PEER-REVIEWED PAPER

The suitability of different types of industry for inter-site heat integration

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Abstract

Several studies have shown that some highly-intensive processes are suitable for heat integration with each other (inter-site heat integration). This paper shows the results of an integration of the waste heat sources and potential sinks across several industries which have not yet received much attention for inter-site heat integration. The purpose of this paper is not to suggest that any particular configuration is currently possible, it is to demonstrate the significant theoretical savings and stimulate discussion of the where future research (e.g. into high temperature heat exchangers or solid to gas heat exchangers). By building two theoretical heat exchange networks, one to maximise heat recovery and one to maximise electricity generation, the characteristics of different process streams which are conducive or obstructive to successful, profitable integration can be identified. Heat recovery is slightly more profitable than electricity generation on first examination, but there are several major issues which are difficult to quantify and will add significant cost. In general, processes involving large quantities of liquids and condensing and evaporating gases, such as refineries, offer significant potential. Processes with incondensable, low-pressure gases and solid streams, such as cement plants, generally gain less profit from inter-site heat integration. All costs are in 2013 Euros.

Introduction

INDUSTRIAL SYMBIOSIS (IS)

Industrial Symbiosis (IS) is defined as "engaging traditionally separate industries in a collective approach to competitive advantage involving physical exchange of materials, energy, water, and by-products. The keys to industrial symbiosis are collaboration and the synergistic possibilities offered by geographic proximity" (Chertow, 2000). The term was first coined in 1989 after the chance discovery of significant symbiosis at Kalundborg in Denmark; the network of flows was mapped by children from the local high school as a project. Other networks have been 'discovered' since. Generally, they cluster around an 'anchor tenant' (or 'hub firm') (Chertow, 2000).

Industrial symbiosis falls within the discipline of industrial ecology, which aims to mimic the cyclical use of resources within nature to develop more efficient processes within society. However, societies are not organised in the same manner as nature, and thus the mimicry can never be complete. For example, some waste streams from an industry cluster may not have a potential use (Tudor et al., 2007).

IS networks bring economic, environmental, business and social benefits to the companies, regions and people involved. These benefits are based on assumption that the improvements can only be achieved through collaboration, improvements are brought about at different levels and innovation is stimulated (Mirata and Emtairah, 2005).

HEAT TRANSFER WITHIN IS

Whilst much work has concentrated on material flows within a single network, relatively little has been done on transferring heat between sites. A UK Government report suggests that 10–

40 TWh of heat is currently lost from industrial sources in the UK (Department of Energy and Climate Change, 2013a). Heat can only be efficiently transported short distances (20–30 km) compared with materials (Fang et al., 2013). However, plenty of reported opportunities for heat transfer between different closely situated sites (inter-site heat integration) exist. Creation of these networks has hitherto been serendipitous rather than planned (Ehrenfeld and Gertler, 1997; Gibbs and Deutz, 2007; Chertow, 2007). The emergence of the concept of planned eco-industrial parks (EIPs), in which a central agency designs the park, has led to the study of spontaneous EIPs such as Kwinana (van Beers et al., 2007) and Kalundborg (Jacobsen, 2006) to understand what makes symbioses successful.

Spontaneous EIPs tend to exchange more material flows than energy flows between their members. Furthermore, the heat flows tend to be concentrated around certain types of industry more than material flows. Refineries and power stations tend to exchange heat, whereas other highly energy-intensive industries, such as steel mills and cement plants, are only rarely deeply involved (Hashimoto et al., 2010). Biofuel plants (Martin and Eklund, 2011), and forest product plants (Karlsson and Wolf, 2008; Sokka et al., 2011) have also been studied.

COMPETITION WITH OTHER USES

Waste heat can be used in district heating systems. One benefit of district heating systems is that the heat does not have to be of high quality, usually being between 100 °C and 40 °C (Lauenburg and Wollerstrand, 2014; Skagestad and Mildenstein, 2002). This use depends on nearby settlements being large enough to use all the heat, and the seasonal variation in demand not being a problem for the industrial plants. For example, a study of Linkoping's district heating system showed ~ 40 GWh July demand, vs 210 GWh for January (Henning et al., 2006).

Another common use of waste heat is for electricity generation. A major benefit for industrial sites of using waste heat in this manner is that there is no dependency on other companies, organisations or governments, as no heat crosses the site boundary. Raising steam or another vapour for a Rankine or Kalina cycle is a common generation technique. If heat is also being generated for use, construction of a combined heat and power (CHP) plant can also generate electricity (Environmental Protection Agency, 2008). UK CHP capacity as of 2013 was 6.1 GW_e, with a technical potential of 18 GW_e by 2020 (Department of Energy and Climate Change, 2013a).

Models of selected industries

SELECTION OF INDUSTRIES FOR INVESTIGATION

An integrated steel mill, cement plant, fertiliser plant and recycled paper plant were chosen as they represent a high proportion of the energy used in the industrial sector but have received little academic study with regards to industrial heat symbiosis. The steel and pulp and paper industries are responsible for 16 % of UK industrial energy demand alone (Department of Energy and Climate Change, 2013b). Fertiliser manufacture is responsible for 1.2 % of total global energy demand (IPCC, 2007).

MODELLING OF THE PLANTS

All the models are simplified versions of the plants, with less energy-intensive sections omitted. Ancillary loads, such as heating of offices and their water supplies, are also excluded. Inclusion of all sections of a plant would greatly increase the complexity whilst only moderately increasing the accuracy of the models. The plants were modelled and internally optimised in Microsoft Excel.

