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1. Abstract

Thermal energy used for heating and cooling represents a significant proportion of total energy use in industrial processes and is largely supplied by fossil fuels. Mechanical operations primarily powered by electricity also consume a large amount of energy. Both heating and cooling operations as well as mechanical operations release large amounts of heat into the environment so careful management of thermal energy is a key factor in reducing overall energy consumption and emissions.

Energy related pressures, incentives and opportunities provide a strong business case to invest in improving energy efficiency. These include customer demand for 'green' products, national taxes and financial incentives, and rising fuel costs. Against this backdrop, the prioritization of the sustainability agenda by research funders coupled with the pressure on research organizations to ensure the transfer of novel technologies to industry create an ideal landscape for substantial advancement in industrial energy efficiency. Successful movement of novel technology to industry should however be supported by concepts, methods and practices derived from industrial context and needs. Accordingly initial implementations often bring to light new research challenges, both technical and methodological.

To enhance the use of energy efficient methods in industry, the definition and measurement of efficiency must be tailored to industrial needs and technologies ready for adoption must be identified and presented in relation to existing technology. In addition detailed case studies of energy use should be documented to provide insights to both researchers and practitioners, identifying both realistic improvements and barriers to application of energy efficient measures.

2. Introduction

The prioritization of efficiency in the use of energy has varied since the 1970s (Ammar et al., 2012), largely due to market price changes and many mature technologies are currently available. In more recent decades increasing energy prices as well as increasing energy demand, the threat of fuel scarcity, environmental concerns like global warming and GHG emissions, have all made efficient energy use a governmental priority (Bunse et al., 2011; Schönsleben et al., 2010; Trianni et al., 2013) evidenced by the legislation established to drive down GHG emissions following the adoption of the Kyoto Protocol which entered into force in 2005, the European Directive 2009/28-33 (EC, 2009a) and the UK Climate Change Act of 2008 which in addition to a long-term target to reduce the UK's greenhouse gas emissions, set a legally binding five-year 'carbon budgets' to meet this target in (HM-Treasury, 2010).

Significant investment and improvements in energy efficiency have been made in industrial processes over many decades, including optimization of process and control systems, improved technologies and methods, reference benchmarks etc., yet there is still potential for further improvements. The industrial sector is reported to have a share of 30-37% of global energy demand (IEA, 2007; EC, 2009b; Gielen and Taylor, 2009; Abdelaziz et al., 2011) and this has continued to increase (IEA, 2013). The 2013 outlook report from the United States Energy Information Administration (EIA, 2013) indicates that currently the industrial sector uses more delivered energy than any other end-use sector, consuming about one-half of the world's total delivered energy, and that this is forecast to increase in the future especially in *non*-OECD (Organization for Economic Cooperation and Development) member countries like China and India.

There are strong links between effective thermal energy management and reductions in thermal energy use, electrical energy use and emissions. Thermal energy for industrial processes, a large proportion of which is lost to the environment, is produced by burning fossil fuels and to a lesser extent through electricity. Electricity is used to power mechanical operations such as compression and grinding, which generate and release large amounts of heat into the environment (Saidur, 2010; EC, 2009b). Careful management of thermal energy is therefore key to reducing energy consumption and emissions.

Change in the economics of energy, government financial incentives, taxation, legal requirements and consumer pressures have all created a business justification for investing in energy efficiency improvement (Chua et al., 2010; Fleiter et al., 2011; Bunse et al., 2011). Particularly in industries where energy constitutes a significant portion of the cost of production, improvements in energy efficiency result in reduced production costs and improved competitiveness. "*A 20% cut in energy costs represents the same bottom line benefit as a 5% increase in sales in many businesses*" (The-Carbon-Trust, 2013).

In addition to the business incentives mentioned above, the prioritization of the sustainability agenda by research funders has triggered a wave of research activity, which in combination with pressure on research organizations to ensure the use of mature research results in society, creates greater opportunities for improvement of energy efficiency in industry. Successful deployment of new technology to industry requires supporting concepts, methods and practices derived from the application of those technologies to industrial contexts and needs. Initial industrial applications often bring to light new research challenges, both technical and methodological which, once addressed, simplify subsequent applications. This cyclical process can be expedited by bridging the gap that often exists between industry and academia (Chai and Yeo, 2012; Bunse et al., 2011), through fostering joint activity and dissemination of literature that is relevant to both groups.

This chapter provides a reference that both practitioners and researchers can draw on in working towards enhancing industrial thermal energy efficiency. The next section presents definitions, key issues and techniques for energy efficiency measurement for industry, highlighting the need for sector-specific treatment. This is followed by a description of some of the latest research developments related to technologies commonly used for improving energy efficiency and individual case studies of energy use in production plants. Energy use, applied technologies and needs can vary greatly between sectors, organization size, location and several other influencing factors and so case studies of individual plants can help identify unique potentials and barriers. The four case studies presented include large and small organizations, a plant in the Far East in addition to plants in the UK, industries regarded as one of the largest energy consumers and one considered to be a relatively small consumer (though large in real terms). Each case study provides an overview of issues affecting the industry in general followed by details of energy use and opportunities for energy efficiency improvements within the presented production plant. The last section presents an overview of current thinking regarding barriers to adoption of new technologies and methods for energy efficiency in industries.

3. ENERGY EFFICIENCY MEASUREMENT IN INDUSTRY

3.1. Background

"*The measurement of the energy efficiency of a system or process is an essential step towards the control of the energy consumption and energy costs*"(Giacone and Mancò, 2012). 'Energy efficiency' is a generic term with a number of definitions and a range of operational indicators. Patterson (Patterson, 1996) provide a discussion of energy efficiency definitions and their indicators. The generalized definition for energy efficiency is a ratio of useful output to energy input. Where contextual variations exist, they define precisely what constitutes "useful" output and what unit best represent energy input. A number of different indicators are used in different scenarios depending on the purpose of the analysis. They may be categorized into four main groups (Patterson, 1996):

1) Thermodynamic indicators: the input and output is measured in thermodynamic units. Three different indicators are described:

   - Enthalpic efficiency also referred to as thermal efficiency or first-law efficiency presents energy efficiency as shown in equation (1).

     $$\frac{\text{Useful energy output}}{\text{Total energy input}} \qquad (1)$$

     The heat content is measured in terms of enthalpic change values. The difference between the energy input and the useful energy output is the energy that is lost.

   - A second indicator is used to adjust for energy quality in order to support comparison, for example in the case where two technologies to be compared use different types of energy inputs with different properties. The energy input is converted to common quality units (like Gibbs free energy change, exergy or available work) representing work potential.

   - A third approach, also called second-law energy efficiency, is obtained by dividing the actual enthalpic efficiency by an ideal efficiency. The most efficient process possible therefore has an efficiency value of 1.

2) Physical-thermodynamic indicators: the input is measured in thermodynamic units and the output is measured in physical units e.g. tonnes of product, kilometres travelled. They are most commonly used in industry and are discussed further below.

3) Economic-thermodynamic indicators: the input is measured in thermodynamic units, output measured in terms of market prices.

4) Economic indicators: entirely economic indicators where input energy and output service are both measured in monetary terms according to market values. The economic productivity of energy.

Different terminologies have been adopted in line with indicators used for the output: 'energy efficiency' is generally used where output is in thermodynamic and physical terms while 'energy productivity' is used with economic indicators. 'Energy intensity' refers to the inverse of both ratios.

3.2. Use of efficiency indicators in industry

Thermodynamic indicators are used in assessing the efficiency of particular technologies for end-use or energy conversion e.g. boilers and generators. For example equation (2) describes the efficiency of a steam boiler (Tanaka, 2008).

$$\frac{\text{Energy of the steam output}}{\text{Energy input to the boiler water}} \tag{2}$$

However, as with most practical applications of generic equations, these measures are tailored for particular technologies and purposes. For example in relation to equation (2), two common indicators used for assessing the efficiency of boilers are *combustion efficiency* and *boiler efficiency* as defined in equations (3 - 6) below (Carbon-Trust, 2012):

Combustion efficiency is defined as the percentage of energy in the fuel that is released after combustion within the boiler calculated as:

$$\frac{\text{Actual energy released during combustion}}{\text{Total energy content of the fuel}} \times 100 \tag{3}$$

or

$$100 - \%\ \text{heat lost due to incomplete combustion of fuel} \tag{4}$$

Boiler efficiency is defined as the percentage of useful energy output by the boiler compared with energy input as described in equation (5). It takes account of all heat losses including from the flue gases, losses due to incomplete combustion of the fuel, radiation losses, convection losses and conduction losses and maybe calculated as:

$$\frac{\text{Useful Energy output by boiler}}{\text{All energy input}} \times 100 \tag{5}$$

or

$$100 - (\text{Percentage of fuel gas losses} + \text{Radiation and other unaccounted losses}) \tag{6}$$

The use of indicators is modified further to meet requirements of the measurement. For example it is important to consider whether any recovered heat should be included in the calculations. The selection of an appropriate indicator is dependent on many factors including the industry (steel, food, transport), the element being analyzed (technology, single process, production process, plant) and the purpose of the analysis. Comparison is one of the main purposes in energy efficiency analysis; comparing the implementation of a new technology vs. not implementing a new technology, comparison of energy efficiency of a plant against a benchmark etc.

Pure thermodynamic indicators are of limited use for considering the efficiency of an end-use service/product provided by an organization. Economic indicators are time sensitive and cannot be used in longitudinal analysis, their advantage is in macro-level review of overall situations (Tanaka, 2008). Consequently physical-thermodynamic indicators are preferred for physical energy analysis of industrial processes, most commonly the *Specific Energy Consumption* (SEC) indicator (Tanaka, 2008; Siitonen et al., 2010; Giacone and Mancò, 2012; EIA, 2013; IEA, 2007), which represents the amount of energy in consumed per unit of product/output.

SEC can be defined as shown below (EC, 2009b) where energy is represented in Joules and products produced are sector specific, for examples tonnes of steel in the steel industry, hectoliters of beer in the brewing industry and tonnes of clinker or cement in the cement industry. The International Energy Agency provides a description of SEC indicators for different industrial sectors (IEA, 2007).

$$SEC = \frac{\text{Energy used}}{\text{Products produced}} = \frac{(\text{Energy imported} - \text{Energy exported})}{\text{Products or outputs produced}} \qquad (7)$$

Efficiency is a relative measure which requires a comparison with a reference in order to draw conclusions, for example by comparing the performance of a plant with industry best or against previous recorded performance of the plant. The energy efficiency indicator (EEI) can be used to monitor the progress of energy efficiency:

$$EEI = \frac{SEC_{ref}}{SEC} \qquad (8)$$

SEC_{ref} is the reference value which may be based on best available technology (BAT) benchmark figures for the sector to which the production process or product belongs, it may be the SEC of the production process/product at a previous year, it may be a set organizational target or a variety of other comparison references. The denominator is the SEC of the product/process being considered.

The implementation of SEC for comparisons is complex in practical scenarios. Several challenges are identified (EC, 2009b; Giacone and Mancò, 2012; Siitonen et al., 2010):

- Complexity of industrial sites and energy flows. For example where there is multiple production processes and/or multiple products produced with differing energy requirements at a site.
- Use of multiple energy types. In order to consider the different energy types equitably, it is important to express the consumption of primary energies such as fossil fuels and secondary energies such as electricity and steam as a single common unit. Ideally the secondary energy is converted to the primary energy content (EC, 2009b).
- Comparison of differing variables of influence (energy drivers). It is difficult to take into account all possible variables in an appropriate manner though often there is a linear relationship between energy consumption and a suitable energy driver (Giacone and Mancò, 2012; Siitonen et al., 2010).

- The influence of production rate on energy efficiency. As energy consumption may not change in line with production rate due to base line costs and efficiencies of scale, comparison where production rate vary may be difficult.

- The complexity in defining system boundaries for measurement when comparing two scenarios to ensure that all energy users are considered equally. System boundaries are incongruent in many situations e.g. where some processes occur within the plant and some occur outside the plant, where the product mix is different in different plants being compared or where comparison is over a time period and some factors have changed over time in an installation (Tanaka, 2008; EC, 2009b).

To aid measurements and comparisons where complexities exist variations on the SEC calculations are suggested (Siitonen et al., 2010; EC, 2009b). Some of these are presented in Table 1.

Table 1: Calculation of SEC for different contexts.

Context	Formula	Notes
Industrial processes use energy in different forms: fuels, steam and electricity.	$\text{SEC} = \frac{E_{Fuels} + E_{Steam} + E_{Electricity}}{\text{Products produced}}$	This shows SEC as final energy consumption.
	$\text{SEC} = \frac{E_{Fuels} + \frac{E_{Steam}}{\eta_{Steam}} + \frac{E_{Electricity}}{\eta_{Electricity}}}{\text{Products produced}}$ E_{Steam} = Steam consumption η_{Steam} = Efficiency of steam production	This shows SEC as primary energy consumption where the cost of steam and electricity production is taken into account.
A number of equally important products are produced.	$\text{SEC} = \frac{\text{Energy used}}{\Sigma \text{ Products produced}}$ or $\text{SEC} = \frac{\text{Energy imported} - \text{Energy exported}}{\Sigma \text{ Products produced}}$	If products are not equally important, meaningful process boundaries have to be decided between the energy balance and the products balance.
There are several product streams, a low number of raw materials streams.	$\text{SEC} = \frac{\text{Energy used}}{\Sigma \text{ Raw material input}}$ or $\text{SEC} = \frac{\text{Energy imported} - \text{Energy exported}}{\Sigma \text{ Raw material input}}$ This method can be used if energy consumption is determined mainly by the amount of raw material and less	This ratio will not reflect the decrease in energy efficiency when raw material and energy consumption remain the same but production quantities decrease.

	by the products (e.g. when the product quality depends on the feedstock).	
There are several products or one product with different specifications and their energy consumption is not similar over a specific period.	$\mathrm{SEC} = \frac{\sum_{i=A,B,C} X_i * SEC_{ref,\ i}}{\left(\frac{Energy\ used\ in\ production\ unit}{Sum\ of\ Products\ A, B\ and\ C\ manufactured}\right)}$ i = the product type of specification Xi = the fraction of *i* on total product produced over the given period $\mathrm{SEC}_{\mathrm{ref,\ i}}$ = the reference energy efficiency factor for i	$\mathrm{SEC}_{\mathrm{ref,\ i}}$ can be calculated, for instance, by averaging the energy efficiency indicator over a reference period when only *i* was produced.
The output is a service. The production criterion related to the energy used is the waste input.	$\mathrm{SEC} = \frac{\text{Energy imported for incineration} - \text{Energy exported}}{\text{Tonnes of waste processed}}$ Where the waste is combustible, this indicator will be negative as heating value of the incinerated waste is recovered as energy exported, which will typically be larger than energy imported.	This is an example formula for waste management facilities.

