Energy savings of inter-company heat integration: tapping potentials with spatial analysis

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Abstract

Industry accounts for approximately 30 % of the final energy demand in Germany. 75 % of this 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.

Inter-company 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 in Europe due to inter-company heat integration have only been estimated for the United Kingdom. The topic was a side issue in a study of the potentials for recovering and using waste heat from industry in 2014. This paper addresses the question of how to identify potentials for inter-company heat integration by providing and applying a general framework.

First, we discuss how spatial data mining can be used to analyse industrial symbiosis potentials in general. Second, we apply a spatial data mining tool to analyse the co-location patterns of economic sectors based on the European Pollutant Release and Transfer Register (E-PRTR). To do so, we combine the tool to detect co-location patterns with information about the process temperatures typically applied in the affected industry sectors taken from the project 'Datenbasis Energieeffizienz'. This demonstrates how promising constellations of industrial production sites might be identified with regard to inter-company heat integration. Finally, we discuss how energy-saving potentials due to inter-company heat integration could be assessed for regions, combining spatial data mining with heat integration methodologies.

Consequently, the paper gives insights into a) how analysing the co-location patterns of economic sectors can be used to identify promising production sites for inter-company heat integration, and b) how the potential energy savings due to inter-company heat integration can be estimated in a structured way for regions. Based on the results of the case study, it can be summarized that promising agglomerations of productions sites can be located geographically by combining spatial co-location mining with publicly available data. Further research is needed to validate the criteria applied for promising agglomerations.

Introduction

Increasing energy efficiency in every sector is a major pillar of Germany's energy policy to tackle climate change and increase supply security (BMWi, 2014). Inter-company 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 inter-company heat integration have not yet been estimated for Europe. This is probably mainly due to the lack of comprehensive data on the heating and cooling requirements of companies in close spatial proximity. For Europe, such information does not currently exist, except in certain case studies. Thus, it would be useful to have a structured procedure to estimate the energy-saving potentials due to inter-company 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. Examples include the demand-side sub-models of the energy system model PRIMES and the energy demand model FORECAST (E3MLab/ICCS 2016, FORECAST 2016). Currently, they do not address the efficiency option of inter-company heat integration, but could be extended by developing a framework to assess its energy-saving potential. Potential energy savings due to inter-company heat integration could then be included in industrial energy demand projections as well.

Furthermore, firms have recognised the role they can play in contributing to sustainability and are addressing this with voluntary initiatives fostering sustainability. These initiatives include whole-system approaches intended to minimise waste, and use resources more efficiently and effectively in almost closed-loops (Lozano, 2011). Inter-company heat integration is one technical option to reduce the amount of waste heat produced. Thus, a structured way to identify agglomerations of production sites with promising characteristics for inter-company heat integration could help firms to achieve their sustainability goals.

This paper presents a methodological framework to systematically estimate these potentials for regions which combines spatial analysis and heat integration. The possible approach to the quantification of energy savings by inter-company heat integration has already been presented in Aydemir et al. 2016 and is only summarized in the section on the framework. This paper focuses on the methodologies from spatial analysis and paves the way for constructing an integrated model.

Waste heat in the context of climate protection goals

Industry accounts for a quarter of the EU's final energy demand. 73 % of this is used to provide heat and cold, of which more than 80 % is for heat generation above 100 °C (EC 2016). It can be assumed that this is mainly due to the process heat required in production processes. In Germany, the situation is similar. Industry accounts for approximately 30 % of final energy demand and 75 % of this share is used to provide heat, of which 65 % is process heat (Rohde, 2013).

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 process heat, they estimate waste heat potentials of between 3 % and 40 % for Germany 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 considered within the "National Action Plan for Energy Efficiency" (BMWi, 2014).

Several measures have to be considered for the evaluation of waste heat potentials (SAENA, 2012). First, measures to eliminate waste heat should be evaluated. If this is not possible, it can be explored 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 within the production site of the company producing the waste heat or also outside the company. Finally, waste heat can be recovered and also used to generate other process media such as electricity or cold.

Inter-company heat integration is a heat recovery measure that takes place across company boundaries. Thus it is a special case of industrial symbiosis. The following sections define the basic terms of inter-company heat integration and industrial symbiosis and present the current state of knowledge.

Heat integration: a technical concept to reduce energy demand

Heat or process integration is a technical concept to minimise the cooling and heating requirements of industrial production sites. 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 of both (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 these production halls. An additional concept is to inter-connect production sites not belonging to the same company. This concept is called inter-company process or heat integration. Here, two or more companies use the same HEN with the aim of reducing their overall energy demand with respect to heating and cooling. This is a special case of industrial symbiosis (Hiete et al, 2012).

The scientific literature addresses inter-company 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 inter-company heat integration only 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. Regions may refer here to cities, urban agglomerations or even whole countries. 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 this heat. Inter-company heat integration might be addressed indirectly among the technological options considered.

