Cost effective greenhouse gas reductions in the steel industry from an Organic Rankine Cycle

Conor Walsh, Patricia Thornley

Tyndall Centre for Climate Change Research
The University of Manchester
Sackville Street
Manchester
M13 9PL
UK
conor.walsh@manchester.ac.uk

Large quantities of low grade heat (LGH) are generated within many process industries, and the recovery of LGH is a potentially significant means of improving process efficiency, but it is often difficult to find an appropriate internal heat load. One alternative is to use appropriate technologies to convert the low grade heat to electricity for use on site. This paper describes the environmental and techno-economic evaluation of a case study examining the potential application of an Organic Rankine Cycle (ORC) to generate electricity from LGH from the stacks of a coke oven used in steel production. 21 MW of LGH was available for recovery at the plant and resource accounting and lifecycle analysis methods were used to evaluate the environmental and economic benefits of the operation of an ORC. The results showed that between 1 and 3% of the CO_2 emitted directly through the production of coke would be offset by installation of an ORC, with lifecycle environmental impacts of coke production reduced by less than 1%, although this was sufficient to offset over 10,000 t CO_2 annually. However, the amount of electricity generated was sufficient to replace all currently imported electricity and economic analysis indicated a relatively attractive discounted payback period of between 3 and 6 years, suggesting this may be a commercially viable option, which could present a relatively cost effective method of achieving greenhouse gas savings in the process industries.

1. Introduction

The production of coke is an integral component of the steel manufacturing process. Annual cast steel capacity in the UK is estimated at 12.93 Mt (McKenna and Norman, 2010). Coke is perhaps the most important reducing agent in hot metal production and is used in blast furnaces to remove oxygen either indirectly through the formation of carbon dioxide (CO_2) or directly based on its carbon content. The recovery of low grade heat (LGH) has been identified as a potential means of increasing the energy efficiency of process industries (Kapil et al., 2010). The University of Newcastle (2010) has identified several streams, both liquid and gaseous, from the steel industry that are sources of LGH. Within the coke production facility in question, the underfiring flue gas stream was selected as the most feasible stream for heat recovery. This is due to the consistent operation of the coke oven (most coke ovens operate continuously), the high thermal quality compared to other sources of LGH as well as the reduced potential for process disruption. The gas stream has a temperature of 221 °C with a flow rate of 66 kg/s. This was estimated to yield 21 MW of recoverable energy (University of Newcastle, 2010).

2. The operation of an Organic Rankine Cycle (ORC)

The Rankine cycle is a thermodynamic cycle which converts heat into work. It is likely that approximately 80% of the electricity generated globally is a result of the Rankine cycle. Within a Rankine cycle heat is supplied externally to a closed loop, which usually uses water as the working fluid. Figure 1 below demonstrates a simplified Rankine cycle. The Rankine systems include these four steps: (1) water is pumped to an evaporator in a heat exchanger where heat is transferred to the working fluid at a constant pressure (2) thermal energy is used to evaporate water into steam, (3) the movement of the vaporised working liquid through the expander produces work generating electricity while reducing the temperature and pressure of the vapour stream, (4) the expanded vapour steam enters the (air or water cooled) condenser at constant temperature whereby the remaining thermal energy in the steam is discharged to the environment or a suitable recovery system. The water then re-enters the pump to be re-pressurised. A Rankine cycle which employs water as a working fluid is not economical if recovering heat below 370°C. For that reason organic chemicals or refrigerants are often substituted for water within a Rankine cycle, resulting in what has been termed the Organic Rankine Cycle (ORC). This allows the recovery of heat from streams that would normally be rejected as being of low thermal quality. The choice of working fluid will depend on a number of operational parameters as such as thermodynamic performance, stability, flammability etc… (Hung et al., 2007).

2.1 Estimation of ORC efficiency

The Aspen Hysys® simulation program was used by the Centre for Process Integration (CPI) at the University of Manchester to estimate the net efficiency of an ORC system used to recover heat from an equivalent waste stream. In this analysis, it was assumed that Benzene was the working fluid (Kapil, 2010). The estimates of the energy consumed (and generated) within the ORC are presented in Table 1 below.

Table 1: Energy analysis of ORC measured in kJ/h. (Kapil, 2010).

Energy generated by Turbine	Energy consumed by Pump	Energy supplied to Boiler	Energy released in Condenser
1,990,000	4,789	17,990,000	15,990,000

Based on this information, the efficiency of the ORC was calculated at 11%. This was estimated by subtracting the energy consumed by the pump from the energy generated by the turbine and dividing by the energy supplied to the boiler. When applied to the recoverable energy estimate of 21 MW results in an electricity generation estimate of 2.31 MW. The carbon savings due to the offsetting of external electricity are estimated based on the emission factor for electricity consumption in 2010 (AEA, 2010), taken as 0.54 kg CO_2/kWh. The operational schedule was assumed to be maintained for 8,580 h/y (assuming 98% availability). This results in an annual carbon saving of 10,702 t CO_2.

