The 14th International Symposium on District Heating and Cooling, September 7th to September 9th, 2014, Stockholm, Sweden

SUSTAINABLE STEEL CITY: HEAT STORAGE AND INDUSTRIAL HEAT RECOVERY FOR A DISTRICT HEATING NETWORK.

Rob Raine[a], Vida Sharifi[a], Jim Swithenbank[a], Victoria Hinchcliffe[b], Andrew Segrott[b]

[a]Energy and Environmental Engineering Research Group, Department of Chemical and Biological Engineering, University of Sheffield, Mappin Street, S1 3JD.
[b]Sheffield Forgemasters International Ltd, PO Box 286 Brightside Lane, Sheffield, S9 2RW.
Keywords: industrial heat recovery, heat pumps, heat storage, CO_2 emissions.

ABSTRACT

Energy intensive industries need to adapt in order to play an important role in the low-carbon economy. Efficient use of energy resources and the minimisation of wasted heat will be important. The role of the steel industry in recovering recycled metals means these industries are important for a sustainable economy, providing employment and supporting manufacturing.

The aim of this project is to investigate the potential uses for heat storage in Sheffield, UK for capturing heat which is produced intermittently at a steelworks for both re-use of heat on site at various temperatures and for heat supply to a city-wide heat network. Site visits were followed by calculations using data provided. Heat storage options were investigated to ensure that waste heat could be re-used effectively. The feasibility of using the district heating network in the city to carry low grade heat away from the plant was considered. Around 4.7 MW of useful heat could be generated from two steelworks sites in Sheffield and a further 10.9 MW from a site in nearby Rotherham. 22,500 tonnes of CO_2 could be saved per year by fully exploiting this waste heat resource.

1. INTRODUCTION

With a growing global population placing pressure on resource supplies and increasing knowledge of the role of greenhouse gases in climate change, it is important to develop businesses with minimised environmental impacts. Much work has already been done within UK industry to optimise systems. For heat-intensive industries such as steel, maximising energy efficiency may involve the capture of low-grade waste heat for distribution through district heating networks.

In the United Kingdom, industry contributes a quarter of the national CO_2 emissions [1] and the government is working to help industry lower the carbon footprint of heat. It is also looking at how heat demands across all sectors can be met at lower cost and environmental impact with technologies including district heating [1].

Sheffield has for decades been a pioneering city in the UK in terms of developing district heating to provide heat at lower cost and environmental impact to the city. The city-centre network is supplied with up to 60 MW of heat from an Energy from Waste combined heat and power (CHP) station marked as site 1 in Figure 1.

In addition, a new CHP power station using biomass is being constructed by E.On at site 2 in Figure 1 and this will supply heat through a new district heating network to sites closer to Sheffield city centre. The new network will be extended to supply new customers and may connect to the city-centre network. The new network also offers the prospect of recovering heat from the city's industrial sector. Finney et al. [2] identified potential for at least 10 MW of industrial waste heat for the city's expanded district heating system. Sheffield and nearby Rotherham have an estimated annual output of 1.07 million tonnes of steel produced each year from four electric arc furnaces; the location of these three sites are marked in Figure 1.

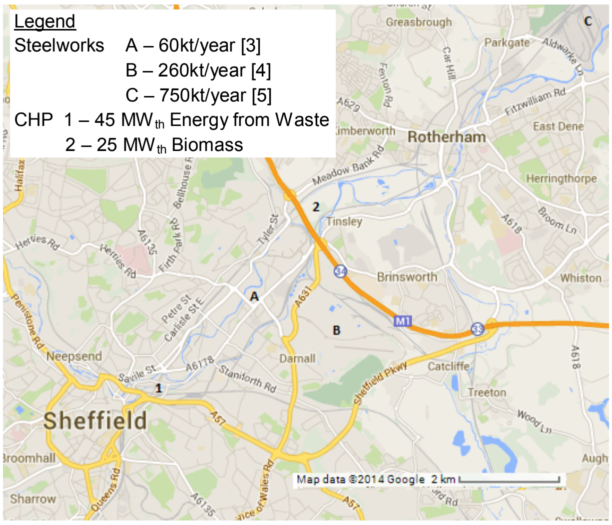

Figure 1: Map of Sheffield and Rotherham with three steelworks and two district heating CHP stations marked.