McKenna and Norman (2010) perform spatial modelling of industrial heat loads and recovery potentials in the UK. Although they localize the occurrence of waste heat, they only estimate the technical heat recovery potential ignoring spatial and temporal constraints. They also did not examine whether heat sinks are available close to the modelled waste heat sources. This was done later by Hammond and Norman (2014) and in a report by element energy (2014). Both works are partly based on the work by McKenna and Norman (2010). In both works the potential for recovering and using waste heat from industry for the UK is estimated by spatially modelling heat loads, related waste heat and nearby heat sinks around the waste heat sources. The recovery potential is then calculated by applying a techno-economic model. Within the models, competing technological options are evaluated for each source of waste heat and the best one is selected with regard to technical or economical objectives. Among the technological options considered, Hammond and Norman (2014) estimate the potential to cover the annual heat demand for different industry sectors through transportation of surplus heat, which is a case of inter-company heat integration. They assume a possible transportation distance of 10 km, and an efficiency of 50 %. In the report prepared by element energy (2014), 'over-the-fence' solutions connecting the modelled waste heat sources and nearby sinks are taken into account, also representing a case of inter-company heat integration. However, in both works, the modelling assumes only a single source-sink technology combination, i.e. point-to-point and not an integrated heat network. This approach may underestimate the potential saving due to inter-company heat integration, especially in 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 inter-company heat integration as well. Thus, papers dealing with the use of industrial waste heat in district heating networks might address inter-company heat integration in a wider sense as well. Examples can be found in Broberg et al. (2012), and Hummel et al. (2014).

Moreover, a few publications are explicitly dedicated to the field of 'inter-company 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 'inter-company energy integration' is the umbrella term for 'inter-company heat integration' and covers 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 inter-company 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 these 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.

Finally, Aydemir et al. (2016) point out the current gaps with regard to assessing the potential energy savings due to inter-company heat integration. A few case studies have been made, but only two (element energy et al. 2014, Hammond and Norman 2014) has addressed the potential savings for an entire region from utilizing waste heat, and also considered inter-company heat integration in a simplified way. Aydemir et al. argue that a framework to systematically assess the energy-saving potentials due to inter-company heat integration for regions might help to close these gaps, allowing structured studies for more regions and the consideration of inter-company heat integration as a saving option.

This is especially relevant given that inter-company heat integration is currently being addressed as a niche solution in the European Union's policy framework on energy efficiency as it is not addressed directly with regard to waste heat utilization compared to other technological options (cf. Article 14 in EP 2016). Studies identifying the potentials for inter-company heat integration for Europe could help to evaluate the prospects of this technological option.

Industrial symbiosis

'Sustainable development meets the needs of the present without compromising the ability of future generations to meet their own needs' (World Commission on Environment and Development, 1987). Industrial ecology aims to design sustainable production processes (Erkman, 1997). A basic concept of industrial ecology is that it looks to 'natural' ecosystems as models for industrial activity. It creates an industrial ecosystem to optimize the consumption of energy and materials. One core concept is to design production processes so that the waste of one process serves as the raw material for another (Chertow, 2000). In terms of material waste, this concept is often referred to as 'closing the loop' in material use or 'cycling'. In this sense, cycling refers to substituting virgin materials in production processes by used materials (Lyons, 2007). In terms of energy waste, industrial ecology aims to utilize generated energy as completely as possible by applying cascade-like processes. Using renewable energy sources for production processes could also be regarded as complying with the basic concepts of industrial ecology, as this is sustainable and based on the natural ecosystem. Industrial ecology also views firms as agents for environmental improvement as they possess the technological know-how to successfully implement the environmentally-informed design of products and processes (R. U. Ayres and L. Ayres, 2002).

Industrial symbiosis is a special case of industrial ecology. It describes a relationship between two or more firms exchanging their waste so that it can be used as feedstock for production (Marinos-Kouris and Mourtsiadis, 2013). The concept of industrial symbiosis was first fully realized in Denmark in an eco-industrial park in Kalundborg (Chertow, 2000).

Many concepts of industrial symbiosis require spatial proximity of the participating production sites. The question of what spatial scale is suitable for industrial symbiosis is discussed in the literature. For example, Marinos-Kouris and Mourtsiadis (2013) analyse previously identified and documented case studies of industrial symbiosis in Greece with regard to the issue of geographic scale. 455 case studies of industrial symbiosis in 16 eco-industrial networks were documented and structured by industry, category of waste utilized and spatial scale. They use five levels to categorize the spatial scale ranging from industrial park and local level up to global level. An interesting outcome with regard to inter-company heat integration is that some types of waste including superheated water are only transported at the smallest spatial scales – the industrial park and the local levels. Cases of industrial symbiosis are assigned to the industrial park scale when the producer and recipient of waste are located in the same industrial park. When the producer and recipient of waste are separated by a distance of up to 20 km they are assigned to the local level. This might serve as a first indication of the spatial proximity necessary for inter-company heat integration. Furthermore, the study concludes 'that industrial symbiosis does indeed have spatial conditions and limits that restrict potential applications'.

Based on the outcomes of this and other studies, it is obvious that the limits set by spatial conditions depend on the type of waste to be exchanged and the production processes applied. For example, the feasible spatial scale to exchange waste heat is obviously more limited than for many other types of material waste exchange due to heat losses. Chertow (2000) points out that especially firms operating pipe-to-pipe transfers of waste materials from primary processing industries that generate continuous-process waste are able to successfully apply industrial symbiosis concepts with nearby or co-located production sites. Lyons (2007) summarizes that 'the co-location model, in the form of manufacturing firms exchanging components within eco-industrial parks, has been less successful at by-product exchanges'. Furthermore, he states that 'pipe-to-pipe transfers or eco-industrial parks are unlikely to become the dominant models (even with the establishment of by-product exchanges) because very few firms will relocate solely to be part of a by-product exchange project'. Greenfield projects applying the eco-industrial park model are therefore a driver of industrial symbiosis. Nevertheless, there are examples where firms already located in close proximity subsequently created new industrial symbiosis linkages (Yang and Lay 2004). Such retrofitting can be described as brownfield development in the sense of applying the eco-industrial park model and it can also be a driver of industrial symbiosis.

