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Cost and carbon reductions from industrial demand-side management: Study of potential savings at a cement plant

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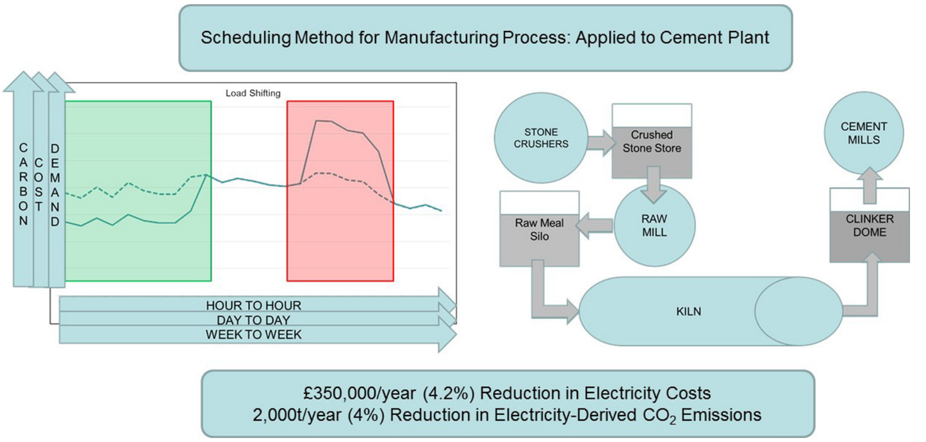
HIGHLIGHTS

- Varying electricity demand from industrial consumers can reduce costs & CO_2 emissions.
- An alternative production schedule was produced for a cement plant using new method.
- This demonstrated potential to decrease electricity cost by 4.2%.
- There was also potential to reduce electricity-derived CO_2 emissions by 4%.

GRAPHICAL ABSTRACT



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ABSTRACT

Demand-side management (DSM) has the potential to reduce electricity costs and the carbon emissions associated with electricity use for industrial consumers. It also has an important role to play in integrating variable forms of generation, such as wind and solar, into the grid. This will be a key part of any grid decarbonisation strategy. This paper describes a method that can be used to develop a new production schedule for a wide range of manufacturing facilities. The new schedule minimises either electricity costs or electricity-derived CO_2 emissions. It does so by rescheduling production to low cost or low carbon periods, without loss of overall production, within the constraints of available inventory storage. A case study of a single cement plant in the UK was performed in order to determine the potential benefits of increased load-shifting DSM using this method. The alternative production scheduled showed the potential to decrease electricity costs by 4.2%. Scaled to values from a typical plant this would lead to a cost saving of £350,000, a substantial saving. A schedule optimised to minimise carbon emissions would save an estimated 2000 tonnes per year of CO_2, a 4% decrease in electricity-derived emissions. It was also observed that the actual electricity consumption of the plant was considerably higher than the minimum consumption predicted by the model. This could indicate potential for significant savings in both cost and CO_2 due to improvements in energy efficiency. The potential savings from DSM doubled when the prices passed to the plant were replaced with a price that varied in proportion to the wholesale cost of electricity. This indicates that a potential mutual benefit exists for both industrial consumers and electricity

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generators by passing on more of the variation in price. A larger share of generation from wind and solar will also lead to increased variation in prices and grid carbon intensity in future. The value of applying the method described in this paper is therefore likely to increase further in future.

1. Introduction

One of the key challenges facing the UK government in aiming to meet its 2050 climate goals is the decarbonisation of electricity generation. As large, centrally controlled consumers of electricity, industrial facilities not only represent a significant proportion of UK electricity use, but also offer a lower-complexity route towards adjusting electricity demand to help the implementation of policy.

1.1. Motivation

Cement production is a significant global consumer of energy and source of carbon dioxide emissions. Only roughly 5% of these emissions come from the electricity used in the process, the remainder being emitted by the materials used in the process (50%), the fuel burned in the kiln (40%) and the transport of both raw material and finished product (5%) [1]. The global warming potential of cement industry is its largest environmental impact, followed by the acidification potential [2]. The material derived emissions can be reduced only by reducing the clinker content of cement, or reducing the amount of binder required to deliver a given strength [3]. Previous work by the authors has found opportunity to reduce fuel derived emissions by up to 20% through operational improvement [4].

The scale of the cement industry is such that even the 5% of emissions due to electricity use is still significant. This paper will estimate the potential for reduction in these emissions due to operational changes. The cement industry consumes 0.4% of UK electricity production, and accounts for 1.5% of industrial demand [5,6]. Moreover even though electricity only comprises 13% of the energy input to the cement making process, it can account for 50% of energy costs [7]. Any opportunity to reduce costs by shifting electricity consumption to low cost times would therefore be advantageous.

The objective of this paper is to demonstrate a new method for rescheduling the production at an electricity-consuming industrial plant. The cement industry provides a good opportunity for such scheduling, due to its high electricity usage, and significant scope for load-shifting. A case study will determine the extent to which Demand Side Management (DSM) could be used to shift the time at which electricity is required by a particular cement plant, without losing production. The paper will also estimate the associated financial and environmental benefits of shifting that demand.

1.2. Literature review

In order to examine the potential benefits for the cement industry from increased DSM it is necessary to first understand the various techniques and technologies that can help manage electricity demand. Equally important is how the need for DSM has been changed over time, particularly due to increased use of renewable electricity generation.

1.2.1. Nature of demand-side management

The concept of DSM grew out of the energy crises of the 1970s. The industry began to challenge its long held model of treating customer demand as fixed, and started to look for ways to optimise demand to suit the needs of the electric utility generators [8]. The basic objectives of DSM include:

- Peak clipping: Reducing demand at peak times to reduce need for generating units only used at to supply the peak.
- Valley filling: Encouraging consumers to use more electricity at off-peak times in lieu of other energy sources.
- Load shifting: Demand making up peak demand is shifted to off-peak time. (ibid)

Different strategies to achieve DSM objectives are outlined by Palensky and Dietrich [9]. These include:

- Energy efficiency: Reducing overall demand through improved efficiency.
- Time of use pricing: Customers are financially encouraged to shift demand to off-peak by pricing signals over a certain period, fixed in advance.
- Demand response: This can include real-time pricing, where the price is varied proportionally to the wholesale cost of electricity in order to incentivise consumers to switch consumption to off peak times. It can also describe a situation where utilities pay a fee to exercise direct control over consumers' assets, having the ability to switch them off in order to rapidly decrease demand.
- Spinning reserve: Loads act as a negative reserve by reducing their power based on the condition of the grid over timescale of seconds. This is principally used to maintain frequency of supply.

1.2.2. Increasing importance of DSM

Pressure on the UK generating industry continues to increase, and the excess capacity margin steadily reducing. However, there is still potential within the existing system to mitigate these challenges. Strbac [10] noted that the utilisation of generation capacity in the UK is only 55%. DSM could shift demand from peak to off-peak. While certain generators are only suitable for peak demand, this could improve the utilisation of plants that provide intermittent power (such as renewables) or which supply baseload power. As generators only receive revenue in return for generation, this would improve the return on investment in such generation plants. Strbac estimated that the value of DSM could be between £250 and £400 per kilowatt, with the significant additional benefit of requiring no planning or construction time in contrast to new generation. In addition, industrial DSM could ease the strain on the transmission network balancing out the north to south power flow at peak time as generation in the North supplies residential demand in the south of the country by reducing demand at plants at peak times.

There can be co-benefits for consumers participating in demand-response schemes. Modelling by Amini et al. [11] found overall cost savings of the order of 10% were possible for consumers able to shift the time of their use of various domestic appliances.

1.2.3. Impact of renewable electricity generation

One factor increasing the need for demand-side management is the increased penetration of renewables into the electricity mix. In the past, electricity has been supplied by baseload power (often from nuclear or coal) and dispatchable sources (i.e. those that can be ramped up quickly on-demand) such as gas turbines. Across the EU as a whole non-dispatchable power, such as wind and solar, is projected to provide up to 19% of EU wide electricity generation by 2030 [12]. Although interconnections between countries have been proposed as a way of smoothing out the variation in demand, adjacency (the likelihood that neighbouring countries will experience similar weather patterns) decreases the usefulness of this approach [13].

The principle renewable source of energy in the UK is wind power, which increased as a portion of the UK generation mix from 0.25% in 2000 to an estimated 3.9% in 2010 [12]. It is projected to grow to between 23% and 27% of generation by 2030. Wind power is inherently variable, and this variability occurs across a wide range of timescales.