3. Methodology

3.1 Impact of an ORC on carbon intensity of coke production

McKenna and Norman (2010) estimate the energy required to produce a tonne of metallurgical coke. It is estimated that 1 tonne of coke requires 2.95 GJ to produce it and that 2% of the energy demand is satisfied by electricity, 5% is satisfied by steam and 93% by a gaseous source. This latter may include natural gas, blast furnace gas or coke oven gas (COG) released during the process itself. The calculation of the direct emissions associated with the production of coke was based on Equation 4.2 published in Volume 3 of IPCC (2006) and shown below. The equation used in the calculation is shown below.

$$tCO_2 / tcoke = \left((1/y).C_{coal} + \sum (Q_{gas(i)} - EF_{gas(i)}) - 1.C_{coke}\right).44/12 \qquad (1)$$

Y refers to the coke yield (t coke/t coal). C refers to the carbon (C) content of coal and coke (% w/w). Q_{gas} refers to the quantity of gas *i* used in coke production and EF_{gas} refers to the emission factor for each specific gas *i* (t C/Mj). The value of 44/12 is used to convert Carbon into CO_2. At the steelworks under review, the underfiring gas used in the production of coke was a mixture of blast furnace gas and COG. The high C content of blast furnace gas results in a high emission factor. However this represents only one potential gaseous fuel mix. Similarly, it could be argued that as the emissions due to coal are not strictly associated with providing energy for the coking process (representing feedstock as opposed to fuel) they should be excluded from an analysis of energy recovery. The effect of adopting a different emission calculation method on the carbon reduction potential of the ORC is shown in Table 2.

3.2 Techno-economic evaluation

The installation of an ORC system is a significant investment requiring not just the purchasing of equipment but will entail considerable additional costs. In order to place the carbon savings in context, the economic benefits of offsetting electricity purchasing was evaluated. The Department of Energy and Climate Change estimate that extra large manufacturing industries paid on average 5.078p (ex vat) per kWh in 2009. The Climate Change Levy (CCL) for electricity was also estimated at 0.47 p/kWh (DECC, 2010). Based on costing data taken from taken from Schuster et al. (2009), Tchanche (2010), and Vescovo (2009), the investment and operational cost of a suitable ORC system was estimated to be 2,023 €/kWe. Based on this, the net present value (NPV) and discounted payback period (DPP) was also calculated using Equation 2, taken from Tchanche et al. (2010).

$$NPV = -C_0 + \sum_{n=1}^{N} \frac{F_n}{(1+k)^n} \quad (2)$$

Whereby n is the time period (year), F_n the net cash flow for year n, C_0 is the initial investment, k the discount interest rate, assumed to be 5% and N is the number of years of the investment's lifetime or until the invest breaks even.

3.3 Lifecycle Analysis (LCA)

In order to examine the lifecycle implications of installing an ORC system, process specific information was incorporated into modules generated by the LCA software Simapro™. The coal and energy (both electricity and gas) requirements were included in the analysis. It was assumed that the coking coal was transported from the Australian port of Newcastle by ship and subsequently by rail. Default emission profiles for coke production were augmented with more recent values (EEA, 2009, USEPA, 2008) and with emission stream data for CO_2, CH_4, and CO (Newcastle University, 2010). The environmental impact of the production of materials within an ORC system was also included in the module. This was based on the heat exchanger area requirement (estimated by the Aspen module). Material compositional information for a suitable turbine and generator system provided was by Siemens (Webster, 2010).

4. Results

4.1 Carbon savings

The normal operations of the plant under review used both blast furnace gas and COG as fuel. Based on the carbon intensity of electricity it was estimated that the integration of an ORC would reduce the carbon intensity of coke production by 1.39 %. The impact of different fuels, and exclusion of coal on carbon savings is shows in Table 2 below.

Table 2: Impact of different calculations on ORC emission savings potential.

Calculation choices	% reduction to CO_2 emissions
50% Blast Furnace gas/COG	1.39
Coal and Natural gas	2.09
50% Blast Furnace gas/COG, no coal	2.66
Natural gas only	7.42
Electricity only	127

As can be seen from Table 2, the introduction of an ORC results in marginal carbon savings. However the results are more positive when compared against natural gas fuel. Specifically an ORC will provide a surplus electricity supply by generating more electricity than is consumed by the coke plant.

4.2 Economic benefits of ORC installation

Based on offsetting of purchased electricity it would suggest the proposed project would break even in between 3 and 6 years, depending on the elements of the calculation. It is reasonable that 5 years represents an upper limit for an acceptable DPP but a period of 3 years would probably be necessary to ensure investment.

Table 3: DPP and NPV for ORC investment based on CCL and Tax.