Approximately 500 kWh of electricity is used in the furnace for each tonne of steel produced [6], meaning an average of around 60 MW of electricity consumption and indirect CO_2 emissions of the order 280,000 tonnes per year from electricity alone. These processes are necessarily heat-intensive in order to melt the scrap metal, and the use of an electric arc allows the process to be carried out in batches of around 100 tonnes in four compact furnaces on these three sites.

2. STATE OF THE ART

2.1 High Temperature Heat Recovery and Storage

The furnace flue gases from steelworks are very hot, in the range 600 to 1500°C and, although they are dust-laden, flue gas heat recovery systems in industry are increasingly common, with one example at Port Talbot steelworks [1]. Tenova Group have developed waste heat boilers for electric arc furnace flue gas heat recovery at sites in Germany and South Korea; both examples include the generation of steam. One of the heat recovery systems uses steam to supply heat to a 2.5 MW organic Rankine cycle (ORC) generator [7]. Higher temperature (higher exergy) energy could be used for power generation or through work processes such as vacuum creation in a steam jet ejector.

High pressure steam accumulators are widely used to balance supply and demand on sites for steam and can be used for storing recovered heat. Regenerator materials mainly made from ceramics are already used on many gas-fired furnaces to recover heat; these materials capture the heat of the exhaust air leaving the furnaces and, when the flow direction periodically changes, use that heat to preheat incoming combustion air. Recuperator systems are an alternative, allowing increased efficiency by exchanging heat from exhaust air with incoming air; this involves a heat exchanger and the heat is not stored.

2.2 Medium Temperature Heat Recovery and Storage

It is possible to recover heat from cooling water on industry sites, for example in the water that cools the electric arc furnace walls or the water that cools the hot gas extraction ducts. Residual heat may also be available from steam processes that operate typically at 200 to 250°C. In Graz, Austria heat is recovered from a gas-fired reheat furnace along with high-temperature cooling water at around 90°C from two electric arc furnaces [8].

Buffer tanks could be used in this instance to store water at temperatures in the range 70 to 110°C which are suitable for district heating. If the water is above its atmospheric pressure boiling point then the tank needs to be pressurised, usually including a cushion of steam or nitrogen at the top of the tank to allow for thermal expansion and contraction processes.

2.3 Low Temperature Heat Recovery and Storage

Many industry sites have relatively low temperature cooling systems that are adapted from, or in some cases still use, river water cooling. Circulation of water to cooling towers reduces the need to import cool water. In some cases, cooling circuits with water treatment are necessary to prevent contaminants in the water from escaping. This water is often not hot enough for building heating but heat pumps could be used to draw useful heat from that water.

Water tanks can be used to store the cooling water ranging from ambient temperatures up to possibly 70°C if the cooling systems are adjusted to run at higher temperatures, but large capacities are needed for lower temperature stores. Underground thermal energy storage is another option that uses the thermal capacity of the ground and can be useful for storing large volumes of low-temperature heat for long periods.

2.4 Using Low Temperature Heat: Heat Pumps

Heat pumps can be used to draw heat from the atmosphere, ground or bodies of water and supply it at a higher temperature suitable for heating. The coefficient of performance (CoP) for the heat pump describes its performance (Equation 1). The emissions factor for UK electricity will determine the environmental impact of a heat pump using electricity. One recent example in Norway draws heat from the fjords in order to supply a district heating system at 90°C [9]. Sheffield's district heating operates at 110°C and delivery of heat from heat pumps at these temperatures is difficult and suitable technology is at an early stage.

$$\text{CoP} = \frac{\text{Heat Delivered}}{\text{Energy Consumed}} \quad (1)$$

The Norwegian heat pump uses ammonia as refrigerant which has its critical point at 132°C and pressures of 41 bar are required for the ammonia heat pump condensers to work [9]. By definition, the latent heat for vapour phase change diminishes as you increase the condensation (heat delivery) temperature towards the critical point from 90°C, as shown in Figure 2, and the working pressures increase too.