Brownfield developments could profit from systems that identify and then support feasible agglomerations of production sites for the application of industrial symbiosis. Such systems could collect the relevant knowledge from different disciplines, structure it and help policy makers and project developers to identify promising agglomerations of production sites. This is especially feasible given the increasing capabilities in gathering knowledge from large data sets such as data mining. Furthermore, industrial actors are measuring and collecting more and more data to optimize their production processes using information and communication technology (Tao et al., 2015). The basic elements which should be included in such systems depend on the scale such systems are intended to cover (geographical, industrial, level of detail, etc.). These basic elements should at least contain information on technology and spatial proximity. Furthermore, information on economics might help to identify the most promising project possibilities.

We apply this basic idea to the field of heat integration and present a methodological framework to systematically estimate these potentials for regions. The framework combines methodologies from spatial analysis and heat integration. Co-location mining is selected as the spatial methodology to be applied within the framework as this seems to be the most suitable approach with regard to our overall objective. The methodology is then applied in a case study in which we combine information on the temperature ranges applied in industry with information on the location of industrial sites.

A framework to estimate energy savings for inter-company heat integration

The framework to estimate possible energy savings from inter-company heat integration proposed in this paper and in Aydemir et al. 2016 is based on two pillars:

- The first pillar focuses on the quantification of energy-saving potentials due to inter-company heat integration.
- The second pillar focuses on the identification of possible agglomerations of production sites with promising conditions for inter-company heat integration.

In this paper, we present a possible methodological approach for the second pillar. A possible methodology for the first pillar was presented in Aydemir et al. 2016. Here, we briefly summarize the first pillar approach in the following section and then discuss how the two pillars can be combined.

QUANTIFYING ENERGY SAVINGS BY INTER-COMPANY HEAT INTEGRATION

In order to quantify the energy-saving potentials of inter-company 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.

One option is to apply mathematical approaches to design theoretical HENs and to derive potential energy savings from these HENs. Mathematical approaches generate feasible HENs automatically. Objective functions are formulated to generate a HEN with minimum energy requirements. 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 minimised. An overview of the basic mathematical approaches to generate HENs is given in Escobar and Trierweiler (2013).

Aydemir et al. (2016) present a mathematical approach to estimate energy savings for inter-company HENs. The approach is based on the 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). Special attention is paid to aspects relevant for inter-company heat integration such as investments in pipes, and heat losses. Time-dependent load variations of the affected companies can also be addressed to a certain extent. The model is applied to evaluate a hypothetical case study of two production sites. The results indicate that relevant factors concerning inter-company heat integration such as the distance between production sites, or possible part-load operation can be plausibly addressed.

IDENTIFICATION OF PRODUCTION SITES FOR INTER-COMPANY HEAT INTEGRATION

A model to quantify energy savings for HENs as presented in Aydemir et al. 2016 and briefly summarized above could be applied to a huge number of case studies automatically. As a result, it would be possible to estimate the energy-saving potentials for regions due to inter-company heat integration. Methods from spatial analysis can be applied to search effectively for promising agglomerations. They can restrict the area regarded by limiting the combinations of production sites to be assessed. For example, a first step could limit the maximum distance between production sites. Given a data set of geo-referenced production sites, for example, co-location mining can identify combinations of sites that do not exceed this distance. These sites could then be evaluated with regard to the potential savings due to inter-company HENs. The framework's basic architecture is given in Figure 1.

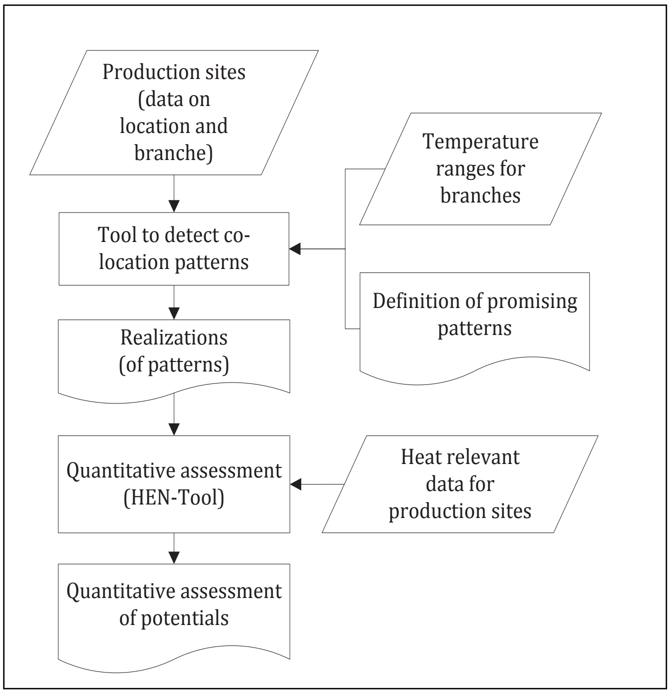

Figure 1. Framework to estimate energy savings due to inter-company heat integration.

Spatial analysis and relevant methodologies

Spatial analysis is the 'process of examining the locations, attributes, and relationships of features in spatial data through overlay and other analytical techniques in order to address a question or gain useful knowledge. Spatial analysis extracts or creates new information from spatial data' (Esri, 2016).

As mentioned in the chapter on industrial symbiosis, distances between production sites, and thus agglomerations of production sites are of major relevance with regard to the potentials for inter-company heat integration. Consequently, we assess methodologies from spatial analysis with regard to this question in the following and then present our reasons for using co-location mining in our analysis.

