Journal of Cleaner Production 135 (2016) 1327–1339

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Potential reduction of carbon emissions by performance improvement: A cement industry case study

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ARTICLE INFO

Article history:
Received 29 January 2016
Received in revised form
27 May 2016
Accepted 25 June 2016
Available online 27 June 2016

Keywords:
Cement
Performance improvement
CO_2 emissions
Fuel efficiency
Energy efficiency
Green manufacturing

ABSTRACT

The cement industry is generally considered responsible for upwards of 5% of anthropogenic greenhouse gas emissions. This is a result of the high energy intensity of the process, significant CO_2 release from the raw materials used, and large global consumption. It is also a high growth sector as emerging economies develop their infrastructure. This paper outlines an investigation into day-to-day performance variation that, if scaled to the global level, represents a potential for improvement of up to 100 Mt CO_2 equivalent per year. Optimising this operational variation is not included in current roadmaps for reduction of cement industry CO_2 emissions, and has the potential to be cost neutral, or even save money for cement producing companies. The paper analyses a case study of a plant in the UK, operating a pre-calciner type kiln commissioned in 1986. Production data was analysed to examine the day-to-day variation in the fuel-derived CO_2 emissions, in order to estimate the potential for operational improvement. Various factors were then analysed to determine what drives this potential improvement, including fuel mix, rate of production, and process airflow. The day-to-day performance of the plant, as measured by the fuel-derived CO_2 emissions per tonne of clinker produced, varied significantly. (Clinker is the material ground and mixed with ~3% gypsum to produce cement). Improvement of the plant to 10th percentile best observed performance levels would represent a 10% drop in CO_2 emissions and a 7% drop in energy consumption, with associated cost savings. Two mathematical models were used, first to examine the energy balance of the plant and then to predict CO_2 emissions from given input conditions. The largest source of energy consumption was the dissociation energy required to form clinker, however, the variation in this was small. Airflow and fuel type were found to dominate the variation of performance. Optimising the factors affecting performance was predicted to reduce energy consumption by 8.5% and CO_2 emissions by 19.5%. The paper concludes that there exists significant opportunity to reduce the emissions from cement plants by operational means, and that fuel mix and excess air ratio should be the focus of future research.

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1. Introduction

The cement industry is one of the leading sources of anthropogenic climate change emissions. While it is often difficult to establish precisely how much greenhouse gas comes from individual sources, and how that compares to an equally uncertain total, estimates in the literature agree that the cement industry emits around 5% of man-made greenhouse gases (Allwood and Cullen, 2011; OECD and IEA, 2009). This would make the cement industry one of the top five individual sources of greenhouse gases, and the second largest industrial source after the steel industry (Allwood and Cullen, 2011) (Ali et al., 2011) estimate that cement consumes 12–15% of total industrial energy use.

Due to the explosion of growth in the developing world, as these nations industrialise and build concrete infrastructure, emissions from the sector are projected to grow (under a business as usual scenario) by 111% between 2005 and 2030 (Nauclér and Enkvist, 2009).

Carbon dioxide emissions from the cement making process come from four main sources. The largest source of carbon dioxide emissions is the material-derived CO_2 driven off when the limestone is heated and decarbonised to form lime. The next largest

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http://dx.doi.org/10.1016/j.jclepro.2016.06.155
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source of CO_2 emissions is the fuel used to provide the heat energy required for this chemical process. The primary fuel used is coal, although many other alternative fuels are used, such as shredded municipal waste, industrial waste, and some biomass. Material-derived CO_2 accounts for 50% of emissions, fuel-derived emissions for 40%, and electricity use and transport each contribute 5% (Gartner, 2004).

1.1. Current trends in cement CO_2 emissions reduction

A number of studies have been done on the overall environmental impact of cement, including using Life Cycle Analysis techniques. Huntzinger and Eatmon (2009) considered the global warming impact to be the 'primary interest,' and Josa et al. (2007) that the greenhouse effect was the only global impact of cement production. Chen et al. (2010) also listed global warming impact as one of the main impacts of cement production, along with acidification, marine ecotoxicity and abiotic depletion. Both Chen and Josa note that the global warming impact is principally dependent on the clinker content of the cement, as it is the production of clinker that leads most of the CO_2 emissions, from the decarbonised limestone and the emissions from fuel.

Accordingly, there has been considerable focus on reducing the energy intensity of and carbon emissions from the cement industry. Much of this literature focuses on the types of technology in use, and how they compare to the best available technology (BAT).

In 2004, the US Department of Energy commissioned an overview of energy use, loss (i.e. wastage) and opportunities in a wide range of industries. Because the cement industry ranks only 13th in energy use among US industries (Energetics Inc. and E3M Inc., 2004) the study did not include an explicit study of energy use and loss in the cement industry. Instead the report used the data from calcining processes across several industries to estimate the opportunity available. The study estimated an 11% potential for improvement on the performance of the newest kilns in use. This potential came from the use of alternative energy sources, improved controls, combined heat and power systems, reduction of electrical energy used for milling, and future improvements in operational practice. For older technologies, such as wet process kilns or long kilns, the potential for improvement was estimated at 50% and 35% respectively (Ibid).

The OECD/IEA 2009 roadmap document details possible strategies for reducing the emissions of CO_2 from the cement industry from the business-as-usual scenario emissions of 2.34 Gt of CO_2e by 2050 to a target of 1.56 Gt of CO_2e in 2050. 10% of the savings required are proposed to come from energy efficiency improvements, such as replacing old plants with new more efficient technology, and a retrofit of energy efficient equipment onto existing plants.

One challenge is to estimate the maximum reduction in carbon dioxide emissions that can be achieved by reducing energy consumption. In order to make this estimate, a minimum energy consumption of clinker production is required.

Table 1 compares the energy consumption of technologies currently in use with targets, best practice values and theoretical minima from literature. Large gaps exist between different technologies, between average and best practice consumption, and between best practice and the theoretical minimum. This shows the extent of the opportunity available to reduce energy consumption through upgrading old technology, improving operational practices and developing new technologies beyond the current state of the art.

The theoretical minimum proposed by Gartner (2010) (see Table 1) only considers the heat required to drive the chemical changes needed to make clinker. No account is taken of entropic or other losses associated with the plant required to deliver the heat energy to the raw materials. The large range proposed by Schneider & Hoenig is due to the range of energy requirements from mineralogical variations and the need for drying of raw materials.

The Cement Sustainability Initiative report (2009) gives current average gross CO_2 emissions (defined as all CO_2 emissions excluding biofuel) at an average of 866 kg of CO_2 per tonne of clinker. Of these emissions, 540 kg of CO_2 are process emissions resulting from the decomposition of calcium carbonate (Ibid).

1.2. Technological improvement

1.2.1. Opportunities for technological improvement

There have been numerous studies on how improvements in the technology being used in the cement industry could lead to reductions in energy consumption and carbon emissions. Notable among these is Madlool et al. (2011), which lists estimates of savings from a number of technologies. The magnitude of the savings varies on the type of technology, and ranges from 0.1 GJ/tonne to 1.4 GJ/tonne. For a plant operating at the global average efficiency this range of savings represents roughly between 2% and 40% of energy consumption. The paper also estimates the capital cost of installing these technologies, given as per tonne of cement values, although of course this must include some assumptions about payback period and the scale of production at the plant. The capital cost of the technologies listed ranges from $0.25 tonne to $41/tonne. By way of comparison, a tonne of cement at wholesale prices costs on the order of $100.