Giacone and Giacone (Giacone and Mancò, 2012) propose a mathematically-based methodology for building a structured framework where the whole energy system of a site is represented using a single matrix equation and where the elements of the matrix are the specific energy consumptions of each single process. Other studies (Pérez-Lombard et al., 2012) propose a methodology for building indicators for specific sectors and show its application to heating, ventilation and air conditioning (HVAC) systems. As shown above designing comparable efficiency indicators is "extremely difficult" (Tanaka, 2008) due to the number and complexity of industrial processes. Accurate and precise calculation of efficiency is still a challenge and in many cases the energy-to-end-product ratio is too variable to be useful (EC, 2009b).

4. TECHNOLOGIES FOR ENERGY EFFICIENCY IN INDUSTRY

Process heating is one of the most prevalent requirements for energy in industrial processes (Hasanuzzaman et al., 2012). The results of a review of technologies for energy savings in combustion-based process heating suggest that significant amounts of energy can be saved by employing heat recovery in process heating systems like boilers and furnaces (Hasanuzzaman et al., 2012). The review reports potential for 10-20% energy savings by using condensing economizers in boiler flue gas waste heat recovery systems to capture both sensible and latent heat and 25% savings in energy by using recuperator in furnaces to pre-heat combustion air. Economic analysis often suggests that the payback period for these technologies is low for example less than two years for condensing economizers and recuperators. Other commonly used technology include heat pumps, compressors, prime movers and depending on sector requirements evaporators, furnaces, gas turbines, ovens, pasteurizers, process coolers, process heaters, sterilization equipment and ventilation equipment (Ammar et al., 2012). This section presents current research results and recommendations for industrial application for three key technologies for thermal energy use: boilers, heat pumps and heat exchangers.

4.1. Developments in industrial boilers

Boilers are used in many industrial sectors for producing steam or hot water and for brewing as part of the production process. Steam and hot water provide the transfer media for diverting heat for process use or for supporting tasks like cleaning or power generation. A large volume of heat is lost through the boiler process and it is standard practice to recycle the released heat to preheat the feed water and the combustion air using technologies like economizers and super-heaters. Due to environmental requirements most use scrubbers and filters to remove acids and particulates from the exhaust. Thermal energy losses from flue gases are in the range of 70 - 200^{o}C (Hebenstreit et al., 2014) depending on the boiler technology and can be divided into the sensible heat of the flue gas and the latent heat of the water vapor in the flue gas. The latent heat can only be recovered if the flue gas is cooled down below the dew temperature of the water vapor in the flue gas. Condensing boilers can recover the latent heat and so are more efficient than conventional boilers with standard economizers. They can also be optimized by the use of scrubbers and filters for emissions abatement, including acids and participle removal. However benefits can depend on implementation as they require site-specific engineering design.

Chen (Chen et al., 2012b) provide an extensive literature review of the technology and application of industrial condensing boilers in various heating systems and identify two technical challenges for implementation; corrosion and return water temperatures. Heat exchangers are a state of the art technology for oil and gas burning boilers, however corrosion is a problem in biomass fuelled boilers and ceramics, carbon and stainless steel are often used as heat exchanger materials to minimize corrosion (Hebenstreit et al., 2014). Chen (Chen et al., 2012b) proposes the use of carbon steel in the heat exchanger, which allows polypropylene to be used as the corrosion-resistant coating material outside the tubes. Three potential benefits are identified: (i) corrosion is minimized, and (ii) efficiency is improved with the increase of the heat transfer area (iii) payback period is shortened, i.e. 2 years compared to 5-7 years required for stainless steel. The second technical challenge, control of return water temperatures, can be met by tailored use of heat pump technology with the condensing boiler or depending on temperatures, through integration with processes.

Other areas of improvement in boiler technology are in the choice of fuel and combustion techniques and analysis:

- The use of biomass fuels e.g. pellets and wood chips are seen as the most promising current alternative to fossil fuels with increased applications and reported sales of biomass boilers in Europe. A review on the use of biomass in boilers has shown benefits like financial savings, and CO_2 and NOx emissions reduction (Hebenstreit et al., 2014). The implementation requires planning for issues like fouling, corrosion and low heating value and research suggests solutions based on application requirements (Hebenstreit et al., 2014; Saidur et al., 2011).
- The use of alternate liquid fuels like oil, emulsion oil and pyrolysis oil has also increased. Emulsion oil is a mixture of base fuel and water with a small amount of surfactant added allowing the two substances to temporarily dissolve. These emulsions can improve efficiency of boilers and reduce CO_2 and NOx pollution. The water - heavy oil emulsion has the potential to reduce energy consumption by 15% compared to that obtained with pure heavy oil (Li et al., 2014).
- Blending different types of coal has been shown to be an effective strategy with several advantages including better combustion and cost savings. There are however reported problems in boiler operation caused by burning blended coal like corrosion, flame stability, slagging, fouling, heat adsorption in the furnace, and other unexpected issues (Baek et al., 2014). Research on blending aims to reduce these problems and by providing analysis of specific blends and blending methods for example Baek (Baek et al., 2014) provide numeric analysis of two methods of blending coal and their effects on combustion characteristics and NOx emission; Akiyama (Akiyama et al., 2011) show the possibility of the use of Upgraded Brown Coal (UBC) without any ash deposition problems in boilers by blending with bituminous coal.
- Oxy-fuel combustion aims to burn fuel in pure/nearly pure oxygen producing only CO_2 and H_2O, making the separation of CO2 from the flue gas easier (Anthony and Hack, 2013; Leckner and Gómez-Barea, 2014). Benefits include lower costs, higher combustion efficiency and higher thermal efficiency of the boiler owing to the reduction in the volume of the flue gas and reduction in conversion of the nitrogen in the fuel to NOx (Czakiert et al., 2006). Conventionally this technology is used with pulverized coal-fired boilers, however its use with fluidized bed combustion (FBC) and circulating fluidized bed (CFB) boilers has become an important technology (Anthony and Hack, 2013; Czakiert et al., 2006). Oxy-fuel combustion presents the possibility of utilizing different and low-rank fuels and the capability to obtain a lower adiabatic combustion temperature, both of which are important because the difficulties with temperature control and heat transfer are the major problems connected with this combustion process (Czakiert et al., 2006). A new design which results lower CO_2 and a smaller boiler requirement than that of the comparable air-fired case is proposed by (Leckner and Gómez-Barea, 2014). Benefits depend on the oxygen concentration and the corresponding flue-gas recirculation.

- Modelling and approximation to support measurement is an effective approach to improve boiler performance. In practice, combustion efficiency, which is related to the heat lost due to incomplete combustion of fuel, is dependent on several factors including steam temperature and pressure, water temperature and pressure, turbine extraction pressures, and excess air ratio for a given fuel, and therefore accurate measurement can be difficult. Mathematical modelling (Gutiérrez Ortiz, 2011) and computational modelling with neural networks (Kljajić et al., 2012) (Bekat et al., 2012) are recent approaches to help analyze combustion efficiency. In addition, (Li et al., 2012) describe three algorithms and propose a new modeling method derived from all three to approximate combustion efficiency of coal fired boilers. Combustion efficiency for coal is much lower than gas and liquid fuels where efficiency is usually around 99% (Carbon-Trust, 2012).

4.2. Developments in heat pumps

Heat pumps are an important but under-used technology with potential to improve energy efficiency in industry, reduce emissions and provide financial savings (Chua et al., 2010). They are able to absorb heat from a relatively colder environment and release it into a warmer environment. For process heating the pump provides heat and for cooling and refrigeration, the pump removes heat. For heat recovery purposes, heat pumps are used to recirculate the heat generated by processes, otherwise released to the atmosphere, back into a heat production process. They are also commonly used to capture and convert waste heat which can then be used for indirect production process uses like producing hot water, space heating, etc.

Heat pumps can be broadly classified into compression and absorption types. Compression heat pumps, typically driven by an electric motor or a combustion engine, are composed of a set of heat exchangers (that function as an evaporator and a condenser), a compressor and an expansion valve that together manage the working fluid which circulates between the heat exchangers. Absorption pumps, consist of an absorber, a solution pump, a generator and an expansion valve, and are heat-driven to achieve fluid compression (Chen et al., 2012b). The working fluid, which is a solution of refrigerant/absorbent, absorbs refrigerant vapor during absorption process in which heat is generated. Water/lithium bromide and ammonia/water are the most common working fluids.

Current research challenges are in optimal integration of the technologies, improving energy efficiency, performance and reliability of heat pumps (Chua et al., 2010). Example developments include:

- Better compressor technology with potential to reduce energy consumption of the vapor compression cycle and subsequently the heat pump. Newer scroll compressors are 10% more efficient than the standard reciprocating compressor. The revolving vane (RV) compressor uses a rotating cylinder that works with the compression mechanism to cut down energy loss, frictional loss and leakage. This means that less input energy is required to perform the required compression. Chua (Chua et al., 2010) in a survey of improvements in heat pump technology indicate that experimental data have shown energy reductions of up to 80% when compared to current systems on the market. Research has also shown that simple measures like keeping compressor motor temperature low during operations offers improved performance (Wang et al., 2008).

- The incorporation of an ejector, also referred to as jet, injector or jet pump, to the heat pump to improve efficiency is an area of focus and a number of improvements to this technology are proposed (Chua et al., 2010). Sarkar (Sarkar, 2012) provides a review of the use of two-phase ejectors in vapor compression refrigeration systems, and indicate that their use has become a promising cycle modification with advantages like a lack of moving parts, a simpler structure, low maintenance requirements and lower cost. Two benefits of using ejectors are identified (Sarkar, 2012; Minetto et al., 2013): improvement in compressor efficiency by acting as an expansion device to replace the throttling valve in the vapor compression refrigeration cycle; and providing support to the compressor by raising the suction pressure to a level higher than that in the evaporator. Zhu (Zhu et al., 2014) propose the use of a novel dual-nozzle ejector enhanced vapor-compression cycle for solar assisted air-source heat pump systems and provide mathematical modelling which shows that the use of the dual-nozzle ejector for recovering the expansion losses improves the cycle performance.

- The application of heat driven heat pumps as heat transformers to boost the temperature of waste heat. Horuz (Horuz and Kurt, 2010) provides a description of absorption heat transformer (AHT) technology which operates in a cycle that is the reverse of the Absorption Heat Pump (AHP). An application of their use in an industrial setting for the generation of hot water is presented in which an industrial company has waste heat sources at approximately 90 ^{o}C and requires hot water for process at 120^{o}C. Parham (Parham et al., 2014) argue the importance of AHTs in the industrial sector for utilization of low-level heat, and provide a comprehensive review of the available technologies including their performance evaluation and economic aspects.

- Other developments in efficiency are achieved by the development of multi-stage cycles employing more than one compression stage to improve the performance of the heat pump system. Research into new refrigerants is also an active area as alternative refrigerants are sought to minimize environmental impact and improve efficiency. Chua (Chua et al., 2010) and Sun (Sun et al., 2012) provide a comprehensive review of current research into alternative refrigerants. There is also a drive to develop hybrid technologies e.g. incorporating desiccant materials into the heat pump cycle to allow better temperature and humidity controls and solar assisted heat pumps that have been effectively used for drying and water heating.

In addition to standard uses of heat pumps like heating and cooling, several novel application possibilities exist, especially with the introduction of some of the technological advances and hybrid technologies mentioned here. These include distillation, desalination, clean use of geothermal energy, drying and co-generation, all of which have been shown to benefit from improved energy efficiency and reduced emissions (Chua et al., 2010).

One of the difficulties of implementation in industry is that research has produced a variety of different types of heat pumps suitable for various industrial processes and selecting the most efficient heat pump for a particular purpose is difficult (van de Bor, 2013). Reviews of technology for particular purposes can be found in recent literature for example Jana (Jana, 2014) indicate that distillation, which is the most widely used separation technology in the chemical and allied industries, is highly energy consuming with low thermodynamic efficiency typically in the range of 5-20%. Thermal integration in this area is becoming more economically feasible and prevalent, with the acceptance of Heat Pump Assisted Distillation (HPAD) as one of the widely accepted schemes for continuous flow distillation columns. Kiss (Kiss et al., 2012) provide a discussion on choosing pumps for distillation columns. Van de Bor (van de Bor, 2013) indicate that with newer heat pumps the discrepancies between a rough estimate and actual performance can be large and that the lack of a simple method to determine the approximate performance of heat pumps hinders the implementation of these novel types in industry. They propose a method, with application to distillation columns, though more widely applicable, to predict the economic performance of different types of heat pumps.

4.3. Developments in heat exchangers

Heat exchangers transfer heat from a hot fluid flow to a cold fluid flow, in most cases through an intermediate metallic wall and without moving parts. They are used in various types of heat pumps for several purposes including in boiler economizers to capture heat lost through boiler flue gas.

The two basic varieties of heat exchanger are the Shell and Tube Heat Exchanger (STHE) and the Plate Heat Exchanger (PHE) though various configurations of each exist. Their technology and usage can affect the efficiency of processes in which they are employed. Reay (Reay, 2002) describe various types of compact heat exchangers and mention their importance in enhancing heat transfer and improving the efficiency of heat pumps. Abu-Khader (Abu-Khader, 2012) presents an overview of current developments in PHE technology and identifies the technical challenges for industry. Ghanem (Ghanem et al., 2013) present the functioning and analysis of the high-efficiency vortex (HEV) heat exchanger. Vortex generators are used in the process industry to enhance heat and mass transfer in heat exchangers and thus increase energy efficiency.

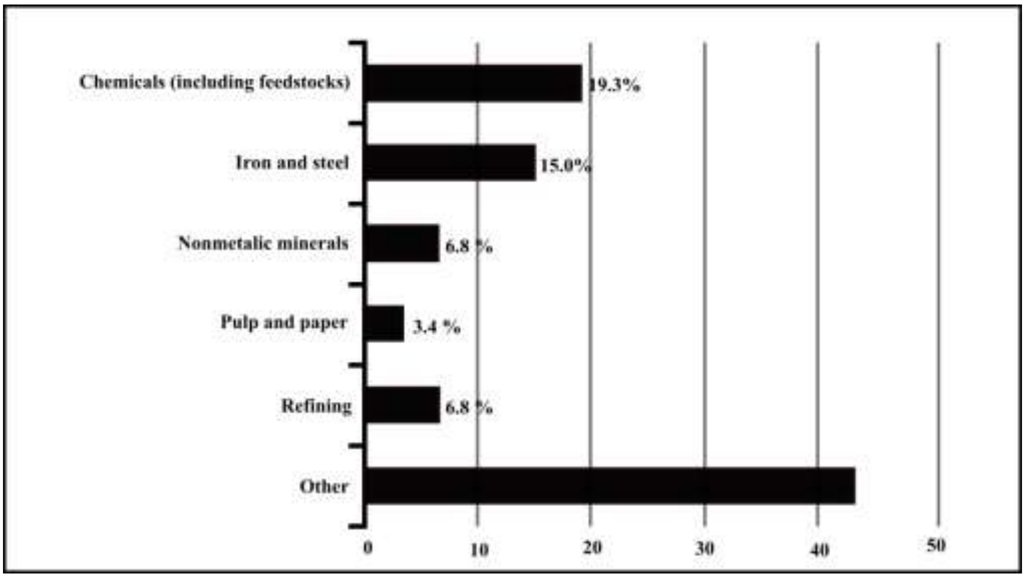
The decision of which type of heat exchanger to use depends on the source and target temperatures, high and low pressure values, the nature of the process fluid used, financial constraints and a number of other considerations. The selection of appropriate exchanger is complex and often supported by software. Stehlík (Stehlík, 2011) provides a review of heat exchanger use in situations where polluted flue gas is the process fluid. They highlight the importance of selecting the correct heat exchanger and provide a strategy for selection. Chen (Chen et al., 2012b) in a review of condensing boilers recommend the use of carbon steel instead of stainless steel in the heat exchanger as it was found to allow greater heat transfer and reduce corrosion.

