ORCA – Online Research @ Cardiff

Accepted manuscript

As a service to our authors and readers, we are putting peer-reviewed accepted manuscripts (AM) online, in the Ahead of Print section of each journal web page, shortly after acceptance.

Disclaimer

The AM is yet to be copyedited and formatted in journal house style but can still be read and referenced by quoting its unique reference number, the digital object identifier (DOI). Once the AM has been typeset, an 'uncorrected proof' PDF will replace the 'accepted manuscript' PDF. These formatted articles may still be corrected by the authors. During the Production process, errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal relate to these versions also.

Version of record

The final edited article will be published in PDF and HTML and will contain all author corrections and is considered the version of record. Authors wishing to reference an article published Ahead of Print should quote its DOI. When an issue becomes available, queuing Ahead of Print articles will move to that issue's Table of Contents. When the article is published in a journal issue, the full reference should be cited in addition to the DOI.

Authors: Anthony Giles, Chris Williams, Daniel Pugh, Phil Bowen, Richard Marsh and Tim O'Doherty

Affiliation: School of Engineering, Cardiff University, Cardiff, CF24 3AA, UK

Corresponding author: Anthony Giles, School of Engineering, The Parade, Cardiff University, Cardiff, CF24 3AA, UK. Tel.: +44 (0) 2920 875931

E-mail: GilesAP1@cardiff.ac.uk

Abstract

Steelmaking is energy intensive, with manufacturing facilities representing some of the biggest point-source

CO_2 emitters in the UK. Efficiency improvements are essential with rising energy costs, driving significant

investment from the UK Iron and Steel sector. However, the industry still finds it difficult to justify waste heat

recovery projects, as individual schemes incorporating waste heat capture and an end-use for the waste heat

often incur high capital costs, resulting in long payback times. This paper describes the conceptual and

numerical development of a strategy for the deployment of waste heat recovery using a large integrated steel

works as a case study. An existing asset was utilised to link individual waste heat schemes together with a single

end-user; thereby reducing the capital requirement for each subsequent project. The proposed strategy and its

development is discussed, followed by the resultant CO_2 and energy savings (estimated to be 2.3Mt and

equivalent to £45M), over the six year period since its implementation.

Keywords: Energy; Infrastructure planning; Sustainability

1. Introduction

The UK became the first major economy to pass laws aimed at ending its contribution to global warming, requiring the reduction of all greenhouse gas (GHG) emissions to net zero by 2050. Prolonged efforts have been made to explore ways of becoming more energy efficient and develop industrial processes that require less energy (ACEEE, 2012). However, the energy-intensive iron & steel sector still accounts for approximately 26% of GHG emissions from UK industry (Griffin and Hammond, 2019) and steelworks sites represent some of the largest point source emitters of CO_2 nationwide (NAEI, 2019).

The UK Steel Industry has made efficiency improvements in recent years (DECC, 2012), however significant further progress is required. Meeting the established emissions targets will require the industry to adopt the key Best Available Techniques (BAT) in the short term; while also preparing to implement new energy efficient techniques and technological innovations in the medium and long term (Griffin and Hammond, 2018). Additionally, to insulate itself from any future price volatility in the energy markets, energy efficiency is vital for a sustainable future for the UK steel industry. The UK imports ~36% of its total energy consumption (DECC, 2019) and government policy is predicted to affect the future competitiveness of UK steel producers, with electricity prices being 62% and 80% higher than respective competitor plants in Germany and France (UK Steel, 2019).

The aim of this study is to describe the development and implementation of a centralised waste heat recovery (WHR) strategy at a large-scale UK steelworks, with multi-vector energy flows and complex process interdependencies. Numerical modelling was undertaken to simulate proposed changes to the energy distribution system to determine if enhancements in by-product fuel utilisation and waste heat recovery (WHR), through the implementation of BAT, could lead to a reduction in site electricity import.

2. Traditional integrated steelworks energy strategy

The TATA-Steel Port Talbot plant was selected as the case study for this work, and can be defined as a traditional blast furnace – basic oxygen steelmaking route integrated steelworks, employing ~4000 staff with an annual product capacity of 5 Mt, and producing ~5.8 Mt CO_2 pa (ENDS Report, 2019).

The material flow diagram for the integrated facility is shown in Figure 1, comprising blast furnaces (BF), basic oxygen steelmaking (BOS) converters, continuous slab casters, hot and cold rolling mills and a continuous annealing line. To provide the process with raw materials the site also has a sinter plant (SP) and two batteries of coke ovens. Indigenous by-product fuels are also generated as part of the integrated process: low calorific blast

furnace gas (BFG) created in vast quantities; batch-produced BOS gas primarily comprising of carbon

monoxide; and hydrogen-rich coke oven gas (COG). Associated research (Giles et al. 2016, Pugh et al. 2014 and

2017) has been undertaken to compare the relative properties of the indigenous steelworks fuel gases and

discuss their operability limitations.