- Microscale (seconds to minutes): This is primarily a regulation issue, and tends to be smoothed across a typical wind power array.
- Mesoscale (minutes to hours): Load following is the key issue at this scale, and this is where a lot of proposed DSM comes in (e.g. tripping out industrial units to lower demand).
- Macroscale (hours to days): A unit commitment issue, and energy storage is the usual solution proposed (e.g. pumped storage) [14].

Moura and de Almeida [15] cite a report by Pedersen (2005) that analyses the impact of increased penetration of wind power. At levels greater than 30%, wind power begins to lead to significant excess production of electricity, leading to wind turbines being derated (turned off) at times of oversupply. This diminishes the economic viability of renewable generation, as the revenue generated by a turbine is reduced.

A study of Flores Island in the Azores [16], where 54% of electricity is supplied by renewables, investigated the potential for demand-side management in the electricity supply. While flywheel storage is used to smooth out some of the variation in supply, this system has a relatively low efficiency and reliability, leading to high installation and maintenance costs. However, the study found that demand-side management could increase the economic viability of renewable investment. The value of being able to strategically increase demand at times of over production (load shifting rather than peak clipping) in order to maximise use of renewables can, in some cases, outstrip the value of simply cutting demand to reduce peak load [17].

The use of DSM to better incorporate wind power into the grid was studied in Moura and de Almeida [15]. The solutions proposed in this paper were mostly energy efficiency measures, reducing the power demand of lighting, cooling or motor units. The effect of this efficiency improvement would naturally be greatest at peak time, and as such would reduce the peak demand (peak clipping). The authors argue that "with lower energy consumption, the installed power in renewable intermittent resources needed to accomplish the minimum renewable targets, will be lower." However, one could argue that using energy efficiency improvements to displace renewable rather than fossil fuel generated electricity diminishes the overall benefit. Moreover in another paper by the same authors [18], the authors acknowledge that the European commission target is for 22% of gross electricity from generation to be from renewables, and that the Portuguese target is 39%. Reducing overall demand would do nothing to help meet these targets.

Finn and Fitzpatrick [19] investigated load shifting in an Irish cold storage facility, and a manufacturing plant. The load shifting was driven by price signals. The study concluded that the cold storage facility was already taking advantage of load shifting, and seeing the benefit, whereas the manufacturing facility responded only after intervention by management, but then saw a 10% reduction in electricity prices. The authors also concluded that for every 10% reduction, due to DSM, in the price a consumer paid for electricity, their consumption of wind power increased by 5.8%.

It is hard to use the existing literature to determine whether DSM in the UK would reduce emissions beyond the effect of increasing consumption of wind power. Studies conducted abroad, for example one in Taiwan [20], and another in Thailand [21] found that demand-side management provided little short-term environmental benefit if the load shifting occurred between times when electricity was generated by different fossil fuel based plants. However, a 1994 study [22] of the UK market, conducted before wind power had a significant presence in the UK energy mix, found that switching demand from peak to night time generation, reduced carbon emissions by 10–20% per kW h shifted.

1.2.4. Industrial applications of DSM

Industrial use of DSM can be categorised as one two main types. The first of these is DSM that uses a medium to store energy. The storage is charged during periods where electricity is cheap, and discharged to reduce consumption from the grid at high-cost times. The second type of DSM is a load-shifting approach, where the factory schedule is partly determined by electricity prices.

1.2.4.1. DSM using storage media. A number of authors have addressed industry specific applications of DSM. One area which has received particular attention is that of thermal storage, where electricity demand is shaped by using electricity at periods of low demand to heat or cool a storage medium, rather than using electricity at peak time to directly provide heating or cooling. Arteconi et al. [13] outline a range of technologies for thermal energy storage (TES). These are divided into hot and cold storage, and types include sensible storage, where a medium such as water rock or concrete is heated but no phase change occurs, latent storage, where a phase change is used, and thermochemical storage.

Dincer and Rosen [23] outline the economic benefits of TES, not only to electricity suppliers but also to end-users, particularly building owners. They outline an example of the pattern of demand being effectively reversed, shifting peak demand for cooling to off-peak times and vice versa. However, thermal storage is only effective to capture variations in price over the course of a 24-h period. Hasnain [24] investigates thermal storage in air-conditioning in Saudi Arabia, and gives an idea of the scale of storage required for an economically viable plant: 14–100 MW h.

There have been extensive studies of the potential for DSM in German industry. A report by DENA [25] investigated ventilation and air conditioning systems across German industry for positive and negative potential for DSM. Positive potential, defined as the ability to reduce demand, was estimated at 1075 MW nationwide. Negative potential, defined as the ability to absorb excess power, was estimated at 141 MW. Cooling and freezing processes in the chemical industry were estimated as being able to provide 572 MW of positive DSM, and those in the food industry an additional 1478 MW of positive potential and 703 MW negative. Khripko [26] investigated thermal storage DSM in the polymer processing and pharmaceutical industries in Germany. Her findings showed potential for DSM from cooling systems in all analysed factories, with an average negative potential of 1.25 MW and average positive potential of up to 0.5 MW.

Limmeechokchai and Chungpaibulpatana [21] investigated commercial scale cooling systems in Thailand, and concluded that DSM could help defer investment in coal-fired power stations. An investigation into Irish industrial firms found that a cold storage unit adapted its load patterns much more regularly than a more traditional manufacturing plant [19].

Another storage medium that can be used for DSM is compressed air storage, as investigated by Kleiser and Rauth [27].

The time period was again of the order of magnitude one day, and the study concluded that cost reductions of around 10% could be achieved, however the scale of industrial application was small, leading to a saving of only around £2250 a year.

Khripko [26] found that most manufacturing production sites analysed in Germany have compressed air available, and that these systems have potential for DSM. However the potential is relatively small, the simulation on average estimating less than 0.5 MW for both positive and negative loads. Across the whole of Germany, DENA (Deustche Energie-Agentur) estimated that compressed air in manufacturing sites can provide 1598 MW of positive DSM and 2680 MW of negative potential [25].

1.2.4.2. Load shifting approach to DSM. Other industrial applications are able to use a load-shifting approach to achieve DSM, without the need for an intermediate storage medium such as thermal storage or compressed air. In this case, the process is using its own inventory as a de facto energy storage medium. Electricity intensive processes are performed when electricity is cheap, and the partly-processed material stored in silos or buffers. No overall production is lost as a result of this method as the plant is assumed to have sufficient capacity to make up for reduced production at peak times. This is in contrast to load-shedding, where production is deliberately sacrificed to reduce demand for electricity.

The advantage of a load-shifting approach compared to using a thermal or compressed-air medium is that it eliminates an energy conversion process. By using processes that are already a necessary part of the overall industrial process it reduces a source of irreversibility, and hence decreases inefficiencies.

Khripko [26] simulated the potential for load shifting in the polymer processing industry. Potential for DSM as a result of load shifting was relatively small, on average less than 0.5 MW of both positive and negative potential.

Another example of load shifting was investigated at a chemical fertiliser plant in India [28]. The authors developed a program for load management, based on the constraints of the plant, such as the interlocked processes involved, and the size of storage buffers available. They then apply this program to real world load data from the plant. They concluded that their methods would not only reduce the peak demand, but also reduce electricity costs by Rs.107,000 a day, the equivalent of around £450,000 a year. A similar approach was also developed at a refinery [29]. This approach, based on a stochastic method using a smart grid, was projected to reduce electricity costs by 6.5%.

In a (non-peer reviewed) study by de Keulenaer et al. [30], 11 industrial processes were investigated for their potential to use load shifting in order to power the process, at least in part, through local wind generation. While the exact nature of the load shifting programs is not clear from the study, the authors that concluded that at a chloro-alkali plant, 69% of electricity used by the plant could be generated from a local wind farm. This would comprise 84% of the generation from the wind farm, the remaining electricity being sold back to the grid. A desalination plant was estimated to be able to get 60% of its electricity needs from a local wind farm, a self-consumption rate of 73%. A cement plant could be powered 51% by such a wind farm, using 63% of the energy from the farm in the process. In all, the study implies that industrial processes could get a large proportion of their power from local renewable sources, which would have the potential for significant cost and carbon savings.

