ENERGY SAVINGS OF INTERCOMPANY HEAT INTEGRATION - A METHODOLOGICAL FRAMEWORK – PART I

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Abstract:

Background and literature review

Heat or process integration is a technical concept to minimize the cooling and heating requirements of industrial plants. The basic idea behind heat integration is to interconnect processes requiring cold with those requiring heat via a heat exchanger, thus reducing the overall energy demand (Kemp, 2007). The more processes that can be interconnected within a heat exchanger network (HEN), the more savings heat integration can achieve. Thus, it is recommended that production sites featuring more than one factory/production hall set up HENs which extend beyond the individual production halls. An additional concept is to interconnect production sites not belonging to the same company. This concept is called intercompany process or heat integration (Hiete et al., 2012).

Several case studies exist that analyse large production sites or industrial estates and assess the potential energy savings due to HENs. The studies focus mainly on the methodologies of how to analyse total sites. Only a few publications are explicitly dedicated to the field of "intercompany energy integration" and discuss the relevant factors.

The potential energy savings due to intercompany heat integration have not been estimated so far for Germany. This is mainly due to the lack of data. However, it would be useful to have a structured method for estimating the energy saving potentials due to intercompany heat integration beyond case study approaches, especially with regard to policy design to increase the uptake of heat integration and industrial energy demand projections. This paper presents part of a methodological framework to systematically estimate these potentials for regions, which combines methodologies from spatial analysis and heat integration. The focus in this paper is on the methodologies from heat integration and paves the way for another paper dealing with the methodologies from spatial analysis.

Methodology to assess HENs and its practical application

To quantify the energy-saving potentials of intercompany heat integration, it is necessary to have information on the heating and cooling requirements of the affected companies and their respective location. Furthermore, a methodology is needed to assess a possible HEN based on this information. In this paper, we present and apply a methodology for assessing intercompany HENs, a step which represents one major pillar of the overall methodological framework.

First, we describe the methodology applied. Special attention is paid to aspects relevant for intercompany heat integration such as investments in pipes and possible part-load operation.

Second, we apply the model to evaluate a hypothetical case study involving two plants. The initial step here is to validate our model based on thermodynamic considerations. Sensitivity calculations are then carried out to show that the factors relevant for intercompany heat integration are addressed. An extract from the results is given in Figure 1. Optimized HENs were generated for different case scenarios, beginning with a site consisting of one plant, and then for a site consisting of two plants.

- Cases 1 to 4: Cases 1 and 2 represent an optimized HEN for a site with one plant and cases 3 and 4 a site with two plants. HENs based only on energetic considerations are generated in cases 1 and 3. Then investments in heat exchangers are included additionally in cases 2 and 4. Integrating investments makes some configurations economically unfeasible and consequently more waste heat is utilized in cases 1 and 3 than in 2 and 4.
- Cases 5 to 7: HENs are generated for the site with two plants that take into account investments in heat exchangers and additional investments depending on the distances involved (e.g. for pipes). As a result, less waste heat is utilized when compared with case 4. Then we scale up the thermal loads of plant P1 so that again more waste heat is utilized (cf. case 6). Finally, we assume that the up-scaled plant P1 also operates at part-load and consider this when generating an optimized HEN. This results in less waste heat being utilized by the optimal HEN in case 7.

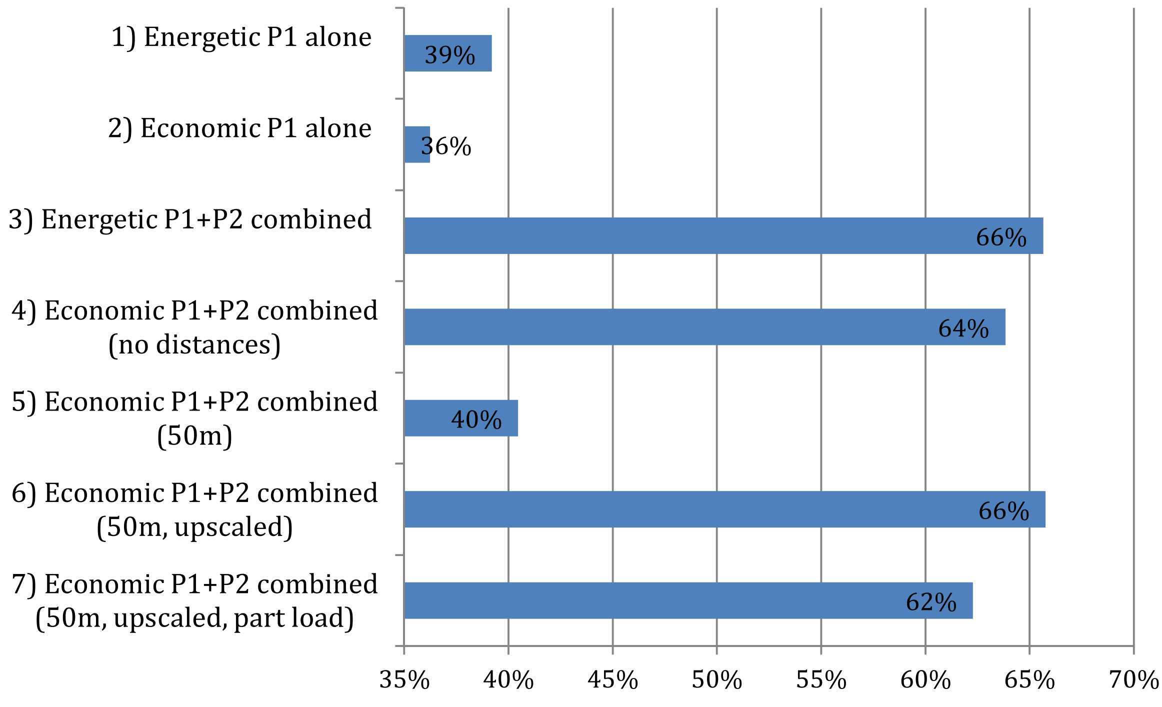


Figure 1 Sensitivity calculations: percentage of waste heat utilized in the HEN per case

Outlook: Methodological framework to estimate energy saving potentials by heat integration

Finally, we present the methodological framework where the model presented before shall interact within.

Keywords: Heat exchanger network, process integration, energy efficiency, industry

1 Background

Increasing energy efficiency in every sector is a major pillar of Germany's energy policy to tackle climate change and increase supply security. Intercompany heat integration is one option to increase energy efficiency in industry. This refers to integrating the heat supply of companies in close spatial proximity to each other. So far, the potential energy savings due to intercompany heat integration have not yet been estimated for Germany. This is mainly due to the lack of data. Thus, it would be useful to have a structured way to estimate the energy-saving potentials due to intercompany heat integration beyond case study approaches, especially with regard to designing policy to increase the uptake of heat integration.

Energy demand models are employed to estimate the possible energy savings due to energy efficiency measures under differing policy scenarios. Currently, they do not address the efficiency option of intercompany heat integration but could be extended by a framework to assess its energy saving potential. Potential energy savings due to intercompany heat integration could then be included in industrial energy demand projections as well.

This paper presents a methodological framework to systematically estimate these potentials for regions, which combines methodologies from spatial analysis and heat integration. The focus in this paper is on the methodologies from heat integration and it paves the way for another paper dealing with the methodologies from spatial analysis.

1.1 Waste heat in the context of policy goals

In Germany, industry accounts for approximately 30% of final energy demand (Rohde, 2013). 75% of this share is used to provide heat, of which 65% is process heat. Thus options to improve the energy efficiency of heat generation in industry are of major relevance for energy policy in Germany.