Globally, ~89% of the total energy input for a traditional BF-BOS integrated steelworks comes from imported

coal, with a further 7% provided in the form of electricity, 3% from natural gas and 1% from other sources

(WorldSteel, 2019). By comparison, the energy breakdown for directly reduced iron and electric arc furnace

route is markedly different, with reduced coal (11%), more electricity (50%) and natural gas (38%) alongside

other sources (1%). A principal energy target for the integrated works is to reduce electricity and natural gas

imports, employing BAT to strive for effective self-sufficiency, with energy transformed from the raw coal

material input (Tata Steel, 2012). Since 2005 there has been considerable investment throughout the case study

facility to improve its overall fuel and electrical efficiency. In total, more than £100M has been invested in

energy projects; such as the BOS Gas Recovery and utilisation scheme, alongside the installation of more

efficient motors, pumps, lighting and variable speed drives. Throughout this process, the primary focus was to

reduce the quantity of flared indigenous gases by improving their utilisation and thereby reducing imported

energy; however, resources were also assigned to the implementation of WHR and enhanced use of the sitewide

steam distribution system.

2.1 CO_2 production in traditional integrated steelworks

A breakdown of the embedded CO_2 for the processes within the case study facility is shown in Figure 2.

The carbon flow represented in Fig. 2 confirms the majority of CO_2 production primarily results from processes

using the raw coal and manufactured coke (BEIS, 2015). The coke ovens convert most of the coal into coke for

use in the blast furnace and sinter plant; with a small portion being used directly in the blast process through the

process of granulated coal injection. Coke, sinter and limestone is mixed into a BF burden, from which the

liquid iron is produced through reduction. The BOS process then converts the molten iron into steel, from which

steel slab is produced by the continuous casters. The coke, iron and steel making activities all produce by-

product carbonaceous fuel gases which are used throughout the site for process heating and for electricity

generation within the facility power plant. Imported electricity and natural gas directly contribute to only a small

fraction of the CO_2 for the end product, as it is coal that fuels the carbon intensive ironmaking process. Proposed

direct reduction technologies such as HISARNA and ULCORED or even the adoption of hydrogen direct

reduction (Vogl et al, 2018) may ultimately replace the traditional blast furnace and its associated processes (Griffin and Hammond, 2019), reducing the CO_2 contributions upstream of the steelmaking and rolling mills which will still be required in some form.

3. A Centralised Waste Heat Recovery Strategy

There are considerable barriers and complexities in defining the usable quantities, suitable recovery technologies and an optimum end use for waste heat sources (US DOE, 2008). Historically within the steelmaking industry, WHR projects try to define a combined 'all-in-one' solution with a localised end use, resulting in relatively high capital expenditure and the corresponding long payback times. De Beer (1998) and the US EPA (2012) provide examples of the quantities of waste heat available and list several examples of WHR projects for the iron and steel industry, with financial paybacks ranging from 2.8-35 years. This wide range in financial paybacks is due to various factors; such as the complexities of retrofitting often involving substantial civil and structural engineering changes to infrastructure (e.g. the implementation of sinter strand waste heat capture would involve substantial building modification), as well as the efficiency gains for some WHR systems being negligible when compared to the costs of process interruption. The challenge for the Port Talbot case study plant was identifying opportunities for WHR that simultaneously offered the most impactful gains with the shortest payback times.

A detailed analysis of the available 'exergy' within the case study facility was undertaken to understand the availability of waste heat sources. A summary of the findings listed several high, medium and low-grade waste heat sources that could be exploited (Newcastle University, 2011). In parallel, an investigation into the site's steam distribution system was undertaken to better understand the energy usage for each of the process locations. Steam is produced by the site's power plant as well as at additional 'service boilers' and distributed to other works areas at 11bar$_g$ for motive power and thermal energy. The 11 bar$_g$ steam is a by-product of the power plant, whose main objective is to power the large air blowers for the BF operation alongside the secondary generation of electricity. The service boilers ensure the pressure and temperature of the steam are maintained at usable quantities for processes at the extremities of the distribution network, necessitated by the scale of the facility (approx. 4.0km by 1.5km). The potential was identified for WHR to provide some of this process steam, thereby releasing the indigenous gases for other purposes such as increased electrical generation or the displacement of imported natural gas. A diagrammatic representation of the 11 bar$_g$ steam system prior to the adoption of the centralised WHR strategy is shown in Fig. 3, with arrow widths proportional to flows.

Identified waste heat sources are also represented by the numbers, with the equivalent quantities and descriptions outlined in Table 1. Further details of the site's steam distribution and waste heat analysis can be found in the PhD thesis of Williams (2015).