However, a paper by Paulus and Borggrefe [17] comes to different conclusions to the study by de Keulaner. Paulus et al. investigated a number of different industries for their potential application of demand-side management by both load shedding and load shifting. They looked for industrial potential to help wind integration by providing positive or negative tertiary reserve (with a minimum offering of 15 MW). Positive tertiary reserve consists of industrial processes that can decrease demand, whereas negative reserve can increase demand in the case of electricity oversupply. The tertiary reserve market is designed to cover eventualities such as power plant outages, load forecast error and wind uncertainty. However they concluded that at current electricity prices load shedding was not widely economically viable, and most industrial interest in demand-side management was for those processes with the potential for load shifting. The chloro alkali process that they investigated was able to decrease its load by 40% on demand, but had such high utilisation rates of its equipment that catching up any lost production would be very slow. Aluminium production similarly had such high utilisation rate that it was only available for load shedding. They also investigated the cement industry. They found average utilisation rates of 80% for cement plant equipment and the industry experts that they interviewed concluded that, in part due to limited storage capacity, cement plants were only suitable for load shedding.

1.2.4.3. DSM in the cement industry. An investigation at a South African cement plant [31], however, found significant potential for load shifting. Focused on a single raw mill with an utilisation rate of 72%, they developed and tested a load management plan, and concluded that it had the potential to reduce electricity costs by 9.6%, leading to approximately £35,000 a year saving. This program included a number of fixed assumptions, such as a predetermined schedule for preventative maintenance. The cement mills were not investigated for potential load shifting because of a concern as to how the temperature of the clinker being ground into cement might affect the quality of the cement produced. Moreover, as only one of three raw mills on site were investigated, it is not known how a load management plan for three mills (feeding a single kiln) would differ from that for a single mill.

A number of studies have attempted to quantify the scope for DSM in the German cement industry. The results vary: von Scheven and Prelle [32] in a study of German energy intensive industries, estimated 313 MW of both positive and negative potential for DSM. Buber et al. [33] estimate 150 MW. DENA estimate 269 MW of negative potential and 45 MW of positive [25].

There is a lack of consensus in the literature (e.g. between de Keulaner, Paulus, Buber and Lidbetter) as to the scope for load shifting demand-side management in the cement industry. Moreover those studies that have directly tried to measure case studies have included implicit financial constraints, such as preventative maintenance. While these constraints are nontrivial, it would be useful to know the full potential for cost saving and emission reduction through demand-side management in a cement plant, and thus put a financial value on such constraints as storage, maintenance or product quality. This paper will endeavour to estimate the full potential for demand-side management through a case study of a cement plant, and estimate the possible financial and environmental benefits.

Coatalem et al. [34] applied an optimisation approach to generation assets owned by industrial sites, including a waste heat recovery generator at a cement works. They found that these units were often operated in a sub-optimal way, and by better matching generation to the electricity market substantial financial gains could be made.

1.2.5. Consumer response to price signals

The literature also offers contrasting evidence on the responsiveness of consumers to price signals. If consumers are responsive to price then generators can counteract the problem of excess demand versus capacity simply by signalling prices to the market. However, Lijesen [35] found low price elasticity over a range of timescales and Patrick and Wolak [36] found that the elasticity of demand to real-time pricing varied widely between industries, depending on the flexibility of their processes. However, Sheen and Yang [37] found that non-metallic mineral producers, which include cement manufacturers, were "very price responsive."

A study taking a game theoretic approach to DSM [38] indicated that users working in their own interest would improve the peak to average ratio, total generation costs as well as the charges to themselves without the need to declare their usage publicly. Given this, and the variation in consumer response to price signals, it may indicate that if consumers are incentivised or helped to develop DSM programs, then these programs will be successful, but the barriers to entry may be too high for the price signals to drive consumers to begin such programs from scratch.

Jiang et al. investigated the effect of consumers response to DSM programs in the day ahead market and real time pricing [39]. In both cases they found that the rational response of consumers to DSM programs would be to artificially enhance their baseline power consumption, as this was financially incentivised by the industrial DSM models they use. They concluded that this would lead to missed opportunities for mutual financial and social benefit.

1.3. Structure of paper

Section 2 of the paper will outline the method used to develop a new, minimum cost or minimum carbon schedule for production. In Section 3, that method will be applied to the cement plant in the case study, and the results compared to the actual electricity costs, and associated CO_2 emissions, for the plant. The scale of the results will also be compared to examples of other DSM schemes from literature. Section 4 contains the conclusions drawn from the results. The overall structure of the paper is summarised in Fig. 1.

2. Methods

This paper will describe a method of load-shifting based on inventory. This is a particular aspect of DSM; while other methods exist, such as load-shedding, they can come with additional costs. As such, only load-shifting will be considered for the purposes of this study. The method described in this section can be applied to any factory for which the following conditions apply:

1. The factory can be modelled as a single production line. Units in parallel can be modelled as a single unit in series with the rest of the factory.
2. Steady-state decoupled production throughput capacities of each unit is known. This allows the bottleneck of the factory to be clearly identified, as the unit with the lowest throughput.
3. The size of the buffers between each unit is known.
4. The electricity consumption of each unit is known.

The following sections will describe how to use this simplified model to develop a new production schedule, designed to minimise either costs or carbon emissions.

2.1. Assumptions

A key assumption made in this paper is that the goal of the factory is to maximise production, and that any attempts to save money or carbon by altering the schedule must be subordinate to that goal. The bottleneck of a factory is the unit that has the lowest decoupled throughput. The output of the factory as a whole cannot be greater than the throughput of this bottleneck [40]. Accordingly, any load shifting program must be designed to keep the bottleneck running for the same period of time as the non-shifted program, otherwise production will be lost.

2.2. Application of method to cement plant

This paper will demonstrate the method by applying it to a single UK cement plant. The exact size and specification of the plant will be kept confidential in order to preserve commercial data being extracted from the results of the paper. However it is similar in scale to the 'typical' plant outlined in Section 2.4. It operates a dry kiln with precalciner, although the method would apply to any cement plant, as well as to other production facilities. The factory was modelled as a single line of units as shown in Fig. 2.

The mills and stone crushers operating in parallel were treated as single production units, with a throughput equal to the sum of the rated throughputs of the individual units. Their power consumption was taken as their rated value. The buffers, in this case the silos and stone stores, were treated as single units with a capacity equal to the total storage capacity available at each stage of production.

In order to make a like-for-like comparison of the throughputs of each unit in the factory, their throughputs were compared in terms of tonnes of clinker equivalent. As such the throughput of the kiln was considered to be its maximum output of clinker, whereas the throughput of the stone crushers and the raw mill was calculated as the amount of clinker that could be produced from the limestone or raw meal that they processed.

Based on the rated throughputs in terms of tonnes of clinker equivalent, the kiln was by some margin the factory bottleneck. In order to maintain factory throughput, the stone crushers and mills have to match kiln throughput. This means that they only need to operate for a proportion of the time, allowing them to be scheduled to take advantage of low electricity prices or carbon footprint.

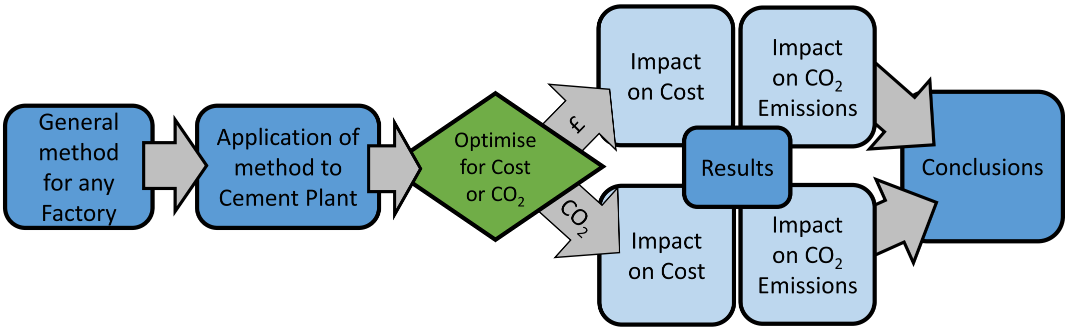

Fig. 1. Structure of paper.

