Methodology for streams definition and graphical representation in Total Site Analysis

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Abstract:

The current regulatory framework in Europe regarding industrial energy consumption puts emphasis on regular energy assessments and increasing energy efficiency. Among the available strategies to identify energy savings opportunities, Total Site Analysis (TSA) can be a powerful method to generate utility savings in industrial sites or clusters, targeting for heat recovery and cogeneration potential.

The grey box representation of the energy requirements focuses on process/utility heat exchanges when defining hot and cold streams. This representation is usually most suitable when carrying out a TSA on large industrial systems, as direct heat recovery schemes are rarely viable. Since its initial problem definition and solving in the 1990s, a high number of theoretical developments and practical applications have expanded the TSA knowledge. Still an important body of work on TSA techniques and case studies only addresses general aspects and issues that are encountered, and no in-depth explanation yet is found on how to consider specific types of heat consumers and producers.

This paper presents a methodology for data collection and streams definition in TSA. It provides a step-by-step approach for defining the process and utility requirements of the main types of heat flows typically found in large industrial systems, including their graphical representations. Using the proposed definitions, it is possible to systematically build composite curves for the total site profiles.

Keywords:

Total Site Analysis, industrial data collection, stream definition methodology, graphical representation

1. Improving industrial energy efficiency

This paper proposes a novel methodology for collecting and handling data related to Total Site Analyses (TSA). First the regulatory context that applies to the European energy-intensive industry is discussed in Section 1.1, followed by a literature review on TSA in Section 1.2. Section 1.3 states the objectives of the paper based on the knowledge gaps identified in the literature review.

1.1. European regulation

In order to decarbonise and secure the European energy system by 2050 [1] (80-95% reduction of greenhouse gas emissions as compared to 1990 levels) the EU has defined intermediate targets for 2030 [2] as a prolongation of the 2020 climate and energy package [3]. One of the key parameters to reach this ambitious objective is the improvement of energy efficiency in the three energy-consuming sectors, buildings, transport and industry, each responsible for approximately one third of Europe's primary energy consumption. Released in 2012, the Energy Efficiency Directive (EED) defines the actual European regulatory framework for energy efficiency [4].

The main EED requirement impacting large industrial companies is the need for regular assessment of their energy performance (article 8). Improving the industrial energy efficiency through energy audits and/or implementation of energy management system (EnMS) is considered as a key measure to reduce the energy consumption and environmental impact of the industrial sector.

Energy audits and EnMS schemes are parallel routes towards EED compliance as they both require industrial companies to put in place and apply methodologies, tools and techniques to be able to understand and analyse their energy consumption, determine their energy efficiency, and identify and evaluate energy savings opportunities. This process is usually referred to as an “energy review” or “energy assessment” [5].

1.2. Available tools and techniques

Depending on the chosen compliance scheme and the expected level of details, different tools and techniques can be applied throughout the energy review process. A walk-through energy audit does not present an industrial site with an in-depth analysis, it is very different from a comprehensive energy management system involving all the energy vectors and the entire production plant.

Among the methods available during the analysis and evaluation of energy performance, data processing and data reconciliation techniques are of high importance to respectively reduce and validate data collection [6]. Statistical methods such as regression analysis can be used for internal benchmarking and monitoring purposes. However, the generation of energy savings opportunities is often technically challenging.

Best practices in energy efficiency are well documented [7, 8] and should be extensively consulted by companies willing to identify opportunities to become more energy efficient. A large number of the presented best practices imply low-investment and low-risk actions, mainly related to maintenance and control. These solutions are often readily implemented in industry as they correspond to “low-hanging fruits”, with short payback times. More complex energy efficiency options involving heat recovery and process integration are recommended but only briefly described. These options do however provide the highest potential for energy consumption reduction [9].

Pinch analysis on single production units can help identify direct and/or indirect heat recovery opportunities through optimised heat exchanges between process streams. Total Site Analysis (TSA) is the application of pinch analysis to large industrial sites or even clusters, extending the potential for energy and resources flow optimisation and industrial synergies.

Based on the process requirements in terms of heating and cooling demands and the existing utilities, TSA identifies heat recovery opportunities and targets cogeneration potential through the modification and/or optimisation of the utility system.

As steam is often responsible for a large share of the total energy consumption, TSA is a powerful method to identify energy saving options in process industry.

1.3. Innovative aspects of the paper

The complexity of large industrial systems, the significant data size, and the lack of time and skills at industrial sites are some of the barriers preventing large (energy-intensive) companies from carrying out site-wide energy integration studies [10]. Although theoretical developments and case studies are widely available in literature, addressing many of the limitations and issues that are encountered in TSA, it is rare to find detailed explanations of TSA studies on industrial sites.

This paper makes its contribution to the TSA methodology by providing a step-by-step approach to properly define the main types of heat flows commonly found in large industrial systems, and model their temperature-enthalpy profiles.

In TSA, the characterisation of process minimum energy requirements is one of the key elements to identify heat recovery opportunities through the intermediate of the utility system. In this work the dual representation of processes by their technological and utility requirements [11] facilitates the streams definition and ensures the closing of heat balances.

Other types of heat flows related to the steam network (e.g turbines, losses) are also included in the analysis as they have a direct impact on the global utility supply efficiency. Graphical representation of the temperature-enthalpy profiles of each type of heat flows and the cogenerated power steam turbines are presented to clarify the data collection and modelling process.

The proposed methodology reduces the time required for the data collection step and simplifies the acquisition of the total site composite curves. Rather than contributing to the problem solving itself, it complements existing literature on TSA in practical applications.

2. A review on Total Site Analysis

Through a Total Site Analysis, the overall heating and cooling profiles of an entire site or cluster are calculated, which permits the identification of heat recovery opportunities from excess heat through a common utility system, with minimised utility generation and maximises cogeneration of mechanical power.

From its initial problem definition and solving in the 1990s, a high number of theoretical developments and practical applications have expanded the TSA knowledge.

The TSA concept was first introduced by [12], extending Pinch technology of a single process to multi-processes linked to a central utility system. It was subsequently intensified by [13-15], targeting the minimum utility cost, cogeneration and emission reduction potential.

