Utilising Waste Heat for Steam Generation Within an Integrated Steelworks: A Methodology for Power Generation and CO_2 Reduction

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ABSTRACT

UK energy prices have doubled over the last decade, which has driven the UK Iron and Steel Industry to invest in energy efficient technologies. However, even with these relatively high prices the industry still finds it difficult to build a business case to justify waste heat recovery projects. The Steel Industry has large quantities of waste heat and there are technologies readily available for its capture, but often the issue has been finding a cost effective 'end use'. Individual schemes incorporating both capturing and an 'end use' for the waste heat often incur high capital costs with resulting long payback times.

This paper defines the development of a strategy and methodology for the utilisation of waste heat recovery in a UK based Steelworks. The methodology involves the utilisation of an existing asset to link the possible waste heat schemes together with a single 'end user' thus limiting the capital requirement for each subsequent project. The paper further discusses the fact that on an individual basis the proposed strategy does not provide the most energy efficient solution for each project, but it provides the most cost effective solution.

The developed strategy stimulated significant capital investments for the steel works discussed in the case study and will generate over 12 MWe and save over 52,500tonnes of indirect CO_2 emissions per annum.

Introduction

The UK has been recognized (ACEEE 2012) for its prolonged efforts over a long period of time in exploring ways to become more energy efficient and develop industrial processes that requires less energy. The UK Steel Industry has also followed suit and is about 13% more efficient since 1990 (DECC 2012a). However, with the UK importing 36% of its energy total energy consumption (DECC 2012b), the steel industry is facing a period of uncertainty with prices increasing and hence subsequent difficulties in controlling its manufacturing costs. The steel industry needs stable and predictable prices, the energy market is becoming more and more volatile and unpredictable. Around 25% of the UK's power generating capacity is projected to close within the next 10years (GOV.UK 2011), this obviously raises real concerns and uncertainties. The possibility of 'industrial blackouts' and ever increasing energy costs are a real threat to future industrial stability.

With the UK government committed to reducing carbon emissions below 80% of the 1990 level by 2050 and the proposed new green tax laws, on top of the European Unions Environmental Trading Scheme and the other taxes, the government is planning to impose an additional £28.30 per MWh for the Steel Industry (ICF 2012). With increasing energy costs followed by real concerns about security of electricity supply and the possibility of increasing green tax liabilities the industry has been forced to invest considerable resource into exploring the optimum road map for increased energy efficiency and driving the self-sufficiency agenda in the context of poor demand for its products.

The steelworks discussed in this case study is what would be defined as a traditional Blast Furnace route Integrated Steelworks. It contains 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 (CO).

In 2005 the site embarked on an improvement drive, known as 'The Journey' to develop a 'sustainable steelworks'. One important element of this drive was to analyse, investigate, benchmark and promote energy saving technologies and strategies. The key was to develop an independent function that was not constrained by both production and existing energy functions within the plant. Thus a separate structure was formed (Burggraaf 2011) titled the 'Energy Optimisation Team'. Working with the other disciplines at the site, a future strategy for increased fuel and electrical efficiency gained momentum. This stimulated investment of over £100m worth of energy projects for example BOS Gas Recovery, efficient motors, pumps, lighting and variable speed drives. The main focus was on reducing the amount of flared indigenous gases, by improving their utilisation and thus reducing imported energy. To support this drive for energy efficiency the case study site sought assistance from a local university who had expertise in this sector. The project had several objectives including the study of waste heat recovery (WHR) and the improved utilisation of the site's steam system.

As highlighted by the US Department of Energy publication the process of defining "quantities", "recovery technology" and an optimum 'end use' for heat recovery can be complex (BCS Inc 2008). The process of detailing possible WHR projects into the three headings, 'quantity', 'technologies for capture' and 'end use' is a way of leading an investigation in such a way to ensure that all options are explored. Historically WHR projects have been looked at in such a way as to try and incorporate an all-in-one solution with a very local end use. This can result in relatively high capital expenditure with resulting long payback times. By considering 'end use' in the wider context other possibilities become viable. Most steelworks studies reference the 'Future Technologies for Energy-Efficient Iron and Steelmaking' (Beer et al 1998) for its detail of 'quantities' of waste heat available. The US Environmental Protection Agency (EPA 2012) list several examples of Waste Heat Recovery projects for the iron and steel industry with financial paybacks ranging from 2.8years to 35years. The challenge for business is to reduce these pay back times and make the projects more financially viable. Higher energy prices and government incentives obviously help but the Industry needs to find and explore more novel ways of reducing capital spend and increasing the benefits.