Several methods are available to measure spatial concentrations based on statistical approaches. In economics, the spatial concentration of one separate sector is traditionally analysed using the Gini-coefficient (Eckey et al., 2009). This method is not suitable for our overall question as inter-company heat integration is not restricted to only one industry.

Regional-econometric models such as the Decay-function or the Bi-Square-function (Eckey et al., 2009) are used to analyse the dependency between several sectors. A dependency between two industry sectors is given if they occur in close proximity to each other more frequently than other sectors. These approaches basically separate the area to be analysed into sub-areas and then measure characteristic values within these sub-areas. However, distances between production sites within the defined sub-areas are not taken into account so these models are also not suitable for our purpose as distance is a crucial factor for inter-company heat integration.

Finally, identifying co-location patterns is another spatial analysis option. Given a set of geographic object types categorized by features, a co-location pattern captures which objects typically frequently occur in close geographical proximity to each other. Examples for the discovery of such patterns can be found in many disciplines, e.g. in ecology, where the presence of different species in the same geographic area has been found for many species. The methodologies used to discover co-location patterns in spatial data sets can be categorized into statistics-based and data mining-based approaches (Van Canh et al., 2012).

Statistics-based methods measure the spatial correlation to characterize the relationships among features – in our case economic activities. A common spatial correlation measure is the cross-K function. The co-location between two different features is measured by comparing their cross-K function value with the cross-K function value of two completely independent features. If the cross-K function is greater for a given radius or distance than the value of the cross-K function of two completely independent features, then the features are said to be co-located. For example, in our case, the co-location of two economic sectors could be analysed by counting, for each production site, the number of sites around this production site from the other economic sector depending on the radial distance. This could then be used to calculate the concentration depending on the radius and compared with the concentration which should occur if the production sites are randomly dispersed (bivariate K-function approach). To depict a random dispersion, for example, the Poisson function might be used (Van Canh et al. 2012, Eckey et al. 2009).

Other approaches use methodologies from data mining. Thus, data mining-based approaches to detect co-location patterns in large spatial data sets are often called spatial co-location pattern mining. These approaches represent a sub-area from the field of spatial data mining. Spatial data mining can be described in general as a process to discover interesting, useful, non-trivial patterns in large spatial data sets. Usually measures are defined to rank patterns. One set of such measures is the prevalence of co-location patterns. The measure is defined based on the frequency of patterns appearing in the spatial data set analysed (Van Canh et al., 2012). However, measures can also be defined flexibly in terms of general needs. We use a co-location mining approach to conduct a first analysis for the following two reasons:

- The measures to rank patterns can be defined flexibly in spatial data mining approaches. For inter-company heat integration and other possible applications of industrial symbiosis, it is worth considering measures beyond frequencies. For example, for inter-company heat integration, information on temperature profiles is useful.
- Even if patterns are ranked and identified based only on frequencies, the structure of spatial data mining approaches usually allows the extraction of all 'realizations' (i.e. characteristic values) of patterns which leads to the ranking of patterns. Thus analyses can be conducted not only based on measuring patterns, but on 'realizations' of patterns.

With regard to our overall central objective – to identify the potentials for inter-company heat integration – a spatial co-location mining approach allows us to answer the two questions listed below.

- Which industry sectors are frequently located close to each other *with* promising conditions for inter-company heat integration?
- Where are the associated agglomerations of production sites located geographically?

For the analysis conducted in this paper, we use a tool which has been developed in a master thesis by our institute together with the Geodetic Institute (GIK) at the Karlsruhe Institute of Technology. The tool is a basic implementation of the co-location mining algorithm presented in Van Canh et al. (2012). It detects co-location patterns using a data mining approach. Furthermore, a measure to benchmark co-location patterns based on prevalence was proposed in Van Canh et al. (2012) and is also implemented in the tool. However, the prevalence measure implemented is based on the frequency of each pattern with regard to the number of objects contained within the underlying feature(s) (in our case production sites per economic activity) and is therefore a relative measure. This means there is a tendency to rank co-location patterns consisting of economic activities with a small number of production sites with higher prevalence indexes. As we are interested in detecting potentials, this benchmark makes no sense in our case. Consequently, we conduct our analysis based only on the frequency of the realizations of each pattern. This implies that we do not define at which threshold the occurrence of two features (i.e. two economic activities) constitutes a co-location pattern. As our goal is to demonstrate a potential model framework for the overall objective, the discussion about when occurrences of features in spatial proximity should be defined as co-location patterns is not our central focus nor relevant.

Database for case study

In our case study, we conduct a 'semi-quantitative' assessment for the combination of different industrial branches with regard to heat integration. To do so, we first analyse production sites listed in the European Pollutant Release and Transfer Register (E-PRTR) with regard to spatial proximity using a co-location mining approach The E-PRTR is treated as a spatial data set as longitude and latitude are assigned for each production site and it therefore contains spatial objects. The feature of each production site is represented by the statistical classification of economic activities in the European Community (NACE classification). The relevant attributes for our objective are the 'temperature profiles' depicting the process heat consumption for each industrial plant. This information is based on the study 'Datenbasis Energieeffizienz' (Rohde, 2013). The analysis therefore combines information on the location of production sites with information on the process heat temperatures typically applied in different branches. The following sections briefly introduce both data sources used.