Other authors have investigated technological options for reduction of energy consumption or CO_2 emissions. Huntzinger and Eatmon (2009) compared the impact of recycling cement kiln dust versus using it to sequester carbon. The paper concluded that cement kiln dust is better used to sequester carbon, as it can absorb up to 0.4 tonnes of CO_2 per tonne of kiln dust, whereas recycling it has little environmental saving. However it is not clear to what extent the sequestering effect represents savings over and above what occurs when the dust is sent to landfill. Morrow et al. (2014) provides a cost benefit analysis on two technologies relevant to the cement industry, kiln shell lagging and improved process control. Based on data from the Indian cement industry the paper concludes that kiln shell lagging would save 0.26 GJ/t (~7%) and cost $0.33/t in capital costs, while improved process controls would save 0.15 GJ/t at a cost of $1.5/t. Engin and Ari (2005) also investigates kiln cladding, alongside technology to preheat raw materials and a waste heat recovery steam generator (WHRSG), based on data from a Turkish plant. Combining these three technologies would reduce energy consumption by 15.6%, with a payback period of less than 1.5 years. Khurana et al. (2002) investigated a plant in India, and also estimates a less than two-year payback period for a WHRSG, and estimates that the technology would improve primary energy efficiency by 10%.

1.2.2. Barriers to technological improvement

However, in contrast to the previous section there is some evidence in the literature to suggest that significant barriers exist for efficiency gains from improved technology. Moors et al. (2005) studied the base metals industry, and concluded that the cost of investment and the risk of committing capital to unproven technologies presented a significant barrier to radical innovation in that industry. Similarly Trianni et al. (2013), in a study of foundries, concluded that budget constraints and availability of capital presented barriers to energy efficiency. A further study on the cement industry in Europe (Pardo et al., 2011) concluded that the uptake of best available technology in Europe would lead to a 10% efficiency improvement, but the payback period would be between two and

Table 1
Comparison of energy consumptions of different kiln technologies, targets & theoretical values.

Consumption value	Energy consumption (GJ/tonne of clinker)	Source
Current Tech Avg: Long Wet Kiln	6.34 GJ/tonne	(Cement Sustainability Initiative, 2009)
Benchmarking Sample Average (Canadian plants only)	4.50 GJ/tonne	(Natural Resources Canada, 2009)
Current Tech Avg: Long Dry Kiln	4.49 GJ/tonne	(Cement Sustainability Initiative, 2009)
Current Tech Avg: Dry Kiln with Preheater	3.70 GJ/tonne	(Cement Sustainability Initiative, 2009)
Current Global Average	3.69 GJ/tonne	(Cement Sustainability Initiative, 2009)
Benchmarking Sample Best Practice: (Canadi	3.40 GJ/tonne	(Natural Resources Canada, 2009)
Current Tech Avg: Dry Kiln with Pre-Calciner	3.38 GJ/tonne	(Cement Sustainability Initiative, 2009)
OECD 2050 Target	3.31 GJ/tonne	(OECD and IEA, 2009)
Current Global Best Practice (OECD)	3.00 GJ/tonne	(OECD and IEA, 2009)
Current Tech Avg: 6 Stage Pre-heater/Pre-Calciner	2.90 GJ/tonne	(Gielen, 2007)
Current Global Best Practice (Lafarge)	2.80 GJ/tonne	(Gartner, 2010)
Theoretical Minimum Range (ECRA) Max:	2.80 GJ/tonne	(Schneider and Hoenig, 2009)
Theoretical Minimum Range (ECRA) Min:	1.85 GJ/tonne	
Theoretical Minimum (Zero Losses)	1.76 GJ/tonne	(Gartner, 2010)

three years. Moreover the study argued that carbon capture and storage and waste heat recovery were both a long way from being cost competitive, in contrast to some of the other literature. The study also outlined how economic conditions could further inhibit investment in more efficient technology. Low energy prices reduce the value of investment in more efficient technologies whereas high energy prices inflict a competitive disadvantage compared to imports from countries with cheaper energy, offsetting savings from the investment.

1.3. Opportunities for operational improvement

Operational improvements are those which can be achieved by altering the operating procedures at a plant, without the need for significant capital investment in new plants or equipment.

1.3.1. Benchmarking

Benchmarking is a method of estimating the opportunity for improvement. There are broadly two benchmarking approaches taken in the literature. The more common approach is to compare BAT to current averages, in order to estimate the scale of improvement possible from technological investment. Saygin et al. (2011) provides one good example of this, contrasting a worldwide average energy consumption of 3.9 GJ/t with a BAT value of 2.9 GJ/t Ke et al. (2013) in setting out a structure for benchmarking argues that it is "better to benchmark to the industry leaders to better understand how large difference in performance is as well as what causes the differences."

However, this approach does not distinguish between potential operational improvement and technological improvement. One way of separating these is to compare similar plants or installations, as a larger proportion of the difference in performance between these installations may be due to operational or other controllable factors. The CSI report (2009) concludes that the average variation in performance between similar installations is around 5%. This implies that there may be operational differences between these installations that could lead to low-cost improvements. Other literature indicates that this variation could be as high as 20% (Chen et al., 2010), implying correspondingly larger opportunities.

1.3.2. Difference between theoretical (or manufacturers') values & operating values

When comparing best available technology to current operational averages the underlying assumption in the literature appears to be that the best available technology will operate at its theoretical or manufacturers value. However this means that the reported potential gain from installing best available technology includes any potential operational improvement on the installed technology, possibly changing the cost/benefit analysis of the investment. Moreover switching to best available technology may still require operational improvement to reach or even approach the theoretical best value.

There is some evidence of a gap between theoretical values and operational values in the literature. The CSI report (2009) notes that the "working average" energy consumption of installations, as quoted in the report, are about 15% higher than values derived from commissioning tests run by equipment suppliers, such as those reported by the International Energy Agency (Gielen, 2007). While an installation will in practice run less efficiently than its commissioning test would imply, it seems reasonable to conclude that this gap could be partially closed in some cases.

Moreover there is some evidence that the best available technology does not perform to the expected standard when installed. Valderrama et al. (2012) examined a Spanish cement plant where a new kiln was installed and compared to the existing installation. The authors expected a 20% reduction in fuel consumption, however the new kiln only performed 14% better than the existing lines. No explanation was given for this discrepancy, save that "the design goal is expected to be achieved in the coming year."

1.3.3. Operational practices

There is not a great deal in the literature quantifying the potential for operational improvement in energy intensive industries in general, let alone cement plants in particular. It is this gap that this paper is intended to address. However there is acknowledgement in the literature that operational practice can affect energy efficiency. Liu et al. (1995) in a discussion of the energy efficiency of China's cement industry mentions that the skills and training of operators are important for energy efficiency, but does not discuss how or to what extent they can affect the performance of the plant.

In a paper on process monitoring and optimisation Klemeš et al. (2012) describes the prevention or minimisation of CO_2 emissions by process optimisation and better training and management as two of the "preferred option[s] of cleaner production." Moreover Trianni et al. (2013) describes how the low status of energy management may lead to lower priority of energy issues within organisations."

