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Implementing Energy Efficiency Measures in Industrial Clusters – A Design Approach for Site-Wide Heat Recovery Systems

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Heat integration between chemical production facilities in an industrial cluster provides significant cost savings opportunities. While single chemical processes are often well integrated, site-wide heat integration based on Total Site Analysis (TSA) tools often identifies opportunities to further increase energy efficiency. However, further development of the TSA methodology is required to improve its applicability for identifying practical heat integration measures and providing key information for investment decision makers. The design of common site-wide heat recovery systems in an industrial cluster is a complex task in which a large number of aspects other than thermal process and utility flows must be considered. This paper presents a procedure for identifying site-wide heat recovery measures based on TSA. The proposed approach is illustrated for a chemical cluster located on the West Coast of Sweden, showing feasible site-wide heat recovery systems achieving up to 42 % of the maximum total site heat recovery target of 129 MW. A number of systems are suggested ranging from low complexity achieving a minor share of the heat recovery potential to complex, strongly interdependent systems demanding large investments and a high level of collaboration. Estimated pay-back periods for the proposed systems range from 3.2 to 4.2 years, while up to approx. 12 % of the cluster's CO_2 emissions can be avoided.

1. Introduction

Fuel savings associated with energy efficiency (EE) measures may well exceed oil fuel usage by 2035 (IEA, 2013). EE is considered the only "fuel" that meets economic, energy security and environmental objectives at the same time. Tapping this potential resource requires large investments in new equipment and design of EE systems. The process industry is a large consumer of primary energy. Modern, single processing plants are often well integrated, while Total Site Heat Integration (TSHI) within industrial clusters still offers considerable primary energy savings potential. Different barriers for implementation of TSHI measures have been identified which cannot be addressed by a purely thermo-economic approach (Chew et al., 2013). Therefore it is often best to identify a number of heat recovery systems in order to be able to accommodate additional requirements such as operability, space availability, safety and cross-company collaboration.

TSA is often used to target heat savings and other energy efficiency improvements via existing utility systems. Industrial clusters lacking common utility infrastructure are not dealt with in detail. Identification, design and evaluation of common heat recovery systems is a complex task. In addition to thermal streams in the processes and utility systems, it is also necessary to consider other aspects such as ownership structure, business strategies, space availability, plant safety, minimum boiler loads, by-product combustion, geographic location of the plants to each other, existing inter-company pipe racks, existing capacity for co-generation, etc.

This paper presents further development of the Total Site Analysis (TSA) methodology towards a holistic approach to target and design practical heat recovery systems. The methodology offers a high degree of freedom in the design of common site-wide heat recovery systems in order to address the barriers

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discussed above related to joint investments in heat recovery infrastructure. A step-wise, bottom-up design procedure is presented and applied to a chemical cluster.

TSA was first introduced by Dhole and Linnhoff (1993) and thereafter extended substantially. Recent overviews of the methodology are presented by Perry (2013) and Varbanov (2013). An overview of barriers and other factors affecting implementation of TSHI measures is presented by Chew et al. (2013). These include issues related to design (e.g. plant layout and fluid characteristics), operation (e.g. different plant operating scenarios and start-up/shutdown), reliability/availability/maintenance (e.g. fouling and leakage) and regulations (e.g. policies and regulations promoting EE). In addition to technical plant related barriers, Walsh and Thornley (2012) discuss financial, market, and strategic barriers. The present work is based on a previous study by the authors (Hackl et al., 2011), in which opportunities for site-wide heat integration throughout an existing chemical cluster were investigated.

The chemical cluster used as a case study in this paper is located in Stenungsund on the West Coast of Sweden, and is Sweden's largest agglomeration of its kind. The cluster consists of 6 process sites within an area of approx. 11 km^2, which produce a variety of products including amines, surfactants, air products, olefins, polyethylene and other speciality chemicals. The cluster is a substantial consumer of fossil fuels and feedstock and a major emitter of CO_2 (on-site CO_2 emissions approx. 900 kt/y). Currently the cluster consumes approx. 122 MW of hot utility produced in boilers for process heating. The exchange of energy flows across the companies' borders is very limited. Previous studies have shown a large potential for site-wide heat integration, which theoretically eliminates the cluster's demand for utility steam currently produced in boilers.