CEMENT PLANT

The cement plant is the simplest model, with 16 streams and 6 components. There are four process units: the preheater, the precalciner, the kiln and the clinker cooler. It is a counter-current process of gases and solids. The plant produces 105 kg/s (3 Mtpa) of clinker. The grinding and homogenisation steps at the beginning and end of the cement-making process are excluded as they use mainly electrical rather than thermal energy. Total plant electrical load is assumed to be 90–150 kWh/t clinker (Bhatty et al., 2011). Losses from the four units modelled are based on literature values (Mujumdar et al., 2007). Stream temperatures are taken from (Bhatty et al., 2011). The heating value of the coal (0.107 kg/kg clinker) is similar to that from others (Barker et al., 2008).

Combustion of fuel in the kiln and precalciner produces heat, which is continuously transferred from gas to solid phase in the kiln, precalciner and preheaters. This is reversed in the clinker cooler. There are several reasons why BAT cannot move much closer to the thermodynamic limit (IEA-WBCSD, 2009). Average thermal energy requirements for cement plants are around 3.9 GJ/t (BAT is around 2.8 GJ/t) (IEA, 2012). This model's thermal energy requirement is about 3.2 GJ/t and about 500 MJ/t clinker leaves the plant via the preheater exhaust at about 590 K, about 16 % of thermal energy demand.

Converting the cooler to accept a warmer stream of air from another process as well as the cool, fresh air would raise the temperature of the secondary and tertiary air entering the kiln, directly reducing fuel requirements. The preheater air is relatively dry, but dusty. After dust removal (which will reduce the temperature) it may be suitable for use in other processes.

RECYCLED PAPER PLANT

This plant produces packaging cardboard from recycled paper. The process to make most paper products from recycled waste is similar. There are 14 units in the simplified process. The mill has 29 streams, but only 4 components (water, paper, oxygen, nitrogen). The paper plant uses a significant amount of electricity, but little thermal energy.

The largest recycled paper mills in the UK produce about 400 ktpa paper ("The mill," 2013; "PM11," 2013). The plant modelled produces ~ 432 ktpa, from ~ 15 kg/s of recycled paper. The recovery rate of paper is 89 %; the losses are in the rejects and the short fibre fines. Because most water is recycled in the process, paper sludge from wastewater (rather than from reject flows) is neglected.

(Fleiter et al., 2012) gives a recycled paper electricity use of 260 kWh/t pulp. There is an electricity demand of 329 kWh/t pulp in this plant. The hot water from the recovery unit heats the water entering the pulper. The steam is used in the dryers and the water heater.

This plant is not very thermally energy-intensive, but some heat is required to bring the pulping water up to 333 K and to dry the paper. A major thermal energy supplier is the refiner, generating 2.6 GJ/t paper product. Most of this is used in the drier, but some is used in the pulping water heating. Hot water is also produced by the refiner and is also used to heat the pulping water.

The hot water cycle could be upgraded by use of higher-grade waste heat to generate medium pressure steam, providing more than the extra energy required for the water heater. Some plants have integrated CHP; this would generate some of the electricity required for the mill. The 6 bar refiner steam could run a turbine, as could medium pressure steam produced by upgrading the hot water cycle, though the pressure here would be dictated by the quality of the waste heat used. For example, the waste heat coming from the cement plant's preheater exits at 473 K, so saturated steam at up to 10 bara could be produced.

Omitted processes

Bleaching, dispersion, and de-inking are the major parts of the pulp-making process omitted because they are mainly chemical processes and thus are not relevant for energy integration; however, the electricity demand is included in the model. Further processing of the paper after drying, which can be rather energy-intensive for some papers, is relatively small for production of packaging cardboard (European Commission, 2001).

STEEL PLANT

The steel plant is the most complicated model, with 42 streams and 7 units. There are 19 components. The production rate used in this report is 121 kg/s, which is slightly larger than the SSI plant at Redcar, UK (61 kt/week) (Karen McLauchlan, 2013). Electricity has not been included in this model, but literature values have been used (Remus et al., 2013). The consumption is approximately 480 MJ/t liquid steel.

Heat is provided by natural gas, coal, coke and the fuel gases produced from the coke oven, basic oxygen furnace and blast furnace. The thermal energy requirement, measured by the amount of coal used within the plant minus the energy content of remaining fuel gases, is 13.5 GJ/t HM, approximately equal to BAT. Global average thermal energy requirement is 21 GJ/t crude steel (IEA, 2012). Most of the energy for the mill comes from the coking coal, which provides about 70 % of the thermal energy. Natural gas provides another 10 %, with bituminous coal injected into the blast furnace providing the balance.

The integrated mill is reasonably high-temperature, and generally an energy donor. The most readily available streams for use in other plants are either the fuel gases going to the power plant or the flue gas coming from it.

Omitted processes

Major omitted processes include the hot rolling and forming stages after the BOF. Although it is possible that they could be integrated into the heat network, the variability in design makes modelling quite difficult. Some of the energy in the product is required and used in the later stages of steel product manufacture, such as forming and rolling. The final product from this plant is assumed to be liquid steel, and energy and exergy are calculated accordingly.