EUROPEAN POLLUTANT RELEASE AND TRANSFER REGISTER (E-PRTR)

The E-PRTR is the European implementation of the 'Kiev Protocol on Pollution Release and Transfer Registers'. Pollutants emitted by industry to air, water and soil are documented in the E-PRTR for the European Union including Iceland, Norway, Liechtenstein, Serbia and Switzerland. Together with its predecessor, the register currently contains emission data for the years 2007 to 2013. The database is continuously updated. Affected companies have to update their data yearly. The European Parliament defines under which circumstances firms are obliged to report emissions from their production sites. Usually firms are obliged to report their emissions if they exceed thresholds for certain pollutants (e.g. SO_2). The goal is to set the thresholds so that 90 % of industrial emissions are covered. Each production site emitting pollutants above these thresholds is identified with a unique 'production site ID'. Besides the emitted pollutants, the longitude and latitude for each production site are contained in the data set. Furthermore, the main economic activity of the production sites is documented using NACE classification. Currently, the register encompasses more than 30,000 industrial production sites covering 65 economic activities across Europe.

The E-PRTR is a suitable data set for the purpose of this paper, which aims to present and apply a framework to identify agglomerations of production sites with promising conditions for inter-company heat integration. This is based on the following reasons:

- Energy-intensive industries usually also emit large quantities of pollutants so the E-PRTR should contain many production sites from energy-intensive industries.
- Because the coordinates for the production sites are given, the spatial dimension can be analysed in great detail.
- Many sectors are covered and the E-PRTR covers more production sites for the European Union than any other known data set (for example the data base for the European Union Emissions Trading System).
- As the main economic activities are given, assumptions can be made about the process temperatures applied to a certain degree.

However, the application of the data set also has weaknesses. Although pollutant emissions are given, the amount of energy consumed at the production sites can hardly be estimated. Pollutant emissions are not reliable indicators of any figure (i.e. the production value per year or capacity) which could help to estimate the energy consumed (own analyses). Furthermore, companies tend to try and decrease their emissions more and more by pollution prevention and end-of-pipe technologies for environmental reasons. So companies/production sites with a positive attitude towards sustainability might not appear in the E-PRTR. Finally, if thresholds are not lowered from time to time, technological improvements will eventually lead to fewer and fewer production sites being listed in the dataset.

THE STUDY 'DATENBASIS ENERGIEEFFIZIENZ'

To depict the process heat consumption of production sites contained in the E-PRTR, we use the relative share of final energy demand applied for process heat in separate temperature ranges categorized by industrial sectors. These shares are derived from the project 'Datenbasis Energieeffizienz'. This project developed a consistent and detailed database for primary, final and useful energy consumption differentiated by sectors (households, industry, commercial and trade, transport) and fields of application for Germany (Rohde et al. 2013).

In the project 'Datenbasis Energieeffizienz', the final energy demand for heat generation within the industrial sector is derived based on the energy balances prepared by the AG Energiebilanzen. In these energy balances, the final energy demand for industrial sectors is given differentiated by energy carrier. The final energy demand for process heat is derived conducting the following steps for each industrial sector:

- First, the final energy demand for fuels is calculated by subtracting the final electricity demand from the overall final energy demand. This calculation is based purely on the values given in the energy balances prepared by the 'AG Energiebilanzen'.
- Second, the share of the final energy demand for fuels used to generate mechanical energy is subtracted from the above result. Nowadays, this share is rather small, as it is mainly limited to applications driven by combustion engines (e.g. pumps and compressors driven by steam turbines). Furthermore, transport activities not included in the transport sector fall under this category. This share is calculated based on assumptions derived from the literature. Some uncertainties regarding sectoral distribution can be tolerated due to the minor share of this application.
- Third, the share of final energy demand for space heating and hot water is subtracted from the above result. This share is derived by combining official statistics and assumptions taken from the literature. In a first step, the office and production floor area are estimated per industry. This is done by multiplying the number of employees per industrial sector with the specific space requirements per employee. No comprehensive data are available on the specific space requirements per employee in German industry, so a specific value based on a comprehensive survey in the trade, commerce and service sector in Germany is applied to industry as well (Fraunhofer ISI et al. 2009). Finally, average values for the specific energy demand for space heating and hot water in German industry are used to calculate the overall share of final energy demand for space heating and hot water based on the areas previously calculated.
- Fourth, the final electricity demand to generate process heat is added to the result above. This is based on the fact that many process heat applications require electrical energy such as the electrolysis process in the aluminium or copper industry. The demand is basically estimated by taking into account the specific electricity consumption for the appropriate process and the production value of the assigned product per year. Thus, the fourth step yields the final energy demand for process heat per industry.
- Finally, the share of process heat per temperature range is estimated. This is defined as the 'temperature profile' in the following. A basic source for this is Hofer (1994), who conducted an analysis of the process temperature ranges applied in different industry sectors. Hofer (1994) analysed the processes applied in the examined industries. The original goal of the analysis was to estimate potentials for combined heat and power plants.

An overview of the approach is given in Figure 2. Finally, we use the estimated final energy demand for process heat per industry sector, and per temperature range presented in Rohde et al. (2015) to calculate a relative share for the separate temperature ranges for each industry sector. The industry sectors are then structured using the NACE classification. Please note finally that we use the temperature profiles from the project 'Datenbasis Energieeffizienz' to depict the process heat consumption for all industrial production sites contained in the E-PRTR. We are therefore assuming that the temperature profiles based on data for Germany are representative for Europe as well.

Analysis based on E-PRTR

Here, we present our approach and an extract of the results for our 'semi-quantitative' assessment of sector combinations contained in the E-PRTR. First, we extract all the co-location patterns (in our case combinations of NACE classes representing industry sectors) contained in the spatial data set including the frequency of realizations. Although distances of up to 20 km for the transport of superheated water can be found in the literature (Marinos-Kouris and Mourtsiadis, 2013), we set a rather conservative maximum distance between production sites of 10 kilometres in line with Hammond and Norman (2014). It should also be noted that we present co-location patterns (called patterns in the following) based on only two features. A pattern is defined as a combination of two or more industry sectors (or NACE classes) occurring frequently in the data set. The realization of a pattern therefore represents two production sites from two industry sectors located in spatial proximity to each other at a maximum distance of 10 kilometres. In principle, combinations of more than two sectors/production sites could be analysed as well.