2. Methodology

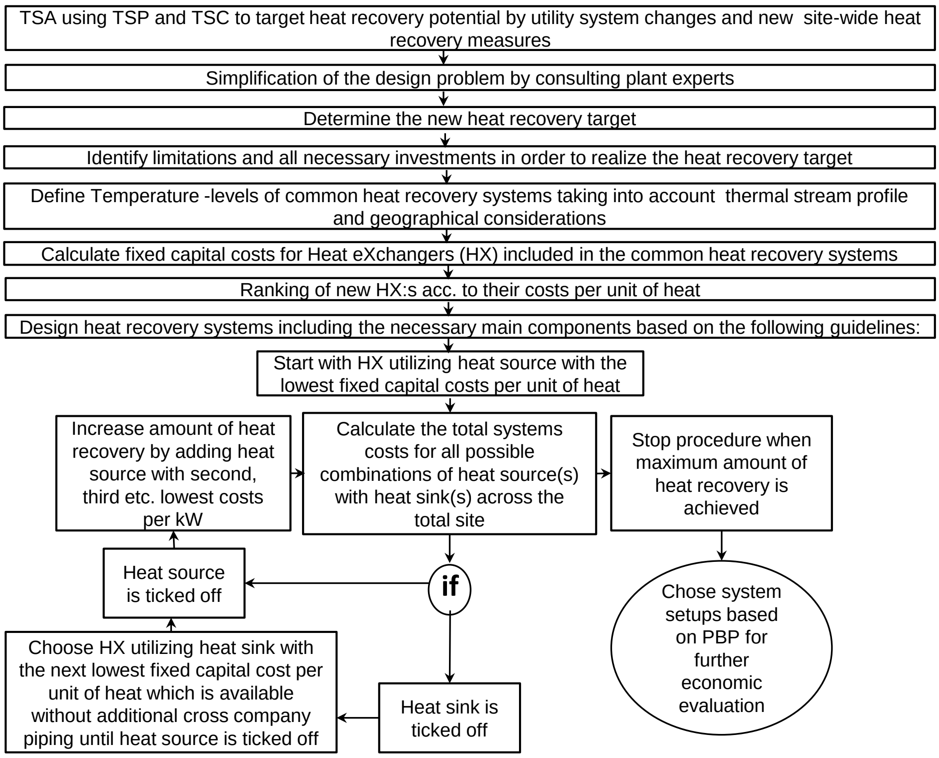

Figure 1: Illustration of the overall design procedure

Figure 1 provides an overview of the overall site-wide heat recovery systems design procedure based on Total Site Analysis (TSA), where Total Site Profiles (TSP) and Total Site Composites (TSC) are applied to target the minimum energy requirement (MER) for an industrial cluster in which unrestricted heat exchange between process plants is assumed via the utility system. Thereafter, it is important to determine a practical reduced heat recovery target based on input from plant experts.

Investments costs for the different heat recovery systems are estimated using standard procedures and by gathering plant specific process and cost data, such as process stream composition, current Heat eXchanger (HX) materials, pressure/temperature levels, distances between the plants, flow rates, site

specific investment cost data etc. The different cost items and associated assumptions and literature references are presented in *Table 1*. A more detailed description of how cost estimation is performed is presented in a report by the authors (Hackl and Harvey, 2013).
Pay-back period (PBP) is used to screen promising designs. The Net Present Value (NPV) is calculated for selected designs, Eq(1). *Table 2* shows data for the economic evaluation. CO_2 emissions reduction is estimated for each design assuming that increased heat recovery leads to reduced firing of natural gas in utility boilers (life cycle CO_2 emissions 217 kg/MWh). CO_2 emissions associated with avoided/additional pump electric power usage are accounted for assuming natural gas combined cycle as power producer.

$$NPV = \sum_{n=1}^{n=t} \frac{CF_n}{(1+i)^n} \tag{1}$$

where,
CF_n = Cash Flow in year *n*, *e.g.* $CF_0 = -{Costs_{Inv}}/{2}$, $CF_1 = -{Costs_{Inv}}/{2} - Costs_{operation} + \mathrm{Re}venues_{fuel/CW\ savings}$,
$CF_2 = -Costs_{Operation} + \mathrm{Re}venues_{fuel/CW\ savings}$, etc.