Waste heat is generated by many industrial processes using process heat. From a technical point of view, waste heat can be described as unwanted heat generated by an industrial process (Pehnt, 2010). From a social point of view, it can be described as heat which is a by-product of industrial processes and currently not utilized, but which could be used for society and industry in the future (Viklund et al., 2014). Pehnt et al. (2011) estimate the waste heat over 140°C for different economic sectors in Germany. With regard to the final energy necessary to generate the appropriate process heat, they estimate waste heat potentials for Germany of between 3% and 40% depending on the sector. The total estimated amount of available waste heat over 140°C corresponds to 12% of industrial final energy consumption. In order to harvest these energy-saving potentials in Germany, the utilization of waste heat is supported by a dedicated funding scheme and accompanying measures are considered within the National Action Plan for Energy Efficiency (BMWi, 2014).

Several measures have to be considered when evaluating the energy-saving potentials of utilizing waste heat (SAENA, 2012). First, measures to eliminate waste heat should be evaluated. If this is not possible, it can be evaluated whether heat recovery measures are energetically and economically feasible.

Heat recovery measures can be applied within or outside the processes generating the waste heat. One example for heat recovery within the process is the use of an economizer in a steam generation system to recover energy from the exhaust gas for pre-heating the feedwater. An example for heat recovery outside the process is using the waste heat from an industrial furnace to heat an office building. Heat recovery applied outside the process can be further differentiated according to whether the measure takes place only inside the company producing the waste heat or also outside the company. An overview of the differentiation of heat recovery measures is given in Figure 2. Finally, waste heat can be recovered and also used to generate other process media such as electricity or cold.

Intercompany heat integration is a heat recovery measure which takes place across company boundaries. In the following, the basic terms of intercompany heat integration are introduced and the state of knowledge is presented.

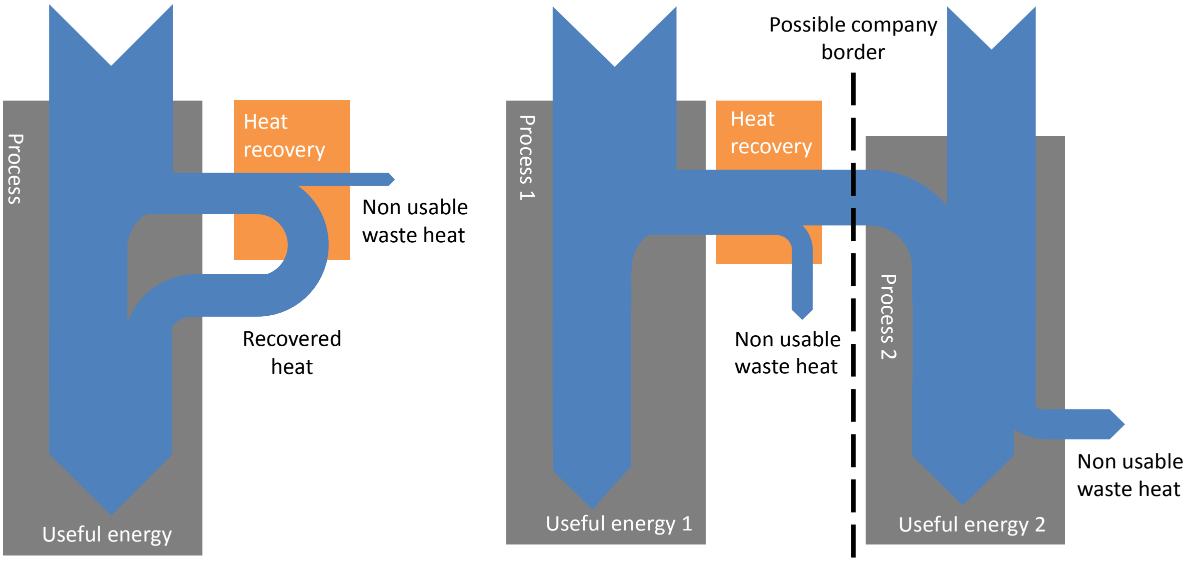


Figure 2: Heat recovery within a process (left-hand side); heat recovery outside a process with possible company border (right-hand side) (adapted from Hirzel et al., 2013)

1.2 Heat integration: a technical concept to reduce energy demand

Heat or process integration is a technical concept to minimize the cooling and heating requirements of industrial plants. The basic idea behind heat integration is to interconnect processes requiring cold with processes requiring heat via a heat exchanger, thus reducing the overall energy demand (Kemp, 2006). A system of heat exchangers interconnecting several processes requiring heat and cold is called a heat exchanger network (HEN). Such HENs are common in the chemical industry (Smith, 2005). The more processes that can be interconnected at reasonable expense within a HEN, the more savings can be achieved with heat integration. Thus, production sites with more than one factory/production hall could set up HENs that extend beyond production halls. An additional concept is to interconnect production sites not belonging to the same company. This concept is called intercompany process or heat integration (Hiete et al., 2012). Here, two or more companies use the same HEN with the aim of reducing their overall energy demand with respect to heating and cooling.

The scientific literature addresses intercompany heat integration directly and indirectly. There are several case studies analysing large production sites or industrial estates to assess potential energy savings. The papers focus mainly on the methodologies for analysing sites and address intercompany heat integration indirectly. For example, Hackl et al. (2011) apply total site analysis (TSA) to an industrial estate consisting of five chemical companies. They show that the current utility demand could be eliminated completely by using a HEN.

Further papers and studies estimate the heat recovery potentials for specified regions. These studies and/or papers deal with how to identify and quantify the amount of waste heat available in regions and how to estimate the technological and economical potentials to recover these amounts of heat. Among the technological options considered, intercompany heat integration might be addressed indirectly as well. For example, in a report prepared by element energy (2014), the potential for recovering and using waste heat from industry is estimated for the UK. To do so heat loads, related waste heat and nearby heat sinks around the waste heat sources are modelled spatially. The recovery potential is then calculated by applying a techno-economic model. Within this model, competing technological options are evaluated for each source of waste heat and the best one is selected with regard to technical or economical objectives. “Over-the-fence” solutions connecting the modelled waste heat sources and nearby sinks are also taken into account. Nearby heat sinks might be district heating networks or other companies. Thus, intercompany heat integration is included as a technological option in this study. However, the modelling assumes only a single source sink-technology combination, i.e. point-to-point and not an integrated heat network. Thus the potential saving due to intercompany heat integration might be underestimated, especially for industrial estates.

District heating networks are also usually operated by companies. With this in mind, a connection between a plant and a district heating network could be considered a case of intercompany heat integration as well. Thus, papers dealing with the use of industrial waste heat in district heating networks might address intercompany heat integration in a wider sense as well. Examples can be found in Broberg et al. (2012), and Hummel et al. (2014).

Finally, a few publications are explicitly dedicated to the field of “intercompany energy integration”. For instance, Hiete et al. (2012) examine a hypothetical case study where a set of companies is located around a chemical pulp manufacturer. They assess a HEN interconnecting these sites including investments in pipes and heat exchangers. Furthermore, they model the decision process whether and how a HEN could be established between the participating companies using game theory. Please note that ‘intercompany energy integration’ is the umbrella term for ‘intercompany heat integration’ and also covers the aspect of two or more companies sharing utilities as well as HENs across company boundaries (Fichtner et al., 2002). Hills et al. (2014) also deal explicitly with intercompany heat integration. They analyse the suitability of different industries for inter-site heat integration. First, they model heat loads for a steel, cement, paper and fertiliser plant. Then, they demonstrate the theoretical savings which could be achieved by interconnecting theses sites using a HEN. The HEN is modelled by applying Pinch analysis and evaluated technically and economically. However, due to the limitations of Pinch analysis, investments for pipes are not taken into account.

2 Methodological framework

In order to quantify the energy-saving potentials of intercompany heat integration, it is necessary to have information on the heating and cooling requirements of the affected companies and their respective location. Furthermore, a methodology is needed to assess a possible HEN based on this information. In this paper, we present and apply a methodology for assessing intercompany HENs, which represents one major pillar of the overall methodological framework.