1.4. Mathematical modelling of cement kilns

This paper will be based on mathematical models developed to investigate cement kiln performance. One example of such modelling dates from nearly twenty years ago. Carvalho and Nogueiraf (1997) developed a modelling tool for the optimisation

of a cement kiln. However, this was focused principally on the abatement of NOx emissions. Gäbel (2001) developed a tool to predict the environmental impact, economic cost and product performance of a cement facility. In a follow-up paper (Gäbel et al., 2004) the researchers modelled eight scenarios in order to look for opportunities to reduce the overall environmental impact (using a life cycle analysis). In addition to a baseline scenario, these included two scenarios varying the raw meal (i.e. raw material) input, two varying the cement mix, and three varying the fuel mix. They concluded that their calculation of environmental impact depended principally on the CO_2 emissions, and that the environmental consequences of transport were much smaller than the impact of the fuel type or material input. They concluded that up to 80% reductions of harmful emissions (including CO_2) were possible. However, this depended heavily on the CO_2 intensity of the alternative fuels compared to fossil fuels. If the CO_2 intensity of the alternative fuels was lower, then the greatest opportunity to reduce emissions was by altering the fuel mix, followed by introducing recovered material, such as fly ash, slag, industrial sand or industrial gypsum, into the cement mix, and finally introducing similarly recovered material into the raw meal.

1.4.1. Heat balances

A number of studies have performed heat balances of cement plants, attempting to estimate the energy outflows and compare them to fuel inputs.

Engin and Ari (2005)performed a case study on and energy audit of a single plant. The model looked at the heat balance on steady state operations, and the calculations of input and output energy balanced to within 8%. Kolip and Savas (2010) compare both an energy and exergy analysis of a theoretical plant. Khurana et al. (2002)studied a working plant in India and performed a heat balance. This heat balance was considered to be in 'good agreement' despite a 15% discrepancy between the energy input and output. The model neglected radiation losses and energy embodied in bypass dust. Moreover, Farag (2012) performed an energy and exergy analysis of an Egyptian plant. All four studies were based on a modern dry process plant with a precalciner. Table 2 summarises the energy outputs as a % of energy input for each of the heat balances. The numbers from Farag (2012) have been normalised to % of input. Not all of the papers performed a complete balance, and some categories have been combined to allow for comparison (e.g. radiation and convection losses, where stated separately, have been combined to 'Shell Heat Losses').

There are some notable similarities between several of the models: Dissociation energy dominates the energy consumption, and most estimated it at around 1.75–1.85 GJ per tonne of clinker, giving 40–50% of the energy consumption, depending on the efficiency of the plant. The energy from hot clinker is consistently estimated as between 2 and 3%, and the stack exhaust is between 15 and 20%.

Farag (2012) is an outlier in terms of its relatively low stack and cooler exhaust energy and very high bypass output. It is possible that some of the energy defined as the bypass in this analysis may have been treated as stack exhaust; the authors also calculated that if the bypass were switched off the stack exhaust would increase and become 22% of the total consumption. The cooler losses also vary widely between different analyses.

Table 3 shows some of the parameters used for the major sources of loss in the studies. It includes the four studies in Table 2 as well as Kääntee et al. (2004), who performed a study on the effect of different fuel blends on energy consumption. It shows that while the clinker dissociation energy is broadly similar across different models, the parameters used to estimate stack flow energy vary quite widely.

One important point to note is that none of the models in the literature reviewed analyse the performance of the plants studied on a day to day basis, but instead use average figures. Given the wide range of performance between different models and variation in the parameters used, a day to day analysis might shed light on opportunity for performance improvement.

1.5. Summary and objectives of paper

In conclusion, the literature identifies a clear trend towards improved efficiency in cement production. This is being driven by a shift to cleaner technologies, which tend to require high capital investment. Some modelling of existing plants has been done, examine the average performance of individual plants. However, there exists a gap in the literature in quantifying what improvements may remain by changing industrial practice. The improvements available will vary depending on local conditions such as the individual characteristics of the plant that lead to performance variation, and deviation from the manufacturer's standard. We therefore conducted a detailed case study of a specific cement plant to shed more light on these issues.

This paper will attempt to address some of the key gaps in the literature. It will establish an 'achievable theoretical minimum' that includes irreversibilities due to combustion of fuel. It will also estimate the opportunity to improve efficiency purely through operational improvement. Finally, it will model the performance of the plant on a day-by-day basis in order to investigate the factors driving any variation in performance.

2. Methods

2.1. Research philosophy

Limited capital budgets and potentially long payback periods on investing energy-efficient technologies can slow the rate at which such technologies are introduced, so reduction in carbon emissions lags behind technological advances. Moreover, it can be argued that

Table 2
Comparison of energy balances in literature.

Paper:	Kolip and Savas (2010)	Engin and Ari (2005)	Farag (2012)	Khurana et al. (2002)
Dissociation energy	51.3%	48.7%	39%	49%
Stack exhaust	20.5%	19.2%	14.9%	18%
Cooler exhaust	11.7%	5.6%	2.9%	16%
Shell heat losses	10.2%	15.9%	11.4%	Not calculated
Water evaporation	3.2%	0.7%	3.0%	Not calculated
Bypass/dust	0.7%	0.3%	24.7%	Not calculated
Clinker discharge	2.6%	2.3%	2.8%	2%
Error/unaccounted	n/a	7.4%	1.1%	15%

Table 3
Key parameters from models in literature.

Paper:	Kolip and Savas (2010)	Engin and Ari (2005)	Farag (2012)	Khurana et al. (2002)	Kääntee et al. (2004)
Clinker dissociation energy (GJ/t)	1.76	1.80	1.73	1.85	–
Stack air flow ($kg_{air}/kg_{clinker}$)	2.03 (Calculated)	2.10	2.11	2.27	–
Stack temperature (°C)	348	315	270	280	–
Stack O_2%	1%	1.8%	5%	5%	2%
Excess air ratio	1.15	–	1.3	–	–

displacing cuts in emissions to the future can reduce their value. Carbon feedback effects drive a limited timescale for cuts to be made, as raising atmospheric carbon dioxide above critical levels will turn carbon sinks such as the oceans into carbon sources (Cox et al., 2000). Moreover, emissions released today will remain in the atmosphere for a century, whereas current climate targets focus on atmospheric carbon levels in 2050. Therefore a 5% reduction in a source of carbon emissions achieved today can be considered to be of similar value to a 10% reduction achieved in 2030. Hence, the speed which with reductions can be made should be considered alongside their magnitude.

Accordingly, this research aims first to establish the size of potential reductions in carbon emissions available from operational improvement. These solutions can be implemented immediately, and require little to no capital investment. Second, the driving factors behind any possible improvement will be isolated and their effect quantified. Beyond the scope of this paper, the research aims to develop, test and implement improvements in industrial settings in future in order to prove their viability and maximise the rate of uptake.

2.2. Production data analysis

The data in this paper are drawn from the Ketton plant, operated by Hanson Cement, part of the Heidelberg group. In order to analyse the average performance of the plant and its variation, production data was acquired and analysed. Data was available from between January 2013 and October 2014, in the form of daily averages for consumption of; coal, Profuel (shredded municipal waste), Cemfuel (solvent waste), MBM (meat and bone meal, an animal byproduct) and Kerosene (used for preheating the kiln at start-up), as well as daily clinker production.