There are often many options for the end use and considerable effort is required to deduce which is the most cost effective. For the Steel Industry the efficient end use might be a fair distance away from the heat source and also part of a different process with potentially differing energy demand pattern. Heat load matching as well as energy transfer losses therefore add another layer of complexity. By mapping potential WHR sources and possible end users a study can be initiated and then developed into a strategy for the works.

During 2010 the plant started to further benchmark itself against its sister plants around the world as well as its competitors. The scale of the opportunity was soon made clear. Part of this assessment process the company's R&D facility undertook a plant wide exergy study (Patsos & Mullan 2011). This activity highlighted a number of high, medium and low grade waste heat sources that could be exploited. This study indicated that there was a potential of about 6GJ per tonne of crude steel, which for the case study plant equates to around $800MW_{TH}$.

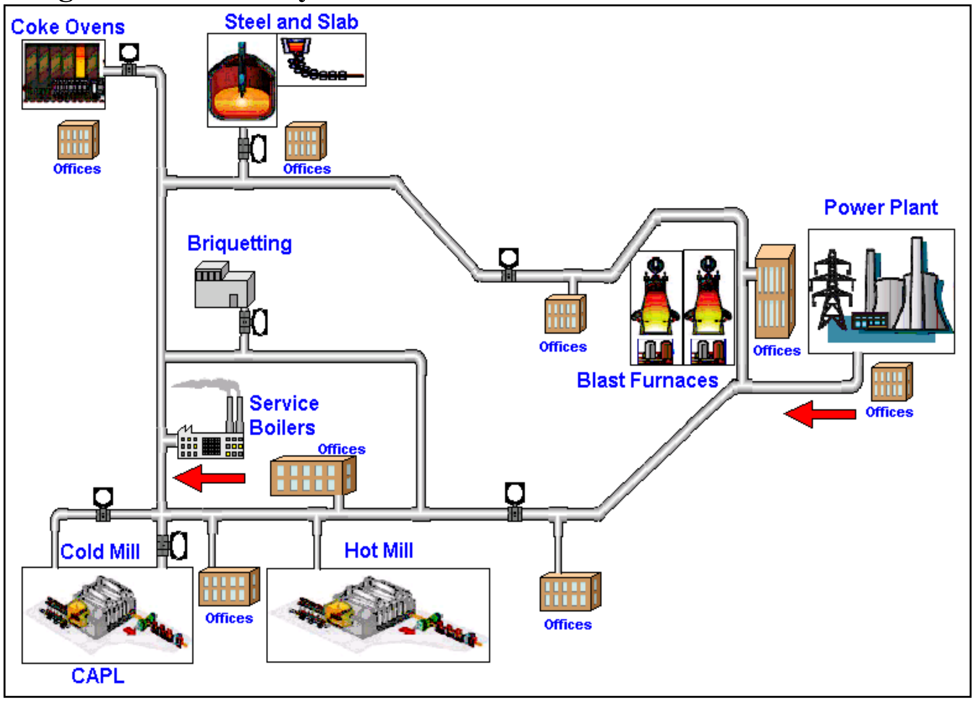
The final phase was to fully understand the optimum 'end use' of the energy, it was clear that the steam system for the works needed to be understood. The case study steelworks has a similar layout to that shown in the BREF document 'Best Available Techniques (BAT) for Iron and Steel Production (BREF 2012). Steam is generated, by burning indigenous gases in traditional boilers, in a power plant. As a typical Combined Heat and Power plant this steam is primarily used for electrical generation and to drive the large air blowers for the Blast Furnaces. Some steam is exported from the power plant at 11barg and distributed to other works areas for use as motive power or thermal energy. Due to the sheer scale of the steelworks (approx 4km by 1.5km) this site also requires additional boilers known as the "Service Boilers" as shown in figure 1. The main objective for these boilers is to ensure the pressure and temperature of the steam at the extremities of the distribution system is sufficient for the relevant processes. These boilers again use indigenous generated fuels

The works is therefore using indigenous fuels for generating 11barg steam for the works areas. The BREF document though, shows a steelworks steam circuit being supplied by waste heat boilers as well as by an export from the Power Plant. This infers that waste heat can be utilised to generate the works steam rather than the indigenous gases. Using waste heat to generate the steam required by the site would thus release the indigenous fuels for other purposes i.e. further electrical generation or displacement of imported natural gas.