Numerous authors proposed methodologies and advanced mathematical programming techniques to deal with different aspects of the TSA such as multi-period analysis [16, 17], restricted heat exchanger network design [18, 19] assisted heat transfer [20, 21], or distance factor consideration [22]. Overview and recent TSA developments can be found in [23, 24].

The potential of site-wide integration in a large chemical complex in Japan was demonstrated by [25], despite the already highly efficient individual process plants. Other case studies in the petrochemical and steel industry respectively from [26] and [27] provide additional examples on the application of TSA in retrofit situations. These studies highlight the increase in energy saving potential through the use of excess heat when process units are studied together rather than individually.

The targeting of minimum energy requirements and heat recovery opportunities is only possible once the full set of hot and cold streams is defined, which is usually the most time-consuming step in a TSA. Depending on the expected level of detail of the analysis and the system constraints, the energy requirements can be represented in several ways.

Practitioners usually consider three broad categories for plants and/or streams definition [28]: black boxes, grey boxes and white boxes. In the first two categories, while the heat load remains identical, streams temperatures differ according to the chosen representation. The last category corresponds to a full pinch analysis.

The grey box representation of the energy requirements is usually most suitable when carrying out a TSA on large industrial systems, where direct heat recovery is rarely viable. It implies heat recovery schemes through intermediate utility systems, allowing greater flexibility and site operability.

While an important body of work on TSA techniques and case studies addresses most of the general aspects and issues that are encountered, in-depth explanation on how to consider specific types of heat consumers and producers is rarely found. The temperature-enthalpy profiles of specific energy flows such as injections, cogeneration, steam losses, turbo-pumps or turbo-compressors have yet to be clearly defined in the literature.

The presented work provides a step-by-step approach for defining the process and utility requirements of the main types of heat flows encountered in typical large chemical or petrochemical sites, including their graphical representations. Using the proposed definitions, it is possible to systematically build composite curves, facilitating the acquisition of total site profiles.

3. Methodology

Industrial production sites convert raw materials into intermediate or finished products. Most of the time the production steps (e.g reaction, separation, drying) require heating and cooling of process streams. The utility system supports the production through the generation and distribution of hot and cold utilities.

The grey box representation implies that only heat exchanges involving process and utility streams are considered in the analysis.

The first objective of TSA is to collect data for the definition of the requirements of all process streams involving heat transfer with utilities, with regard to their temperature levels and heat loads.

Data collection is of major importance as it results in the definition of a consistent set of process streams with respect to mass and energy balances on utilities, and is the direct input to the energy integration analysis itself. It is usually the most time-consuming step and can prove to be quite challenging depending on the size of the industrial system under study. It is therefore interesting to follow a systematic approach when defining the process and utility hot and cold streams.

The methodology divides data collection into three interconnected steps: classification, characterisation and graphical representation of heat flows. The most common types of process heat flows are presented in Section 3.1 followed by the required data sets to be collected for process streams definition in Section 3.2. Utility streams are discussed in Section 3.3. Finally in Section 3.4, the graphical representation of the temperature-enthalpy profiles of process and utility streams are detailed and illustrated.

3.1. Process streams classification

3.1.1. Cold process streams

Cold process streams consume hot utilities to increase their energy content. The highest temperature required by the process usually defines the minimum pressure requirement of its steam consumption. The remaining process requirements influence the infrastructure of the rest of the steam network and hot utility system. Cold streams can be classified in six main categories:

- Heaters: Counter-current heat exchangers are most commonly used to heat up process streams. These heat flows can correspond to single-phase heating or involve the phase change of one or several components. Condensates should be collected, valorised if possible and returned to the boiler house.
- Injections: Steam is directly injected inside the process. Injected steam is mostly used for separation purposes (stripping, desorption, venting) but also for cracking (refineries), cleaning or water heating.
- Reboilers: Heat exchangers usually found at the bottom (sometimes on the side) of distillation columns, used to revaporise the liquid process stream and send it back to the separation area.
- Tracing/Storage: Steam is used to maintain a fixed temperature in the distribution pipes, so that process streams do not change phase when being transported from one point to another or stored in intermediate tanks.
- Buildings: Offices and workshops require heating, depending on the ambient temperature. Mostly the heat is supplied by the global utility system via the steam or hot water networks.
- Losses: Lack of maintenance and poor insulation are responsible for losses through steam traps and leaks. Depending on the system, steam losses can be significant.

While not directly being linked to the production process itself, the last two steam consumption types need to be considered, as they are an integral part of any large industrial site or cluster.

3.1.2. Hot process streams

Hot process streams are cooled by cold utilities. In the chemical and petrochemical sector, cooling is most of the time carried out by aero or water coolers. Hot streams can be classified in three main categories:

- Coolers: Cooling down of process streams.

- Condensers: Heat exchangers usually found at the top of the distillation columns. Condensers partially or totally condense the exiting process stream.
- Reactor cooling: Chemical reactions can be exothermic and release a large amount of heat. Due to security and quality constraints some reactors require continuous cooling to avoid reaching too high temperatures.

In certain cases, the exothermic reaction takes place at high temperature, enabling the production of steam from the heat released.

3.2. Process streams characterisation

3.2.1. Basic data set

According to the type of stream, data should be collected to be able to properly define streams and prepare the analysis of the total site composite curves. A stream is characterised by: its temperature-enthalpy profile $T_p \in [T_{p,in}, T_{p,out}]$, its heat load ($\dot{Q}$) and its contribution to the minimum temperature difference of the heat exchange ($\Delta T_{min}/2$).

Using the grey box approach, the load of the heat transfer can be calculated either from the utility or the process side, via the dual representation. When data on utility flows and thermodynamic properties are available, it is easier to calculate the heat load from the utility side. The best case is to have access to validated measurements on mass flows, temperatures and pressures of the utility streams. If not, mass and energy balances can be calculated to determine missing parameters, followed by the use of design data. The last option is to make informed estimations.

Process stream temperatures are most of the time measured, easily found in design data or through discussions with operators.