In the following, we first present different approaches to generate HENs. We discuss Pinch analysis as the most common approach to generate energetically-optimized HENs. We then look at mathematical approaches to generate energetically-optimized HENs. Based on this, we present arguments why mathematical approaches are best suited to the central question here; estimating the energy saving-potentials of intercompany heat integration.

Second, we describe the methodology applied in our framework, which combines approaches from Pinch analysis and operations research. Special attention is paid to aspects relevant for intercompany heat integration such as investments in pipes, and heat losses. We also describe how to address time-dependent load variations of the affected companies to a certain extent.

2.1 Approaches to generate energetically-optimized HENs

For two processes interconnected by one heat exchanger, the amount of heat which can be exchanged theoretically can be estimated quite simply, given the boundaries set by temperatures, type and mass flow of the affected process media. If more than two processes are being operated, it is still generally possible to interconnect each of them with more than one of the other processes using a HEN. However, it is more difficult to calculate the amount of heat which can be exchanged theoretically as the boundaries set by each process are less clear (Raskovic, 2009). This is also the problem when designing a feasible HEN, mainly due to the high number of possible networks which have to be evaluated. For five hot and five cold processes, the number of possible (not valid) network combinations is $25! \approx 1.5 \cdot 10^{25}$.

2.1.1 Pinch analysis

Different techniques and approaches to design feasible HEN configurations exist. Among them, Pinch analysis-based approaches are the most common in industry (Natural Resources Canada, 2003). They provide a framework to generate feasible HENs with the aim of reducing the overall energy demand based on thermodynamic considerations (Radgen, 1996). The basics of Pinch analysis were introduced by Linnhoff et al. (1978). They presented design rules on how to generate feasible HENs with minimum energy requirements. The methodology was then further developed to account for the trade-off between capital costs and energy recovery (Linnhoff and Ahmad, 1990). The final Pinch design method was presented in Linnhoff and Ahmad (1990), and Ahmad et al. (1990). One way to categorize the approaches used to design HENs is to distinguish between Pinch analysis-based approaches and approaches using mathematical programming, i.e. mathematical approaches (Koraviyotin and Siemanond (2015)).

The basic idea of Pinch analysis is to identify the so called 'pinch', which separates the overall system into two thermodynamically distinct regions, resulting in two separate design problems. The processes are divided up into those that have to be heated up and those that have to be cooled down and separated according to temperature intervals. The temperature intervals used to separate the flows are generated based on the inlet and outlet temperature of each process flow and the minimum temperature difference chosen for the heat exchanger. These intervals finally serve to identify the heating and cooling demand for the overall system. This is done by calculating the energy requirements of each process within each temperature interval using the heat capacity and mass flow of the affected processes under the assumption that heat capacities are independent of temperature. The calculated amounts are then usually summed up and visualised in diagrams that plot the so called hot and cold composite curves. The pinch is the temperature where the hot and cold composite curves are closest to each other considering a minimum temperature driving force. The minimum heating and cooling requirements can then be estimated directly based on the diagram.

To design a HEN with minimum energy requirements, the corresponding network is then formed by applying design heuristics considering the so called pinch rules. The design is separated by the pinch, resulting in a design problem above and below the pinch. The pinch rules then prescribe that the HEN is designed for both problems such that no cold utilities are used above the pinch, no hot utilities below the pinch, and that no heat is transferred across the pinch. The central design heuristic suggests creating networks for both problems by starting at the pinch, where the problem is most constrained.

Software exists to create HENs based on Pinch analysis. This supports engineers in creating feasible HENs considering the pinch rules (i.e. PinCH, www.pinch-analyse.ch). It provides the user with suggestions on how to develop the HEN. As the designer still controls the procedure, such approaches can be classified as semi-automatic. However, semi-automatic Pinch analysis-based approaches do not guarantee the optimal solution, i.e. the HEN with minimum energy requirements (Stanislaw Sieniutycz and Jacek Jezowski, 2013). Furthermore, a HEN that achieves minimum energy targets by separating the problem into a design above and below the pinch usually needs more heat exchangers, than if the pinch division had been ignored (Kemp, 2006). Thus, options ignoring pinch rules might offer advantages in some design cases (Radgen, 1996). Finally, large problems could lead to combinatorial challenges for the designer.

2.1.2 Mathematical approaches

Mathematical approaches generate feasible HENs automatically. Objective functions are formulated to generate a HEN with minimum energy requirements. Cerda et al. (1983) presented the first mathematical approach to generate feasible HENs using the transport algorithm. Other approaches exist, such as models using transhipment algorithms (Papoulias and Grossmann (1983), Chen et al. (2015)) and superstructure models to retrofit HENs and for HEN synthesis (Ciric and Floudas (1989), Yee and Grossmann (1990)). An overview of the mathematical approaches to generate HENs is given in Escobar and Trierweiler (2013).

The advantages of mathematical models are that they are systematic and can be implemented automatically. Furthermore, they can be extended flexibly by adjusting objective functions and/or adding constraints so that, for example, the number of heat exchangers can be minimized. Finally, generating HENs using linear formulated mathematical models is much faster than using Pinch analysis-based approaches.

2.1.3 Conclusion based on requirements

Our goal is to develop a model framework for estimating the energy-saving potentials of intercompany heat integration in regions to be specified. With regard to intercompany HENs, the distances between participating companies are of major relevance as investments in piping can crucially influence the cost efficiency of intercompany HENs (Ludwig, 2012). Pinch analysis-based approaches currently do not provide the possibility to address investments for piping by taking distances into account, which is one of their major drawbacks. Furthermore, we want to provide a framework which allows flexible adaptation of the size of the region depending on policy research needs. This means the framework must be able to assess industrial estates, cities, metropolitan areas and much larger regions using the same approach. For example, for metropolitan areas, it is typically necessary to evaluate intercompany HENs for several hundred companies. This would be very time consuming using Pinch analysis-based approaches and is another drawback in terms of our goal.

Therefore, we argue that mathematical approaches are best suited to evaluating intercompany HENs. We use a transport algorithm in our framework. As a linear model is formulated, it can be guaranteed that intercompany HENs are evaluated and compared rapidly and reliably. The structure of the model also allows several topics relevant for intercompany HENs to be addressed, such as investments in piping and the dynamic loads of the assessed companies. In the following, we describe how we address such factors in our model to assess intercompany HENs.

2.2 Generating intercompany HENs using the transport algorithm

Cerda et al. (1983) demonstrate how to generate energetically-optimized HENs by combining approaches from Pinch analysis and operations research. In Pinch analysis, each hot and cold process flow is separated according to temperature intervals to calculate the energy requirements for each process in each interval. This approach is used in classical Pinch analysis to create composite curves to identify the pinch and generate an energetically-optimized HEN based on heuristic rules (Stanislaw Sieniutycz and Jacek Jezowski, 2013). However, this separation also allows each cold process flow to be represented by a set of energy demands and each hot process flow by a set of energy supplies. This is why the task of generating an energetically-optimized HEN can be formulated as a general transport problem.

The transport problem has its origins in operations research and deals with the task of minimizing the transport costs between supplies and demands, given the cost for each possible route between supply and demand (Fourer et al., 2003). The objective function of the general minimization equation for transport problems is as follows: $min_{x_{ij}} \sum_i \sum_j c_{ij} \cdot x_{ij}$. The costs per unit transported from supply i to demand j are indicated by c_{ij}, and x_{ij} represents the quantity transported from the same supply to the same demand.

To generate a HEN, we require not only the quantities provided by supplies and required by demands, but also the temperature levels of the affected constellations between supply and demand. This is based on the fact that heat can only be transferred from higher to lower temperature levels.