Monthly or batch values were available for the fuel net calorific values and fuel chemical analysis (including carbon and hydrogen percentage by mass). The daily hours of run time for the kiln were also recorded. From these values the daily energy consumption per tonne of clinker produced could be calculated, as well as the mass of fuel derived carbon dioxide per tonne of clinker. In order to exclude days where a large part of the energy consumption was used for heating the kiln rather than producing clinker (thus leading to an abnormally high energy consumption per tonne for that day) the values were calculated only for those days on which the kiln had been running for at least 15 h. In practice, this meant that calculations were made for 534 days out of 643 for which data was available. However, only 27 days on which there were production were excluded, and these 534 days represented 98% of clinker production. Had these 27 days been included, however, they would have distorted calculation of mean and median values as the small tonnages produced.

In order to estimate the magnitude of potential performance improvement through operational changes, a comparison was made between the averages and the 90th percentile of performance (i.e. lowest 10%) for energy consumption and fuel derived carbon emissions per tonne. This estimate compared the average value with a level of performance that was frequently, but not consistently achieved, while discounting any outliers that might lead to overestimation of the opportunity.

2.3. Energy outputs model

To investigate the variation in energy consumption a model was developed comparing the energy output with the energy inputs as calculated from fuel consumption and its calorific value. A control volume approach was adopted in order to simplify the process and allow calculations from the data available, as shown in Fig. 1 below. First, an energy balance was calculated using representative values to validate the model, and then an Excel visual basic (VBA) script used to run this calculation using daily values where available. It was observed that the sensor values for oxygen measurement were unfeasibly high during 2013. Immediately after the January 2014 plant refit, the O_2 readings dropped by 25%. It was therefore assumed that false air or faulty readings were causing the improbable values in 2013, so only data from 2014 was used. Days with kiln run time of <15 h or insufficient sensor data to calculate the model were also excluded. This left 158 data points, each representing one daily average, for which calculations were made, out of 278 available in 2014, and 643 available in total. These 158 data points represented 68% of clinker production in 2014, and 28% of the total production in 2013–2014.

Daily values were calculated for:

- Dissociation Energy (Eq. (1))
- Top of Tower Energy (a proxy for energy lost to stack – Eq. (2))
- Bypass Energy (Eq. (3))
- Vaporisation Energy of Fuel Water Content (Eq. (4))

$$Dissociation\ Energy = \Delta H_{CaO} + \Delta H_{MgO} + \Delta H_{Al_2O_3} - \Delta H_{Fe_2O_3} - \Delta H_{SiO_2} \quad (1)$$

Dissociation Energy

$$\sum_{All\ Gases} Molar\ flow \times Cp \times \left(T_{preheater\ exit} - T_{ambient}\right) \quad (2)$$

Top of Tower Flow

$$\sum_{All\ Gases} \left[Molar\ flow_{Bypass} \times Cp \times \left(T_{bypass\ exit} - T_{ambient}\right)\right] + \frac{Energy\ Consumption}{Tonne\ of\ Clinker} \times \dot{m}_{bypass} \quad (3)$$

Bypass Energy

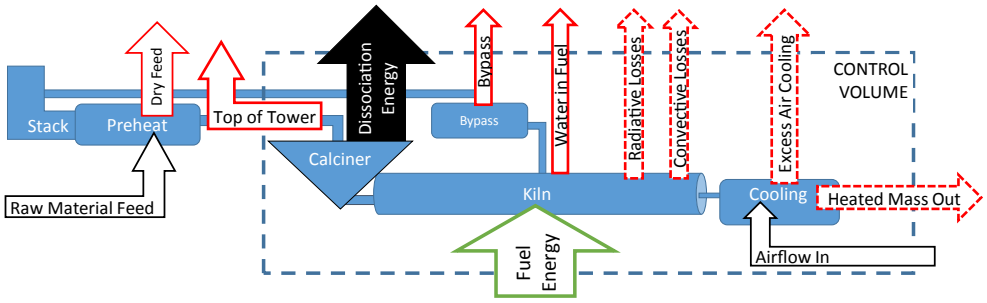

Fig. 1. Energy outputs model control volume.

$$Molar\ Flow_{Fuel\ H_2O} \times\ Vaporisation\ Energy_{/Mol} \tag{4}$$

Vaporisation Energy of Fuel Water Content

Values were calculated for the factors listed below based on yearly average numbers, or one off values where no other inputs were available. For example, temperatures for heat losses were based on available numbers from kiln shell scans as the shell temperatures were not monitored on a daily basis.

- Excess Air Cooling (Eq. (5))
- Radiation Energy Loss (modelling calciner and kiln in 5 sections – Eq. (6))
- Convection Energy Loss (modelling calciner and kiln in 5 sections – Eq. (7))
- Heated Mass Out (Eq. (8))

Excess Cooling Air Energy

$$\dot{m}_{excess\ air} \times Cp_{air}(T_{cooler\ exit} - T_{ambient}) \tag{5}$$

Radiative Losses

$$\sum_{All\ Sections} \varepsilon_{oxidised\ iron}\sigma\left(T^4_{section} - T^4_{ambient}\right)A_{section} \tag{6}$$

Convective Losses

$$\sum_{All\ Sections} (T_{section} - T_{ambient})\left(\frac{Nu_L k}{L}\right)A_{section} \tag{7}$$

Heated Mass Out

$$Mass\ flow\ of\ clinker\ \times Heat\ capacity\ of\ clinker\ \times (T_{clinker\ exit} - T_{ambient}) \tag{8}$$

Where:

Nu_L: Nusselt number based on length
Cp: Specific heat capacity at constant pressure
σ: Stefan Boltzmann Constant
k: Thermal conductivity
ε: emissivity

2.4. CO_2 Emissions Prediction model

The Energy Outputs model gave insight into how the energy consumption varied per tonne by examining the output values of energy. However, in order to develop operational protocols or tools to deliver improvements, it is necessary to estimate the energy consumption and carbon emissions that would result from a given set of operational inputs. A model to predict this consumption and these emissions from such inputs was therefore developed.

First, the base energy requirement of the plant was estimated. The components of this were as follows:

- Dissociation Energy: Net energy required to complete the chemical processes necessary to convert raw meal into clinker. This value does not include the energy required to heat the clinker.
- Dissociation CO_2 stack energy: Energy required to heat CO_2 driven off $CaCO_3$ in the raw meal from ambient temperature to Top of Tower Temperature.
- Fixed Energy Costs: Energy required to run the plant, independent of production rate. These were estimated as the average Bypass Energy, Radiation and Convection losses, based on the Energy Output model.
- Variable Energy Costs: Energy required to run the plant, proportional to rate of production. Based on the Energy Output model, these consisted chiefly of waste heat rejected from the clinker output, and were estimated as the average Heated Mass Out and Excess Air Cooling energy flows from the Energy Output model.