Calculation	Cap Ex		Cap Ex +25%		Cap Ex -25%	
	DPP (yr)	NPV (£)	DPP (yr)	NPV (£)	DPP (yr)	NPV (£)
CCL, no Vat	4.16	726,858	5.34	538,936	3.03	873,752
No CCL, no Vat	4.59	323,554	5.91	66,120	3.34	543,436
CCL, 17.5% Vat	3.53	489,834	4.52	480,941	2.59	448,748
No CCL, 17.5% Vat	3.84	159,518	4.85	150,625	2.81	195,069

4.3 Lifecycle analysis

The results of each activity within the lifecycle of coke production are provided in Table 4 below. The different impact categories are normalised, weighted and expressed in units of millipoint (mPts). Each "point" represents the environmental impact of an average European during a single year.

Table 4: Lifecycle Analysis results for coke production, including ORC recovery.

Process/Activity	mPts/kg Coke
Hard coal coke at Plant	67.90
Coke production plant	1.11
Hard coal Mix	104.00
UK Grid Electricity	0.50
Water and Chemical Inputs	0.01
Blast furnace gas	1.40
Ocean and Rail Freight	29.61
Total (no recovery)	**205**
ORC components	0.004
Recovered electricity	-0.64
Total (with recovery)	**204**

As can be seen from Table 10 above, the lifecycle impact of the ORC is minimal. The impact of coal production represents the single largest contributor to the overall weighted impact. An ORC system will have no capacity to affect the impacts associated with the production of coal. By comparison, the impact of UK generated electricity used within the coking process is relatively insignificant. However the results do reinforce that the avoided impacts due to the recovery of low grade heat exceed the impacts of the electricity consumed by the coking ovens themselves.

5. Discussion and conclusions

The economic and environmental analyses provide disparate appraisals of the impact of the ORC to recover LGH from flue gas emitted during coke production. The process under review is a carbon intensive process, particularly when blast furnace gas is used. Therefore the emission savings associated with electricity generation from an ORC will be small when compared against the carbon emissions associated with coke production. This is apparent when an LCA is undertaken. The rationale for the inclusion of the ORC is its unobtrusive interaction with the process. (When viewed in isolation the annual saving of 11,000 t CO_2 remains a significant carbon offset.) However this means that an ORC will not displace the need for coal or gas, regardless of whether (such as in the case of carbon intensive blast furnace gas) it is supplied by the steel manufacturing process itself. Despite this, the potential savings due to on-site electricity generation suggest a DPP of less than 4 years. This is reliant on the difference between electricity selling and purchase prices. If the site operator were to sell the electricity it would likely be at less than the current price, meaning the revenue would potentially be much lower than the cost savings incurred by offsetting the purchase of electricity from an external supplier.

References

AEA., 2010, Guidelines to Defra / DECC's GHG Conversion Factors for Company Reporting. Department of energy and climate change, London.

DECC., 2010, Energy price statistics. Department of Energy and Climate Change, UK.

EEA., 2009, EMEP/EEA emission inventory guidebook 2009. Combustion in energy and transformation industries, European Environmental Agency, Denmark.

Hung T.C., Shai T.Y. and Wang S.K. 1997, A review of Organic Rankine Cycles for the recovery of low-grade waste heat, Energy, 22, 661–667.

IPCC., 2006, Guidelines for National Greenhouse Gas Inventories, prepared by the National Greenhouse Gas Inventories Programme, Eds. Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K., IGES, Japan.

Kapil A., Centre for Process Integration, Personal Communication, 5th August, 2010.

Kapil A., Bulatov I., Kim J.K. and Smith R. 2010, Exploitation of Low-Grade Heat in Site Utility Systems, CET. 21, 367-372.

McKenna R.C. and Norman J.B., 2010, Spatial modelling of industrial heat loads and recovery potentials in the UK, Energy Policy, 38, 5878-5891.

Schuster A., Karellas S., Kakaras E. and Spliethoff H., 2009, Energetic and economic investigation of Organic Rankine Cycle Applications, Appl. Therm. Eng. 8–9: 1,809–1,817.

Tchanche B.F., Quoilin S., Declaye S., Papadakis G. and Lemort V., 2010, Economic feasibility study of a small scale Organic Rankine Cycle system in waste heat recovery application, in Proceedings of ESDA 2010, July 12-14th, Istanbul, 249-256.

University of Newcastle, 2010, National sources of low grade heat available from the process industry, EPSRC: Thermal Management of Industrial Processes.

USEPA., 2008 Emission Factor Documentation for AP-42 Section 12,Coke Production: Final Report. United States Environmental Protection Agency, N. Carolina, USA.

Vescovo R., 2009, ORC recovering industrial heat. Cogeneration and on-site production. March-April, 54-57.

Webster, M., Siemens, Personal Communication, 27th August, 2010.