FERTILISER PLANT

Modern fertiliser plants are well-integrated, with several processes occurring on one site. The model for this plant is significantly different from the others, as it treats each of the major process units within the site as black boxes, rather than modelling each unit. This is due to a lack of information in the literature. Although this reduces the amount of detail, modelling of the inputs and outputs of the NPK production route was possible. The fertiliser modelled is 20 % nitrogen, 6 % P_2O_5, 12 % K_2O, and 20 % SO_3 on a weight basis. Excess heat is usually captured and transferred between processes as saturated or superheated steam up to 40 bara in pressure. Some electricity (4.5 MW) is generated from expansion of some of the high-pressure steam.

This plant produces 500 ktpa. To put this in context, the largest European plant is BASF's Antwerp plant (1200 ktpa) and the UK's largest is Kemira GrowHow (630 ktpa) (European Commission, 2007).

Natural gas (930 MJ/ton of product) is required for heating. The plant produces more steam than it requires. Steam transports significant flows of heat from the sulphuric acid and nitric acid plants to the other processes, especially the ammonia, phosphoric acid and neutralisation plants.

Methodology: Heat Exchanger Network

By placing a heat exchanger (HEX) between two streams, one having excess heat (the 'hot' stream) and the other requiring heat (the 'cold' stream), energy can be passed between them.

The hot and cold streams are usually passed through a heat exchanger which keeps the two streams separate. Sometimes, however, the streams come in direct contact, such as the solid and gaseous phases in cement production. The energy transferred across a heat exchanger can be calculated by:

$$Q = UA\Delta T_{lm}$$

Q is the heat transferred (W), U is the overall heat transfer coefficient (W/m^2K), A is the contact surface area of the heat exchanger and ΔT_{lm} is the log mean temperature difference across the heat exchanger.

HEAT EXCHANGER NETWORK (HEN) SYNTHESIS VIA PINCH ANALYSIS

Coupling of a small number of hot and cold streams is simple, but when there are many, trial and error is no longer sufficient. Pinch analysis is used across the process industries to develop more effective and efficient heat exchanger networks (HENs). It does not necessarily minimise cost or maximise payback, and it does not include any costs of HEN construction and operation.

Pinch analysis has several stages. Firstly, the streams requiring heating and cooling, their heating duties and the utilities currently required must be characterised. A first-law analysis quantifying the heating and cooling duty can be undertaken. This is relatively easy but because it does not include temperatures, the result does not necessarily abide by the second law of thermodynamics (Douglas, 1988; Seider et al., 2008).

As heat transfer is proportional to the temperature difference of the two streams, a very low temperature difference will lead to very large heat exchangers, so a minimum approach temperature is defined. This is incorporated into a cascade diagram, which is used to find the 'pinch point' of the system. Heating utilities should only be used above the pinch temperature, and only cooling utilities below. Heat must not be transferred across the pinch temperature. Correct identification of the pinch temperature and following these rules prevents the overuse of fuel and cooling water.

The HEN for the site is then developed, working out from the pinch. This generates a heat exchanger network that should contain a number of heat exchangers equal to the sum of the number of streams and utilities, minus one. Some streams will flow through more than one heat exchanger, and some streams may temporarily split to better effect network synthesis.

In this paper, η_1 represents the energy efficiency of the system, η_2 represents the exergy efficiency including the exergy leaving in all streams, and η_3 represents the exergy efficiency only taking into account the exergy that leaves in the primary product stream.

Results from the TMES model

Exergy analysis of the original plants

The exergy consumption of the original plants is shown in Table 1. Note that there are several other exergy-containing streams (such as ores) flowing into the plant which have not been quantified; however, these will not change due to heat integration and their exergies are relatively small compared with fuels and products. Positive values represent flows out of the system, and negative values flows in to the system. Thus, the overall balance should be a negative value. It is also important to note that the negative values for energy are due to losses within the plant such as heat loss from pipes, rather than emission of the material from the pipe, as the latter are accounted for in the values included in Table 2.

The recycled paper plant has by far the highest exergy efficiency of the plants. This is mainly because the processing does not involve many chemical changes, but mainly re-pulps and dries the paper. The fertiliser plant, on the other hand, destroys significant exergy owing to the need to produce energy-intensive chemical compounds such as ammonia. Although a large quantity of exergy leaves the plant in the fertiliser stream, the use of natural gas as a fuel and feedstock results in lower exergetic efficiency.

THE INTER-SITE HEAT EXCHANGER NETWORK

First-law analysis

Table 2 shows the streams which were integrated in a heat exchanger network after the analysis of the original plants, and their heating or cooling requirements included in the analysis. Note that the blast furnace gas, coke oven gas and basic oxygen furnace gas in the steel mill are not considered to be waste heat streams as they are used effectively as fuel gases in the steel mill. Note that the first-law analysis shows that there is less demand for waste heat than supply; however, this does not take into account the temperature of the heat. Streams which lose both sensible and latent heat are counted as two separate streams for pinch analysis purposes.

A program originally developed for teaching heat integration, called Hint, was used in this study (Martin, 2002). A cascade diagram and grand composite curve were generated. With the selected minimum approach temperature (ΔT_{min}) of 10 K, the hot streams are of sufficient quality (i.e. temperature) to satisfy all of the heating demands of the cold streams. In other words, there is no theoretical requirement for extra heating beyond that which is inherent in the combination of processes, and the cooling demand is 154 MW, as demonstrated by the first law analysis. Thus, the pinch is above the maximum temperature in this system, which is 1,918 K after alterations for ΔT_{min}. There is significant excess heat in the 400–800 K range. Some of this is used for heating colder streams but the rest could be used in waste heat recovery systems.