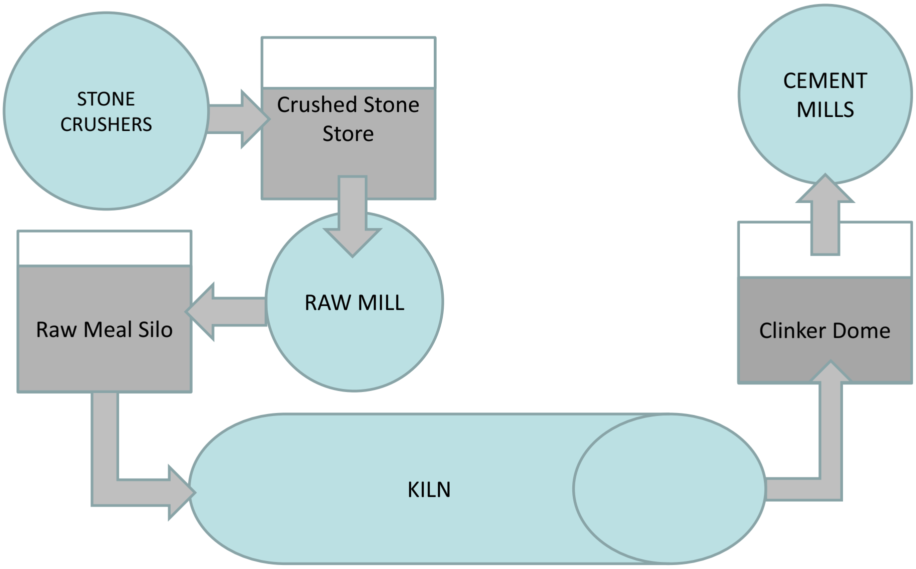

Fig. 2. Simplified model of factory.

2.3. Calculating an optimum schedule

The objective of this paper is to compare the actual electricity costs and associated carbon emissions with an "achievable optimum," and quantify the benefits from the various constraints broken in order to achieve that optimum. The following method was used:

- Choose the period for which forecasting data is assumed to be available. For example, it can be assumed that electricity prices are available for two weeks in advance during the year. In this paper, the effect of having prices in advance for 1 year, 1 month and 1 week were calculated.
- Choose the frequency of scheduling. In this paper it was assumed that scheduling would be performed twice during the forecasting period, so every week for a two-week forecast of prices, or every three days for a week's forecast.
- Choose whether to define 'cost' as electricity price or carbon footprint.
- Assume the silo is half full on the first day of the year.

2.3.1. Minimum-cost schedule

A necessary intermediate step is to calculate a baseline schedule, where the mill only runs at the lowest cost periods. The cost of running the mill for these hours is assumed to be the absolute minimum possible. It is very unlikely the mill could be scheduled for these times in reality, as it does not take into account the constraints imposed by the size of the silos. However it is a useful comparison point for the final schedule, as it allows us to estimate the degree of optimisation of the final schedule.

To calculate this schedule, the following method was used for each mill in turn:

- Set the mill to 'Off' for all days.
- Calculate the number of hours mill has to run in order to meet overall kiln production by dividing the kiln production during the forecasted period by the maximum mill throughput.
- Identify the lowest cost time slots (half hourly periods) in the forecasted period and schedule the mill to run during those times. For example if the mill had to run 40% of the time to meet kiln production, it would be scheduled for the lowest cost 40% of hours.

2.3.2. Meeting silo constraint

In order to meet the constraints imposed by the finite silos, first it is necessary to calculate the effect of the minimum-cost schedule on silo levels.

- If the kiln is "On", subtract maximum kiln throughput from silos upstream, or add it to silos downstream.
- If the mill is "On" subtract maximum mill throughput from silos upstream, or add it to silos downstream.
- Allow silos to be recorded as overfilled or negatively filled (below empty) if required.
- Each silo is then categorised as over-full, below empty, or OK (i.e. has contents between minimum value and maximum value). In this paper the minimum value was set as half-an hour's kiln production, and the maximum at the capacity of the silo.

The algorithm in Fig. 3 can then be used to ensure silo contents are within limits.

The values 'Fill Time' and 'Empty Time' are properties of each mill, and can be found using the process in Fig. 4.

The process must then be repeated for the next scheduling period. If this period is less than the forecast period (e.g. a schedule every 3 days for a 1 week forecast) then it will be necessary to reschedule the days covered by the overlap.

2.3.3. Electricity costs and carbon emissions

Once the schedule has been established for all three mills, the financial cost and carbon emissions resulting from the new schedule can be calculated according to Eqs. (1) and (2). The spot price per half hour used to calculate costs was the amount actually charged to the cement plant. The half-hourly grid CO_2 intensities were calculated by averaging the 5-min intervals of power generation [41], and applying the CO_2 intensities in Table 1. One consideration when calculating grid intensity is the role of embedded wind power. This is wind power that is not metered, and therefore not present in the data. The role of this was estimated by increasing the metered value of wind power by 30%. However, given the approximate nature of this estimate, values of the model were calculated both with and without the inclusion of embedded wind.

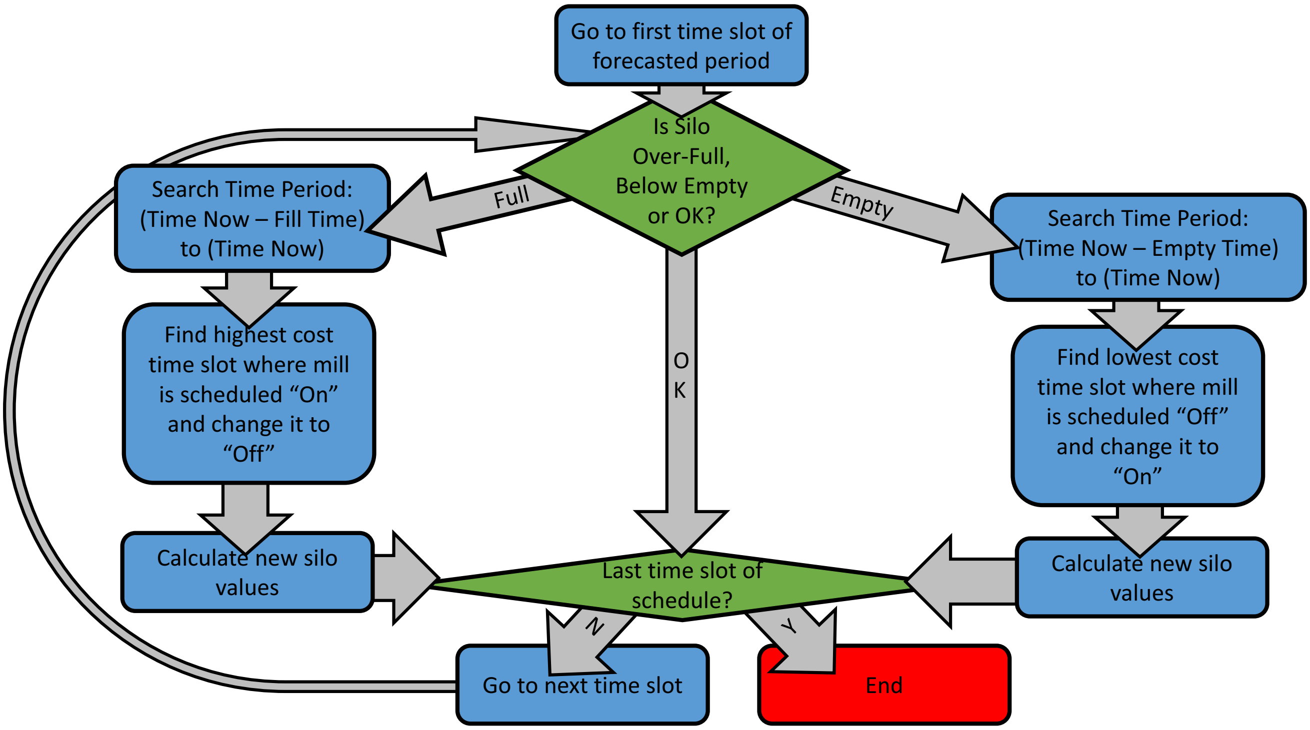

Fig. 3. Algorithm for meeting silo constraint.