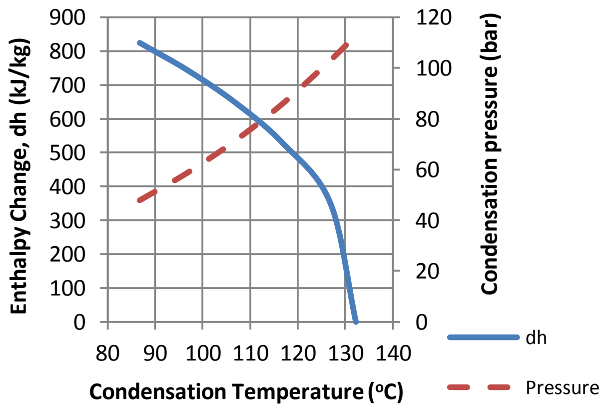

Figure 2: Condensation temperatures, pressures and enthalpy changes for ammonia, data from [10].

3. METHODOLOGY

3.1 System Optimisation

Industrial sites typically have a range of heating and cooling needs depending upon the stage of the industrial process being carried out. Finding ways to pass heat effectively between parts of the process can save a lot of heating or cooling energy. This method is termed process integration, and the practicality of such steps was considered. The use of district heating opens up opportunities for using waste heat streams for a new purpose and this could become more widespread in future, particularly in the UK. The many options for system arrangement, including how components such as heat storage are integrated, create uncertainty over the optimal way to achieve economic and environmental goals.

The method used here comprises a model built in the C++ programming language to investigate how system components interact. This modelling environment was chosen in order to give high flexibility over component arrangement as well as providing means to adjust appropriate parameters such as the heat storage capacity and the prices of energy under different future scenarios. It is these cost and environmental benefit estimates that will guide decisions.

Understanding the potential for using heat pumps is important, they give potential to extract heat from cooling water at the steelworks. If an ammonia heat pump is being used then it may be more effective to only raise the water to 90°C, as high pressures are needed for temperatures above that. The output temperature could then be topped using heat from the flue gases.

3.2 Heat Source Modelling

A site visit to one of the steelworks was undertaken to assess the potential for heat capture. The waste heat sources are primarily flue gases from furnaces (at high temperatures) and the cooling water from the electric furnace (at low temperatures).

The electric arc furnace melts scrap metal at very high temperatures and removes impurities. It produces hot and dusty off-gas which must be extracted and filtered before release. Typically, one extraction duct captures gas from close to the furnace, while a canopy duct captures any fugitive emissions from around the furnace (Figure 3). Some furnaces preheat scrap metal in the extraction duct allowing energy to return to the furnace when the scrap is loaded; this reduces electricity consumption but the nature of processes at the sites in Sheffield makes this approach difficult.

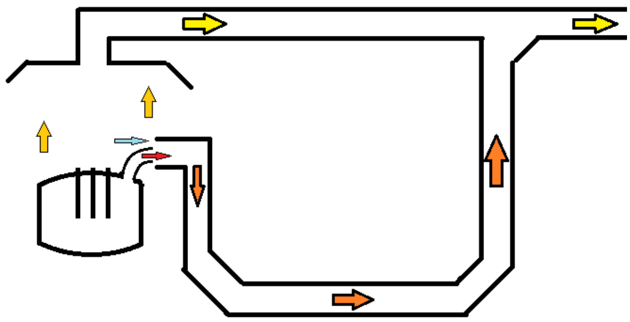

Figure 3: Schematic for the arc furnace (lower left) and its gas extraction ducts.

There are also gas fired furnaces and cooling water where heat could be recovered as detailed in Table 1. Various approaches were investigated in the models.

Table 1: The main features of heat sources on site.