However, the historical development of the case study plant has already resulted in an excess of indigenous fuels, which is in some cases are continuously flared. Little investment had been made in the power plant resulting in a lack of capacity and an excess of low calorific blast furnace gas. As shown in figure 2, 11barg steam is exported from the power plant via a pass-out turbine, thus the higher the demand from the works, the higher the electrical generation of the power plant. If waste heat was therefore used to generate steam for the site, then the power plant would export less steam and reduce its electrical generation. Waste heat projects would therefore have a negative payback. Defining the optimum 'end use' would therefore necessitate a rethink of the works steam system and power generating philosophy.

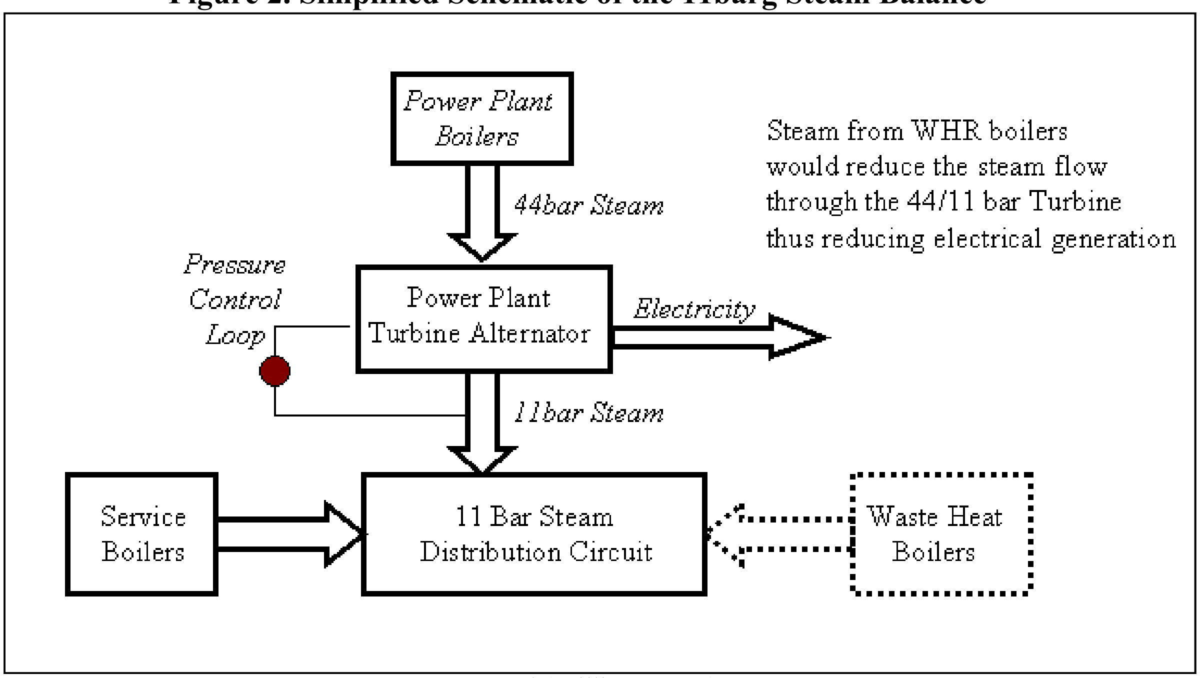
The 11barg steam system was seen as an 'old fashioned' element of the works and had limited investment over the years in terms of both maintenance and /or process improvement. What made things worse of course was the fact that because electricity was generated from the pressure reduction down to 11 barg, hence the less efficient this system was the more electricity was generated. There were no financial drivers for an efficient steam system. The lack of investment was evident by the number of leaks and areas of missing insulation. Questions were being asked about the future of the steam system and decentralisation seemed the way forward. The steam system was surveyed and studied and calculated losses of at least 6 tonnes per hour were recorded. It was recognised that this was wasting energy but again there wasn't the financial incentive for rectification or improvement. The steam mains cover virtually the whole area of the case study site and total over 20km in length. Even though the pipework looked tired it was sound and was regularly inspected in accordance with the relevant pressure regulations. Large diameter steam distribution circuits are expensive to install and can cost well over a £1,000 per meter. The steam mains were therefore recognised a valuable asset to the works but was underutilised, needed some investment but even more importantly was already in place ready to be used if required.