The basic data set to be able to characterise each stream is the combination of process temperatures ($T_{p,in}$, $T_{p,out}$) and information on utilities ($\dot{m}_u$, $T_{u,in}$, $T_{u,out}$, $P_{u,in}$, $P_{u,out}$). When one or several parameters are missing and cannot be recovered or calculated, complementary data should be collected on the process side ($\dot{m}_p$, P_p, composition) to determine the stream heat load. Large compounds databases and modelling software [29, 30] can be very useful at this stage, facilitating calculations.

The minimum temperature difference of heat exchanges (ΔT_{min}) is an important parameter for TSAs, as it has a direct impact on the heat recovery potential and associated investment costs.

In a heat exchange, each stream contributes to the minimum temperature difference ($\Delta T_{min}/2$). Depending on the type of stream (gaseous, liquid, phase-changing stream, multi or single components) and other constraints (location, security margins), different $\Delta T_{min}/2$ can be attributed.

As TSA is usually carried out on extensive industrial systems and involving indirect heat recovery schemes, a single and sufficiently large minimum temperature difference should be selected. Typical values of ΔT_{min} are between 10°C and 20°C [27].

3.2.2. Complementary data

In specific cases additional data can also be required to properly define and graphically represent process streams (Table 1).

Table 1. Complementary data collection for process stream definition

Type	*Utility side*	*Process side*
Phase-change heaters/coolers	-	T_{evap}, T_{cond}, TBPs
Injection	P_{actual}, ΔP_{min}, $\Delta T_{superheating}$	-
Tracing/Storage	P_{actual}, P_{min}	T_{min}
Reactor cooling	-	$X_{reaction}$, $\Delta H_{reaction}$

In the case where evaporation or condensation occurs in heat exchangers, the stream phase-change temperature has to be known. When a stream is mainly made of a single component, the phase transition is represented as a straight line. However if the stream is composed of a mixture of components having different boiling points, the condensation will take place over a wide temperature range.

Depending of the multi-components stream forms an ideal or non-ideal mixture, several thermodynamic methods can be applied to approximate the temperature-enthalpy profile of the evaporation [31]. In the refining and petrochemical industry, the true boiling point (TBP) method is an efficient way to determine thermal properties of hydrocarbon streams, which may be made up of millions of components [32]. TBPs give the fraction of fluid evaporated or condensed according to the temperature, over the whole phase transition temperature range.

The minimum pressure for steam injection (based on the required overpressure) and the level of superheating should be determined. Tracing and storage heat requirements are based on the product temperature and the minimum steam pressure. For these two heat flows, the objective is to establish the minimum requirements of the process stream.

The cooling load of reactors can be determined based on the heat of reaction and reaction conversion or through the heat evacuated by the cooling system, a simple calculation in the case of water-cooling.

Losses cannot be directly measured and are sometimes hard to estimate. Data reconciliation tools and verification exercises on steam traps and piping can help in the determination of losses.

Instead of representing building heating as a black box requirement, the heat demand can be determined according to the external temperature, the surface to be heated and the buildings insulation. Standards can be found on indoor temperature criteria according to the geographical location and the heating degree-day method [33] can be used to calculate the required energy demand. Choosing to represent building heating as a grey box enables the identification of heat recovery opportunities at low temperatures.

3.2.3. Energy balance

Once the complete list of streams is determined, its consistency should always be checked with energy balances. The sum of the cold and hot stream heat loads should respectively match the hot and cold utility consumption. Also the heat provided to the production process system should be removed. This balance can be expressed as:

$$\dot{Q}_{hot} = \dot{Q}_{cold} + \dot{Q}_{reaction} + \dot{Q}_{losses} \qquad (1)$$

$\dot{Q}_{reaction}$ corresponds to the heat of reaction. It is negative when the reaction is exothermic and positive when endothermic. $\dot{Q}_{hot}$ and $\dot{Q}_{cold}$ are respectively the heat loads supplied to and removed from the production process via the utility system. Providing that raw materials and products exit the system at similar temperature, the balance in (1) should be closed.

3.3. Utility streams

In TSA, process and utility temperature-enthalpy profiles are plotted together. As soon as a process stream is defined, the corresponding utility stream should be characterised as well. The dual representation simplifies data collection and ensures the consistency of results.

Since data on utility consumption has already been gathered in the process stream definition (section 3.1.1.3) no further data collection is required to characterise utility streams. Before moving onto the graphical representation of streams, specific flows typically found in industrial steam networks should be discussed.

3.3.1. Deaerator

A deaerator is found in any boiler house system. It is used to remove non-condensable gases such as oxygen and carbon dioxide from boiler feed water, preventing corrosion issues. Steam is injected in the deaerator for both heating and partial pressure reduction purposes, due to water make-up and condensates return containing dissolved gases.

3.3.2. Letdowns and turbines

Steam can be transported between the different steam headers via letdowns or steam turbines.

In the first case steam goes from a higher to a lower pressure through an isenthalpic transformation, (without producing any mechanical power). Water injection brings the resulting superheated steam to the steam header properties. Letdowns are not visible in TSA since they are not directly linked to a process requirement. Their locations and steam mass flows should however be noted since they correspond to cogeneration potential.

When high-pressure steam flows through back-pressure and condensing steam turbines, electricity is cogenerated. Although TSA focuses on heat exchanges, the cogenerated power and isentropic efficiencies of turbines should be noted, as it can be the subject of thermo-economic optimisation.

3.3.3. Intermediate utility systems

Intermediate utility systems are sometimes used to supply heating and cooling demands of process streams. In these situations it is important to evaluate their necessity. If intermediate utility systems cannot be modified or removed due to specific constraints (security, equipment limitations), the process requirement is seen as a black box and represented by the intermediate utility stream. Otherwise, the stream is defined according to the process needs.

3.4. Graphical representations

Once the classification and characterisation steps are carried out, the temperature-enthalpy profile of each stream can be represented graphically, depending on the heat exchange type. Several typical heat exchanges identified in chemical and petrochemical sites are detailed below.

3.4.1. Hot and cold utilities

Hot utilities can be produced in conversion units (e.g boilers, cogeneration units) or from process heat. Common hot utilities on industrial sites are steam, hot oil and hot water. Fig. 1 shows the temperature-enthalpy profiles of these heat transfer fluids.