3. Case study results

3.1 TSA, simplification of the design problem, practical limitations and necessary investments

A previous TSA study of the cluster (Hackl et al., 2011) indicated that the cluster's demand of external hot utility can be eliminated by extensive TSHI ($Q_{rec,target}$=129 MW). *Figure 2* illustrates the necessary adjustments to the utility systems throughout the cluster in order to achieve this target. The key heat recovery measure found by TSA is the introduction of a hot water (HW) circuit recovering and distributing 96 MW of excess process heat across the cluster and increased recovery of 33 MW LP-steam. Other required measures are adjustments to the levels at which steam is recovered and used in the processes.

Table 1: Cost functions and additional data for estimating heat recovery systems investment costs

Equipment	Reference	Main assumptions and inputs
Heat exchangers	(Smith, 2005); (CHE, 2012)	HX area estimated based (Sinnott and Towler, 2009), U-value estimated based on current process fluid and suggested utility, estimated HX area is increased by 25 % to allow for peak loads; current process pressure, temperature and materials assumed, CEPCI used to update to year 2012, Lang factor of 3.6
Hot water piping	(Nordenswan, 2007); (CHE, 2012)	Cost estimation for Swedish district heating pipes per length depending on diameter; standard piping diameter estimated based on estimated flow rates, costs for piping in "urban environment" assumed, plant distance estimated from maps; CEPCI used to update to year 2012
Steam and condensate piping	(Ulrich and Vasudevan, 2006); (CHE, 2012)	Standard piping diameter for steam and condensate pipes estimated based on steam flow rate, insulation cost estimated based on expert discussions, factors for contingencies, fees, site development and off-site costs from (Ulrich and Vasudevan, 2006), CEPCI used to update to year 2012
Hot water pumps	(Smith, 2005); (CHE, 2012)	Pump power estimate as 2 % of total heat savings ; HW at below 100 ºC and moderate pressure → no additional material, pressure and temperature factors apply, base year 2007, Lang factor of 3.6
Fuel pipes	Company expertise	Costs estimated based on plant internal cost data

Table 2: Data for economic evaluation

Economic life time	15 y*
Interest rate, i	11 %*
HP steam price	400 SEK/MWh**
Electricity price	600 SEK/MWh***
Maintenance+Operation	2 % of total fixed capital, HW pump power; 2 % of total heat savings
Additional operation cost savings	CW pumping; 2.5 % of CW savings

*Acc. company standards.
**Steam produced from natural gas in boilers (η_{boiler}=0.9), natural gas import price Europe 2020 (IEA, 2013) = 292 SEK/MWh_{LHV}, distribution cost 12 %, tax 25 SEK/MWh_{LHV}, CO_2 cost 44 SEK/t
***Expected price acc. to plant energy experts.

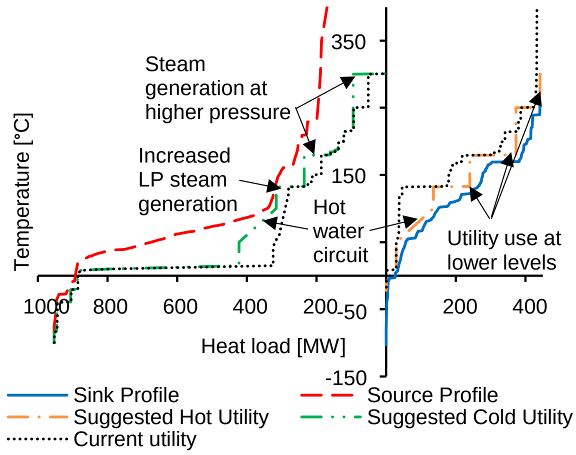

Figure 2: Suggested changes to the clusters utility systems based on TSP (Hackl et al., 2011)