Heat Source	Features	Useful Sources
Electric Arc Furnace (EAF)	• Heating process uses a lot of electricity. • A lot of heat is carried off at high temperatures in the flue gases [12][13]. • Waste gas stream is dust laden, but such problems have been solved for waste incinerators with heat recovery. • 10% of the total input energy is assumed recoverable.	Dixon and Bramfoot (1985) [11] Jones (1997) [12] Zuliani et al.(2010) [13]
Gas fired reheat furnaces	• Maximum fuel burn rate equates to around 10 MW on large furnaces. • For furnaces with a recuperator, around 24% of fuel energy input leaves via the exhaust [14]. • Exhaust temperatures will be variable. • A heat recovery of 5% of the input energy is assumed. • Bringing the exhaust gas to temperatures below 150°C increases the risk of acid corrosion on the heat exchanger.	Tenova Group (2014) [14]
Cooling systems	• Water cooling systems protect the lining of the arc furnace. • Cooling towers dissipate some of this heat, as does river water subject to environmental permitting constraints. • 7 to 17% of energy input to arc furnace leaves through cooling [12][13] • Cooling also needed for steam processes on site.	Walling and Otts (1967) [15]

3.3 Heat Storage Options

High temperature heat is already stored on sites using regenerator materials and in a steam accumulator. The accumulator matches steady production of steam from boilers to the short discharge needs of the vacuum processes. If more heat is to be recovered then the thermal capacities of the ceramic regenerators or the steam accumulator could be used to balance supply and demand of waste heat, although modifications will be needed to make such connections. If flue gas heat is recovered for generating steam then using existing steam storage facilities may be sufficient.

Medium to low temperature heat could be stored using hot water tanks which can be linked to district heating networks. If the water in the store is circulated in the network then this prevents temperatures losses through heat exchangers. However, the water quality needs to be sufficiently high and the temperatures and pressures of operation need to be compatible with the network. In the case of Sheffield's district heating, the store would need to operate between 70 and 110°C.

For low temperature waste heat, underground thermal energy storage could be used and would give potentially a high heat capacity at low cost. Storing the cooling water is an option, but low temperatures mean a large volume of storage would be needed and this increases expense. If electricity is needed to run a heat pump and upgrade this heat at the time of use then this may be costly if it is needed at peak demand times.

3.4 Environmental Analysis

Any heat recovery project needs be evaluated, not just in economic terms, but also in terms of its environmental impacts. This can help industry meet environmental objectives and there are economic incentives in the UK supporting good practice. It is important to calculate overall impacts on CO_2 emissions while also for looking at how other gas emissions and resource use levels would be affected.

3.4.1 Assigning CO_2 Emissions

If heat is recovered and used to generate process steam then this displaces use of gas-fired steam boilers. If x units of gas avoid being burned then the carbon dioxide saving is given by equation (2). The standard gas boiler is assumed to operate with efficiency of 81% and using a fuel of 0.185 kg CO_2 equivalent per kWh, bringing the total to 0.228 tCO_2 per MWh delivered to the customer, as laid out in UK carbon reporting regulations [16].

$$\mathrm{CO_2\ saved} = x\ \mathrm{MWh}\ \times 0.228\ \mathrm{tCO_2/MWh} \qquad (2)$$

If y MWhs of heat are recovered for distribution through a heat exchanger and along district heating, this displaces the traditional use of gas boilers saving carbon. Heat losses with district heating are typically 5% and this replaces a gas boiler emitting 0.228 kg CO_2 per kWh of heat delivered. The CO_2 equivalent saving in this situation is given by equation (3).

$$\mathrm{CO_2\ saved} = y\ \mathrm{MWh}\ \times 0.95 \times 0.228\ \mathrm{tCO_2/MWh} \qquad (3)$$

When using a heat pump to supply z MWh of heat, the picture is more complicated, and if the heat pump is electricity-driven then the carbon emissions associated with that electricity need to be accounted for, the figure used here is for the UK electricity in 2011 and assigns 0.484kg CO_2 equivalent to each kWh consumed [16]. The electricity consumed relates to the output heat energy using equation (1), and overall carbon dioxide saving is calculated using equation (4).

$$\mathrm{CO_2\ saved} = z\ \mathrm{MWh}\ \times 0.95 \times 0.228\ \mathrm{tCO_2/MWh} - \frac{z\ \mathrm{MWh}}{\mathrm{CoP}} \times 0.95 \times 0.484\ \mathrm{tCO_2/MWh} \qquad (4)$$

3.4.2 Other Emissions

Modern industry recognises the need to monitor, control and minimise emissions of particles and harmful gases from their processes. One example of an emission that is closely monitored is dioxins, and while over 90% of human exposure is from dioxins present in food [17], industry is regulated to minimise dioxin emissions. High temperatures of over 850°C are required to destroy these particles [17], and there is a chance of reformation between 500 and 250°C. Many steelworks use quenching of gases with water spray to pass this critical temperature zone [18]. With flue gas heat recovery, heat exchanger design should account for this issue.