Cerda et al. (1983) extend the formulation of the transport problem to address this circumstance so that information on the temperature range of each supply and demand is included. Each cold process is separated into a set of demands a_{ik}, where i indicates the process affected and k the temperature range. Each hot process is separated into a set of supplies b_{jl}; j indicates the process affected and l the temperature range. It is assumed that a cold utility a_{C1} exists, capable of cooling down all hot processes, i.e. demands (cf. Eq. **(1)**). The existence of a hot utility b_{HL} is also assumed, capable of providing the heat needed by all hot processes, i.e. supplies (cf. Eq. **(2)**). The quantity of heat transported from supply b_{jl} to demand a_{ik} is then denoted by $q_{ik,jl}$. In addition, the HEN shall be generated in such a way that all demands are covered by the heat delivered from supplies or the hot utility (cf. Eq. **(4)**). Analogously, all supplies have to release their heat to demands or the cold utility (cf. **(5)**). The boundary conditions are summarized in Table 1.

Table 1 Boundary conditions

$$a_{C1} \geq \sum_{j=1}^{H-1} \sum_{l=1}^{L} b_{jl} \tag{1}$$

$$b_{HL} \geq \sum_{i=1}^{C-1} \sum_{k=1}^{L} a_{ik} \tag{2}$$

$$a_{ik} = \sum_{j=1}^{H} \sum_{l=1}^{L} q_{ik,jl} \qquad i = 1,2,\dots,C \qquad k = 1,2,\dots.,L \tag{3}$$

$$b_{jl} = \sum_{j=1}^{H} \sum_{l=1}^{L} q_{ik,jl} \qquad i = 1,2,\dots,H \qquad k = 1,2,\dots.,L \tag{4}$$

$$q_{ik,jl} \geq 0 \text{ for all } i,j,k \text{ and } l \tag{5}$$

With

a_{ik}	demand: thermal energy required by cold stream i in temperature interval k.
b_{jl}	supply: thermal energy to be removed from hot stream j in temperature interval l.
L	number of temperature intervals
$q_{ik,jl}$	quantity of heat transferred from supply b_{jl} to demand a_{ik}. Note: a set of $q_{ik,jl}$ for the problem represents a HEN, determining which processes have to be interconnected and how large the heat exchanger has to be to interconnect them.

Finally, the objective is to generate a HEN for a set of *H-1* hot and *C-1* cold process streams that minimizes the demand of a_{C1} and b_{HL}. The objective function for this is given in Eq. **(6)**; $q_{ik,jl}$ is multiplied by the associated cost $C_{ik,jl}$ and summed up for the overall problem. Heat is not allowed to be transported to demands hotter than the supply. To comply with this, the associated costs for such configurations are assigned a very large (infinite) number.

$$min_{q_{ik,jl}} \sum_{i=1}^{C} \sum_{k=1}^{L} \sum_{j=1}^{H} \sum_{l=1}^{L} C_{ik,jl} \cdot q_{ik,jl} \qquad (6)$$

To determine the HEN with minimum energy requirements, the associated cost of all $q_{ik,jl}$ interconnecting utilities with supplies or demands are valued with 1 and all $q_{ik,jl}$ interconnecting supplies and demands via a feasible heat exchanger with 0. All equations formulating the problem are linear. Solving the optimization problem reliably yields the global minimum. Other approaches to generate a HEN using the transport algorithm also address the capital cost for the necessary equipment and operating costs. The optimal HEN is then determined by the minimum cost (Geldermann et al., 2005). All the cost factors included are represented in terms of the energy transport from supply to demand (e.g. in EUR/kW). We formulate the transport problem to generate an intercompany HEN including the costs for heat exchangers, utilities, pumps and pipes.

The investments necessary for heat exchangers are assumed to be dependent on the amount of energy to be exchanged, and the composition of the affected fluids. In our model, implementation investments and operating costs for utilities depend on the thermal power to be provided or removed, and the efficiency.

Investments and operating costs for pumps, compressors and piping are generally determined by the amount of energy to be transported from supply to demand and the distance between the two. Taking distances into account is especially relevant when generating intercompany HENs. Ludwig (2012) addresses this issue and develops an approach to approximate the investments in pipes to interconnect processes in intercompany HENs. We use the same approach to estimate the investments in pumps and the associated operating costs as well. We furthermore take heat losses occurring in the pipes into account by treating them as a cost factor. The cost parameter $C_{ik,jl}$ finally represents the specific cost for transporting a unit of energy from supply to demand. The factor is summarized in Table 2 for an energetic and an economic optimization calculation.

Table 2 Cost factors for energetic and economic optimization

	energetic	economic	
$C_{ik,jl} =$	0	$c_w + c_{pi} + c_{pu} + c_{hl}$	i and j are both process streams, match is allowed
	0	0	i and j are both utility streams
	1	c_u	i or j is a utility stream
	M	M	otherwise, M is a large (infinite number)
		specific cost for	c_w : heat exchangers c_{pi} : pipes c_{pu} : pumps c_{hl} : heat losses c_u : utilities

In order to assess intercompany HENs in a wider, systemic context, it might be relevant to address the dynamic load profiles of the participating plants as well. Let us assume that a plant provides “waste”-heat to another plant via a HEN. If this plant then starts to operate at part-load and provides less heat to the interconnected plant than under the original design conditions, then the interconnected plant has to make up the missing heat using its own utilities. This circumstance could be addressed by simulating the behaviour of HENs derived by optimization on an hourly basis and then optimizing the HEN again with regard to variable load behaviour. This is a system dynamics approach, which is also possible due to the hourly simulation of storages etc. However, this would increase the size of the problem and the calculating time as well. We want to develop a model framework applicable to estimating the energy-saving potentials in “larger” regions. This usually requires the assessment of HENs for several hundreds of companies, making calculating time a significant factor. Therefore, we have to compromise between technologically very detailed modelling (system dynamics approach) and taking dynamic aspects into account by addressing dynamic load behaviour in the formulation of the transport problem. For the estimation of energy-saving potentials due to intercompany heat integration, the assumption is that companies include predicted load variations in the assessments of a possible HEN between them. Such an approach has the advantage that the problem is still linear, and the calculation time per constellation does not increase in general. Therefore, we extend the formulation of the objective function as follows:

$$min_{q_{tik,tjl}} \sum_{t=1}^{T} \sum_{i=1}^{C} \sum_{k=1}^{L} \sum_{j=1}^{H} \sum_{l=1}^{L} C_{tik,tjl} \cdot q_{tik,tjl} \qquad \textbf{(7)}$$

The quantity of heat transported from supply b_{tjl} to demand a_{tik} is then denoted by $q_{tik,tjl}$; t indicates the time in the formulation. As heat exchanger surfaces cannot be adjusted from time step to time step, further boundary conditions are necessary to guarantee that the network generated is technically feasible. First, we add a constraint to guarantee that no links are generated between supplies and demands from different time steps (cf. Eq. **(8)**).

$$\begin{aligned} q_{tik,tjl} &\geq 0 \text{ for all } i,j,k,l \text{ and } t, \text{ but} \\ q_{tik,tjl} &= 0 \text{ if } t \text{ from supply and demand is not equal} \end{aligned} \qquad \textbf{(8)}$$

Second, we add a constraint to guarantee that the heat exchanger can work at full capacity, but not above. Therefore, we always model the first time step as a full load case for all processes. We further assume that the thermal requirements of processes are linearly dependent on the load in the plant. Thus, we introduce a part-load factor PF. PF represents a lower load of the processes where the supplies and demands come from. For example, for a hot and a cold process, one demand and one supply is generated for two time steps. The supply operates at 50% part load in the second time step, but the demand stays at full load. Thus, the heat which can be exchanged between the supply and demand in the second time step is restricted with regard to the first time step as follows: $q_{211,211} \leq q_{111,111} \cdot 0.5$. Accordingly, the constraint is given in Eq. **(9)**.

$$q_{tik,tjl} \leq q_{1ik,1jl} \cdot PF_t \text{, for all } i,j,k,l \text{ and } t \text{, with } PF_t \leq 1 \qquad \textbf{(9)}$$

Figure 3 illustrates the extended approach. Heat source number one (red ball) provides heat to sink number two (blue), and the cost to interconnect them is valued as zero. A connection from source number one to sink number three is not allowed so the interconnection costs are valued as infinite. Interconnections from heat source number one in time step one to heat sinks in time step two are generally valued with the same cost applied within one time step. However, Eq. **(8)** stops connections being generated between different time steps. Furthermore Eq. **(9)** compares the possible connection between heat source one and heat sink two for different time steps and forces them to stand in a certain relation to each other .