The synthesis and analysis of heat exchanger networks for heat integration in the process industries, (most notably in the chemical sector) and the determining of optimal retrofit of existing heat exchanger networks are current research challenges. Retrofit with minimal topology modification is desirable and many optimization strategies are proposed: Ciric (Ciric and Floudas, 1990) for example proposes a mathematical model of optimization for retrofit of a network; Wang (Wang et al., 2012) proposes a novel design approach to solve heat exchanger network retrofit problems based on heat transfer enhancement and Smith (Smith et al., 2010) provide a review of various methods and presents a methodology for complex industrial revamps based on a modified network pinch approach combining structural modifications and cost optimization in a single step to avoid missing cost-effective design solutions. Muster-Slawitsch (Muster-Slawitsch, 2014) propose a new pinch analysis tool for systematic heat integration with intelligent storage systems which can reduce thermal energy consumption. This is especially relevant for heat integration in discontinuous process streams e.g. in brewing sites. Over the past 30 years there has been a large advance in the compact nature and performance of heat exchangers and current challenges are in identifying ideal technology for specific contexts.

5. CASE STUDIES

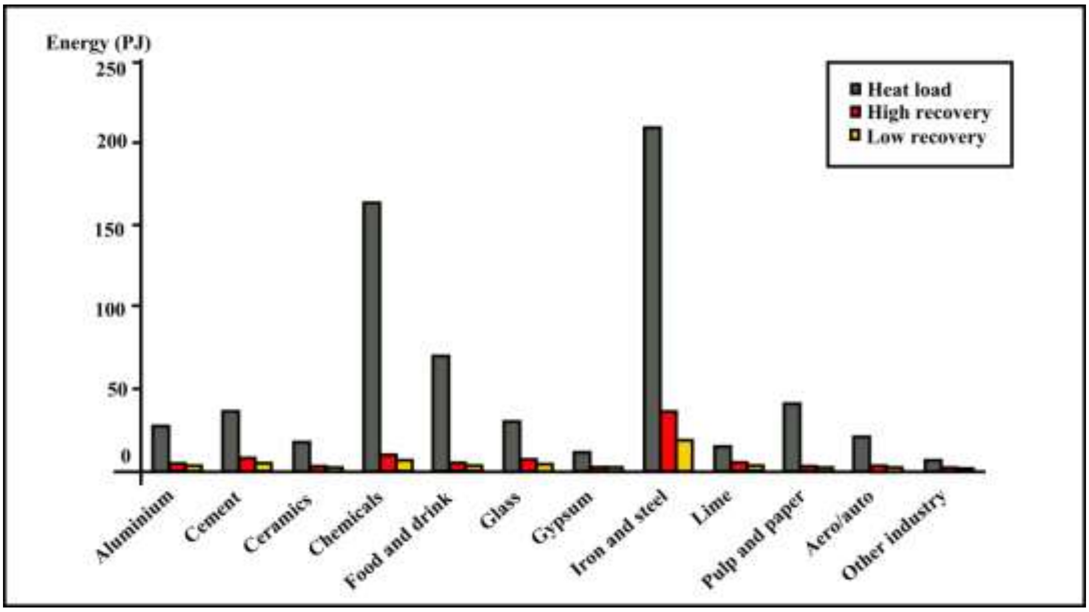
International sectorial data, presented in the International Energy Agency's 2013 outlook report show that the chemicals and petrochemicals sector, in combination with the iron and steel sector account for almost half of all worldwide industrial energy usage (IEA, 2007). Other sectors that account for a significant share are non-ferrous metals, non-metallic minerals and the pulp and paper sector (UNIDO, 2010). Figure 1 shows the final (delivered) energy consumption in the various industries.

Figure 1: Shares of total world industrial sector delivered energy consumption by major energy-intensive industries, 2010, as a percent of total (EIA, 2013).



Specific energy consumption (SEC) can differ significantly between countries and sectors as a result of differences in resource availability, energy prices, and other local factors; in the UK, Iron and steel production is the largest energy consumer, see Figure 2.

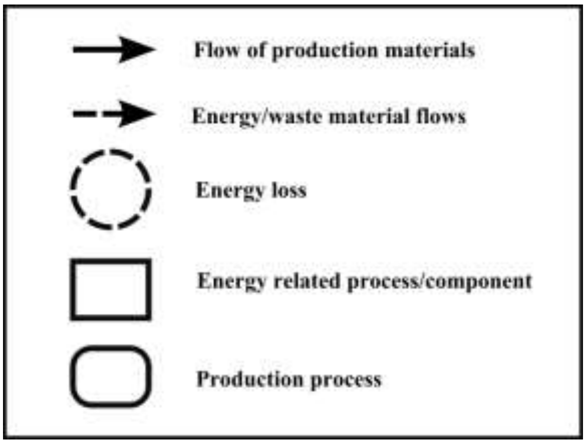
Figure 2: Energy use for heat and estimated recovery potentials by sector (McKenna and Norman, 2010).



Energy use, applied technologies and needs can vary greatly between sectors, organization size, location and several other influencing factors. This section presents four case studies with a variety in influencing factors. The steel production case study is based on an organization with large production volumes, is a large consumer of energy and invests in efficiency technologies. The paper production case study shows a large producer who is relatively self-sufficient in energy terms. The breweries case study presents a typical medium sized brewery in the UK and the cement production plant is a major producer in the Far East. All case studies were conducted as part of EPSRC funded research projects to study energy use in industrial processes.

For each case study, an overview of the issues affecting the sector and a forecast based on literature is presented. A high-level view of processes within each organization is provided followed by a closer inspection of energy use and where appropriate, recommended improvements are identified. The key to figures for all case studies is shown in Figure 3.

Figure 3: Key to figures.

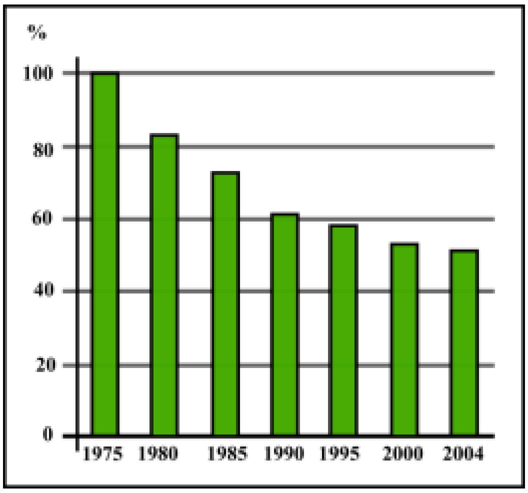


5.1. Case study 1: Steel Mill

5.1.1. Industry overview

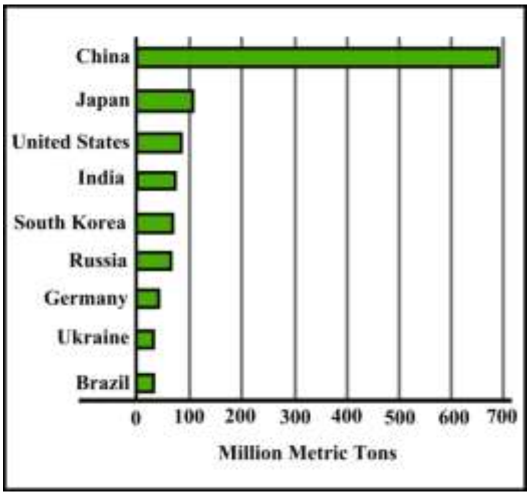
Iron and steel production is the second largest energy consuming industrial sector in the world accounting for 15% of industrial sector delivered energy consumption in 2010 (EIA, 2013). Steel is an alloy of iron and carbon produced by chemical reduction of iron ore in the presence of coke which is produced by heating coal in the absence of oxygen. The process has high requirements for thermal energy and releases large amounts of carbon dioxide. Approximately 1.3 billion tonnes of steel was produced in 2007 and this figure is expected to double by 2050 (Worldsteel, 2008). The cost of energy is reported to be in the range of 20% to 40% of the cost of production (Worldsteel, 2008) which has provided a business incentive to invest in energy efficiency technologies. There are also requirements to reduce emissions and subsequently energy consumption in the industry has reduced steadily over the last 40 years. Figure 4 shows reductions of approximately 50% in energy use for the industry in North America, EU and Japan since 1975.

Figure 4: Average energy consumption per tonne of crude steel produced for North America, EU 15 and Japan (Worldsteel, 2008).



However there has been a large increase in demand for steel consumption in developing countries over the past decade and so total energy use by the industry has increased despite the improvements in efficiency. Figure 5 shows steel production figures for major world producers.

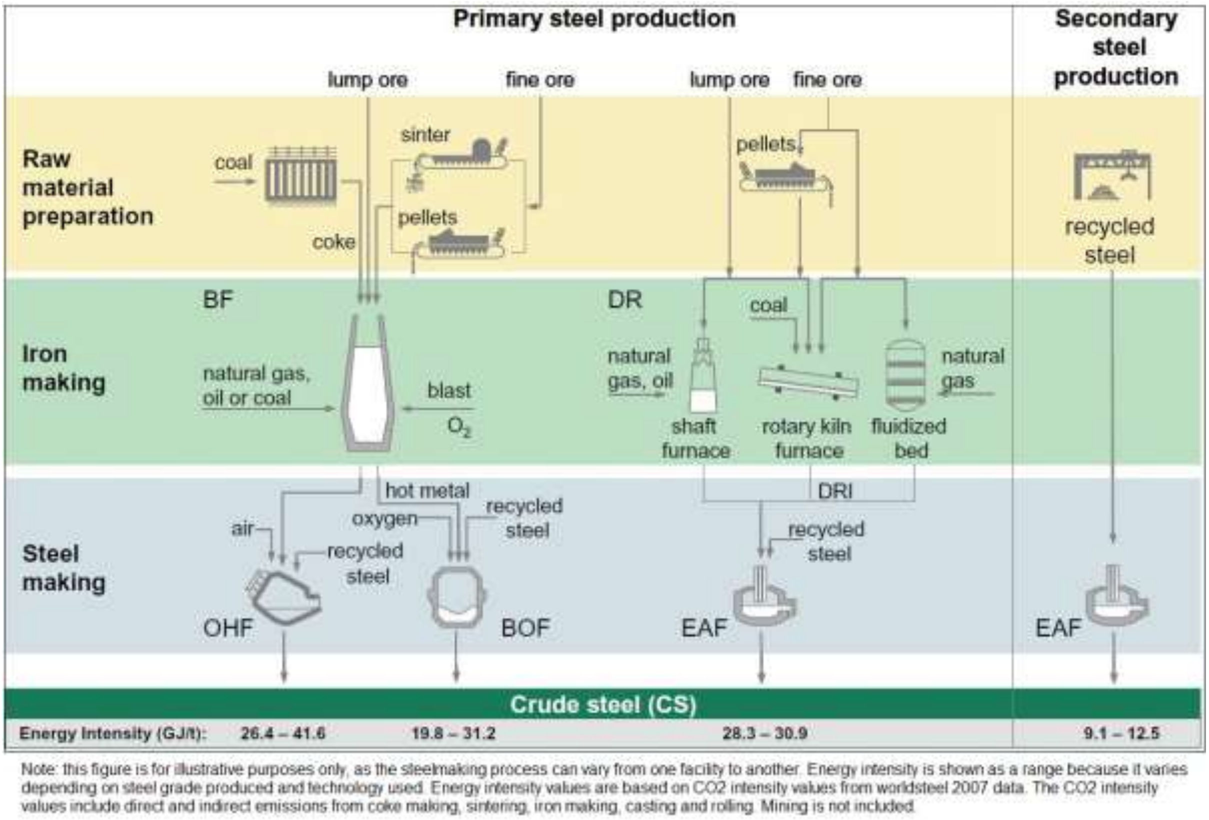
Figure 5: Steel production in major producing countries, adapted from (EIA 2013).



Steel is a unique in that it is completely recyclable, repeatedly and without any loss in quality. Despite this primary steel production (production of new steel) is still a large industry because steel products are used for a long period of time and there is increasing demand. China's steel production is 90% primary in order to meet the growing demand. Approximately one third of world steel production and 60% of steel produced in the USA and India is through secondary production using scrap steel (EIA, 2013). Secondary steel is produced by melting recycled steel using an electric current.

Recycled steel is used in both primary and secondary steel production, as illustrated in Figure #3 which presents an overview of steel production. Primary steel production requires large amount of heat to produce coke, which is used as a reducing agent for the production of molten or pig iron from iron ore. The *Open Hearth Furnace* (OHF) method, the *Basic Oxygen Furnace* (BOF) method and the *Electric Arc Furnace method* (EAF) are possible approaches in the process of creating steel from iron. Both OHF and BOF involve a blast furnace (BF) while EAF uses electric current. Compared to BOF and EAF which are widely applied in most steel mills, OHF is not common and its use continues to decline due to environmental concerns. With the recent increase in EAF use in European countries, the use of *direct reduction* (DR) which produces direct reduced iron which is then used to produce steel in the EAF is expected to increase in the long term. The main energy requirement in secondary steel production is for electricity while most of the energy for primary production is provided by fossil fuels. During the process, impurities such as sulfur, phosphorus, and excess carbon are removed and alloying elements such as manganese, nickel, chromium and vanadium are added. The processes of casting, hot rolling and cold rolling turn molten steel into usable end products for manufacturing. By melting recycled steel with electric current, secondary steel production involves less energy intensity.

Figure 6: Steel production routes and energy intensity per route (Worldsteel, 2008).



Current practices for improving efficiency include:

- enhancing continuous production processes to reduce heat loss;
- increasing recovery of waste energy from process gases;
- efficient design of electric arc furnaces e.g. scrap preheating, high-capacity furnaces, foamy slagging, and fuel and oxygen injection;
- utilizing new energy management systems; and
- optimizing and maximizing the recycling of scrap steel.