Another important issue for heat recovery is the flue gas level of sulphur oxides, if these gases combine with moisture they create acid and this can corrode any heat exchanger increasing maintenance needs. In some instances, lime can be used to counter acidic gases, and activated carbon can be used to capture dioxins and heavy metals.

3.4.3 Water Use

The amount of water consumption at a steelworks is another issue with environmental implications. approximately 14 to 28 m^3 of water is required per tonne of steel produced in electric furnaces [15][19]. For some processes, the water is limited to a certain temperature rise in the cooling circuits to prevent corrosion, and high water velocities are needed to prevent particles from settling in cooling systems [15].

The adjustment of cooling systems is a complex issue and will require detailed work by engineers to consider consequences before proceeding, however use of high temperature cooling has been achieved in some instances [8] and this would carry benefits in terms of transferring heat to district heating as well as reducing water use. Even the current low temperature cooling could provide water suitable for a heat pump.

3.5 Economics of Heat Recovery

Fuel prices for UK industry have been rising over recent years as shown in Figure 4. For example, industrial gas prices rose 10% between 2012 and 2013 (8% when accounting for inflation) [20]. The economics of heat recovery in future years will depend upon the price of natural gas over the lifespan of the project, since natural gas is the alternative for industrial heating and main competitor to district heating.

If preheating of scrap were possible this would reduce the amount of electricity needed. The recovery of heat to generate steam would significantly reduce use of natural gas in the steelworks. The larger steel sites (B and C) in this instance are further from the district heating networks swinging the favour in the direction of electricity generation using technologies such as organic Rankine cycles (ORCs). Furnace processes are more continuous on the larger sites further increasing feasibility; for example on one site the electric furnaces runs for six days per week [5]. The processes at site A are unlikely to be sufficiently continuous to justify the production of steam for electricity generation.

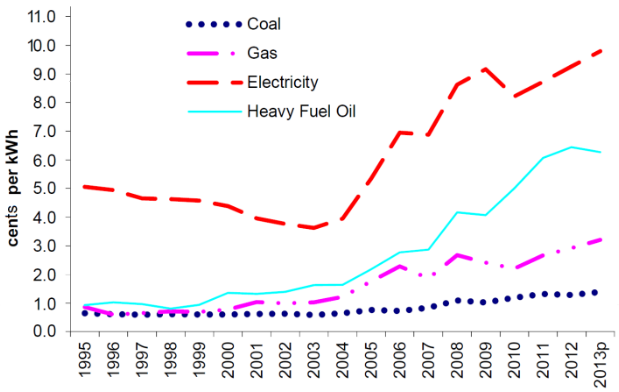

Figure 4: Industrial energy prices in the UK from 1995 to 2013, in euro cents. Source: DECC [20].

Site A is already adjacent to a district heating pipe, therefore heat feed in would be relatively easy. To connect site B to the district heating network will require around 1.5 km of new district heating trench but there may be potential new customers along the way. Connecting site C to a heat network will only become feasible if Rotherham develops a heat network infrastructure, which may happen in the long term. Then, perhaps 2 kilometres of extra trench would be required from a town centre network. District heating extension costs are approximately €630 to €1.390 per metre in the UK depending on the circumstances [21].

In areas with clustering of industry steam networks may be viable for trading heat, and new industries could be located nearby to take advantage of this. However, the timing of steam supply and demand may not match up and the pressure and temperature required by different customers also may not match.

There are many policy incentives in the UK driving improvements in environmental performance, comprising four main elements [1]:

- EU Emissions Trading System;
- Climate Change Levy;
- Climate Change Agreements;
- Carbon Reduction Commitment Energy Efficiency Scheme.

There are also support mechanisms for funding energy efficiency projects such as exemption from Enhanced Capital Allowances on energy efficiency equipment as well as funding opportunities from the UK's Green Investment Bank or the EU Regional Development funds [1]. Finally, the UK's Renewable Heat Incentive gives financial support for ground source heat pumps and from 2014 will allow these to access the heat in industrial waste heat streams [22].