Heat exchanger network

The properties of the heat exchanger network are shown in Table 3. Several of the steam streams in the fertiliser plant have the same pressure; for this reason they were merged to flow into one heat exchanger as this is more cost-effective. The only 'net' replacement of fuel within the resulting network is of natural gas and other fuel gases in the blast furnace stoves (part of the steel mill). This is achieved by using a mixture of high temperature streams such as the slags, as well as lower grade heat such as coke oven flue gas. Thus, the difference in exergy between those fuels and the streams now used for stove heating is saved.

Use of excess steam – power generation and carbon capture

With an excess of steam on site, it would seem sensible to co-locate another plant that could use it. Thermal power plants require steam, and could use this energy to generate electricity. Carbon capture plants also require significant quantities of energy; amine scrubbing plants require 2.2–3.5 GJ/t CO_2 captured (Ahn et al., 2013). The lower pressure steam, whilst not particularly suitable for efficient power generation, could be used to provide energy to capture CO_2 emissions emanating from the industrial plant on-site. An amine-based CO_2 capture plant making use of all of the excess steam available from the network could capture 4.0–6.4 Mt CO_2/y. For comparison, a steel plant on the scale modelled here would produce 10.4 Mt CO_2/y. The rest of the energy for capture would have to come from other sources. Alternatively, an amine capture plant could be built to capture only the most concentrated CO_2-containing streams whilst carbon prices are low. As the carbon price rises and capture technologies become increasingly cost effective, a larger plant could be built to capture the remainder of the CO_2 emanating from the EIP. Estimation of the larger capture plant's footprint would have to be taken into account when designing the layout of the EIP.

Exergy results

The 485 MW fuel savings are very high in exergetic efficiency; indeed, the assumptions about their exergetic efficiency mean that this is 485.4 MW of exergy savings, too. However, there are some changes in other streams. Apart from the fuel savings, the blast furnace slag is now enters the environment at a different temperature, and the steam produced in paper manufacture is now not used. The 40 bara steam is now kept within the utility system rather than expanding to generate 4.5 MW_e. The net effect is that energy savings are reduced by 138 MW to 347.6 MW but exergy savings are only reduced by 0.5 MW due to the higher quality of the remaining energy.

Table 1. Unaccounted energy and exergy losses in the four plants before integration.

Description	Fuel inputs	Unaccounted Losses	
	Energy = Exergy (MW)	Energy (MW)	Exergy (MW)
Cement Plant (η_2=58 %)	2,738	118	151
Steel plant (η_2=68 %)	365	112	879
Paper plant (η_2=86 %)	327	21	47
Fertiliser plant (η_2=42)	3,556	47	119
Total	**6,986**	**-298**	**-1,196**

Table 2. Hot and cold streams from the four selected industries. Note that an S at the end of a stream code denotes sensible heat, and an L denotes latent heat (i.e. phase change).

Plant	Stream	Heat Capacity (kW/K)	Initial temperature	Target temperature	Energy available (MW)
HOT					
Steel	S2	39.4	1,373	353	40
	S14	165	1,773	373	231
	S24	20.7	1,923	373	32
	S42	587	1,123	600	307
Cement	C2	200	1,200	589	122
	C13	101	1,650	373	129
Paper	P12	16.4	440	330	2
	P13L		440	440	25
	P13S	51.7	439	353	4
Fertiliser	F6S	33.3	693	485	7
	F6L		485	485	23
	F7L		373	373	16
	F8S	14.5	693	524	2
	F8L	9,848	524	523	10
TOTAL					943
COLD					
Steel	S4	134	300	560	-35
	S38	400	300	1,373	-430
Cement	C1	175	300	1,069	-135
	C14	172	300	1,048	-129
Paper	P23S	56.0	301	353	-3
	P23L		353	353	-20
	P2	265	300	333	-9
Fertiliser	F1		453	453	-13
	F2		453	453	-4
	F3		443	443	-6
	F4				-6
	F5		453	453	-3
TOTAL					-791

Table 3. Properties of the heat exchanger network.

Characteristic		Value	Unit
Steam production (energy)	5 bara	0.1	MW
	40 bara	96.8	
Fuel savings (energy)		485.5	MW
Number of heat exchangers		16	
Of which for steam generation		2	
Total heat transfer area of HEN	Heat integration	20,205	m^2
	Steam generation	5,263	
Lowest heat transfer coefficient		106	W/m^2K
Highest heat transfer coefficient		2,000	
Cost of HEN	Heat integration	13.5	€M
	Steam generation	1.3	
Specific cost of HEN		17	€/kW
Payback period		43	Days

Table 4. Energy and exergy savings.

		Energy requirement	Energy not in product	Exergy in	Exergy destroyed
Steel	MW	2,738	1,303	2,737	879.3
Cement	MW	362.8	171.3	364.3	151.4
Paper	MW	327	76	327	47.5
Fertiliser	MW	128	69.3	183.3	106.1
TOTAL	MW	3,555.8	1,619.6	3,611.6	1,184.3
Savings	MW	347.6	347.6	484.9	484.9
		10 %	**21 %**	**13 %**	**41 %**

Table 5. Costs of the four fuels used in this report (Department for Energy and Climate Change, 2013c).