The total baseline energy requirements are given by Eq. (9) below:

Baseline Energy Requirements

$$\frac{Baseline\ Energy}{Tonnes\ of\ Clinker} = Variable\ Energy\ Losses + \frac{Fixed\ Energy\ Losses}{Rate\ of\ Production} + Dissociation\ Energy + Material\ Derived\ CO_2\ Stack\ Energy \tag{9}$$

These energy requirements must be met by burning fuel. This comes with additional energy burdens from vaporising any water content in the fuel and from heating the combustion air determined by the stoichiometric requirements of the fuel, plus excess air, depending on the operating conditions of the plant that day. All of this requires further energy, which again comes with additional burdens. The overall effect of this is shown in Eq. (10) below:

Energy Requirements of Combustion Air

$$\frac{Total\ Energy}{Tonnes\ of\ Clinker} = \left(\frac{Baseline\ Energy\ Requirements}{Tonnes\ of\ Clinker}\right)\sum_{n=1}^{\infty} 1 + \left(\frac{Stoichiometric\ Combustion\ Air\ Energy}{GJ\ of\ Fuel} + \frac{Excess\ Air\ Energy}{GJ\ of\ Fuel} + \frac{Water\ Vaporisation\ Energy}{GJ\ of\ Fuel}\right)^{n} \quad (10)$$

Given that the energy requirements per GJ of fuel sum to less than 1 (otherwise the fuel would not deliver useful energy), this can be simplified as an infinite geometric progression to give Eq. (11):

Energy Requirements of Process

$$\frac{Total\ Energy}{Tonnes\ of\ Clinker} = \frac{Baseline\ Energy\ Per\ Tonne\ Clinker}{1 - [(Combustion\ Air\ Stack\ Energy\ per\ GJ\ Fuel) \times (1 + Excess\ O_2\%) + Fuel\ Vaporisation\ Energy)\ ]} \quad (11)$$

The total carbon emissions per tonne can then be estimated using the CO_2 emissions per GJ energy delivered of the overall fuel blend as per Eq. (12).

CO_2 Emissions per GJ

$$\frac{CO_2\ Emissions}{Tonnes\ of\ Clinker} = \frac{Total\ Energy}{Tonnes\ of\ Clinker} \times \frac{CO_2 Emissions}{GJ\ of\ Fuel\ Energy} \quad (12)$$

3. Results & discussion

3.1. Production data analysis

Fig. 2 shows the day-to-day fuel consumption of the Ketton plant per tonne of clinker produced. On average, the plant consumes 3.9 GJ of fuel for each tonne of clinker produced. This is 14% higher than the average of 3.4 GJ/tonne for a plant with a pre-calciner/pre-heater system (Cement Sustainability Initiative, 2009). However, it is worth noting that the Ketton kiln is an early design of pre-calciner. Also of note was the variation in this consumption on a day-to-day basis. Choosing the 90th percentile as a 'repeatable-best' point of comparison, the analysis revealed that the plant was capable of regularly achieving an energy consumption 6% lower than its current average. If the plant were to perform consistently at the levels achieved 10% of the time, considerable savings in both fuel bills and carbon emissions could be achieved.

Fig. 3 shows the S curve for fuel-derived CO_2 emissions per tonne of clinker. This shows a wider spread of performance than the energy consumption curve. The median average of 335 kg/tonne is around 12% above the corresponding average value found by the CSI (Cement Sustainability Initiative, 2009). Given that CO_2 emissions per tonne are driven by energy consumption of the plant and carbon index of the fuel used, this would indicate that Ketton's fuel mix has a carbon index slightly higher than average. However, this analysis has looked at absolute carbon emissions, without adjusting for biomass, whereas other sources may treat biomass as carbon neutral. Moreover, Fig. 3 also shows a wider variation in emissions performance than the variation in energy performance, with a 10% difference between the average and 90th percentile emissions.

This is, qualitatively, an expected result. Two independent random variables, when multiplied together, will have a variance greater than the product of their variances (Frishman, 1971) Hence,

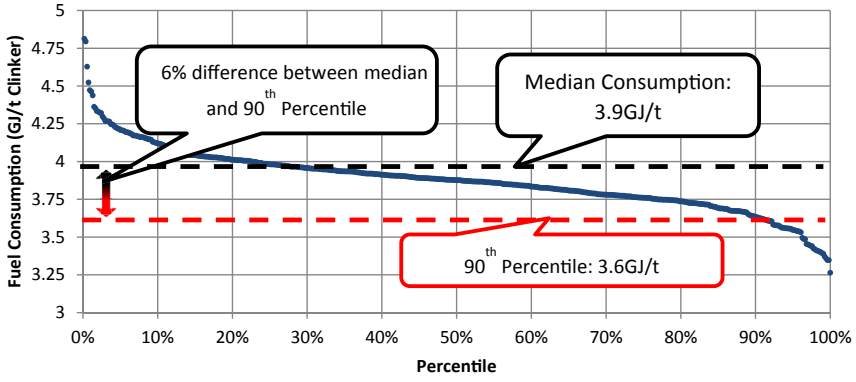

Fig. 2. Day to day fuel consumption of ketton plant.

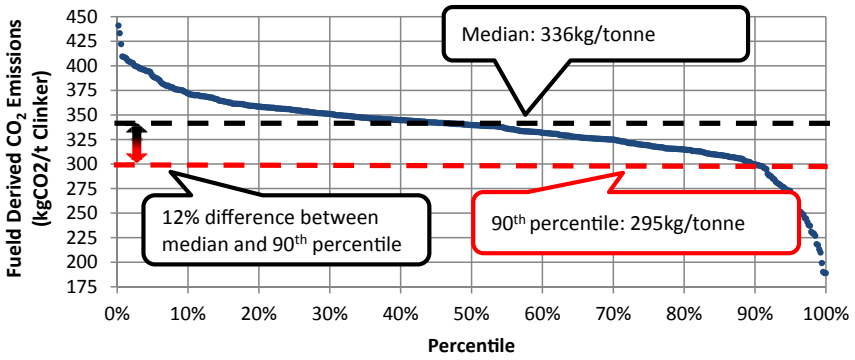

Fig. 3. Day to day CO_2 emissions from ketton plant.

Table 4
CO_2 emissions for 24 hour run time.

	Clinker produced (t)	CO_2 produced (t)	CO_2/tonne clinker
24 Hour run	87%	86%	0.354
Total	100%	100%	0.357

if the carbon index of the fuel varies independently of energy consumption, and the emissions performance is proportional to the product of the two, the emissions performance will vary more widely than either the carbon index or the fuel consumption.

However, the size of the variation is significant: with the correct operating conditions, the data indicates that this plant regularly produces clinker with fuel-derived carbon emissions 10% lower than its average result. If the factors driving this variation can be identified and controlled, considerable energy and carbon savings can be made. The expectation is that this could be implemented without any major capital investment in the plant, as the plant has been shown capable of operating at this level in its current state.

In order to estimate the effect of kiln shutdowns on energy consumption, the total tonnage of clinker produced on days where the kiln ran for 24 h was compared to the total tonnage produced over the year. Similarly, the total tonnage of CO_2 emissions from 24 h runs was compared to the overall total. 24 h runs produced 87% of the clinker, and 86% of the carbon emissions. Hence, eliminating kiln shutdowns entirely would only save 1% of overall carbon emissions, justifying the focus on those days with $\geq$15 h of production, as shown in Table 4 below. Data has been normalised as percentages in order to preserve confidentiality of production figures.

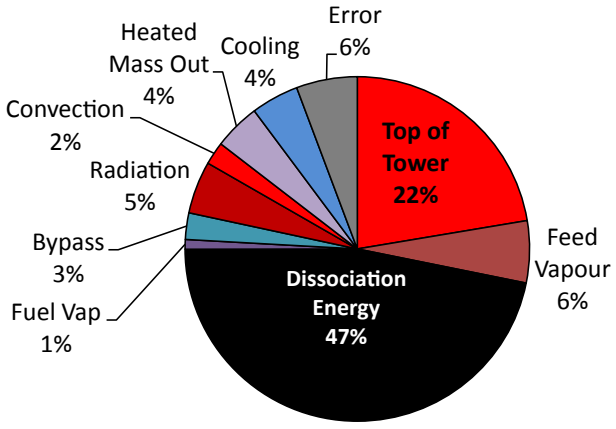

Fig. 4. Average outputs from energy model as % of total.