In addition to the sources of high-grade waste heat identified, the historical development of the chosen facility (including a recent investment to capture and utilise the BOS gas) resulted in there being an excess availability of indigenous by-product fuels. The 11 bar_g steam distribution network (shown in Figure 3) covers the entire facility and in total comprises of over 20 km in insulated pipework. Prior to the WHR strategy, 11 bar_g steam was considered to be a low value by-product, and therefore the network was an under-utilised asset to the works with the future of the entire 11-bar_g steam system being questioned. However, once waste heat sources were considered, it was shown that the distribution system was recognised as a useful asset and enabler for WHR projects. A detailed numerical appraisal of the work's steam system and power generating philosophy was subsequently required to ensure the efficacy and optimised impact of any proposed solutions.

3.1 WHR: BOS Plant Off-Gas System

BOS gas cooling presented an opportunity for WHR, with preparatory work already underway for a scheduled replacement of the plant's water-cooled off-gas system, which since 1997 had employed a conventional cooling tower to vent the extracted heat to atmosphere. The 'Best Available Techniques (BAT) for Iron and Steel Production' (Remus et al, 2012) and the work of Kasalo (2010) indicated that an evaporative cooling system in which the waste heat is used to generate steam was a desirable option, however these systems were considered to be technically challenging in terms of installation and any financial benefits difficult to determine.

For a BOS plant off-gas system, such as that utilised on the Port Talbot site, typical gas flows of 150,000 Nm^3/min at temperatures of over 1500 ℃ (Kasalo 2010) would be capable of generating at least 23 tonnes of pressurised steam per oxygen blowing event (or heat) at pressures of between 20 and 40 bar_g - this wide range in possible pressure being a function of hot metal quantity, oxygen blowing rate and combustion control. For the case study facility, the BOS plant operates at an average of 1.8 heats per hour, therefore providing a potential steam export flow of 40 tonnes per hour (tph).

Two options for the local generation of electricity were initially considered:

1. Supplying a saturated steam turbine directly off the steam export line. This would generate a maximum of 5 MW_e.

2. Fitting a superheated steam turbine, utilising surplus BFG to superheat the steam. This would generate a maximum of 7.6 MW_e and in effect an extra 2.6 MW_e would be generated using 18GJ (5 MW_T) of by-product that would otherwise be flared.

Both above generation options were initially assessed with an assumed steady state steam export from the BOS plant. To understand the actual steam export rate, a model was developed based on dynamic data, stored from previous years' operation, incorporating typical BOS steam export characteristics (Gopalakrishnan et al 2007). Steam accumulators were shown to be an essential requirement for recovery, buffering the batch operation to provide a smoothed export and enabling a controlled ramp up and down of the steam supply to the turbine. Even with the provision of steam accumulators, regular periods of zero steam export were predicted and up to 100 days of electrical generation lost. Furthermore, due to thermal stress issues that arise when turbines are exposed to frequent turndown periods, prolonged operation necessitates a continuity of the steam supply. It therefore became evident that local utilisation of the steam produced by the BOS gas WHR system would require supplementary steam from another source. One feasible source identified was the 11 bar_g steam distribution circuit. Operating this turbine with an inlet supply pressure of 11 bar_g would require the steam produced by the BOS plant WHR system to be super-heated and pressure reduced. However, the extra energy requirement and inefficiencies this introduces are offset by the option of continuously operating the turbine using the 11 bar_g steam supply as a base load.

3.2 Centralised Waste Heat Utilisation

The complex multifaceted interdependencies of the site energy system meant simple capacity calculations were not adequate to ensure the efficacy of the proposed system. Hence a detailed model of the steam distribution circuit was developed employing compressible flow calculations in commercial software (‘*Fluidflow*’ NI, 2014). In order to verify the proposal of a centralised steam turbine for the generation of electricity supplied from the 11 bar_g steam network, the pipework, insulation, boilers and consumers for the whole of the steam distribution circuit were surveyed and the model validated for differing boiler and consumer loadings. Modelled temperature and pressure values were compared against actual values from plant instruments and a satisfactory agreement obtained after model validation, with percentage errors for pressure and temperature being approximately 3%

and 4% respectively (further details can be found in chapters 5 and 6 of Williams, 2015). The WHR project was subsequently added to the model and the influence of the extra steam evaluated. It was found that the principle operating proposal - in which the turbine would be kept running using a base load of steam from the distribution circuit, supported by steam from the BOS plant waste heat boiler - would not have any detrimental effect on other site consumers. Additionally, the concept introduced other possible benefits:

- Any unused site process gases that would otherwise be flared could be used to generate additional 11 bar_g steam utilising the spare capacity in the service boilers, increasing the new turbines electrical output.