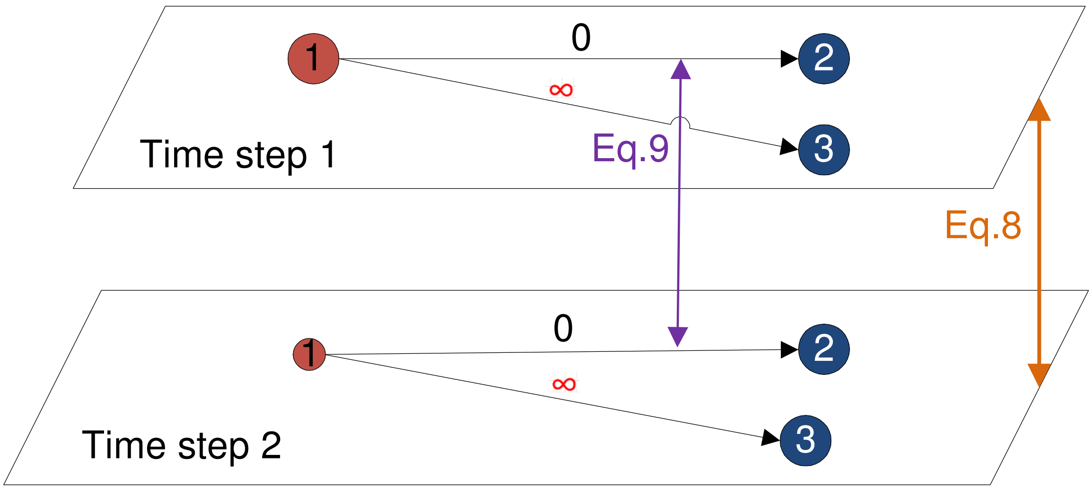


Figure 3 Visualisation of the extended approach (blue: heat sinks, red: heat source)

3 A case study of intercompany energy integration

We apply the model in a case study to evaluate the hypothetical interconnection of two plants within a HEN. The goal of the case study is to provide:

- A validation of the energetic optimization calculation.
- A comparison of the economic optimization calculation with a consultant report.
- A sensitivity test with regard to the factors relevant for intercompany heat integration.

We chose a coating plant (P1) as the first plant for the system to be optimized. This represents a plant which could potentially deliver heat to another plant. The chosen coating plant has already been analysed by a team of consultants from the Swiss Energy Agency with regard to its energetic optimization potentials (Grieder et al., 2011). They employed Pinch analysis using the commercial software PinCH to assess thef potential energy savings of using a HEN.

Two coating processes are applied within the plant. For component parts with high coating requirements, a process is used with organic pulverized paint (EPS-coating). Other component parts are coated with porcelain enamel (Enamel-coating). The components are pre-treated prior to each coating process.

This pre-treatment includes degreasing, washing and drying. An overview is given in Figure 4. To start with, component parts are transported to the degreasing bath. The bath operates at 55℃ and the energy is provided by a hot water boiler. The temperature of the exhaust gas from the degreasing bath is approximately 50℃. The component parts are then sprayed with cold water to wash them. Finally, the component parts are dried at 160℃ before entering a storage hall where they are left to cool down. They are then treated by either Enamel or EPS-coating.

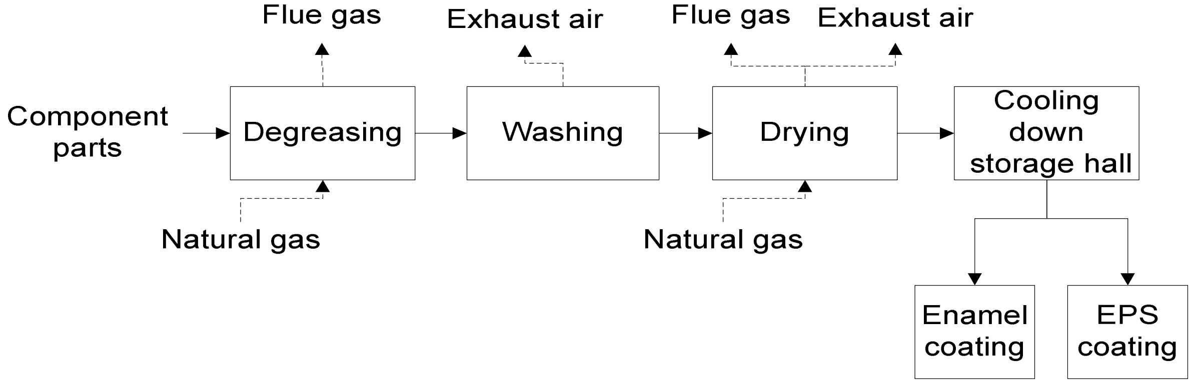


Figure 4 Pre-treatment in coating plant

The EPS-coating process is illustrated in Figure 5. Component parts are coated with organic pulverized paint. The first step is to electrically charge the component parts so that the pulverized paint adheres to them. This coating is then melted in an oven at 200℃ heated by a natural gas burner. The component parts leaving the oven are 150℃ hot and are left to cool down in a storage hall afterwards.

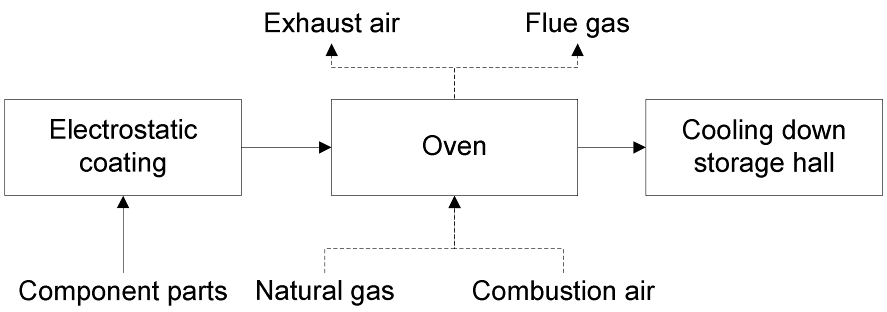


Figure 5 EPS-coating

Figure 6 shows a diagram of the enamel-coating process. Component parts are coated with dry or wet porcelain enamel in a coating cabin. The paint is then burned-in at temperatures between 830°C and 850°C in an oven. Parts which were wet coated are dried before entering the burning oven at 150°C. The heat for the dryer is mainly provided by the exhaust gas of the burning oven. Finally, the component parts are left to cool down in a storage hall.

We chose a manufacturing plant operating a hot water and steam system (P2) as the second plant for the system to be optimized. This plant only contains heat sinks, so it represents a plant which could potentially absorb waste heat from the first plant. The underlying mass and energy flows are constructed for this second plant. This was done because we plan to use also generic plant profiles to assess intercompany heat integration potentials in a further research paper that combines bottom-up, to-down modelling and spatial analysis.