We then apply the temperature profiles for each combination of sectors and derive a characteristic combination of temperature profiles for each pattern. We observe combinations where one of the two sectors has high shares at higher temperatures and the other has high shares at lower temperatures. This might be called a V- or U-shaped combination and an example including frequency is shown in Figure 3.

We also observe sector combinations where both sectors have high shares at either lower temperatures (L-shape) or higher ones (J-shape). An example is given in Figure 4. Overall, 240 patterns with approximately 25 thousand realizations formed the basis for analysis. Please note that so called 'self-

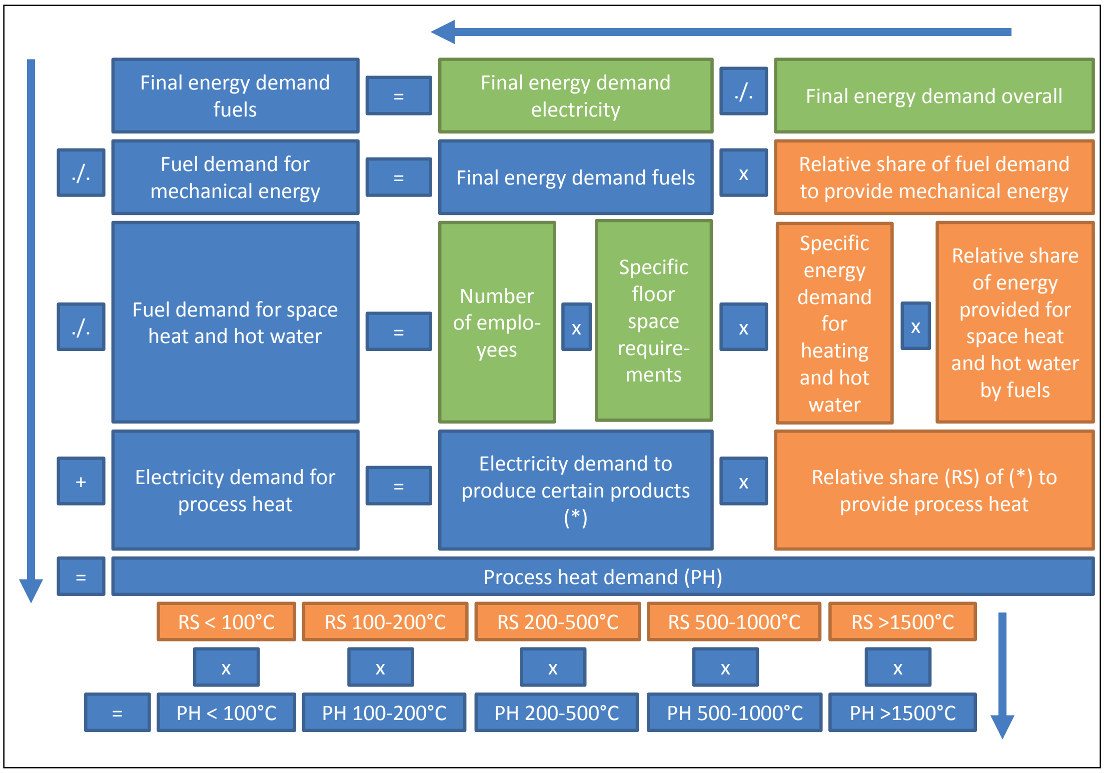

Figure 2. Concept to estimate the process heat demand in line with the study 'Datenbasis Energieeffizienz'; 'x' indicates a multiplication; './.' indicates a subtraction. Green: derived from statistics; Orange: derived from literature; Blue: calculated/modelled.

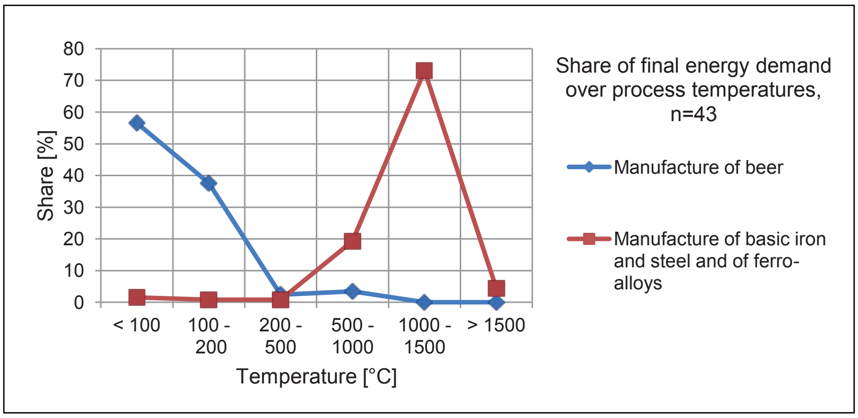

Figure 3. Example of a V- or U-shaped combination (n indicates how often the pattern consisting of the two sectors "Manufacture of beer" and "Manufacture of basic iron and steel and of ferro-alloys" occurs in the data set).

patterns' are included within these 240 patterns. These refer to two production sites of the same sector occurring in spatial proximity. For 25 % of these 240 patterns, the number of realizations was 4 or below; another 25 % had 34 realizations or below; a further 25 % had realizations of approximately 98 or below and the pattern with the most realizations was a 'self-pattern' with approximately 2,410 realizations. The average is around 100 and the standard deviation about 225.