4. RESULTS

Values for technically recoverable heat were developed based upon estimated annual production figures that were in the public domain and these were combined with estimates for energy consumption per unit produced along with how much heat could be recovered from different waste heat streams. The results are summarised in Table 2 for these three sites.

Table 2: The estimates for technically recoverable heat at the three sites.

Annual Output (tonnes)		Flue Gas Heat Recovery		EAF cooling water heat recovery (MWh/year)
		Gas furnace (MWh/year)	EAF (MWh/ year)	
A	60,200	2,000	3,000	3,000
B	260,000	8,700	13,000	13,000
C	750,000	24,200	37,400	37,400

The amount of heat that can be recovered depends upon how that heat is to be used, for example if the heat is to be used to generate high pressure steam then only heat above a certain temperature will be useful. A two-part heat exchanger could be used in order to generate hot water for district heating from the partly cooled flue gases allowing for a greater level of heat recovery. These would be aspects to consider in the detailed design of heat recovery equipment.

It is assumed here that where cooling water heat is recovered for district heating, a heat pump coefficient of performance (CoP) 3.0 is used. Vapour compression heat pumps require electricity to run a compressor and the high carbon intensity of UK grid electricity leads to only a small carbon saving. There is roughly twice as much heat in the EAF flue gases as is needed for steam generation and correspondingly that heat is divided between steam and hot water production. The use of waste heat and the carbon savings calculated using equations (2), (3) and (4) are given in Table 3.

Table 3: The expected carbon dioxide savings for heat recovery.

Heat Recovery Project	Site	Heat output (MWh/ year)	Annual CO_2 Saving (tCO_2)
Steam from EAF flue duct.	A	1,500	342
	B	6,500	1,482
	C	18,700	4,264
Hot water from EAF flue duct.	A	1,500	325
	B	6,500	1,408
	C	18,700	4,050
Hot water from gas furnace flue duct.	A	2,000	433
	B	8,700	1,884
	C	24,200	5,241
Hot water from cooling water heat pump.	A	4,500	285
	B	19,500	1,235
	C	24,200	1,533
TOTAL		136,500	22,482

Instead of electricity, steam from flue duct heat recovery could be used to drive an absorption-type heat pump; then the carbon savings would be much greater. Finding an appropriate heat pump technology able to deliver at the right temperatures with a low carbon footprint is vital for making a significant environmental saving while the UK grid electricity emissions factor remains so high.

For the contribution of heat to district heating a new heat store would be required. If the heat is just used when demand is available, and discarded when demand is not then this avoids the need for heat storage however it also reduces the environmental benefits. A hot water store could be off-site if connected via district heating, although the feed-in temperature and rate needs to be carefully controlled if feed in to the heat network is instantaneous. If the heat store is operational as part of the network then it can also provide services to the district heating operator.

Table 4 shows the estimated storage needs for different heat recovery scenarios. The cost of the additional storage needed for recovering cooling water heat, and the low economic and environmental gains make that option the least appealing and therefore unlikely to be practical.

Table 4: The nature of heat storage need in each heat recovery scenario.

Waste Heat	Production Variability	Storage Need
Steam from arc furnace flue gas	Produced and used 4 days/ week at site A, around 1,500 MWh/year.	Use existing steam buffers
Hot water from arc furnace flue gas	Produced and used 4 days/ week at site A, around 1,500 MWh/year.	20 MWh ($600m^3$) Pressurised hot water store
Hot water recovered from reheat furnace flue gas	Most likely to be economically recoverable at site A, around 2,000 MWh/year	20 MWh ($600m^3$) Pressurised hot water store
Cooling water	Recoverable if heat pump solution is practical	35 MWh hot water store at site A or on the DH network

5. DISCUSSION

The carbon footprint of an electric steelworks depends heavily upon the carbon emissions associated with using grid electricity. This is currently high in the UK, but is likely to fall in the medium term from its current value of around 0.484 kg CO_2/kWh as the amount of low-carbon energy generation increases. However, the emission intensity is already much lower in competitor countries such as France and Sweden.