Figure 1. Case Study Steelworks Steam Distribution Circuit



Source: Tata Steel (Williams 2012)

Figure 2. Simplified Schematic of the 11barg Steam Balance



Source: Tata Steel (Williams 2012)

Development of the First Waste Heat Recovery Project: Water Cooled BOS Plant Off Gas System

The BOS plant area was suffering from continued manufacturing delays from failures of the water-cooled off gas system. This key system had been replaced in 1997 but was well beyond its designed lifecycle and thus needed to be replaced. It can be assumed that due to cheap energy prices and the lack of an obvious 'end use' the decision was made to opt for the least cost option of a simple 'open cooling' water system and not consider the option with heat recovery. Since 1997 the heat extracted from the cooling system was therefore simply vented to atmosphere through a conventional cooling tower. Research has identified the three options available for off gas ductwork (Kasalo 2010). In principle these options are:

1. Open cooling system. The off gas ductwork is simply cooled with recirculated water directly from cooling towers. This option results in difficult water chemistry control and resultant corrosion issues.
2. Closed cooling system. The cooling tower is separated from the ductwork with heat exchangers thus improving water chemistry control and reducing the risk of corrosion.
3. Evaporative Cooling. Is essentially using the waste heat to generate steam from the cooling water in a boiler / steam drum assembly. This is the most expensive option but generates considerable quantities of steam.

A 'closed cooling' (option 2) was being considered rather than an open cooling (option 1) for the replacement the off gas system. This would improve the long term water chemistry control and thus extend the life cycle of the off gas ductwork The third option of evaporative cooling was seen as technically challenging in terms of installation and as there wasn't an obvious 'end use' for the steam the financial benefits were undetermined. As stated earlier, any steam put into the steam distribution circuit would reduce the electrical generation of the power plant and thus have a negative impact financially. It was at this stage where the site and the University came together and the challenge was set to understand what the total benefit of the steam could be.

As discussed by Kasalo (Kasalo 2010) with typical gas flows of 150,000Nm^3/min and at temperatures of over 1500 ^{o}C for the case study plant it is possible to calculate that at least 23 tonnes of steam per heat at 20-40 barg could be generated (depending on the hot metal quantity, oxygen blowing rate and combustion control). Then depending on the number of heats per hour, steam accumulators can be employed to provide a steady steam export flow. For the case study steelworks this would average at 1.8 heats per hour so an expected steam export of an estimated 40 tonnes per hour. Also an 'externally fired' Superheater would also be required, since the steam distribution circuit requires superheated steam. The steam export from the waste heat boiler would be saturated. More importantly, as previously described, any additional steam fed into the steam mains would reduce the amount of steam supplied to the site by the power plant and thus reduce the amount of electricity generated. Therefore exporting steam from the BOS plant into the existing steam distribution circuit, as per the BREF document would not make financial sense.

Two options were therefore considered:

1. Fitting a saturated steam turbine directly off the BOF steam export line. This would generate a maximum of 5MWe

2. Fitting a superheated steam turbine by utilising some of the flared BF gas to superheat the steam. This would generate a maximum of 7.6MWe and in effect an extra 2.6MWe would be generated with 18GJ ($5MW_{TH}$) of free fuel.

Both above generation options were 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 minute-by-minute data from the previous year's operation. The modeled year suffered a weak order book, but was never-the-less seen as what would typically be expected in further weak trading and should therefore be assessed as a worst case scenario. The model included a calculation of steam export based on BOS production rates; with an allowance for steam accumulation and a basic control philosophy is assumed. It then became clear that there would have been a considerable amount of the year with zero steam export and thus no electrical generation. Controlled steam ramp down and ramp up would also have to be considered. The model predicted that BOS would not export steam up to several times a day, in fact in total of about 150,000 minutes or 100days a year could be lost due to intermittent steam export.

Typical BOS steam export characteristics have been analysed and modeled (Gopalakrishnan et al 2007). Gopalakrishnan defined the development of a model to improve the capture of steam from a U.S. BOS plant waste heat recovery boiler. This was defined based on typical steam make per blow and its interaction with the works steam system. It was stated that steam accumulators would be an essential addition for recovery from the batch BOS plant operation. The model was built with an assumed 'buffer' from the steam accumulators to simulate a smoothed export. Even with the addition of steam accumulators the model showed there would be regular periods of zero steam export.