Energy Carrier	Natural Gas	Coal	Electricity	Diesel
Cost (€/GJ)	8.01	3.54	24.83	41.71

ECONOMIC AND TECHNICAL ANALYSIS OF THE TMES NETWORK

Costing methodology

It is well-documented that uncertainties in costs decrease as the detail with which a design is produced increases. At the level of detail undertaken here (i.e. the process is only at the conceptual level), the cost uncertainties are about 30–50 % (Green and Perry, 2007; Gerrard, 2000). With large fluctuations in the prices of fuels and equipment likely in future, the economic viability of the results below are very general and the quantitative results are used to draw only qualitative conclusions. The costs are calculated in 2013 EUR using the exchange rate of 3rd June 2013 of \$1.30 = €1.00 = £0.85 (International Monetary Fund, 2013).

Purchased and installed cost of process equipment

A heat exchanger, boiler or other piece of process equipment must be bought from a supplier. In this paper, averages of purchased costs calculated from (Douglas, 1988); (Seider et al., 2008; Loh et al., 2002; Gerrard, 2000; Peters et al., 2003) were used. The Chemical Engineering Process Cost Index (CEPCI) (Dorothy Lozowski, 2014) was used to inflate costs with time. Garrett factors were used to include the installation costs from purchased costs. An automation factor of 1.2 was included (Brown, 2000).

Other issues and assumptions

Installation of heat exchangers and associated equipment to reduce fuel use will lead to redundancy of boilers and coolers. However, the retention of these units enables continued production during heat exchanger maintenance or when one or more plants are not operating at design output. Independent operability is expected to be required plant managers in the symbiotic relationships; indeed, plants often have back-up boilers for when certain units or heat exchangers go offline. Thus, their cost is not subtracted when installing new units. In reality there may be reduced O&M costs, improving heat exchange network economics.

Finned tubes are used in some of the heat exchangers. Their effective surface area is 8.4 times that of bare tubes and relative cost to an identically sized bare tube exchanger is 1.5 for gas-gas heat exchangers and 1.4 for liquid-gas heat exchangers.

A pressure drop of 0.5 bar is assumed for each heat exchanger. A pump (in the case of liquids) or a fan or blower (in the case of gases) is therefore required to push low-pressure fluids through a heat exchanger, and costs are included here.

Some couplings, such as the raw meal with the coke and slags, would be difficult to operate as there are no fluids involved. One possibility for both situations is to use an inert gas to pass the energy from the hot stream to the cold stream, but this is more complicated and would reduce efficiency and require two heat exchangers. For the processes of producing a very approximate estimate of capital and operating costs, a 10 bara nitrogen gas loop was introduced. This requires two heat exchangers and one fan.

Costing results

Only one of the heat exchangers in the network already exists (HEX 7), and is excluded from the costing. Of the others, six are gas-solid heat exchangers. Due to the lack of literature data for these units, they were modelled as air-cooled heat exchangers. Two heat exchangers were modelled with a nitrogen loop transferring heat between the streams to reduce contamination. Air-cooled heat exchanger correlations were used for the heat exchangers because no correlation for the cost of a solids cooler was found. The costs of compressing, and keeping compressed, the nitrogen in the loop was not included. The optimum pressure of the loop will depend on the characteristics of the compressors used as well as the capital costs of upgrading the necessary units to handle pressurisation.

The most expensive heat exchanger in the network is that between the coke oven flue gas and the cement raw meal, because of the large size (€4.1 M).

Comparing the two main types of heat exchanger in this network, the weighted-average capital cost of 1 kW of heat exchanger capacity for the air-cooled heat exchangers is €19, whereas the nitrogen-loop heat exchangers cost €54. The shell and tube exchangers are the cheapest at €13/kW. This reflects the relative complexity of the designs.

Payback period

The payback period is defined as the period of time in which the savings made from the heat exchanger network, minus the operating costs, are equal to the capital spent on the network. In this network, the network substitutes waste heat for the natural gas and other fuel gases used in the steel plant's stoves. It is assumed that the other fuel gases can be used around the EIP to replace natural gas use, and that steam is generated on-site from natural gas. Thus, the energy saved can be directly accounted for using the price of natural gas. 485 MW of energy is provided by combustion in the original steel plant's stoves. The annual savings are €112.0 M. The running cost (electricity and maintenance costs) of the heat exchangers and fans is €1.5 M/y and the payback period for the network is 43 days.

The costs do not include salaries, pipes or extra support infrastructure that would be required. Furthermore, extra stoves would probably be required at the steel plant to make up for the fact that the heat from the waste gases cannot be transferred as quickly from the waste gases to the stoves than by the combustion of fuels. This cost could easily exceed that of the heat exchanger network itself, thus more than doubling the payback period. Financing costs, which could be in the order of 10 % per year, would further reduce the internal rate of return.

Effect of the Carbon Price Floor (CPF)

By including the Carbon Price floor at the rate introduced in April 2013 of €0.303/GJ natural gas in the calculations, the yearly savings increases by €4.58 M/y (HM Revenue & Customs, 2014). This reduces the overall payback period to 47 days. It is unlikely, therefore, that the CPF will have a great influence on the likelihood of the emergence of EIPs such as the one modelled here at its current rate. However, the price is due to escalate rapidly, and will therefore become more important to industries recovering heat.