Much literature is available on opportunities for energy savings in the industry, for example the U.S. Environmental Protection Agency sponsored Energy Star guide for energy and plant managers for the iron and steel industry (Worrell, 2010) provides detailed descriptions of energy saving opportunities within individual processes. Energy management is a key element of future improvements in steel mills (Worldsteel, 2008) and the European Commission’s Best Available Techniques (BAT) documents for iron and steel production (Remus, 2013) provide detailed uses for process gases within iron and steel production plants. The challenge is the efficient distribution and use of process gases in combination with purchased fuels, facilitated by tailored plant layout

5.1.2. Organization Profile

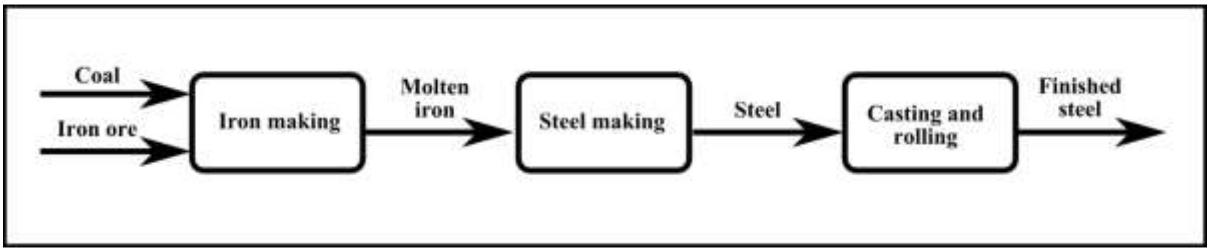
This case study is based on information collected from a UK-based organization operating an integrated steel mill producing both steel and coke which is required to make steel. The mill uses the BOF method to produce nearly 5 million tonnes of steel slabs per year. Steel production is continuous and therefore the waste heat sources are highly consistent over time.

The mill operates a power plant which captures the main sources of thermal energy: the combustion gas from the blast furnace and coke oven. Waste heat from steam has not been quantified by the thermal energy audit used for this study but according to the mill, the steam energy lost from the 11 bar system is estimated at 0.83 PJ/year, which is equivalent to ~ £5millions of natural gas utilization. An assessment of the steam thermal energy losses is currently being conducted with the view to redesigning the steam distribution system.

5.1.3. Processes

Steel production is described here in three parts; iron making from raw iron ore, steel making using liquid iron and oxygen, and the finishing processes of steel casting and rolling, see Figure 7.

Figure 7: Overview processes in steel mill.

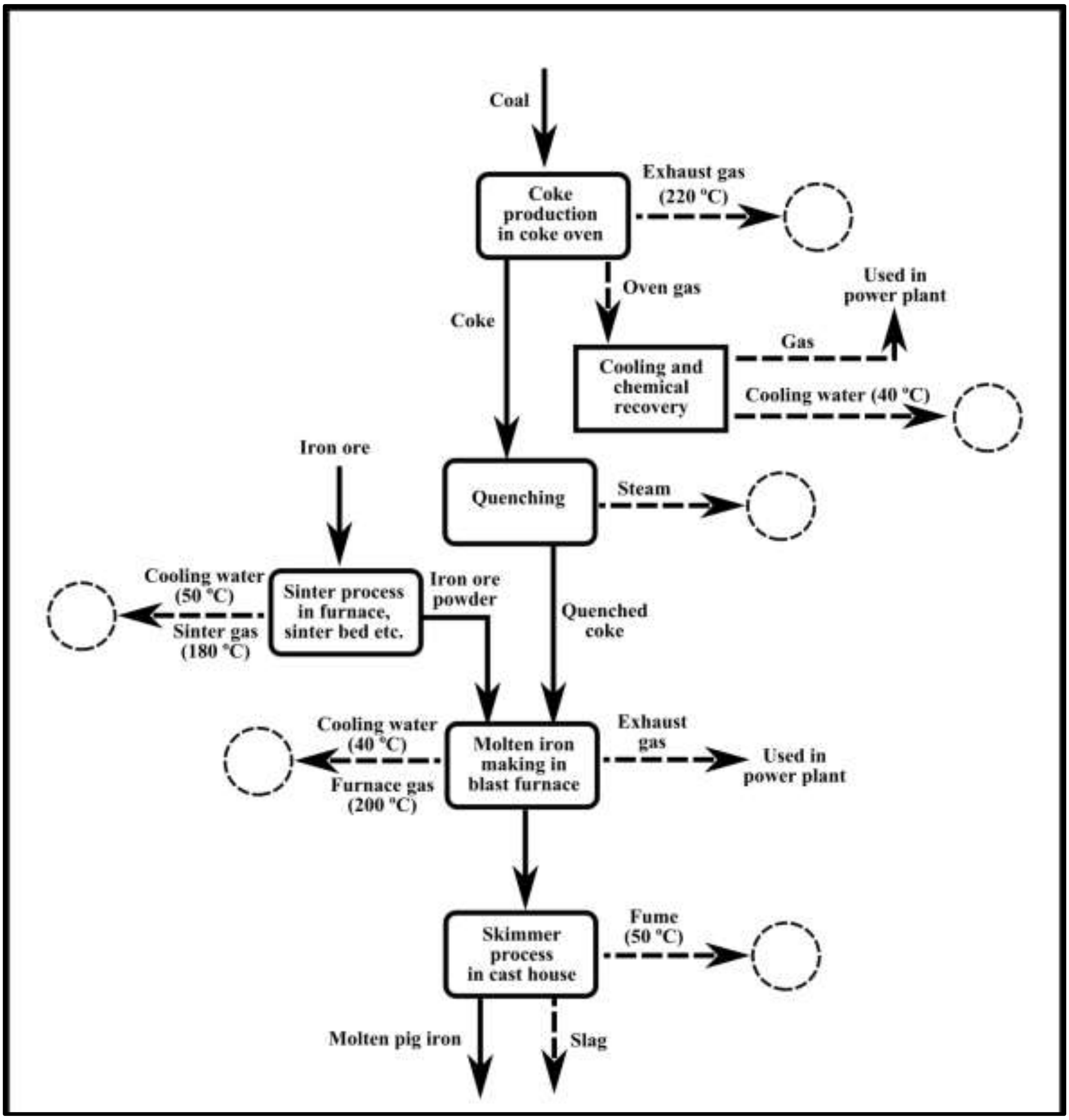


The next sections detail the processes and the energy flows involved at each of the three stages. Where data is available the quantity and rate of discharge are also provided.

iron making

Figure 8 shows the processes involved in iron making and the section below provide a description of the individual processes.

Figure 8: Iron making.



coke production: This involves heating coal to a temperature in the range of 1000 to 1200 °C for several hours in a coke oven to drive off volatile compounds and moisture. For every tonne of coke approximately 3.5 - 5.0 GJ of energy is required accounting for around 10% of the energy demand in a typical Basic Oxygen Furnace plant (IEA, 2007).

Coal used as a reducing agent is metallurgical or “coking” coal with a lower ash and sulfur content. It can be costly and difficult to source but its quality can affect the emission, consumption and energy demand; a 1% increase in the ash content of coke may increase the coke demand by 2% (IIP, n.d.).

Most of the gas from the coke oven itself is used in other processes and any remainder is used in the power plant to generate electricity. The gas is cleaned through chemical recovery of toxic elements like tar and sulfur. This process requires cooling, and produces gas with the highest calorific value of all process gases in the mill and is used to enrich the value of the gases used in the blast furnace. Remaining gas is available in large volumes and may be used for other purposes like re-heating furnaces, underfiring of the coke oven or in the blast furnace as an alternative reducing agent. The main sources still available for thermal energy recovery from this process are:

- gas from under-firing at a maximum temperature of 220°C, produced at a rate of 11kg/s; and
- cooling water at 40°C produced at a rate of 556kg/s as a result of cooling and chemical recovery of the raw gas output.

sinter process: This process produces a fine powder of iron ore, or sinter using high temperatures. This process is important to make reduction in the blast furnace faster, minimizing energy demand. The sinter temperature can reach over a 1000°C, and at the end of the process, it is cooled and the finished sinter is size-screened. Sinter gas released at a maximum temperature of 180°C and cooling water at 50°C, 8 kg/s are the main streams available for recovery.

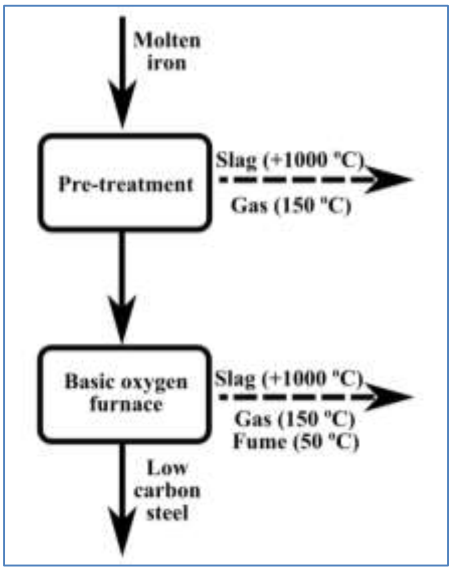
blast furnace: The furnace is the vessel within which the powered iron ore is reduced by the coke at high temperatures to yield molten pig iron. The main sources available for heat recovery are cooling water at maximum temperature of 40°C, and blast furnace flare gas at 200°C which may be reused within the blast furnace. Large amounts of combustion gas from the furnace is also produced which is reused in the power plant.

The cast house and skimmer process: Here the slag is separated from the iron. In the blast furnace, the molten iron trickles down and collects at the bottom and the impurities that are removed by the aid of Calcium Oxide to form a slag that floats on the molten iron. This slag has market value that is widely used as an efficient raw material for cement production. The process releases fume or air at a temperature of 50 °C at a rate of 285 kg/sec.

steel making

After the iron making process, the molten iron is used to make steel as shown in Figure 9.

Figure 9: Overview of steel making.



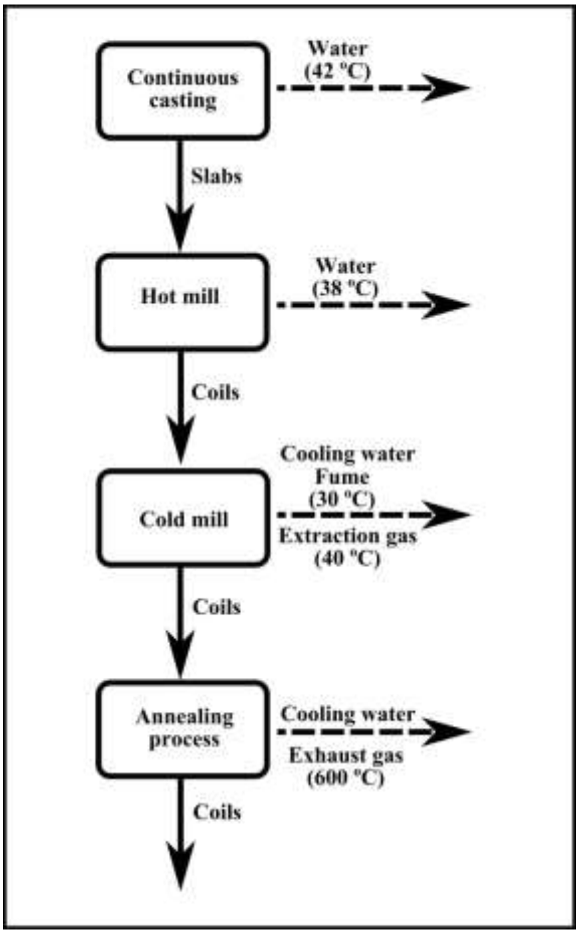
pre-treatment process: Pre-treatment for the BOF removes sulfur, silicon and phosphorus from the hot metal. The decision to pre-treat depends on the quality of the raw materials in the molten iron and the required final quality of the steel. The steel mill described here conducts a de-sulfurizing pre-treatment, which produces slag (1300°C at 2.7 kg/s) and hot gas (150°C at 10 kg/s).

Basic Oxygen Furnace (BOF): The BOF converts the liquid iron into steel in the presence of oxygen. A water-cooled lance is lowered into the vessel and high purity oxygen is blown through the lance to remove the carbon, as well as amounts of silicon, manganese and phosphorous. The oxygen combines with impurities and this oxidation produces heat. The waste heat sources are from the fume (air) at a maximum temperature of 50°C, gas at a maximum temperature of 150°C and cooling water at 35°C.

steel casting and rolling

The last stage in steel making is illustrated in Figure 10.

Figure 10: Overview of steel casting and rolling.



continuous casting: This is the solidification of liquid steel to produce steel slabs, where liquid steel flows out of the ladle into a holding tank and then is fed into a water-cooled copper mold. Solidification begins in the mold, and continues through the caster. Iron and steel making, traditionally involving several batch processes, has benefitted from significant energy and material savings since the introduction of continuous casting in the 1970s-80s. The vast majority mills use a continuous process and the current best practice is to enhance this process to reduce heat loss. Water is the only waste heat source available in continuous casting with a maximum temperature of 42°C.

The slabs are reheated in the furnace for malleability and rolled into metal sheets. A distinction is drawn between hot- and cold-rolled sheets as described below.

The hot mill: Here hot-rolled sheet in coil form is produced from the slabs, which are reduced to certain thicknesses by rolling and annealing before winding into a roll. The steel entering the hot mill needs to be reheated in order to be malleable enough to roll. In this process the waste sources are available as water at a maximum temperature of 38°C.

The cold mill: Here, cold-rolled sheet in coil form is produced by removing rust from hot-rolled sheet. This is done by "pickling" the hot-rolled sheet in a weak acid solution, then washing, brushing, drying, oiling and unrolling the sheet. Finally the sheets are cold-rolled by passing the sheet through a reducing mill under pressure to turn it into a roll. Cold-rolled steel is a highly finished product and has a smoother surface, greater dimensional accuracy (in terms of thickness, width and length) and greater strength. The metal passes through rollers at a temperature below its recrystallization temperature in order to increase metal yield strength and hardness. The fume produced is released at a temperature of 30°C at the rate of 12 kg/s and extraction gas (air) is at 40°C with the flow rate of 22kg/s. These gases are not considered to be relevant for recovery by the steel mill. No data is currently available for the cooling water from this process.

The annealing process: This process induces metal ductility in the steel coils from the cold mill. The waste heat source which has been identified and available for recovery from this process is in the exhaust gas stream from the heat treatment process at 600°C. As with the cold mill process, no data is currently available for the cooling water.

5.1.4. Summary

Iron and steel production releases large amounts of carbon dioxide to the atmosphere. It is also the second largest energy consuming industrial sector in the world (EIA, 2013). Technology developments and legislation requirements have significantly improved energy use and emissions over the last several decades. However, the growth in worldwide demand means that production has increased. This case study has focused on a primary production steel mill based in the UK employing BOF Technology. The mill employs careful cleaning of exhaust gases and re-uses much of the heat produced in its processes. In addition an analysis of heat flows has been conducted identifying further potential for savings.

5.1.5. Industry forecast

The EIA outlook predicts that in the long term, energy use is set to decline as increasing amounts of scrap steel become available, and the use of EAF technology become more prevalent. It is expected that there will be a larger shift towards secondary production and use of EAF for primary production which consumes significantly less fossil fuels. This trend can more easily be seen in OECD (Organization for Economic Cooperation and Development) member countries where demand is stabilized.

However in the medium term, despite the recyclability of coal and the improvements in efficiency of production, energy use by the industry is likely to increase due to increasing demand for steel, especially in countries which are undergoing large scale industrial development. The demand for steel is expected to double by 2050 (Worldsteel, 2008) and with a need for best practices to be more widely disseminated, a lack of financial investment and a lack of strict emission control policies, international developments in this sector are of vital importance.