Discussions with potential steam turbine suppliers raised real concerns over the lack of continuity of the supply of steam. Due to thermal stress issues turbines are not capable of coping with frequent periods of no steam. The only practical way of running a turbine would be to supplement the steam from the BOS plant with steam from another source. That way the turbine would always be supplied with a minimum amount of steam and would not be required to stop frequently. So in theory the generation of electricity directly from the BOS steam was possible but in practice, due to the periods of no steam, was not plausible. This was discussed and analysed in some detail within the Steel Works. There was a real worry about the ability to cope with too much variability and the possible manning consequences of having to closely monitor a steam turbine with an independent steam feed only from the BOS plant. This resulted in the necessity for the consideration of Option 3: Utilising steam from the local steam distribution circuit to supplement the BOF steam make.

The project was then developed for a turbine mounted off the steam distribution circuit. The steam from the BOS plant would be pressure reduced and superheated before feeding into the turbine. The 'externally fired' Superheater would have to superheat around 40tonnes per hour of steam so it would consume an estimated 14GJ/hour of gas (£84/hour @£6/GJ ~ £655,200/year (50weeks)). Should the BOS plant stop making steam then steam would be drawn from the distribution circuit. The amount of electrical generation would drop to 7.2MWe but, due to the additional steam supply from this circuit and generation would be more consistent over the year. So the electrical generation would reduce from 7.6MWe to 7.2MWe but the turbine would run more consistently and would not have stopped for the modeled 100days per year. This equates to an annual increase of 8000 MWh electricity. So a 0.4MWe loss of potential generation (or 3500MWh over a year) is justified when one considers an additional generation of 8,000MWh is gained by a more consistent operation. To put that into a financial context, for a 50 week year, at £79/MWh the 7.2MWe would be worth £4,700,000 per year. One would then have to deduct the £655,200 for the gas for the superheater so a net gain of an estimated £4,000,000 per year.

Even though this option does not technically maximise the use of the available energy it does maximise the annual output from the turbine. As the proposal developed it then became clear that the new turbine could also make use of spare steam capacities in the service boilers. The works also has excess gas and flares significant quantities during the year. The service boilers are run at a minimum output to ensure pressures are maintained to the south end of the works but also maximise the supply from the power plant to ensure maximum electrical generation. By putting a new turbine off the steam distribution circuit this spare capacity could also be utilised to increase the steam make and maximise the financial benefit of the new turbine.

The service boilers had a spare capacity of over 20 tonnes per hour (tph). The model was then developed further to include an additional 20tph for the boilers that would in effect feed directly into the new turbine. This would increase generation to 10MWe worth £6,636,000 per year (at £79/MWh for 50 weeks). This would require more Blast Furnace Gas for the service boilers but for the case study works this is only a proportion of the gas flared and so is available for free.

In principle the turbine would be kept running using a base load of steam from the distribution circuit and then topped up by steam from the BOS plant waste heat boiler. This concept then introduced other possible benefits:

- The steam export from the power plant could be increased – increasing generation
- Flared gas could be used to further utilise the spare capacity in the Service Boilers
- Distributed steam then becomes valuable and investments in its improvement can be financially justified.

In order to verify the proposal a proprietary software package, Fluidflow3*,* was used to model the steam distribution circuit. The pipework, insulation, boilers and consumers for the whole of the steam distribution circuit were surveyed and programmed in the software package. A series of calibrations were undertaken for differing boiler and consumer loadings. Modeled temperature and pressures values were compared against actual values from plant instruments. Some alterations had to be made for missing insulation and some unmetered consumers. The model showed a close relationship to actual. The BOS waste heat project was then added to the model and thus it became possible to predict the effect if the extra steam on the whole system.