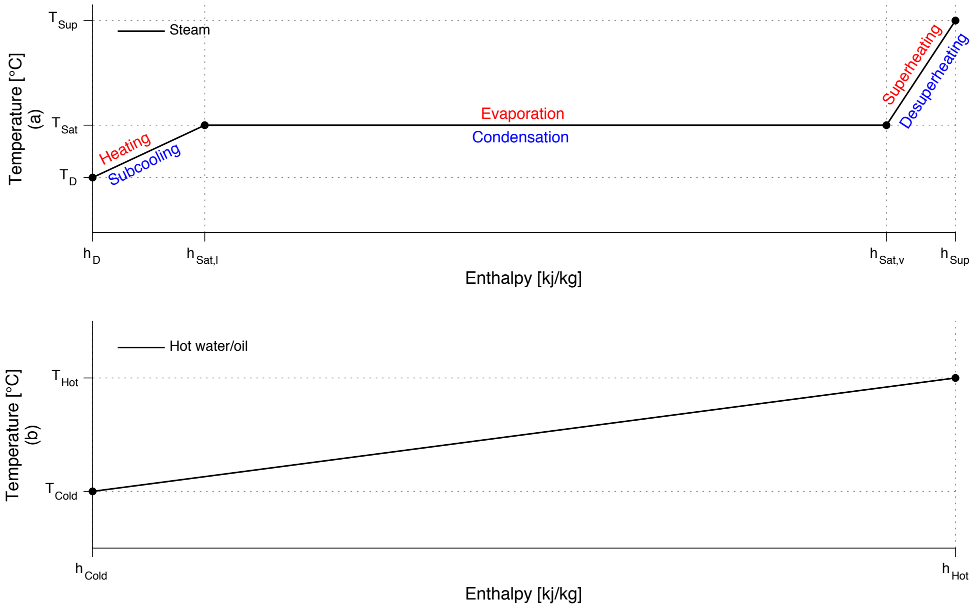

Fig. 1. Modelling of superheated steam (a) and hot oil/water (b) streams

In the upper graph (a) the lowest temperature T_D is the desuperheating temperature. It corresponds to the condensate temperature in case of condensation and to the deaerator or demineralised water temperature in case of evaporation. The thermal capacity of water and steam is assumed to be constant outside the phase change. In the lower graph (b) a hot oil or hot water stream is represented. Oil or water can be heated or cooled between their hot T_{hot} and cold T_{cold} temperatures and the thermal capacities of both fluids are assumed to be constant.

As steam is the most common energy vector, it is used as the heat transfer fluid for the following representations.

3.4.2. Single-phase process streams

When a process stream is heated up or cooled down without undergoing phase transition, the thermal capacity is assumed to be constant throughout the heat transfer. The stream is then represented by a straight line from its initial to final temperature, respectively $T_{p,in}$ and $T_{p,out}$, of an horizontal magnitude equal to the load of the heat exchange.

3.4.3. Phase-change heaters and reboilers

Fig. 2 shows the temperature-enthalpy profile for the evaporation of a single component process stream. Multi component process streams are modelled using TBPs as seen in Fig. 3.

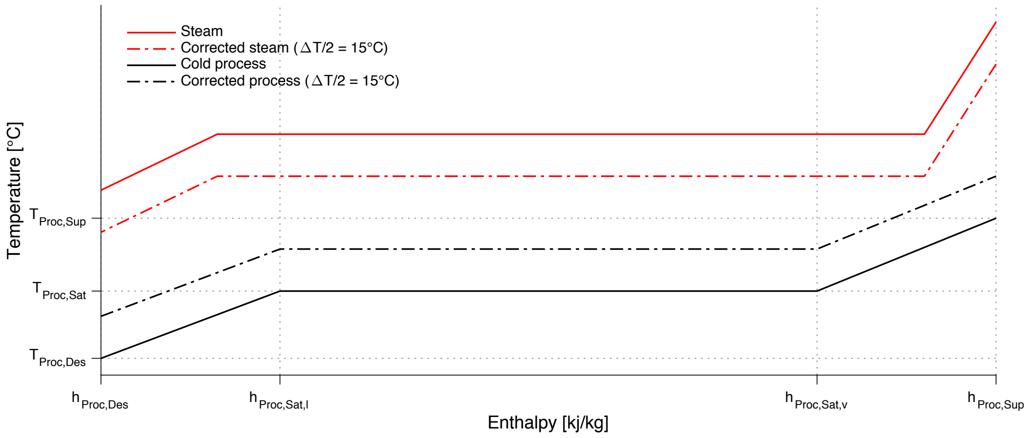

Fig. 2. Modelling of single component process evaporation by superheated steam

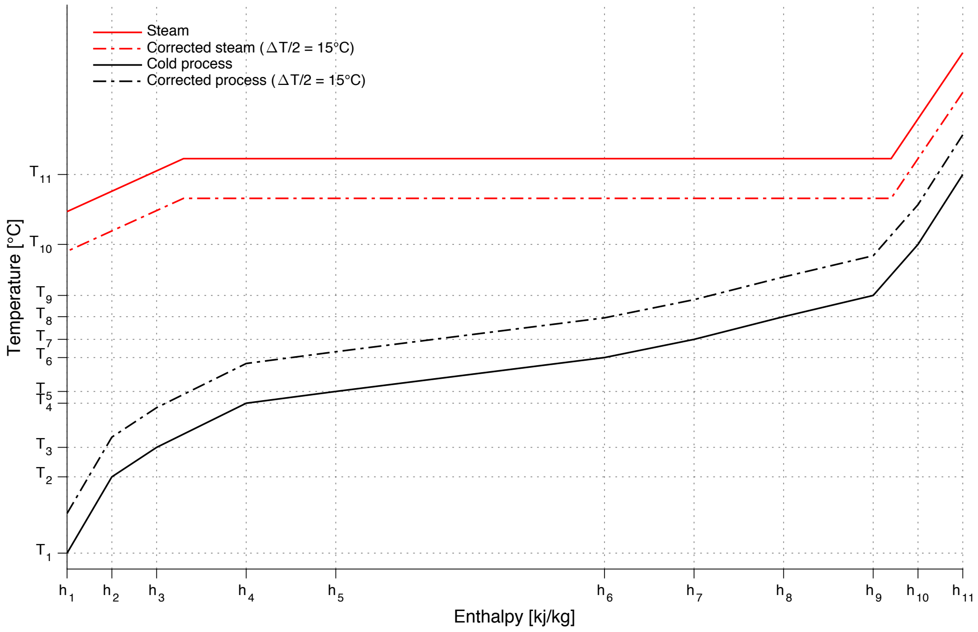

Fig. 3. Modelling of multi components process evaporation by superheated steam

The straight and dotted line respectively correspond to real and corrected streams temperatures. Corrected temperatures are obtained by increasing initial and final temperatures of cold streams by