Technical issues – words of caution

In the TMES, there are some couplings that are ultimately unlikely to be feasible, owing to the nature of the streams. For example, one heat exchanger couples wet paper with the calciner gases from the cement plant. These gases contain particulates, including ash from the fuel combustion. For this reason it could not be passed directly over the paper, and it could cause severe operational issues in the equivalent of a steam drum (which is currently used) as it would deposit solids inside. It is important to note that this heat exchanger network is illustrative only. Many of the heat exchangers would be difficult or impossible to build, especially at the high temperatures of the liquid slags, for example. It is important to remember that the fans must work at very high temperatures, too. The costs of the units are based on carbon steel construction, and using other materials could increase the purchased cost very significantly. The heat exchanger network shows the *theoretical* maximum savings, but the practical energy and exergy savings will be significantly lower than indicated here. The relative simplicity of the models means that several other, albeit small, sources and sinks of energy are excluded.

Calculation of theoretical maximum electricity generation (TMEG)

An alternative use of waste heat in industrial processes is for electricity production. Benefits include the lack of dependence on other industries for heating or cooling duty. There are two ways that this can be achieved, combined heat and power (CHP) or waste heat recovery. District heating has not been included here.

CHP is a method of generating both electricity and heat from the same energy source. It makes use of the waste heat coming from electricity generation via a steam cycle, and the power-to-heat ratio can be adjusted to provide an optimal split. This solution is suitable for supplying heat sinks. CHP plants can have an overall efficiency (η_1) of over 80 %, leading to significantly reduced energy use. The cost of a CHP unit depends on the technology used, which in turn is dependent on several factors including the power-to-heat ratio required and the temperature of the heat.

For processes which produce waste heat, some of the exergy in the stream can be recovered by generating pressurised

Table 6. Heat exchangers within the network.

Heat Exchanger number	Hot stream	Cold stream	Energy transferred (MW)	ΔTlm (K)	Area of heat exchanger (m^2)	Cost of heat exchanger (k$)
1	S24	S38	11.8	135	219	879
2	S24	S38	20.3	32	1,601	983
3	S14	S38	231.0	201	2,871	1,621
4	C13	S38	129.0	163	1,981	1,220
5	S2	S38	37.1	40	2,316	1,256
6	S2	C1	3.1	144	236	623
8	S42	C14	128.7	254	9,160	4,089
9	S42	S4	34.8	436	1,441	1,357
10	S42	F1 2 4 5	26.0	368	141	93
11	S42	F3	5.6	795	14	61
12	S42	C1	9.3	455	51	496
13	S42	P23	22.7	428	132	760
14	S42	P2	8.7	412	42	69
Total			790.3		20,206	13,507
1	S42	40 bar	71.2	128	5,260	1,216
2	P12	5 bar	0.1	12	3	59
Total			71.3		5,263	1,275
Grand total			861.5		25,468	14,782

vapour to rotate a turbine. The temperature of the waste heat dictates which vapour is used; the Rankine cycle uses steam, the organic Rankine cycle (ORC) uses hydrocarbons such as butane and propane, and the Kalina cycle uses a mixture of two fluids, often water and ammonia (Johnson and Choate, 2008). These cycles are suitable where the heat is a by-product, such as the flue gases of the cement and steel plants.

METHODOLOGY

All the hot streams coupled together in the TMES analysis were analysed for potential heat recovery for electricity generation and all the cold streams were analysed for CHP potential. For the hot streams, the only suitable technology is ORCs. Other technologies, such as Kalina cycles, thermofluidic oscillators and supercritical ORCs, are in development and may be available in a few years. (Markides, 2013) suggests that ORCs with a waste heat source at 100–300 °C will have a thermal efficiency of 8–20 % and an exergic efficiency of 25–45 %. (Walsh and Thornley, 2011) suggest a capital cost of an ORC plant suitable for use on a steel plant to be €2,023/kW_e. An ORC sales company suggests operating expenditure of €40,000/year and an installed cost of €1–3/W (Vescovo, 2009).

For the cold streams, the target temperature of the fluid, the thermal load and the type of fuels already used on site were used to determine the type of CHP technology chosen. Six types of CHP technology were evaluated: steam turbines, reciprocating engines, gas turbines, microturbines and fuel cells (all gas-fired) and coal-fired steam turbines (Environmental Protection Agency, 2008). The microturbines, gas-fired steam turbines and fuel cells were eliminated immediately, because their profit margin was too small. However, the steam turbine, reciprocating engine and gas turbine designs were retained.

RESULTS

Tables 7 & 8 show that, in the conditions of the model, both CHP and ORC plants are an attractive investment. There is significant CHP capacity in the UK, but little or no ORC capacity; note that ORC technology is much newer than CHP and the costs come from experience of constructing only a few plants. Capital investment was €222 M and the simple payback period 1.92 years.

Discussion of TMES and TMEG models

The TMEG payback periods illustrate the opportunity cost for industrial heat symbiosis; thus, in order for industrial symbiosis to be selected over the status quo or electricity generation it must be higher than these. This simplistic view does not take into account several other issues, which may not necessarily be easy to describe in financial terms.

Payback periods

The payback periods for electricity generation are in the same range as most process improvements. Payback periods for the TMEG are also greatly dependent on the relative value of the heat and electricity, but at 1.92 years the payback period is significantly longer than for the TMES.