- The distributed 11 bar_g steam becomes an economic asset, with a value directly related to the electricity price. Improvements in steam usage efficiency throughout the site can be financially justified.

Modifications to the model to include the available spare capacity of the service boilers (estimated to be approximately 20 tph), demonstrated the potential for additional electrical generation of up 10 MW_e from this alone. From the results of this modelling work it became apparent that the installed turbine should be selected with sufficient spare capacity to not only allow for this increased output of the service boilers, but to also allow for steam generated by other future waste heat projects; reducing the capital expenditure and hence increasing the payback of each future project. A representative flow schematic of the 11 bar_g steam circuit incorporating the new turbine is shown in Figure 4.

Based on this work, an 11 bar_g steam turbine with a total capacity of 100tph (maximum rated output of 18 MW_e) was selected and installed at the case study facility. Alongside the evaporative cooling system, this corresponded to an investment of £53M. The turbine capacity was envisaged to be sufficient to manage the steam produced by the BOS plant WHR scheme, the extra steam from the service boilers operating at higher capacity and to provide sufficient spare capacity for future WHR boilers (such as those listed in Table 1).

4. Adoption of the Waste Heat Recovery Strategy: Results

The implementation of the BOS plant WHR project and installation of the new steam turbine at the case study facility has significantly changed utilisation of the 11 bar_g steam distribution system. An example of average steam flows incorporating the WHR scheme shown in Figure 5. The steam network now forms a central part of the strategy for maximising potential waste heat opportunities as part of future strategic maintenance plans. As such, a maintenance programme has been undertaken to maximise efficiency of the steam mains. The new 11 bar_g turbine alternator successfully manages the utilisation of the batch steam production of the BOS plant

evaporative cooling WHR system. Installation of the system allows not only utilisation of the steam generated by the BOS plant evaporative cooling, but also enables the facility power plant and boilers to operate at increased capacity, enhancing utilisation of plant by-product gases.

Prior to the installation of the new turbine alternator on the 11 bar_g steam distribution circuit, it was difficult to provide a justification for WHR schemes. However, the plant subsequently invested a further £2.4M to install a low-grade waste heat boiler on the Continuous Annealing Process Line (CAPL); which when operational, enables an extra 1 MW_e generation from the 11 bar_g steam turbine.

This strategy has facilitated an additional capacity of 12 MW_e, corresponding to an import reduction of ~10%, from the following sources:

- Steam from the BOS plant can be simply superheated and plugged into the steam mains (7 MW_e)

- Spare capacity can be utilised within the service boilers thus creating more steam for no capital expenditure (3 MW_e)

- Lower grade waste heat recovery utilised from the CAPL line (1 MW_e)

- A programme of steam system maintenance to be undertaken to maximise the efficiency of the steam mains (1 MW_e)

Using UK government emissions conversion factors (Department for Business Energy & Industrial Strategy, UK Government, 2019), since its installation in 2013 the WHR scheme and new turbine alternator has saved the equivalent of over 2.3Mt of CO_2, from reduced electricity import.

The success of the evaporative cooling scheme and the centralised waste heat recovery strategy can be best represented by the improved relative operation of the BOS plant; shown in Figure 6.

Prior to the introduction of the recovery and utilisation of the by-product BOS gas, the BOS plant at the site was a net importer of energy. The BOS gas recovery project resulted in the plant being a net *exporter* of energy to the works, although its performance was lower than that of the perceived BAT at the time (Voest Alpine plant, Linz). The introduction of the WHR strategy and its subsequent effect on the plant's operation, together with continued additional energy saving schemes, has now resulted in the BOS plant at the Port Talbot site being able to exceed the values previously set as BAT.

Conclusions

Through the development of a centralised waste heat recovery strategy and numerical modelling, the 11 bar$_g$ steam distribution system was identified as an essential resource and enabler for the introduction of waste heat recovery at the Port Talbot integrated steel works. An initial investment of £53M on the first phase of the strategy, namely BOS plant evaporative cooling (incorporating heat recovery/steam generation) and an 18 MW$_e$ steam turbine was undertaken.

Thus far:

- The investments have enabled an expansion of the electrical generation capacity of 12MW$_e$ and an indirect reduction in 2.3Mt of CO_2 over the 6 years since installation in 2013.

- Spare capacity can now be utilised within the service boilers, thus creating more steam and increasing the facility by-product process gas utilisation for no capital expenditure.

- Steam efficiency savings now result in electrical and thus financial benefits for the works (estimated to be £45M to date), facilitating enhanced investment in WHR projects.

- Future waste heat schemes can be simply added to the steam distribution circuit. Each waste heat scheme will not therefore require the associated capital expenditure of a turbine and cooling tower, effectively reducing their payback times.