To effectively use industrial waste heat the operational principles need to be established early with the district heating operator, including what charges and payments apply for supplied heat as well as when and how much heat can be fed-in at various times of day. There will be knock-on effects for other heat sources on the network. For example a flexible CHP unit can be switched from electricity to heat production and therefore the injection of industrial heat increases the capacity to add electricity production to the grid. However, the relative amount of heat and power production can affect the eligibility for renewable energy incentives in the UK. If electricity is used for a heat pump then heat injected to district heating, this could have a negative effect on emissions associated with delivered heat and the way this is accounted will be important.

Investment in heat recovery has to compete against other possible investments that can help with energy saving. For example, sites B and C have invested in variable speed drives for the flue gas extraction systems in recent years and this may also be a possible energy-saving investment for site A. If placing a heat exchanger into the flue gas duct increases the electricity consumption of the extractor fan then the process of energy recovery increases the overall carbon emissions. Also, if the process efficiency is negatively affected (for example the slower dust removal means the melt takes longer and therefore heat losses from the furnace increase).

Altering operational temperatures on the heat network would make the recovery of heat more feasible but the temperatures need to be sufficient to satisfy the needs of all the customers. If the new network connects to the old one then the water needs to be hot enough to be used by an absorption chiller unit in the city centre. In the long term, lower temperatures could assist the integration of geothermal and solar energies too.

Overall, it is quite probable that the energy spent in running a heat pump is inhibitive to the economics and therefore that only the flue gas heat which is much hotter can be recovered. However, if significant charges are associated with river water use for cooling then saving water by recovering heat may have better economics. The amount of heat that is recovered will depend upon the economics of the project and the sale price which heat can achieve through the network.

6. OUTLOOK

The expanding heat networks have the potential to provide a heat sink for excess heat created on these three sites and there may be other companies in the city that are generating waste heat which could also feed into the heat network. The UK has advantages in that there is likely to be significant expansion of heat network use in future; planning heat networks to run close to industry sites and early investigations of possible heat customers along those routes can help to reduce investment uncertainty. Co-location of industries is another important option, particularly with high-temperature heat which can be distributed over small distances using a steam network rather than a hot water network.

In order to minimise costs of feasibility studies, forging a partnership between these companies to investigate and invite consultants may lead to greater chances of success, even for the sites some distance from the district heating network there may be benefits for recovering heat for use in steam generation although there is understood to be significant excess steam produced by heat recovery. A shared expertise in operating and maintaining heat recovery equipment between these sites may lead to a significant cost saving on staffing.

7. CONCLUSIONS

Recovering heat from high-temperature industrial heat sources can boost the overall system efficiency and give environmental advantages; however there are barriers to making this feasible. In particular, the up-front cost of constructing district heating networks means that connections to industry can be capital-intensive. High-temperature heat pumps are a quickly developing technology, but some designs have practical limits on delivery temperatures which may limit their applications. In the UK, the high carbon intensity of grid electricity reduces the environmental advantages of electricity-driven heat pumps. Adjusting district heating networks to run at lower temperatures in future will increase both efficiency and volume of recoverable industrial waste heat. Working to maximise heat recovery will help energy intensive industry contribute to reducing the economy's carbon intensity.

8. ACKNOWLEDGEMENTS

The authors would like to thank staff of Sheffield Forgemasters International Ltd., Sheffield City Council, E.On Energy Solutions, and Veolia Environmental Services, who have assisted in this study. This project had been funded by the UK's Engineering and Physical Sciences Research Council through the E-Futures DTC at the University of Sheffield.

9. REFERENCES

[1] Department of Energy and Climate Change, "The Future of Heating", March 2013, https://www.gov.uk/government/publications/the-future-of-heating-meeting-the-challenge (last accessed 31.7.14).

[2] K.N. Finney, V.N. Sharifi, J. Swithenbank, A. Nolan, S. White, S. Ogden (2012), "Developments to an existing city-wide district energy network – Part I: Identification of potential expansions using heat mapping", Energy Conversion and Management, Vol. 62: pp165-175

[3] S.C.L. Koh, A.A. Acquaye, N. Rana, A. Genovese, P. Barratt, J. Kuylenstierna, D. Gibbs, J. Cullen, "Supply Chain Environmental Analysis", Centre for Low Carbon Futures (2011) http://www.shef.ac.uk/polopoly_fs/1.153241!/file/SCEnAT-Report.pdf (last accessed 31.7.14).