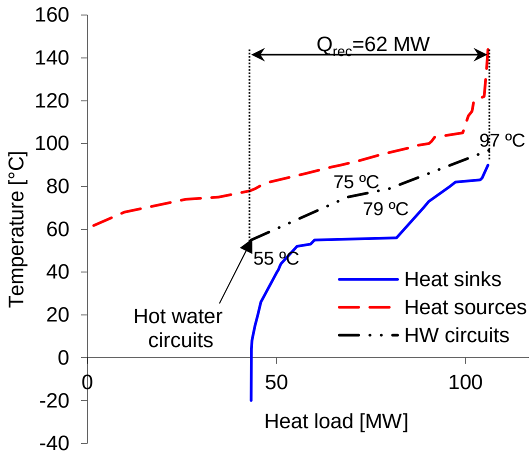

Figure 3: Heat sources/sinks available for TSHI; HW circuits transferring heat

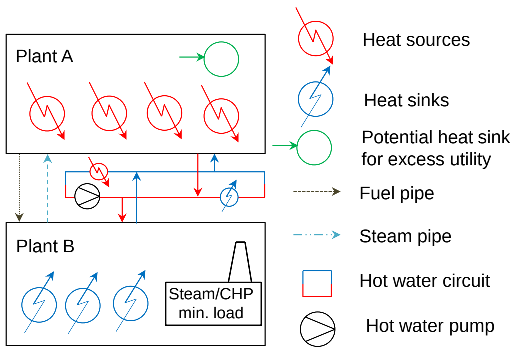

Figure 4: Illustration of all components necessary for implementing a common site-wide heat recovery system

The actual availability of all process streams affected by the modifications indicated in *Figure 2* was discussed with energy and process experts at the different plants. Increased recovery of LP steam was not considered a feasible opportunity. *Figure 3* shows the hot and cold composite curves of process streams that were considered available for delivering/using heat from common HW circuits. The figure also indicates the temperature levels of HW circuits which can be used to transfer process heat across the different plants. It can be seen that there is more process heat available in the hot streams than there is demand. This gives an additional degree of freedom in choosing heat sources to the HW systems and also enables for heat loss compensation by adding more process heat. Due to geographical constraints two HW circuits are suggested (55–79 ºC and 75–97 ºC). As indicated in *Figure 3* the new site-wide heat recovery target is 62 MW, compared to 129 MW in the initial TSA study.

Practical limitations and necessary investments associated with the new heat recovery target are illustrated in *Figure 4* and described below.

Practical limitations:

- In order to achieve primary energy savings it is necessary that recovered heat replaces utilities which are generated by fuel combustion in boilers → utility replaced by recovered heat, which doesn't directly decrease the fuel demand must be redistributed to a plant where it can replace boiler utility.
- The demand for excess hot utilities can additionally be increased by replacing HX:s that use unnecessarily hot utility from a boiler by HX:s utilising excess hot utility.
- Once demand for excess utility is met at all plants, further heat recovery does not lead to primary energy savings; in this case maximum demand of excess utility is 53.8 MW.
- By-products that have to be incinerated must be redistributed if boiler steam demand falls below a certain level as a result of heat recovery, preferably to a plant with existing co-generation potential.
- 10 % heat losses in the HW circuits are compensated for by adding process heat (Tyndall Centre, 2010).
- HW piping is assumed to collect and distribute HW in parallel.

<u>Necessary investments:</u>

- HX:s delivering heat (heat sources) to a common HW system.
- HX:s receiving heat (heat sinks) from a common HW system.
- Back-up HX:s supplying and extracting heat to and from the HW circuit.
- HW pipe circuit between the different plants to transfer heat.
- Steam piping between the plants to transfer excess steam between plants.
- Fuel piping to transfer excess by-product fuel between the plants.
- New HX:s that can utilise excess hot utility created when process heat recovery is increased and utility generation cannot be regulated directly by decreasing boiler load.
- HW pumps.

3.2 Screening for site-wide heat recovery systems

Figure 5 shows estimated PBP for a number of heat recovery systems identified applying the procedure illustrated in *Figure 1*. As there is almost no existing common utility infrastructure within the cluster, large investments are necessary. The fixed costs for this infrastructure are rather high, which explains why PBP drops rapidly from approx. 7.6 to around 3.2 y when increasing the amount of heat recovery from 1.4 to 20.7 MW. Thereafter PBP is rather stable when the amount of heat recovery is increased further. A sudden increase in PBP occurs above 23.8 MW of heat recovery, because it is necessary to invest in a fuel pipe between Plant F and Plant D (see label in *Figure 5*). Thereafter the estimated PBP is relatively constant at around 4 y with a minimum (3.7 y) at 30.6 MW of heat recovery. After that PBP increases slightly up to 4.2 y for recovery of 53.8 MW of heat, due to the increased complexity of the systems.
Once a certain threshold of heat recovery is reached, HX:s that currently use MP or HP steam have to be converted to use LP steam in order to increase the demand for excess LP steam. Above 40.3 MW of heat recovery, the demand for low pressure steam at plant F is met and an additional steam pipe between the Plant D and Plant E is required. A number of promising heat recovery systems (System 20, System 30, System 40, System 50 and System 54) are marked in *Figure 5*. The numbering reflects the amount of heat recovered. These systems were investigated in more detail with respect to economic performance and CO_2 emissions reduction potential. An example of the final design of such a system is given in *Figure 6*, showing System 54 with all new heat exchangers, new inter-company piping, heat flows and other design considerations.