The symbiotic relationships seem to be cost-effective, but they are dependent on the agreement of the companies to relocate to the site, the technical viability of the heat exchange networks and other costs not modelled here. The fuel savings in this particular setup all exist in the steel mill, although much of the steam utility requirement in the paper and fertiliser plants is also saved. This unequal distribution of the financial gains will require some mechanism for sharing out the gains. There are several different approaches to this, such as game theory (Lou et al., 2004). The alternative would simply be for a diversified industrial company to operate all of the plants. This would also be legally and operationally more simplistic.

It has been observed that managers are more risk-averse to energy conservation measures than investments that increase production, and thus can require payback periods of 1–2 years (Martin et al., 2011; Department for Energy and Climate Change, 2012). This suggests that it may be possible to persuade decision-makers in companies involved in these processes to relocate to EIPs on the basis of heat synergies. Other benefits can come from co-location, such as material synergies and communal access to utility networks and a trained workforce. However, the large amount of integration required within the plants may mitigate towards investment in the less risky TMEG.

Size and adequate siting of additional equipment

Several of the heat exchange systems suggested in the TMES are very large, and would require significant quantities of land. In the EIP the use of all waste heat such as flue gases would require the plants to be very closely sited. Very careful planning would allow these streams to be brought into contact with their coupled heat sinks; a site with many heat exchangers in the centre, the heat sinks and sources adjacent, and other process units further away could be optimal. This intimate configuration may lead to process issues, such as materials being transported longer distances whilst in processing. Maintenance and replacement requirements may change.

Issues surrounding the relocation of an industrial plant

Relocating industries next to each other minimises the distance that waste heat has to flow to find a use; however, material flows into and out of the plant (the supply chain) must also be considered. Facilities may currently be sited for good reasons such as proximity to raw materials, utilities, a market or human resources. Lengthening supply lines costs both energy and money.

Another possibility is that of commutes to and from the site lengthening. An example of the importance of worker transportation is given by (Cole, 1998) who found that approximately one-half of residential construction energy for various case studies was spent transporting workers to and from the site, assuming a 50 km round trip for each worker. 2,000 employees who commute an extra 20 km/day use the equivalent of 1.3 MW averaged over the day, assuming no modal change in commuting habits. The energy required to move all the raw materials and products an extra 20 km on average is 7.4 MW. This is only a small fraction of the 457 MW energy saved in the EIP. However, the cost of 7.4 MWy of diesel is about €9.8 m, and increases the overall payback period to 51 days.

MOST PROMISING OPPORTUNITIES

From this analysis, it appears that inter-site heat recovery is potentially economically attractive. Whilst integration of two plants which happen to be next to each other might be able to

Table 7. Results from the CHP model.

Stream	S4	S38	C1	C14	P23	P2	F1, 2, 4, 5	F3	TOTAL
Heat load (MW)	34.8	429.6	134.5	128.7	23.0	8.7	26.0	5.6	790.9
Technology used	Steam cycle (coal)				(Natural) Gas turbine				
Overall efficiency	0.8	0.8	0.8	0.8	0.725	0.725	0.725	0.725	
Electricity output (MW)	7.0	85.9	26.9	25.7	23.0	8.7	26.0	5.6	208.8
Capital cost (k€)	4,417	54,559	17,084	16,348	21,736	8,252	24,536	5,286	152,217
Fuel cost (k€/y)	5,318	65,697	20,572	19,686	14,638	5,557	16,523	3,560	151,550
Operating cost (k€/y)	231	2,854	894	855	1,146	435	1,294	279	7,989
Electricity value (k€/y)	4,974	61,441	19,239	18,411	16,448	6,244	18,567	4,000	149,324
Heat value (k€/y)	4,029	49,771	15,585	14,914	6,030	2,289	6,806	1,466	100,889
Annual profit (k€/y)	3,454	42,660	13,358	12,783	6,694	2,541	7,556	1,628	90,674
Payback period (y)	1.28	1.28	1.28	1.28	3.25	3.25	3.25	3.25	1.68

Table 8. Results from the ORC model. Operating cost was assumed to be constant at €40 k/y and energy efficiency was constant at 0.14.

Stream	Energy available (MW)	Energy for ORC (MW)	Capital cost (k€)	Electricity generated (MW)	Value of electricity (k€)	Payback period (years)
S2	40	13	3,572	1.77	1,263	2.9
S14	231	50	14,023	6.96	4,957	2.9
S24	32	6	1,762	0.87	623	3.0
S42	307	43	12,131	6.00	4,288	2.9
C2	122	17	4,746	2.35	1,678	2.9
C13	129	30	8,565	4.23	3,027	2.9
P12	2	2	511	0.25	181	3.6
P13L	25	25	7,173	3.55	2,535	2.9
P13S	4	4	1,258	0.62	445	3.1
F6S	7	6	1,774	0.88	627	3.0
F6L	23	23	6,410	3.17	2,266	2.9
F7L	16	16	4,436	2.19	1,568	2.9
F8S	2	2	612	0.30	216	3.5
F8L	10	10	2,789	1.38	986	2.9

save some energy, the relocation of energy-intensive plants to reside alongside a hub firm such as a steel mill may lead to a large reduction in energy use. This is despite the fact that many of the plants are already well-integrated. That said, the heat exchangers required for the network are large because of the low energy density of flue gases. Furthermore, much of the energy in the largest plants must be provided in a certain form or at a very high temperature. This limits the opportunities within the plants unless a new process route is taken.