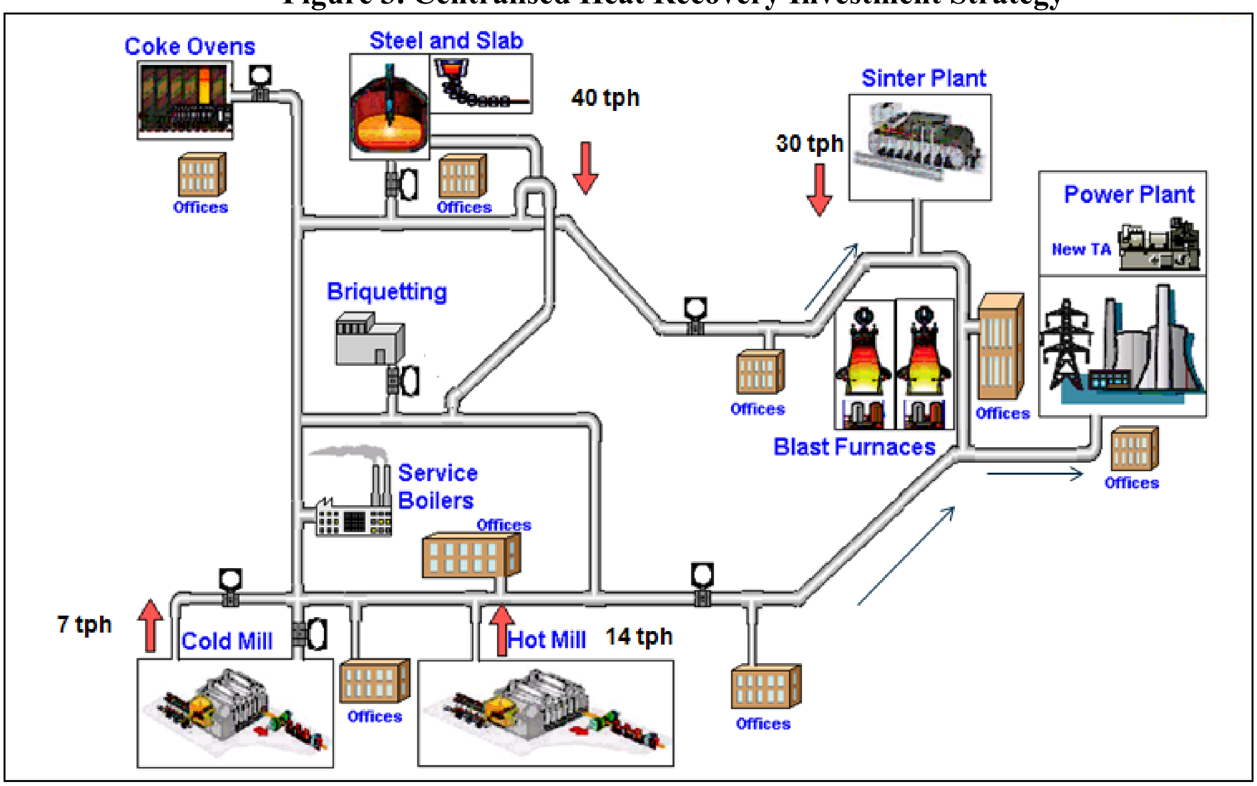
From this modeling work it then became apparent that the same principle could be applied to future waste heat recovery projects. If the installed turbine was purchased with spare capacity then other waste heat projects could simply plug into the steam main saving each project having to purchase a new turbine. This would reduce the capital expenditure and hence increase the payback of each future project.

The Strategy

The concept of installing a new steam turbine and the use of the steam distribution circuit started to develop into a proposed strategy for further waste heat projects as is shown in figure 3. The concept strategy became known as the “Centralised Heat Recovery Investment Strategy”. The turbine could be installed with spare capacity for further waste heat projects plugged into the steam mains. The quantities of steam generation would depend on the technology employed and the steel volumes produced. The maximum turbine size was also dictated by the high voltage capabilities of the local electrical infrastructure and the amount of steam generated by future waste heat boilers. It was therefore decided to install a turbine that would accept up to 100tph of steam that would generate 18MWe maximum. This would provide capacity for the BOS plant, extra steam from the service boilers and leave extra capacity for future waste heat recovery boilers. The additional cost of installing an increased size turbine building with crane, cooling tower and ancillaries was proportionally financially viable.

Not having to install turbines for each subsequent project and having the steam distribution circuit already on site considerably reduces capital expenditure (CAPEX) for all future schemes. Thus enabling relatively low cost connection and routing of the energy from the waste heat to the new ‘end use’. It is recognised that this is not the most energy efficient option but it does provide an obvious and flexible ‘end use’ thus helping to guarantee maximum financial benefits over the years. The strategy therefore provides the most financially efficient option for the future.