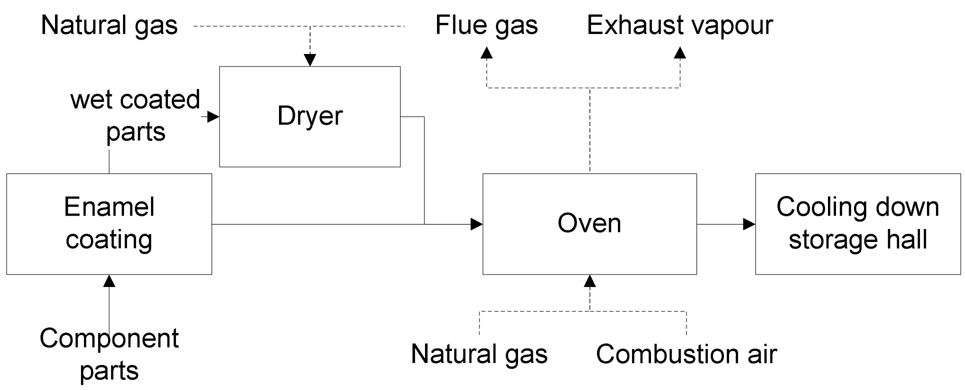


Figure 6 Enamel coating

3.1 Energetic optimization (validation)

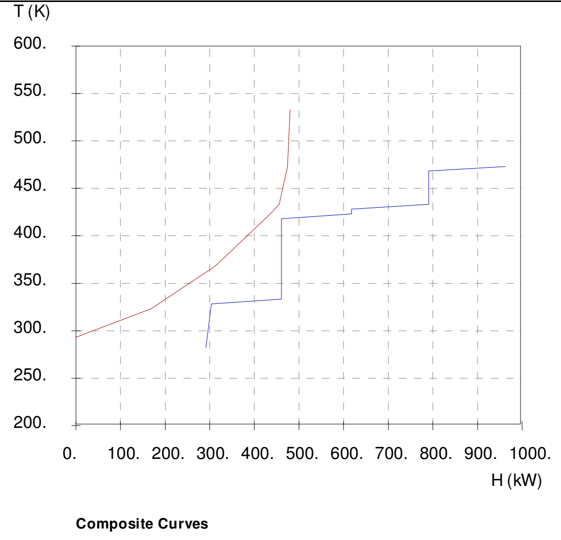
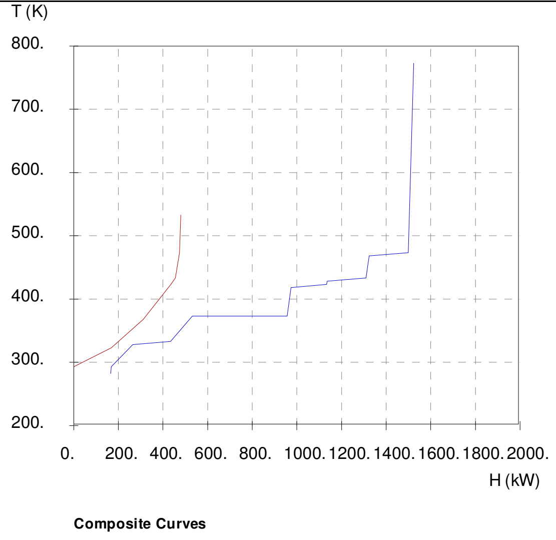
Table 3 shows the process stream data for the system to be optimized consisting of two plants. To validate our energetic optimization calculation, we implement our model without taking costs or investments into account. We then compare the resulting minimum energy requirements with the values resulting from the Pinch analysis for the same system. We conduct this comparison for the coating plant on its own, and for the combined system consisting of both plants.

Table 3 Process stream data

Description		Medium	Tin [°C]	Tout [°C]	cp [kJ/kg*K]	Q [kW]	Plant
Degreasing , Hot bath	Cold	Water	55	60	16,840	157	P1
EPS oven, Hot cabin	Cold	Air	195	200	1,000	173	P1
Dryer enamel, Hot cabin	Cold	Air	145	150	1,000	157	P1
EPS oven, Combustion air	Cold	Air	9	55	1,004	9	P1
Dryer enamel, Combustion air	Cold	Air	9	55	1,004	3	P1
Dryer pre-treatment, Hot cabin	Cold	Air	155	160	1,100	173	P1
Degreasing , Exhaust air	Hot	Air	50	20	0,991	-73	P1
EPS oven, Flue gas	Hot	Air	260	20	1,104	-20	P1
EPS oven, Exhaust air	Hot	Air	200	20	1,004	-70	P1
Enamel oven, Exhaust vapour	Hot	Air	95	20	1,004	-70	P1
Dryer enamel, Exhaust air	Hot	Air	150	20	1,101	-33	P1
Dryer pre-treatment, Exhaust air	Hot	Air	160	20	1,303	-213	P1
Hot Water	Cold	Water	20	100	4,183	198	P2
Steam (incl. energy for vaporisation)	Cold	Water	100	200	2,042	463	P2
Steam	Cold	Water	200	500	1,975	26	P2

The composite curves for the coating plant on its own and for the combined system are given in Table 4. The minimum temperature difference chosen is 25 K in accordance with the existing report.

Table 4 Pinch analysis for the coating plant and for the combined system

	
Minimum energy requirements resulting from the Pinch analysis	
Only coating plant: • Energy target (heating): 483.8 kW. • Energy target (cooling): 291.7 kW	Combined system: • Energy target (heating): 1044.4 kW. • Energy target (cooling): 165.8 kW.
Minimum energy requirements resulting from our model implementation	
• Energy target (heating): 483.7 kW. • Energy target (cooling): 291.8 kW	• Energy target (heating): 1043.8 kW. • Energy target (cooling): 165.8 kW.

The comparison of the results from the Pinch analysis with the results from our model shows that we derive identical heating and cooling requirements for the system consisting only of the coating plant accurate to lower than 0.1%. For the combined system we also derive the same minimum cooling and heating requirement accurate to round about one kilowatt. The small difference is based on the treatment of phase changes within the model.

Overall, the comparison indicates that the minimum energy requirements derived using our model are more or less in line with the values derived by Pinch analysis. As Pinch analysis is the most common method to generate HENs in industry, this shows that our model is suitable to quantify the energy-saving potentials due to intercompany HENs in industry. There may be minor deviations in the results, but our approach achieves very similar benchmark values to Pinch analysis with additional advantages – it is able to analyse many more configurations in a much shorter time.

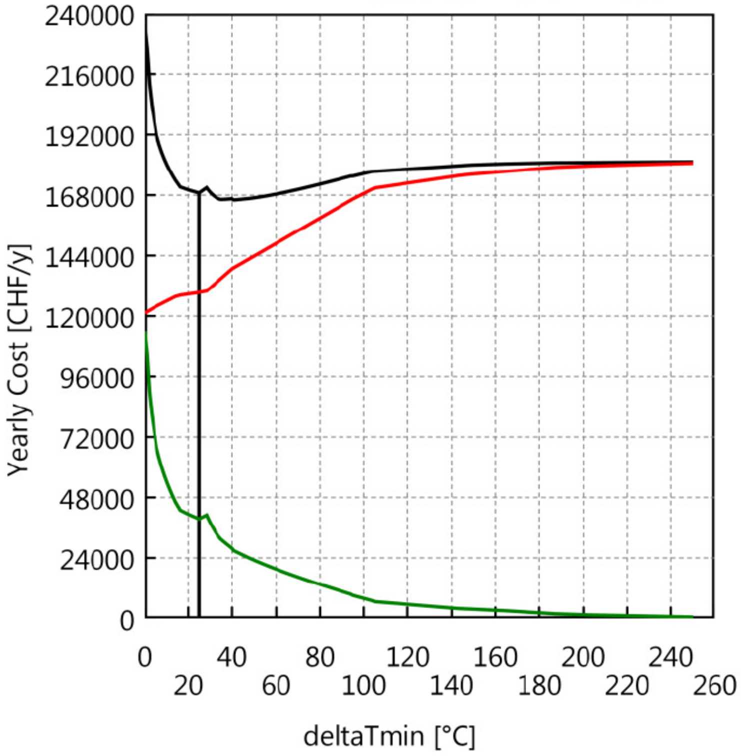
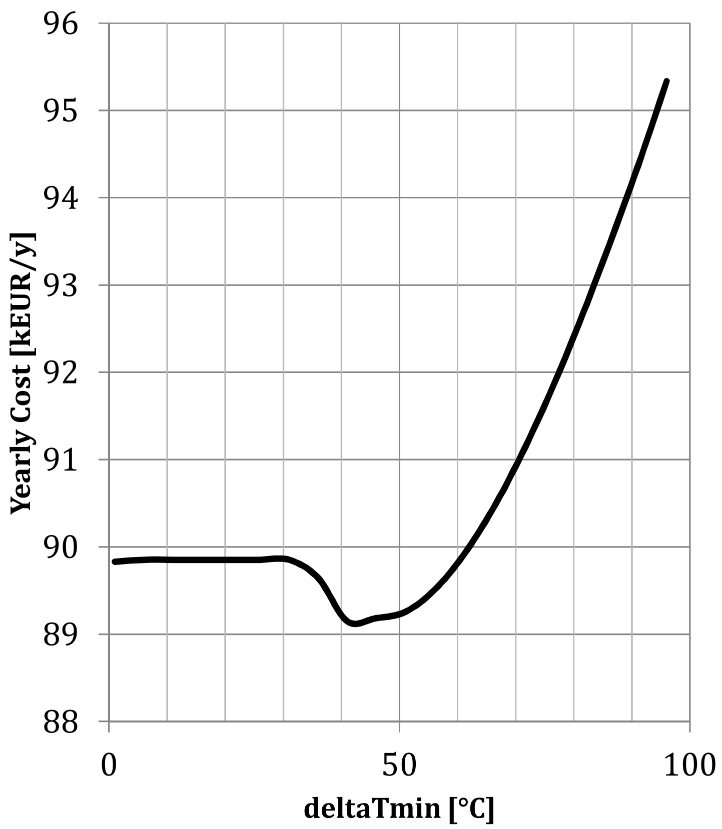
3.2 Economic optimization