5.2. Case study 2: Cement Plant

5.2.1. Industry overview

Cement production accounts for approximately 12 to 15% of total industrial energy use (Madlool et al., 2013) with China being the major producer responsible for over half of all global cement production (IEA, 2007; EIA, 2013). Energy costs are reported to constitute between 20 - 40% of the total cost of production (Kabir et al., 2010; Schorcht et al., 2013; EIA, 2013) and in combination with legislative pressures to reduce emissions, create a strong incentive to implement energy efficient technologies.

Emissions from cement plants are hazardous and technologies for capturing pollutants from exhaust streams are widely implemented to meet legislative requirements. The emissions which cause the greatest concern are dust, hazardous nitrogen oxides (NOx) and sulfur dioxide (SO_2) (Schorcht et al., 2013). Additionally cement production is one the main sources of CO_2 emissions responsible for almost 5-7% of global emissions with a rate of 900 kg CO_2 per tonne of cement produced (Benhelal et al., 2013). Strategies to reduce energy consumption, fuel consumption and CO_2 emissions are interrelated with heat losses indicated as a direct contributor to increased CO_2 emissions (Benhelal et al., 2013).

To produce cement, raw materials of particular composition are ground to fine powder, heated to high temperatures to form “clinker” and then mixed with other ingredients and ground further. The grinding of raw materials to fine powder and the grinding of the cement mixture account for the majority of the electricity requirement while heat for the production of clinker is the main requirement for thermal energy and fuel. Production plants may employ wet or dry processes and a number of different kiln types which all affect the energy requirement. In the dry process, which uses dry raw ingredients containing less than 20% moisture by mass, there is a 13% reduction in electrical energy and a 28% reduction in fuel requirement in comparison with the wet process where water is added to the raw ingredients to form “slurry” (Madlool et al., 2013). Thermal energy represents 20 - 25% of the total production cost (Madlool et al., 2013) and cement producers are moving towards dry processes where possible, including semi-dry and semi-wet processes, however, the quality and moisture content of the raw material available can affect the type of processes that can be used with wet processes consuming more energy than dry processes mainly due to the extra need for drying (IEA, 2007). Current best practice is to incorporate a number of pre-heating steps within the dry process to reduce total heat requirement, employing heat recovery and reuse within the pre-heating & clinkering process.

Strategies for reducing thermal energy requirement include reducing the clinker to cement ratio by substituting some of the clinker with materials like granulated blast-furnace slag or limestone. This practice depends on availability of materials with the required properties, cost and intended application of the cement (Pardo et al., 2011; Schorcht et al., 2013). A proportionately large percentage of thermal energy use is required for the processes involved in producing clinker and it is recommended that indicators represent energy per tonne of clinker and electricity use per tonne of cement (IEA, 2007) although many published studies still report energy use only in terms of tonnes of cement.

The industry has made significant progress in thermal efficiency and emissions control over the last two decades. Electricity generation from waste heat is widely used as an alternative to importing electricity and there is a drive to use sustainable fuels in place of coal. The latest kiln designs are more energy efficient and energy demand in clinker production has been significantly reduced over the last few decades. Best available techniques (BAT) levels of energy use per tonne of clinker for various types of plants are provided by the European commission (Schorcht et al., 2013).

5.2.2. Organization profile

This case study is based on data collected from a cement producer located in the Far East in a semi-urban area. There are small residential and commercial units in close proximity of a few metres from the plant providing a potential consumer base for waste heat recovery. There are four production units with a combined total production of approximately 6 million tonnes of cement per year. Apart from a total of 15 days, operation is continuous throughout the year.

Coal and diesel oil is used for thermal energy requirements and all electricity required is imported from the grid. The organization reports consumption of 534 648 610 kWh electricity, 830 000 tonnes of coal and 40 000 tonnes of industrial diesel oil per year. Assuming 6 million tonnes of production per annum, energy use is 4.6 GJ per tonne of cement produced. The organization estimates energy use at 4GJ per tonne of clinker. Although reported figures vary, industry standard for specific energy consumption ranges between 2.9 GJ and over 5.5 GJ per tonne of cement depending on the processes and technology employed (Kabir et al., 2010).

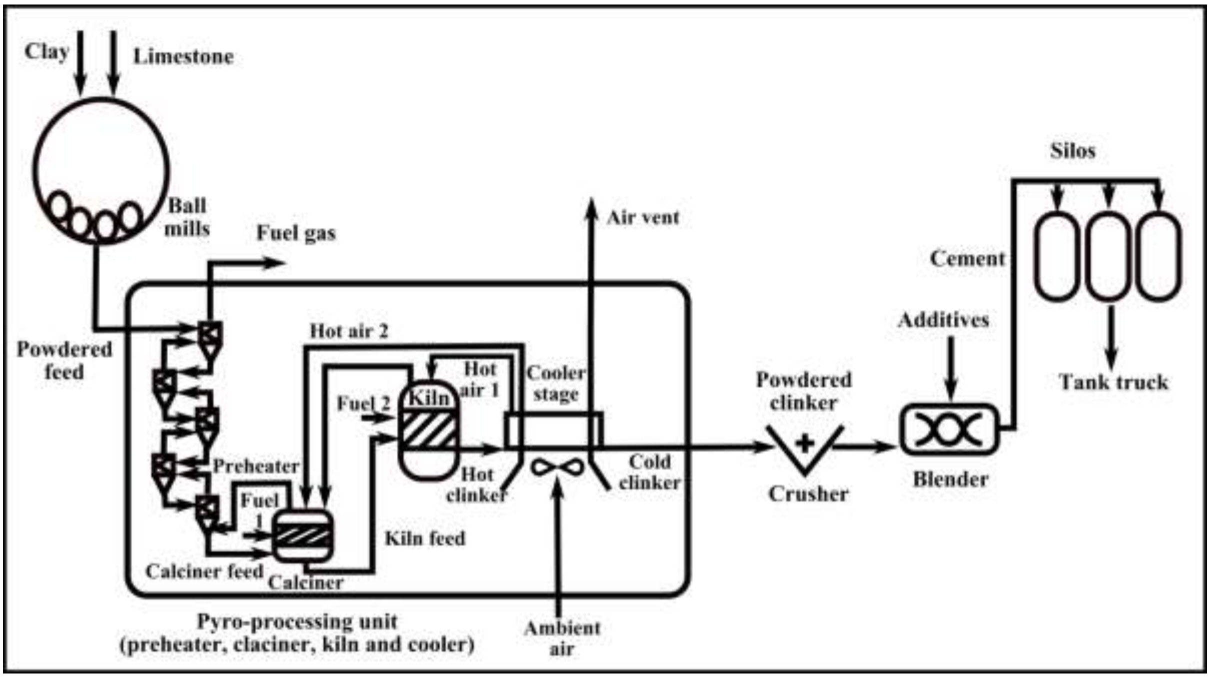
The plant uses a dry process employing a dry kiln with a suspension pre-heater and pre-calciner. This is widely used and fuel efficient technology yet over half of the thermal energy input is estimated to be lost: 44.25% is lost as part of the exhaust gas from the clinker cooler and cyclone preheater; 2.46% is lost directly from the clinker into the atmosphere; 3.4% is lost in the form of radiation and convection from the kiln cell; and additionally there is an unaccounted loss of 4.65%. Thermal efficiency of the plant is low though not atypical; other studies have reported similar results for example Khurana (Khurana et al., 2002) report that in a cement plant in India (4th largest producer of cement) whose processes are close to best practice, waste heat is estimated to be 35% of energy input, Kabir (Kabir et al., 2010) report 41% losses from a plant in Nigeria.

In addition to the large amount of thermal energy produced, the plant generates high pollutant from burning fossil fuel and from chemical reaction during clinker formation releasing a huge amount of hot flue gas streams rejecting CO_2, (Sulfur oxides) SO_x and (nitric oxides) NO_x to the atmosphere. Recently there has been an organizational move to reducing emissions and capital has been allocated for incorporating sustainable technology.

5.2.3. Processes

This section describes the main processes involved in cement production, identifying existing energy efficiency related practices and potential for improvement. Figure 11 shows a high level view of cement production.

Figure 11: Block diagram of cement production process (adapted from (Benhelal et al., 2013)).

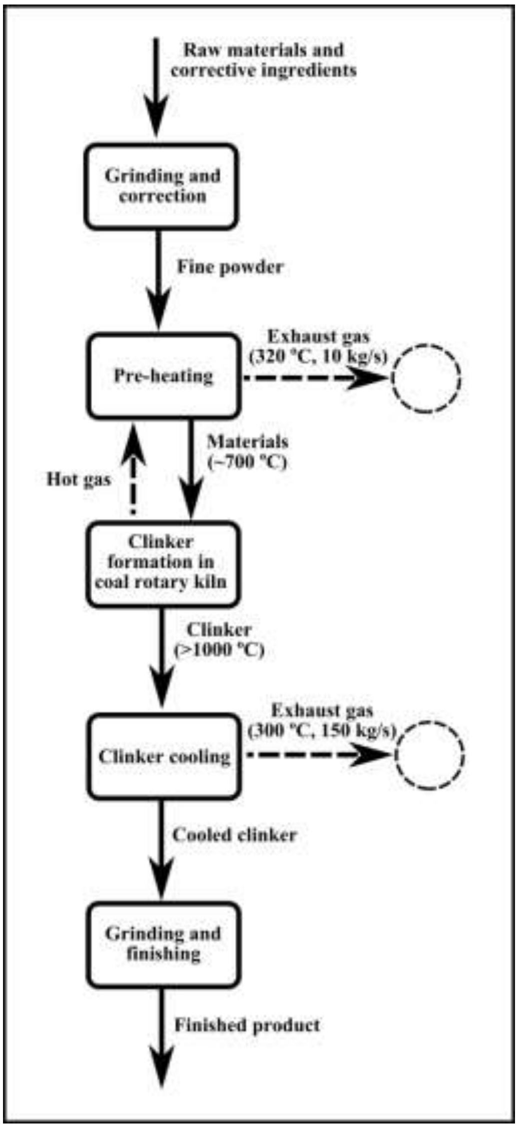


Pyro-processing, see Figure 11, refers to subjecting materials to high temperatures to bring about a chemical change. In cement production, raw materials are heated in a kiln to produce clinker, often referred to as "clinkering". The diagram in Figure 12 and following sections consider processes within the pyro-processing unit and identify the main thermal flows.

grinding & correction

Cement is made from a combination of compounds including lime stone, marl, clay and silica. For ease of transportation from the mine or quarry the materials undergo preliminary crushing and then are further processed on arrival at the plant in preparation for the production process. Preparation involves filtering and grinding the materials into fine powder. To obtain proper composition, some corrective ingredients such as iron ore, sand and bauxite are added. The main requirement for electricity in this plant is for grinding, which includes grinding during the later stages of production. The priority for the cement production industry is to reduce the fuel and heat usage during clinker production and similarly the plant does not intend to modify grinding and correction processes.

Figure 12: Main energy flows in cement production.



pre-heating & pre-calcination

The raw materials in fine powder form are fed into a cyclone pre-heater for drying. This process is energy intensive because the materials are heated to high temperatures at different stages: first, the material is heated from ambient temperature to 200°C during which free water is removed, then to 400°C during which absorbed water is removed and further heating to 700°C ensures clay raw materials are dehydrated i.e. combined water is expelled. In this process, metakaolin is formed through the dehydration of kaolinite in a process known as pre-calcination. The energy requirement for this process is estimated to be 4 MJ/kg clinker and hot gas for this purpose is provided by the coal rotary kiln, as shown in Figure 12.

Heat is lost from this process through the flue gas and there is potential for recovery. Some of the thermal energy of the exhaust gas from the cyclone preheater is currently reused to dry the clay in clay dryer unit (within the pre-heater) but there is still an opportunity for energy recovery - in each of the 4 production units flue gas at approximately 320°C leaves the preheater at the rate of 10 kg per second. If this gas is to be used outside the process, there is a requirement for further processing as it could contain acid depending on the chemical composition of materials in the kiln.

clinker formation
Materials from the preheater enter the coal-powered kiln and are heated further. Inside the kiln, decomposition of metakaolin and other compounds take place between temperatures of 700°C and 900°C resulting in a mixture of oxides. Clinker formation causes the release of large quantities of carbon dioxide through the oxidation of organic carbon in the raw material; calcium carbonate (limestone) is oxidized to form calcium oxide and carbon dioxide while magnesium carbonate is oxidized to form magnesium oxide and carbon dioxide. The "clinkering" takes place at temperatures above 1260°C. The EU IPPC reference document (Schorcht et al., 2013) on best available techniques reports energy use of 3000-4000 MJ per tonne of clinker for dry rotary kilns with pre heater and pre-calciner (which this plant employs).

clinker cooling
The resulting clinker exits the kiln and is rapidly quenched to 100-200°C in order to protect the alite (3CaO SiO_2) from decomposing and for safer handling. It is then cooled slowly to room temperature. Exhaust gas from the cooler is not corrosive but may contain high levels of dust which needs filtering, however it represents the biggest potential for waste heat recovery with a flow rate of 150 kg per second at temperatures in the range of 250 -300°C from each of the 4 plants. The organizational focus for improving energy efficiency is in this process and construction of a 2.5 MW Rankine electric power plant is underway to capture exhaust gas from one of the 4 plants.

grinding & finishing
The clinker is then mixed with additives such as gypsum and iron sulphate and finely grounded to form cement. This grinding and the initial grinding of the raw materials represent the main requirement for electricity at the plant.

5.2.4. Summary

The cement production plant presented here uses coal and diesel oil for its thermal energy requirements and purchases all electricity required. The main thermal energy requirement is for clinker production in the kiln while the main requirement for electrical energy is grinding. The plant employs pre-heating and pre-calcination which reduces the heat requirement for the kiln but large amounts of coal are still required for this process which, in combination with the clinker cooling process release a large amount of heat and pollutants to the atmosphere.

The main sources of waste heat that can be captured are available as exhaust gas from the clinker cooler and cyclone preheater. The flow rate of exhaust gas of clinker cooler for each of the four production units is 150 kg/second on average with a temperature of approximately 300°C while the flow rate of exhaust gas from the cyclone preheater, for each production unit, is 10 kg / second at approximately 320°C. Some of thermal energy of exhaust gas from the cyclone preheater is re-used to dry the clay in clay dryer element. The organization plans to use the thermal energy of the exhaust gas from the clinker cooler in one of production plants to produce electricity.

5.2.5. Industry forecast

The US Energy Information Administration (EIA)'s projection for 2014 (EIA, 2013) suggest that energy efficiency in cement production will increase as a result of the use of additives to reduce the cement to clinker ratio. Other energy efficiency strategies include the use of recycled materials for heating fuel and improved kiln technology. However, the report also suggests that the use of cheap fossil fuels, especially petroleum coke, in some countries will offset the benefits of improved kiln technology.