Acknowledgements

List of notations

BAT   Best Available Techniques
BF   Blast furnace
BFG   Blast furnace gas
BOS   Basic oxygen steelmaking
COG   Coke Oven Gas
GHG   Greenhouse Gas
SP   Sinter plant
tph   Tonnes per hour
WHR   Waste heat recovery

References

ACEEE (American Council for an Energy Efficient Economy) (2012) International Energy

Efficiency Scorecard. ACEEE report number E12A.

BEIS (Department for Business, Energy & Industrial Strategy) (2015) Industrial

Decarbonisation & Energy Efficiency Roadmaps to 2050: Iron and Steel. See

https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/416667

/Iron_and_Steel_Report.pdf (accessed 13/12/2019)

BEIS (Department for Business, Energy & Industrial Strategy) (2019) Government emission

conversion factors for greenhouse gas company reporting. See

https://www.gov.uk/government/collections/government-conversion-factors-for-

company-reporting (accessed 13/12/2019)

de Beer J. (2000) Future Technologies for Energy-Efficient Iron and Steel Making. In:

Potential for Industrial Energy-Efficiency Improvement in the Long Term. Eco-

Efficiency in Industry and Science, vol 5. Springer, Dordrecht

http://dx.doi.org/10.1146/annurev.energy.23.1.123

DECC (Department of Energy and Climate Change) (2012) Industrial Energy Consumption

in the UK since 1970. Publication URN: 12D/292, pg. 5

DECC (Department of Energy and Climate Change) (2019) UK Energy in Brief 2019, pg. 11

Department for Business Energy & Industrial Strategy, UK Government, (2019) Government

emission conversion factors for greenhouse gas company reporting (accessed

13/12/2019).

ENDS Report (2019) Focus on: carbon emissions. See

https://www.endsreport.com/article/1583008/focus-on-carbon-emissions (accessed

13/12/2019)

Ferreira H, Leite MGP (2015) A Life Cycle Assessment study of iron ore mining. Journal of

Cleaner Production 108(A): 1081-1091. https://doi.org/10.1016/j.jclepro.2015.05.140

Giles AP, Marsh R, Bowen P and Valera Medina A (2016) Applicability of the Peclet

number approach to blow-off and flashback limits of common steelworks process

gases. Fuel 182: 531-540. http://dx.doi.org/10.1016/j.fuel.2016.05.082

Gopalakrishnan B, Banta L, Bhave G (2007) Modelling steam-based energy supply chain in

an integrated steel manufacturing facility: A simulation-based approach. International

Journal of Industrial and Systems Engineering, 2(1), 2007

https://doi.org/10.1504/IJISE.2007.011433

Griffin PW, Hammond GP (2018) Analysis of the potential for energy demand and carbon

emissions reduction in the iron and steel sector. Energy Procedia (158), 3915-3922,

https://doi.org/10.1016/j.egypro.2019.01.852

Griffin PW, Hammond GP (2019) Industrial energy use and carbon emissions reduction in

the iron and steel sector: A UK perspective. Applied Energy, 249(c): 109-125,

https://doi.org/10.1016/j.apenergy.2019.04.148

Kasalo J (2010) Utilisation of evaporation waste gas cooling systems to counteract rising

energy cost. Kasalo J. AISTech Iron and Steel Technology Conference Proceedings

2010

Kittipongvises S (2017) Assessment of Environmental Impacts of Limestone Quarrying

Operations in Thailand. Environmental and Climate Technologies, 20: 67-83

https://doi.org/10.1515/rtuect-2017-0011

NAEI (National Atmospheric Emissions Inventory) (2019) Emissions from NAEI large point

sources. See https://naei.beis.gov.uk/data/map-large-source (accessed 13/12/2019)

Newcastle University (2011) National sources of low grade heat available from the process

industry. Progress Report EPSRC: Thermal Management of Industrial Processes

NI, F. S. 2014. Fluidflow 3 Website [Online]. Available at: http://www.fluidflowinfo.com/

(accessed. 13/12/2019)

Pugh, D. A.P. Crayford, P.J. Bowen, T. O'Doherty, R. Marsh, J. Steer, (2014) Laminar flame

speed and markstein length characterisation of steelworks gas blends, Applied Energy

136 1026-1034. https://doi.org/10.1016/j.apenergy.2014.04.044

Pugh, D. P.J. Bowen, R. Marsh, A.P. Crayford, J. Runyon, S. Morris, A. Valera-Medina, A.