$\Delta T_{min}/2$ and decreasing the temperatures of hot streams by $\Delta T_{min}/2$, ensuring the feasibility of the heat exchange with respect to the minimum temperature difference constraint. This description is valid for Fig. 2 to Fig. 11 as well as the fact that only counter-current heat exchangers are considered in the graphical representations.

3.4.4. Phase-change coolers and condensers

Fig. 4 shows the temperature-enthalpy profile for the condensation of a single component process stream. Multi component process streams are modelled using TBPs as seen in Fig. 5. Both air and water-cooling streams are represented between their operating temperatures.

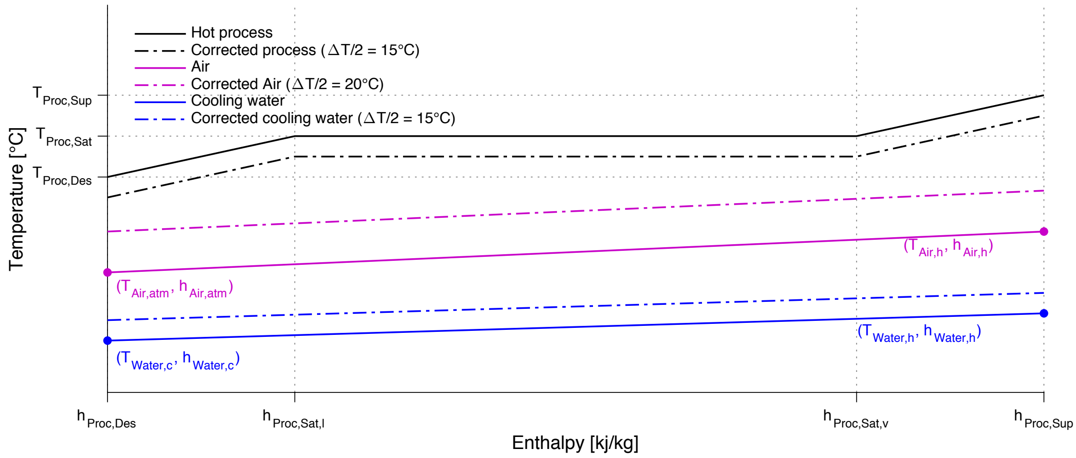

Fig. 4. Modelling of single phase process condensation by air or cooling water

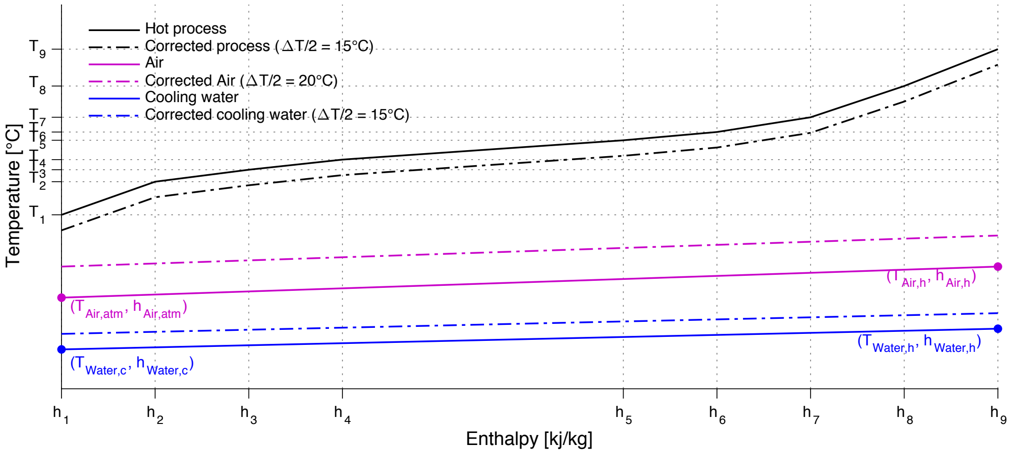

Fig. 5. Modelling of multi phase process condensation by air or cooling water

3.4.5. Injections

The main requirement of steam injection is to reduce the partial pressure of the process stream, enabling the separation of the most volatile components.

The process requirement corresponds to a pressure requirement, which is represented by the production of steam at the minimum pressure permitted by the system from the deaerator (or demineralised water) temperature.

Steam injections are directly responsible for water make up (no condensates return), inducing a heating requirement located in the deaerator. The graphical representation of the deaerator steam injection requirement is similar to the one in Fig. 6 except that the initial temperature is the make-up temperature.