Much work on analysis of energy use and economically viable strategies for energy savings (Madlool et al., 2013; Pardo et al., 2011; Schorcht et al., 2013; Khurana et al., 2002; Kabir et al., 2010) for energy reduction is available. Benhelal (Benhelal et al., 2013) provides a list of studies aimed at reducing CO_2 emissions. Current research indicates that availability of technical knowledge, investor's awareness and effectiveness of policies are the current drivers for energy efficiency in the sector.

5.3. Case study 3: medium size brewery

5.3.1. Industry overview

The brewing process is energy intensive, with high thermal energy requirements for the mashing and boiling processes and high electrical energy requirements for cooling during the fermentation and maturing stages. Sustainable practices are encouraged within the industry and the energy efficiency of breweries globally has steadily improved over recent decades with over 50% reduction in specific energy consumption between 1976 and 2006 (BBPA, 2006) and a further 9.6% reduction between 2008 and 2012, reported in a survey of large breweries (Campden-BRI, 2012). However, energy still constitutes 3 - 8% of production costs, depending on brewery size and other variables (BAC, 2011).

The raw material used to produce beer is malted grain – typically dried barley which has been soaked and allowed to partially germinate. In the brewery, malt goes through a mashing process and is then drained to extract "wort", which is the liquid containing the sugar produced by mashing. The wort is then further prepared by boiling and adding "hops" (flowers from the hop plant used for flavoring and as a stability agent in beer). The fermentation and maturing stage which follow require careful monitoring of conditions to ensure quality of beer.

Water is the most important raw material used for the production of beer; in addition to being a main constituent of beer (approximately 90%), it is also used for cleaning, steam production, cooling and as heat supply media in heat exchangers. Water usage and energy efficiency are closely linked – reduced usage means less pumping demand and lower heating and cooling loads. Reductions in water usage also lead to reduction of discharge of trade effluent (WBA, 2011). The amount of water needed to brew beer can be several times the volume brewed and its reduction is a priority for brewers.

The Worldwide Brewing Alliance (WBA) which represents nearly 88% of the world beer production, including the brewing sector in Australia, Canada, China, Europe, Russia, and the USA, disseminates good practice and information on energy use and environmental sustainability in addition to other industry practices. Strategies for reducing evaporation are widely employed as are other industry specific techniques such as increasing use of winter barley for beer production which requires less water and energy due to the off-peak growing cycle (WBA, 2011). Some commonly recommended process (WBA, 2011; Sturm et al., 2013) improvements are:

- boiling hops separately from the wort;
- utilizing innovative refrigeration designs;
- recovering energy from vapors by including heat recovery systems that capture steam and condensation from kettle boiling during brewing for reuse to pre-heat process water;
- installing energy storage systems;
- induction fans that pull cool winter air into refrigeration units to chill beer;
- investing in alternative energy sources (e.g. biomass); and
- incorporating process automation systems.

Even though solutions for reducing waste heat and waste water are widely available, the take-up of technologies has mostly been by large-scale corporate breweries and as a result the main remaining potential for improvement in this sector is in small and medium size breweries (BBPA, 2006; Sturm et al., 2013). This may be because smaller breweries have access to less capital investment for upgrades and implementation of new technologies or may not be in a secure enough business position to make long term investments. Additionally many breweries are part of a niche market where the traditional techniques and technologies they employ are considered important to the taste and quality of beer.

5.3.2. Organization profile

This case study is based on earlier works (Hugenschmidt, 2011; Sturm et al., 2013) which investigated the production process in a typical medium sized brewery in the UK and identified potential for reducing water and energy demand. This brewery produces 250 000 hectoliters (hl) of beer (2010 figures) using a production process which runs without interruption all year. 90% of the beer produced is bottom-fermented with low alcohol content (3.2-3.5%) and high gravity.

The "gravity" of beer refers to the relative density of the wort compared to water which is largely dependent on the sugar content. During fermentation, yeast converts sugars into carbon dioxide and alcohol, lowering the density of the wort. Gravity is expressed in terms of the Plato scale (°P) which is the percentage of sucrose by weight; wort measured at 20°P, a high gravity, has the same density as a water–sucrose solution containing 20% sucrose by weight. For high gravity beer production, water is often added after fermentation and so high gravity brewing benefits from lower evaporation rates of 3.4-5% compared to low gravity brewing often with higher evaporation rates of up to 8-12% (Sturm et al., 2013).

After observation for a 2-week period, the brewery's energy use is estimated to be between 203 and 247 MJ/hl (Hugenschmidt, 2011); of this, thermal energy accounts for 157-181 MJ/hl and the remainder, electricity. Thermal energy for the processes and for heating the buildings is provided by natural gas and the main consumer of electricity, purchased from public supply, is the chilling process. Water consumption varies between 6.4 and 7.2 hl/hl. This usage is in line with other published usage figures; the worldwide brewery industry *Water and Energy Benchmarking Survey* (Campden-BRI, 2012), reveals that between 2008 and 2012, water and energy use reduced on average from 5.2 hl to 4.3 hl and 229 MJ/hl to 207MJ/hl respectively; the Canadian brewing industry suggests energy usage in a "*a well-run brewery*" would be 8-12 kWh electricity, 5 hl water, and 150 MJ fuel energy per hl of beer produced (BAC, 2011) although they indicate that smaller breweries can have up to twice the specific energy use relative to the output of large breweries due to inherent inefficiencies.

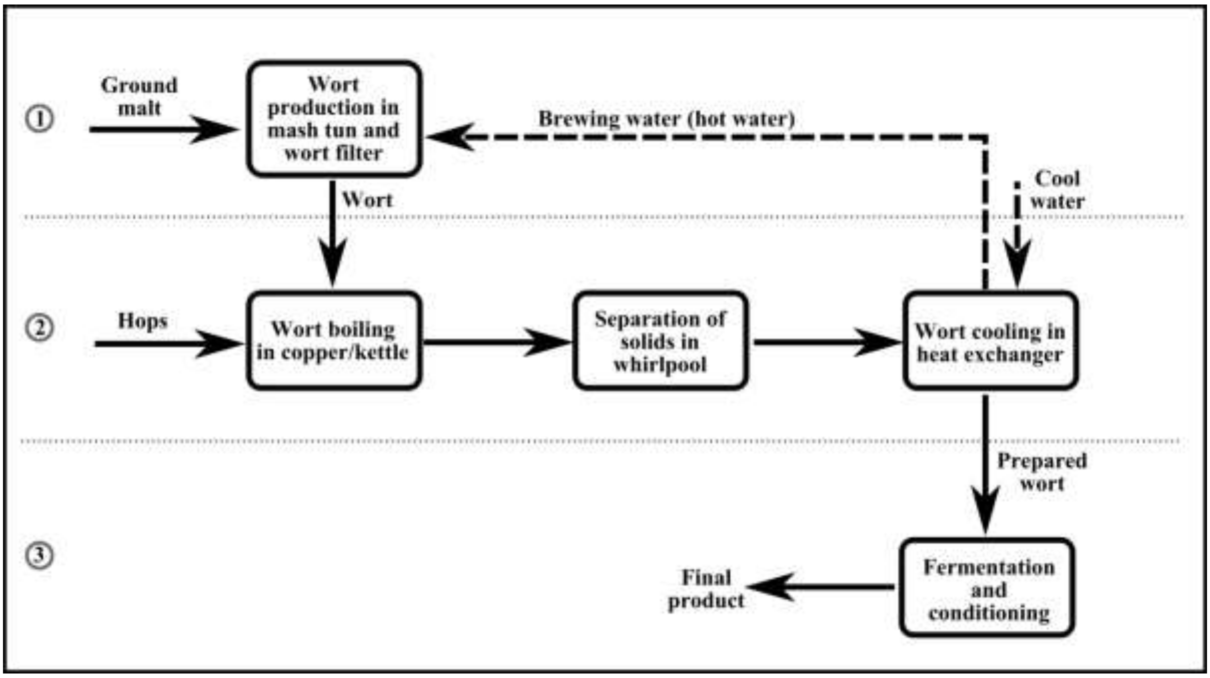
5.3.3. Processes

The first major use of heat and potential for heat recovery in the production of beer is in the malting of barley. Malting involves soaking barley at controlled temperatures to allow it to partially germinate, which produces "biogenic" heat and then drying with hot air. Breweries usually source this malted grain from suppliers so its production is not one of the direct energy costs from the brewers. The industry encourages sustainable practices in barley suppliers such as recovery of biogenic heat, an approach that can offer savings to such an extent that some organizations have become independent of external sources of energy for heating their malt houses (WBA, 2011).

The brewery presented here imports and stores malted barley in a silo ready for production. Different batch sizes are brewed depending on beer type and market conditions. The figures provided here relate to an average brew size of 265 hl.

In the first energy consuming process, requiring electrical energy, measured quantities of malted barley are ground in a roll mill to create the "grist" in the required composition of fines, coarser particles and husks. In some breweries, wet crushing is employed which uses additional energy since it requires steam pre-conditioning of the grain. Figure 13 shows the overview of the production process following the production of the ground malt. Later sections describe these processes in more detail.

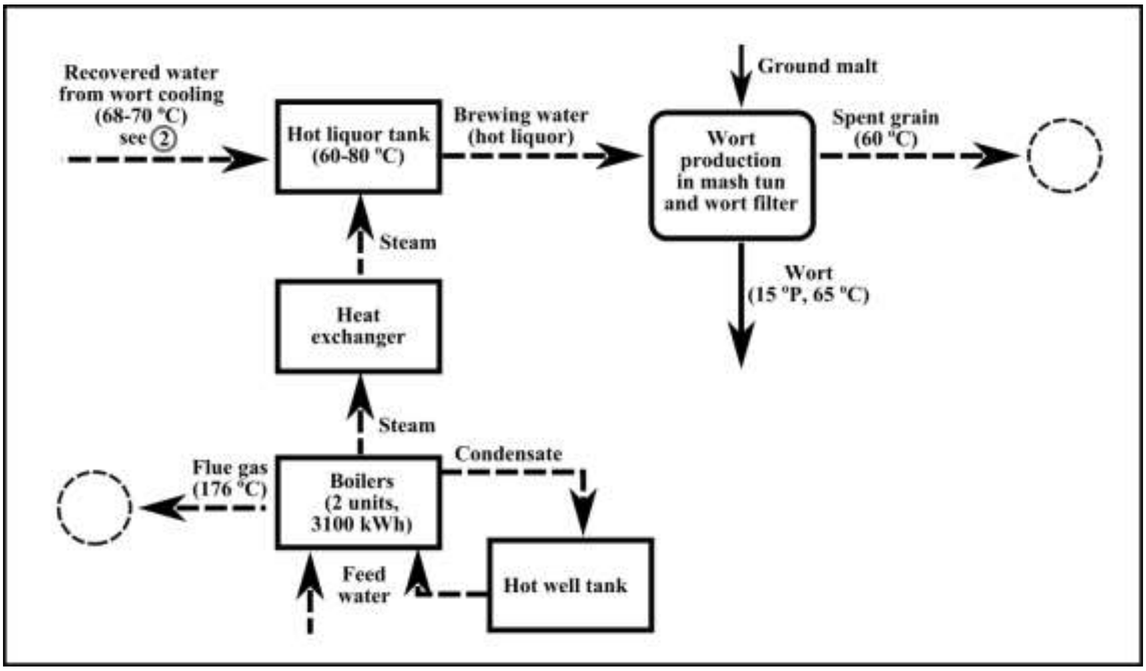
Figure 13: Main brewing processes.



wort production

Within the brewery, the first heating - cooling cycle happens in the production of wort. The ground malt from the mill is transferred into a "mash tun" and mixed with brewing water or "hot liquor" at temperatures between 60 - 80°C, as shown in Figure 14.

Figure 14: Energy flows in wort production.



Heated process water, a by-product from cooling the wort before fermentation (see later section "Fermentation & conditioning") is recovered at about 68-70°C and reused here in the hot liquor tank. A set of 2 gas combusting boilers generate steam, at a nominal pressure of 6 bars corresponding to 159°C, and in combination with a plate and frame heat exchanger maintain the hot Liquor tank at 60 - 80°C for use in the mash tun. 17.8 – 18.6 m^3 of hot water is required for 4 tonnes of malted grain.

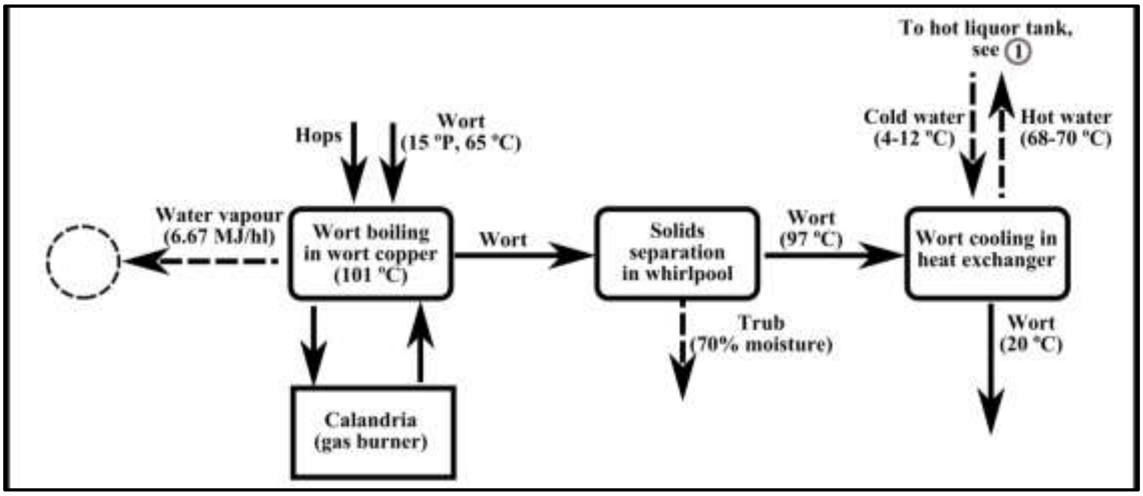
The condensate from the steam is collected and transferred to a hot well tank where it is reused to produce steam by the boilers. Flue gas (exhaust gas from the boilers) at a temperature range between 140-212°C is currently discharged to the environment. An economizer could used here to divert the boiler exhaust gas to preheat the feed water to the boiler. Sturm (Sturm et al., 2013) indicates that this could improve efficiency of the boiler by up to 5% and reduce the need for natural gas by up to 160 kWh/brew of 265hl. Other improvements can be obtained through better insulation of the hot liquor tank, which is currently worn-out, and poor sealing of the tank which allows water vapor to escape. Current heat loss from the hot liquor tank is estimated at 500 kWh/day.