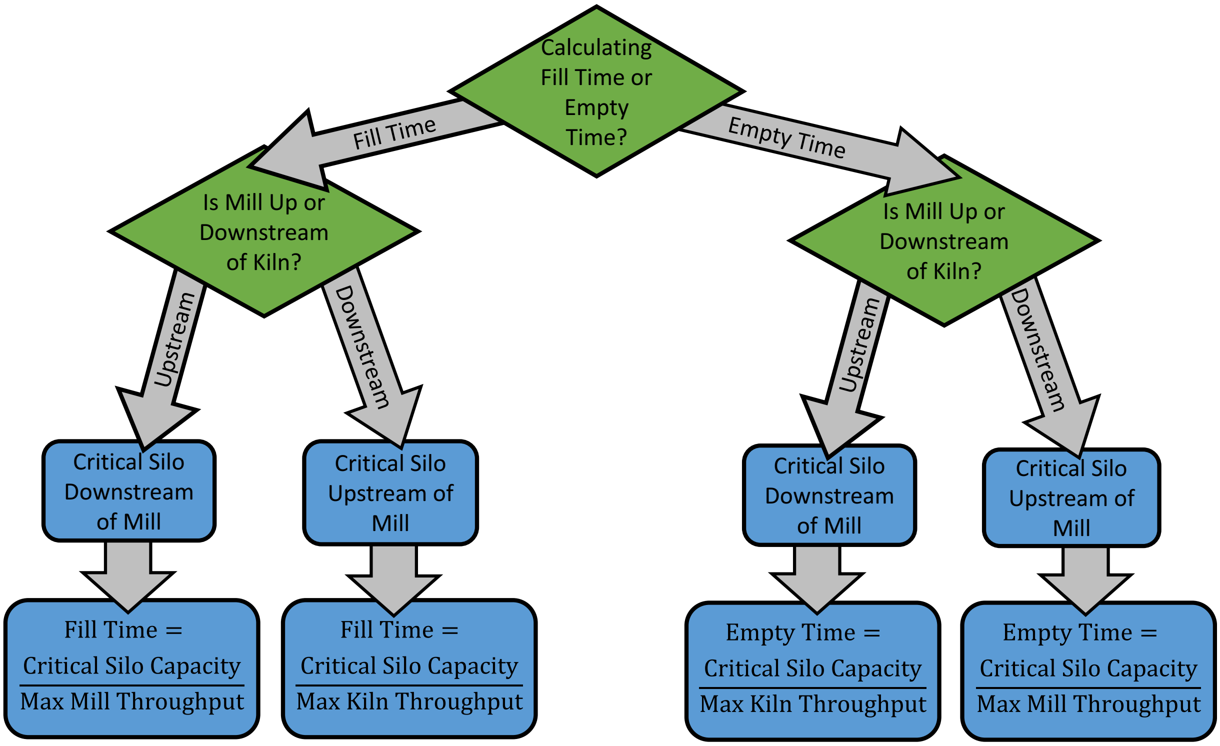

Fig. 4. Process to calculate fill & empty times.

Eq. (1): Financial cost of schedule.

$$\sum_{\text{Allhalf hour periods}} E_{\text{half hour}} \times (SP_{\text{half hour}} + AO) \tag{1}$$

where: E = energy used in kW h, SP = spot price in £/kW h, and AO = price add-ons in £/kW h.

Eq. (2): Carbon Emissions from schedule.

$$\sum_{\text{Allhalf hour periods}} E_{\text{half hour}} \times (GI_{\text{half hour}}) \tag{2}$$

where GI = Grid CO_2 intensity in g/kW h.

A further calculation was made using electricity spot prices in place of the actual values charged by the electricity supplier [43]. Spot prices are the wholesale price of electricity, and as such vary in proportion with the cost of production. Using these in lieu of the

Table 1
Assumed carbon intensities of grid sources [42].

Source	Intensity (TCO_2/MW h)
Coal	0.91
Nuclear	0
CCGT	0.36
Wind	0
French Interconnector	0.09
Dutch Interconnector	0.55
Irish Interconnector	0.45
East West Interconnector	0.45
Pumped Storage	0
Hydro electric	0
Oil	0.48
OCGT	0.61
Other	0.3

actual prices will determine how the scope for DSM would change if suppliers passed on more of the variation in cost to their consumers.

2.3.4. Kiln schedule

Given that in reality the kiln does not run 24 h a day 365 days a year, the effect of being able to shift the kiln schedule to avoid high cost periods was also estimated. Since the kiln is only shut down for maintenance, it was assumed that the kiln would need a minimum 24 h scheduled run period, rather than being calculated on a half-hourly basis. Accordingly, the number of days run by the kiln during the year was calculated, and the kiln scheduled to run on either the cheapest days, or the lowest carbon days, depending on whether the schedule was being optimised for carbon intensity or electricity price. The schedule optimisation process was then re-run to estimate the total benefit of scheduling kiln-shut downs for low cost or low carbon days. This will likely produce an overestimate, as not all kiln shut-downs are planned, and therefore not all stoppages could be scheduled in advance. Moreover, shut-downs usually last considerably longer than 24 h. However, by capturing the maximum possible benefit from rescheduling the kiln, this method will indicate whether it is an option worth further investigation.

2.3.5. Kiln hours estimate

Data was not available on the exact times for which the kiln ran in 2015. Instead, the total kW h consumed on a half-hourly basis was available, as were the total kiln run hours per day. This gave accurate actual values of electricity cost and carbon footprint, but the demands of the kiln had to be estimated (necessary to calculate an optimised schedule the mills for those scenarios where the kiln demand was taken as fixed). It was decided to assume that the kiln was running when the total consumption of the plant was greater than a certain threshold. This threshold was chosen to minimise the total error between kiln hours run over the course of the year and estimated kiln hours used by the model. This was in order to ensure that the actual production of the plant would match the production from the optimised schedule.

As such, the total kiln hours for the plant and for the model agreed to within 0.01%. The run hours on a daily basis were predicted with an accuracy of ±5%. This was deemed sufficiently accurate to provide a 'realistic' kiln schedule for the mill schedule to supply.

2.3.6. Baseload

Initial investigation of the data showed that the actual power consumption of the plant was considerably higher than that predicted by the model. This is to be expected, as the assumptions made in the model are 'best case' estimates. Some of the difference between the 'predicted' and actual value will be due to necessary operational requirements, such as a need to run mills at reduced throughput (without reduction in power consumption) in order to produce finer grinding. It might be possible to shift this additional consumption to lower-cost hours. Some of the difference may occur due to inefficient operation, such as unnecessarily running equipment, or running machinery off-design or below maximum efficiency.

In order to exclude this 'extra' power from the calculation of the benefit of shifting the known loads, the difference between the predicted and actual consumption was included as a constant-value 'additional baseload' power, over and above the rated baseload of the plant, in order to make the total power consumption of the factory the same for both modelled and actual values.

The possible benefit of shifting this additional baseload power to low cost times was separately estimated. This was achieved by modelling the additional baseload power consumption as a single unit with power rating given by Eq. (3). It was additionally assumed that no silo constraints applied to this unit, so it could be run at the lowest-cost times. This is likely to provide an overestimate of the possible benefit from rescheduling this additional power, but will indicate whether it can be neglected or if it is worthy of further investigation.

Eq. (3): Additional power rating.

$$P_{base} = \sum_{all\,mills} P_{Mill} \times (1 - U_{Mill}) \qquad (3)$$

where P_{base} = additional baseload power in kW, P_{Mill} = Mill power in kW, and U_{Mill} = Mill utilisation %.

In addition, the difference between the optimal schedule and the actual power consumption of the plant may include opportunities for electrical energy efficiency. At best, only a proportion of this difference is likely to be available for potential savings. However, if the difference is large, it might indicate opportunities for savings, and therefore should prompt further investigation.

2.4. Benchmarking

In order to protect the sensitive commercial data provided by Hanson UK, but still give a sense of the scale of savings available from load-shifting, the following benchmark data were used:

Any theoretical reductions in cost or carbon emissions calculated from the optimised schedule will be expressed as a percentage reduction of the actual value. These percentage reductions will then be applied to the values in Table 2 in order to give reductions in terms of £/year or tonnes of CO_2.

Table 2
Benchmarking values.

Benchmark	Value	Unit	Source
Cement Plant Specific Electrical Energy Consumption	111	kW h/tonne cement	[44]
Annual UK cement capacity	12,000,000	Tonnes/year	[45]
Number of UK plants	11		[45]
Capacity of typical plant	1,090,000	Tonnes/year	Calculated from above
Average electricity price	7.251	p/kW h	[46]
Carbon footprint of electricity	353	g/kW h	See Table 1
Carbon footprint of cement	846	kg CO_2/tonne	[47]
Typical annual electricity cost	£8,780,000	£/year	Calculated from above
Typical electricity-derived CO_2	42,745	Tonnes/year	Calculated from above

3. Results & discussion

The model produced four sets of outcomes: The effect on cost and the effect on CO_2 emissions when the schedule was optimised by electricity price, and the effect on cost and on CO_2 emissions when the schedule was optimised for carbon intensity of electricity.

3.1. Schedule optimised for electricity price

Fig. 5 shows the potential cost reductions of the various schedules, scaled to benchmarked costs (see Section 2.4). The first column (Shift Load: Weekly Forecast) shows the cost reduction available from shifting load, assuming that electricity prices are known a week in advance, and the schedule is set every three days. The next two columns (Shift Load with Monthly Forecast & Shift with Annual Forecast) show the *additional* value of knowing the prices a month in advance, or a year in advance accordingly.