One suggestion is to use the frequency of patterns to delimit the total number of patterns to promising ones. Patterns with a high frequency, i.e. with a high number of realizations, could be treated as promising with regard to inter-company heat integration. One possible argument supporting this is that there are reasons why some industries frequently occur close to each other in the supply chain. For instance, if one industry is the supplier for another industry in close spatial proximity. If relationships between sectors and thus production sites already exist, this would indeed be an advantage with regard to realizing inter-company heat integration concepts. However, whether certain types of sectors are a good match in terms of inter-company heat integration does not depend only on the perspective of supply chains. The process temperatures usually applied also have to be taken into account. Certain industries which are not linked by their supply chains may be a good fit in terms of the process temperatures applied. One example is a primary steel factory located near a paper producer. Primary steel production usually requires high temperatures and produces waste heat between 130 °C and 650 °C (Hirzel et al., 2013). This heat could be used to generate the steam needed for pulp and paper production. Thus, we delimit the patterns using information on the process temperatures typically applied. We assume V- or U-shaped patterns to be the most promising ones for inter-company heat integration. This presumes that the sector which uses process heat at higher temperatures produces waste heat at higher temperatures as well, which could then be used to supply heat to the sector with high shares at lower temperatures. Inspecting all the figures only visually might be too subjective, so we defined two criteria for a V- or U-shaped pattern. For six temperature intervals given, the criteria are defined as follows:

$$\left| \sum_{T_i}^{T_n} RS_{Sector\ 1,\ T_i} - RS_{Sector\ 2,\ T_i} \right| \geq 0.3\ ,$$

for i = 1 to n=3 (lower end), and for i = 4 to n=6 (upper end).

The resulting number of promising patterns is given in Table 1 and compared to the frequency of patterns. Using the approach presented above, we identified 51 interesting patterns accounting for 19.3 % of realizations. The results are illustrated on the map in Figure 5. The blue interconnections (blue bars) indicate promising constellations according to our definition.

The regions featuring promising patterns could be assessed in the next step with regard to inter-company heat integration. This would involve filtering promising constellations of production sites. We do this step for a randomly chosen region in the province of Gipuzkoa, Basque Country, Spain, as an example. A section of this region is shown on the map in Figure 6. Within the section, 13 production sites are located with 26 possible interconnections between them not exceeding a distance of 10 kilometres. The sectors and number of production sites are given in Table 2.

Of the 26 possible combinations, 12 seem to be promising for further assessment at first sight. A further step would be to gather information about the heat requirements including information about the energy carriers (hot water, steam, etc.), heat, power and amount required, load profiles etc. to assess the combinations in a more detailed analysis using methodologies from heat integration. Taking piping and associated costs into account would be of major relevance and a methodology similar to that presented in Aydemir et al. (2016) could be applied in further case studies.

Summary

This contribution began by pointing out the current gaps with regard to assessing the potential energy savings due to inter-company heat integration. A few case studies have been made, but only two (element energy et al. 2014, Hammond and Norman 2014) has addressed the potential savings for an entire region from utilizing waste heat, and also considered inter-company heat integration. Element energy (2014) and Hammond and Norman (2014) analysed the potential for recovering waste heat from industry in the UK and included 'over the fence' solutions, i.e. inter-company heat integration. Furthermore, there are no known studies for Germany or other countries. Thus, we argue that a framework to systematically assess the energy-saving potentials due to inter-company heat integration for regions might help to close these gaps and allow structured studies of more regions.

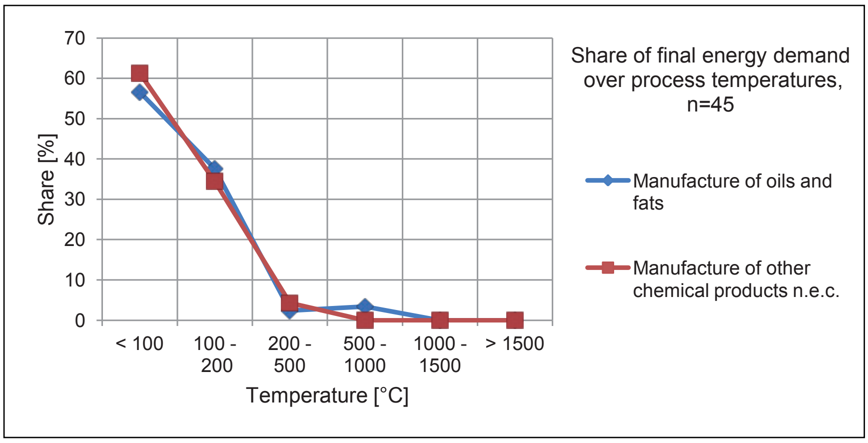

Figure 4. Example of an L-shaped combination.

Table 1. Patterns per type in the analysis.