In the mash tun, the mixture or "*mash*" is stirred and heated then left to stand for 60 minutes where an average temperature of 65°C is maintained. During this process sugars are extracted from the grains and dissolved in the water to produce wort. The wort is separated from the spent grains by draining the mixture through a wort filter; this drained wort is re-circulated through the filter grains. Then water at 73°C is trickled through the grains to extract any remaining sugars. Once the wort is clear, it is pumped into the Wort Copper for boiling. The spent grains are sold as animal fodder to local farms but present an opportunity for energy recovery, with an average moisture content of 75 - 82% and temperature of 60°C.

wort boiling & preparation

Wort boiling is the most energy intensive process in beer production. In the wort copper (a kettle), see Figure 15, the wort is heated to boiling temperature (101°C) by circulating it through an external gas burning heater called a "Calandria", a tall, thin cylinder with vertical tubes. Assuming that wort has the same specific heat capacity as water, heating of the wort from 65 to 101°C requires 2872 MJ. Pre-heating lasts approximately 2 hours (Hugenschmidt, 2011) so this corresponds to a thermal power requirement of 399 kW.

Figure 15: Energy flows in wort preparation.



During boiling, a volume of liquid, approximately 4% of total wort, is lost through evaporation. During this process hops are added to affect flavor; "*Several factors such as length, intensity, temperature and pressure of wort boiling are of great importance for the taste and quality of the beer*" (Sturm et al., 2013).

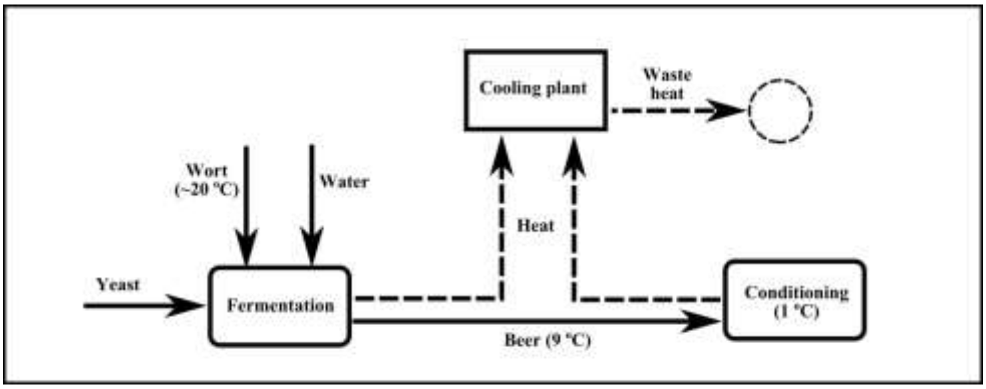
There is potential for energy saving because the wort copper is open to the atmosphere and approximately 784 kg water vapor containing 177 MJ latent heat is released to the atmosphere without recovery. This represents approximately 6.67 MJ/hl and provides one of the biggest potentials for energy saving in the brewery. Sturm (Sturm et al., 2013) recommends using heat exchangers or a thermal store to capture heat from vapor to pre-heat the wort before entering the copper and to use the remaining heat to supplement the hot liquor tanks.

The resulting bitter-tasting wort is separated from trub (coagulated proteins and other suspended particles) in the "whirlpool". The liquid wort, still at a temperature of around 97°C is then cooled to the fermentation temperature of around 20°C, which is the required temperature for the type of beer produced, by pumping it through a heat exchanger. Cold water comes into the heat exchanger at 8 – 12°C in summer and 4 – 8°C in winter. The resulting heated water 68 – 70°C is pumped into the hot liquor tank. The remaining trub with an estimated moisture content of 70% is discarded leaving potential for water recovery.

fermentation & conditioning

As illustrated in Figure 16, when wort is at the required temperature for fermentation, yeast is added (“pitching”) and because wort boiling increases gravity, it is diluted with process water at the beginning of fermentation to an original gravity of around 9°P.

Figure 16: Energy flows in fermentation and conditioning.



During the fermentation process brewing yeast metabolizes the usable sugars of the wort into alcohol, carbon dioxide and new yeast mass. This process must be closely controlled as it is crucial to the taste and quality of the beer produced. Fermentation is an exothermic reaction which releases heat that must be monitored and removed to maintain fermentation temperature.

At the end of the fermentation process, the temperature of the beer is reduced to 9°C in order to stop further fermentation. The beer is then cooled further in a conditioning tank (to 1°C) and kept cool for a maturing period varying between several days and a few weeks depending on the brew type. The demand for cooling the beer after fermentation requires refrigeration at 35 – 40% of capacity.

The cooling plant consists of two screw compressors equipped with slide valves enabling a step-less control of the refrigeration capacity. Each compressor has a refrigeration capacity of 238 kW absorbing 77 kW of electrical power when operating at 100%. At base load the cooling plant refrigerator runs in the range of 15 – 25% of capacity. Constant refrigeration is required for maintaining the temperature during the fermentation and conditioning period. Waste heat is available from the compressors for recapture and may be used for space heating.

5.3.4. Summary

The case study presented here draws on the work by Hugenschmidt (Hugenschmidt, 2011) and Sturm (Sturm et al., 2013) which identified opportunities for reducing water and energy demand in a typical medium sized brewery in the UK. The work acknowledges that large breweries have typically adopted available practices for energy efficiency but a number of barriers to adoption are present in small and medium sized breweries such as the security of income required for long-term investments and the business importance of authenticity of traditional processes.

Analysis of the brewery presented here shows that its energy use is consistent with current trends in usage figures of similar sized breweries. The main recommendations are (Sturm et al., 2013):

- improvement of insulation of the hot liquor tanks;
- heat recovery from the vapor produced in wort boiling – currently this happens in an open kettle and although evaporation rates are comparatively small, vapor is unnecessarily lost to the environment; and
- heat recovery from boiler flue gases.

The site currently recovers water from wort cooling and utilizes the heat in the hot liquor tank and, since the study, the brewery has achieved improved efficiency through a retrofit of the brew house although the main driver for this has been to expand production capacity rather than to improve energy or water consumption. The open copper boiler will not be replaced as this traditional technology is seen as key to the flavor of the beer.

5.3.5. Industry forecast

There is a variance between efficiency improvements expected from large and smaller breweries. Most large breweries employ best practices including use of efficient boiler technologies and other methods to reduce evaporation and water consumption. Smaller breweries face barriers to implementing new technology due to factors like availability of capital, risks associated investments with long payback periods and the need to maintain traditional methods of brewing. Improvements may be achieved through supporting processes like packaging, storing and recycling.

Reducing water use and evaporation are closely linked to energy demand and many brewers associations around the world have aims to reduce water consumption and CO_2 emissions. For example (WBA, 2011), as part of an agreement on energy efficiency in the Netherlands brewers, including small brewers, aim to reduce energy use by 30% by 2020. In 2010, the UK brewing industry committed to a number of targets for 2020 including:

- the use of less than four hectoliters of water for each hectoliter of beer produced,
- reduction of carbon emissions by 67% by 2020 compared to 1990
- increased use of renewable energy within the sector;

The report on initiatives by the brewing sector by the Worldwide Brewing Alliance presents initiatives from a number of breweries around the world and the technologies put in place to reduce water use, energy use and emissions (WBA, 2011).

5.4. Case study 4: integrated paper board mill

5.4.1. Industry Overview

The paper and pulp industry is the fourth most energy intensive sector in the world accounting for 3.4% of global industrial sector delivered energy consumption (Chen et al., 2012a; EIA, 2013). Notably, this sector is also a large generator of energy and the industrial trend is to implement gas-powered and biomass Combined Heat and Power (CHP) plants to generate power (CPI, 2013). Paper mills typically generate approximately half of the total energy required and many are able to generate more electricity than they need, exporting power to the grid (UNIDO, 2010; EIA, 2013). Many plants recycle waste heat for power and steam generation. Biomass from wood waste or a fuel rich by-product of paper pulping known as “black liquor” in chemical pulp mills are also widely used to produce energy.

Product recycling is also common in the industry reducing the energy intensity of production - the specific energy consumption (SEC) of waste-paper pulp is approximately three times less than that of wood pulp and so the reported SEC of paper mills is low in industrialized countries because of the higher percentage of waste-paper pulp used (Utlu, 2013).

Consistent accounting of energy demand is challenging due to the high level of energy integration (UNIDO, 2010) but published figures indicate that production-processes, most significantly pulping, contribute to approximately 50% of the operational costs and that thermal energy requirement may be between 5-17 GJ depending on the grade of the paper produced and the technology used (Utlu, 2013).

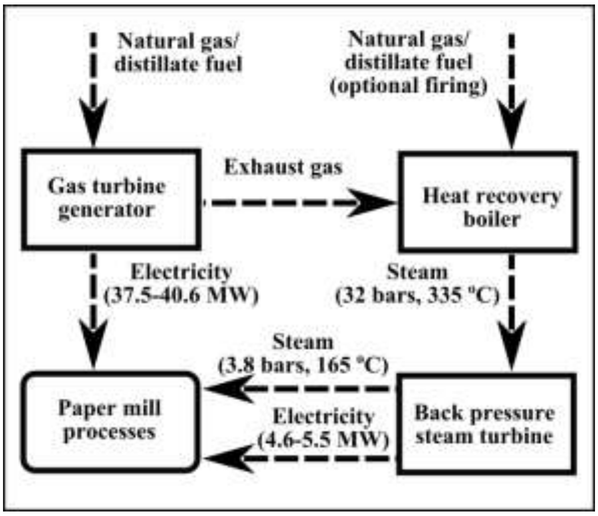
5.4.2. Organization Profile

The organization presented here is an integrated pulp and paper board mill located in the United Kingdom. The mill imports 350000 tonnes of virgin timber per year, which is delivered to site, and produces approximately 300000 tonnes of folding carton-board per year.

Approximately 70% of all the electrical energy is used in the pulp mill and stock preparation areas. The remaining requirement is for the wood yard in debarking and chipping the logs, for machine drives, vacuum pumps, air compressors, fans and site lighting, with a small amount used in the finishing department for conversion of the board into sheet or reel form. The main consumer of steam on the site is the drying section of the board machine, using approximately 70% of the total steam energy. 15% of the steam energy required is used in the pulp mill, mainly for preheating of the equipment, but this is an intermittent use. The remainder is used in space heating, preheating the air entering the drying process and prevention of condensation in the high humidity areas of the mill building.

The plant on current loads needs to import very little power from the grid supply and the net export from the site is 6.43%. However, the volume of production is increasing and a new refiner system to meet new loads is planned which will increase energy requirements. The mill incorporates an on-site dedicated gas-fired Combined Heat and Power (CHP) plant and generates all of its electricity and steam requirements. The CHP plant consists of a gas turbine generator, a heat recovery boiler and a back pressure steam turbine as shown in Figure 17.

Figure 17: CHP plant.



gas turbine generator

The plant uses natural gas, and if necessary, distillate fuel from an interruptible supply to fire a gas turbine generator. The generator has a maximum rated capacity of 42 MW but output varies depending on the value of the ambient air temperature. Any excess electricity which is not required by the mill is exported to the grid. The exhaust gas is routed to the heat recovery boiler to generate steam.

heat recovery boiler

The heat recovery boiler is capable of generating 58 tonnes of steam per year at 32 bars and 335°C and can be supplementary fired either by gas or distillate to increase the output up to a load of 100 tonnes/year which is the steam load required for drying. Independently, the maximum steam capacity of the boiler is 105 tonnes/year without the use of exhaust gases from the gas turbine – this capacity is required to ensure the supply of total steam requirements in periods of gas turbine generator maintenance. The organization maintains two backup boilers as part of the CHP plant in case of failure or maintenance requirements in the heat recovery boiler.

back pressure steam turbine

The steam generated is at a relatively high pressure (32 bars) and is passed through a back pressure steam turbine to reduce its pressure for use in the paper making process. Steam is required at two different pressures. The low pressure (LP) steam of 3.8 barg and 165ºC is used in all areas and for most processes, mainly for the drying process. The medium pressure (MP) steam of 10.3 barg and 200ºC is used in thermo-compressors to help recover the flash steam generated by the condensate system. The other area where the MP steam is used is in providing an intermediate pressure steam at 5 barg for use on the after dryers of the board machine. The split in usage is 12.5% MP, and 87.5% LP. The turbine additionally generates electricity which supplements that being produced by the gas turbine. The steam turbine has a rated capacity of 8 MW but the output varies between 4.6 MW and 5.5 MW, depending on the steam mass required to meet process requirements.

5.4.3. Processes

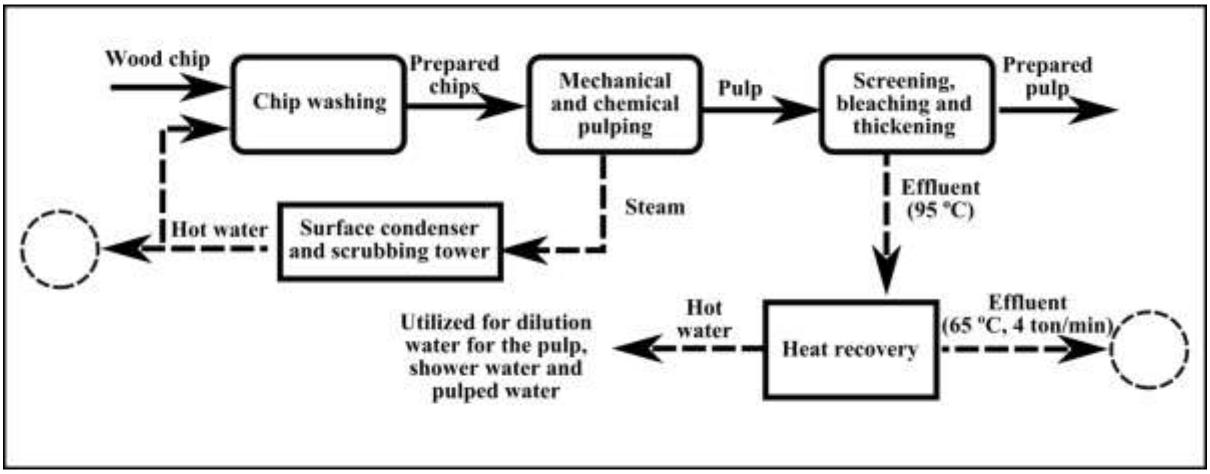
Timber is delivered to the wood yard, where the bark is removed from the timber by debarking machines and sold to external companies. Many pulp mills use this wood bark as biomass for power generation and the mill described here considers the possibility of a similar use for the bark. Preliminary analysis showed that current volumes of bark would not be sufficient for purpose but showed that required volumes could be generated if the bark was supplemented with trimmings that are normally left in the forest and unused bark from other plants belonging to the organization.

The debarked timber is then turned to wood chip in preparation for the production process. Then there are two main stages in the production of paper board; the stock preparation stage in the pulp mill and the paper making stage in the board machine where the stock is dried and turned into paper board. In the stock preparation stage the woodchip is put through various types of pulping to produce a liquid “stock “. The stock is a suspension of fibers and other additives in water in the right condition and composition in order to produce a sheet of paper on the paper making machine. The next sections describe these processes.

pulp mill

The pulp mill has high energy requirements and generates large volumes of heat with potential for recovery. The following sections describe the energy usage and recovery procedures used within the different processes. An overview of the pulp mill processes is illustrated in Figure 18.