The 'Shift Kiln' column shows the additional saving possible if it were possible to schedule the days on which the kiln ran according to average electricity prices for the day, rather than assuming that the kiln schedule was fixed. The 'Expand Silos' column shows the additional savings available if the size of the silos is not treated as a constraint. The size of this value can also be seen as a measure of the effectiveness of the optimisation algorithm in Fig. 3, as a more complex algorithm may be able to more effectively meet the silo constraint.

The final two columns deal with the difference between the actual power consumption of the factory, and the 'minimum required' consumption predicted by the model. Being able to shift this additional consumption to the cheapest times would result in the additional savings in the 'Shift additional load' column. Being able to eliminate this consumption entirely would result in the savings in the 'Theoretical Baseload' column. These opportunities are mutually exclusive, so are not shown as additive savings. It is also worth noting that this opportunity for savings is not directly comparable with the other values, as it is unlikely that all of this opportunity would be recoverable.

3.1.1. Potential cost savings from shifting load

Fig. 5 shows that the financial value of shifting the mill schedules according to the forthcoming week's electricity prices is substantial −4.2% of electricity costs, or £370,000 when scaled to benchmarked values. Given that electricity costs can make up half of the fuel costs of a plant, this is a substantial saving. This finding would indicate that there is most probably significant scope for increased load shifting in this plant, even if the electricity prices are only known a week in advance, as in the current scheduling system.

Moreover, the additional value of switching to a monthly forecast is very small, and indeed the calculated additional value of the annual forecast is slightly negative. In other words, repeating the scheduling process every 15 days results in a schedule that uses fractionally less electricity than the single-pass schedule with a year's forecasting data. However, this negative value is negligible (0.02% of total costs), and as such is represented in Fig. 5 as a zero additional benefit to scheduling with an annual forecast. This small benefit from a longer-range forecast indicates that most of the variation in the electricity price that scheduling can capture occurs on the hour-to-hour or day to day scale, rather than week-to-week or larger.

3.1.2. Other opportunities for cost savings

The value of shifting kiln shut-downs to high cost days is relatively small. Given that this is also a high-complexity opportunity, as kiln-shut downs are not always predictable or easily scheduled, this small value would indicate this opportunity is not worth further investigation at this stage.

The relatively small value of neglecting the silo constraint (shown in the Expand Silos column) indicates three things. First, it reinforces the indication that most of the price variation is on the hour-to-hour or day-to-day scale. If the price variation on the macro scale was large, there would be greater value in being able to use larger silos to shut down mills during long periods of high electricity prices. In addition, it indicates that the relatively simple algorithm in Fig. 3 produces a solution to the silo constraint close to the solution that neglects that constraint, and as such a more complex algorithm is not necessary in this case. Finally, it indicates that the silos are large enough that they are not the principal constraint on load shifting, and as such the value of expanding them would be relatively small.

Finally, the values associated with the 'additional load' – i.e. that load not predicted by the rated values used in the model, are large. Being able to shift this additional load to low cost times is of similar value to rescheduling mills. As such it is certainly worthy of further investigation. In additional, the size of this 'additional load' is substantial, such that being able to reduce it by 35% would have a similar cost saving effect to rescheduling the mills on a week-to-week basis. While it is not likely that it will be possible to eliminate this entire 'additional load,' as some of it will be due to operational constraints not accounted for by the model, some of it may well be possible to eliminate. For example,

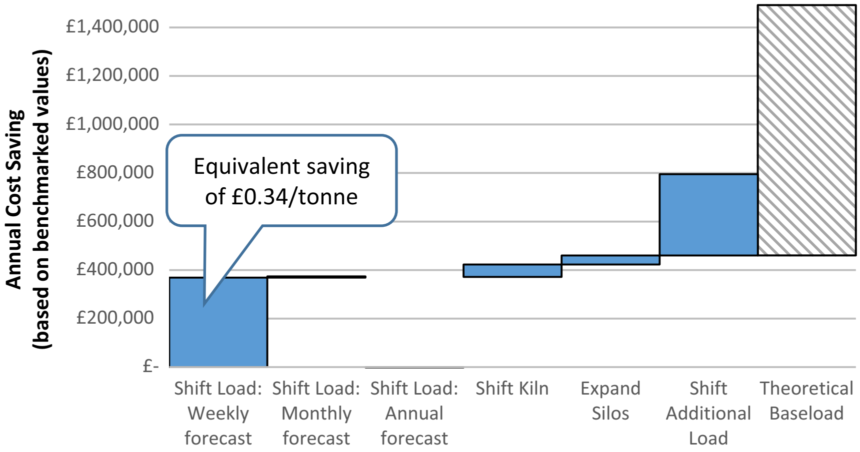

Fig. 5. Potential cost reductions, schedule optimised for price.

if mills are run below full capacity they may be operating off-design, and as such operating at lower efficiency. While it is likely that these opportunities will be more challenging to turn into savings, their substantial size indicates they are at least worthy of further investigation.

3.1.3. Effect of load shifting on power profiles

The analysis compared the actual power consumption of the plant to the projected power consumption of the optimised schedule (with annual forecast, no shifting of kiln or baseload), over various timescales. It is worth noting the total power consumption of both schedules was the same over the year (see Section 2.3.6); only the time of use of the power varied. Fig. 6 shows the variation between the two schedules on an hourly basis. This shows that the largest difference between the schedules occurs on an hourly basis, shifting load to from day to night time. Fig. 7 also a modest shift in consumption, from Thursday and Friday to the weekend. The difference between power consumption in different months, shown in Fig. 8, is much smaller. This reinforces the conclusion that the price variation is most significant on an hour-to-hour scale, hence the low value of longer forecasting. The power shifted from peak to off-peak is, on average, 0.5 MW. When the forecasting is restricted to a week in advance, the power shifted from peak to off-peak is 1 MW (~30% of total consumption). The larger shift from peak to off-peak when only a shorter price forecast is available is an expected result, as the optimisation process will then focus on short-term price fluctuations.

It is also worth noting that the hourly profile of the actual schedule is more or less flat. This would imply that, currently, the plant is not particularly responsive to the variation in prices currently charged by the electricity provider.

3.1.4. Carbon savings from cost-optimised schedule

Fig. 9 shows the carbon reductions associated with a schedule intended to minimise electricity costs. The relative size of the carbon reduction from each opportunity shows a similar pattern to the cost reductions. Shifting based on a weekly forecast would save just under 1000 tonnes per year of CO_2. Being able to predict prices a month or year ahead gives very little carbon reduction to the week-ahead forecast. Similarly, there is little carbon reduction associated with shifting the kiln shutdowns to high electricity price days. Increasing the size of silos (eliminating the silo constraint, and allowing the mills to operate only on lowest cost days) would have only a small effect on CO_2 emissions.

Shifting the ‘additional baseload’ to low-cost times would provide modest additional carbon savings. However, if this additional baseload could be eliminated completely, the savings would be much larger. This indicates that the potential carbon savings from reducing electricity use are larger than savings from shifting power usage to lower price times.

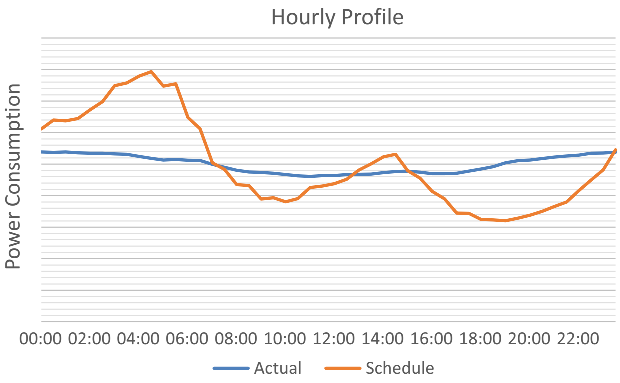

Fig. 6. Power consumption hourly variation.

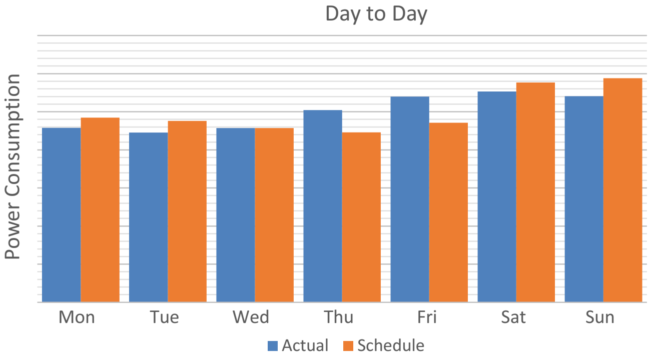

Fig. 7. Power consumption daily variation.