3.3 Economic evaluation

Table 3 presents important results of the economic evaluation, and the CO_2 emissions reduction achieved by the selected heat recovery systems as input for decision makers. It can be seen that despite the lower

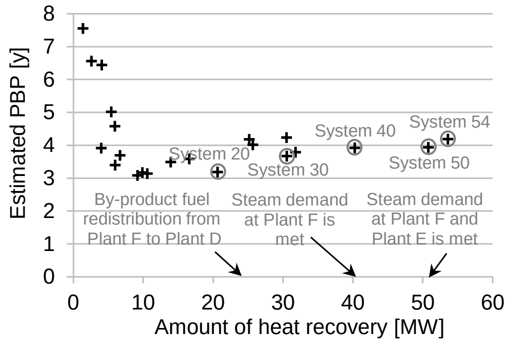

Figure 5: PBP of different heat recovery systems

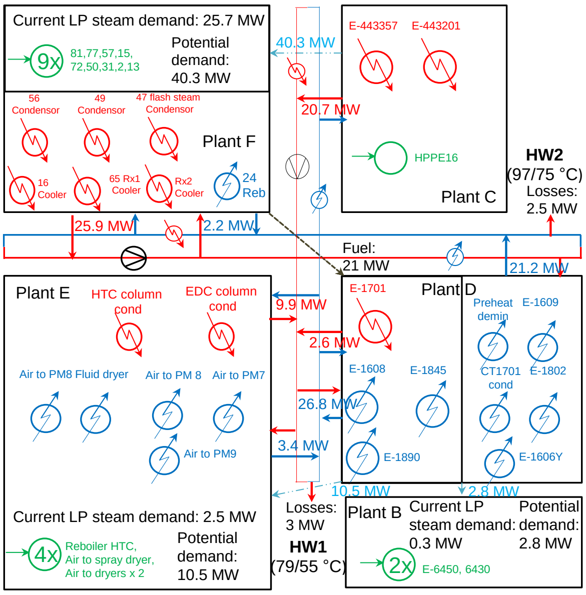

Figure 6: Example of a heat recovery system (System 54) as a result of the suggested methodology; legend see Figure 4

risk (lower PBP) and complexity (less companies involved, less interdependencies) of projects achieving lower heat recovery, they also show a significantly lower NPV_{15} and therefore are less profitable in the long run. The decision in which project to invest has to be based on the companies' short and long term strategies and their ambitions to decrease CO_2 emissions.

Table 3: Economic performance and CO_2 emissions reduction of site-wide heat recovery systems.

TSHI system	Heat savings [MW]	Total investment [MSEK]	No. of collaborating companies	PBP [y]	NPV_{15} [MSEK]	Avoided CO_2 [kt/y]	% of total cluster CO_2
System 20	20.7	199	2	3.2	261	41	4.6
System 30	30.6	336	2	3.7	341	61	6.8
System 40	40.3	472	2	3.9	419	80	8.9
System 50	50.8	597	3	3.9	523	101	11.3
System 54	53.6	667	4	4.2	513	107	11.9

4. Concluding discussion

In order to identify practical site-wide heat recovery systems based on TSA, it is important to account for other issues than optimal heat integration based on thermal streams. Decreasing the heat recovery target from maximum recovery to a more realistic target in collaboration with plant staff was found very important in order to catch the participating companies' attention. The procedure presented in this paper proved useful in order to design different site-wide heat recovery systems with consideration to practical issues and evaluate them. The case study presented shows the ability of the suggested methodology in identifying a number of TSHI measures that achieve various levels of the heat integration target.

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