3.2. Energy outputs model

Fig. 4 shows the outputs of the energy model. The model was intended to help understand why the energy consumption varied, by modelling energy outputs and creating an energy balance. On average, the model accounted for 94% of heat input, leaving a 6% error. As expected, the energy consumption was dominated by dissociation energy and top of tower energy. Including the part of the top of tower energy used to dry the feed vapour, these two energy sources account for 75% of energy consumed by the plant. Wasted heat in the mass out (either in the heated mass itself, or rejected to atmosphere through the excess air cooling system) accounts for a further 8%, and heat losses from the kiln/calciner shell an additional 7%. This model indicates that the most probable cause of variation in energy consumption is variation in either the top of tower energy flow, or the dissociation energy required, as percentage swings of the order of magnitude of 100% would be required in the other flows in order to account for the overall variation.

Fig. 5 shows a comparison between this model and the models from the literature summarised in Table 2. The model accounts for a greater proportion of the energy consumed than two of the other models, and estimates values for dissociation energy, bypass and cooler exhaust that are within the ranges covered by the other models. The value for the stack exhaust is fractionally higher than but similar to the value calculated by the other models. The model diverges from those in the literature in estimating lower heat losses from radiation and convection. It may be that the energy unaccounted for by the model is lost as heat in this way. The slightly higher value for energy lost as hot clinker may be explained by the relatively low value for the cooler exhaust as these two values are closely linked.

In order to provide insight into the causes of variation, the size of the energy outputs estimated by the model were calculated on a daily basis, and compared with the energy input value from that day. This comparison is shown in Fig. 6. On average, the model accounts for 94% of energy inputs with an average deviation of 2% from this 94% line of best fit. Generally speaking, days with high energy consumption have correspondingly large energy outputs, and vice versa, but the R squared value is only 0.28, implying that the model only accounts for 28% of the variation observed.

However, the model is still accurate enough to draw broad conclusions about the overall variation. The size of the variation in

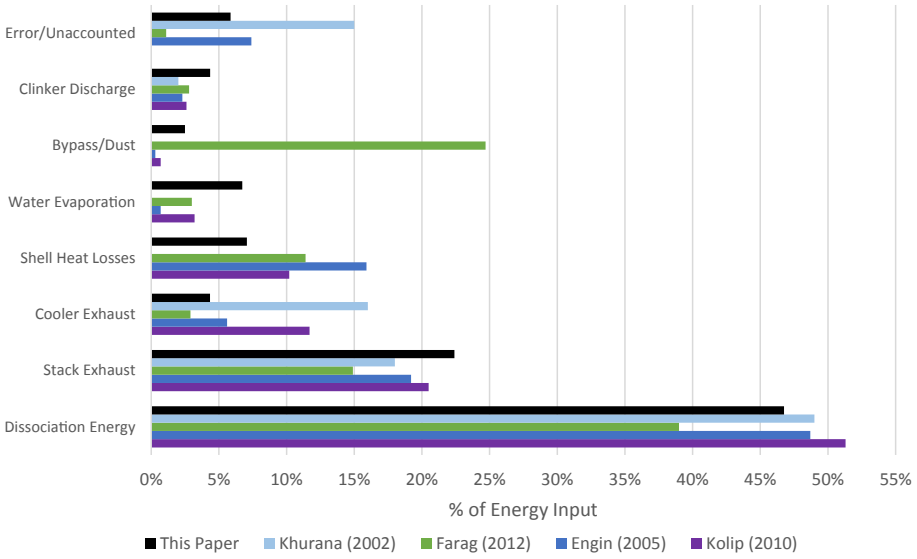

Fig. 5. Comparison between energy model and models in literature.

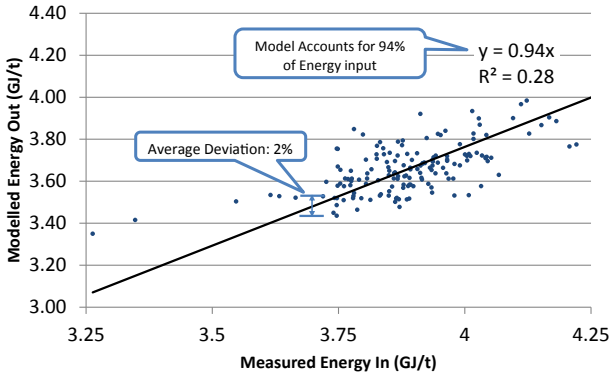

Fig. 6. Accuracy of energy model.

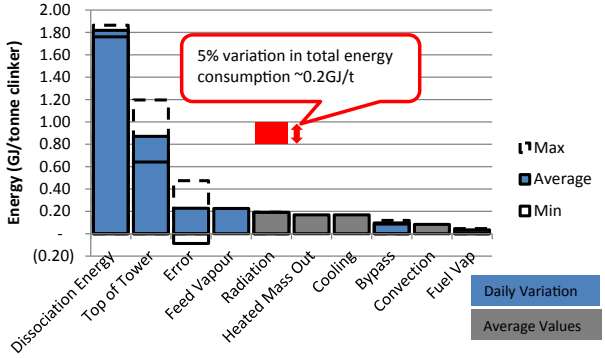

Fig. 7. Values and variation of model outputs.

energy consumption being investigated is around 6% of the total (see Fig. 2). More than 95% of the time, the deviation between the modelled energy out and the energy consumption was smaller than this value.

Hence, while the model is not perfectly accurate, it can still provide some insight into where the additional energy consumed on high consumption days exits the system.

Fig. 7 shows how the various calculated energy outputs vary between their maximum and minimum observed values compared to their average. Of those energy outputs for which a daily value was calculated, only the Top of Tower energy flow, and the model error (defined as the energy flow not accounted for by the model), varied enough to account for the observed variation in energy consumption. This would mean that either the Top of Tower energy is the dominant source of variation, or the model does not include the energy flow that accounts for the variation, or some combination of the two. Statistical analysis indicates that Top of Tower energy flow is more strongly positively correlated with energy

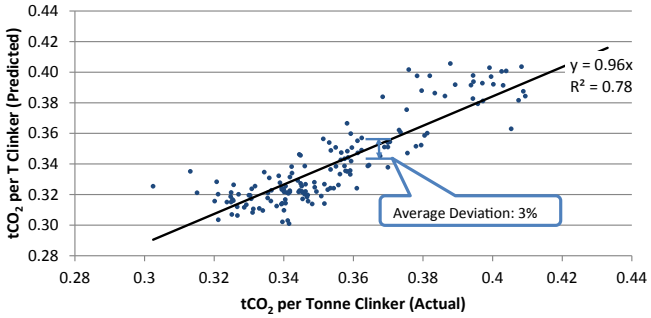

Fig. 8. Accuracy of prediction model.

Table 5
Variation in temperature and flow rate.