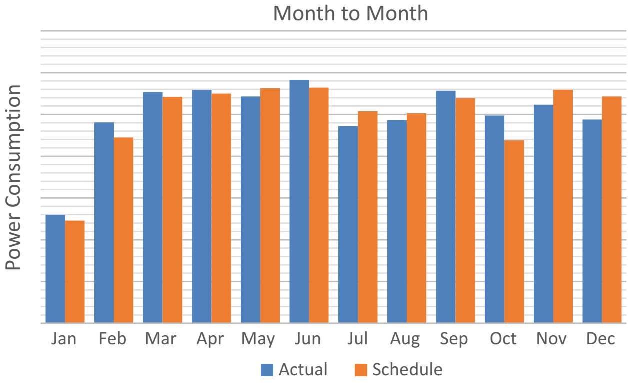

Fig. 8. Power consumption monthly variation.

It is worth noting that, given that the total carbon emissions from a typical plant (based on Table 2: Benchmarking Values) are of the order of magnitude of 750,000 tonnes of CO_2 per year, the size of potential savings (of order 1000 tonnes/year) is relatively small.

3.2. Schedule optimised for electricity carbon intensity

Fig. 10 shows the effect of optimising the production schedule to run at times when the electricity supply had the lowest carbon intensity. The potential saving from optimising with a week’s foreknowledge of carbon intensities is around twice that when the schedule is optimised for electricity price, as in Fig. 9. The saving from this, of the order of 2000 tonnes per year, is still small relative to the overall carbon emissions of the plant, but would be the equivalent of reducing the average carbon footprint of electricity consumed by the plant from 351 g/kW h to 336 g/kW h. The average value for the carbon footprint of the grid as whole was calculated at 353 g/kW h. If similar savings were achieved at all of the UK’s cement plants, it would save ~20,000 tonnes of CO_2 per year.

The additional benefit of being able to forecast carbon intensity further in advance is small. There would be an additional saving of ~1200 tonnes of CO_2 from scheduling kiln shutdowns on days where the average carbon intensity is high. However, according to the model’s assumptions, this would require being able to forecast carbon intensities a year in advance, which would be impractical, and assumes kiln shutdowns are all scheduled in advance, and can always be as short as 24 h. As such it is unlikely that all of this opportunity would be easily recoverable.

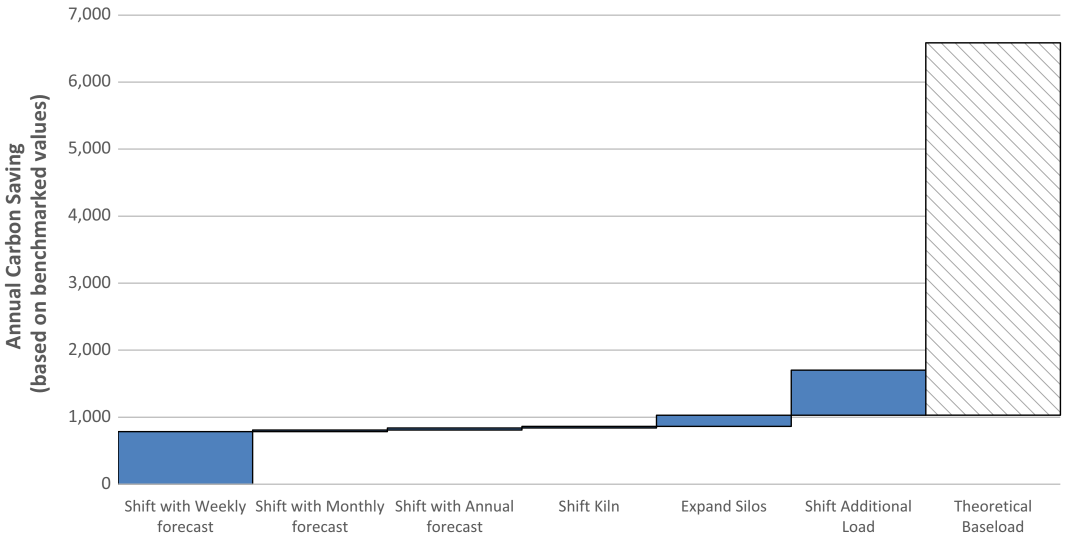

Fig. 9. Potential carbon reductions, schedule optimised for price.

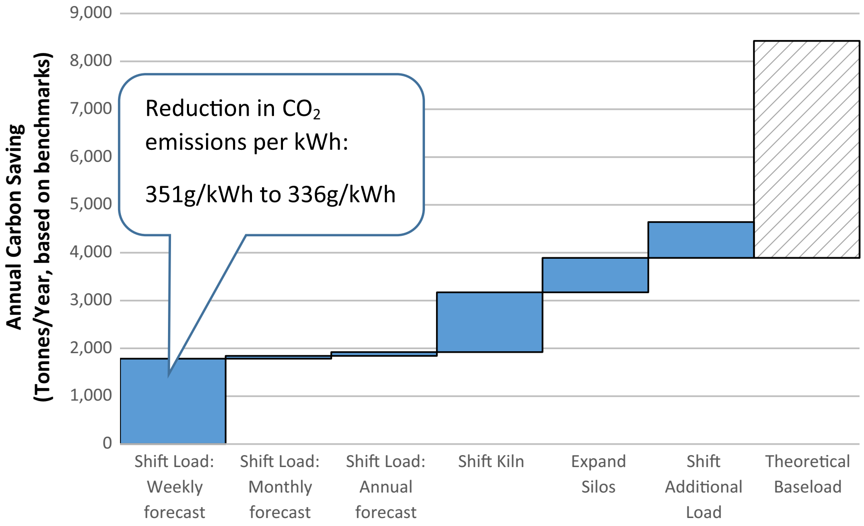

Fig. 10. Potential carbon reductions, schedule optimised for carbon.

The additional benefit of eliminating the silo constraint is moderate compared to the benefit from shifting the modelled load. Relatively speaking, it is larger than the reduction in cost from expanding silos in the cost-optimised schedule (see Fig. 5). This could imply that the variation in carbon intensity of electricity has fluctuations that are more volatile than the cost passed on to consumers, with the result being that the plant is less able to operate at the lowest-carbon times than the lowest prices times. Alternatively, it could imply that a recursive optimisation algorithm would capture more of this potential reduction than the simplified one described in Section 2.

The additional reduction of CO_2 of shifting the additional baseload to low-carbon times is of similar size to that of shifting it to low cost times, as seen in Fig. 9. The saving associated with eliminating this additional baseload is slightly smaller, as some of the benefit from eliminating electricity use has already been realised by shifting to lower-carbon days.

Fig. 11 shows the cost reductions associated with a schedule optimised for carbon. They are still substantial, but around half that associated with the schedule optimised for electricity price. The result indicates that a plant could still achieve cost reductions of around 2% while focusing its efforts on minimising the carbon emissions associated with its electricity use by scheduling the plant to run at low carbon times (based on a week-ahead forecast). This would save ~£200,000 and ~2000 tonnes of CO_2 per year.

The pattern in the relative sizes of the opportunities is similar to that in Fig. 5, in that the largest savings are associated with shifting load based on a week's forecasted data. The additional benefit of longer forecasting is very small. The financial benefit of shifting the kiln is fairly small, at most ~£70,000/year and, given the complications discussed above, unlikely to compensate for the logistical difficulties of scheduling kiln shut downs for low-carbon days.