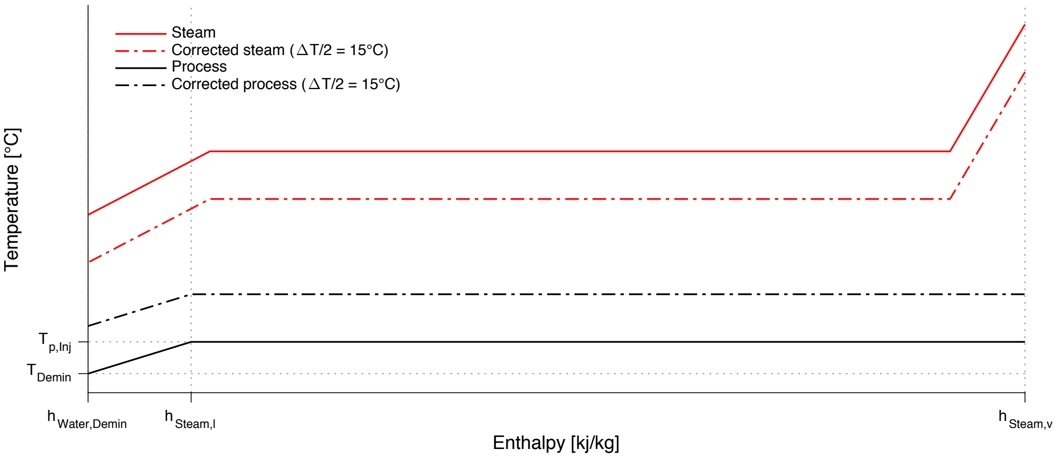

Fig. 6. *Modelling of steam injection*

3.4.6. Tracing/storage

Steam tracing or storage requirement is defined as a heat supply to process streams at constant temperature T_{fluid}.

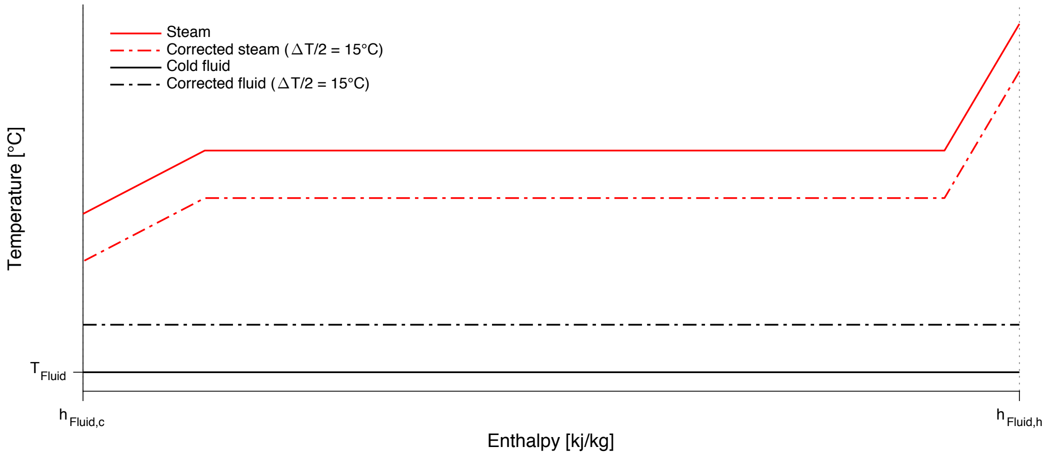

Fig. 7. Modelling of steam tracing and storage

3.4.7. Losses

Mass and heat losses illustrate the utility system inefficiencies. A straight line at the ambient temperature represents losses, as in reality the hot utility is consumed to heat up the environment.

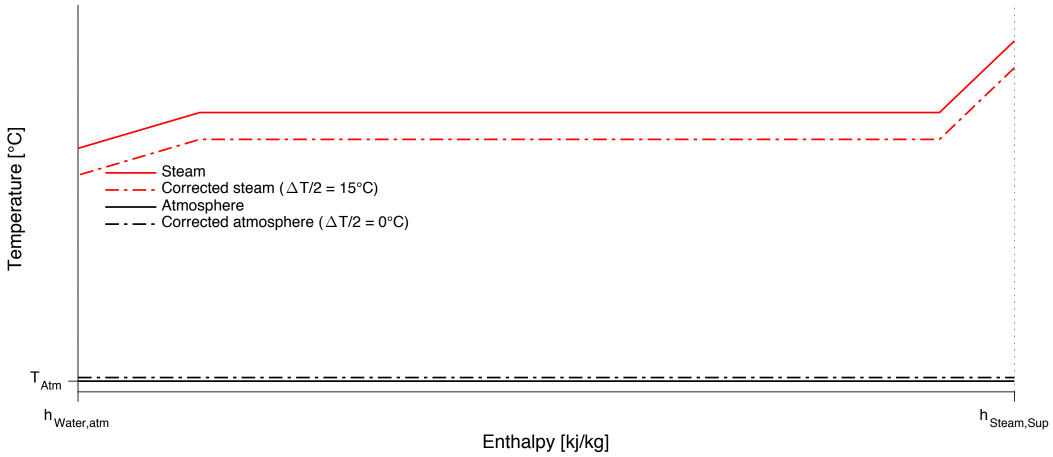

Fig. 8. Modelling of steam losses (leaks and traps)

3.4.8. Steam production

3.4.8.1. Conversion units

Generally, conversion units such as boilers or cogeneration devices produce superheated steam at the highest required pressure. Fig. 9 shows the resulting temperature-enthalpy profiles in the case of a boiler. Demineralised water is preheated, evaporated and superheated. The combustion heat is transferred via both radiation and convection. Fumes are sent to the chimney at T_{fumes}.

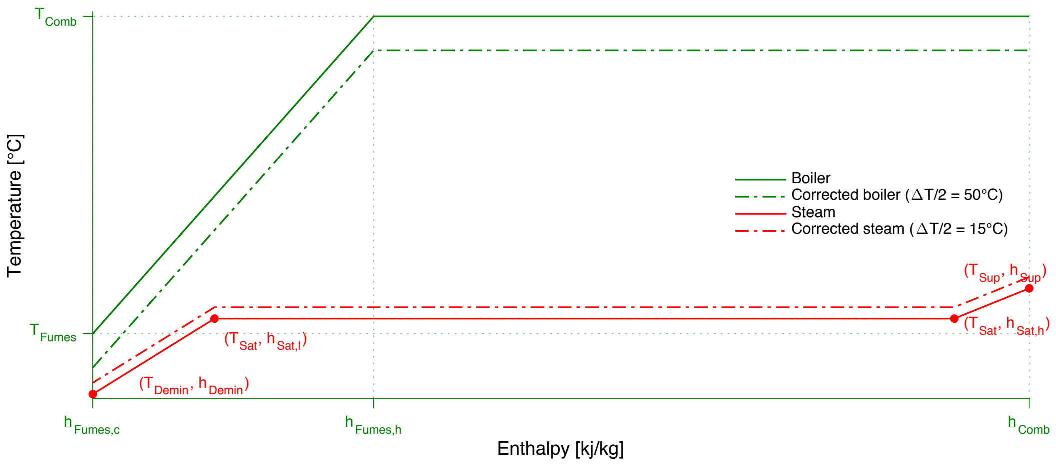

Fig. 9. Modelling of superheated steam generation in boilers

3.4.8.2. Exothermic reactions

When an exothermic reaction generates heat at relatively high temperature, saturated steam can be produced. Fig. 10 represents the steam production of a process stream with a constant heat capacity. Usually demineralised water is used under the same conditions as boiler feed water.