Variable	Average value	90th percentile value	10th percentile value	% Variation
Top of tower temp (°C)	446.13	449.22	443.35	1%
Top of tower flow (NM^3/hr)	203,100	215,000	187,700	13%

consumed than with the model error. It therefore seems reasonable to investigate Top of Tower flow as one of the most probable causes of variation in overall energy consumption, even if there may be other factors involved.

The Top of Tower energy flow was driven by two factors: temperature at the exit, and flow rate of flue gas, measured in normalised metres cubed per hour. The variation in these values between their 10th and 90th percentile values is shown in Table 5. Flow rate varies far more than temperature, and Equation (2) indicates that energy flow has a linear relationship with both mass flow and Top of Tower temperature. Hence we conclude that the variation in fuel consumption is strongly linked with the flow rate of flue gas through the kiln/calciner system.

3.3. CO_2 Emissions Prediction model

The Energy Outputs model gave insight into how the energy consumption varied per tonne by examining the output values of energy. However, in order to develop operational protocols or tools to deliver improvements, it is necessary to estimate the energy consumption and carbon emissions that would result from a given set of operational inputs. The CO_2 Emissions Prediction model took operational inputs and calculated predicted fuel-derived CO_2 output per tonne of clinker.

Fig. 8 compares the Tonnes of CO_2 per tonne of clinker calculated from the daily fuel input and production rate with the CO_2 emissions predicted based on the input conditions. The prediction model accounts for 96% of emissions, and has an average 3% deviation from this 96% value. It also correlates well with observed values. This accuracy might be slightly overstated as both input and output values are based on the chemistry of the fuel. However, this is the only way to measure CO_2 emissions, and how emissions are calculated for regulations. It is worth noting that the correlation with the energy predictions was less good, with accuracy falling off at extreme low or high values. Overall, however, it predicted 95% of consumed energy, with an average deviation of 3%, and a maximum deviation of 13%.

While the accuracy is not good enough to take values for individual days as perfectly accurate, it should be sufficient to work out broad trends and average values. This gives confidence that we can use this model to predict the effect of controlling individual inputs on CO_2 emissions per tonne, while keeping other values constant.

3.4. Sensitivity analysis

The CO_2 Emissions Prediction model can be used to estimate the sensitivity of the CO_2 emissions and energy consumption to alterations in each of the inputs. Fig. 9 shows the total reduction in CO_2 emissions (grey) or both Energy & CO_2 (red) when each of the controlling factors is reduced by 10% from its average observed value.

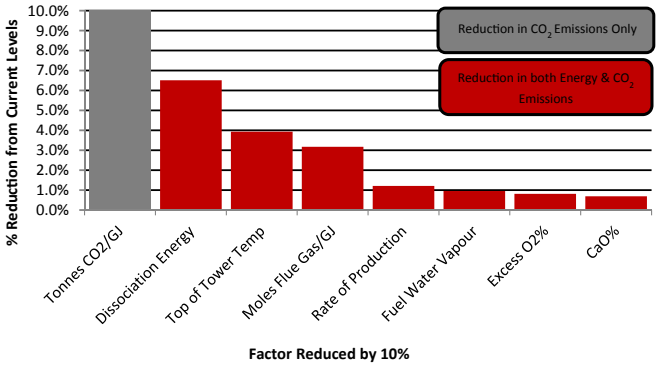

Fig. 9. Sensitivity analysis: Energy & CO_2 emissions.

As expected, reducing the carbon intensity of the fuel scales linearly with reduced CO_2 emissions, without affecting energy consumption (the model treats the carbon intensity independently of the moles of flue gas generated per GJ). It is worth noting that while the dissociation energy accounts for 47% of energy consumption (Fig. 4), reducing it by 10% would reduce total energy requirements by 6.5%. If the relationship were linear, the total consumption would only reduce by 4.5% in this case. The additional reduction is a result of the positive feedback effect of reducing energy requirements: lower energy requirements require less fuel, which in turn requires less combustion air to be heated, which reduces fuel requirements further, and so on. So, reducing dissociation energy by 10% reduces energy requirements by 4.5% directly, and 2.5% by reducing the amount of heat lost to combustion air, fuel water vapour etc.

While clinker chemistry is carefully controlled, this effect should be taken into account when assessing the effect of using alternative raw materials such as pulverised fly ash. This positive feedback effect also applies to other methods of reducing energy consumption; reducing the top of tower temperature by 10% reduces the energy loss through the stack by 13.7%. This 13.7% reduction in stack loss is equivalent to 3.9% of total energy consumption, as shown in Fig. 9.

3.5. Theoretical minimum energy requirements

Several attempts have been made in literature to quantify 'minimum' energy requirements for clinker production. However, these values either cover a very wide range, or do not take into account the necessary irreversibilities associated with burning fuel to generate heat for the chemical processes required. Table 6 shows each of the input values used to calculate a minimum value for the energy required to run an 'idealised' cement kiln, along with the associated assumptions.

Comparing this minimum requirement to the values in Table 1, we see that it falls in the range expected: lower than the best available technology currently being used, but higher than the minimum values calculated by Gardner and ECRA which do not take combustion into account, but only look at the thermal energy demand for clinker production and drying of materials. This therefore gives a better estimate than those hitherto available for the lowest possible levels of energy consumption available in a real-world plant.

This minimum energy requirement represents a 47% reduction in energy consumption compared to the average consumption observed in the Ketton plant, and a 31% reduction compared to 'best available technologies.' This gives an estimate of the maximum possible improvement from energy efficiency developments.

3.6. Potential operational improvements

In order to estimate the potential for operational improvement at the Ketton plant, the '90th percentile observed' levels of each factor were used as inputs to the model. These estimate the effect of controlling each factor at a level it reaches at least 10% of the time. The effect of this is shown in The figure shows the predicted reductions in CO_2 emissions or both CO_2 emissions and energy, by reducing a given input to its 90th percentile observed level, and assuming all other inputs to be at their average observed levels.

However, the energy model indicates that much of the performance variation is down to variation in airflow; the top of tower flow rate variability was calculated to account for as much as 56% of

Table 6
Theoretical minimum energy requirements.

Input values (Units)		Assumptions
Fixed energy losses (GW)	0	No radiative/convective heat loss from kiln
Variable energy losses (GJ/tonne)	0.17	Exit Temperature of Clinker 180 °C (heat assumed not recoverable below this temperature) No Excess Cooling Air (heat used to preheat combustion air)
Production (tonnes/hour)	110	Irrelevant (No fixed losses)
CaO (%)	66%	Minimum Observed
Excess O_2 (%)	0%	Ideal: Stoichometric Combustion
Dissociation energy (GJ/tonne)	1.76	(Gartner, 2010)
Moles flue gas/G J fuel (Mol/GJ)	9000	Pure Carbon Fuel (theoretical limit)
Top of tower temperature (°C)	150	Heat Exchange Limit – heat assumed not feasibly recoverable below this temperature
Fuel water vaporisation energy	–	Dry Fuel
Minimum Energy Requirement		**2.07 GJ/Tonne**

The bold is used because the minimum energy requirement is a result of all the inputs in the summary above.

Table 7
Comparison of airflow parameters with literature values.

