12053-017-9575-7
18. Papapetrou M, Kosmadakis G, Cipollina A, La Commare U, Micale G. Industrial waste heat: estimation of the technically available resource in the EU per industrial sector, temperature level and country. *Appl Therm Eng*. 2018;138:207-216. https://doi.org/10.1016/j.applthermaleng.2018.04.043
19. Bühler F, Petrović S, Karlsson K, Elmegaard B. Industrial excess heat for district heating in Denmark. *Appl Energy*. 2017;205:991-1001. https://doi.org/10.1016/j.apenergy.2017.08.032
20. Bühler F, Nguyen T-V, Elmegaard B. Energy and exergy analyses of the Danish industry sector. *Appl Energy*. 2016;184:1447-1459. https://doi.org/10.1016/j.apenergy.2016.02.072
21. Ammar Y, Joyce S, Norman R, Wang Y, Roskilly AP. Low grade thermal energy sources and uses from the process industry in the UK. *Appl Energy*. 2012;89(1):3-20. https://doi.org/10.1016/j.apenergy.2011.06.003
22. Oluleye G, Jobson M, Smith R, Perry SJ. Evaluating the potential of process sites for waste heat recovery. *Appl Energy*. 2016;161:627-646. https://doi.org/10.1016/j.apenergy.2015.07.011
23. Kapil A, Bulatov I, Smith R, Kim J-K. Site-wide low-grade heat recovery with a new cogeneration targeting method. *Chem Eng Res Des*. 2012;90(5):677-689. https://doi.org/10.1016/j.cherd.2011.09.001
24. Kapil A, Bulatov I, Smith R, Kim J-K. Process integration of low grade heat in process industry with district heating networks. *Energy*. 2012;44(1):11-19. https://doi.org/10.1016/j.energy.2011.12.015
25. Marton S, Harvey S, Svensson E. Investigating operability issues of heat integration for implementation in the oil refining industry. In: *Eceee Industrial Summer Study Proceedings*. Berlin, Germany; 2016. Vol 2016-Sept.:495-503.
26. Marton S, Svensson E, Harvey S. Operability and technical implementation issues related to heat integration measures—interview study at an oil refinery in Sweden. Manuscript under review.
27. Klemeš JJ, Varbanov PS, Walmsley TG, Jia X. New directions in the implementation of Pinch Methodology (PM). *Renew Sustain Energy Rev*. 2018;98(October):439-468. https://doi.org/10.1016/j.rser.2018.09.030
28. Morandin M, Hackl R, Harvey S. Economic feasibility of district heating delivery from industrial excess heat: A case study of a Swedish petrochemical cluster. *Energy*. 2014;65:209-220. https://doi.org/10.1016/j.energy.2013.11.064
29. Eriksson L, Morandin M, Harvey S. Targeting capital cost of excess heat collection systems in complex industrial sites for

district heating applications. *Energy*. 2015;91:465-478. https://doi.org/10.1016/j.energy.2015.08.071

30. Andersson V, Franck P-Å, Berntsson T. Industrial excess heat driven post-combustion CCS: The effect of stripper temperature level. *Int J Greenh Gas Control*. 2014;21:1-10. https://doi.org/10.1016/j.ijggc.2013.11.016
31. Woolley E, Luo Y, Simeone A. Industrial waste heat recovery: A systematic approach. *Sustain Energy Technol Assessments*. 2018;29:50-59. https://doi.org/10.1016/j.seta.2018.07.001
32. Jouhara H, Khordehgah N, Almahmoud S, Delpech B, Chauhan A, Tassou SA. Waste heat recovery technologies and applications. *Therm Sci Eng Prog*. 2018;6:268-289. https://doi.org/10.1016/j.tsep.2018.04.017
33. IEA. Tracking Clean Energy Progress 2017 - Energy technology perspectives 2017 excerpt. Report, International Energy Agency (IEA); 2017. www.iea.org/etp/tracking. Accessed July 1, 2019.
34. Swedish Energy Agency. Energy in Sweden 2019. Report, Swedish Energy Agency; 2019. https://energimyndigheten.a-w2m.se/Home.mvc? ResourceId=5789. Accessed July 1, 2019.
35. Svensson E, Morandin M, Cruz I, Harvey S. Availability of excess heat from the Swedish kraft pulping industry. In: *Proceedings of ISEC, 3-5 October, 2018*. Graz, Austria; 2018. http://www.aee-intec.at/0uploads/dateien1467.pdf. Accessed April 25, 2019.
36. Kemp IC. *Pinch analysis and process integration: a user guide on process integration for the efficient use of energy*. Butterworth-Heinemann; 2007.
37. Smith R. *Chemical Process: Design and Integration*. Wiley; 2014.
38. Klemeš JJ. *Handbook of Process Integration: Minimisation of Energy and Water Use, Waste and Emissions*. Woodhead Publishing; 2013.
39. Bühler F, Nguyen T-V, Jensen JK, Holm FM, Elmegaard B. Energy, exergy and advanced exergy analysis of a milk processing factory. *Energy*. 2018;162:576-592. https://doi.org/10.1016/j.energy.2018.08.029
40. Hackl R, Harvey S. Framework methodology for increased energy efficiency and renewable feedstock integration in industrial clusters. *Appl Energy*. 2013;112:1500-1509. https://doi.org/10.1016/j.apenergy.2013.03.083
41. Liew PY, Theo WL, Wan Alwi SR, et al. Total site heat integration planning and design for industrial, urban and renewable systems. *Renew Sustain Energy Rev*. 2017;68:964-985. https://doi.org/10.1016/j.rser.2016.05.086
42. Hackl R, Andersson E, Harvey S. Targeting for energy efficiency and improved energy collaboration between different companies using total site analysis (TSA). *Energy*. 2011;36(8):4609-4615. https://doi.org/10.1016/j.energy.2011.03.023
43. Méchaussie EM. Methodology for efficient use of thermal energy in the chemical and petrochemical industry. Doctoral thesis, EPFL, Lausanne, Switzerland; 2018. https://doi.org/10.5075/epfl-thesis-8485
44. Strömberg J, Berntsson T. A new methodology for utility integration in retrofit situations: application with cogeneration plants. In: *Proceedings of ECOS'96, June 25-27, 1996*. Stockholm, Sweden; 1996.
45. Wallin E. Process integration of industrial heat pumps in grassroot and retrofit situations. Doctoral thesis, Chalmers University of Technology, Göteborg, Sweden; 1996.
46. Nordman R, Berntsson T. Use of advanced composite curves for assessing cost-effective HEN retrofit I: Theory and concepts. *Appl Therm Eng*. 2009;29(2-3):275-281. https://doi.org/10.1016/j.applthermaleng.2008.02.021
47. Rehfeldt M, Fleiter T, Toro F. A bottom-up estimation of the heating and cooling demand in European industry. *Energ Effic*. 2018;11(5):1057-1082. https://doi.org/10.1007/s12053-017-9571-y
48. Naegler T, Simon S, Klein M, Gils HC. Quantification of the European industrial heat demand by branch and temperature level. *Int J Energy Res*. 2015;39(15):2019-2030. https://doi.org/10.1002/er.3436
49. Svensson E, Bokinge P, Harvey S, Normann F. Chalmers industrial case study portfolio—contents, structure and example applications. Report, Chalmers University of Technology, Göteborg, Sweden; 2019. https://research.chalmers.se/publication/507813. Accessed February 19, 2019.

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