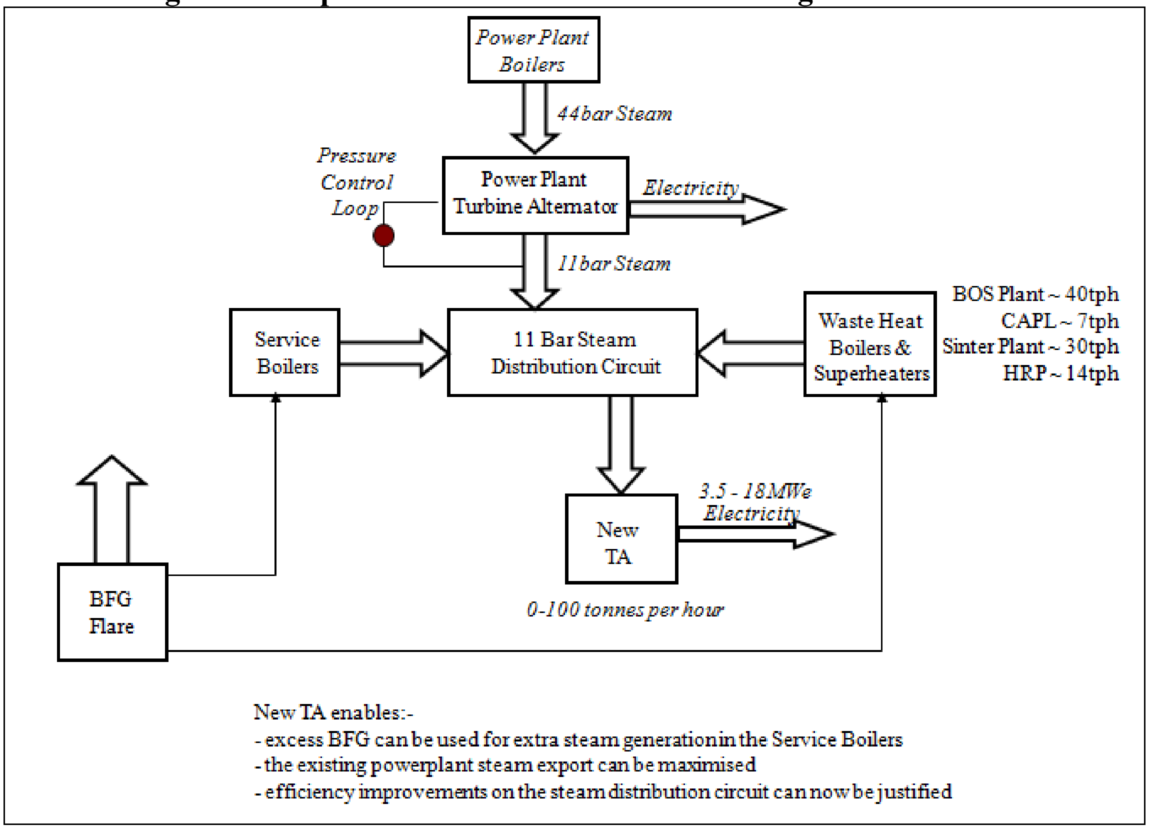
Figure 3. Centralised Heat Recovery Investment Strategy



Source: Tata Steel (Williams 2012)

Figure 3 then shows the strategy as applied to the case study steel works. Figure 4 shows an overview of the new steam system showing how future waste heat recovery boilers can simply plug into the steam mains and utilize the spare capacity within the new TA.

Figure 4. Simplified Schematic of the New 11barg Steam Balance



Source: Tata Steel (Williams 2012)

The steam distribution system is therefore being transformed from what was seen as an ‘old fashioned’ asset, possibly redundant part of the works, to an essential element of the future of the works. The steam system though had very little investment and looked its age. A program of work would therefore be required to modernise the system and improve its efficiency.

A project team was then established to pull together and engineer the first phase of the Strategy i.e. the BOS plant Evaporative Cooling Project. The total cost was calculated as being £53m for the replacement of the open water cooled off gas cooling system with an evaporative cooled new off gas system (incorporating heat recovery/steam generation), superheater, steam main modifications, 18MWe Steam Turbine with associated ancillaries and cooling tower. The energy benefits were defined as £6m per year of electricity equating to a reduction of 44,000tpa of indirect CO_2. The project was authorised during 2011, installed during 2012 and commissioning was complete in 2013. The majority of the £53m investment was committed to essential replacement of the ‘off gas’ system. The element associated with electrical generation from waste heat has a simple return on investment of 3 years.