The emergence of carbon capture plants may benefit from the extra medium-grade and low-grade heat available at industrial sites. The waste heat is not available in sufficient quantities to completely satisfy the energy requirement of the plant, but it will reduce fuel use.

Characteristics of processes suitable/unsuitable for heat symbiosis

Although the processes here are not particularly suitable for heat symbiosis, there are several examples of successful heat symbiosis within the petrochemical, pulp and paper (as opposed to paper recycling in this study) and power generation industries. Based on the findings of previous studies of these more suitable industries and the findings of this paper, it is possible to identify some process characteristics aiding symbiosis. These are:

- Many streams involving liquids and condensation/evaporation (including steam). Liquids have much higher sensible heat capacities than gases, and it is generally easier to transfer heat from them than from solids. Condensing and evaporating fluids have even higher heat transfer coefficients than liquids or gases alone. This makes heat exchangers using liquids and/or condensing gases relatively compact, and thus cheaper.
- High pressure gases. These are easy to transport via pipeline, propelled by a pressure gradient. Their higher density than low pressure gases makes heat transfer more efficient.
- Existing steam generation and distribution systems. If a steam utility system is already in use at a plant, it is likely that expansion will be significantly cheaper than the construction of a complete utility system. This will reduce capital expenditure and therefore payback periods.
- Characteristics that generally impair successful heat symbiosis are:
- Atmospheric or very low pressure gases. Flue gases and similarly low pressure non-condensable gases tend to have a low energy density and are bulky to transport around a plant. The lack of a medium or large pressure gradient can make the use of electricity-hungry blowers or fans necessary. Heat exchangers tend to require significant finning to minimise size, but if there are particles in the gaseous stream they can accumulate and reduce the effective surface area.
- A lack of liquid processes. As mentioned above, liquids are useful heat transfer media. A lack of liquid streams, such as in cement manufacture, can make heat transfer more difficult.
- A high percentage of electricity in the energy demand. Electricity is difficult to replace with other heat sources in most processes, as it is often used only if no other energy source is available or suitable. Thus, processes such as paper recycling have limited inter-process integration potential.

Implications for industrial policy

Relocation of industries to eco-industrial parks has both significant benefits and drawbacks. In this model, the short payback period suggests that, all other things being equal, it is economically desirable to build integrated plants. Looking more broadly at the costs of co-locating, accurate forecasting of the changes in supply chain length and also construction of extra process units, such as steel plant stoves, are necessary to ensure that major financial costs are included.

Whilst processes using significant quantities of liquids or condensing gases can transfer heat using heat exchangers with a relatively small surface area and a simple design, heat transfer in processes with non-condensable gases and solids are challenging. Whilst still economic under the assumptions made in this model, the installation of difficult heat transfer processes such as inert gas loops can cost twice as much capital per unit of energy capacity than simpler systems, and this is if they can be built at all. Furthermore, conveying low-pressure gases requires the installation and operation of fans. These add both capital and operating costs.

Whilst industrial heat symbiosis is an important aspect of industrial symbiosis, it is unlikely that the industries studied in this paper would relocate solely to use some heat from another plant. This is because they tend to require most of their energy in a certain form (e.g. coke for reduction in blast furnaces), at very high temperature (cement kiln) or are quite heavily dependent on high-grade energy, such as electricity (paper recycling). There are several other possible non-heat-related symbiotic relationships that may encourage plants to co-locate, such as waste up-cycling, and all opportunities should be included in any full analysis. A standardised framework for undertaking such studies would help to identify and compare the relative, benefits drawbacks and payback periods of different relocation opportunities. Furthermore, the short payback period of the electricity generation scenario may persuade decision-makers that the risk of co-location is not worth the extra savings available.

Technology currently precludes the use of traditional heat exchangers for very high-temperature applications due to the melting points of the alloys used. Investment in the development of new high-temperature alloys, and their application within heat exchangers, would help to increase the amount of heat and exergy that can be practically recovered.

Conclusions

The construction of a heat exchanger network (HEN) between a steel mill, cement plant, fertiliser plant and recycled paper facility in an eco-industrial park (EIP) would have a payback period of a few months. It would save 348 MW (21 %) of energy losses and prevent 485 MW (41 %) of exergy destruction. The production of extra low-pressure steam on-site could be very useful for capturing some CO_2 from the EIP using first-generation technologies such as amine scrubbing.

Inclusion of extra costs incurred outside the HEN, such as extensions of supply chains and extra process units' construction, should be taken into account when evaluating the financial and environmental attractiveness of an EIP scheme. These extra costs could possibly double the payback period and reduce the annual profit made from the scheme.

The payback period for the HEN is shorter than for construction of combined heat and power (CHP) for cogeneration and organic Rankine cycle (ORC) plants, which would turn the waste heat into electricity. Thus, this strategy is not as financially attractive as the HEN. However, the ability to remain independent from other companies and retain current supply chains and plants will probably outweigh the extra savings on offer.

In the symbiotic network, the majority of the financial savings were concentrated in the steel plant. To ensure that buy-in is collected from all the plants, a suitable financial gain distribution strategy must be devised.

Although there is a large amount of waste heat available in the process industries, it is often too low grade to be economically recoverable. This limits the benefits of co-locating industries. That said, some processes inherently have more potential for inter-site integration. By accepting that only some industries are likely to gain much from IS, and concentrating on those, policy can be more effective.

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