Giles (2017) Dissociative influence of H2O vapour/spray on lean blowoff and NOx

reduction for heavily carbonaceous syngas swirling flames, Combustion and Flame

177, 37-48. https://doi.org/10.1016/j.combustflame.2016.11.010

Rao P, Muller M (2007) Industrial Oxygen: Its Use and Generation. ACEEE Summer Study

on Energy Efficiency in Industry: Panel 6 - Energy Efficiency in Specific Industries

Remus R, Roudier S, Delgado Sancho L, Aguado-Monsonet MA (2012) Best available

techniques (BAT) reference document for iron and steel production. Publications

Office of the European Union. https://doi.org/10.2791/97469

Tata Steel (2012), Port Talbot Works Review of General, Coke, Sinter, Iron and Steel

processes against Iron and Steel BAT Conclusions, March 2012. See

https://naturalresources.wales/media/2104/tata-reg-60-bat-response.pdf?lang=en

(accessed 13/12/2019)

UK Steel (2019) Press Release Energy Price Disparity Report. See

https://www.makeuk.org/news-and-events/news/2019/10/08/persistently-high-

electricity-prices-threaten-steel (accessed 13/12/2019)

US EPA (Environmental Protection Agency) (2012) Available and Emerging Technologies

for Reducing Greenhouse Gas Emissions from the Iron and Steel Industry. Sector

Policies and Programs Division Office of Air Quality Planning and Standards

US DOE (Department of Energy) Industrial technologies Program (2008) Waste Heat

Recovery: -Technology and Opportunities in U.S. Industry

Vogl V, Åhman M, Nilsson LJ (2018) Assessment of hydrogen direct reduction for fossil-

free steelmaking. Journal of Cleaner Production 203: 736-745

https://doi.org/10.1016/j.jclepro.2018.08.279

Williams C, (2015) PhD Thesis. A Waste Heat Recovery Strategy for An Integrated

Steelworks. Cardiff University (Download link http://orca.cf.ac.uk/87146/).

WorldSteel (2019) Energy use in the steel industry… See

https://www.worldsteel.org/en/dam/jcr:f07b864c-908e-4229-9f92-

669f1c3abf4c/fact_energy_2019.pdf (accessed 13/12/2019)

Table 1. High-grade waste heat sources identified

#	Location	Description	Approx. Temp	Heat Available
1	Coke Ovens	Hot Coke Quenching	950 °C	40 MW$_T$
2	Coke Ovens	Ammonia Incineration	1100 °C	2 MW$_T$
3	BOS Plant	BOS Gas	1500 °C	45 MW$_T$
4	BOS Plant	BOS Slag	1650 °C	22 MW$_T$
5	Sinter Plant	Sinter Cooler	650 °C	70 MW$_T$
6	Continuous Casting	Hot Slab	800 °C	73 MW$_T$
7	Blast Furnaces	Blast Furnace Slag	1550 °C	45 MW$_T$
8	CAPL	Exhaust Gases	600 °C	10 MW$_T$
9	Hot Mill	Hot Slab	1100 °C	70 MW$_T$
10	Hot Mill	Hot Coil	650 °C	34 MW$_T$

Figure Captions

Figure 1. Site process flow diagram-

Figure 2. Site flows as a Carbon Dioxide equivalent (Sources for values are from site data and: a) BEIS, 2019

b) Ferreira and Leite, 2015 c) Kittipongvises, 2017 d) Rao and Muller, 2007)

Figure 3. Site 11 bar steam flows (prior to WHR strategy) and available waste heat sources