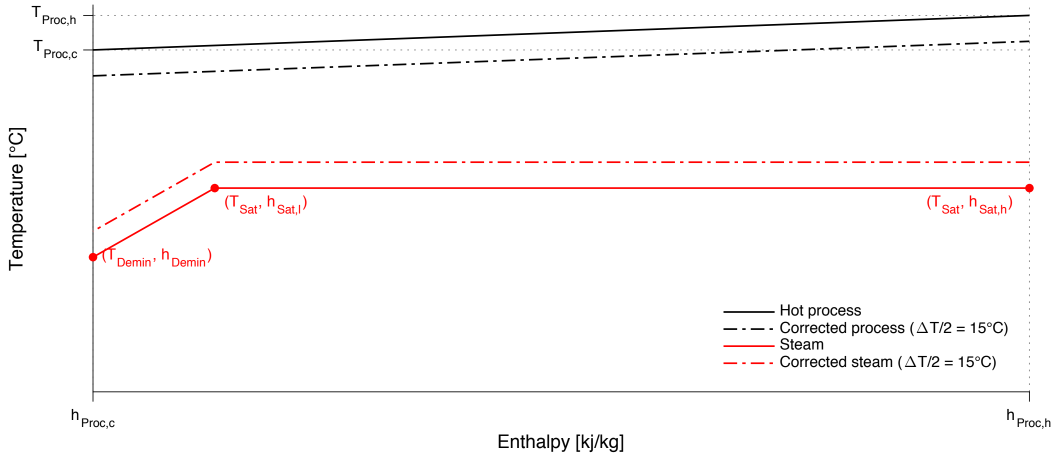

Fig. 10. Modelling of saturated steam generation by a process with constant thermal capacity

3.4.9. Turbines

Cogenerated mechanical power via steam turbines is not represented in total site composite curves, TSA being focused on thermal power.

A schematic representation of electricity generation from the conversion of high pressure (HP) to low pressure (LP) steam is shown on Fig. 11. HP steam enters the turbine in superheated state $h_{Sup,HP}$ and exits either in superheated (Fig. 11) or saturated state at a lower pressure, depending on the pressure differential, the thermodynamic properties of the HP steam and the turbine isentropic efficiency. The cogenerated electrical power is the difference between inlet and outlet steam enthalpies and can be read on the horizontal axis. The green dotted line represents the level of superheating of the HP steam while solid lines show the pressure differential via condensation temperatures.

The two steam streams are not represented simultaneously in the curves, as it would result in double accounting. Only the lower pressure steam should appear if directly supplied to end-use consumers. It is however of high interest to include the cogenerated power in steam turbines since it influences the steam network efficiency, gives a better picture of the overall energy consumption of a site and can be subject to thermo-economic optimisation.

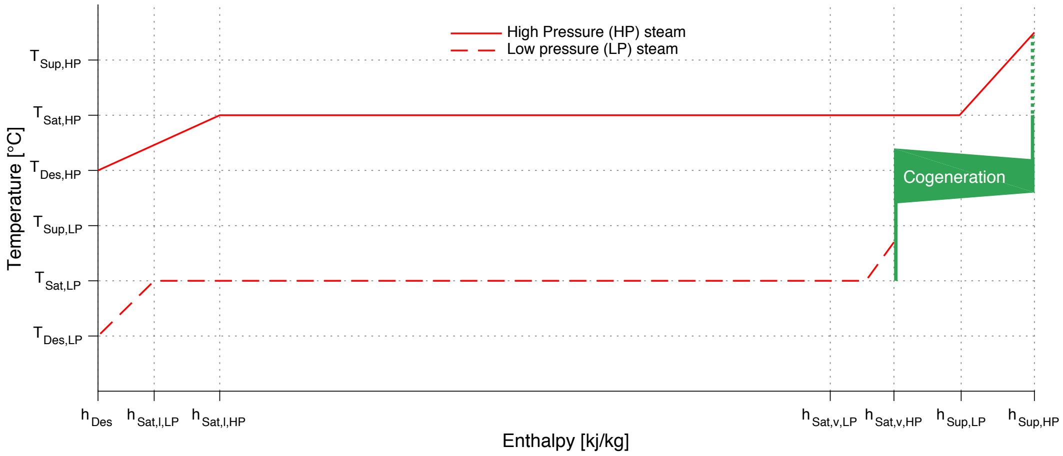

Fig. 11. Schematic of mechanical power conversion

4. Key points & Outlook

A methodology for data collection in Total Site Analyses has been proposed, providing support to practical applications of energy optimisation studies at large industrial sites or clusters. TSA targets the highest degree of complexity for energy saving opportunities, mostly involving modification of the existing processes and utilities configurations. However, a comprehensive study of all utility consumers facilitates the identification of other opportunities, eg linked to best practices, maintenance actions and operation control.

In this paper data collection has been divided in three interconnected steps to properly establish the list of streams in process industry: classification, characterisation and graphical representation.

Depending on the end-user utility consumption type as well as the data availability and accessibility, a specific data set to collect and a calculation strategy has been proposed in order to determine the load of the heat exchange as quickly and efficiently as possible. Once process streams are characterised together with the corresponding utility streams, a next step is the generation of the total site composite curves. To this end graphical representations of the different types of heat flows have been proposed. As a result the hot and cold composite curves corresponding to the process cooling and heating requirements can be obtained and represented together with the actual utility supply.