Discussion

The development of the BOS plant project and the modeling of the steam system have therefore developed into an important strategy for the case study plant. Installing a turbine with spare capacity for the steam generated by future waste heat recovery projects has significantly reduced the expected capital requirements of these future projects, which dramatically improves their business case.

The Strategy also tackles the main steam issue for the plant, that is, any reduction in steam export from the power plant reduces the electrical generation. Previous explorations into waste heat recovery have therefore shown as a negative financial benefit and not been explored further. The addition of the new turbine alternator (TA), mounted off the steam distribution circuit, acts as the 'Rosetta Stone' unlocking the full financial benefit of the waste heat available.

The tactic of building waste heat recovery into an essential replacement project for an area of plant allows the spread of expense and eases the financial justification for the waste heat boiler components. With this strategy the plant now has the ability to build waste heat recovery projects into its strategic maintenance plans.

A clear roadmap has therefore been developed that requires further detailed analyses, assessment and modeling to ensure the maximum value of each source of waste heat is obtained. To ensure a continued focus on this strategy the case study plant has allocated a permanent resource to steer, promote and develop the most beneficial option for each waste heat opportunity. The plant has already taken the next step on the roadmap and invested a further £2.4m to install a waste heat boiler on the Continuous Annealing Process Line (CAPL). The boiler will enable an extra 1MWe generation from the new turbine.

The strategy has also transformed the case study plant's philosophy that the steam distribution system was as 'old fashioned' and 'tired'. Now it must be seen as an essential asset, turning an obvious weakness into a future strength. The recognised weaknesses in the distribution system can now be capitalised upon. The inefficiencies in terms of leaks and losses can now be rectified for financial gain. This completely changes the philosophy and relationship that the case study plant had historically had with the system. Quite large financial gain can be achieved by relatively little expenditure. The spare capacity in the turbine is hungry for any available extra steam. Surveys of the steam system identified these losses in excess of 6tph which when fed into the new turbine would generate 1MWe. Programmes of work have been developed for the rectification of the system inefficiencies and for the first time, the added benefit of financial gain.

The University and the steelworks are now investigating the use of medium and low-grade waste heat to reduce the steam consumption of the works. The concept is to utilise lower grade waste heat for building and bays thus releasing more steam for the new turbine.

This paper has then described the process of investigations that led to the development of the Centralised Heat Recovery Investment Strategy. This Strategy provides a clear route to enable investment in waste heat recovery for the case study steelworks. As further areas of plant require essential replacement then the option of waste heat recovery is more easily understood and thus more likely to happen. To assess the application of waste heat recovery the process was used of using the three elements:

1. Quantifying the energy
2. Identifying the technology to capture the energy
3. Developing the optimum ‘end use’ for the energy

The strategy provides a clear solution to the final element for future waste heat recovery projects. This strategy has enabled 12MWe of generation reducing indirect CO_2 emissions by 52,500tCO_2 pa. It allows the following:

- Steam from the BOS plant can be simply superheated and plugged into the steam mains (7MWe)
- Spare capacity can be utilised within the service boilers thus creating more steam for no capital expenditure (3MWe)
- Lower grade waste heat recovery to be utilised from the CAPL line (1MWe)
- A programme of steam system maintenance to be undertaken to maximise the efficiency of the steam mains (1MWe)

Conclusions

The case Study Iron and Steelworks embraced the ‘Centralised Heat Recovery Investment Strategy’ and invested heavily to ensure its realisation. The investments have enabled a total generation of 12MWe (worth £8,000,000 pa) and a reduction of 52,500tonnes of indirect CO_2 emissions per year with a simple return of investment of around 3 years.

The developed strategy therefore enables:

1. Spare capacity can be utilised within the service boilers thus creating more steam for no capital expenditure
2. Any steam savings now result in electrical and thus financial benefits for the works.
3. Future waste heat schemes to simply ‘plug and play’ into the steam distribution circuit. Each waste heat scheme will not therefore require the associated capex of a turbine and cooling tower

Acknowledgements

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