Figure 4. Flow Schematic of new 11 bar steam circuit

Figure 5. Site steam flows incorporating new WHR strategy

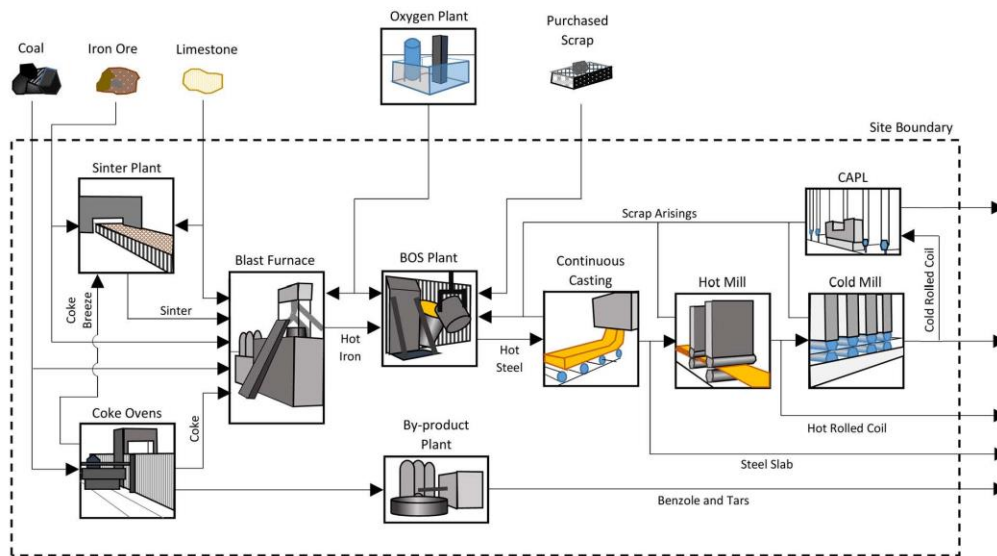**Figure 6.** Progression of the Tata-Steel Port Talbot BOS facility towards BAT
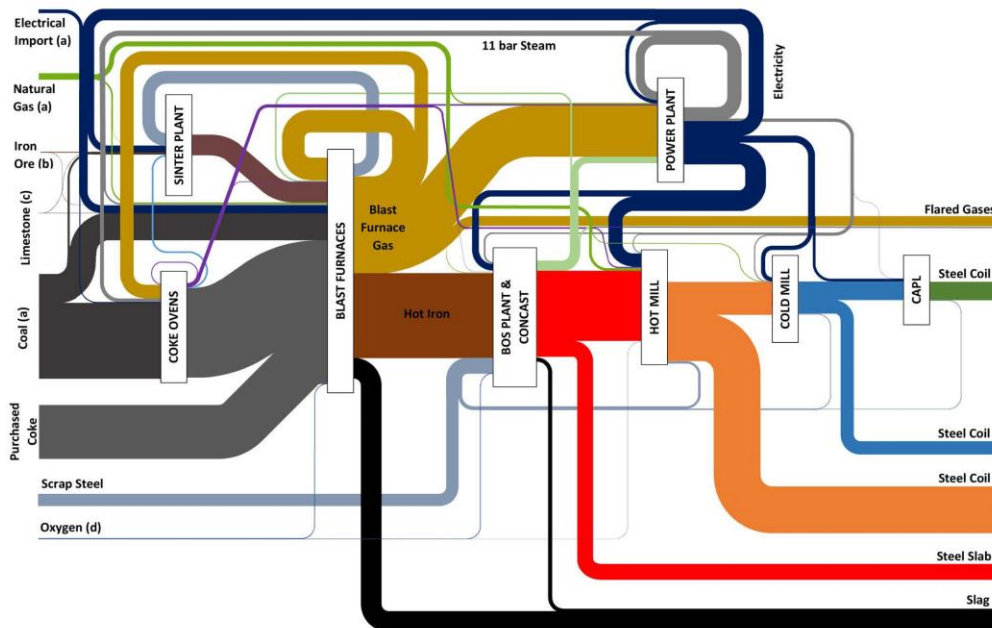
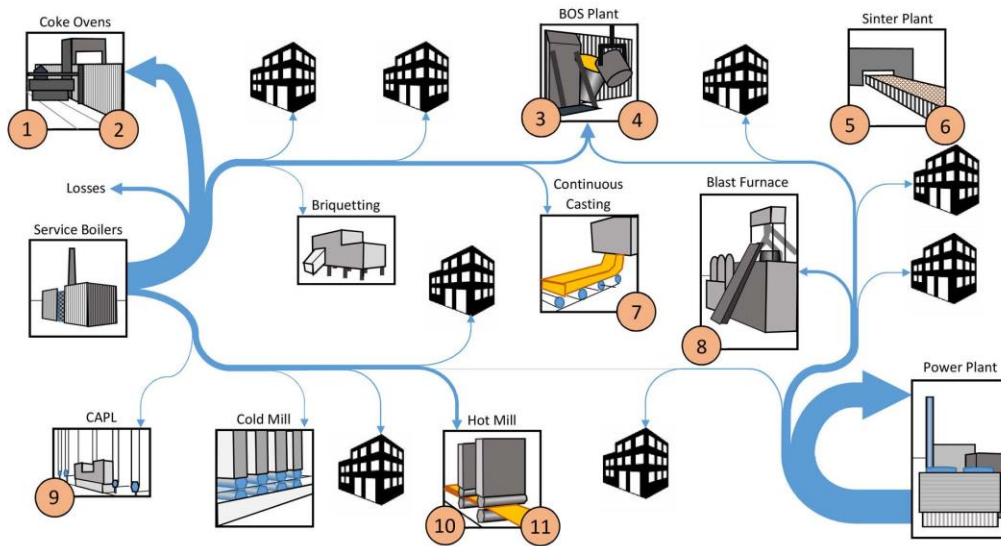Fig 1 - Site process flow diagram HighRes