The presented methodology complements existing works on TSA applications. It focuses on a systematic approach for data collection and streams definition, reducing the complexity and duration of these steps. Industry can use it as a direct support to energy integration studies.

More generally, the paper also introduces the interest of carrying out TSA in the framework of energy auditing and energy management systems. Indeed the systematic approach to identify and characterise utility consumers enters directly into the energy review process. From a research point of view it invites to further investigate how far TSA and energy review methodologies can be linked, in view of maximising and optimising the outputs of energy integration studies for energy auditing of energy management purposes.

Nomenclature

Abbreviations

EED	Energy Efficiency Directive
EnMS	Energy management system
LP	Low pressure
HP	High pressure
TBP	True boiling point
TSA	Total site analysis

Letter symbols

h	enthalpy, kJ/kg
P	pressure, bar
$\dot{Q}$	heat load, kW
T	temperature, °C
X	reaction conversion

Subscripts and superscripts

$cond$	condensation
$evap$	evaporation
p	process
sat	saturated
sup	superheated
u	utility
v	vapour

References

[1] European Comission, 2050 Energy Strategy. Available at:< https://ec.europa.eu/energy/en/topics/energy-strategy/2050-energy-strategy> [accessed 10.1.2016].

[2] European Comission, 2030 Energy Strategy. Available at: < http://ec.europa.eu/energy/en/topics/energy-strategy/2030-energy-strategy> [accessed 10.1.2016].

[3] European Comission, 2020 climate & energy package. Available at: < http://ec.europa.eu/clima/policies/strategies/2020/index_en.htm> [accessed 10.1.2016].

[4] European Directive 2012/27/EU on Energy Efficiency, Official Journal of the European Union, 14.11.2012.

[5] International Organization for Standardization. ISO 50001:2011 – Energy management system.

[6] Bungener S., Data reconciliation of steam networks in refineries and petrochemical sites. Lausanne, Switzerland: Ecole Polytechnique Fédérale de Lausanne, Industrial Process and Energy Systems Engineering; 2015. Technical report No.: EPFL-REPORT-215087.

[7] European Commission. Reference document on best available techniques for energy efficiency. Integrated Pollution Prevention and Control (IPPC), February 2009.

[8] Energy-related best practices: a sourcebook for the chemical industry. Iowa State University; 2005.

[9] Pouransari N., Bocquenet G., Maréchal F., Site-scale process integration and utility optimization with multi-level energy requirement definition. Energy Conversion and Management 2014;85:774-783.

[10] Ren Tao., Barriers and drivers for process innovation in the petrochemical industry: A case study. Journal of Engineering and Technology Management 2009;26:285-304.

[11] Brown D., Maréchal F., Paris J., A dual representation for targeting process retrofit, application to a pulp and paper process. Applied Thermal Engineering 2005;25:1067-1082.

[12] Dhole V. R., & Linnhoff B., Total site targets for fuel, co-generation, emissions, and cooling. Computers & chemical engineering 1993;17:101-109.

[13] Raissi K., Total site integration [dissertation]. Manchester, UK: The University of Manchester; 1994

[14] Hui C. W., Ahmad S., Total site heat integration using the utility system. Computers & chemical engineering 1994;18(8):729-742.

[15] Klemeš J, Dhole V, Raissi K, Perry S, Puigjaner L., Targeting and design methodology for reduction of fuel, power and CO2 on total sites. Applied Thermal Eng 1997;17(8):993–1003.

[16] Marechal F., & Kalitventzeff B., Targeting the integration of multi-period utility systems for site scale process integration. Applied Thermal Engineering 2003;23(14):1763-1784.

[17] Bungener S., Hackl R., Van Eetvelde G., Harvey S., Maréchal F., Multi-period analysis of heat integration measures in industrial clusters. Energy 2015;93:220-234.

[18] Becker H., & Maréchal F., Energy integration of industrial sites with heat exchange restrictions. Computers & Chemical Engineering 2012;37:104-118.

[19] Pouransari N., Maréchal F., Energy integration of large-scale industrial sites with target-compatible sub-system division strategy, Chemical Engineering Transactions 2014;39:43-48.

[20] Bagajewicz M, Rodera H. Energy savings in the total site heat integration across many plants. Comput Chem Eng 2000;24(2):1237–42.

[21] Bandyopadhyay S, Varghese J, Bansal V. Targeting for cogeneration potential through total site integration. Applied Thermal Engineering 2010;30(1):6–14.

[22] Wang Y., Wang W., Feng X., Heat integration across plants considering distance factor, Chemical Engineering Transactions 2013;35:25-30.

[23] Perry S. Total site methodology. Handbook of process integration (PI); minimisation of energy and water use, waste and emissions. Cambridge, UK: Woodhead Publishing; 2013. p. 201e24.

[24] Varbanov PS. Extending total site methodology to address varying energy supply and demand. Handbook of process integration (PI): minimisation of energy and water use, waste and emissions. Cambridge, UK: Woodhead Publishing; 2013. p. 226e60.

[25] Matsuda K., Hirochi Y., Tatsumi H., Shire T., Applying heat integration total site based pinch technology to a large industrial area in Japan to further improve performance of highly efficient process plants. Energy 2009;34(10):1687-1692.

[26] Matsuda K., Tanaka S., Endou M., Iiyoshi T., Energy saving study on a large steel plant by total site based pinch technology. Applied Thermal Engineering 2012;43:14-19.

[27] 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: 4609-4615.

[28] March L., The methodology and benefits of total site pinch analysis. Linnhoff March Energy; 2000. Available at: <http://www.environmental-expert.com/articles/the-methodology-and-benefits-of-total-site-pinch-analysis-2957> [accessed 21.1.2016].

[29] Aspen suite software. <https://www.aspentech.com/>

[30] Belsim Vali software. <http://www.belsim.com/>

[31] Poling B. E., Prausnitz J. M., O'Connell J., The properties of gases and liquids. McGraw-Hill Professional; 2000.

[32] Smith R. L., Watson K. M., Boiling points and critical properties of hydrocarbons. Industrial and Engineering Chemistry 1937;29(12):1408-1414.

[33] Kreider J. F., Rabl A. Heating and cooling of buildings. New York: McGraw-Hill; 1994.