As mentioned, the coating plant in our case study had already been analysed by a team of consultants from the Swiss Energy Agency. Unfortunately, only a few monetary values and underlying assumptions were included in the underlying report (Grieder et al., 2011), so a comparison of absolute monetary values was not possible. However, we did compare the optimal minimum temperature difference derived using our model for the coating plant (P1 only) with the same value taken from the published report.

This comparison indicates whether the relative difference between the specific cost for the heat exchanger and the operating cost for utilities are in the same range. This is based on the reason that the relative difference determines which possibility is chosen; either heating by utility, or heating by connecting hot with cold streams.

Table 5 shows the comparison of the optimal minimum temperature difference based on our model with the value from the report. The global minimum occurs for both at approximately 40℃. However, the cost curve from our model implementation is very flat for temperatures lower than 30℃. This is not the case for the cost curve from the report. This indicates that our model implementation might underestimate the cost of heat exchangers with small temperature differences even though it is based on the most up-to-date handbook available for estimating the costs of process equipment (Loh et al., 2002).

Table 5 Comparison of the optimal minimum temperature

	From the report (Grieder et al., 2011) (black curve): • Local minimum at 25 °C • Global minimum at 40 °C
	Our model implementation: • No local minimum • Global minimum at 41 °C

3.3 Sensitivity test

The sensitivity test was to see whether our model responds plausibly to the factors relevant for intercompany heat integration. We generated HENs for the coating plant only and for the system combing the coating plant with the manufacturing plant varying thermal loads, distances and load behaviour. An extract is given in Figure 7. In the following, we discuss the results and present arguments for the model's plausibility.

Energetic and Economic alone:

The sensitivity calculations “Energetic and Economic alone” represent optimized HENs for the coating plant only (P1).

In the first case “Energetic P1 alone”, the HEN was generated based only on energetic considerations. In the second case “Economic P1 alone”, additional investments in heat exchangers were included, so that each energetically possible interconnection between heat sink and source is benchmarked with its specific costs. The specific costs for utilities to provide heat or cold for each heat sink or heat source were also taken into account. To generate a HEN, the model decides whether the thermal needs for each heat sink and source are best satisfied by connecting the heat sink and source by a heat exchanger or by using utilities with regard to the overall objective function - minimizing the costs of the overall system. Thus, sometimes it is cheaper to use utilities than to interconnect heat sources and sinks. This can be seen in Figure 7. Figure 7 illustrates how much of the heat needed by all the heat sinks is provided by heat exchangers between heat sources and sinks, i.e. how much “waste heat” would be utilized in the HEN. It can be seen that less waste heat is utilized for the case “Economic P1 alone” than for the case “Energetic P1 alone”.

Energetic and Economic combined:

The sensitivity calculations “Energetic and Economic combined” represent optimized HENs for the system consisting of the coating plant (P1) and the manufacturing plant (P2). Again, two HENs are generated; one based on energetic and one based on economic considerations. Consequently, more waste heat would be utilized by a HEN in the case “Energetic P1+P2 combined” than in the case “Economic P1+P2 (no distances)”. Please note that, for the second case, no investments related to distances are taken into account.

Economic combined, 50m, 50m-upscaled and 200m-upsclaed:

In the case “Economic P1+P2 (50m)”, a HEN is generated for both plants taking into account the investments for heat exchangers and those related to the distances between the sites (e.g. for pipes), in this case for a distance of 50m. As a result, less waste heat is utilized than in the case “Economic combined (no distances)”, as interconnections across company borders have to compete with utilities situated at each site. The reason is that especially potential interconnections where only small amounts of heat are transferred become not competitive.

Then the amount of waste heat from the first plant is scaled up by increasing the thermal loads in the case “Economic P1+P2 (50m, up-scaled)”. The result is that some interconnections between P1 and P2 are now competitive compared to the utilities, so that more waste heat is utilized than in the previous case with no upscaling.

In the next case: "Economic P1+P2 (200m, up-scaled)", the distances for the upscaled system are increased to 200m so that, again, less waste heat is utilized because of the increased investment costs.

Economic combined, 50m, up-scaled, part load:

In the case "Economic P1+P2 (50m, upscaled, part-load)", we assume the system consists of an upscaled coating plant (P1) and the manufacturing plant (P2) with a distance of 50m between them. We further assume that the coating plant operates 50% of the time at 10% part-load, while the manufacturing plant always operates at full load. We consider this by assuming two time steps and generating an optimized HEN by applying the dynamic model extension (cf. Eq. **(7)** - **(9)**). Including part-load operation makes some interconnections uneconomical compared to the utilities. This is due to the fact that less heat is available for transfer from the coating plant to the manufacturing plant during part-load operation and the rest of the required heat has to be covered by utilities. Consequently, these interconnections are not generated when calculating the optimized system, reducing the amount of heat utilized compared to the equivalent case "Economic P1+P2 (50m, up-scaled)", where no part-load operation is addressed.