Figure 18: Overview of pulp mill processes.



chip washing and pulping: Pulpers have very high energy requirements; at this site, there is one large 18MW pulper and 7 lower-powered pulpers, the load at full production at the site is around 36MW. Most of this energy is released as steam (1 tonne of steam can be generated by each MW of pulper power). This steam contains wood fiber and other impurities which prevents it from being directly used for heating in other processes. Currently the steam is put through a surface condenser to produce hot water for the pulping preparation process (chip washing). Steam from the lower powered pulpers is at atmospheric pressure and requires a large fan to collect it; this produces hot water using a scrubbing tower. Current scale of operations do not warrant further investment in heat recovery equipment, however the potential for future investment is considered which would include a large refiner to replace the 4 MW units and a re-boiler which will provide 38 tonnes of clean steam which could be used directly in other processes on site for heating purposes.

screening bleaching & thickening: After the pulping process, the pulp goes through a screening and bleaching process. This and the thickening of the pulp using screw presses produces very hot effluent (95°C) consisting of water laden with short fibers, china clay and pigment. The mill recovers some of this heat to heat dilution water for pulping and for other processes. The fiber content of the effluent limits the type of heat exchangers that can be used; currently wide gap plate and spiral exchangers are used. An experimental plant was built that utilized fluidized glass balls circulation with the water, but this has now been decommissioned. Even after current heat recovery the effluent leaves the paper mill at a rate of 4 tonnes/min at 65°C, presenting large potential for waste heat recovery. It is then kept in settlement in the effluent treatment plant before being discharged as:

- water to the sea, at temperature in excess of 35°C, a potential for low grade heat recovery; and
- solid wastes, sold to animal hygiene companies (potential biomass source).

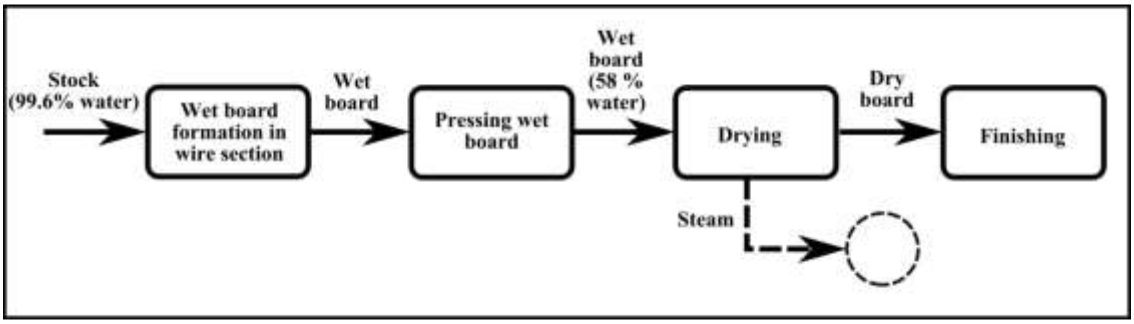
A common utilization for surplus heat from production plants is domestic heating and the mill has investigated this possibility. The initial barrier was that the mill is isolated from population centers requiring transport of the heat. The surplus heat has been offered to new housing developments planned in closer proximity, but this has not generated interest from developers. The investigations indicated that this may be because it is outside the experience of the housing developers to incorporate district heating into their plans.

The organization plans to utilize this heat to preheat the incoming air to the building. However the plans have been costed and even though the scheme has a very good payback it has still not been initiated. As with many organizations, the company mind set is that production improvements have first priority on capital investments. The case is not helped by the fact that the mill operations are not divided into profit centers; therefore energy cost reductions do not benefit the department making them. Operations at this site are very complex and the consequences of changes to the process are sometimes not fully analyzed and communicated internally.

paper making

The overview of the papermaking process applied in this plant is shown in Figure 19. Paper stock from the pulp mill is typically 0.4% fiber and 99.6% water. This is dried in various stages and turned into paper board in widths of 5.5 metres in the board machine. The production speed is 315 metres/min and 28.5 tonnes per hour.

Figure 19: Overview of paper making processes.



wire & press section: The stock containing mostly water is passed through a wire mesh forming a "paper web". Several layers are needed to produce the wet paper board which is then pressed between vacuum rolls to remove more of the moisture content. A 1% reduction in the moisture content of the board leaving this section results in a 4% reduction in drying steam requirement later. Moisture content of the board leaving this section is ~58%.

drying: The board is then dried further to a moisture content of approximately 6% by passing it over several steam heated rolls or drying cylinders. There are 77 steam-heated rolls at this mill and the temperature of the condensate varies from 165°C to 98°C depending on the stage of drying. The flash steam and condensate is collected and reused in the lower pressure cylinders; passing the condensate into lower and lower pressure parts of the system allows maximizing the heat recovery from the steam.

finishing: Several finishing processes exist depending on the type of paper being produced. At this board mill, the board is coated back and front by a printable liquid medium and dried using gas fired infrared radiators. It is then wound onto 300 mm diameter metal drums to form reels 2.7 m in diameter. The power requirements mainly lie in the production of vacuum and the main energy usage is for the steam drying the products. Current steam drying systems are efficient and most of the heat from the steam is used without the need for condensers.

5.4.4. Summary

Paper production requires a large amount of energy especially for pulping and subsequent drying. However, the industry is also a large producer of energy with many plants approaching self sufficiency due to the availability of usable by-products like forest logging residues, bark and black liquor which are biomass resources. This case study has presented a large paper board producing mill which has an on site CHP plant for electricity and steam generation which uses natural gas and distillate fuel. There are plans to use the wood bark currently sold, as biomass for power generation to meet future growth demands. Further enhancements in efficiency are planned alongside expected growth in operations mainly investment in further heat recovery equipment to capture more of the steam for use in the power generation.

5.4.5. Industry forecast

Demand for paper is expected to grow mainly in non-OECD countries while there is some evidence that demand may be stabilizing in some parts of the world (EIA, 2013). Despite this trend, the US Energy Information Administration forecasts that the share of global industrial sector delivered energy consumption accounted for by paper and pulp production will remain the same through to 2040 (EIA, 2013). Even though paper production has large energy requirements, the trend is for paper mills to employ heat recovery technology and the use of biofuels which are generated by the production processes to generate power to meet requirements of production. The use of recovered paper is also a contributing factor to the reduction in energy demand. Current trends indicate that the collection of recovered paper (or 'paper for recycling') in the UK will meet the paper recycling target of 70% by 2015 (CPI, 2013).

The Sector 2050 Roadmap by the CPI (CPI, 2013) highlight that the paper making sector incorporates currently available efficiency measures and that in order to move beyond limits set by existing technology, new "breakthrough" technologies are needed. Research studies suggest that improving energy distribution and equipment efficiency may provide the greatest energy saving potential (Utlu, 2013) in the paper and pulp industry.

6. BARRIERS TO ADOPTION OF EFFICIENCY ENHANCEMENTS

For most industrial sectors, information about industry benchmarks and best practice is available from government initiatives (EC, 2009b) and industry representative organizations e.g. worldsteel. Recent developments in research and availability of economically viable solutions provide opportunities for deploying state-of-the-art technologies. Even though there has been progress due to these efforts, there is still a "significant potential" for further deployment of available technology and processes optimizations (IEA, 2013).

The European Commission 's Best Available Techniques (BAT) document (EC, 2009b) notes that implementation of BAT usually makes economic sense and is generally adopted in new or significantly upgraded plants or processes. However, within an existing installation, there are challenges of economic and technical viability due to the pre-existing infrastructure and local circumstances.

Research into application of new techniques in industry have uncovered several types of barriers and much research on understanding barriers has been conducted within specific contexts (Trianni et al., 2013; Sturm et al., 2013; Benhelal et al., 2013). A study of small and medium sized breweries (Sturm et al., 2013), one of which is the basis of case study 3 earlier, identifies the following barriers:

- Smaller breweries tend to supply specialist beer at higher prices and the pressure to reduce costs through minimizing energy use is low.
- Old brewery sites that have grown through improvised extensions often have fragmented sites making implementation of some technology practically difficult.
- Replacing inefficient but functioning equipment will disrupt operations.
- Smaller organizations in general view long-term investments as risky.
- The traditional methods of production are part of the marketing strategy and cannot be changed.

Another survey of small breweries in Canada identified a number of general reasons for the non-adoption of energy saving technologies. These include issues like: energy issues not seen as a priority; man power & time constraints; no defined accountability for energy efficiency; and lack of awareness of opportunities (NRC, 2011).

Studies in different sectors have highlighted the importance of education, the problem of limited technical knowledge and lack of awareness of potential technologies (Madlool et al., 2011; Schneider et al., 2011). Studies of particular technologies also highlight knowledge-based barriers for example a study on heat pumps suggest that despite being a mature and effective technology they are not as widely applied as expected due to problems like difficulty of systems design and integration and the lack of provision of large-scale heat pumps by major vendors (Chua et al., 2010). Case study 4 shows such a knowledge-barrier where excess heat generated by the paper mill presented may be used for residential heating in a neighboring housing development.

Chai and Yeo 2012 extract the following key barriers to energy efficiency from a survey of the relevant literature:

- Fear of technical risk / cost of production loss;
- perceived high cost of energy investment;
- other capital investments are more important;
- uncertainty about future energy prices;
- lack of experience in technology;
- lack of information in energy efficiency and savings technology;
- lack of trained manpower;
- lack of energy metering;
- lack of access to capital;
- lack of government incentives;
- weak policies and legislations;
- resistance to change; and
- legacy system.

Barriers are varied in nature reflecting the varied nature of the industrial sector with factors like size of the organization, type of industry, the existing technology, customer base all affecting adoption of technology. Research has taken a generic approach resulting in models and taxonomies for analyzing and resolving barriers (Cagno et al., 2013; Sorrell, 2011; Fleiter et al., 2012; Chai and Yeo, 2012). The term "barrier" to energy efficiency is defined as "*a postulated mechanism that inhibits a decision or behavior that appears to be both energy efficient and economically efficient*" (Sorrell, 2004). Studies that use this definition e.g. (Fleiter et al., 2011) do not include issues like the absence of government support since the a barrier is a hindrance to the economical acceptance of a technology.

A major study (Sorrell, 2011) based on the earlier work by Sorrell (Sorrell, 2004) and a review of 160 post-2000 studies on energy efficiency proposes a taxonomy for the types of barriers is shown in Table 2.

Table 2: A taxonomy of barriers to energy efficiency (Sorrell, 2011).

Barrier	**Claim**
Risk	The short paybacks required for energy efficiency investments may represent a rational response to risk. This could be because energy efficiency investments represent a higher technical or financial risk than other types of investment, or that business and market uncertainty encourages short time horizons.
Imperfect information	Lack of information on energy efficiency opportunities may lead to cost-effective opportunities being missed. In some cases, imperfect information may lead to inefficient products driving efficient products out of the market.
Hidden cost	Engineering-economic analyses may fail to account for either the reduction in utility associated with energy efficient technologies, or the additional costs associated with them. As a consequence, the studies may overestimate energy efficiency potential. Examples of hidden costs include overhead costs for management, disruptions to production, staff replacement and training, and the costs associated with gathering, analysing and applying information.
Access to capital	If an organization has insufficient capital through internal funds, and has difficulty raising additional funds through borrowing or share issues, energy efficient investments may be prevented from going ahead. Investment could also be inhibited by internal capital budgeting procedures, investment appraisal rules and the short-term incentives of energy management staff.
Split incentives	Energy efficiency opportunities are likely to be foregone if actors cannot appropriate the benefits of the investment. For example, if individual departments within an organization are not accountable for their energy use they will have no incentive to improve energy efficiency.
Bounded rationality	Owing to constraints on time, attention, and the ability to process information, individuals do not make decisions in the manner assumed in economic models. As a consequence, they may neglect opportunities for improving energy efficiency, even when given good information and appropriate incentives.

Each barrier represents a potential answer to one or more of the following questions (Sorrell, 2011):

- Why do organizations impose very stringent investment criteria for projects to improve energy efficiency?
- Why do organizations neglect projects that appear to meet these criteria?
- Why do organizations neglect energy efficient and apparently cost-effective alternatives when making broader investment, operational, maintenance and purchasing decisions?

A thorough understanding of the barriers to adoption is necessary for energy efficiency policies to be effective but their incorporation into policy models is complex and a recent review of bottom-up models found that currently only a few of the observed barriers are explicitly considered (Fleiter et al., 2012). Chai and Yeo (Chai and Yeo, 2012) categorize barriers based on the four stages in the adoption and implementation of energy efficient practices: Motivation, Capability, Implementation and Results. They argue that "*the overall effectiveness of energy efficiency policies is only as strong as the weakest link in the four stage framework*".

In addition to using taxonomy and considering barriers in the stage at which they occur, a number of other critical factors are also highlighted for consideration when incorporating them into a policy model. These include differentiating between real and perceived barriers, recognizing the interactions and causal relationships between barriers and the effect of barriers on decision making (Cagno et al., 2013; Chai and Yeo, 2012; Fleiter et al., 2011). These highlighted factors indicate that the elements between which a gap exists include policy instruments as well research outcomes and industrial implementations.

7. Conclusion

Improving energy efficiency is seen as an important activity by governments, industry representative organizations, individual businesses and consumers. Much research, industrial analysis and policy implementations have been directed towards this endeavor resulting in large improvements in most sectors. However despite the large efficiency improvements, demand for energy has increased due to the industrialization of developing countries. Most energy for industrial processes is still produced by burning fossil fuels and reduction in energy consumption and improved efficiency remains a challenge. This chapter focusses on measures to improve the use of thermal energy which is closely linked to emissions and electrical energy use.

Many studies indicate that there is still significant potential for improving industrial use of thermal energy and that a gap exists between available technology and its use. This chapter presents published research results from practical implementations of mature energy efficiency measures in four key aspects, each of which are necessary for closing the gap between availability and use of energy efficient technology and methods:

- Energy efficiency measurement techniques should be tailored to a practical context based on the element being measured, the environment, affecting factors and the purpose of the measurement. A number of different indicators are suggested in literature for use in various contexts and further challenges are identified.
- Latest technological developments reported by researchers are presented in relation to boiler, heat pumps and heat exchangers. Efficiencies are achieved in improved design of technology and by recovering heat lost from processes.
- Four case studies in which details of energy use and recovery, and plans for any future enhancements are presented. Case studies are an important tool in analysis and discussion for future work.

- Despite the availability of reliable and cost effective technology, which in many cases provides financial benefits, a number of barriers inhibit their adoption. Current state of research in solving this problem is based on understanding barriers and studying methods of incorporating them into policy systems.

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Figure captions

Figure 1: Shares of total world industrial sector delivered energy consumption by major energy-intensive industries, 2010, as a percent of total (EIA, 2013).

Figure 2: Energy use for heat and estimated recovery potentials by sector.

Figure 3: Key to figures.

Figure 4: Average energy consumption per tonne of crude steel produced for North America, EU 15 and Japan (Worldsteel, 2008).

Figure 5: Steel production in major producing countries, adapted from (EIA 2013).

Figure 6: Steel production routes and energy intensity per route (Worldsteel, 2008).

Figure 7: Overview processes in steel mill.