Fig 2 - CO2 Sankey

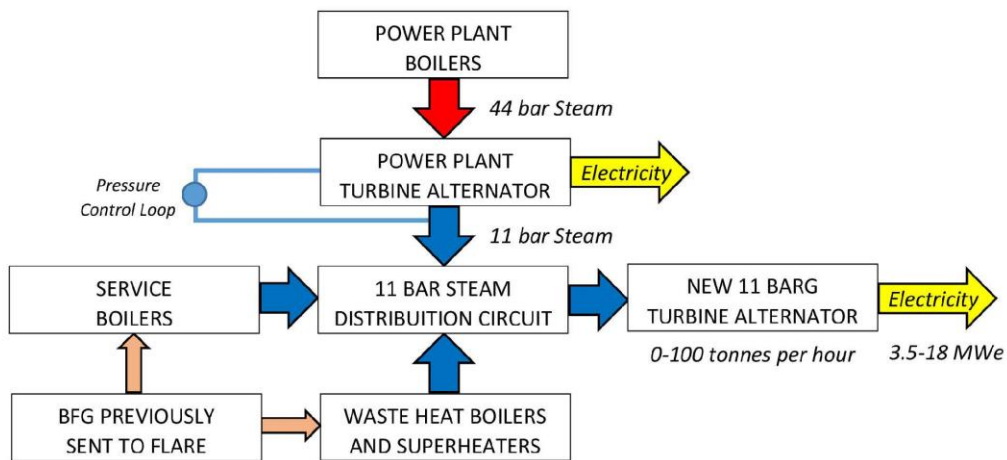Fig 3 - Site steam flows and waste heat sources
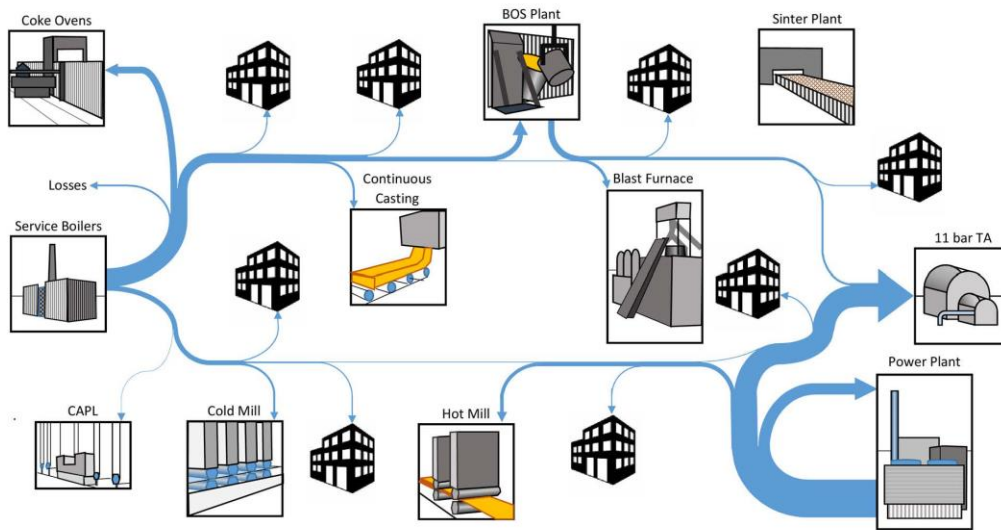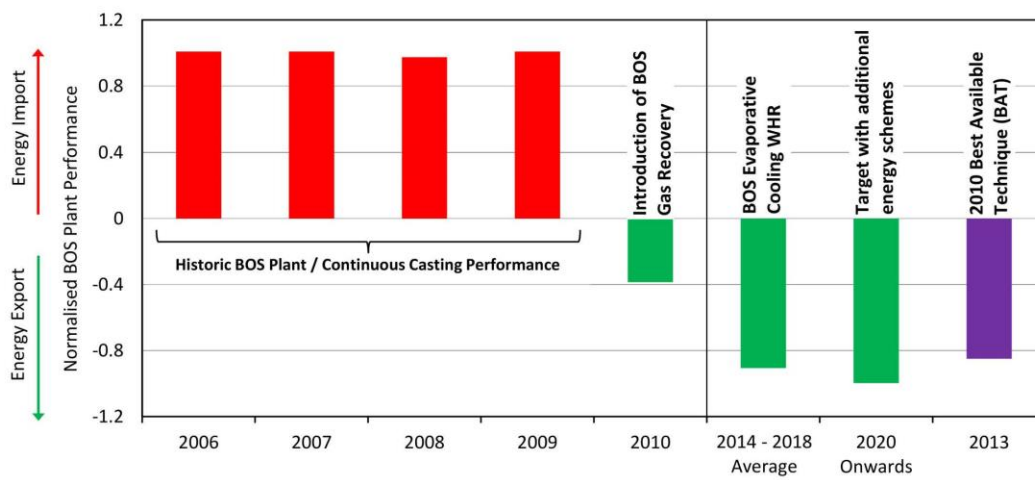
Fig 4 - Scematic of New 11 barg Steam Balance

Fig 5 - Site steam flow with WHR

Fig 6 - BOS plant progress towards BAT