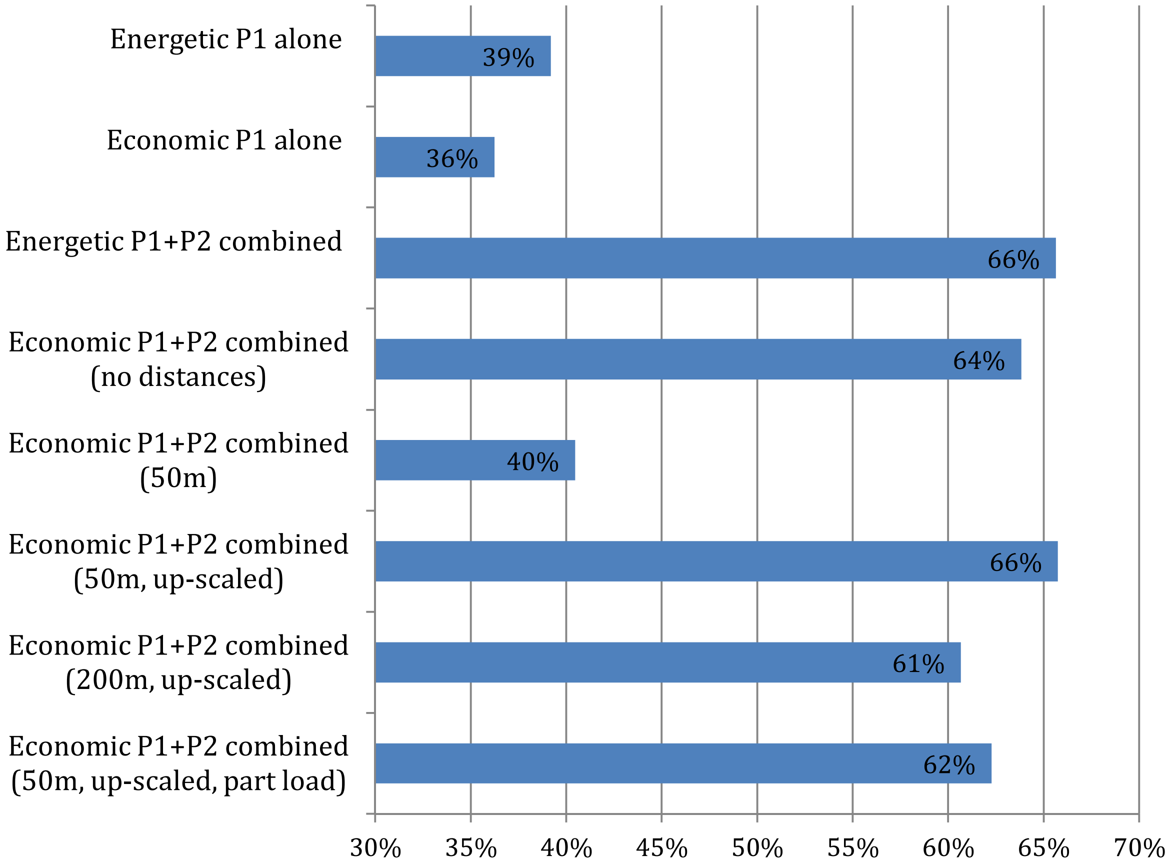


Figure 7 Waste heat utilized per case of sensitivity test

Based on the results of the sensitivity tests, it can be concluded that our model plausibly addresses the factors relevant for intercompany heat integration. This approach to evaluating the energy-saving potentials due to intercompany heat integration for larger regions is worth considering because it can be applied automatically.

4 Summary

This contribution began by pointing out the current gaps with regard to assessing the potential energy savings due to intercompany heat integration. A few case studies have been made, but only one (element energy et al., 2014) has addressed the potential savings for an entire region from utilizing waste heat, and also considered intercompany heat integration. Element energy (2014) analysed the potential for recovering waste heat from industry in the UK and included "over the fence" solutions, i.e. intercompany heat integration.

However, the modelling assumes a single source-sink technology combination and does not include integrated heat networks. Furthermore, there are no known studies for Germany or other countries. In addition, intercompany heat integration is not addressed as an efficiency option in models of industrial energy demand projections. Thus, we argue that a framework to systematically assess the energy-saving potentials due to intercompany heat integration for regions might help to close these gaps; allowing structured studies for more regions and the consideration of intercompany heat integration as a saving option in models of industrial energy demand projection.

Second, we presented a model to evaluate the energy savings due to intercompany HENs based on information about the heating and cooling requirements of the affected companies and their distance to each other. The model operates using the transport algorithm and represents a mathematical approach to generating HENs, which means it offers the possibility to evaluate many cases automatically and quickly. This is a great advantage compared to semi-automatic approaches such as Pinch analysis with regard to the overriding problem - providing a framework to systematically estimate the energy-saving potentials due to intercompany heat integration for regions.

Finally, we applied the model to evaluate a hypothetical case study of two plants. The results indicate that the theoretical energy savings derived with our model are valid for combinations of plants. The results are also very similar to those derived using Pinch analysis, which is the most common approach to generating HENs in industry. If investments in heat integration are also addressed, it can be further shown that the relevant factors concerning intercompany heat integration such as the distance between plants, or possible part load operation are also plausibly addressed.

5 Outlook

The model implemented here could be applied to a huge number of case studies automatically to estimate the energy-saving potentials for regions due to intercompany heat integration. To do so, first the region would have to be specified and data collected on the heating and cooling requirements for the companies in that region. This data collection could be done via expert interviews or surveys. As this approach is cost-intensive and time-consuming, it is worth considering more generic approaches. For some energy-intensive industries, commercial databases exist on plant locations (e.g. steel, pulp and paper production, cement). These usually contain information on location, capacity and historical production per year. As these industries are more or less homogeneous with regard to the production processes applied, generic "bottom-up modelled" process schemes could be developed for them. The cooling and heating requirements for the plants contained in the databases could then be differentiated by temperature depending on the activity data contained in the databases (i.e. production per year). As energy-intensive industries often have still unused waste heat (Persson et al.,2014), this would at least capture the energetically-relevant companies for intercompany heat integration.

Some commercial databases also exist for non-energy-intensive companies, which contain financial figures such as turnover differentiated by company or site (i.e. Hoppenstedt, http://www.hoppenstedt-firmendatenbank.de). Analysing economic sectors with regard to energy costs and applied fuels and combining this with information on the typical temperature ranges applied in each sector (Wagner, 2002) allows the construction of generic plant profiles for non-energy-intensive sites. Non-energy-intensive plants could then at least be represented by a set of heat sinks in specific temperature ranges. Based on these data, promising combinations of sites for intercompany HENs could be identified.

Methods from spatial analysis can be applied to restrict the area regarded by limiting the combinations of sites to be assessed. For example, a first step could limit the maximum distance between companies. Given a data set of geo-referenced plant sites, co-location mining can identify combinations of sites not exceeding this distance. These sites could then be evaluated with regard to the potential savings due to intercompany HENs. Qualitative assessments of sector combinations are also possible based on the output of co-location mining. A potential architecture of the framework is given in Figure 8.

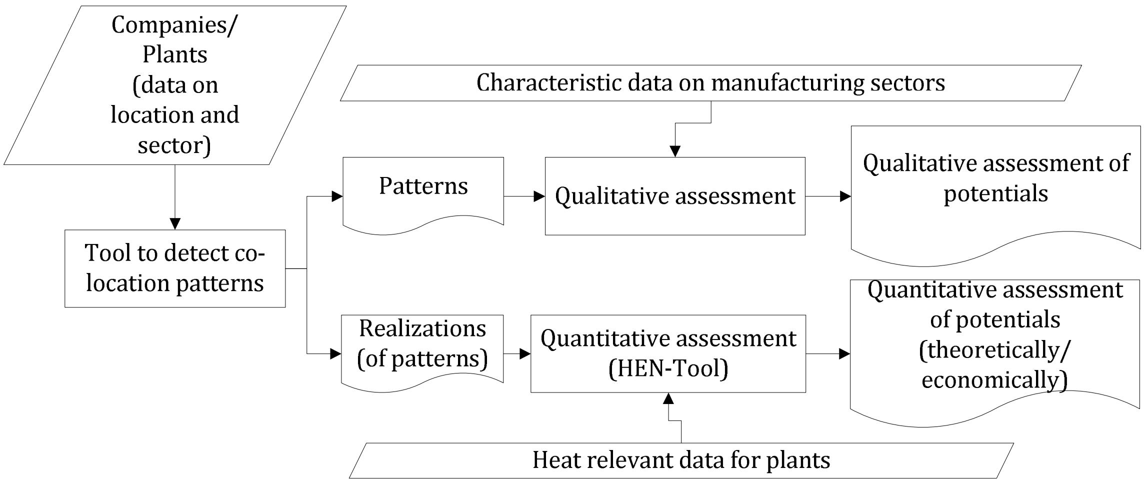


Figure 8: Framework to assess the energy savings due to intercompany heat integration

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