[4] ABB (2011), press release: www.abb.co.uk/cawp/seitp202/3bee34c9a33f1ac4c125784f0050e05a.aspx (last accessed 31.7.14).

[5] ABB (2014), press release: http://www.abb.co.uk/cawp/seitp202/3a295cb73f37c9ecc1257c63003c268a.aspx (last accessed 31.7.14).

[6] R. Remus, M.A.A. Monsonet, S. Roudier, L.D. Sancho, "Best Available Techniques Reference Document for Iron and Steel Production", European Commission, 2013,

http://eippcb.jrc.ec.europa.eu/reference/BREF/IS_Adopted_03_2012.pdf (last accessed 31.7.14).

[7] Tenova Group (2012), press release: www.tenovagroup.com/pdf/press/146-TENOVA%20RE%20ENERGY.pdf (last accessed 31.7.14).

[8] Schlemmer, P. (2011), "Wärmeaufbringung und Wärmeverteilung in Graz", Fernwärmetage 2011: http://www.gaswaerme.at/de/pdf/11-1/schlemmer.pdf (last accessed 31.7.14).

[9] K. Hoffmann, D.F. Pearson (2011), "Ammonia Heat Pumps for District Heating in Norway – a case study", In Proc. Inst. R. 2010-11. 7-1, http://www.ammonia21.com/web/assets/link/Hoffman7thApril2011London%20colour.pdf (last accessed 31.7.14).

[10] R.H. Perry, D.W. Green, Perry's Chemical Engineers' Handbook, McGraw-Hill, 1997 p 214.

[11] J. Dixon, S. Bramfoot, "Design of waste heat boilers for the recovery of energy from arc furnace waste gases", Commission of the European Communities, 1985.

[12] J. Jones, "Understanding Electric Arc Furnace Operations", EPRI Center for Materials Production (1997): http://infohouse.p2ric.org/ref/10/09047.pdf (last accessed 31.7.14).

[13] D. Zuliani, V. Scipolo, J. Maiolo, "Opportunities for increasing productivity, lowering operating costs and reducing greenhouse gas emissions in EAF and BOF steelmaking", In Proc. AISTech 2010: www.millennium-steel.com/articles/pdf/2010%20India/pp35-42%20MSI10.pdf (last accessed 16.7.13).

[14] Tenova Group, "Tenova's approach to the future energy scenario", 2014: tenovagroup.com/pdf/technical/AceroRaggioLuglio.pdf (last accessed 31.7.14).

[15] F.B. Walling, L.E. Otts (1967), "Water Requirements of the Iron and Steel Industry": pubs.usgs.gov/wsp/1330h/report.pdf (last accessed 31.7.14).

[16] DEFRA, "2013 Government GHG Conversion Factors for Company Reporting: Methodology Paper for Emissions Factors", July 2013, https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/224437/pb13988-emission-factor-methodology-130719.pdf (last accessed 31.7.14).

[17] World Health Organisation (2010), "Dioxins and their effects on human health", Fact Sheet No.225, www.who.int/mediacentre/factsheets/fs225/en/ (last accessed 31.7.14).

[18] C. Born, R. Granderath, "Benchmark for heat recovery from the offgas duct of electric arc furnaces", MPT International, February 2013, pp32-35.

[19] World Steel Association (2011), "Water Management in the Steel Industry", article, www.worldsteel.org/media-centre/press-releases/2011/water-management-report.html (last accessed 31.7.14).

[20] Department of Energy and Climate Change (2014), "Quarterly Energy Prices", March 2014, https://www.gov.uk/government/publications/quarterly-energy-prices-march-2014 (accessed 31.7.14)

[21] DECC, "Cost of District Heating", http://chp.decc.gov.uk/cms/cost-of-district-heating (last accessed 31.7.14).

[22] Ofgem, "Non-Domestic Renewable Heat Incentive Scheme – Non Domestic RHI spring amendments" April 2014, https://www.ofgem.gov.uk/ofgem-publications/87364/es851nondrhifactsheetweb.pdf (last accessed 31.7.14).