	Number of patterns (including self-patterns)	Number of realizations	Relative share
V-or U- shaped (number of realizations <34).	16	148	0.5 %
V-or U- shaped (number of realizations ≥34).	35	5,607	18.8 %
Other	205	24,219	81.2 %
Sum	240	29,826	100.0 %

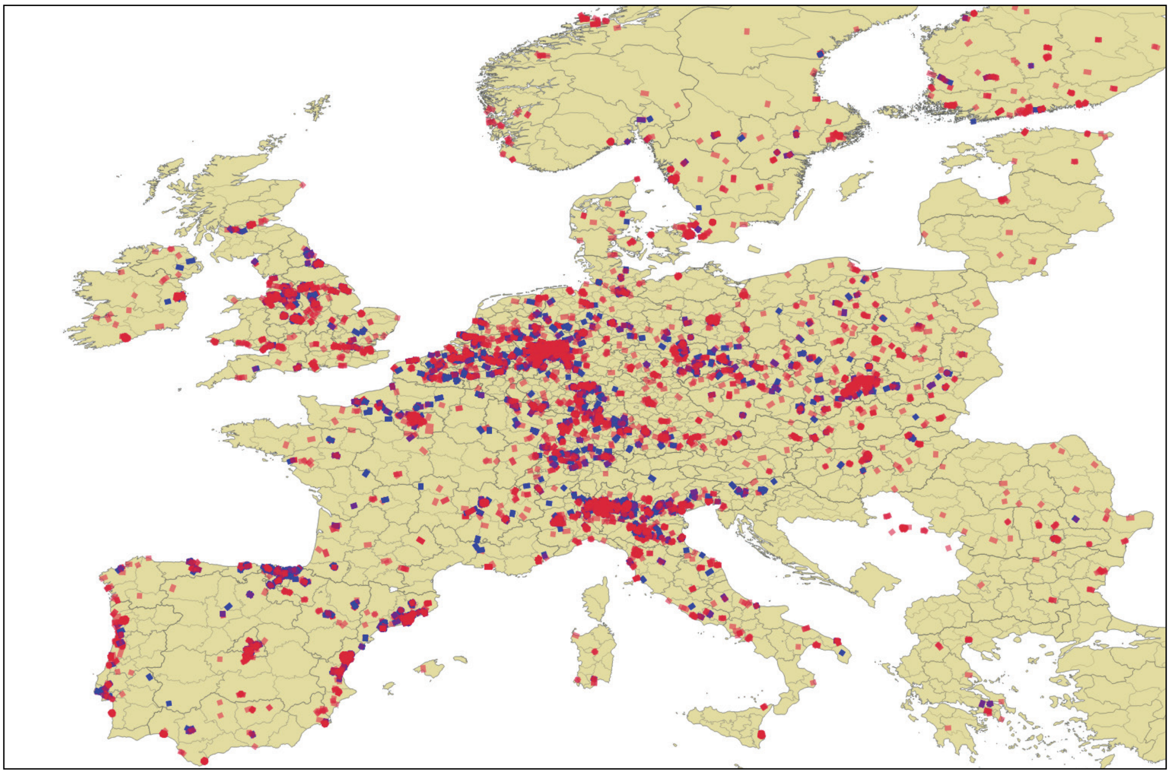

Figure 5. Map of the analysis based on the E-PRTR (possible interconnections of two production sites represented by blue bars fulfil the criteria mentioned above).

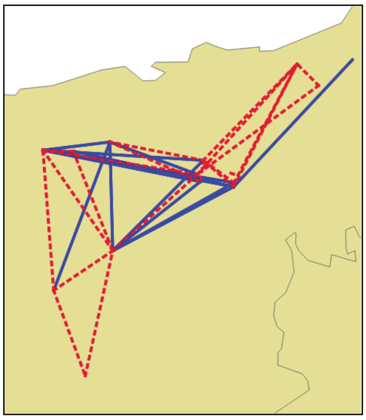

Figure 6. Section of exemplary filtering (possible interconnections of two production sites represented by solid lines fulfil the criteria mentioned above).

Table 2. Facilities within the exemplary section.

Number of production sites	Sector
3	Manufacture of paper and paperboard
5	Manufacture of other inorganic basic chemicals
1	Manufacture of plastics in primary forms
1	Casting of light metals
1	Casting of iron
2	Treatment and coating of metals

We then pointed out that inter-company heat integration is a special case of industrial symbiosis, introduced basic terms and placed them in the context of inter-company heat integration. The spatial proximity of participating production sites plays a major role for economic efficiency, especially for inter-company heat integration. This raises the general question of what spatial scale is suitable for industrial symbiosis. Several papers addressing this question were summarized with the conclusion that the spatial conditions limiting the potentials for industrial symbiosis depend on the symbiotic actions considered. Finally, a first indication of the maximum feasible spatial scale for inter-company heat integration of 20 kilometres was found based on a study of industrial symbiosis in Greece.

We then presented the proposed methodological framework to estimate energy savings from inter-company heat integration. This combines methodologies from spatial analysis and heat integration. We argued why spatial co-location mining seems to be the most suitable spatial methodology with regard to the overall objective.

Finally, spatial co-location mining was applied in a case study. Within the case study, information about the location of production sites was combined with information about the process heat temperatures typically applied in different branches and used to identify agglomerations of production sites with promising conditions for inter-company heat integration. We demonstrated that spatial co-location mining can help to identify interesting agglomerations of production sites for inter-company heat integration.

Outlook

Further research is needed to validate the criteria applied to filter promising agglomerations of production sites for inter-company heat integration. Based on this, prevalence measures for inter-company heat integration could be developed. These measures could be implemented directly in the spatial co-location mining approach. Moreover, prevalence measures could be developed to include other fields of industrial symbiosis as well and be implemented in the co-location mining approach. This could be done, for example, with regard to topics dealing with material efficiency. Furthermore, the data basis for analysis could be improved. A first step would be to depict the process heat temperatures applied in production sites using a bottom-up approach so that the technologies used are addressed in more detail. This would help to estimate industrial symbiosis in general. Finally, the next step would be to develop an integrated model that combines spatial co-location mining including new prevalence measures with simplified methodologies for heat integration and then to conduct sensitivity analyses.

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