The value of shifting the 'additional baseload' to lower carbon times would come with substantial financial saving. While this is likely to be more challenging than shifting the modelled loads, as first the nature of the additional baseload would need to be identified, the value would certainly indicate that this is worthy of further investigation. As expected, the 'theoretical baseload' saving remains large, as it would involve finding and eliminating

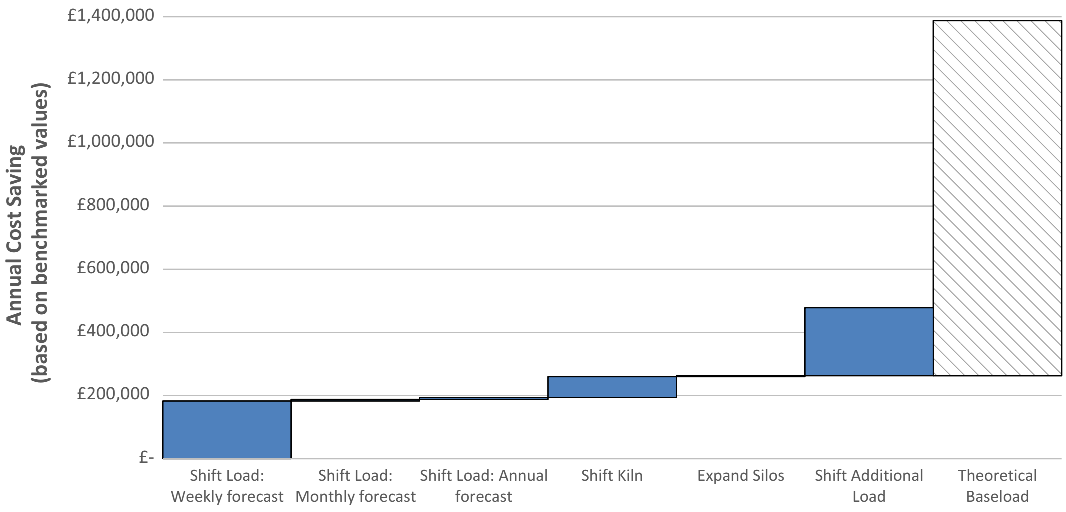

Fig. 11. Cost reductions, schedule optimised for carbon.

electricity use above that predicted by the model, rather than shifting the use to lower cost times.

3.3. Effect of spot prices

A large part (approximately 50%) of the cost of electricity charged to the cement plant comes from fixed charges levied by the supplier, meaning that only part of the cost varies between half-hour periods. In addition, the pricing model does not always match variations in the spot price. However, if spot prices were fed into the scheduling tool, the potential decrease in electricity cost (compared to the observed schedule) was approximately twice that of the savings shown in Fig. 5. This implies that there could be significant co-benefits to both consumers and suppliers if cement companies adopted increased DSM, and more variation in pricing were passed to industry.

3.4. Comparisons with literature

The results were compared with the study on DSM in Ireland [19] that found that manufacturing facilities can increase their use of wind power by 5.8% for every 10% decrease in cost they achieve through DSM. This study finds a similar result: that carbon intensity decreases by 4.4% for every 10% decrease in cost achieved through rescheduling of load, when the load is scheduled to seek lower costs. However, if the schedule is optimised for carbon intensity, the carbon intensity decreases by 20% for every 10% decrease in costs. This implies that the cost of electricity is not aligned with carbon intensity of generation.

Studies of Thermal Energy Storage systems [24] indicate that storage of around 100,000 kW h is required to make such a system commercially viable. The de facto energy storage of cement plant inventory can be estimated by multiplying each silo by the power consumption per tonne of the appropriate mill. The energy represented by the inventory is considerably larger than the viability threshold from literature, with even the smallest store representing around 300,000 kW h of storage.

When the schedule is based on a 1 week forecast of energy prices, around 1 MW of power is shifted from peak to off-peak, resulting in a £370,000 annual saving. This prices the saving at £375/kW, similar to values of DSM found in literature [10].

The magnitude of potential cost savings also falls within the range found in literature. Studies of other industries [19,27,29] found potential for cost savings of between 6.5% and 10%. These are of similar magnitude to the 4.2–9.1% cost savings available from the various load-shifting scenarios found in this study. As described in Sections 1.2.4.2 and 1.2.4.3, literature studies of the cement industry varied from considering DSM not possible in the cement industry [17], to being able to reduce costs from a single mill by 9.6%, or £35,000 [31]. This paper would reinforce conclusions from the latter, indicating that there is potential for wider savings by applying DSM across the whole plant. Studies of the German cement industry estimate a potential capacity of 150–313 MW [25,32,33] across 55 plants [48], or roughly 3–6 MW per plant. The estimate of 1 MW of potential for DSM found in this paper is below this level, but supports the idea that the cement industry can provide DSM, helping to mitigate variability in electricity generation.

4. Conclusions

The comparison between a theoretical and actual schedule for a cement plant shows that there exists the possibility for significant financial savings if the plant were to adopt a more flexible schedule to increase the level of demand-side management. Using the scheduling methods described in this paper, costs could be reduced by 4.2%. The value of this saving was estimated at £350,000 per year by using benchmarked values for a typical plant. These savings could be achieved using existing price forecasts, without the need for longer range price forecasts at half hourly intervals. The resultant reduction in power consumption at peak times would be around 1 MW. The plant's capacity for load shifting is not significantly constrained by the silo space available.

In addition, the study found that the actual demand for electricity was significantly higher than would be expected if the plant was using its electrically driven assets at maximum theoretical efficiency. While this area would need further study before savings could be realised, and some of this discrepancy may well be explained by legitimate operational need, there could also be scope for reducing electrical consumption by changing the way assets are used.

The reduction in carbon emissions associated with using electricity at times when the generation is less carbon intensive is of similar magnitude to the cost savings, of the order of 2% if the schedule is optimised for electricity cost, or 4% if the schedule is optimised for carbon intensity. In the latter case the cost savings would be roughly half that of the former. However, the magnitude of savings, of the order of 1000–2000 tonnes of carbon dioxide per year, is small compared to the overall carbon emissions from a cement plant. If the load shifting techniques applied in this paper can be applied more broadly, particularly to other industries, then the environmental benefits of renewable generation can be maximised by mitigating the intermittency of wind and solar generators.

While the precise magnitude of the potential savings will depend on the operational parameters of other plants, it is likely that applying the scheduling method described in this paper to other cement plants would uncover opportunity for DSM, and allow an estimate of the financial and environmental benefit of using such scheduling techniques. The authors encourage enquiry from industry as to how the techniques described can be applied, and the models used (stripped of sensitive commercial data) will be available online.

The financial value of DSM would, according to results, be approximately doubled if the price for electricity paid by the consumers at the cement plant varied in direct proportion to the spot price. Savings would then be of the order of £650,000, when scaled to benchmarked values, assuming that the average price of electricity remained the same but that the half hourly prices varied more widely, in proportion to the spot price. Collaboration between industry and electricity suppliers to pass on more of the price variation to those industrial consumers with the flexibility to shift loads could therefore be beneficial to both parties.

It is likely that increased generation from wind power in future will increase the variation in both electricity price and carbon intensity. In this case the scale of possible savings, both financial and in terms of carbon emissions will increase. Future work in this area should focus on estimating the nature of this increase. In addition it would be worth assessing the extent to which a cement plant could be powered directly from a variable output renewable generators such as wind farm, given the large storage capacity and scope for DSM found in this paper. There is also scope to apply the method described in this paper to a wide range of industries in order to estimate the potential scope for load-shifting. Again, the authors warmly encourage enquiry from industries who would be interested in making such an estimate.

Given the likely intermittent nature of future electricity generation, it is possible that future manufacturing plants could be designed with larger capacity for inventory, and larger spare capacity in their non-bottleneck electricity using units. For example, a future cement plant could be designed, based on the theory described in this paper, with large enough silos and mill capacity that it could be run entirely off renewable energy. This would lead to higher inventory costs, but these are unlikely to affect the cement industry, as raw material costs are low, and much of the cost associated with inventory comes from electricity use. As such, current inventory levels in the cement industry tend to be high, so it is unlikely large increases would be required in order to allow for savings. However, for manufacturing industries with higher inventory costs, the trade-off between electricity savings and increased inventory costs would have to be evaluated before implementing any changes resulting from the findings.

The key findings of the paper can be summarised as follows:

1. A method was demonstrated that produces a low cost (or low carbon) schedule for any production process with spare capacity in electricity-consuming machinery. It was demonstrated on a case study of a cement plant.
2. It was estimated that rescheduling the milling to minimise cost could save £350,000/year in electricity costs (4.2% of total), and reduce CO_2 emissions by $\sim$1000 tonnes/year (2% of electricity-derived emissions). This would require electricity prices to be known a week in advance.
3. Alternatively, rescheduling the milling to minimise CO_2 could reduce emissions by 2000 tonnes/year (4% of emissions) and save £180,000 (2% of costs).
4. This alternative schedule would reduce power consumption at peak times by around 1 MW.
5. The actual power consumption of the plant was significantly higher than that theoretically required to achieve the recorded production. Investigating this discrepancy could lead to substantial carbon and cost savings, either by reducing unnecessary electricity use or shifting more load to off-peak times.
6. Increased volatility in pricing or carbon emissions in future will increase the value of the load shifting described in this paper. This increase could occur due to policy changes, such as passing on spot prices directly to consumers, or an increased share of renewable energy in the generation mix.

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