Paper:	Kolip and Savas (2010)	Engin and Ari (2005)	Farag (2012)	Khurana et al. (2002)	Kaantee et al. (2004)	This paper (average values)
Stack air flow ($kg_{air}/kg_{clinker}$)	2.03 (Calculated)	2.1	2.11	2.27	–	2.34
Stack O_2%	1%	1.80%	5%	5%	2%	4.1%
Excess air ratio	1.15	–	1.3	–	–	1.33

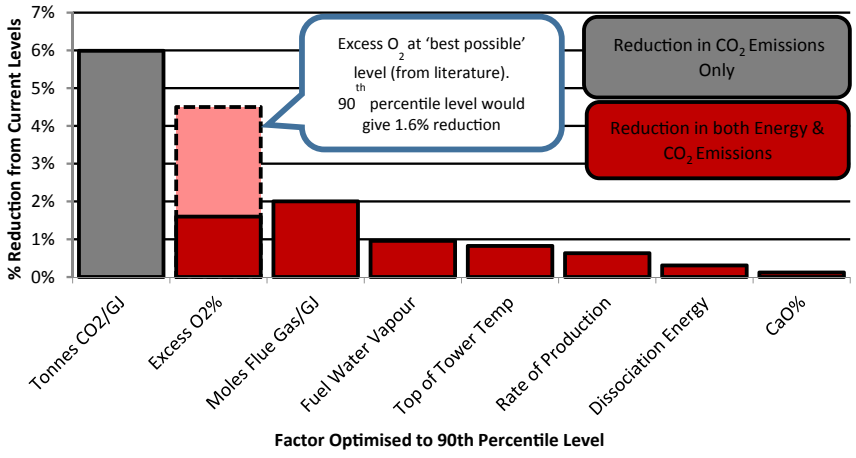

Fig. 10. Potential operational energy & emissions reductions.

the variation observed in the overall performance of the plant. Given this, and the fact that the excess air ratio is an operational decision that can be altered more easily than other factors, the key air flow parameters were compared to values found in literature. This comparison is summarised in Table 7.

Notably, all three parameters are higher than most of the values assumed for heat balances and similar calculations in the literature. Accordingly, the calculations used to estimate possible improvements were re-run, this time assuming excess O_2 levels to be at 2% by volume in exhaust gas (~14% excess compared to stoichiometric). This value was taken from literature (Kääntee et al., 2004) as a 'reasonable' target value for excess O_2 values in exhaust gases, as it is among the lower values reported for both O_2 by volume and excess air ratio, without being the very lowest. Fig. 10 also shows the results of these calculations. The potential reduction from reducing excess O_2 values to this 2% level from literature is 4.5% of overall energy and CO_2 emissions. This is a significant decrease in energy, potentially achieved by controlling an operational factor to an achievable level.

Fig. 10 indicates that substantial reductions in energy and

Table 8
Optimal predictions vs best observed.

Output	Prediction model (multiple inputs optimised)	% reduction vs average	98th percentile value (2013–2014 production data)
Energy consumption (GJ/tonne clinker)	3.52 GJ/tonne	8.5%	3.40 GJ/tonne
Fuel derived CO_2 emissions (kg/tonne clinker)	280 kg/tonne	19.8%	295 kg/tonne

emissions are available by controlling input conditions of cement production to levels observed during current production runs. Moreover, the inputs with the largest impact on emissions are those over which there is direct operational control (particularly fuel blend and excess O_2 levels), whereas those which are determined by cement quality considerations (CaO% and Dissociation Energy) have minimal impact. If multiple inputs were optimised, then even more substantial improvements could be made, corresponding with best observed levels (98th percentile value) from production data. These potential improvements are summarised in Table 8.

It is worth noting that two of the input factors, CO_2 emissions per GJ and Combustion Air per GJ are both dependent on the chemical composition of the fuel and therefore not independent. For the above comparison, values were chosen that corresponded to 90th percentile levels, and it was confirmed that there were observed cases where the fuel mix had these properties. It is proposed to develop a tool that compares a new metric, blending these two formulae with other constraints on fuel mix, such as cost and fuel availability. This metric would be 'Net GJ/per tonne CO_2,' as calculated in Eq. (13).

Net GJ/Tonne CO_2

$$\frac{Net\ GJ}{Tonnes\ of\ CO_2} = \frac{Tonnes\ of\ CO_2/GJ}{1 - (Combustion\ Gas\ Energy_{At\ 446^{\circ}C} + Water\ Vaporisation\ Energy)} \quad (13)$$

This metric would allow for comparison between different fuel types based on their overall impact on the performance of the plant. Given the importance of fuel blend in determining plant performance, it is proposed to make this the subject of further study in this field.

4. Conclusions

Analysis of the factory data found a significant variation in both the energy consumption and the CO_2 footprint. Finding a day-to-day variation of 7% between the average and 90th percentile values in the energy consumption implies a possible opportunity to save fuel, and hence reduce costs through operational changes. Additionally the increased variation seen in the CO_2 footprint implies that optimising the fuel mix could lead to further reduction in carbon emissions without necessarily affecting cost or performance. The data indicates that this variation is not due to plant shutdowns, but rather operational variation during continuous operation. As such, it gives an estimate for the levels of performance improvement that could be achieved by operational changes.

The energy model gave a robust understanding of both the average energy balance, and the variation of the individual factors involved. It went beyond the existing literature by examining heat balances on a day-to-day basis, rather than taking one-off or representative values. The model indicated that while the largest single demand for energy came from the dissociation energy required to manufacture the clinker, it was shown that this demand was highly consistent, due to the consistency of the chemical composition of the clinker, and therefore not responsible for the variation in performance observed. Instead, the airflow through the kiln and calcining accounted for much of the variation. An important sub variable driving this airflow was the excess oxygen percentage (a measure of how lean the kiln was running).

The prediction model was used to estimate the likely impact of altering each individual driver of CO_2 footprint. The carbon footprint of the fuel, levels of excess oxygen, and the combustion properties of the fuel were found to be key drivers of performance. Optimising all these drivers to '90th percentile best observed' levels, or to improved levels derived from literature, was calculated as potentially providing an 8.5% reduction in energy consumption, and a 19.5% reduction in CO_2 footprint. These predicted levels were very close to the 98th percentile best observed performance of the plant. If these findings are repeatable at other plants, this represents a significant opportunity to reduce energy consumption and carbon emissions without the need for capital investment. It also calculated a minimum value for energy consumption in a 'real world' plant, estimating that new technology could deliver a maximum improvement of 31% on the current 'Best Available' technology.

Based only on a single case study, the conclusions of this paper are not yet robust enough to be applied at an operational level. However, it indicates a potential for improvement that could be extremely valuable and environmentally important, as well as identifying some operational factors, particularly fuel mix and excess air ratio, which merit extensive further investigation.

This research will continue by investigating how to optimise the fuel mix based on the specific demands of an individual cement plant, and the scope for reducing excess oxygen levels. It will also examine case studies of further plants in order to assess the applicability of the findings to other installations.

Acknowledgements

Funding to support this research was gratefully received from the Engineering and Physical Sciences Research Council (Grant number EP/K503009/1).

Thanks to Hanson Cement for providing access to their factories and supplying the data on which the research was based.

Particular thanks to Hanson employees Iain Walpole, Greg Webber, Elliot Wellbelove and Dominka Crow for their help in collecting the data required and patiently explaining the intricacies of the plant.

Note on access to underlying data: As the models used in this paper are based on commercially sensitive data we are not able to make them directly available online. Please contact the corresponding author (dls43@cam.ac.uk) to arrange access to the data if required.

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